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RESEARCH ARTICLE

Too young to die: Mapping nursery areas for early juveniles of the endangered sandbar shark (*Carcharhinus plumbeus*) to inform conservation in the Mediterranean Sea

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Abstract

1. Globally, elasmobranch species have been declining in abundance due to fishery activities. This conservation issue calls for effective management strategies and increasing efforts to protect these species. The declining status of elasmobranchs in the Mediterranean Sea is alarming as well. Reversing such dramatic trends requires tackling fishing pressure using multiple methods, including a fine-tuned spatial resolution in conservation strategies incorporating robust evidence on species spatial use at different life stages and its overlap with fishing pressure. In particular, a scientifically sound identification of nursery grounds is crucial to define key spatial management targets promoting the recruitment of such depleted species.
2. Here we focused on the sandbar shark (*Carcharhinus plumbeus*), listed as endangered by the IUCN, and on the nursery of its early juveniles such as newborns (i.e. a few months old) and young-of-the-year individuals (i.e., <1 year old), both characterized by a total length below 71 cm. First, by monitoring a small-scale fishery fleet in the North-Western Adriatic Sea, we unambiguously identified a local multiyear nursery site for early juveniles of this species.
3. Then, we combined such novel information with a bibliographic review on the presence and absence of early juveniles across Mediterranean regions to construct a species distribution model predicting favourable nursery areas throughout the entire Mediterranean Sea. To do so, a Bayesian approach was applied to construct a generalized linear model with spatial effect estimated by a Gaussian random field (INLA-SPDE). Model-based inference indicates that, in summer, which is the main pupping season, important nursery areas for this species are found along the North-Western coast of the Adriatic Sea, in the coastal area of the Gulf of Gabes, and in the Gulf of Iskenderun (North-Eastern Levantine Sea).
4. *Synthesis and applications*: These key areas should be prioritized to apply conservation measures to foster the recruitment of this species since intense fishing

activities were also documented. Model predictions also allowed to determine where unknown nursery grounds may potentially occur, a valuable information to direct future monitoring efforts and clarify any further occurrence of nursery areas.

KEYWORDS
Adriatic Sea, conservation, elasmobranch, fishery, management, Mediterranean Sea, nursery

1 | INTRODUCTION

The decline in elasmobranch abundance represents a global environmental concern. Fishing pressure has caused a worldwide decrease in the abundance of cartilaginous fish in past decades (Dulvy et al., 2021; Pacoureau et al., 2021; Sguotti et al., 2016) and centuries (Fortibuoni et al., 2010; Lotze et al., 2011). Elasmobranchs are prone to overfishing, either as target or bycatch, due to their characteristic life history traits such as large size, slow growth and late sexual maturity, which increase their vulnerability, especially before reproduction, with respect to most bony fish (Dulvy et al., 2017). Typical elasmobranch behaviours such as long migrations, aggregations, philopatry and site fidelity further increase their vulnerability to fishing pressure (Chapman et al., 2015). Despite the widespread disappearance of these predatory fish worldwide, its ecological consequences, including far-reaching trophic cascades (Myers et al., 2007), are largely unexplored, management actions are rarely enforced (Milazzo et al., 2021), and the urgent search for sustainable conservation solutions remains incomplete (Dulvy et al., 2017; Pacoureau et al., 2021). A promising conservation approach for neritic shark, which make use of coastal and pelagic water within their life cycles, is an integrative management strategy that includes the identification and protection of nursery areas, as well as subadult life stages from fishing mortality (Kinney & Simpfendorfer, 2009). Nursery areas can be identified according to the abundance of newborn (i.e. few months old) and young-of-year (i.e. less than 1 year old) individuals, residency and interannual use. These areas are essential for population recruitment by providing prey availability and refuge from predators (Heupel et al., 2007). In neritic sharks, the environmental conditions of marine waters shaping a nursery area are usually shallow depth and calmer and warmer waters compared to adjacent areas, although site fidelity and philopatry are also crucial determining factors (Chapman et al., 2015; Heupel et al., 2007; Knip et al., 2010; Latour et al., 2022).

The Mediterranean Sea has experienced one of the longest lasting and most severe declines in elasmobranch abundance worldwide (Barausse et al., 2014; Fortibuoni et al., 2010; Lotze et al., 2011), especially for large sharks (Ferretti et al., 2008). Environmental management in the Mediterranean Sea is complex: its biodiversity, disproportionately high for the sea surface area, faces multiple threats, including fisheries, eutrophication, pollution, transportation, habitat loss and degradation, climate change and alien species (Bianchi & Morri, 2000; Coll et al., 2010, 2012; Lotze et al., 2011). These threats are mostly related to human activities along the coasts, which have been inhabited for millennia, which is why the Mediterranean elasmobranch decline dates so far back into history (Fortibuoni et al., 2010; Lotze et al., 2011). The institutional framework is also fragmented: the Mediterranean is at the crossroad of three continents and is bordered by 24 sovereign countries (of which eight are member states of the European Union), a potential obstacle to the implementation of joint conservation strategies. Gathering robust ecological information to make informed decisions represents a precondition to achieve conservation goals in the face of this complexity. Here, we contribute to building a better knowledge base for the conservation of the sandbar shark (*Carcharhinus plumbeus*), a neritic species classified as endangered globally and in the Mediterranean by the International Union for Conservation of Nature (Ferretti et al., 2016; Rigby et al., 2021).

Biological information on this placental viviparous shark is incomplete in this basin: reproductive and pupping seasons occur in summer (Saïdi et al., 2005), but a comprehensive map of nursery areas is lacking. In the Western Atlantic Ocean, juveniles up to 10 years of age showed site fidelity and natal homing for foraging purposes after seasonal migration in more favourable conditions (Merson & Pratt, 2001). Niche overlap between neonates and young-of-the-year of size range between 45.5 and 70.5 cm in total length and older juveniles of size range 71–116.5 cm (Latour et al., 2022) is low–medium, and different movement ranges between young and older juveniles have been reported (Conrath & Musick, 2010). Furthermore, secondary nursery sites for *C. plumbeus* were reported, presumably formed by the results of break-off groups from migrating adults (Baremore & Hale, 2012).

