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Integrating citizen science and spatial ecology to inform management and conservation of the Italian seahorses

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ABSTRACT

Citizen science and spatial ecology analyses can inform species distributions, habitat preferences, and threats in elusive and endangered species such as seahorses. Through a dedicated citizen science survey submitted to the Italian diving centers, we collected 115 presence records of the two seahorses occurring along the Italian coasts: *Hippocampus hippocampus* and *H. guttulatus*. From this dataset, we used 85 seahorse validated records to identify the ecological features of these two poorly known species and quantify the effects of human activities on their habitat suitability through geographic information systems and species distribution modelling. Our results indicated a continuous suitable area for both seahorses along the Italian coasts, with a single major gap in the central Adriatic Sea (Emilia-Romagna and Marche regions). They co-occurred in most of their Italian range, particularly in the central and southern Tyrrhenian coasts, and their ecological niches resulted to be significantly similar, although not equivalent. The least-cost paths of both species were concentrated in southern Italy (Apulia, Calabria, and Sicily), suggesting that more data is needed to improve the spatial resolution of the available information, especially in the northern and central Italy. Human activities influenced 38% and 42% of the habitat suitability of *H. hippocampus* and *H. guttulatus*, respectively, while only 25% and 30% of their potential distributions, respectively, are protected by Italy's existing conservation area system, in accordance with the global average for seahorses. In particular, the central Adriatic Sea represents a critical area where the occurrence of these seahorses is lower and the anthropic impact is higher. Considering all the Italian regions, fishing effort is the main human activity impacting both species. These findings will support the implementation of more efficient conservation actions. We encourage the application and interaction of citizen science and spatial ecology analyses to facilitate the assessment and sustainable management of elusive organisms.

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1. Introduction

Citizen science consists in the active and direct involvement of members of the general public in scientific research, particularly data collection, analysis, and monitoring, to increase scientific knowledge (Fraisl et al., 2022). In the last decade, increasing partnerships between citizens and scientists have improved public engagement and conservation efforts worldwide (Kelly et al., 2020). Scuba divers are the marine users that contribute the most to some marine citizen science initiatives, both in terms of quantity and duration (Lucrezi et al., 2018; Martin et al., 2016). They can help speed up the scientific process by allowing more information to be obtained with reduced costs, time, and resources for tasks that would otherwise require more substantial efforts to be performed at the required temporal or spatial scales (e.g., Lucrezi et al., 2018). In addition to data gathering, scuba divers can contribute to data analysis and dissemination activities (e.g., Martin et al., 2016). Collaborations between citizens, scientists, and local stakeholders can increase the success of conservation initiatives as they improve access to local and traditional knowledge, inspire conservation-minded behaviours, foster relationship-building, and raise the credibility of the science and data used (Ballard et al., 2017; Fulton et al., 2018; Kelly et al., 2019; Ottinger, 2010). Marine citizen science can bridge gaps in scientific information by using “people skills” to collect data in remote areas, in real time, and in large quantities, as shown in the Secchi Disk Project (Seafarers et al., 2017), Redmap Australia (Pecl et al., 2019) and iSeahorse (Lourie et al., 1999). The latter initiative is an online database of seahorse sightings developed by researchers at the University of British Columbia, which takes advantage of the power of citizen science to gather data for research and conservation. Seahorses' sighting is a worldwide growing form of ecotourism focused on observing seahorses underwater either by snorkelling or scuba diving (e.g., Freret-Meurer et al., 2018; Giglio et al., 2019; Loh et al., 2016; Najera-Medellin et al., 2023) and can contribute substantially to increasing knowledge on the distribution of these fishes.

Seahorses (*Hippocampus* spp.) are iconic and charismatic animals whose conservation is of global concern (Camins Martinez et al., 2023; Vincent et al., 2011; Zhang and Vincent, 2018; Zhang and Vincent, 2019a). Protecting seahorses is tightly linked to preserving their diverse habitats, such as seagrasses (for example, *Posidonia oceanica* and *Zostera marina*), mangroves, coral reefs, estuaries, and seaweeds, and all the organisms that live therein. Due to their popularity in collective imagery, these fish are interesting attractions in the wildlife viewing sector, are commonly used as flagship species for global conservation efforts, and are particularly effective in drawing citizen towards community science initiatives (Vincent et al., 2011, iSeahorses). *Hippocampus guttulatus* and *H. hippocampus* are currently distributed in Europe and North Africa, including the Atlantic Ocean, Mediterranean Sea, and Black Sea (Pierri et al., 2022). They are included in the IUCN Red List of Threatened Species, where both species are assessed as Data Deficient (Pollom, 2014; Pollom, 2017). These animals are vulnerable to anthropogenic activity, including habitat loss caused by commercial, residential, and touristic coastal development as well as unintentional by-catch through destructive fishing gear such as trawls and dredges (Woodall et al., 2018). Due to their apparently scattered distribution, low density, and cryptic behavior, ecological data on seahorses are limited (Foster and Vincent, 2004). All these characteristics make seahorses particularly challenging to survey, evaluate, and track the state of their populations to improve their conservation status. Understanding the threats, distribution, and habitat preferences of these fishes is key to their conservation (Camins Martinez et al., 2023; Monteiro et al., 2023; Zhang and Vincent, 2018; Zhang and Vincent, 2019b) and requires detailed knowledge about their geographical distributions. In fact, obtaining a good resolution of their distribution is crucial to validating their presence and identifying hotspots and potential risks. Finally, increasing habitat-preference knowledge is essential to protecting species at the local scale, where conservation actions are more easily implemented and effective (Zhang and Vincent, 2018; Zhang and Vincent, 2019a).

