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Research Paper

# A model combining landings and VMS data to estimate landings by fishing ground and harbor

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ABSTRACT

At present, the assessment and management of Adriatic Sea fishery resources are based on data that do not fully account for the complex spatial patterns arising from fleet behavior and/or species' behavior and biology, mainly because logbooks do not guarantee adequate coverage of the fishing activity exerted by the fleet. For data collection, the Adriatic Sea is divided into two management areas (namely FAO Geographical Sub-Areas–GSAs). To account for these spatial patterns while using the data available, we propose a method for estimating the monthly landings of Italian trawlers operating in the Adriatic Sea at a higher spatial resolution than the GSA. We use a stepwise approach based on the combined analysis of questionnaire-derived vessel-specific landings and the spatial activity of the vessels with respect to a set of fishing grounds. Thus, we sequentially 1) analyze the available vessel monitoring system data, 2) partition the study area into fishing grounds (the origin of the landings), 3) cross analyze vessel-specific fishing efforts with the available vessel-specific monthly landings to estimate the LPUE of each fishing ground, and 4) estimate the monthly landings (by vessel, fishing ground, and harbor) for the whole fleet and the monthly fluxes between fishing grounds (origin) and landing harbors (the destination of the landings). We apply the method to two species: the Norway lobster and the European hake. For both species, we find a few fishing grounds to be consistently more productive than others and the landings per harbor to vary greatly but with few harbors regularly receiving a significant share. In particular, the results suggest that the Pomo/Jabuka pit area represents a critical area for both species. Additional outcomes include a detailed characterization of the activity of the Adriatic bottom trawling fleet, highlighting the strengths and shortcomings of the official data available. We discuss the results in the context of the current management paradigm.

## 1. Introduction

In the Mediterranean Sea, resources are managed at the Geographical Sub-Area (GSA) scale (Cataudella and Spagnolo, 2011). The definition of GSAs is based on jurisdictional and management convenience, rather than biological inference (Smedbol and Stephenson, 2001; Stephenson, 1999). Official fishery-dependent data (i.e., catches and landings) are delivered at the same scale. To appropriately account for complex patterns of fleet behavior and/or different aspects of species behavior and biology, the assessment of the status of several species of commercial interest may need to be based on data collected at a higher spatial resolution than the GSA. The FAO General Fisheries Commission for the Mediterranean (GFCM) and the EU Scientific, Technical and Economic Committee for Fisheries (STECF) have repeatedly recognized the limits of a GSA-based approach, but an alternative has yet to be found (STECF, 2014). However, the modification of National Programs for the Data Collection Framework (DCF) may not be possible or immediately feasible and would not solve the problem for past data. In this paper, we propose a method to split the official GSA-based landings into sub-zones of interest both in terms of the landings origin (i.e., the fishing ground) and destination (i.e., the harbor) by estimating the monthly landings according to a higher spatial

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resolution. The proposed method would also allow the application of modern modeling approaches based on a spatial management of fishing effort (Bastardie et al., 2014; Campbell et al., 2014; Dunn et al., 2011; Holland, 2003; Mchich et al., 2006; Pelletier et al., 2009; Russo et al., 2014a; Russo et al., 2017; Sampson et al., 2011; Zeller and Reinert, 2004). In fact, these methods entail the reconstruction of the origin and the fate of catches and landings in terms of well-defined areas and times in which resources are harvested and harbors to which they are delivered for sale, respectively. Although fishing logbooks could represent the master source for estimating the landings by species and harbor (Gerritsen and Lordan, 2011), there is evidence that fishers are reluctant to provide complete information about the location of fishing grounds (Sampson, 2011). Additionally, for several reasons such as the high number of fishing vessels (more than 13,000), the numerous landing locations scattered over 8000 km of coastline, the high number of species landed, and the consequent difficulty in ensuring appropriate monitoring and control of the landings declared in the logbooks, logbooks do not record all Italian landings. Consequently, Italian landings data are collected through a statistical sampling scheme, based on questionnaires, and official landings are estimated from a subsample of the fleet, that are then raised to the total of the fleet (EC, 2008; EUROSTAT, 2015). This, and similar methodologies, are applied in other Mediterranean countries with similar characteristics. To integrate this approach, the method we propose combines questionnaire-derived vessel-specific landings with the spatial origin of the landings as reconstructed *a posteriori* using the Vessel Monitoring System (VMS). In EU waters, the VMS comprises a tracking device on board each fishing vessel with length overall (LOA) ≥ 15 m (EC, 2011) that periodically sends data on vessel position, speed, and heading to a network of land-control stations via satellite transmission. VMS data are widely used in the scientific literature for analyzing fishing effort patterns (Campbell et al., 2014; Lambert et al., 2012; Russo et al., 2016) and for assessing fishing impacts (Eigaard et al., 2016; Gerritsen et al., 2013; Scarcella et al., 2014). We apply the method to two species fished by Italian trawlers operating in the Adriatic Sea: the Norway lobster (*Nephrops norvegicus*, L. 1758–NEP hereafter) and the European hake (*Merluccius merluccius* L. 1758–HKE hereafter). It is our hope that this method will provide a standard that could be applied to any Mediterranean GSA should the necessity of splitting official data into smaller spatial entities arise. At the time of writing, the smallest spatial unit for data collection (and assessments) in the Mediterranean is the GSA. This means that any stock whose areal distribution/definition is smaller than the GSA has to be aggregated with all other stocks in the GSA to be assessed together at a GSA level. In situations where the population dynamics of these smaller "stocks" or stocklets are different from others within the same GSA (e.g., NEP in GSA 17), assessments at a GSA level will provide distorted pictures of the situation. Among the outputs of the methodology we propose are estimates of the landings for sub-zones of a GSA, allowing stock assessments of these particular species to be based on the best ecological knowledge available rather than having to tailor them to the structure of the official data at hand.

## 2. Materials and methods

### 2.1. Study area

The Adriatic Sea (Fig. 1) is the portion of the Mediterranean basin located between the Italian Peninsula and the Balkan Peninsula. It is more than 150–200 km wide, covering an area of approximately 138,000 km$^2$, and can be divided into three basins (northern, central and southern) characterized by different widths and topographic gradients. A combination of geopolitical and geomorphological characteristics led to the subdivision of the Adriatic into two GSAs for the purpose of fishery management (Fig. 1a). GSA 17 (north and central Adriatic) includes Croatia, Bosnia-Herzegovina, Italy and Slovenia, while Italy, Albania and Montenegro comprise the southernmost GSA 18. The Pomo/Jabuka pit area comprises three depressions (> 200 m depth) in the middle of the Adriatic Sea (Fig. 1a), covering an area of approximately 2000 km$^2$. Owing to a peculiar combination of bottom morphology and position, it hosts important spawning and nursery areas for several species of commercial interest, including the species targeted in this study (Colloca et al., 2013). The resources in the Pomo/Jabuka pit area are shared among the fleets of different countries (mainly Italy and Croatia) and are subjected to high fishing pressure. With the aim of protecting the main HKE nursery area in the Adriatic Sea, an area corresponding to approximately 2750 km$^2$ and including the Pomo/Jabuka depressions in international waters was closed to bottom trawling for over one year (~15 months from 25/07/2015 to 16/10/2016) within an Italian-Croatian management agreement (Italian Administrative Order. 03/07/2015). This agreement demonstrates a shift from the traditional Mediterranean management paradigm resting on the regulation of fishing capacity towards one based on spatial planning.

### 2.2. The fleet, the main target species and the fishery

Mediterranean Sea and Black Sea fisheries are classified by "métier" (https://datacollection.jrc.ec.europa.eu/wordef/fishing-activity-métier), which represents a group of vessels with the same "exploitation pattern" (i.e., gear used and target species) over time and reflects the fishing intention at the start of the fishing trip (Marchal, 2008). Demersal fishing in the Adriatic Sea consists of only one métier, namely bottom otter trawl (OTB) (Fouzai et al., 2012). According to the Common Fleet Register (CFR-EC, 2010), Adriatic trawlers do not exceed 25 m in LOA. The NEP is the most valuable crustacean species landed in the Adriatic Sea, where it is exploited predominantly by bottom trawls (Ungfors et al., 2013; Vrgoč et al., 2004). In the Adriatic Sea, the NEP occurs at depths from approximately 50 m to over 400 m (Wieczorek et al., 1999), with important concentrations occurring at approximately 70 m depth off Ancona and at approximately 220 m in the Pomo/Jabuka pit area and in the Croatian channels (Anon., 1994; Froglia and Gramitto, 1988, 1986, 1981; Karlovac, 1953). The NEP population in the Pomo/Jabuka pit area is of particular interest owing to the high density of individuals, which, for a number of possible reasons, are characterized by slower growth compared to those present in the rest of the Adriatic Sea (Anon., 1994; Froglia and Gramitto, 1988, 1981).

The HKE is the most important demersal species in the Adriatic Sea in terms of both catches and commercial value (IREPA, 2012; UNEP-MAP-RAC/SPA, 2014). With the exception of a small area north of the Po river, the HKE in the Adriatic is found from several meters depth in the coastal areas to 800 m of the south Adriatic (GSA18), but the most abundant population is located at depths between 100 m and 200 m (Jukić-Peladić et al., 1999; Kirinčić and Lepetić, 1955; Ungaro et al., 1993; Županović and Jardas, 1986). The Pomo/Jabuka pit area comprises its main HKE nursery area in the Adriatic Sea (Colloca et al., 2013).