Based on systematic data collection for a small-scale fishery fleet, we document the existence of an important nursery area for early juveniles of *C. plumbeus* in the Northern Adriatic Sea, one of the most human-impacted Mediterranean subbasins, where elasmobranch fish have experienced a long-term decline driven by fishing pressure (Barausse et al., 2014; Lotze et al., 2011). We then review the scientific literature on the presence and absence of nursery sites for early juveniles of the sandbar shark in the Mediterranean Sea and combine this information, including information on the novel nursery site we report, to construct a species distribution model predicting the favourability of nursery habitats for early juveniles in the Mediterranean Sea. Lastly, we use the model to map potential nursery areas for early juveniles of the sandbar shark with the aim of contributing to build a solid knowledge base to promote a spatially explicit management of endangered and migratory species in the Mediterranean Sea.

2 | MATERIALS AND METHODS

2.1 | Study area

The Mediterranean Sea is a semi-enclosed basin in the temperate climate zone displaying high heterogeneity in chemico-physical and biological features. Hydrodynamics are influenced by cold inflowing Atlantic waters with lower salinity, while river inputs affect regional primary production patterns. The annual mean sea surface temperature increases from north to south and from west to east (Tanhua et al., 2013). Steep and narrow shelves are found in the southern Mediterranean, except in the Gulf of Gabès, whereas extended shelves are present in the Northern subbasins, such as the Northern-Central Adriatic Sea (Coll et al., 2012). In the Northern Adriatic Sea, shallow depths coupled with intense river discharges determine high nutrient availability, which, in turn, sustains strong planktonic productivity that fuels nekton and benthic communities, which are heavily exploited by semi-industrial and artisanal fisheries (FAO, 2022).

2.2 | Data collection and processing

2.2.1 | Northern Adriatic nursery sites

To identify nursery areas for early juveniles of *C. plumbeus*, we collected data from small-scale fisheries (SSF, 'fishing vessels of an overall length of less than 12 m and not using towed gear', FAO, 2022) in the North-Western Adriatic Sea (Figure 1). This fleet segment comprises low-tonnage vessels (1–4 GT) with seasonal turnover of passive fishing gear. Gillnets are deployed from April to January, mainly targeting the common sole (*Solea solea*), with the maximum effort occurring in August (Grati et al., 2018). Following a few sightings of neonates, SSF data collection was carried out in Cervia (Emilia-Romagna region, Italy, Figure 2) in July–August 2019 and July–August 2020 through: (i) a daily survey at the harbour to record the number of fishing trips (i.e. the number of fishing boats that went out to fish) and, for each landed shark, its capture coordinates, total length (TL), sex and umbilical scar presence (Costantini & Affronte, 2003); and (ii) passive monitoring of the distribution of fishing effort of gillnets by a GPS tracker (GARMIN® eTrex20) in one of the seven fishing vessels operating in 2019 and one of the five operating in 2020. The typical activity of the rest of the fishing fleet was assumed to be represented by the tracking of a single vessel for each year (see also Grati et al., 2018).

To increase the accuracy of spatial representation of the occurrence area, the GPS location of each registered shark was obtained by an on-board fishery observer or by direct report of the fishers belonging to the monitored fleet.

The species and sex of all landed sharks were identified using morphological characteristics (Ebert & Dando, 2020). The number of landed sharks was corrected for the high variability of SSF fishing practices (Humphries et al., 2019) by dividing it by the number of fishing trips to calculate landings per unit effort (LPUE). Length frequency distribution plots (Figure 2 and Figure S1.1 in Supporting Appendix S1) were obtained by 'ggplot2' R package (Wickham, 2016). Biases in the sex ratio and differences in LPUE or TL of landed sharks were tested with χ^2 and Mann–Whitney tests using R (RStudio Team, 2020) respectively. The effect size (ES) for Mann–Whitney tests was calculated on 'rstatix' R package (Kassambara, 2021) while for the χ^2 test, the following formula was used to calculate the EF: $\sqrt{\chi^2 / n}$ where *n* is the sample size. To reconstruct the fishing effort distribution and generate the captured shark distribution using minimum convex polygons, the GPS coordinates of each gillnet start point and end point were superimposed to catch coordinates using QGIS v3.1 (www.qgis.org). To describe the environmental features of the area, this distribution was plotted against potential abiotic and biotic factors averaged over July–August 2019 and 2020: sea surface temperature (SST), net primary production (NPP), turbidity (KD), sea surface salinity (SAL) and current velocity and direction (CUR), taken from the Copernicus Marine Environment Monitoring Service (Table S2.1 in Appendix S2). This study did not require ethical permit since the monitoring was on dead specimens from accidental catches in professional small-scale fishery.

2.2.2 | Nursery areas for early juveniles in the Mediterranean Sea

To collect presence/absence (PA) data on nursery areas of sandbar sharks in the entire Mediterranean Sea, we performed a search in peer reviewed and grey literature using the following criteria to construct a nursery PA dataset: each paper should (i) report elasmobranch catch; (ii) describe fishing activity conducted during summer, which is the pupping season of *C. plumbeus* (Saïdi et al., 2005), in the last 20 years; (iii) describe sampling effort with monthly replicates; and (iv) be based on fisheries using trammel nets (GTR), gillnets (GNS) or set/drifting longlines (LLS/LLD, with hook sizes N. 2 and 3, which in our experience allow one to catch neonates), or scientific surveys such as underwater visual census and baited remote underwater video. To qualify as the presence of nursery site for early juveniles, the occurrence of at least one newborn individual (i.e. few months old) with an open fresh or partially healed, umbilical scar or young-of-the-year (<1 year old and <71 cm of TL as in Latour et al., 2022) had to be reported, while absences were assigned when all criteria were met and no early juveniles were documented, even though the occurrence of large juveniles, above 71 cm of TL as in Latour et al. (2022), adults, or aggregation sites such as reported by Cattano et al. (2021) was possibly reported. Following the selection of the studies, the published maps, reporting the study area (i.e. fishing or the survey distribution), were georeferenced using at least four reference coordinate points as per plugin's guidelines in QGIS to be classified as PA data (Table S1 and Figure S1.2).