Spatial ecological analyses of elusive species such as seahorses are particularly useful to assess how they can be impacted by current and future environmental and anthropogenic drivers of climate change (Monteiro et al., 2023; Zhang and Vincent, 2018; Zhang and Vincent, 2019b). Geographic Information System (GIS) analysis and Species Distribution Models (SDMs) provide quantitative descriptions of the relationship among species occurrences, ecological requirements, and potential threats that can be easily visualised on geographic maps and provide useful and accessible information to plan efficient conservation actions (IUCN Standards and Petitions Subcommittee, 2017; Zhang and Vincent, 2018; Zhang and Vincent, 2019a).

Here, we aim to contribute to the effective monitoring and management of seahorses by providing crucial information on their distribution, habitat preference, the degree of protection currently granted by marine protected areas, and anthropogenic threats affecting the two *Hippocampus* species inhabiting this area of the Mediterranean Sea. We combined solid presence data on *H. guttulatus* and *H. hippocampus* obtained through an accurate citizen science survey in Italy with advanced GIS and SDM methodologies. Previous studies described some of these features in these species at a small spatial scale (e.g., Gristina et al., 2015; Lazic et al., 2018, 2023; Spinelli et al., 2020; Vivas et al., 2023) or through a citizen science approach (Goffredo et al., 2004; Lazic et al., 2022). However, the spatial resolution of these studies was rather limited, and they did not provide more accessible and detailed information, such as geographically-referenced presence/absence records, as, for example, in a map. Then, we integrated citizen science as well as spatial ecological analysis tools for the analysis of distribution in the Italian *H. guttulatus* and *H. hippocampus* populations as a case study for more solid and evidence-based conservation actions as an example to use in other countries.

2. Materials and methods

2.1. Presence records

H. guttulatus and *H. hippocampus* (Fig. 1) records were collected through a dedicated citizen science survey using a questionnaire submitted to Italian diving centers. To fully capture the biological features and spatial distribution of both seahorses, we involved the most important Italian diving associations, such as the Professional Association of Diving Instructors (https://www.padi.com) and Professional Scuba Schools (https://www.pssworldwide.org), that together represent the main Italian diving centers, Italian seahorse experts, and included the known species' information from literature (e.g., Lourie et al., 2004). The questionnaire form is freely accessible at https://docs.google.com/forms/d/e/1FAIpQLScZh-lPR8-kgBCra7lZbQf7fkIgjfxNqlAj7mNK5kTJdrNi5A/viewform. Data collection started on January 7th and ended on November 3rd in 2022. The questionnaire was sent by email to the Italian diving centers after being described through online seminars dedicated to the associations' members, shared on social media (Facebook, Twitter, and Instagram), and submitted through an interview during the main European diving event such as EuDi (European Diving) Show 2021 (https://www.eudishow.eu/site/) that includes also non-recreational divers. We received 115 replies to our questionnaires including geographical coordinates of *H. guttulatus* and *H. hippocampus* sightings. As citizen scientists typically have varying types and levels of expertise, to ensure data accuracy and quality, all the reported occurrences were visually inspected using Google Earth Pro v. 7.3.2 (https://www.google.it/earth/download/gep/agree.html) to retain only the points falling in areas that were consistent with the known species' geographical distribution shown by Zhang and Vincent (2018). Undefined, unclear (for example, points fell on land or in the high sea, far from the coasts), ambiguous, or duplicate records were excluded from our analyses. For the modelling analysis, we only used occurrences that exceeded the following procedures: 1) photo-identification, the respondent provided a seahorse' picture; 2) if the reporter previously

Fig. 1. *Hippocampus guttulatus* (left) and *Hippocampus hippocampus* (right). Pictures courtesy of Fabio Russo.

demonstrated a reliable ability to discriminate between the two seahorses when completing the questionnaire; 3) if the record fell "in" or at a "maximum of 1 km away" from the habitat suitability binary maps of *H. guttulatus* and *H. hippocampus* previously published by Zhang and Vincent (2018). Lastly, to avoid redundancy, we removed the spatially auto-correlated points from our dataset, deleting all the records falling within a distance of 1 km by using the Spatially Rarefy Occurrence Data tool of SDMtoolbox v. 2.5 (Brown et al., 2017, hereafter SDMtoolbox) in ArcGIS v. 10.8 (http://www.esri.com/software/arcgis, hereafter ArcGIS). The final datasets used for *H. guttulatus* and *H. hippocampus* modelling analyses included 46 and 39 points, respectively (Figs. S1 and S2). This sample sizes are well above the minimum requirement of 20 generally deemed to be suited for SDMs (Guisan et al., 2017; Merow et al., 2014). Further details on how to get our presence data can be found in the Data Availability section. The questionnaire included also details on sightingh sites such as habitat features and number of encountered specimens, and percentages on the total number of responses were computed for each of these values.