According to the most recent STECF (STECF, 2016) and GFCM (SAC, 2015) reports, the HKE in the Adriatic Sea is overexploited, while the status of the NEP is unassessed. In Italy, landing points are scattered along the coast, 39 of which are in the Adriatic Sea: 27 in GSA 17 and 11 in GSA 18 (Fig. 1a). The landings for both the NEP and the HKE are entirely sold at market, and demand largely exceeds landings (Parliament European, 2008), without export to foreign countries. The NEP and the HKE are consumed fresh, without processing.

### 2.3. Rationale of the model

Given a partitioning of the Adriatic Sea into $G$ fishing grounds (see section 2.5), a fleet composed of $V$ vessels, targeting a set of $S$ species, over a time frame of $T$ time intervals (months), the model presented in this paper firstly aims at estimating the $LPUE_{s,g,t}$ for the species $s$ in the fishing ground $g$ during the month $t$ for all the V vessels. The study

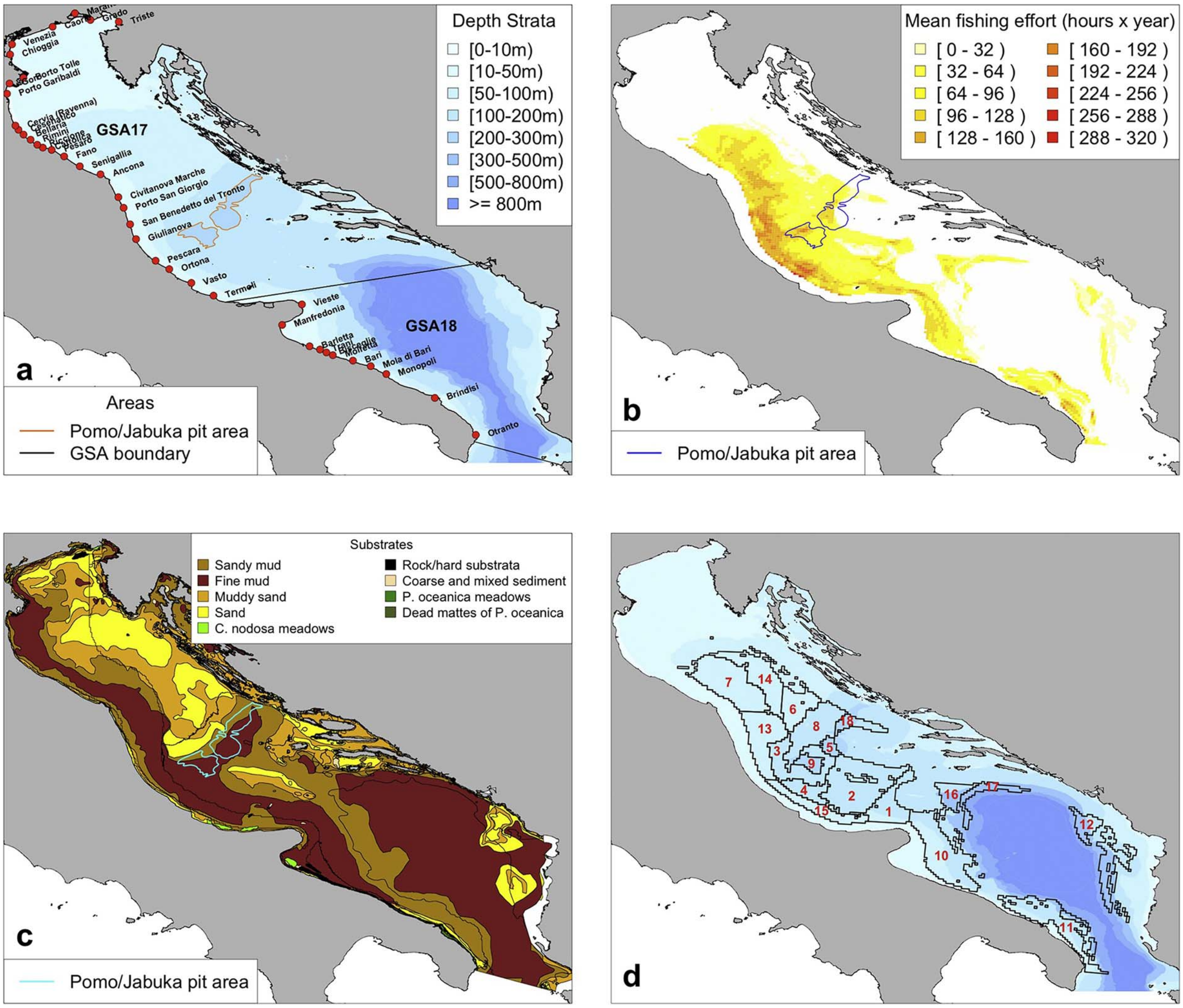


**Fig. 1.** a) Study area: the Adriatic Sea and its Italian harbors. The two FAO Geographical Sub Areas (GSAs) (blue line), the bathymetric strata and the Pomo/Jabuka pit area (red contour) are shown; b) fishing effort pattern in terms of mean totals for the years 2007–2014 in each cell of the 3 km × 3 km grid; c) bottom substrates obtained from the European Marine Observation Data Network (EMODnet) Seabed Habitats project (http://www.emodnet-seabedhabitats.eu/); and d) the 18 fishing grounds identified by the constrained clustering. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

period covers the years 2009–2014 (corresponding to $T = 72$ months) and the LPUE during each single month, $t$, is assumed to be constant.

In general, the capacity of a fishing vessel is the fishing power related to the vessel's ability to catch fish (Pascoe et al., 2001). A common assumption is that some physical characteristics (notably, size and engine power) of a fishing vessel translate to its fishing power so that "*The bigger the vessel, the greater the fishing power, in particular for trawlers*" (Reid et al., 2011). In this study, the fishing power was computed using the recent findings of EU BENTHIS Project (Eigaard et al., 2016; http://benthis.eu/) relating the *overall footprint size* OFS (i.e. the opening of the towed gear) to vessel length ($l_v$) using the following equation:

$$OFS_v = a \times l_v + b \tag{1}$$

Where terms $a$ and $b$ assumed the values described for the OT_MIX_CRU_DMF métier in Table 4 of Eigaard et al. (2016). This métier considered in BENTHIS corresponds to bottom otter trawling in the Mediterranean Sea and parameters $a$ (3.9273) and $b$ (35.8254) were estimated using observations including the Italian Adriatic trawlers (A. Sala pers. comm.).

Thus, if $e_{g,t,v}$ is the fishing time (total duration of the hauls in hours) exerted by a vessel $v$, during fishing trips taking place in the time period $t$, on fishing ground $g$, and $l_v$ is the LOA of the vessel $v$, fishing effort, $f_{g,t,v}$, is given by:

$$f_{g,t,v} = e_{g,t,v} \times OFS_v \tag{2}$$

We will also assume that, on average, the landings (kg), $L$, corresponding to the fishing activity of a vessel $v$ at time $t$ in the fishing ground $g$ are given by:

$$L_{s,g,t,v} = LPUE_{s,g,t} \times f_{g,t,v} \tag{3}$$

where $LPUE_{s,g,t}$ is specific to fishing ground $g$ at time $t$ for species $s$.

We did not directly investigate catches, but only the landings; the discard component (if any) was thus excluded from our analyses. In support of this, the discards of both the NEP and the HKE in the Adriatic trawl fishery are reported to be very low (European Commission, 2011) and constant, thus not influencing the correlations obtained between the LPUEs and the CPUEs.

The total landings of species $s$ harvested by vessel $v$ in a given month $t$, $L_{s,t,v}$, is given by the sum of the contributions of the different fishing grounds:

$$L_{s,t,v} = \sum_{g=1}^{G} L_{s,g,t,v} \tag{4}$$

The estimation of $LPUE_{s,g,t}$ for all fishing grounds within the period considered is at the core of this approach. The estimates of $LPUE_{s,g,t}$ were obtained using three main data sources: [1] the VMS data to compute the amount of fishing time exerted by all Italian trawlers with LOA ≥ 15 m; [2] the LOA of each vessel as reported in the CFR; and [3] questionnaire-derived, vessel-specific, monthly aggregated landings data for a subset of the entire Italian fleet collected within the Italian DCF. Additional details are provided in section 2.7.

The estimation of the $LPUE_{s,g,t}$ for each species and for all fishing grounds within the period allowed us to apply Eqs. (3) and (4) to estimate the landings for all vessels for which landing information was not available but for which fishing activity could be assessed through VMS data. Given that all the fishing vessels considered in this study show a high harbor fidelity within the chosen (monthly) time frame, VMS data allowed us to assign these estimated landings to their respective landing harbor for each month.

Given the estimates of $LPUE_{s,g,t}$, and denoting the subset of vessels landing in harbor $h$ with $V(h)$ *in time period* $t$, we estimated:

- The total landings ($H_{h,s,t}$) for each harbor $h$, species $s$, and time $t$:

$$H_{h,s,t} = \sum_{V(h)} \sum_{g=1}^{G} L_{s,g,t} \cdot f_{g,t,v} \tag{5}$$

- The total landings ($L_{s,g,t}$) for each fishing ground $g$, species $s$, and time $t$:

$$L_{s,g,t} = \sum_{v=1}^{V} L_{s,g,t} \cdot f_{g,t,v} \tag{6}$$

- The flow ($F_{t,g \to h}$) of resources originating from fishing ground $g$ and arriving at landing harbor $h$ for each time $t$:

$$F_{t,g \to h} = \sum_{V(h)} LPUE_{s,g,t} \cdot f_{g,t,v} \tag{7}$$

Finally, to evaluate their goodness, the estimated values of $LPUE_{s,g,t}$ were compared with the catches per unit effort (CPUE) computed for a set of hauls monitored within the national observer program (Santojanni et al., 2015).