The areas of each georeferenced PA map from selected studies were divided into a regular points grid (0.0277° spacing,~3 km) and at each point a value of zero was assigned for absence or one for

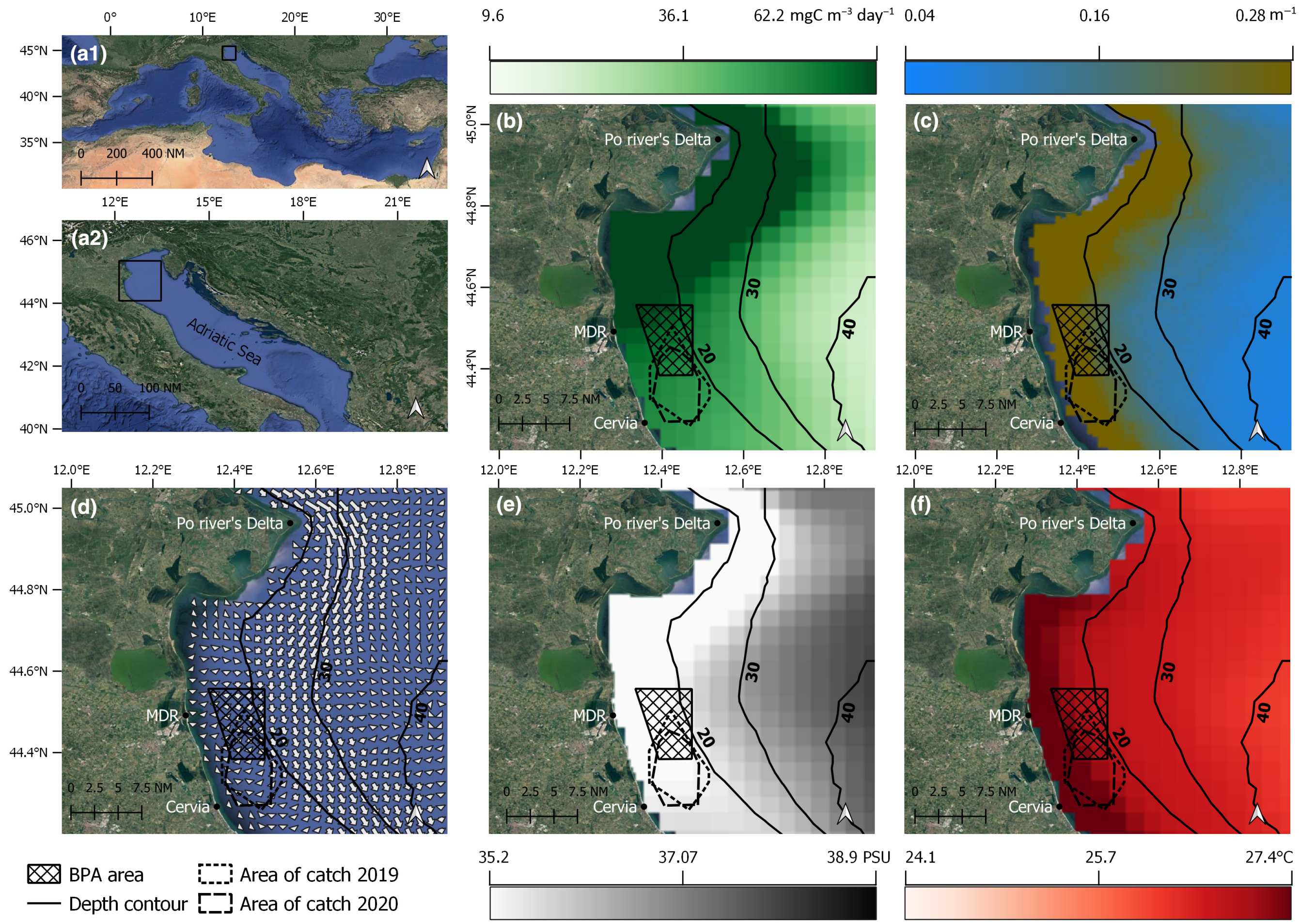

FIGURE 1 The novel sandbar shark nursery site in the Northern Adriatic Sea, Mediterranean (a1, a2) identified in this study between Cervia and Marina di Ravenna, and the local environmental conditions (b–f). Abiotic and biotic conditions were obtained from CMEMS (Table A3.1) and include net primary production (b), turbidity (c), current direction and velocity (the latter is proportional to the arrow length); (d), salinity (e) and sea surface temperature (f). At this site, a biological protection area (BPA), as shown on the map, was established in 2004 where trawling has been banned, whereas artisanal fishery is still permitted (Tassetti et al., 2019). The shark catch distribution is partially downstream of the productive Po River plume and the BPA.

presence. The collected spatial data presented in this study regarding the Adriatic nursery site were included in the PA dataset.

To characterize the environmental conditions at each PA point, abiotic and biotic factors (SST, SAL, CUR, KD and NPP; Table S2.2) were obtained from the Copernicus Marine Environment Monitoring Service in raster format and matched to the PA areas. The function extraction from the 'raster' package (Hijmans, 2021) of the R software was used to match the PA dataset with the environmental conditions during the sampling period; environmental conditions were computed by averaging the monthly values for the months of June–August and for each sampling year of the selected studies (Table S2.S2). For areas not covered by the resolution of the environmental dataset (e.g. too close to the coast or inside narrow bays), the values were taken from the adjacent available cell which was considered representative of the coastal area, given the spatially autocorrelated nature of environmental variables and the large-scale scope of the model. The bottom depth and slope were also extracted for each point to describe the PA sites (Table S2.2).

2.3 | Modelling and prediction of nursery areas in the Mediterranean Sea

The newly constructed PA dataset, also including the novel data collected in the North-Western Adriatic Sea, was used to map the nursery areas for early juveniles of sandbar shark using a species distribution modelling approach.