2.2. Environmental predictors

To investigate the current potential distribution of *H. guttulatus* and *H. hippocampus*, we considered a set of 72 benthic marine variables at an average depth extracted from the Bio-ORACLE database (Assis et al., 2018, https://www.bio-oracle.org/index.php), the bathymetry from the Global ocean & land terrain models (GEBCO, Tozer et al., 2019, https://www.gebco.net/data_and_products/gridded_bathymetry_data), and the habitat availability maps from the European Marine Observation and Data Network Seabed Habitat (https://emodnet.ec.europa.eu/geoviewer/).

Bio-ORACLE is a set of GIS rasters providing geophysical, biotic, and environmental data for surface and benthic marine realms. The Bio-ORACLE values are averaged over 14 years (2000 to 2014). The data are available for global-scale applications at a spatial resolution of 5 arcmin (approximately 9.2 km at the equator). As seahorses are benthic animals (Correia et al., 2018), we chose our predictors from the available benthic layers. The benthic layers were produced with an interpolation process that considers the geographic position and depth of cells, as inferred from a bathymetric layer. The downscaling process for benthic layers considered the geo-graphical position and depth of cells as inferred from the general bathymetric chart of the oceans (GEBCO). Given that focal cells included a range of depth values, the benthic layers were produced for the minimum, average, and maximum depths of GEBCO. The current gridded bathymetric data set, the GEBCO_2023 Grid, is a global terrain model for ocean and land, providing elevation data, in meters, on a 15 arc-second interval grid. Habitat availability maps are outputs of habitat distribution modelling at a spatial resolution of 30 arc-second (approximately 1 km at the equator).

We clipped all the predictors on Italian coasts through the tool "clip" and converted them into ASCII files using the conversion tool "raster to ASCII" in ArcGIS. Then, all predictors were converted to 1 km resolution using the resample tool in ArcGIS to get all the variables at the same spatial resolution. We used bilinear interpolation to resample the predictors, a method that computes the value of each pixel by averaging (weighted for distance) the values of the surrounding four pixels, and is suitable for continuous data such as our environmental data. The model predictors and resolution were selected according to the available biological knowledge on these species, with a special focus on distribution, home range, feeding, and swimming requirements (Foster and Vincent, 2004; Monteiro et al., 2023; Zhang and Vincent, 2018). Then, we generated a Pearson's correlation matrix with the SDMtoolbox (version 2.2) (Brown et al., 2017) in ArcGIS and selected only the variables for which $r < 0.7$ to remove the highly correlated ones. This led to a final set of eight predictors used for our seahorse models: mean temperature (°C), mean salinity (PSS), mean current velocity (m/s), mean phytoplankton (umol/m^3), bathymetry (m), habitat availability of *Posidonia oceanica*, coral reefs, and maerl (presence values ranging from 0 to 1).

2.3. Species distribution models

The potential distribution of *H. guttulatus* and *H. hippocampus* was modeled using the maximum entropy method (Maxent, Phillips et al., 2006, https://biodiversityinformatics.amnh.org/open_source/maxent/), a presence-background algorithm that performs with high predictive accuracy, stability, and sensitivity (Duan et al., 2014; Elith et al., 2006; Valavi et al., 2022). This algorithm typically results in good predictive models compared with other presence-only models or ensemble models (e.g., Ahmadi et al., 2023; Hao et al., 2020; Kaky et al., 2020; Montoya-Jiménez et al., 2022; Valavi et al., 2022; Wilkes et al., 2023; Zhao et al., 2021) and and is especially suited to deal with scarce presence-only data as elusive species like seahorses (e.g., Ali et al., 2021; Jha et al., 2022). Maxent is one of the most widely used SDMs (e.g., Jha et al., 2022; Liu et al., 2022; Martínez-Díaz and Reef, 2023; Shi et al., 2023; Sutton and Martin, 2022) and produces results that are both predictable (extrapolative) and complex (interpolative) and may be considered an excellent method to cope with imbalanced-biased data in species distribution modelling approaches (Ahmadi et al., 2023). An important issue in the modelling procedure concerns the use of a single algorithm model, such as Maxent, or an ensemble model, such as Biomod2 (Thuiller et al., n.d.) or *sdm* (Naimi and Araujo, 2016), but it has been widely demonstrated that there is no significant difference between using ensembles and single algorithm models (e.g., Hao et al., 2020; Kaky et al., 2020). The most impactful step on the reliability of species predictions remains a scrupulous parameter selection (Morales et al., 2017; Zhu and Qiao, 2016). For this reason, we used the R package ENMeval (Muscarella et al., 2014) to detect the optimal Maxent setting for modelling current distribution of *H. guttulatus* and *H. hippocampus* (ENMeval R script is published in the supplementary materials, Appendix 1). In our analysis, a range of regulation multipliers from 0 to 5 (with increments of 1) combined with different feature combination selections (Hinge, Linear, Linear-Quadratic, Linear-Quadratic-Hinge, Linear-Quadratic-Hinge-Product and Linear-Quadratic-Hinge-Product-Threshold) were tested, resulting in 30 possible combinations. Since we have fewer than 50 occurrence points for both seahorse species, we used the jackknife by random k-fold method. We used the delta from the Akaike Information Criterion (AIC), AICc, the difference between training and testing AUC (AUC. DIFF) and the 10% training omission rate (OR10) to evaluate the model's fitting degree and complexity on species distribution (Shi et al., 2023). The AIC corrected for small sample sizes reflects both model goodness-of-fit and complexity. The model with the lowest AICc value (i.e. ΔAICc = 0) is considered the best model out of the current suite of models; all models with ΔAICc <2 are generally considered to have substantial support (Muscarella et al., 2014). The model parameter settings with the lowest AICc values (ΔAICc = 0) for both *H. guttulatus* and *H. hippocampus* were chosen to establish the final Maxent models (ENMeval outputs in supplementary materials, Appendix 2).