### 2.4. VMS data processing

VMS data were used to reconstruct the fishing activity for each Italian trawler using the VMS base R package (Russo et al., 2014b) and the procedures described in Russo et al. (2014a, 2011a, 2011b). The Italian fishing fleet operating in the Adriatic Sea comprises 666 vessels with LOA ≥ 15 m equipped with VMS. VMS data are recorded as a matrix reporting a series of pings (consecutive signals sent by the Blue Box at regular time intervals) for each fishing vessel. VMS pings belonging to the same vessel can thus be partitioned into tracks belonging to a unique fishing trip that starts and ends in the same harbor. The procedure is based on the detection of in-harbor positions as the VMS pings with speed values near to zero and within a defined buffer distance from the harbor. The high-frequency interpolated (10 min in this study) VMS pings are inspected, and fishing set positions are identified using combined speed and depth filters (see Russo et al., 2014b for details). At the end of this analysis, it is possible to obtain two datasets: I) the positions and time durations of the hauls for each fishing trip of each vessel and II) the respective harbor of landing. According to the distribution of the two species, the model's spatial domain was defined as the portion of the Adriatic Sea having a depth at sea bottom between −50 and −800 m. A 3 × 3 km grid was generated, and the subset of cells in which fishing effort falls was defined (Fig. 1b). Referring to Eq. (1), the fishing effort was then computed for each vessel, for each cell $c$ of this grid and for each month $t$.

### 2.5. Identification of fishing grounds: a constrained clustering approach

The total value of the fishing time by year, computed as the sum of the fishing time exerted by the whole fleet for each year and for each cell of the grid, was used to compute the mean fishing time across the different year (Fig. 1b). In addition, each cell of the grid was associated with its dominant type of bottom substrate (Fig. 1c). The constrained clustering approach provided by the "skater" function of the R package "spdep" (Bivand et al., 2016) was used to identify the best partitioning of grid cells with respect to three variables: depth, substrate and mean yearly fishing effort. The constrained clustering, which in this case was based on the Manhattan distance, is a semi-supervised learning algorithm, which guarantees that the fishing grounds occupy fully connected subareas of the Adriatic Sea as groups of cells having similar characteristics in terms of depth and substrate. These fishing grounds represent areas with low internal heterogeneity of fishing effort and high heterogeneity with respect to adjacent areas. The output of this clustering is represented in Fig. 1d.

### 2.6. Monthly landings and cross analysis of VMS-derived effort data

Fishing effort was intersected and cross analyzed (using fishing vessel and temporal range of the fishing activity as references) with the questionnaire-based landings data collected, within DCF, on a sample of approximately 1500 vessels accounting for approximately 10% of the total Italian fleet. This dataset included information for 83 vessels (of the total 666) operating in the Adriatic Sea for the years 2009–2014.

Questionnaires were completed by data collectors scattered along the Italian coast, on the basis of direct observation at harbor docks during the landing operations. The cross analysis resulted in a new dataset in which each of the 83 vessels in the subsample was assigned a corresponding landing (kg for each species) for each month.

### 2.7. Estimation of the LPUE and prediction of the monthly landings

The information stored in this VMS-landings cross dataset contains several zero or very low values. These low or zero landings originate mostly from vessels whose fishing goals do not include the NEP or the HKE, i.e. their fishing activity in the specific month is only marginally conducted on fishing grounds with high LPUE for NEP and HKE, which thus become an accidental catch. However, even a small number of such records may distort the estimation procedure, since the assumptions upon which Eq. (3), – (5) are based are not meaningful for non-target species. To avoid a bias in the LPUE estimates, these fishing vessels should be isolated and excluded.

The dataset has been randomly partitioned into an estimation set (80% of the observations) and a validation set (20% of the observations). Using the data of the first set, two regressions have been estimated. The first one is a Logit model characterizing records with low landings. Monthly landings were classified as a binary variable ($L_{s,t,v}^{*}$): low landings (lower than a threshold defined at 200 kg × month$^{-1}$) or high landings (higher than the threshold).

In the Logit model we regress $L_{s,t,v}^{*}$ on the spatial and temporal effort pattern of each vessel ($f_{g,t,v}$). In this way, we assume that the spatial and temporal effort pattern reflects the target species of different vessels, given that the fishing grounds are characterized by large differences in terms of LPUE for the different species in different months.

The second one estimates a model for Eq. (3), which we can rewrite as

$$L_{s,t,v} = \sum_{g=1}^{G} LPUE_{s,g,t} \cdot f_{g,t,v} \tag{8}$$

Using only effort data for the validation set, the Logit model is used to identify records with low landings. Excluding these records, a prediction on the landing for the remaining vessels has been provided using the second regression model.

In more detail, using the estimation set, the following can be described:

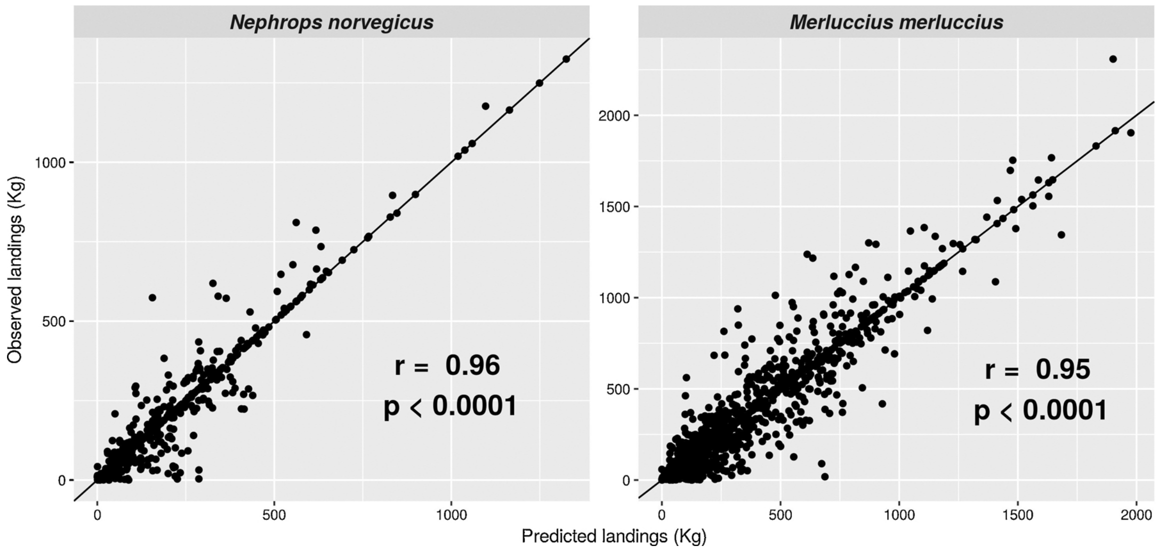


**Fig. 2.** Scatterplots representing the correlation between the predicted (nnls regressions) and the observed landings for a set of records not used for model estimation. Pearson's correlation and related $p$-values are reported.