Point density plots were drawn for each variable to explore their distribution in the PA sites. Redundant variables (Pearson's correlation coefficient $r > 0.8$) were excluded from subsequent analyses (Zuur et al., 2010). To investigate whether the occurrence of nursery areas could be shaped by environmental features, a spatial explicit GLM was fitted to the PA points as a binary response variable, using a logit link function for Bernoulli distribution, with different combinations of abiotic and biotic factors as predictors. The model was built using a Bayesian framework by the R package *'sdmTMB'* (Anderson et al., 2022). This package allows the construction of a spatially explicit GLM, estimating the spatial effect with a Gaussian random

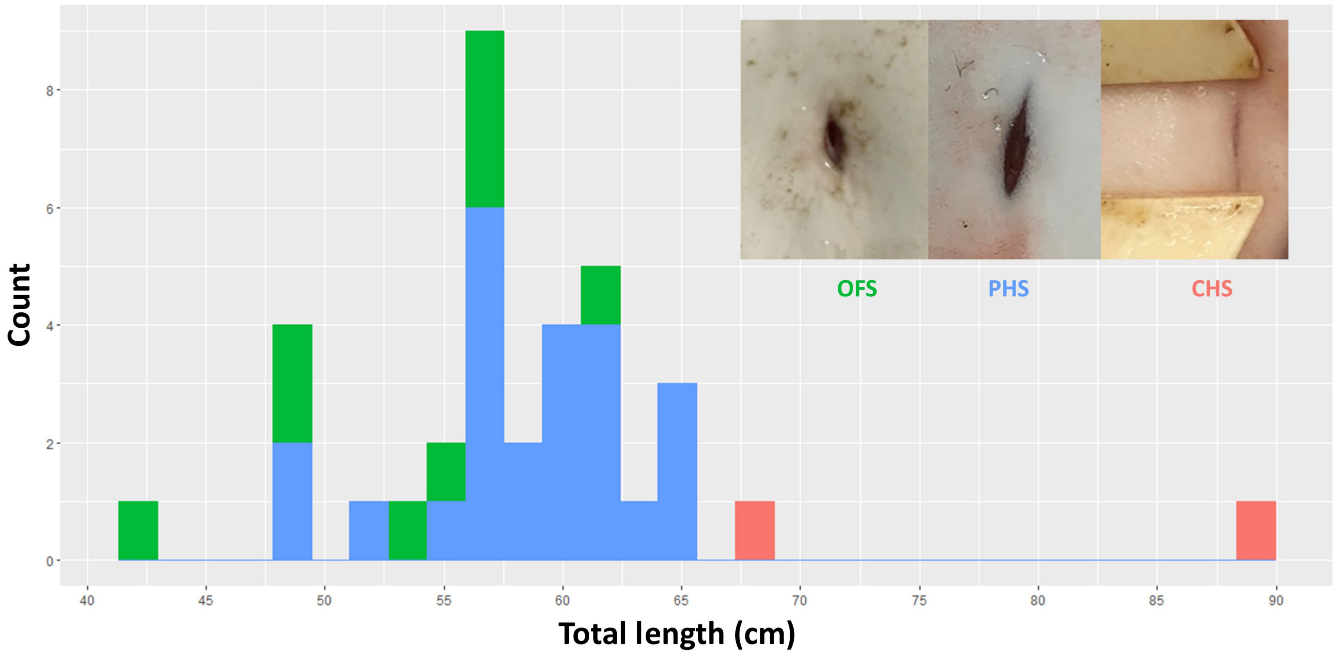

FIGURE 2 Total length frequency distribution of the sandbar sharks recorded in 2019 and 2020 in Cervia's landings. Colours indicate the umbilical scar condition of each individual: green for an open fresh scar (OFS, the opening is present through the skin and superficial muscle tissues), blue for a partially healed scar (PHS, only the two skin edges are unhealed, and red for a completely healed scar, CHS). The inset pictures show examples of umbilical scar conditions.

field, constrained by a Matérn covariance function, with Integrated Nested Laplace approximation with a Stochastic Partial Differential Equation approach (INLA-SPDE package, Rue et al., 2009). For the Bayesian priors of the spatial component, the native range of the spatial random field was chosen to be 15 km (~0.13°) according to the maximum distance registered in a tracking study on early juveniles of sandbar shark (Rechisky & Wetherbee, 2003), while the sigma range was equal to 1. The model formula was as following:

$$\mathrm{logit}(\mathrm{PA}) = \beta_0 + \beta_1 x_1 + \ \dots \ + \beta_p x_p + u$$

where x_i are the predictors, β_i the corresponding model parameters and the spatial component u accounts for spatial autocorrelation, that is, it is a numeric vector associating each observed event to a spatial location, accounting for region-specific pattern in the observation which cannot be ascribed to the environmental covariates (Anderson et al., 2022). Linear terms for the predictors were chosen as the most obvious initial choice according to the parsimony criterion, although the performance of non-linear terms was also explored and it did not improve the fitting (see Barbato, 2022). Retrospectively, the goodness of the choice of simpler linear terms was also justified by the good model performance (shown in the Section 3).

Before building the model, all linear predictors were standardized (the difference from the mean was divided by the corresponding standard deviation) and, given the large number of absence entries in the initial PA dataset (14,671 absence and 971 presence), 10 subsets were created where the absence data (3884 entries) were randomly chosen for each subset in equal proportion among the selected areas to account for 80% of total data (which include a total of 4855 entries) compared to the presence data (971 entries) which were kept the same in the 10 subsets (Acevedo & Real, 2012). Then, the subsets were used to fit all possible combinations of predictors.

For model selection, the Akaike's information criterion (AIC) for each predictor combination model was calculated (Burnham & Anderson, 2002) and then averaged over the 10 subsets. To validate the model with the lowest AIC, the 10 subsets were divided into two partitions accounting for 80% of the data for training (3884 entries) and 20% for validating (971 entries), maintaining in each partition the same proportion of PA data and areas. Consequently, the models built with the 10 training subsets were used to predict the observed PA data from the validating subset. Given that the occurrence of this species is represented in the dataset by a relatively small number of observations and that these are not randomly distributed across environmental variables, we estimated favourability instead of suitability using the probability of occurrence. Environmental favourability reflects the variation of the occurrence probability and is less affected by the presence/absence ratio (Tovar Verba et al., 2023). It can vary between 0 (location unsuited for the species) and 1 (an ideal location for the occurrence of the species). Favourability is here defined as 'the variation in the probability of occurrence of an event in certain conditions with respect to the overall prevalence of the event' (Real et al., 2006). This definition has been demonstrated by the comparison of several modelling approaches to be useful in habitat selection, since outcome is levelled regarding the prevalence of each event in the dataset (Acevedo & Real, 2012). The favourability was calculated as:

$$F = \frac{\frac{P}{(1-P)}}{\frac{n_1}{n_0} + \frac{P}{(1-P)}}$$

where favourability (F) can be estimated from the probabilities of presence (P) obtained from any method and n_1 and n_0 being the number of presence or absence samples in the dataset.

