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# Mapping essential juvenile habitats of exploited marine fish: Complementary insights from a scientific survey-based model, fishers' knowledge and fisheries-dependent data

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## ABSTRACT

In the Bay of Biscay (BoB, Northeast Atlantic), a preexisting habitat suitability model (HSM) fitted on ecological scientific trawl survey data with restricted partial coverage revealed the concentration of Young of the Year (YoY) common sole (*Solea solea*) on restricted coastal and estuarine nurseries. To extend the nursery map of sole in the BoB to zones where survey data are lacking and fit with the sole population and stock management extent, we crossed HSM, fishers' ecological knowledge (FEK) and fisheries-based (FB) data. FB and FEK data also complemented knowledge on juvenile sole habitat and seasonal migration. Thirteen fishers with potential knowledge about the YoY sole distribution were directly interviewed. Direct interviews included both information about the location of juveniles and YoY distribution mapping. With good consensus among fishers, FEK allowed the identification of four new areas hosting essential juvenile habitat for the common sole, revealed the accuracy of the HSM model outside the spatial coverage of the ecological survey, and provided spatial refinement. The FB observation data confirmed the locations of the essential juvenile habitats given by FEK and the spatial distributions of YoY densities predicted from the scientific data. In addition, FB confirmed the seasonal migration of YoY sole, which was preliminarily hypothesized from a local and short-term survey-based study. Our results emphasized the local accuracy of FEK. These findings also underlined the interest in combining several sources of data and methods to map essential fish habitats outside areas well covered by ecological scientific surveys, on order to inform future spatial management measures.

## 1. Introduction

Nurseries are essential fish habitats (EFHs), crucial for the renewal of marine fish populations. The quantity and suitability (i.e., the capacity to support a population) of habitats (Dahlgren et al., 2006) drive the number of juveniles and their survival rate. They are therefore a major drivers of marine fish recruitment, especially for flatfish (Archambault et al., 2014; Iles, 2000; Rijnsdorp et al., 1992). For a large proportion of exploited marine fish, nurseries are located in coastal and estuarine areas (Seitz et al., 2014) which face significant and cumulative pressures from human activities (Brown et al., 2018; Halpern et al., 2008). Their functionality is threatened by activities that either reduce their quantity (i.e., their surface: port development, extraction of granular material, etc.) or impact their quality (terrestrial or marine pollution) (Archambault et al., 2018). Thus, the identification of nurseries is

crucial to help preserve their functionality and sustain population renewal (Champagnat et al., 2021).

Several methods coexist to locate EFH, but each has its respective limitations (Raymond et al., 2010):

- Where available, ecological scientific surveys provide precise, quantitative data but are limited in time and space. Based on these surveys, habitat suitability models (HSMs) have been proven to be an efficient way of identifying EFHs. HSMs associate structural features of a habitat with the density of a fish population (Kellner et al., 1992) and allow the generation of quantitative maps (Le Pape et al., 2014). However, these methods rely on the availability of ecological survey data. For areas where these data are lacking, other sources of knowledge are required to infer EFH locations.

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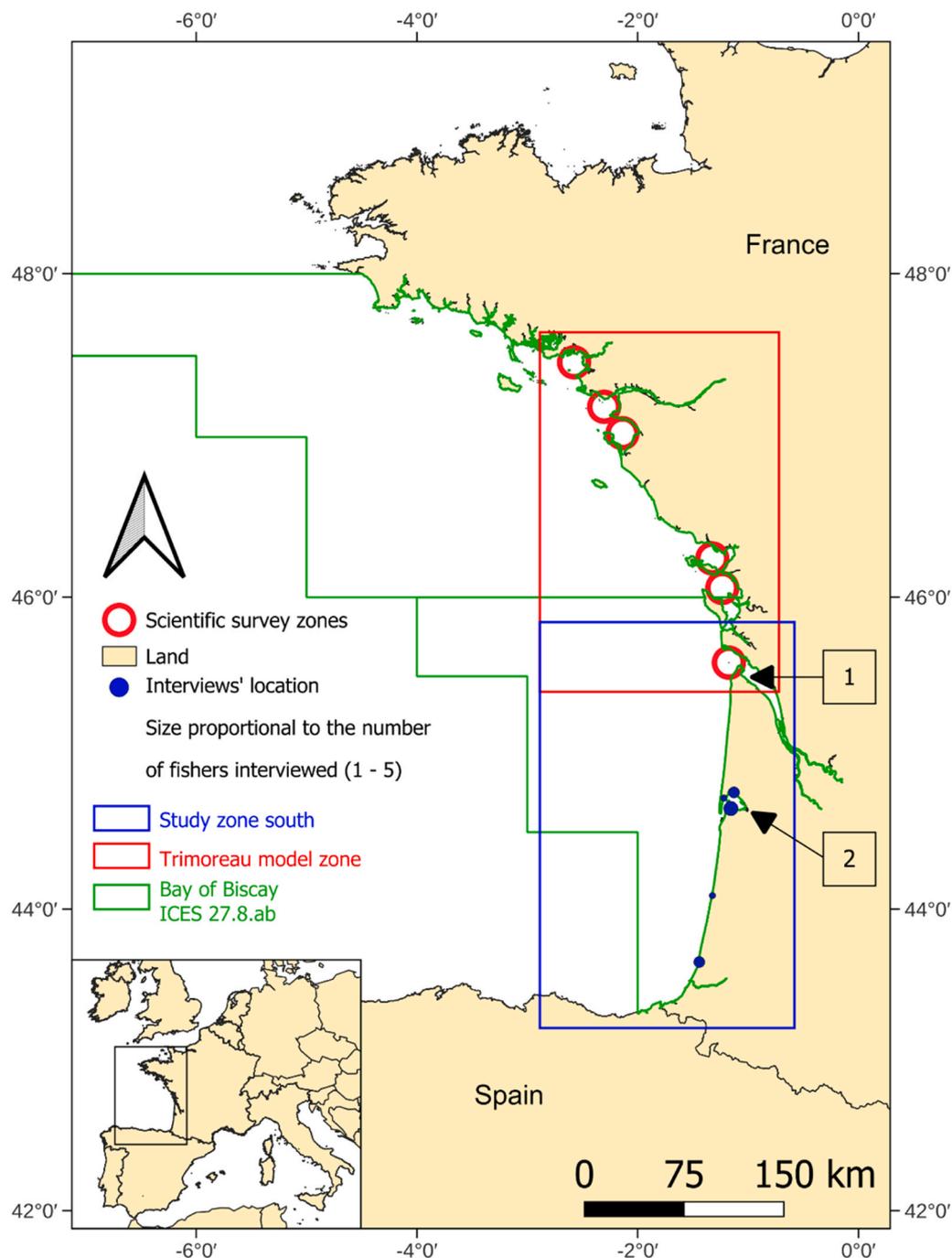
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– Fisheries activities provide an alternative source of data to gain information on EFHs, with, for example spatialized fishing declaration and fishery observer data (fishery-based data, hereafter referred to as FB data) (Aglave et al., 2023). In a fishing-intensive area, FB data are interesting because they are broadly available spatially and throughout the year. However, FB data are a specific example of preferential sampling (i.e., fishing intensity depends upon the biomass of the target species), which needs to be accounted for (Aglave et al., 2022). Preferential sampling biases the spatial prediction of fish density and, moreover, might prevent collating data for nontargeted species and/or life stages under the minimum

landing size. In particular, information on juvenile fish is scarce in FB data.