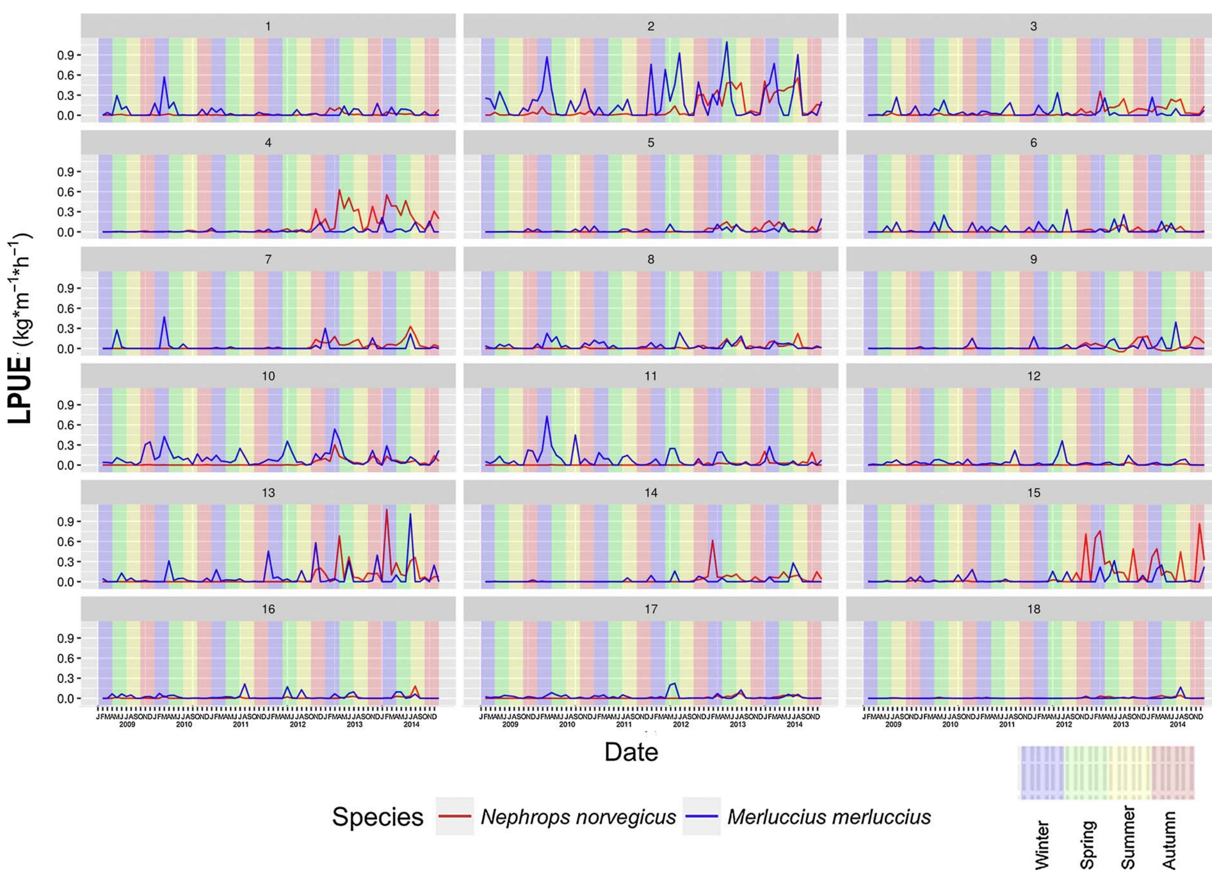


**Fig. 3.** Trends for the LPUE of both species in the 18 fishing grounds identified by the constrained cluster analysis. Each panel of the figure shows the trends for both species (identified by different colors).

1. Monthly landings were classified as a binary variable ($L^*$): low landings (lower than a threshold defined at 200 kg × month$^{-1}$ for the species considered) or high landings (higher than the threshold). A Logit model regressing $L^*$ on $f_{g,t,v}$ was estimated using the basic R function glm with the family set to binomial.
2. The records belonging to the higher landings group were used to estimate Eq. (1). The non-negative least square (NNLS) method (Lawson and Hanson, 1995) was applied to constrain the estimates of $LPUE_{s,g,t}$ to non-negative values, using the nnls function of the R package nnls (Mullen and van Stokkum, 2015).
3. The Logit model has been used to infer low landings records in the validation set. Values of $L_{s,t,v}$ were then predicted for the inferred higher landings group. The values of the inferred quantities ($L^*$ and $L_{s,t,v}$) were compared to the observed ones to assess the reliability of the predictions.

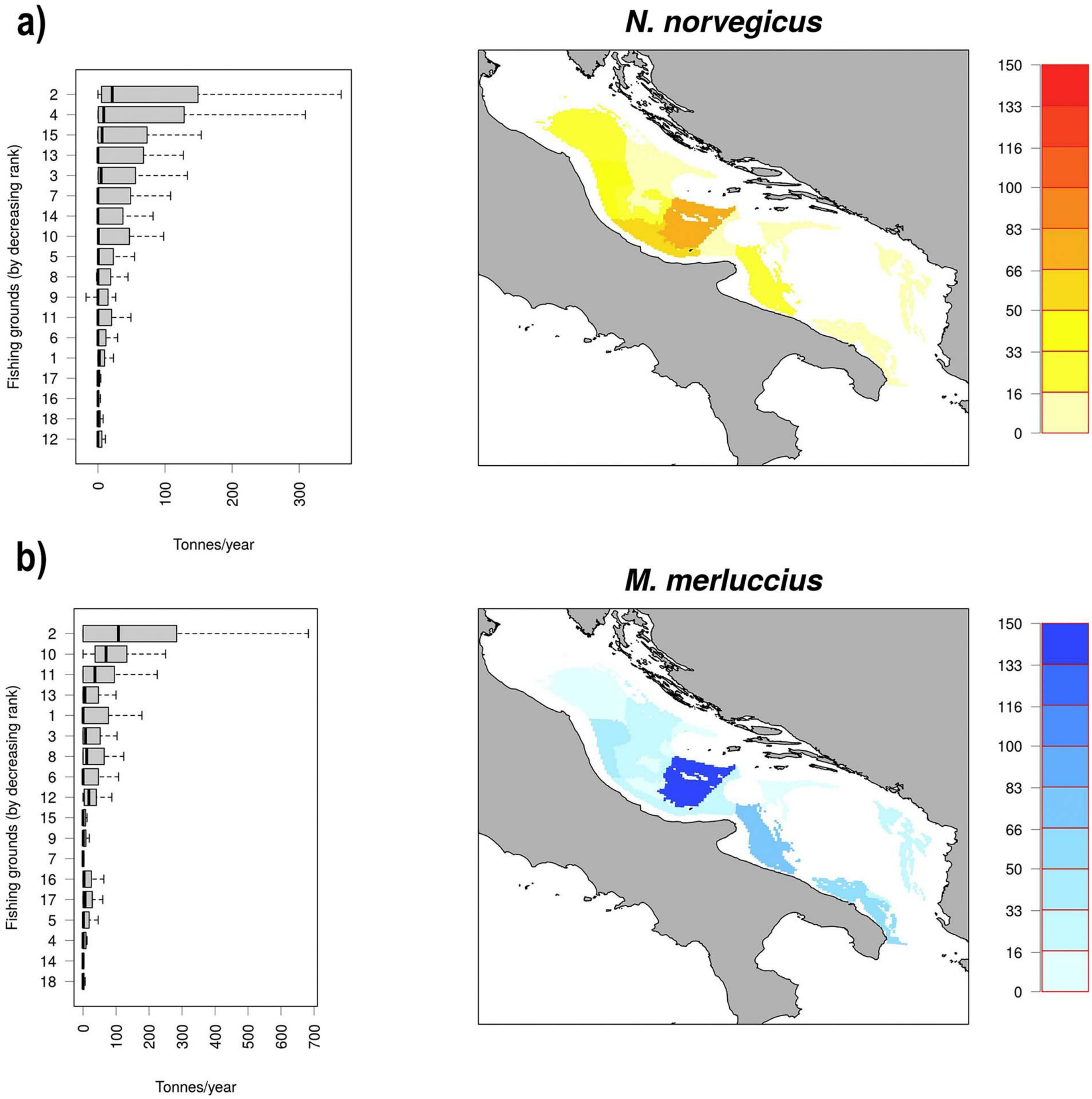


**Fig. 4.** Boxplot and related maps of the landings, by fishing ground, for a) the NEP and b) the HKE.

The same methodology was finally applied to obtain the values of $L_{s,t,v}$ for the vessels not covered by the questionnaire-based survey.

The procedure allowed us to obtain different outputs, which were analyzed as follows:

- The LPUE of each fishing ground was represented as a monthly time series.
- The mean annual landings for each species and harbor were computed from total monthly landings per harbor ($H_{h,s,t}$ in Eq. (4)) and mapped.
- The mean annual landings for each species and fishing ground were computed from the total monthly landings per fishing ground ($L_{s,g,t}$ in Eq. (5)) and mapped.
- The mean landings fluxes between each fishing ground and each Adriatic harbor were represented by river plots for each species (see the R package "riverplot"—Weiner, 2015).

### 2.8. Socio-economic drivers for the landings

The estimated pattern of the mean annual landings for the 39 Adriatic harbors was analyzed in the context of external "socio-economic" data (Table 3):

- The size of the fleet (number of trawlers for each harbor) was used as a proxy of the fishing capacity of each harbor.
- The size of related cities (number of citizens) was used as a proxy of the demand for both species.
- The total amount of fisheries resources sold out at market (tons/year) was used as a proxy for the market size.
- The position of each harbor with respect to the fishing ground was characterized by computing, for each harbor and species, a Centrality Index (CI):