Using the 'PresenceAbsence' R package (Freeman & Moisen, 2008a), a confusion matrix was computed with the matches and mismatches between observation and favourability. This allowed to calculate the sensitivity or true-positive rate (TPR), the specificity or true-negative rate (TNR) and finally the true skill statistic (TSS), according to the following formulas (Somodi et al., 2017):

$$\mathrm{TPR} = \frac{\mathrm{TP}}{\mathrm{TP} + \mathrm{FN}} \quad \mathrm{TNR} = \frac{\mathrm{TN}}{\mathrm{TN} + \mathrm{FP}} \quad \mathrm{TSS} = \mathrm{TPR} + \mathrm{TNR} - 1$$

where the number of matches or mismatches in the confusion matrix is represented by the true positives (TPs), false negatives (FNs), true negatives (TNs) and false positives (FPs). The use of TSS is thought to give greater reliability to the goodness-of-fit measure, considering the prevalence dependence of a binary event (Somodi et al., 2017). The 10-fold validation process also allowed to set a favourability threshold by the '*optimal.threshold*' function and '*MaxKappa*' method (Freeman & Moisen, 2008a) using the 20% partitions of observed PA data. Instead of using the arbitrary 0.5 cut-off, such a threshold would provide an unbiased estimate of species prevalence (Freeman & Moisen, 2008b). The best-fitting model from each of the 10 subsets was used to predict the probability of occurrence of nursery sites for sandbar sharks using as input the averaged summer values for environmental factors over 2016–2020 on a 0.0277° cell grid across the Mediterranean Sea. The probability outcome was then averaged over the 10 subsets and finally favourability was calculated. This prediction workflow was applied with and without the spatial random effect models, herein defined respectively as spGLM and GLM. The spatial effect represents the intrinsic spatial variability of the data without the effect of environmental variables. So, the spatial term may be strongly influenced by the presence data which in our database are limited to a few areas. This approach allowed a prediction comparison to possibly identify those unreported favourable sites of nursery for early juveniles that were masked by the effect of the spatial random effect a. The areas characterized by prediction variables whose values fell outside the range of those same variables when used to build the models were identified, herein defined as out-of-the-range areas, and plotted onto the prediction map. Analyses were performed in RStudio (RStudio Team, 2020), and final plots were created by QGIS3.

3 | RESULTS

3.1 | Nursery site in the North-Western Adriatic Sea

The total number of sandbar sharks caught by Cervia's SSF was 21 in 2019 and 14 in 2020. All individuals were classified as newborns (the presence of open fresh or partially healed umbilical scars), except for one young-of-the-year (TL = 68 cm and completely healed scar) and one juvenile, (TL = 89.5 cm, Figure 2). The TL distribution (42.5–89.5 cm in 2019 and 48–68 cm in 2020) did not significantly differ between years (Figure S1.1, $W = 99$, $p = 0.109$, ES = 0.274) and the sex ratio (12 males and nine females in 2019 and six males and eight females in 2020) was balanced in each year ($\chi^2 = 0.42$, $p = 0.502$, ES = 0.14 in 2019, $\chi^2 = 0.57$, $p = 0.789$ and ES = 0.20 in 2020). Due to gear turnover and weather conditions, fishing occurred on 69% (29 over 42) and 68% (37 over 59) of the monitored days in 2019 and 2020 respectively. The number of operating fishing vessels varied between days, up to a maximum of 7 in 2019 and 5 in 2020, and the length of gillnets ranged from 1.4 km to 6 km depending on the fisher's habits. The gillnet soaking time when a shark was caught was, on average, 10.6 ± 4.2 h (mean and standard deviation). The daily LPUE was characterized by irregular frequency of no- and positive-catches days and mean LPUE and standard deviation was equal to 0.108 ± 0.104 in 2019 and 0.133 ± 0.284 in 2020. However, the overall daily LPUE did not significantly differ between the 2 years ($W = 697.5$, $p = 0.121$ and ES = 0.187). Based on the fishing distribution of 101 monitored trips and catch coordinates data, captured newborn and juvenile sharks were distributed within 6 nautical miles (NM) east of the Italian coast and extended from north to south between Cervia and Marina di Ravenna (MDR). The area of catches is characterized by shallow and warm waters, is downstream of the productive Po River plume, and is located along a calm current front. Furthermore, this nursery area showed higher turbidity than the offshore waters (Figure 2).

3.2 | Modelling Mediterranean nursery areas for early juveniles

In total, 14 studies over 2000–2022 met the criteria for inclusion in the PA dataset, of which four reported the presence of early juveniles. Such studies, covering different Mediterranean subbasins (Table S1 and Figure S1.2), included 52 areas from which 15,642 points (14,671 absence, 971 presence) were extracted. Ten subsets were assembled with a constant proportion of 80% absence (3884) and 20% presence entries (971) to build the model. The density plot of the PA points showed a marked contrast in presence and absence in relation to several variables, CUR and SST in particular, with the exception of KD (Figure S3.1 in Appendix S3). Therefore, KD was dropped from further analyses, also given its high correlation with NPP (Figure S3.2). The 20 lowest AIC models were inspected for interpretation (Table S3.1). The lowest AIC model (#28) included DEP, TEMP and CUR as predictors (Table S3.1). A few alternative models were supported by the collected observations in a relatively close manner (e.g. four models were within ΔAIC <2 with the respect to the best scoring model according to AIC), yet the structure of the five best models was similar as they all shared DEP, TEMP and (except for the second-best model) CUR as predictors. Therefore, the model displaying the lowest AIC was selected as the best, most parsimonious model, because its empirical support was two times that of the second-best model according to the evidence ratio and, also, it contained all the three above-mentioned predictors (Burnham & Anderson, 2002). Such selected best model is:

$$\text{logit}(PA) = \beta_0 + \beta_1 \cdot DEP + \beta_2 \cdot SST + \beta_3 \cdot CUR + u$$

The parameter coefficients of the spGLM and GLM had different magnitudes, but they had the same signs (Table 1). High posterior means of the spatial effect were present mostly in the North-Western Adriatic Sea and the Gulf of Gabés (Figure S3.3). TSS was equal to 0.99 and 0.97 respectively for the spGLM and GLM during the validation process, hence highly reliable. The favourability threshold was calculated to be 0.76 for the spGLM and 0.85 for GLM. In addition, the model coefficients indicated that nursery sites for early juveniles were more likely in areas with shallow depth, calm and warm waters.