– In a data-poor context (Bevilacqua et al., 2016), fishers' ecological knowledge (FEK) is a recognized source of data that could provide an interesting contribution to scientific knowledge (Johannes et al., 2000; Silvano et al., 2023; Silvano and Valbo-Jørgensen, 2008). FEK is acquired through experience and is "contextual knowledge and sensitivity about the social-ecological system as a result of fishers' or fishing communities' experiences from working in that system" (Steins et al., 2022). FEK is mostly qualitative and needs to be carefully used in a scientific framework (Björkvik et al., 2021). In



**Fig. 1.** Map of the Bay of Biscay. The green box is the ICES fishery management unit 27.8.ab, which is used for the common sole stock in the Bay of Biscay, where fisheries-based data are collated. The red box is the area covered by the original sole nursery map from Trimoreau et al. (2013), which is based on scientific trawl surveys collated in the areas indicated by red circles. The blue box is the area where FEK was collected, with the locations of the interviewed fishers in blue circles. In the lower left corner: general location of the study site in the northeast Atlantic. 1: Gironde estuary, 2: Arcachon Basin.

recent decades, interest in FEK in marine studies has increased worldwide (Hind, 2015; Stephenson et al., 2016; Anbleyth-Evans and Lacy, 2019; Calderwood et al., 2023). Knowledge elicitation methods, both qualitative and quantitative, allow the integration of FEK for fish habitat comprehension and mapping. Many studies have shown application examples for different EFHs, species and ecosystems worldwide (e.g., Bergmann et al., 2004; Bezerra et al., 2021; Bliss et al., 2023; DeCelles et al., 2017; Grant and Berkes, 2007), although such examples have remained scarce for young stages (Da Silva et al., 2023; Le Fur et al., 2011; Leite and Gasalla, 2013).

To address the different data sources, their combination have proven to be consistent in many cases (Alglave et al., 2022; Damasio et al., 2015; Leite and Gasalla, 2013; Roux et al., 2019; Silvano and Valbo-Jørgensen, 2008). Through a case study of the young of the year (YoY) common sole (*Solea solea*) in the Bay of Biscay (BoB), our study proposes an application of a combination of these data sources to complement the existing partial map of essential juvenile habitats and provide new insights into nursery functionality and dynamics. The common sole is a coastal and estuarine nursery-dependent flatfish species (Le Pape et al., 2003; Riou et al., 2001) of main commercial interest for fisheries, especially in the Bay of Biscay (BoB; Fig. 1; common sole stock 27.8ab; ICES, 2022). Concerns are rising about its stock status: Spawning stock biomass is below the precautionary value, and recruitment remains low despite decreasing fishing mortality.

The BoB is partially surveyed by ecological scientific beam trawl survey programs (Brind'Amour and Lobry, 2009) restricted to the central part of the management unit (Fig. 1). An HSM model was developed based on these survey data (Trimoreau et al., 2013) to predict and map the density of young of the year (YoY) sole during summer, when juveniles are concentrated in shallow estuarine and coastal areas. Based on restricted data from a bay in the northern BoB, Dorel et al. (1991) evidenced that YoY soles move offshore and disperse in deeper grounds until Spring. The localization of their distribution in summer, when they are concentrated in restricted areas, is of main importance (Le Pape et al., 2003). HSM have revealed that environmental factors play important roles in habitat suitability for the common sole YoY (Le Pape et al., 2003; Trimoreau et al., 2013; Vasconcelos et al., 2013; Vinagre et al., 2006). Shallow and protected areas, with a fine sediment structure and under river plume influence, have proven to be the most suitable areas for YoY (Trimoreau et al., 2013). However, the effective concentration of common sole YoY may also vary with other factors, such as the larval dispersion process (Delerue-Ricard et al., 2019; Savina et al., 2016). Other areas in the BoB not covered by ecological scientific surveys, particularly in the southern part (Fig. 1), are consistent with the characterization of nurseries given by the HSM, i.e., soft-bottom estuaries and sheltered bays (Trimoreau et al., 2013). Complementing the existing mapping of nurseries to fit the population extent and the fishery management unit is of main interest to increase the knowledge of juvenile habitats for the common sole in the BoB and, ultimately, for future spatial management measures.

To investigate the location of sole nurseries in areas of the BoB where scientific ecological survey data are lacking, we used a multisource approach. We first adapted the existing HSM to use it outside its original area. We then collected FEK data regarding the location and characteristics of the YoY habitat in the southern part of the BoB. Finally, the presence of YoY in the fishery-based data was compared with the findings of the two other sources of data.

Through this case study, our work aimed to 1) propose a methodology to locate nurseries through FEK, 2) evaluate the advantages and limitations of the three different data sources (trawl surveys, FEK and FB), and 3) complement the spatial and seasonal coverage of preexisting knowledge on sole nurseries in the BoB.

## 2. Materials and methods

### 2.1. Data sources and areas of the study

Our work compared three data sources and methods to identify YoY sole locations in the BoB (Table 1). The methods used and comparisons conducted between data sources are described in the following subsections.

Fig. 1 shows the different zones considered in Table 1. BoB is defined by the ICES zone 27.8.ab. The ecological scientific surveys used by Trimoreau et al. (2013) were conducted on six zones indicated by red circles. These six zones are composed of ecosystems recognized as suitable for common sole juveniles (i.e., the three main French estuaries and three shallow and muddy bays of the Bay of Biscay; (Le Pape et al., 2003). Our specific study area for nursery mapping of the FEK was located in the southern BoB, which is mainly outside the area covered by ecological scientific surveys. This zone is a sandy coast, interrupted by the Gironde estuary in the north, the Arcachon Basin in the center and several small estuaries in the south (Fig. 1).

### 2.2. Extrapolation of the habitat suitability model based on scientific trawl surveys

Mapping fish habitats using an HSM based on ecological scientific surveys consists of the use of a statistical model that links relevant descriptors of the marine environment to the spatial distribution of fish

**Table 1**

Description of the three methods used in the study. Each method exploits a specific data source with a given spatial coverage. Details about the data sources and methods are provided in the last column.

Method	Data source	Data spatial coverage	Description of data and information gathered
Habitat suitability model (HSM)	Scientific trawl surveys (Trimoreau et al., 2013)	Partial coverage of the central part of the ICES fisheries assessment unit 27.8.ab (see Fig. 1, Trimoreau model zone).	HSM provides a prediction of YoY sole density following habitat characteristics. High YoY density areas reflect the location of sole nurseries in summer. The HSM described in our study was adapted from a previous work and used outside its original bonds, employing an exploratory approach.
Fishers' knowledge	Fishers' ecological knowledge collected during the study	Southern part of ICES fisheries assessment unit 27.8.ab (see Fig. 1, study zone south).	Individual interviews were conducted with fishers to collect their knowledge on the locations and on the characterization of sole nurseries within their summer fishing areas and to map their distribution.
Fishery-based data	On-board observers on fishing vessels from the OBSMER program (Alglave et al., 2023)	ICES fisheries assessment unit 27.8.ab.	Data provide a fine description of fishing operations sampled, including fishing gear and location, species caught and their length. Data were too scarce to directly map sole nurseries but provide information on the presence of YoY sole in fishing operations throughout the year.

density and then the use of georeferenced predictions from these models to map habitats into geographic information systems (Le Pape et al., 2014). Trimoreau et al. (2013) used an HSM to describe and map the habitat of the YoY common sole in several areas located in the central part of the BoB (Fig. 1, red box). Here, we used the original model from Trimoreau et al. (2013) to extrapolate this model-based map to the whole BoB (Fig. 1, green box). The data and methods are explained below, but Trimoreau et al. (2013) provide further detailed specifications of the model.

### 2.2.1. Trawl survey data

The model was based on multiple standardized scientific trawl surveys conducted between 1980 and 2011 from late summer to early autumn, when YoY sole are concentrated in coastal and estuarine areas (Le Pape et al., 2003). All these surveys were conducted with a three meters wide beam trawl with a 20 mm stretched mesh at the cod end for 10–20 minutes during daylight. A total of 1643 trawl hauls were retained in the analysis; standardized catches of YoY sole per trawled surface were calculated for each trawl haul and used as a proxy of the YoY density.

### 2.2.2. HSM

For each sampling point, the original model crossed the density of YoY sole observed in surveys with four environmental descriptors (bathymetry, sediment structure, salinity, and coastal exposure) and an additional descriptor that distinguishes the six geographical zones covered by scientific trawl surveys in the BoB (Trimoreau et al., 2013). As scientific trawl survey data are not available outside the spatial extent (Fig. 1, red box) of the map produced by Trimoreau et al. (2013), this geographical descriptor was deleted from our model to allow for extrapolation outside survey areas.