$$CI_{h,s} = \frac{\sum_{g=1}^{G} \overline{LPUE_{s,g}}}{d_{h,g}} \tag{9}$$

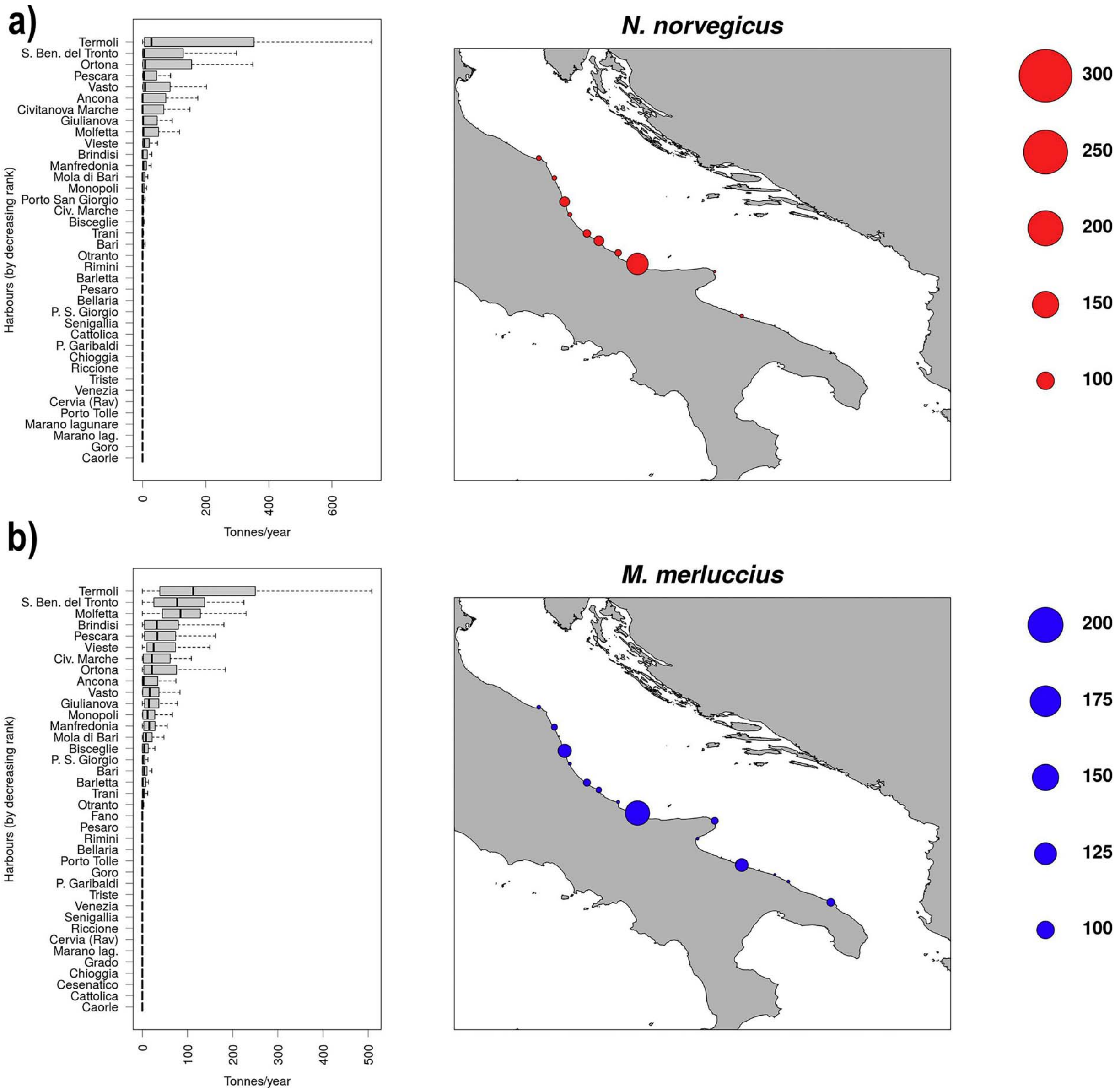


**Fig. 5.** Boxplot and related maps of the landings for a) the NEP and b) the *HKE*.

where $\overline{LPUE_{s,g}}$ is the yearly mean LPUE of fishing ground $g$ for species $s$ and $d_{h,g}$ is the distance between the centroid of the polygon of fishing ground $g$ and harbor $h$ in km.

The Pearson correlations between the mean total landings (tons·year$^{-1}$) and these variables were explored and visualized using the "chart.Correlation" function of the R package "PerformanceAnalytics" (Brian et al., 2015).

### 2.9. Comparing the estimated LPUEs with independent data

To validate the estimated $LPUE_{s,g,t}$ values, they were compared with a set of 477 independent records collected by onboard observers. To standardize the temporal window of the data, these temporally scattered observations were used to compute their respective monthly means. A weighted Pearson's product-moment correlation was computed, where the weight of each observation was proportional to the number of records used to compute the mean.

## 3. Results

### 3.1. Model accuracy

The fitted Logit models can correctly predict the value of $L^*$ for the validation dataset in 90% of cases for the NEP and 85% for the HKE. The model presented in the Eq. (3) and (4) was devised only for predictive purposes; hence, it was tested with this perspective. The performances of the fitted nnls regressions in predicting the landings for the validation dataset are very good (Fig. 2).

### 3.2. LPUE and the landings by fishing ground

The estimated LPUE for both species ranged between zero and less than one kg for each hour of fishing and meter of vessel length. The fishing grounds showed highly fluctuating trends, with spikes frequently occurring in autumn for both species (Fig. 3). A visual inspection highlights that, for both species, the majority of fishing grounds have a low average annual LPUE, indicating that the bulk of the landings comes from a few areas (Fig. 4). The NEP landings mainly

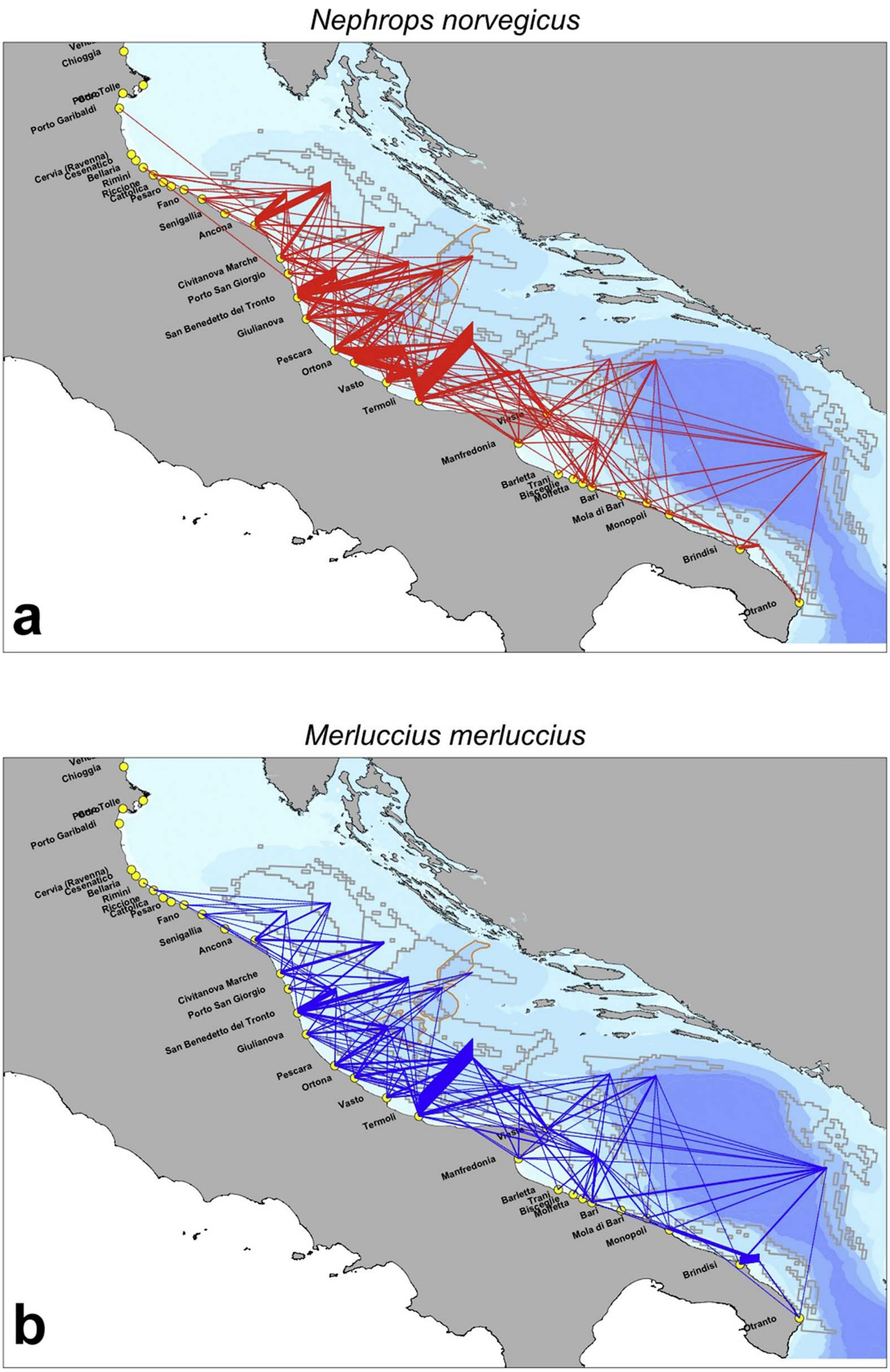


**Fig. 6.** The mean landings fluxes [2009–2014] between fishing grounds of origin and landing harbors for a) the NEP and b) the HKE, represented as straight lines connecting fishing grounds with harbors. The thickness of the lines is proportional to the quantity of the landings fished in the fishing ground and landed with the corresponding harbor. For the identification of fishing grounds refer to Fig. 1d.

come from the central Adriatic fishing grounds: 2 and 4 further offshore and 15 and 13 inshore (Figs. 1d and 4a). Fishing grounds 2 and 4 appear to yield the most consistent LPUEs over time, although the LPUE in fishing ground 4 increases markedly from April 2012 onwards (Figs. 3 and 4a). Fishing ground 15 exhibits a more evident seasonal component, while fishing grounds 13 and 14 (further north and coastal, off Ancona and offshore, respectively) are consistently productive at specific times of the year, generally peaking between January and July (Fig. 3).