The following parameters were used in Maxent: random seed; remove duplicate presence records; write plot data; regularisation multiplier (obtained from ENMeval analysis); 5000 maximum iterations, this value was increased to 5000 to allow the model time to converge (Bulgarella et al., 2014); 10,000 background points obtained by using buffer distance from observation points (further details in the ENMeval analysis in Appendixes 1 and 2); cloglog format, i.e., this output appears to be the most appropriate for estimating the probability of presence (Sillero et al., 2019; Zarzo-Arias et al., 2019) regularisation multiplier and bias file (obtained from ENMeval analysis, Appendixes 1 and 2) 70% and 30% for training and testing data, respectively; 100-replicated run type selected as bootstrap, i.e., replicate sample sets chosen by sampling with replacement. We choose bootstrap as the replicated run type as this method offers the best performance and robust results of Maxent models obtained with a limited presence-only dataset (e.g., Butler and Sanderson, 2022; Chaitanya and Meiri, 2022; Henderson et al., 2023). The remaining model values were set as defaults.

Our maps were binarised into presence-absence values using a threshold that maximised both sensitivity (the percentage of correctly predicted presence) and specificity (the percentage of correctly predicted absence, Liu et al., 2005). Such a threshold has been often used (e.g., Salinas-Ramos et al., 2021) and constitutes one of the most accurate approaches. To obtain the hotspot map, we overlapped the Maxent binary maps of *H. guttulatus* and *H. hippocampus* producing two classes of species richness: a) 1 species; and b) 2 species. We assigned values of 0 and 1 to areas of absence and presence, respectively. Then, we summed the maps by using the “Raster calculator” tools in ArcGIS.

2.4. Model validation

The model's performance was evaluated using the Area Under the receiver-operator Curve (AUC). The AUC values range from 0 to 1, where values closer to 1 indicate a higher accuracy of model prediction (Fielding and Bell, 1997). In addition to the AUC, the True Skill Statistics (TSS) was calculated. TSS values range between -1 and $+1$. A TSS value of $+1$ means complete agreement between observed and predicted distributions, whereas values of ≤ 0 denote no better than random performance (Allouche et al., 2006). AUC and TSS are the methods most commonly used to assess the model performance in species distribution model studies (e.g., Gaier and Resasco, 2023; Mondanaro et al., 2023; Song and Estes, 2023).

To further assess the accuracy of our seahorse models, we created an independent dataset using *H. guttulatus* and *H. hippocampus'* presence records obtained from widely used open access biodiversity databases such as Global Biodiversity Information Facility (https://www.gbif.org/, GBIF, 2022a, 2022b), Ocean Biodiversity Information System (OBIS, https://obis.org/), INaturalist (https://www.inaturalist.org/), AquaMaps (https://www.aquamaps.org/, Kaschner et al., 2007), and from literature such as Zhang and Vincent (2018) to achieve model validation (e.g., Konowalik and Nosol, 2021; Westwood et al., 2020). The maps of all *H. guttulatus* and *H. hippocampus'* presence records obtained from the open access biodiversity database are available in the supplementary materials (Figs. S3 and S4). We calculated the distance between all the occurrences in the above-mentioned dataset and their binary maps by using the “Near” tool in ArcGIS. To achieve this aim, we converted all the records and the seahorse binary maps into a point feature. As suggested in the ArcGIS Help section, we selected the geodetic methods to calculate all the distances to consider the curvature of the spheroid and correctly deal with data near the dateline and poles. Then, we assigned a score of 0 (poor prediction), 0.5 and 1 (good prediction) depending on whether the seahorse records fell at a greater distance from 1 km, in a distance range from 0 to 1 km and inside (0 distance) the presence pixel of the seahorse binary maps, respectively. We chose the threshold of 1 km in relation to the resolution of the environmental predictors used to run the models. Finally, we calculated a mean value and assessed the performance of our models following the slightly modified method by Konowalik and Nosol (2021). Three performance classes were considered: poor (0–0.335), medium (0.336–0.665), and good (0.666–1).