Owing to the low proportion of YoY present in the data, a delta approach was implemented (Le Pape et al., 2003). This approach couples two submodels: 1) a first submodel describing the presence/absence of YoY, and 2) a second model explaining the variation in the densities in samples where presence of YoY was recorded.

The first submodel (Eq. 1) is a generalized linear model (GLM) based on a binomial distribution where the probability of the presence of YoY sole,  $Y_{0/1}$ , depends upon environmental descriptors through a logit link function:

$$Y_{0/1} = \mu_{0/1} + F_{\text{salinity}} + F_{\text{sediment}} + F_{\text{Bathymetry}} + F_{\text{Wave}} + \varepsilon_{0/1} \text{link} = \text{logit} \quad (1)$$

The second submodel uses a Gaussian linear model on log-transformed positive densities of YoY sole,  $Y_+$  (Eq. 2).

$$\ln(Y_+) = \mu_+ + F_{\text{salinity}} + F_{\text{sediment}} + F_{\text{Bathymetry}} + F_{\text{Wave}} + \varepsilon_+ \text{link} = \text{identity} \quad (2)$$

For each submodel, the selection of explanatory factors was based on the Akaike information criterion (AIC), with a difference of three considered significant (Bozdogan, 1987). YoY sole density is calculated by combining the two submodels (Eq. 3).

$$\hat{Y} = \hat{Y}_{0/1} \times e^{\ln(\hat{Y}_+)} \times e^{\frac{\hat{\sigma}^2(Y_+)}{2}} \quad (3)$$

### 2.2.3. Mapping

Environmental descriptor maps were collected to cover the whole BoB and formatted according to the original model from Trimoreau et al. (2013):

- Bathymetry data are available as a 0.001° raster for the entire study area (SHOM, 2015). Four classes were defined (in meters), [0:–5], ]-5:–10], ]-10:–20], and ]-20:–35].
- A sediment structure map was created as a combination of three sources. A general map of the Bay of Biscay (Garlan et al., 2018), a

recent detailed map of the Aquitaine continental shelf (Cirac et al., 2016) and a specific map of the Arcachon Basin (Hamdi et al., 2010).

- Salinity was extracted from a hydrographic model (ECOMARS 3D) at a 4 km raster and split into three classes (in the PSS): <30, [30:32] and >32.
- Coastal exposure was described as the average observed summer wave height, available as a 2 km raster and split into three classes (in meters): <0.3, [0.3–0.5], and >0.5.

To visualize the YoY density across the BoB, habitat descriptor maps were vectorized following the descriptor classes described above and combined using Geographic Information Systems (QGIS software). The resulting map is the intersection of the four habitat descriptor maps, and polygons are drawn for each unique combination of descriptors. Predictions of YoY sole density from the HSM were calculated for each polygon with Eq. 3 and then imported into Geographic Information Systems to visualize juvenile habitat maps.

## 2.3. Fishers' knowledge collection

### 2.3.1. General methodology

We focused our collection of professional fishers' knowledge on the southern part of the BoB (Fig. 1, blue box). Harbors and fishing communities in this zone are concentrated in a few hotspots around the Arcachon Basin and small estuaries. These hotspots were identified through the knowledge of the local producer organization (PO). POs are professional structures regrouping fishers to organize their production and commercialization. These organizations have precise knowledge of fishers' activity and provide a useful bridge between academics and fishers. They also identified fishing profiles (e.g., fishers who use specific gear or target specific species) likely to have knowledge of juveniles' distribution and provided the corresponding contact list of fishers. Indeed, only a small number of professional fishers use fishing gear that can potentially capture YoY sole owing to their small mesh size. Three relevant fishing profiles were defined based on the listings provided by the PO:

- **Trawlers that target wedge sole.** Vessels use bottom trawls to target wedge sole (*Dicologlossa cuneata*) from June to October in coastal areas (mostly between zero and three nautical miles from the coastline). This corresponds to the period when juveniles are concentrated on summer nursery grounds. The trawling mesh sizes for wedge sole are 40–45 mm, allowing for the capture of juvenile sole. The fishing vessel length is between 12 and 18 m.
- **Coastal gill netters.** Vessels use various gill nets to target a large variety of species in a small-scale fishery (e.g., sole, cuttlefish, seabass, seabream, red mullet). The gill nets used to target specific species, such as red mullet (*Mullus surmuletus*), have a small mesh size capable of catching YoY sole during the summer period. These vessels operate all along the coast of our study area. The vessel length is between 10 and 12 m.
- **Arcachon Basin gill netters.** Vessels use the same gear as coastal gill netters but operate only in the Arcachon Basin. In addition, these vessels occasionally use fyke nets for eel (*Anguilla anguilla*) fishing with a mesh size allowing them to catch YoY sole. The vessel length is between six and 10 m.

Public meetings were organized to present the research project to these fishers and identify those willing to be surveyed. Their knowledge was collected during individual interviews. Knowledge about essential fish habitats gained through fishing activities could be a sensitive topic. In-person and semi-structured interviews are recommended in this context so that objectives and expected results can be openly discussed (Gustavsson, 2021; Kraan et al., 2014). The interviews were conducted between March and September 2023.

### 2.3.2. Direct interviews on fishing practices and knowledge

Semi-structured interview methods aimed at 1) establishing a fishing profile of the respondent and 2) collecting his knowledge about sole nurseries. The fishing profile was established by asking the respondent to describe his fishing experience and activity through open-ended questions. The principal information gathered was the different fishing gear and mesh sizes used, during which period of the year the interviewee fished and which species were caught. The period during which the fisher was potentially in contact with sole nurseries was identified, according to his annual calendar and over the course of his career if his activity had changed (Table 3).

Fishers were preliminarily informed about the seasonal size of YoY sole to estimate whether their juvenile catch was YoY. To do so, age-length data of YoY sole from 115 scientific coastal trawl surveys carried out by Ifremer (French National Institute for Ocean Science and Technology) between 1976 and 2006 were compiled. For each month between June and December, the length for which 75 % of the sole captured in the survey were YoY was estimated (Table 2) and was considered the limit size for YoY. The June boundary month was chosen arbitrarily, considering that YoY are likely too small to be captured by fishers before June, according to survey data and previous knowledge about the spawning period and larval drift duration (Savina et al., 2016).

Finally, the fishers were asked about their knowledge of sole nurseries. All the questions were open-ended, and the specific information sought was as follows: 1) the location of YoY sole nurseries, 2) the characteristics of those areas, and 3) the fishers' perceptions of the temporal evolution of the nurseries (Table 3).

### 2.3.3. Summer nursery mapping

The following part of the interviews was intended to map the YoY sole habitats known by fishers with a geographical information system (GIS) tool. The literature offers many examples of studies that use GIS tools to map FEK (Bliss et al., 2023; DeCelles et al., 2017; Leite and Gasalla, 2013; Martinez-Levasseur et al., 2017). Fishers were first asked to draw their summer fishing grounds to identify the spatial limits of their knowledge. Second, they were asked to draw (Bezerra et al., 2021; Schmitz Nunes et al., 2021) the YoY sole distribution from June to September, when juveniles are concentrated in coastal areas (Le Pape et al., 2003). These zones were drawn by the fishers themselves with QField software on a numeric tablet. QField is a portable implementation of QGIS software allowing users to manually draw zones. The base map displayed for drawing was a nautical chart. Bathymetry and sediment structure maps were available to support the drawing.

We used geoprocessing tools in the QGIS to compile individual maps of fishers. We first merged the fishing grounds of the fishers surveyed to identify the spatial limits of the gathered information. Summer nurseries identified by fishers were compiled, keeping information on the overlapping areas between fishers.