As for the NEP, most of the HKE landings originated from fishing ground 2 (Fig. 4b). This result is followed by the coastal grounds in the southern Adriatic (fishing grounds 10 and 11) and fishing ground 13 off Ancona (Fig. 4b). Once again, the time series are indicative of a possible seasonal and/or yearly effect on the LPUE of this species, which varies depending on the fishing ground in question (Fig. 3). Fishing ground 2 has been consistently more productive over time, followed by the very

**Table 1**
Summary of the percentage of average production of *Nephrops norvegicus* and *Merluccius merluccius* contributed by each of the four most important fishing grounds as well as those included in the area closed to fishing (5, 9 and 18) to each of the five most important landing harbors for each specified fishing ground.

| *Nephrops norvegicus* | | | *Merluccius merluccius* | | |
|---|---|---|---|---|---|
| FG | Harbour | % | FG | Harbour | % |
| FG.2 | Termoli | 63.9 | FG.2 | Termoli | 65.3 |
| FG.2 | Vieste | 7.1 | FG.2 | Vieste | 6.8 |
| FG.2 | Ortona | 6.2 | FG.2 | Ortona | 6.3 |
| FG.2 | Pescara | 5.7 | FG.2 | Vasto | 5.2 |
| FG.2 | Vasto | 5.0 | FG.2 | Pescara | 5.0 |
| FG.15 | Termoli | 42.8 | FG.10 | Molfetta | 50.5 |
| FG.15 | Vasto | 22.5 | FG.10 | Vieste | 9.8 |
| FG.15 | Ortona | 17.1 | FG.10 | Bisceglie | 7.9 |
| FG.15 | Pescara | 12.2 | FG.10 | Bari | 6.5 |
| FG.15 | Vieste | 2.0 | FG.10 | Mola di Bari | 6.2 |
| FG.13 | San Benedetto del Tronto | 52.3 | FG.11 | Brindisi | 64.3 |
| FG.13 | Giulianova | 19.4 | FG.11 | Monopoli | 25.0 |
| FG.13 | Civitanova Marche | 10.7 | FG.11 | Otranto | 5.2 |
| FG.13 | Pescara | 9.2 | FG.11 | Mola di Bari | 3.9 |
| FG.13 | Porto San Giorgio | 4.7 | FG.11 | Molfetta | 1.2 |
| FG.4 | Ortona | 36.4 | FG.13 | San Benedetto del Tronto | 51.2 |
| FG.4 | Termoli | 23.7 | FG.13 | Civitanova Marche | 17.0 |
| FG.4 | Vasto | 21.3 | FG.13 | Pescara | 11.4 |
| FG.4 | Pescara | 15.5 | FG.13 | Giulianova | 9.3 |
| FG.4 | Giulianova | 1.6 | FG.13 | Porto San Giorgio | 9.3 |
| FG.9 | Pescara | 35.1 | FG.9 | Ortona | 34.5 |
| FG.9 | Ortona | 30.3 | FG.9 | Pescara | 33.2 |
| FG.9 | Giulianova | 17.4 | FG.9 | Giulianova | 13.9 |
| FG.9 | San Benedetto del Tronto | 10.5 | FG.9 | San Benedetto del Tronto | 10.6 |
| FG.9 | Termoli | 3.9 | FG.9 | Vasto | 4.6 |
| FG.5 | San Benedetto del Tronto | 43.6 | FG.5 | San Benedetto del Tronto | 45.6 |
| FG.5 | Pescara | 34.1 | FG.5 | Pescara | 32.3 |
| FG.5 | Ortona | 11.2 | FG.5 | Ortona | 12.7 |
| FG.5 | Giulianova | 5.6 | FG.5 | Termoli | 5.2 |
| FG.5 | Termoli | 3.5 | FG.5 | Giulianova | 3.7 |
| FG.18 | San Benedetto del Tronto | 60.5 | FG.18 | San Benedetto del Tronto | 57.0 |
| FG.18 | Giulianova | 17.8 | FG.18 | Pescara | 31.7 |
| FG.18 | Pescara | 16.1 | FG.18 | Giulianova | 9.8 |
| FG.18 | Ortona | 2.3 | FG.18 | Ortona | 0.8 |
| FG.18 | Civitanova Marche | 1.9 | FG.18 | Termoli | 0.3 |

**Table 2**
Summary of production fluxes (percentage average annual production of *Nephrops norvegicus* – NEP – and *Merluccius merluccius* – HKE) between fishing grounds (FG; origin) and harbors (fate) grouped on a GSA basis.

| | GSA 17 FGs | GSA 18 FGs | % Total |
|---|---|---|---|
| Nephrops norvegicus | | | |
| GSA17 Harbours | 84.11 | 0.6 | **84.71** |
| GSA18 Harbours | 8.03 | 7.26 | **15.29** |
| Total | 92.14 | 7.86 | **100** |
| Merluccius merluccius | | | |
| GSA17 Harbours | 62.06 | 1.28 | **63.34** |
| GSA18 Harbours | 11.76 | 24.9 | **36.66** |
| Total | 73.82 | 26.18 | **100** |

high but very seasonal LPUE in fishing ground 13, and a lower but constant LPUE in fishing grounds 10 and 11 (Fig. 3).

### 3.3. Landings by harbor

The landings estimated varied greatly depending on the harbor considered and were characterized by an unequal but stable distribution (Figs. 5a and b). For both species, few harbors constantly gathered a significant share of the landings (up to approximately 20%) while the average landing per harbor was relatively low (Figs. 5a and 5b). For the NEP, Termoli was the main fishing harbor followed by S. Benedetto del Tronto, Ortona and Pescara (Fig. 5a), and for the HKE it was Termoli followed by S. Benedetto del Tronto, and Molfetta (Fig. 5b).

The origin and destination of the average landing [2009–2014] of both species are illustrated *via* two flux diagrams (Fig. 6). For the NEP, the greatest average flux is by far the one between fishing ground 2 and the harbor of Termoli, accounting for 10.7% of the total Adriatic landings; this result is followed by fishing ground 15 and Termoli (6.5%), fishing ground 13 and San Benedetto del Tronto (4.9%), fishing ground four and Ortona (4.5%) and fishing ground 15 and Vasto (3.4%) (Fig. 6a).

The five most important recipients of the landings from fishing grounds 2, 15, 13, 4 and 15 are listed in Table 1. It is important to note that the average landings from fishing ground 2, which are the highest for the NEP overall, are predominantly in Termoli, Vieste, Ortona, Pescara and Vasto and a similar situation is true for fishing ground 15 (Table 1). Fishing ground 13 contributes mostly to the landings further north (Table 1). The fishing grounds comprising the closed Pomo/Jabuka pit area (fishing grounds 5, 9 and 18), on the other hand, contribute to the landings in harbors further north along the coast, mainly San Benedetto del Tronto, Pescara, Ortona, Giulianova and Civitanova Marche (Table 1). Similar to the NEP, the largest average flux of the HKE landings is the one between fishing ground 2 and the landing harbor of Termoli, accounting for 16.1% of the total Adriatic production; this result is followed by fishing ground 10 and Molfetta (6.5%), fishing ground 11 and Brindisi (6.0%), fishing grounds 13 and 8 and San Benedetto del Tronto (4.0% and 3.0%, respectively) (Fig. 6b). The average landings of the HKE coming from fishing grounds 2, 13, 9, 5 and 18 is distributed to harbors in a very similar manner as the NEP, while fishing grounds 10 and 11 supply harbors further south, in GSA 18 (Table 1). Taking into account the spatial partitioning defined within the DCF, GSA 17 is the most productive of the two Adriatic sub-areas for both species (Table 2), and, for both species, the inter-GSA production fluxes are not negligible (Table 2). This result is mainly in the form of landings originating in fishing grounds within GSA 17 being landed in harbors within GSA 18 (more than 8% of the average annual NEP production and more than 11% of the average annual HKE production) (Table 2). The opposite phenomenon (i.e., the amount of biomass originating in fishing grounds within GSA 18 but being landed in harbors within GSA 17) is much less noticeable (approximately 1% for both species). When the mean annual landings for the 39 Adriatic harbors were compared, for each species, with the data on city size, fleet size, market size and centrality (Table 3), the correlations represented in Fig. 7 were observed. Direct and significant correlations were detected 1) between the mean annual landings and the centrality index and 2) between the mean annual landings and market size. The correlations are always higher for the NEP. In contrast, the size of the fleet and that of the city was uncorrelated with the mean annual landings.

### 3.4. Comparing the estimated productivities with independent data

The comparison of the LPUE predicted by our model and the CPUE recorded by onboard observers revealed a high and highly significant ($R = 0.7119$, $p = 0.0002$) weighted Pearson correlation for the NEP and a lower but significant ($R = 0.4785, p = 0.0209$) weighted Pearson correlation for the HKE (Fig. 8).