The range of independent variables used to build the models was not identical to that of the prediction dataset over the whole Mediterranean Sea. Scattered out-of-range areas were identified in Mediterranean open ocean and coastal sites to indicate that the prediction was not reliable (Figure S3.3).

The map generated by projecting the spGLM over the whole Mediterranean Sea predicted the North-Western Adriatic Sea, Gulf of Gabés and, to a smaller extent, the Gulf of Iskenderun as favourable areas for the nursery of *C. plumbeus* (Figure 3). The prediction according to the GLM highlighted additional favourable spot-like coastal sites, with different extents, along Libyan, Egyptian, south-eastern Turkish, Northern Aegean, western and eastern Ionian, eastern Tyrrhenian, western Adriatic and southern Spanish coasts (Figure 4).

4 | DISCUSSION

This study provides novel data that unequivocally confirm the occurrence of a multiyear nursery site of early juveniles for sandbar sharks in the North-Western Adriatic Sea and integrates data from the sparse literature to robustly predict where potential nursery sites may be located based on environmental conditions in the Mediterranean Sea.

4.1 | Adriatic nursery site

Several records (e.g. occasional catches, museum samples, citizen science data) of sandbar shark presence have previously been reported in the Northern Adriatic Sea, suggesting the occurrence of a nursery area (Jambura et al., 2021). Our systematic sampling allows documenting the interannual persistence of early juvenile presence, hence a nursery site for early juveniles (Heupel et al., 2007), given the occurrence of individuals with open or partially healed umbilical scars. Although no data on the persistence of the umbilical scar are available for the sandbar shark, in a congeneric species, the blacktip reef shark (*C. melanopterus*), neonates caught in the wild had the healing capacity to reduce the umbilical scar area within 30 days in reared conditions (Chin et al., 2015); therefore, a similar period may also be conceivable for the sandbar shark. This supports the use of the identified areas in the Northern Adriatic Sea by early juveniles of the sandbar shark.

The environmental conditions of the Cervia-MDR site are comparable to those of the nursery areas found in the Western Atlantic Ocean (Baremore & Hale, 2012; Conrath & Musick, 2010; Rechisky & Wetherbee, 2003), thus confirming the importance of near-shore habitats, where the combination of shallow, calm and warm waters may contribute to creating a refuge and a combination of environmental characteristics that favour growth and foraging for early juveniles. In addition, the early juveniles of sandbar sharks tend to be site attached to their nursery area, with only occasional excursions (Rechisky & Wetherbee, 2003). Thus, seasonal residency may be probable in the Adriatic nursery area identified in this study, likely until early autumn, given the occasional reports of catches in this period as well (Jambura et al., 2021). Our methodology could be applied to other neritic elasmobranch species through multiyear systematic data collection to create a robust knowledge base to define nursery areas (Heupel et al., 2007).

4.2 | Modelling approach, limitation and methodological comparison

In this study, a species distribution model was applied for the first time to map favourable areas for the nursery of early juveniles of a neritic endangered shark in the Mediterranean Sea. The constructed model was simple, with few monotonic predictors, including a spatial effect for spatially autocorrelated data (Latour et al., 2022), yet it performed exceptionally well in fitting the PA data. Overall, shallow, calm and warm marine environments have been reported as

TABLE 1 The coefficients for standardized predictors such as depth, sea surface temperature (SST) and current velocity (CUR) of the best models, with and without the spatial effect, predicting the favourability of nursery sites for early juveniles in the sandbar shark in the Mediterranean Sea. The native range (α) of the spatial random field was 2.27° with its standard deviation (σ) of 4.09°.

	Spatial explicit GLM		GLM	
	Coefficient	Standard error	Coefficient	Standard error
Intercept	−55.5	57.5	−70.9	9.1
Depth	−36.9	43.6	−51.6	6.8
SST	1.2	0.7	0.3	0.1
CUR	−3.1	2	−4	0.4