## 2.4. Onboard observation data

To complement FEK, we used onboard observation data from the OBSMER program (see Table 1) (Cornou et al., 2021). These data were collected between 2003 and 2021 on fishing vessels and reflect the

**Table 2**

Maximum size of YoY sole, based on scientific surveys. No scientific survey data are available for the month of August.

Month	Max length (cm)
June	9
July	10
September	15
October	15
November	16
December	18

**Table 3**

Data collected during semistructured interviews.

	Data collected
Fishing profile	Years of fishing experience Actual and past métiers (fishing gear used and species targeted) Typical activity calendar
Knowledge about sole nurseries	Period when fishing YoY sole Presence of YoY sole in the fisher's fishing zone Physical characteristics of YoY sole habitats Evolution of YoY sole abundance and location during fishing experience

composition of catches during the sampled fishing trips. For each fishing operation, the gear used, the precise location and catch composition (species, weight, number and length) are registered. Thus, OBSMER data provide precise information about the catch composition of all types of fishing vessels. Only the fishing practices potentially catching juvenile sole were selected, i.e., fishing operations using gear for which YoY soles were (even scarcely) captured in OBSMER data (gill- and trammel nets and trawls, with a total of 6483 fishing operations).

To identify YoY sole in the OBSMER data, we crossed the length of soles captured with the monthly limit maximum size of YoY based on scientific survey data (Table 2). Soles in the OBSMER data were categorized as YoY if their length was lower than or equal to the corresponding limit length. The low overall number of fishing operations with YoY sole catches (107) was not sufficient by itself to map potential nurseries. However, the highly 0-inflated data revealed the presence of YoY sole in fishing operations. Punctual presence was described by the location of fishing operations that catch YoY sole; absence was described by the location of fishing operations that did not catch YoY sole, although the operations used fishing gear and a mesh size that potentially could catch them.

We first selected summer (June to September) data to compare summer nurseries mapped from the fisher FEK and YoY catches in the OBSMER data. Only OBSMER fishing operations that took place in one of the fishing grounds covered by at least one fisher interviewed to collate FEK were retained. The distance between the OBSMER fishing operation location and nursery polygons determined through FEK in summer was calculated using the Dist2Line function in the R package geosphere. This distance was used to evaluate the spatial overlap between the OBSMER data and YoY sole catches and the locations of the nurseries provided by the fishers. OBSMER fishing trips were also attributed to the same fishing profiles used for the collection of FEK. The fishing trips of trawlers targeting wedge sole were directly identified by the gear used. Gill netters' fishing trips were selected by the gear used and then geographically segregated according to their location (i.e., inside or outside the Arcachon Basin) to attribute them to coastal or Arcachon Basin gill netters. All other data were attributed to a last mixed group.

Finally, we explored the seasonal evolution of the spatial distribution of YoY sole from OBSMER FB data from June to December. To do so, all of the 6483 selected OBSMER data in the BoB were used. We considered summer nurseries the areas with predicted YoY densities above the median of the predicted values used on the HSM-based map. The distance between these nurseries and the presence of YoY in the OBSMER data was calculated monthly to visualize the seasonal distribution of YoY in the FB data and to compare the observed seasonal patterns with those previously described for YoY in a dataset of scientific trawl surveys led on a two year period in a restricted area located in the north of the BoB (Dorel et al., 1991).

## 3. Results

### 3.1. YoY nurseries based on an HSM tuned on scientific surveys

Removing the "sector" effect integrated in the original model for

extrapolation outside the area covered by scientific surveys reduced the predictive capacity of the HSM model. With respect to Trimoreau et al. (2013), the explained deviance was reduced by 3 % for the presence/absence submodel and 5 % for the positive density submodel. The two submodels explained 13 % and 16 %, respectively, of the deviance (Table 4). However, the four tested environmental descriptors had significant effects on both presence and positive densities (p values less than 1 %, and the AIC decreased dramatically). The descriptors of habitat that had the greatest effects (i.e., the greatest decreases in residual deviance and AIC) were the bathymetry data and the sediment structure for the presence submodel and the bathymetry and salinity data for the positive-density submodel.

Fig. 2 presents the results of our extrapolated HSM for the Bay of Biscay. With respect to the positive effect of estuarine influence (Table 4), YoY densities in the southern BoB did not reach the high densities encountered in areas close to the northern estuaries. In the southern zone, the model predicted the presence of YoY all along the coastline from the Gironde estuary to the southern limit. The highest densities were found on a thin band of low bathymetry (0 to -5 m). The Arcachon Basin supports higher YoY sole densities in relation to the positive influence of shallow soft-bottomed and sheltered areas for juvenile sole in the HSM (Table 4).

### 3.2. FEK and fishers' mapping of sole nurseries

#### 3.2.1. Fishing profiles and fishing grounds surveyed

Thirteen skippers distributed along the coast were interviewed. Three were skippers of wedge sole trawlers, five were coastal gill netters, and five were Arcachon Basin gill netters. Compared with the overall number of fishers identified for the three fishing profiles in our study zone, our sampling represented 75 % of wedge sole trawlers, 62 % of coastal gill netters and 55 % of Arcachon Basin gill netters. Among the fishers interviewed, 11 were experienced fishers, and two were young fishers (mean fishing experience: 28.5 years; standard deviation: 12 years).

#### 3.2.2. Nursery locations

Fig. 3a shows the extent of the fishing areas of the interviewed fishers. Wedge sole trawlers operate in the northern part of our study area, coastal gill netters in the southern part, and Arcachon Basin gill netters inside the basin. The overall coverage of our study area was satisfactory.

3.2.2.1. *Large scale.* At a large scale, nurseries known by fishers are located in four areas (Fig. 3b). In the northern zone, two nurseries were mapped by wedge sole trawlers, one located offshore of the Gironde estuary (1), identified by a single fisher present in this zone, and the other located on the northern half of the coast (2), identified by the three

**Table 4**

Analysis of deviances, p values and Akaike information criterion (AIC) values for the presence and positive density submodels.

MODEL	Residual Degrees of freedom	Residual Deviance	P value	AIC
<b>Presence subsubmodel (Eq. 1; <math>Y_0</math>)</b>				
Null	1642	2235		2237
+Salinity	1640	2211 (-24)	6.57e-06	2217
+Sediment	1638	2140 (-71)	3.91e-16	2150
+Bathymetry	1635	1967 (-173)	3.8e-37	1983
+Wave	1633	1932 (-35)	1.58e-08	1952
<b>Density subsubmodel (Eq. 2; <math>ln</math>)</b>				
Null	953	2694		3702
+Salinity	951	2588 (-106)	9.3e-11	3667
+Sediment	949	2539 (-49)	2.54e-05	3653
+Bathymetry	946	2317 (-222)	8.52e-21	3572
+Wave	944	2243 (-74)	9.63e-08	3545

wedge sole trawlers. The third zone was located in front of the Arcachon Basin (3), identified by coastal gill netters, and the last zone was located in the Arcachon Basin (4), identified by local gill netters.

In contrast to the prediction of the HSM, nurseries known by fishers were not distributed all along the coast. In particular, no coastal nursery was identified in the southern part of the coast, south of the Arcachon Basin. The functionality of the small estuaries in this area was discussed with fishers, although they were located outside their fishing grounds. The fishers considered that no nurseries were present in these estuaries, as they did not catch any juveniles leaving these estuaries. However, they suggested that they may have lost their nursery functionality, as many species previously present have disappeared in recent decades.

3.2.2.2. *Fine scale.* Nursery characterizations collected during semi-structured interviews provided more insights into nurseries mapped by fishers at a fine scale.

Fishers linked northern nurseries 1 and 2 to a fine substrate zone. The sediment map revealed the presence of "very fine sand" in the zone mentioned by the fishers and the absence of this substrate in the southern part of the coastline (Fig. 3b). This characterization indicates that sediment structure is a main driver of nursery distribution along the southern coast of the Bay of Biscay. However, in nursery 4, the sandy sediment structure is similar to that of the rest of the coastline. The fisher who identified this nursery considered that the proximity to the Arcachon Basin explained the presence of YoY in this area.