2.5. Niche analysis

To investigate niche similarity between the *H. guttulatus* and *H. hippocampus*, we performed a niche overlap analysis (Di Cola et al., 2017). This analysis included three steps: (1) estimating the density of occurrences of each species along the environmental axes using a multivariate analysis; (2) measurement of niche overlap along the gradients of this multivariate analysis; (3) testing for niche equivalency and similarity.

For the first step, the PCAENV approach (Broennimann et al., 2012) was applied using the eight selected variables (Table 1) and the two species' occurrences. The environmental space was divided into a grid of 100 × 100 cells and the frequency of species occurrences for each combination of environmental conditions in each grid cell of the environmental space was calculated using a kernel smoother density function (Di Cola et al., 2017). Then, we calculated the differences in occurrence densities between the two species and estimated the degree of niche overlap using the ecospat R package (v. 3.2, Di Cola et al., 2017) and the Schoener's D metric (Schoener, 1968), which ranges from 0 (no overlap) to 1 (complete overlap). Finally, we used the species' density in the environmental space to test whether niches of the two compared species are equivalent (show constant overlap as estimated by the Schoener's D metric, p-value <0.05) or different (no overlap) when occurrences are randomly shuffled 100 times across the ranges (Broennimann et al., 2012; Warren et al., 2008). Similarly, the niche similarity test estimated if the niches of the target species are more similar than expected by chance using 100 repetitions while taking into account the environmental conditions of the geographic space across the study area, a main limitation of the niche equivalence test (Warren et al., 2008). Niche analysis script is in the supplementary materials, Appendix 3.

2.6. *Least-cost paths*

The paths of *H. guttulatus* and *H. hippocampus* were identified by computing the least-cost paths through the tool “Calculate Least-Cost Corridors and Paths” of SDMtoolbox in ArcGIS. This tool creates a polyline shapefile of least-cost paths between pair-wise combinations of input points. A single least-cost path between sites can oversimplify landscape processes, while habitat heterogeneity and its varying roles in dispersal can be better captured by using categories of cost paths that include paths with slightly more costly path lengths (relative to the least-cost paths). To do this, we created a friction layer for both seahorses through the tool “Invert SDM/ENM” of SDMtoolbox in ArcGIS. A friction layer is a raster that depicts the ease of dispersal from each locality through the landscape. This tool inverts a SDM for use as a friction surface. Areas of high suitability were converted to areas of low dispersal cost. All the presence records of two seahorses obtained from the open access biodiversity database (described in the model validation paragraph) that completely fell into the binary maps of *H. guttulatus* and *H. hippocampus* were used as inputs.

2.7. *Conservation gap analysis*

A conservation gap analysis based on the binarised potential distribution maps (e.g., Ramirez-Villegas et al., 2022; Southwell et al., 2022; Wang et al., 2023) was used to assess the degree of protection granted to *H. guttulatus* and *H. hippocampus* by all the protected areas in Italy. We overlaid the map of each seahorse and the hotspot map with the shape files containing the boundaries of all Marine Protected Areas in Italy. The shape files of all the protected areas in Italy were downloaded from the UNEP's World Conservation Monitoring Centre (www.protectedplanet.net, downloaded in May 2023). Further details, for example, on the size and distribution of the Marine Protected Areas can be found at https://www.protectedplanet.net/en/thematic-areas/marine-protected-areas.

Table 1
Details on the *H. guttulatus* and *H. hippocampus'* sightingh sites reported in the citizen science survey.

Type	Value	*H. guttulatus* (%)	*H. hippocampus* (%)
Depth	0–5 m	21.82	37.50
	6–10 m	38.18	31.25
	11–15 m	25.45	12.50
	16–20 m	7.27	16.67
	> 20 m	7.27	2.08
Substrate	Artificial	5.45	6.25
	Mixed subtsrate	41.82	50.00
	Rocky	29.09	22.92
	Sandy	23.64	20.83
Habitat	Coralligenous	25.45	18.75
	Other marine plants	10.91	14.58
	Posidonia oceanica	29.09	25.00
	Seaweed	34.55	41.67
Number of specimens	1–3	89.09	81.25
	4–10	9.09	18.75
	> 10	1.82	0

2.8. *Assessing the impact of anthropic activities on habitat suitability of H. guttulatus and H. hippocampus*