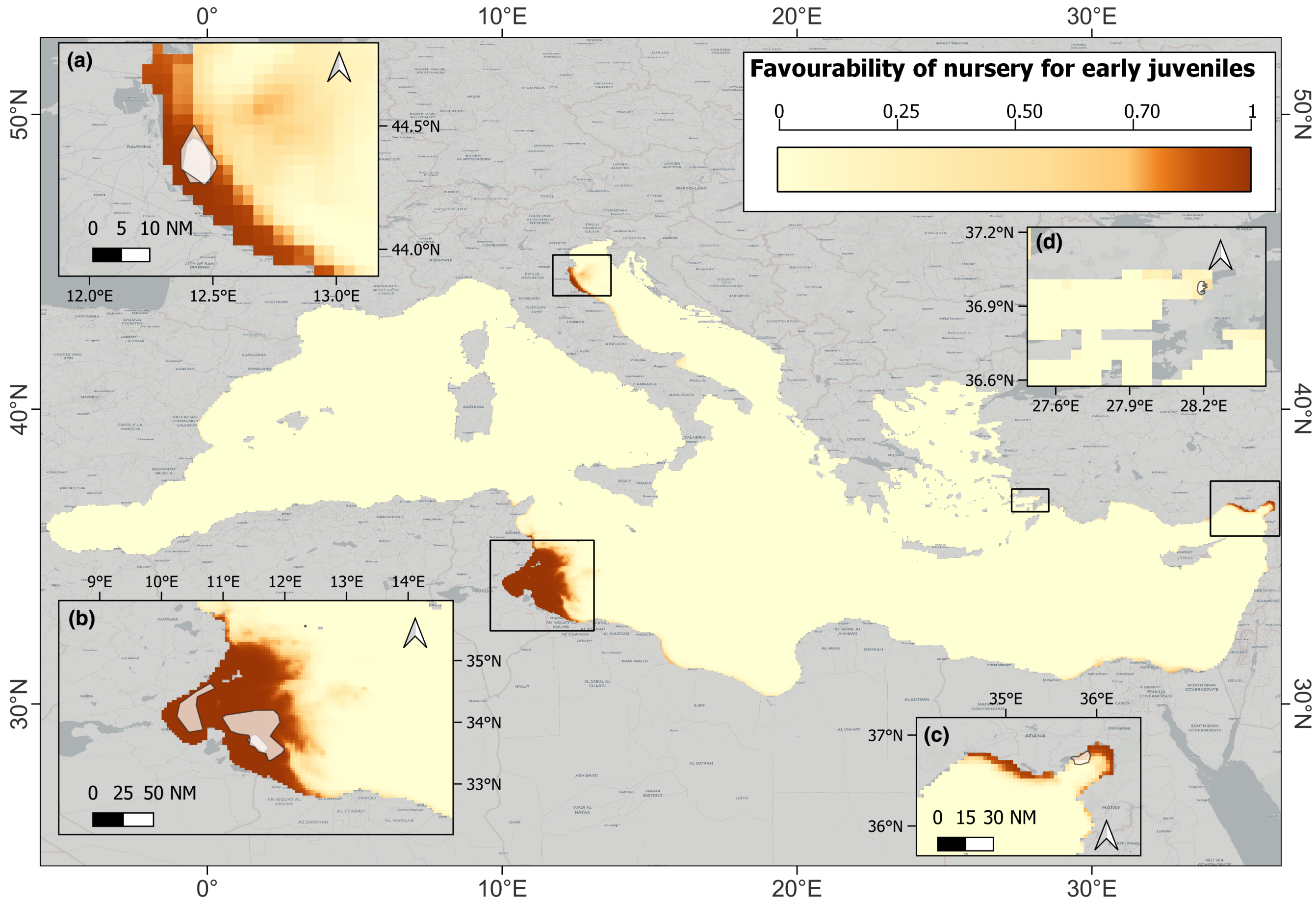

FIGURE 3 Predicted favourability by spGLM of nursery sites for the sandbar shark throughout the Mediterranean Sea, with a zoom onto the sites where there are records of the presence of early juveniles according to our literature review. (a) the Adriatic Sea (Cervia-MDR, Italy); (b) Gulf of Gabés(Tunisia); (c) Gulf of Iskenderun (Turkey); (d) Bunkuk Cove (Turkey). Polygons in the zoomed locations indicate the recorded presence areas for early juveniles of the sandbar shark, which were used to construct the model.

ideal conditions for sandbar shark nursery in other oceans (Baremore & Hale, 2012; Conrath & Musick, 2010; Kinney & Simpfendorfer, 2009) as well as for other shark species (Knip et al., 2010; Schlaff et al., 2014), providing our model-based inference with solid biological support.

Given the strong influence of shallow depth on nursery favourability, we believe that the low favourability predicted in out-of-range areas identified in offshore waters could be considered reliable. However, in those close to the coast, low favourability should not be considered fully certain. When considering the spGLM prediction compared with PA observations, an interesting component of the model emerges. High nursery favourability is predicted at sites where scientific evidence for nursery is strong (Bradai et al., 2005) or where there are several anecdotal or museum reports (Başusta et al., 2021; Jambura et al., 2021). In contrast, the model computes a low nursery favourability in Boncuk Cove (Turkey), where a nursery site was hypothesized after eyewitnesses reported a delivery and two stillborns (Clò & de Sabata, 2004). A subsequent study documented only adults, forming a year-round aggregation there (Filiz, 2019). Although our predictions could be biased by the limited spatial resolution available for environmental factors, our model agrees with the latter study in a manner that should be reliable given the spatially autocorrelated nature of the satellite telemetry data and the proximity of the adjacent cells used to fill the gaps.

The map generated by projecting the spGLM may suffer from an underestimation of nursery extension and occurrence since the native range of spatial random field may act as a mask preventing prediction outside the observed areas of presence because records of early juvenile presence are very limited. On the other hand, the fact that the GLM model without spatial effect predicts high nursery favourability also in spot-like areas where no early juveniles were reported may reflect several factors. First, the lack of reports does not equate to evidence of newborn absence given the widespread deficiency or ambiguity of landing and scientific survey data for endangered elasmobranchs in Mediterranean countries, which is related to the lack of dedicated and systematic monitoring effort and data collection (Cashion et al., 2019). In fact, it is worth noticing that sporadic reports of newborn of sandbar shark were recently documented in the Northern Tyrrhenian coast in agreement with the GLM prediction (Mancusi et al., 2023). Alternatively, some historical nursery sites might have disappeared due to the loss of shark behavioural knowledge (e.g. philopatry and/or cultural