FEK also provided complementary insights into the nursery distribution in the Arcachon Basin (Fig. 4). The HSM predicted relatively high YoY densities across the entire basin. Both the spatial resolution of the trawl sampling data used to develop the HSM (> 1 km; Le Pape et al., 2003) and the maps of the environmental descriptors used to map the YoY distribution from the HSM model predictions were coarse enough to discriminate zones at such a fine scale. The nurseries identified by fishers are located in the half north of the basin and in one channel close to the basin's mouth. These areas are shallow (zero to height meters below the sea level at low spring tides) muddy channels. The fishers considered that YoY used these channels as shelter areas and fed on the surrounding intertidal grounds during high tide.

### 3.3. Validation of YoY sole nurseries with FB onboard observation

#### 3.3.1. Summer distribution of YoY sole in the southern BoB

We compared summer nurseries mapped by interviewed fishers (Figs. 3-4) and YoY catches in the OBSMER summer data. The fishing grounds covered by the OBSMER data were adequate for investigating the areas fished by interviewed fishers in summer, with the exception of the southern offshore fishing zone, where only two fishing trips were recorded (Fig. 5). In the OBSMER data, 11 fishing operations captured YoY sole within the fishing grounds of the interviewed fishers, with 399 operations without YoY catches. YoY catches in the OBSMER data took place inside or close to nurseries identified by fishers, unlike fishing operations without YoY catches, which were widely distributed (Fig. 5b). In particular, no YoY juveniles were captured on the southern part of the coast, after the Arcachon Basin, in accordance with FEK.

The percentages of YoY captured inside a nursery located through FEK were 94 % for wedge-sole trawlers, 100 % for Arcachon Basin gill netters and 67 % for coastal gill netters. The percentage of YoY catches inside the mapped nurseries for the other profiles was 50 %. The maximal distance (Fig. 5b) from a YoY sole catch and a mapped nursery was 4 km (for all fishing profiles). Comparatively, fewer OBSMER fishing operations without YoY took place inside a nursery for all fishing profiles. The distance to a nursery for these operations ranged from five km to more than 50 km, depending on the spatial extent of fishing areas of each fishing profile. This highlights the consistency between the OBSMER data and FEK-based nursery locations.

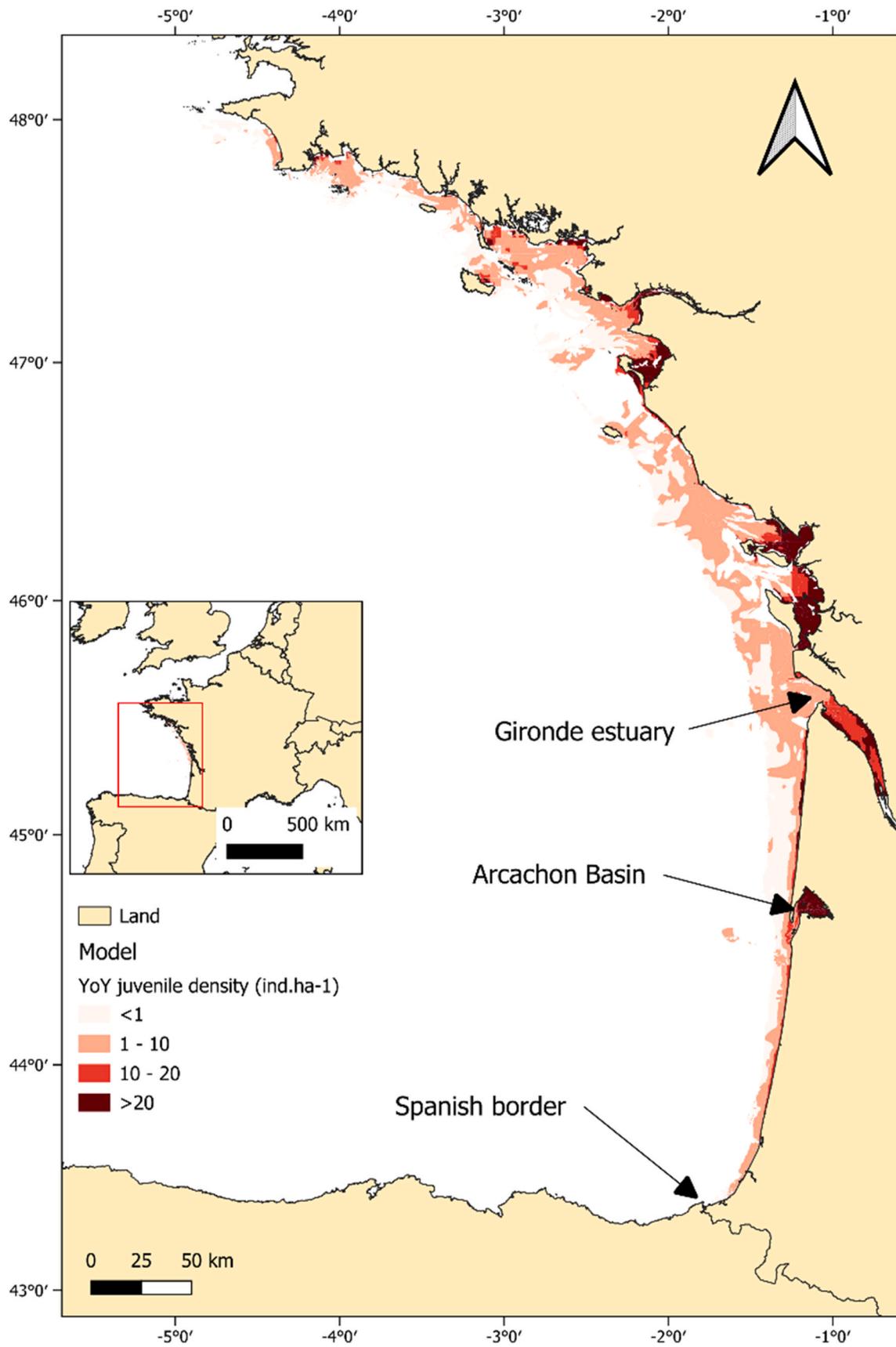
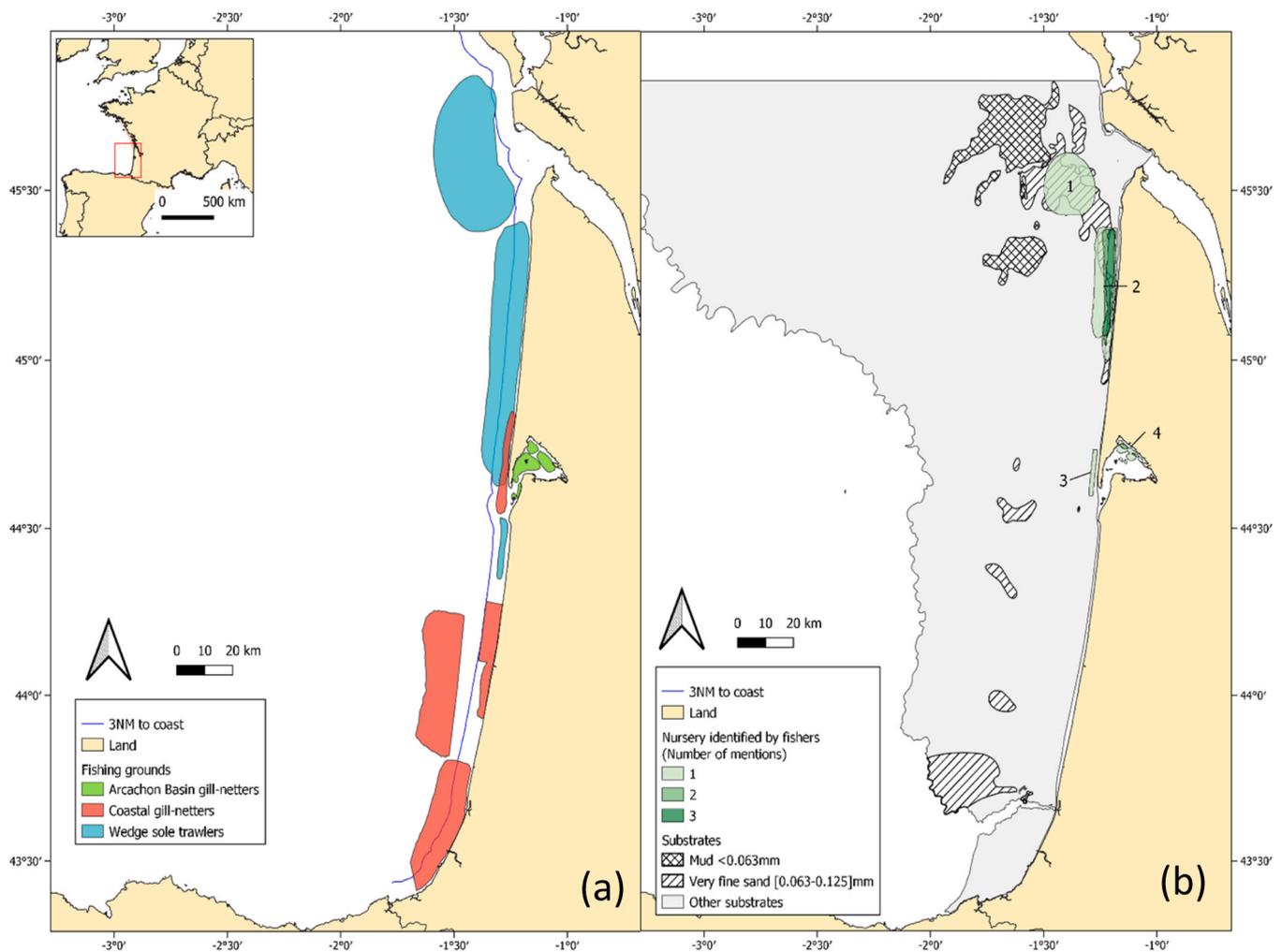