We generated risk maps to assess the impact of anthropic activities on the potential distribution of *H. guttulatus* and *H. hippocampus* along the Italian coasts. To achieve this aim, we used the binary map of both the seahorses and the shapefiles of the Italian regions (from the Italian National Institute of Statistics, https://www.istat.it/ambiente/cartografia), and anthropic activities (from the EMODnet map viewer, https://emodnet.ec.europa.eu/geoviewer/). We considered the main anthropogenic activities threatening the conservation of seahorses such as fishing effort, discharge, dredging, cable, port, oil, and natural gas exploration (IUCN, 2016; Pollom et al., 2021). Further layer details can be found in the metadata file available in the EMODnet map viewer by clicking on each of the shapefiles here considered. Then, we assessed the amount of seahorse's suitable habitat that overlapped the EMODnet human activities through the “Intersect” tool in ArcGIS. To do this, we first converted the binary maps into features. The tool computes a geometric intersection of the input features. Features or portions of features that overlap in all layers and/or feature classes were written in the output feature class. Furthermore, we overlaid the hotspot map and the six layers of human activities to quantify their effects on the seahorse richness distribution. Risk maps for *H. guttulatus* and *H. hippocampus* in Italy were obtained for all the human activities that fell into the seahorse binary maps for each Italian region. Then, we split the results obtained for each region into five classes (e.g., Zhang and Vincent, 2019a) by using the Natural Breaks – Jenks methods in ArcGIS. The Natural Breaks classes are created in a way that best groups similar values together and maximizes the differences between classes. The features are divided into classes whose boundaries are set where there are relatively big differences in the data values. We used the same procedure for producing the risk maps for *H. guttulatus* and *H. hippocampus* paths. However, we used only paths with 1 km of length as seahorses have usually very short home ranges (Foster and Vincent, 2004).

3. Results

3.1. *Citizen science*

According to our surveys, divers mainly encountered few speciemens of *H. guttulatus* and *H. hippocampus* at a depth of 6–15 m and 0–10, respectively, both in mixed and rocky substrates in presence of seaweeds and *Posidonia oceanica* (Table 1).

3.2. *Species distribution models*

Our results indicate that the mean temperature (80.78%), habitat suitability of *P. oceanica* (14.12%), and bathymetry (3.61%) were the main drivers of the potential distribution of the Italian populations of *H. guttulatus*. In particular, this species is more likely to occur where the mean temperature ranges between 18 and 21 °C, *P. oceanica* is more abundant, and in shallow waters (< 50 m). Our model predicted a suitable area of 25,285 km^2 and high probability of occurrence along the entire Italian coasts, mainly in the Tyrrhenian, Ionian, Sardinia and Sicily seas. Few areas at low probability were found along Marche and

Emilia-Romagna coasts (Fig. 2a and c). Considering only the Italian regions with access at sea, the highest values of habitat suitability were observed in Sicily, Sardinia, Apulia, Tuscany, Calabria, Lazio, and Campania (> 1500 km^2), whilst Veneto, Friuli Venezia Giulia, and Emilia-Romagna regions exhibited the lowest areas of suitable habitat (< 100 km^2). In *H. hippocampus,* the mean temperature (73.06%) emerged as the main contributor of its Italian distribution, followed by the habitat suitability of *P. oceanica* (10.37%), bathymetry (9.14%) and habitat suitability of coral reefs (5.50%). This seahorse exhbited a preference for areas with mean temperature ranges between 19 and 21 °C, bathymetry <50 m and high values of habitat suitability of *P. oceanica* and/or coral reefs. Our model predicted a suitable area of 20,169 km^2 and high probability of occurrence along the entire Italian coast, mainly in the Tyrrhenian, Ionian, Sardinia, and Sicily seas. A gap in *H. hippocampus*' habitat suitability was found from the northern coast of Abruzzo to Emilia Romagna (Fig. 2b and d). Sicily, Sardinia, Apulia, Calabria, Tuscany, and Campania regions (> 1500 km^2) had the highest values of suitable areas for *H. hippocampus* while the lowest one (< 100 km^2) were found in Molise, Emilia-Romagna, and Marche regions.

The hotspot map showed that the areas that included a single Italian *Hippocampus* species had an extension of 6249 km^2 and were located mostly in the north of the Tyrrhenian and Adriatic seas (Fig. 3). The areas with both seahorses' species were in the southern areas of Italy and along the coasts of Lazio and Tuscany regions (Fig. 3) for a total surface of 19,602 km^2. Sicily, Sardinia, Apulia, Calabria, Campania, Tuscany, and Lazio (> 1500 km^2) were the regions with the highest values of suitable areas for both the seahorses' species, while the lowest ones (< 100 km^2) were found in Veneto, Friuli Venezia Giulia, Molise, Emilia-Romagna, and Marche regions.