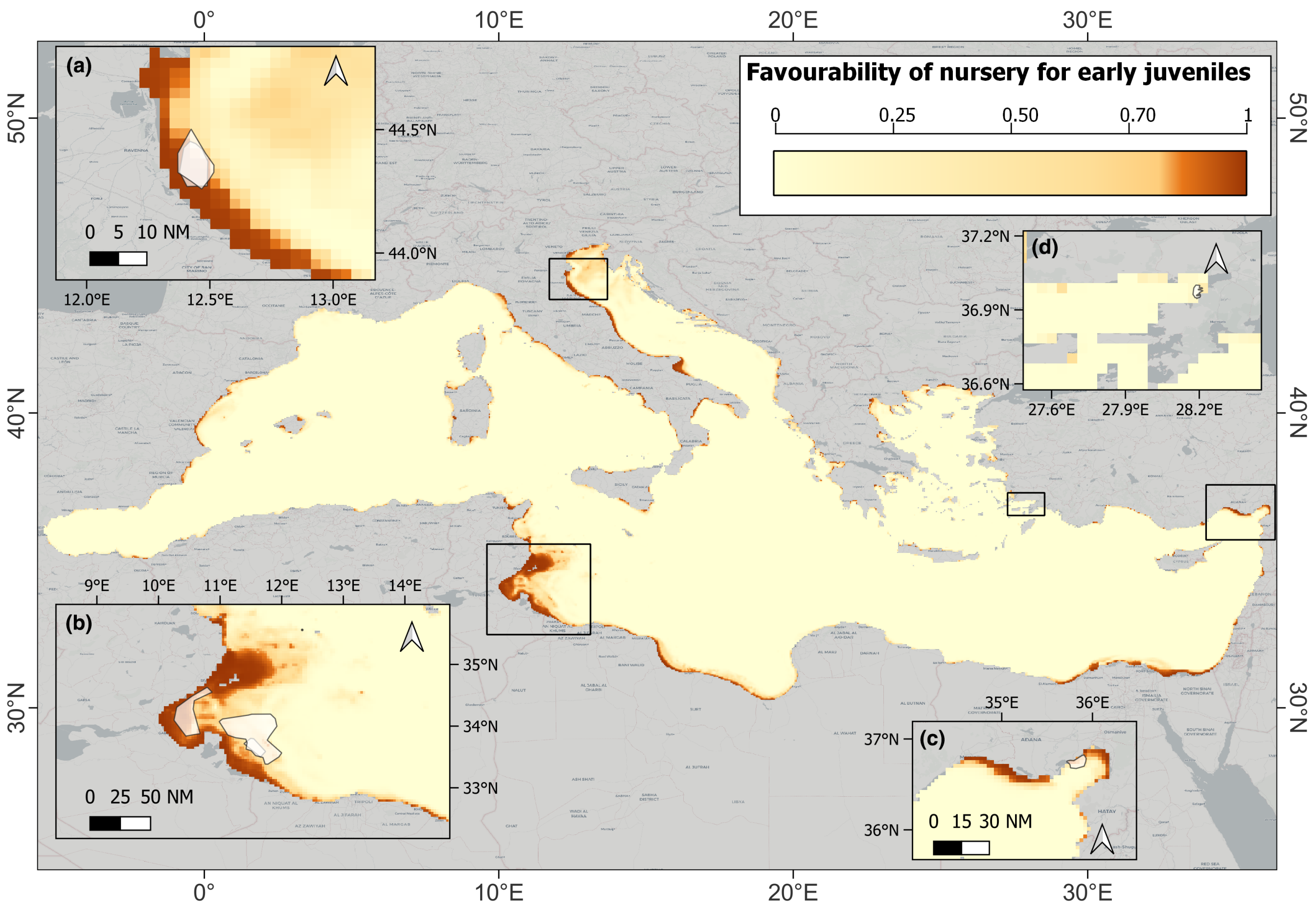

FIGURE 4 Predicted favourability by GLM of nursery sites for the sandbar shark throughout the Mediterranean Sea, with a zoom onto the sites where there are records of the presence of early juveniles according to our literature review. (a) the Adriatic Sea (Cervia-MDR, Italy); (b) Gulf of Gabés (Tunisia); (c) Gulf of Iskenderun (Turkey); (d) Bunkuk Cove (Turkey). Polygons in the zoomed locations indicate the recorded presence areas for early juveniles of the sandbar shark, which were used to construct the model.

transmission of parturition sites, Warner, 1988) following an abrupt population decline (Ferretti et al., 2016) or the onset of anthropogenic stressors such as habitat loss, pollution or noise (Coll et al., 2012), making sites unfit for the early juveniles. Finally, the model was constructed with data spanning 20 years, but its predictions were built on environmental data from 2016 to 2020. Because of warming coastal waters due to climate change, the availability of habitat for nursery may have increased over time, thus making unused sites in the past more favourable in the present climatic conditions. However, the availability of new favourable habitats does not mean that they will certainly be used as nurseries: their use would require a behavioural shift (Crear et al., 2020).

Overall, some aspects of the use of space by this species remains largely unknown. For instance, our model predictions are focused on summer environmental conditions as being the main pupping season (Saïdi et al., 2005). As an ectotherm species, the neonates of sandbar shark could find overwintering nursery grounds within or in neighbouring Mediterranean subbasins that undergo large seasonal variations in temperature that, in turn, influence their seasonal use of space (Schlaff et al., 2014). Indeed, occasional reports of neonate and juvenile occurrence were reported during winter or early spring in the Southern Adriatic Sea (Ćetković et al., 2022), the Western Ionian coast (Leonetti et al., 2020) and the Southern Tyrrhenian Sea (Consoli et al., 2004). The seasonal use of space remains to be studied in detail by complementary approaches (e.g. telemetry or conventional tagging), as it may substantially provide a comprehensive understanding of wintering nursery ground as well.

5 | CONCLUSIONS

Our findings provide evidence that nursery areas for early juveniles can be found to a large extent along the North-Western coasts of the Adriatic Sea and in the Gulf of Gabès according to spGLM prediction. However, throughout the Mediterranean Sea, the spGLM-based inference also shows that other coastal nursery sites may occur, with a small extent, as in the Gulf of Iskenderun, where favourable environmental conditions are found during the main pupping season in summer. On the other hand, the GLM-based prediction may indicate where accurate monitoring effort can be addressed. This study provides essential information on Mediterranean areas that are crucial to the endangered sandbar sharks, which decision makers can use to tailor management and conservation plans. Given their coastal location, nursery sites for early juveniles in the Mediterranean Sea are likely to overlap with fishing pressure, especially by small-scale fisheries (Lloret et al., 2020), as well as the cumulative impacts of anthropogenic pressures that concentrate along coasts (Coll et al., 2012). Accurate landing monitoring, protection schemes in nursery areas and aggregation sites (Cattano et al., 2023) and improved fishery management through bycatch reduction devices or catch restrictions on immature individuals (Brewster-Geisz & Miller, 2000) are pillars for defining conservation strategies for the sandbar shark and other endangered sharks in the Mediterranean Sea (Dulvy et al., 2021; Milazzo et al., 2021). Conservation issues for large predators are often transboundary (Maguire et al., 2006), and given the fragmented jurisdictions across the Mediterranean Sea, an effective spatially explicit governance for Mediterranean migratory marine species is urgently needed.

AUTHOR CONTRIBUTIONS

Matteo Barbato, Carlotta Mazzoldi and Simone D'Acunto conceived of the idea. Matteo Barbato and Simone D'Acunto collected and coordinated the data. Carlo Zampieri and Matteo Barbato performed the statistical analyses and modelling. Alberto Barausse, Maria Grazia Pennino and Carlotta Mazzoldi supervised the project and statistical and modelling analysis. Matteo Barbato wrote the manuscript with support from Carlo Zampieri, Alberto Barausse, Maria Grazia Pennino and Carlotta Mazzoldi. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

All authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data available from the figshare data repository: https://doi.org/10.6084/m9.figshare.14500248 Barbato et al., 2023).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Supplemetary Adriatic nursery results and presence-absence database for SDM.

Appendix S2. Reference of satellite remote sensing database.

Appendix S3. Supplementary model results.

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