Fig. 2. Map of YoY sole relative density (number of captured individuals.hectare<sup>-1</sup>) fitted by the extrapolated HSM.



**Fig. 3.** (a) Fishing grounds of the three group groups of interviewed fishers. (b) Nursery drawn by fishers and sediment structure. The green scale indicates the number of times each zone was mentioned. Numbers 1–4 indicates the different nursery areas mentioned in the text. For the sediment structure, mud and very fine sand are indicated, and other substrates (i.e., coarser sediments and rocks) are pooled.

### 3.4. Seasonal patterns of YoY juveniles in the BoB

In June and July OBSMER data, YoY sole were captured within or very close to the nurseries identified from the extrapolated HSM model (Fig. 6). The median distance from a fishing operation without YoY catches to a nursery was dramatically greater. From September to December, the YoY catches in the OBSMER data drifted away from these areas (on average 20 km) and dispersed progressively (Fig. 6).

## 4. Discussion

### 4.1. Three sources of data with their respective strengths and weaknesses

Survey data offer quantitative (Trimoreau et al., 2013; Vasconcelos et al., 2013) estimates of juvenile fish density that are useful for developing HSMs and mapping nursery habitats (Le Pape et al., 2014). They provide relative (not absolute) estimates of density but benefit from a standardized sampling design and can be considered unbiased (Alglave et al., 2022). However, these data are constrained by their spatiotemporal availability. Surveys usually occur once a year and may sample a relatively small number of spatial locations. Moreover, a significant proportion of ecological surveys are conducted only one time, or on a single occasion or during two or three years and do not allow reliable matching with interannual variability, which is dramatically high for fish density and spatial distribution and even more so for juveniles (Le

Pape et al., 2020).

FEK is an alternative source of data for fish habitat mapping (Bergmann et al., 2004; DeCelles et al., 2017; Bezerra et al., 2021; Björkvik et al., 2021; Bliss et al., 2023); however, it is rarely used for nursery identification (Da Silva et al., 2023; Leite and Gasalla, 2013). Compared with predictions from scientific data, FEK offers fruitful spatial refinement facilitated by the direct drawing of nurseries (Bezerra et al., 2021). However, FEK collection and usage for nursery mapping have several limitations. First, few fishing practices are allowed in coastal areas, where juveniles are concentrated for a large proportion of species (Seitz et al., 2014; Brown et al., 2018), and few types of fishing gear can capture juvenile fish, especially YoY, which are dramatically smaller than the minimal landing size. Fishers with practical experience in YoY fish location are not numerous. In practice, help from Producers Organizations or other professional structures was crucial to determine the fisher population with potential knowledge of the distribution of YoY sole and to identify individual fishers. These structures have been integrated into the project since its beginning and have played a key role in fishermen's participation, following good practice recommendations (Kraan et al., 2014; Stephenson et al., 2016). Another major limitation of FEK for nursery mapping is the impossibility of inferring standardized information on the density of juveniles in each zone. The best information was a semiquantitative density ranking between zones for one fisher. Few respondents were able to make this ranking, whether because they did not think such a difference existed or because they