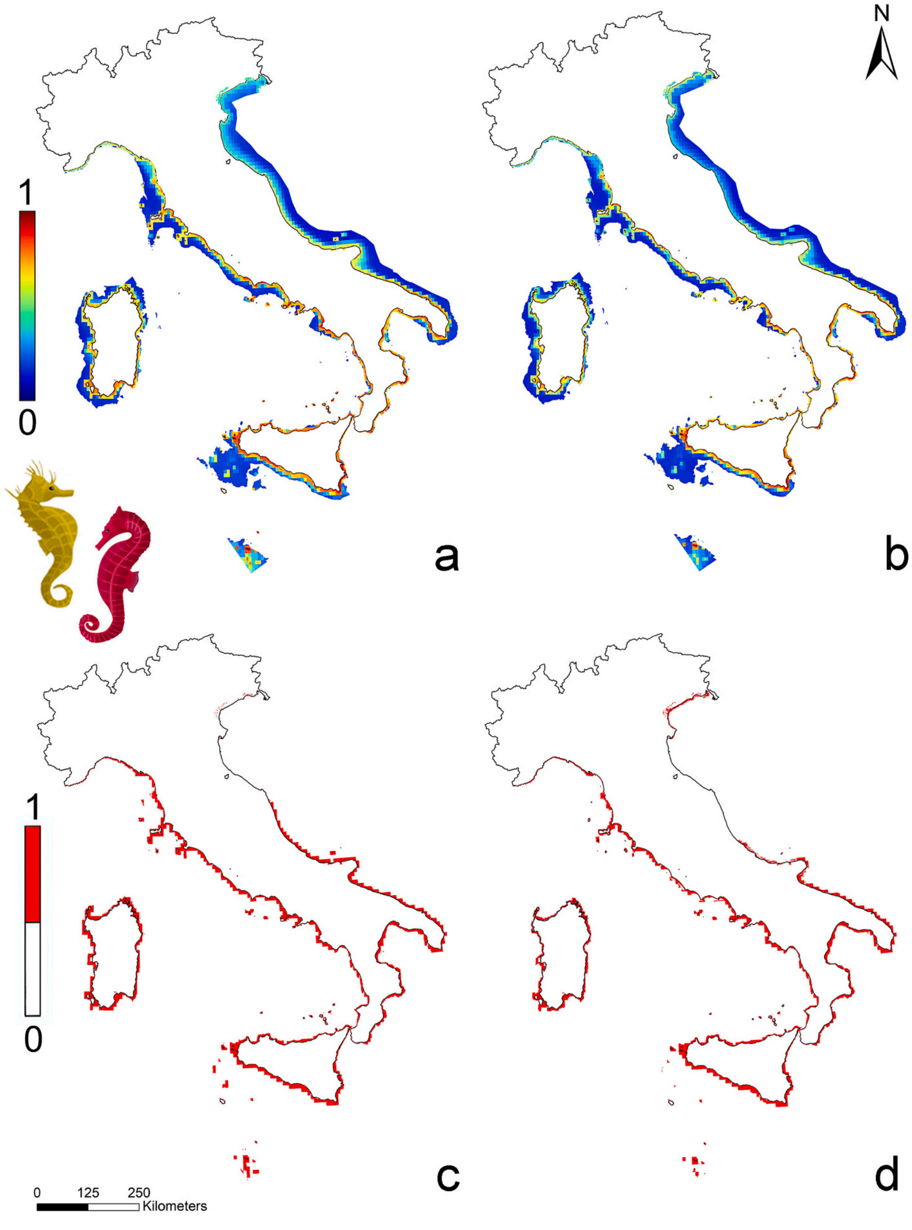

Fig. 2. *Hippocampus guttulatus* (a and c) and *Hippocampus hippocampus* (b and d) continuous (up) and binary (down) maps of habitat suitability. Continuous values close to 1 indicate an area with high probability of seahorse's presence, close to 0 suggest a low probability of seahorse's presence. Binary maps: red areas = presence; white areas = absence. Italy's boundaries are denoted by the black continuous line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

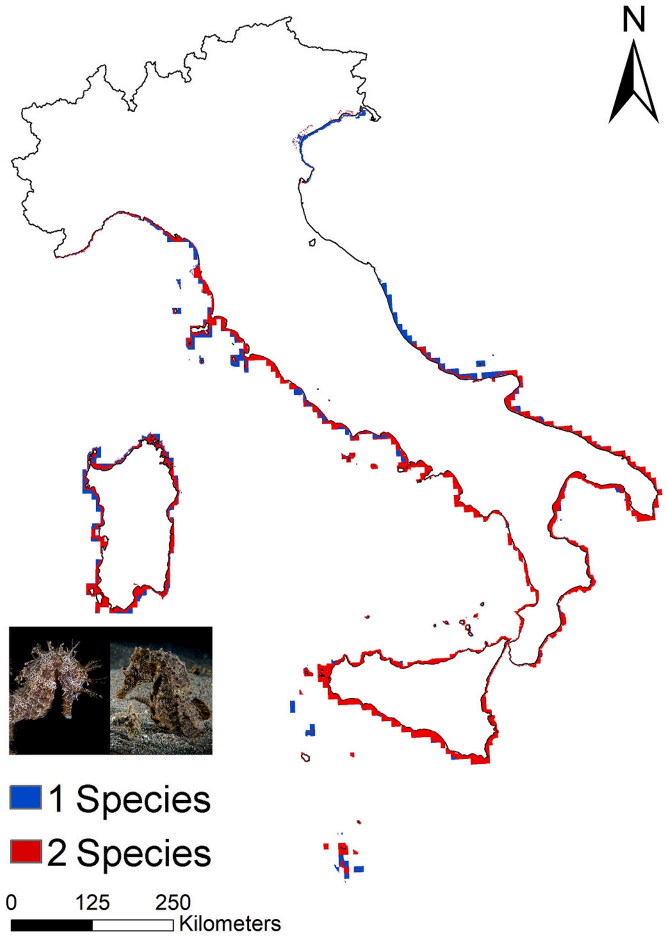

Fig. 3. Hotspot map of potential seahorse species richness in Italy. We defined two categories as follows: a) 1 species (blue areas); and b) 2 species (red areas). Italy's boundaries are denoted by the black continuous line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Model validation

SDMs showed an excellent level of predictive performance, as indicated by the AUC and TSS values of 0.91 ± 0.02 (mean ± standard deviation) and 0.68 ± 0.02 in *H. guttulatus* and 0.92 ± 0.03 and 0.69 ± 0.03 in *H. hippocampus.*

The high predictive performance of our models was confirmed by validation using multiple databases (Table 2).