## 4. Discussion

The most important outcome of this study is represented by the estimates of the landings attributed to each fishing vessel, associated with the information regarding their spatial origin (i.e., the fishing ground from which they are taken) and their final destination (the harbor in which they finally land). Starting from 1) a subdivision of the exploited area into several fishing grounds, 2) the monthly landings of a

**Table 3**
External socio-economic data and centrality index for which the correlation with the mean yearly landings was computed.

| Harbour | City Size (Citizens) | Fleet Size (Trawlers) | N. norvegicus | | | *M. merluccius* | | |
|---|---|---|---|---|---|---|---|---|
| | | | Landings (Tons/year) | Sold out at market (Tons/year) | CI | Landings (Tons/year) | Sold out at market (Tons/year) | CI |
| Termoli | 33739 | 39 | 300.8 | 403.92 | 0.703 | 186.6 | 1107.59 | 0.426 |
| S. Benedetto del Tronto | 47425 | 51 | 168 | 197.64 | 0.579 | 101.8 | 1606.71 | 0.363 |
| Ortona | 23317 | 28 | 147.6 | 93.78 | 0.619 | 43.5 | Unavailable | 0.392 |
| Pescara | 120525 | 58 | 136.7 | 433.55 | 0.570 | 55.5 | 1443.27 | 0.363 |
| Vasto | 41209 | 13 | 97.9 | 37.73 | 0.781 | 25 | 70.11 | 0.475 |
| Ancona | 100721 | 57 | 96.6 | 97.53 | 0.473 | 29.5 | 1564.60 | 0.298 |
| Civitanova Marche | 41902 | 28 | 88.7 | Unavailable | 0.535 | 46.8 | Unavailable | 0.337 |
| Molfetta | 59874 | 51 | 64.6 | Unavailable | 0.433 | 98.8 | 403.43 | 0.264 |
| Giulianova | 24050 | 24 | 62.6 | Unavailable | 0.553 | 23.2 | Unavailable | 0.351 |
| Vieste | 14006 | 10 | 52.9 | Unavailable | 0.603 | 52.9 | Unavailable | 0.364 |
| Manfredonia | 57279 | 168 | 24.6 | 50.06 | 0.498 | 22.1 | 154.74 | 0.305 |
| Brindisi | 88126 | 0 | 21.1 | Unavailable | 0.494 | 60 | Unavailable | 0.294 |
| Fano | 60888 | 24 | 12 | 1.96 | 0.352 | 1.6 | 87.17 | 0.222 |
| Mola di Bari | 25695 | 49 | 9.5 | Unavailable | 0.391 | 16.2 | Unavailable | 0.236 |
| Monopoli | 49133 | 40 | 8.7 | Unavailable | 0.374 | 23 | 51.92 | 0.225 |
| Rimini | 148214 | 43 | 6.8 | Unavailable | 0.282 | 1.1 | Unavailable | 0.178 |
| Bisceglie | 55481 | 27 | 6.5 | Unavailable | 0.442 | 8.9 | Unavailable | 0.270 |
| Bari | 325183 | 16 | 4.7 | Unavailable | 0.411 | 7.1 | 1.60 | 0.249 |
| Trani | 56107 | 21 | 3.9 | Unavailable | 0.452 | 4.4 | Unavailable | 0.276 |
| Barletta | 94732 | 16 | 3 | Unavailable | 0.455 | 5.4 | Unavailable | 0.278 |
| Otranto | 5724 | 6 | 3 | 4 | 0.263 | 4.4 | Unavailable | 0.158 |
| Pesaro | 94512 | 1 | 2.4 | Unavailable | 0.321 | 1.4 | Unavailable | 0.203 |
| Bellaria | 19517 | 10 | 0.6 | Unavailable | 0.269 | 0.2 | Unavailable | 0.171 |
| Porto S. Giorgio | 16027 | 13 | 0.5 | 0.86 | 0.569 | 7.6 | 8.88 | 0.356 |
| Cesenatico | 25796 | 26 | 0.2 | Unavailable | 0.260 | 0 | 3.49 | 0.165 |
| Senigallia | 44796 | 6 | 0.2 | Unavailable | 0.400 | 0 | Unavailable | 0.252 |
| Cattolica | 17084 | 14 | 0.1 | 2.92 | 0.305 | 0 | 29.29 | 0.193 |
| Chioggia | 49706 | 87 | 0.1 | Unavailable | 0.201 | 0 | Unavailable | 0.128 |
| Goro | 3828 | 35 | 0.1 | Unavailable | 0.220 | 0 | Unavailable | 0.140 |
| Porto Garibaldi | 4034 | 39 | 0.1 | Unavailable | 0.226 | 0 | Unavailable | 0.143 |
| Caorle | 11672 | 35 | 0 | Unavailable | 0.199 | 0 | Unavailable | 0.127 |
| Cervia | 28940 | 4 | 0 | Unavailable | 0.255 | 0 | Unavailable | 0.161 |
| Grado | 8251 | 17 | 0 | Unavailable | 0.205 | 0 | Unavailable | 0.131 |
| Marano lagunare | 1844 | 30 | 0 | Unavailable | 0.195 | 0 | Unavailable | 0.125 |
| Porto Tolle | 9826 | 45 | 0 | Unavailable | 0.225 | 0.1 | Unavailable | 0.143 |
| Riccione | 35487 | 0 | 0 | Unavailable | 0.294 | 0 | Unavailable | 0.186 |
| Triste | 204292 | 5 | 0 | Unavailable | 0.214 | 0 | Unavailable | 0.137 |
| Venezia | 262246 | 12 | 0 | Unavailable | 0.195 | 0 | Unavailable | 0.124 |

representative sample of the fleet, and 3) VMS data for the entire fleet, it was possible to obtain the LPUE values associated with each fishing ground exploited in the Adriatic Sea and to estimate the monthly landings for the entire fleet by fishing ground of origin and harbor of destination. The estimates obtained were compared with a test dataset (namely the per-haul CPUEs recorded by observers), obtaining acceptable values of correlations, in particular for the NEP.

The outcomes highlighted remarkable differences both in the contribution of different fishing grounds to the annual quantity of the landings and in the distribution of the landings among Adriatic ports. The analysis of the spatial origin of the landings as portrayed by the model leads to the conclusion that, on average, 14 out of 18 fishing grounds considered do not contribute much to the annual quantity of the NEP landed. On average, over 50% of the NEP annual landings comes from four fishing grounds only: 2 and 4, situated just south of the Pomo/Jabuka depression, and inshore fishing grounds 15 and 13. Two of these, fishing grounds 2 and 15, displayed a high and constant LPUE over time, while fishing ground 4 showed a sudden increase in the LPUE from April 2012, and fishing ground 13 was characterized by an increasing trend over time.

The landings per harbor varied greatly depending on the harbor considered and were characterized by an unequal but constant distribution among harbors: a few harbors consistently gathered a significant share of the landings (up to approximately 20%), while the average harbor importance (expressed as a percentage of the annual total landings per harbor) was relatively low.

When the pattern of the landings per harbor was compared with data accounting for harbor size, city population, market size and location of the harbors with respect to fishing grounds (as captured by a centrality index), significant relationships were detected for both species. Given that both these species are heavily exploited and that market demand is greater than the supply, these results could be interpreted using Occam's razor (i.e., as they are): for both species, harbors located near the fishing grounds with the highest LPUE are characterized by higher landings, and, consequently, their markets sell higher quantities.

From a methodological point of view, it is important to stress that the approach presented in this study allows the overcoming of the lack of reliable and representative logbooks by combining two main sources of information: VMS and landing questionnaires. This result could represent an important application for other fisheries in the Mediterranean Sea where exhaustive logbook data are not available. Moreover, it could represent a control method for validating the reliability of available logbooks. The method seems to be effective at capturing the relationship between the selected area of fishing activity and the corresponding landings. In this way, the quantity of resources landed by a given vessel is simply a function of vessel size and of the distribution of fishing effort with respect to a set of areas. Starting from the estimation of the LPUE by area (fishing grounds), the other steps of the method simply represent the application of standard approaches for data from tracking devices (i.e., VMS). In possible future developments,

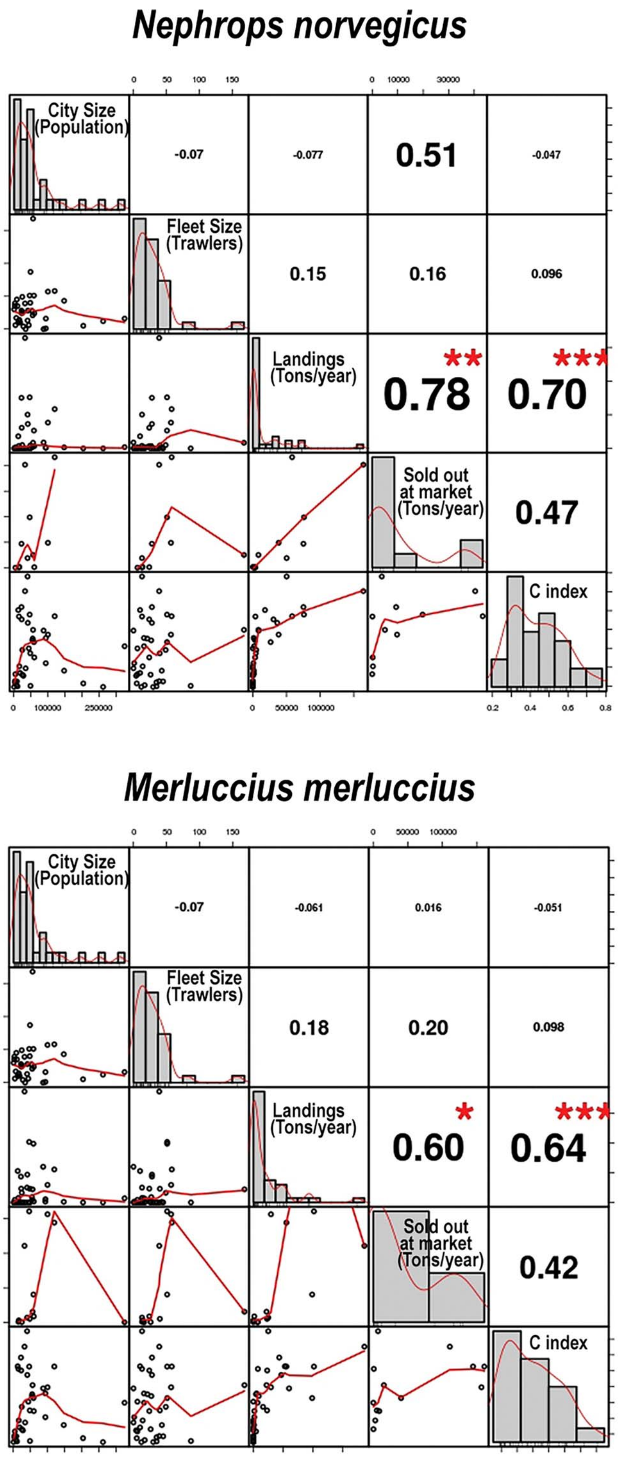


**Fig. 7.** Visualization of a Correlation Matrix between the variables in Table 3, grouped by species. Absolute values of the correlations are reported on the top; bivariate scatterplots are plotted on the bottom, with a fitted line; and the distribution of each variable is represented on the diagonal using a histogram.