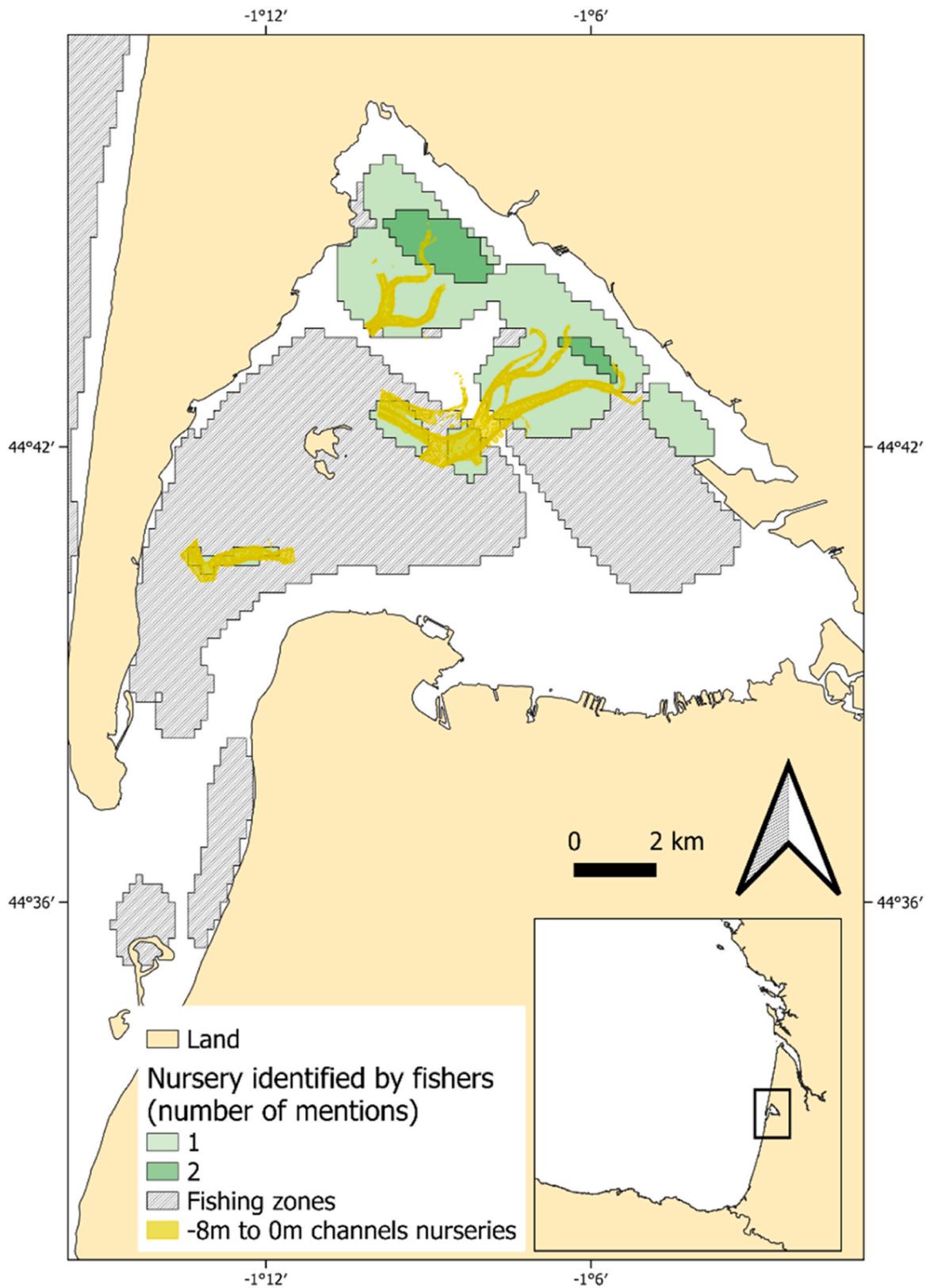
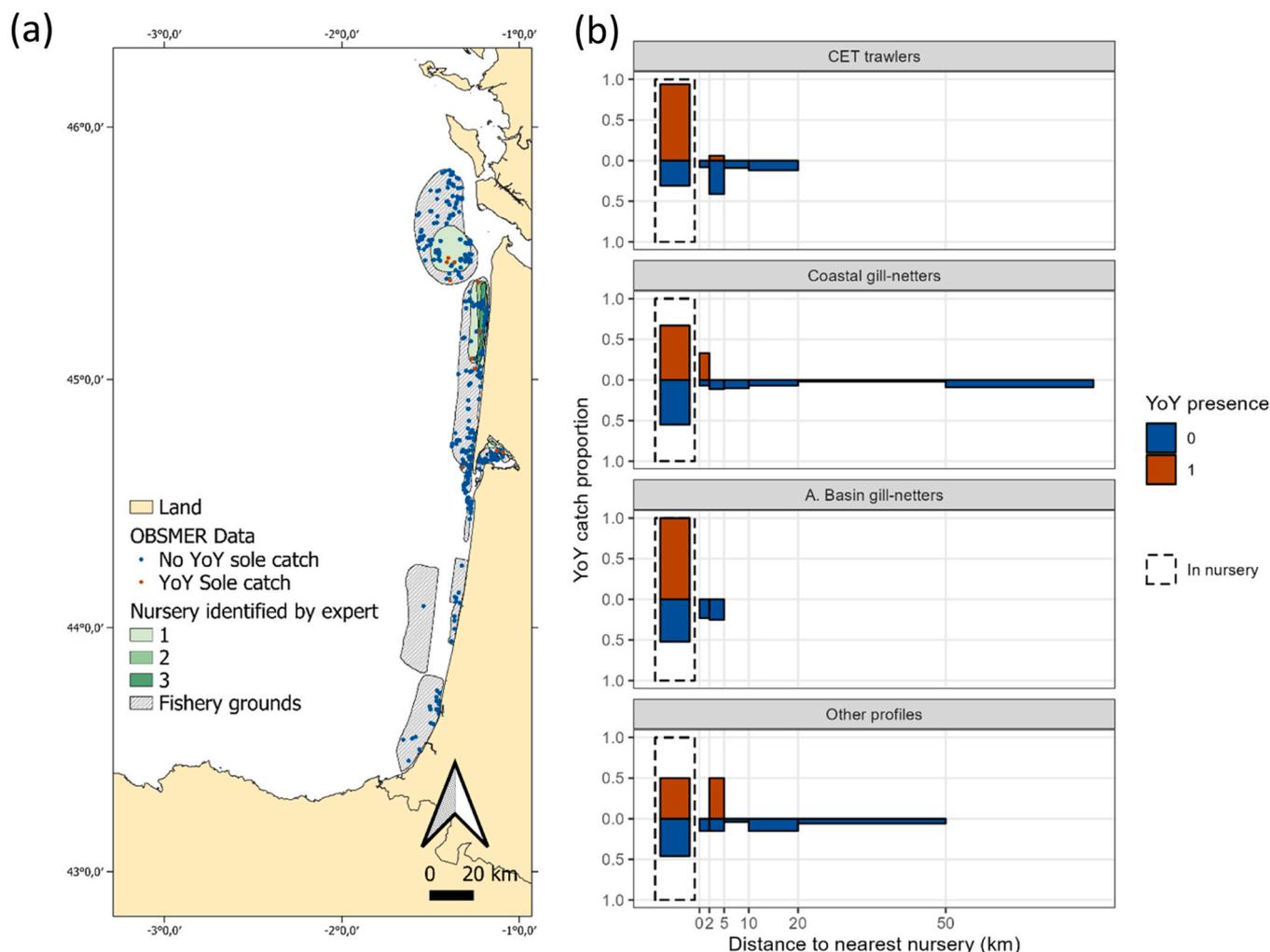


Fig. 4. Nurseries drawn by fishers in the Arcachon Basin.

were not able to quantify it. Moreover, extrapolating an overall ranking of nurseries identified by different fishers was not possible (i.e., no standardized proxy of fish density existed among interviewed fishers). A remaining limitation was the potential confusion between species (Madsen et al., 2020). In the Arcachon Basin, fishers mention that they

currently catch mostly *Solea senegalensis*. They were not able to identify the species for YoY. Thus, the proportion of YoY *Solea solea* may be changing and remains to be investigated. Despite these limitations, the representativeness of our study population of fishers was appropriate, both quantitatively and qualitatively. Quantitatively, 55–75 % of the



**Fig. 5.** (a) Location of fishing operations in OBSMER summer data, with or without presence of YoY sole in catches, between June and September inside fishing grounds of fishers interviewed for FEK. (b) Proportions of OBSMER fishing operations according to distance to the nearest FEK nursery. In blue and on the bottom side, fishing operation without YoY catches, in red on the top side, with YoY catches. Proportions of catches directly in nurseries (distance=0) are indicated in the dashed box. The three fishing profiles accounted for in fishers' interviews are detailed, and other profiles existing in the OBSMER data are gathered in the fourth panel.

overall number of fishing vessels were interviewed for the three studied fishing métiers, and the overall number of fishers interviewed (13) seemed sufficient given the relatively small area considered and its environmental consistency. Qualitative representativeness is reached when new interviews do not yield new information (Calderwood et al., 2023), and our interviews revealed a consensus among fishers. The overall number of fishers interviewed also seemed sufficient given the relatively small area considered and its environmental consistency.

FB data are another source of information that obviously benefits from high sampling effort, with high spatiotemporal coverage (Alglave et al., 2022). These methods offer a reliable source of information for inferring fish habitat (Alglave et al., 2023). However, focusing on juvenile fish, which are dramatically smaller than the minimum landing size, prevents the use of declarative data, which are not informative for non-targeted species and/or life stages. Only the restricted part of the FB data based on onboard observer programs can be used for that purpose. These programs cover a limited fraction of the entire fleet (e.g., only 1 % of all sea trips are covered by French observer programs; Alglave et al., 2023). The observation data are also largely 0-inflated, especially for young fish, even when a subsample of fishing gear potentially catching juvenile fish is selected (here, only 1.7 % of fishing operations with YoY sole catches in the selected OBSMER dataset). Moreover, FB data result from a preferential sampling strategy; the higher the biomass, the

greater the fishing effort (Alglave et al., 2022). Accordingly, onboard observation data were not sufficient to map sole nurseries. These data were used as a complementary source of data only (López-Angarita et al., 2021), to validate the presence of YoY sole in some areas during different seasons.

#### 4.2. Combining data sources for a critical assessment of nursery maps

Our work combined several sources of data with their respective limitations. Our extrapolation of an HSM model was an exploratory approach outside the original scope of the survey data. Such extrapolation requires complementary information to be validated. A comparison of scientific data with FEK and FB data demonstrated the usefulness of this approach (Berkström et al., 2019; DeCelles et al., 2017).

With respect to fishers' knowledge, our interviews revealed a great consensus among fishers with the same fishing profile, both to map nurseries when fishers shared the same fishing grounds (wedge sole trawlers) or to characterize nurseries otherwise. The spatial refinement provided by FEK was especially useful for complementing nursery maps based on scientific trawl surveys. Combining the two mapping approaches, i.e., the HSM, which is based on scientific surveys, and FEK, for the southern BoB, we can infer that FEK gives a precise location of sole nurseries, whereas the HSM gives an estimation of their density.

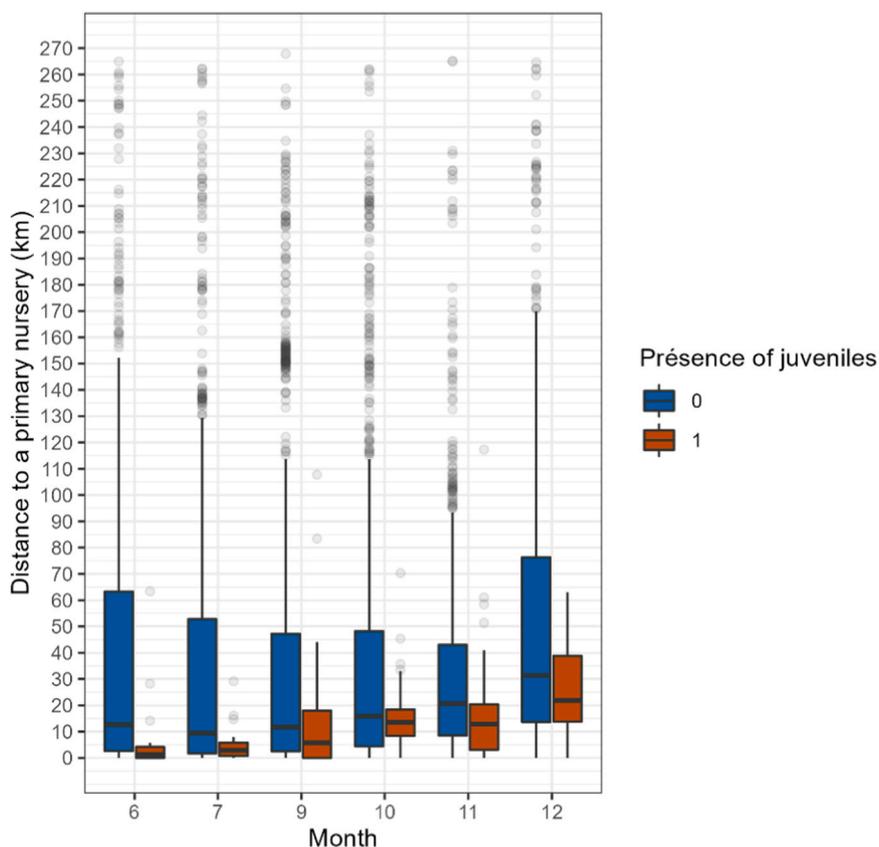


Fig. 6. Boxplots of the monthly distances between fishing locations in the OBSMER data, with (red) or without (blue) YoY catches, and nursery zones based on the HSM.

This emphasizes the interest in linking FEK with scientific data to mitigate their respective limitations (Bevilacqua et al., 2016; Björkvik et al., 2021; Calderwood et al., 2023; Lopes et al., 2019; Silvano and Valbo-Jørgensen, 2008) and to integrate FEK elicitation in a wider framework (Björkvik et al., 2021; Martinez-Levasseur et al., 2017).

In the southern BoB, no constraints in YoY densities were evidenced from the extrapolated HSM along the coastline. FEK offered a new outlook. Fishers indicated a clear difference between the northern and the southern parts along the coastline: YoY sole are concentrated in specific areas along the northern half of the southern BoB: offshore of the productive Gironde estuary (Pasquaud et al., 2008), under an estuarine food supply sustaining sole juvenile growth (Kostecki et al., 2010; Le Pape et al., 2013), and in front of the productive Arcachon Basin (L'Heureux et al., 2022). These discrepancies may indicate that the HSM missed some additional explanatory driving factors in the southern zone of the BoB, such as the amount of larval supply (FEK and also Le Pape et al., 2003; Savina et al., 2016), fine descriptions of the sediment structure (Cirac et al., 2016) and refinements in the description of land–sea influences (Le Pape et al., 2013). In the Arcachon Basin, fishers were able to indicate precisely restricted channels sheltering YoY soles, a spatial resolution fully impossible to achieve with HSM (the scientific trawl survey resolution used in the HSM is up to one kilometer; Le Pape et al., 2003).

Moreover, the overlap between FEK collection and FB data coverage allowed us to validate FEK (Björkvik et al., 2021; López-Angarita et al., 2021; Martinez-Levasseur et al., 2017). Fishers sampled by the OBSMER program capture YoY sole, although in very small proportions, and the YoY catch locations in the FB data were in good agreement with the FEK nursery maps. By doing so, our case study represents an interesting assessment of FEK accuracy for future works. This cross-validation supports the use of FEK as reliable information in areas where other data are lacking (Bevilacqua et al., 2016; Le Fur et al., 2011; Silvano

et al., 2023).

More generally, the FB data also proved useful for inferring juvenile fish distributions in data-poor situations (Bevilacqua et al., 2016). The FB data confirmed the HSM potential to infer the relative YoY density outside its original area. However, the FB data confirmed some weaknesses of the HSM extrapolation, which were also pointed out by the FEK: in some areas outside scientific trawl survey coverage, the HSM predicted some nurseries that were not confirmed by the FB data or FEK, possibly indicating false-positive nursery prediction. Moreover, the seasonal distribution of YoY catch in the FB data allowed us to confirm the seasonal migration of juvenile sole toward deeper areas in autumn–winter, as shown previously using only a restricted (on both spatial and temporal scales) scientific trawl survey (Dorel et al., 1991).

#### 4.3. FEK's benefit for coastal nursery ground management

Nurseries are sensitive habitats that are subjected to many stresses that can impact their functionality (Archambault et al., 2018). These multiple threats to the nursery functions of estuarine and coastal habitats (Brown et al., 2018) highlight the need for their conservation/restoration. To do so, a first step consists of identifying and mapping nurseries (Le Pape et al., 2014), and the complementary insights from scientific survey-based HSM, FEK and FB observation data offer fruitful opportunities in that context.

Studies integrating FEK may also raise early alerts on nursery modifications witnessed by fishers (Le Fur et al., 2011). Typically, fishers interviewed in our study mentioned a loss of nursery functionality locally in both the Arcachon Basin and the southern estuaries. As an enclosed, shallow area, the Arcachon Basin is particularly exposed to water quality degradation (Lheureux et al., 2022; Plus et al., 2010), and the decrease in shoals' seagrass cover (Ganthuy et al., 2013; Kombiadou et al., 2014; Plus et al., 2010) leads to the filling of channels, reducing

the area available for juvenile sole. The Arcachon Basin thus faces two main sources of loss in nursery functionality, i.e., a decrease in habitat size and degradation of the quality of the remaining nursery areas (Champagnat et al., 2021; Gernez et al., 2023), and similar pressures have impacted southern estuaries.

The nursery modifications mentioned by the fishers in our study involved known problems in our study area (e.g., the degradation of nursery habitats in both the Arcachon Basin and the southern estuaries). It also revealed new challenges that still need to be investigated. For example, increasing sea temperatures may have impacted Arcachon Basin nursery functionality and the relative proportions of *Solea solea* and *Solea senegalensis* juveniles (Vinagre et al., 2006). Ultimately, considering FEK throughout the knowledge acquisition process can increase its acceptability (Stephenson et al., 2016) and its use to help decision on management measures (Hamelin et al., 2024).

### CRedit authorship contribution statement

**Olivier Le Pape:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Youen Vermard:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Gabriel Lahellec:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

### Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gabriel Lahellec reports financial support was provided by France Filière Pêche. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data Availability

Data will be made available on request.

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