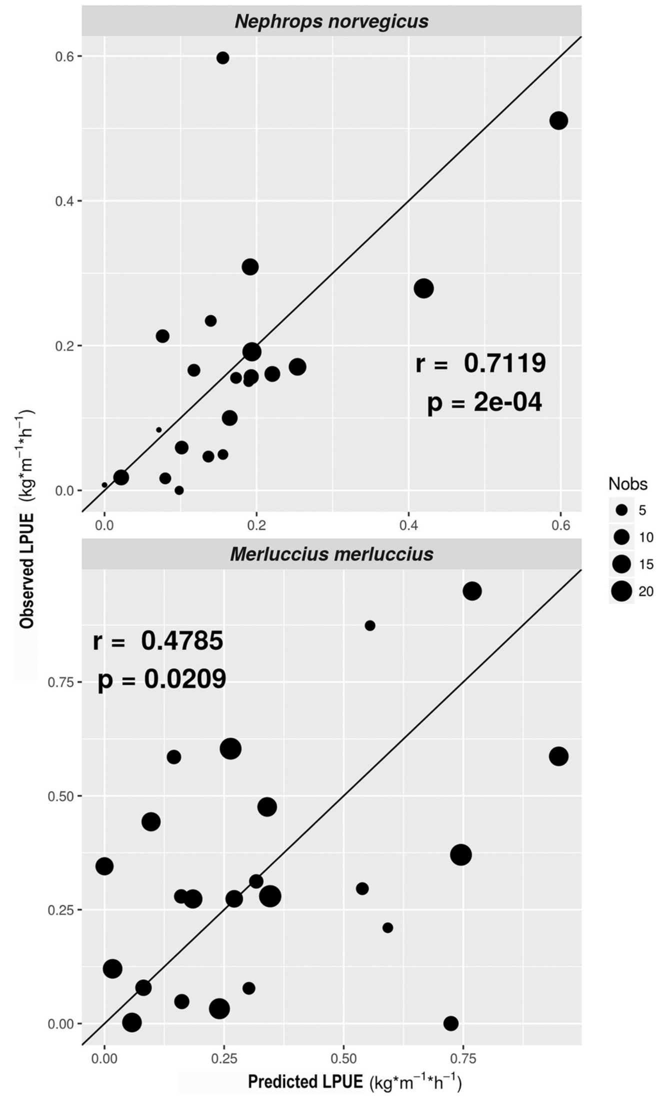


**Fig. 8.** Comparison of the observed CPUE and the predicted LPUE for the *NEP* and the *HKE*. The size of the dots is directly proportional to the number of observations associated with each point.

the model could include 1) the specific characteristics of the vessel and of the gear, which at the moment is limited to vessel size only; 2) a downscaling of the temporal frame of the model to weeks (or days); and 3) the size composition of the landings, should this level of detail be available in the landings data. Importantly, through the *post hoc* aggregation of the monthly landings from different fishing grounds of interest, the estimates produced using this method will result in time series of the estimated landings for geographical units smaller than the GSA level (the smallest unit being the single fishing ground) and time frames shorter than the year (the smallest unit being the month). If the sampling of the length frequency distributions of the landings were also conducted at the same finer geographical and temporal scales, then the fishery-dependent dataset available for assessments would be adequate for the use of the more complex models available. The potential applications of this model should thus include the use of its outputs in the context of the best possible evaluation of stock status for each of the target species, e.g., the use of Integrated Assessment methods (or Integrated Analysis) where several sources of information, in a raw format, are combined into one single analysis that is performed using a likelihood function that foresees multiple sources of data (Edwards et al., 2012; Maunder and Punt, 2013). Similarly, the outputs of this model could also be integrated into more complex platforms accounting for the biological dynamics of resources (Angelini et al., 2016; Bastardie et al., 2014; Russo et al., 2014c) and devised to analyze and predict the effects of spatial and temporal management strategies of fisheries.

This work also allowed us to draw a number of secondary but important conclusions. The analysis of the VMS data of fishing effort delivered a detailed picture of the fleet's activities in GSAs 17 and 18. The simple allocation of fishing vessels to the ports in which they actually operate, for instance, allowed a better insight into the actual proportion of the fleet landing in each harbor. Firstly, this highlighted the shortcomings associated with the use of the CFR: usually, the landings estimates for different areas (GSAs) are obtained by expanding landing sample data to the total official fleet (for the specific GSA) reported in the CFR. The CFR, though, may be very misleading in terms of where a vessel operates: it provides a (seldom updated) list of where each vessel is registered, but vessels are free to fish wherever they like within Italian territorial waters, irrespective of their harbor of registration. Thus, using the CFR as a reference can potentially yield wrong results. Secondly, an important outcome of the VMS data analysis is the identification of inter-GSA landings flow: fishing vessels belonging to the harbors of the two GSAs exploit all the fishing grounds identified in this study, irrespective of their GSA of origin (Fig. 6). Any analysis of fishing activity aimed at assessing the resources and/or the fishing pressure in GSA 17, if performed disregarding this phenomenon, would thus probably underestimate the effects of fishing activities on the resources as well as on ecosystem structure.

Traditional management systems have failed to ensure the long-term sustainability of fisheries in the Mediterranean Sea, allowing resources to reach a status of overfishing (Colloca et al., 2013; Vasilakopoulos et al., 2014). This failure is slowly leading to a progressive shift from traditional management, based on the control of fishing capacity in the Mediterranean, towards a management system based on the spatial planning of fishing activities, which takes into account the spatial distribution of marine areas where peculiar communities and/or phases of biological cycles that regulate the population (e.g., nursery areas) have evolved. A notable example is the multi-annual management plan for the fisheries exploiting the European hake and the deep-water rose shrimp in the Strait of Sicily (GSAs 12–16). This plan was adopted in 2016 and has resulted in the establishment of three Fishery Restricted Areas to protect known nurseries in the area (GFCM Recommendation GFCM/40/2016/4). By yielding 1) information regarding the spatial origin of the landings, 2) an estimate of the most productive fishing grounds, 3) the possibility of exploring the amount of spatial overlap between fishing grounds and sensitive areas, 4) the evaluation of the fishing pressure exerted on these areas, and finally, 5) the distribution of the landings among the Adriatic ports, the knowledge provided by this study aligns perfectly with the new, spatially explicit, management approach described above. In other words, the proposed approach aims at combining the spatial patterns of the resources with the spatial positioning of the exploitation activities, making them accessible for implementing the Ecosystem Approach to Fisheries (Angelini et al., 2016).

Upon reflection, some results of the present study are suggestive of the need for a substantial re-thinking of the classical approaches to both monitoring and managing fishing resources in the Mediterranean Sea. Most importantly, both resources and fleets operate without considering the spatial structure defined by the FAO-GFCM GSAs, which instead represent the basis for DCF and, consequently, for stock assessment. Moreover, all approaches relying on official fleet register-based analyses of Italian fleet capacity could be biased by the mismatch between the official vessel membership with respect to the harbor/GSA and the true area of fishing activity. In contrast, spatially inspired management approaches (e.g., Real Time Incentives *sensu*–Kraak et al., 2014, 2015) could benefit from the definition of fishing grounds, such as the one presented in this study, which could be more effective in capturing both the biological dynamics of stocks and the related activity of the fleets. For example, contrary to expectation, the deeper parts of the Pomo/Jabuka pit area (> 200 m)–corresponding to fishing grounds 5, 9 and 18–did not rank high in importance for the NEP, and those between 100 m and 200 m north of the pits (e.g., fishing ground 8) did not rank high for the HKE. Importantly, though, the group composed of the neighboring fishing grounds 2, 4 and 15 reasonably represents a critical area for both species. Fishing grounds 5, 9 and 18 comprise the bulk of the area closed to fishing in 2015–2016 and, together with fishing ground 8, represent the main HKE nursery area in the Adriatic as well as an area of very high NEP densities. The results of this study, indicating fishing grounds 2, 4 and 15 as the most important to the trawling fleet for these two species, are indicative of the fact that a combination of these seven fishing grounds (2, 4, 5, 8, 9, 15 and 18) should be analyzed further and that they possibly provide the basis for supporting an expansion of the closed area to include all seven fishing grounds. Furthermore, in the case of the NEP, a sedentary, burrowing, crustacean with different population dynamics within the Pomo/Jabuka pit compared to elsewhere in the Adriatic Sea (Anon., 1994; "Froglia e Gramitto_1988.pdf," n.d.), these seven fishing grounds should likely be considered as a stand-alone unit ("stocklet" or "functional unit") in stock assessment models.

Future research will aim to expand the analyses to include more species and more gear types (e.g., pelagic pair trawl, rapid trawl, longline and purse seine) and to enhance our knowledge regarding fleet characteristics (e.g., engine power and types of nets).

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