3.4. Niche analysis

The first and second principal component of the ecospat PCA of both species explained 35.4% and 22.2% of the variability in the study area, respectively (Figs. 4a-g). The correlation plot showed that the mean temperature, mean currents velocity and habitat availability of *P. oceanica* and maerl were positively correlated, while bathymetry and mean salinity were negatively correlated (Fig. 4d).

Table 2
Performance classes' evaluation of the presence records of *H. guttulatus* and *H. hippocampus* obtained from different sources: GBIF, INaturalist, OBIS, AQUAMAPS, and Zhang and Vincent (2018). Three performance classes were considered: poor (0–0.335), medium (0.336–0.665) and good (0.666–1).

Source	*H. guttulatus* (class)	*H. hippocampus* (class)
GBIF	0.77 (good)	0.82 (good)
INaturalist	0.74 (good)	0.73 (good)
OBIS	1.00 (good)	1.00 (good)
AQUAMAPS	0.70 (good)	0.85 (good)
Zhang and Vincent (2018)	0.90 (good)	1.00 (good)

The similarity tests showed that the niches of the two seahorses were significantly similar (Table 3, Figs. 4e and f) but not equivalent, as indicated by the equivalency tests (Fig. 4g), despite the mean Schoener's D index indicated high overlap (Table 3).

3.5. Least-cost paths

We obtained 8125 polylines for *H. guttulatus* with the least-cost-path cost values ranging from 0.011 to 234.985 and the least-cost-path distance values ranging from 1 km to 3946 km (Fig. S5). In *H. hippocampus,* we calculated 4454 polylines with least-cost-path cost values ranging from 0.008 to 229.120 and a least-cost-path distance values ranging from 1 km to 4163 km (Fig. S6). Since we selected only the path <1 km, we obtained 23 and 19 paths in *H. guttulatus* and *H. hippocampus,* respectively (Tables S1 and S2). The least-cost paths were found mainly in Apulia, Calabria and Sicily regions in Southern Italy for both the seahorses (*H. guttulatus* = ca. 87%; *H. hippocampus* = ca. 95%).

3.6. Conservation gap analysis

The overlay between the existing system of conservation areas in Italy and the binary map of the *H. guttulatus* or *H. hippocampus* potential distribution showed that around 30% and 25% of their potential habitats were protected, respectively. Areas were both of the twospecies were protected represented 25% of their co-occuring distribution (Fig. 5).

Specially Protected Areas of Mediterranean Importance (31.95%), and International significance Natural Marine Area (26.28%), and Special Areas of Conservation (18.38%) were the main types of protected areas that overlapped the binary map of *H. guttulatus,* while Special Areas of Conservation (27.73), and International significance Natural Marine Area (26.04%) were the most effective in the protection of *H. hippocampus'* habitat suitability map. Hotspot maps, where both species co-occurred, were covered mainly from Special Areas of Conservation (27.20%), Specially Protected Areas of Mediterranean Importance (26.34%), and International significance Natural Marine Area (20.16%); and Specially Protected Areas of Mediterranean Importance (38.82%) and International significance Natural Marine Area (33.66%) in the case of one species. Further details and names of the protected areas where our model predicted the potential presence of the seahorses can be found in the supplementary materials (Tables S3 – S6).

Around 9% and 26% of *H. guttulatus* and *H. hippocampus* paths were covered by protected areas, respectively.

3.7. Assessing the impact of human activities on habitat suitability and paths of *H. guttulatus* and *H. hippocampus*

Around 42% and 38% of *H. guttulatus* and *H. hippocampus'* habitat suitability, respectively, was affected by anthropic activities (Fig. 6a and c) Considering all the Italian regions, fishing effort (mean = 96%), port (mean = 2%), oil and natural gas exploration (mean = 1%) were the main anthropic activities that impacted *H. guttulatus* (Fig. 6b), while fishing effort (mean = 97%), discharge (mean = 1%), and natural gas exploration (mean = 1%) mainly fell in *H. hippocampus'* binary maps (Fig. 6d). Dredging was the human activity with the lowest potential impact for both seahorses (Fig. 6b and d).

The regions where *H. guttulatus* faced the highest potential risk of being impacted by human activities were Emilia Romagna (63%), Abruzzo (54%), Sicily (50%), and Marche (49%), while Basilicata (30%), Veneto (8%), and Friuli Venezia Giulia (5.71) were the regions characterised by the lowest potential risk (Fig. 7a and Table S7)). Instead, we found that Emilia Romagna (61%), Marche (60%), Abruzzo (51%), and Campania (45%) were the regions with the highest potential

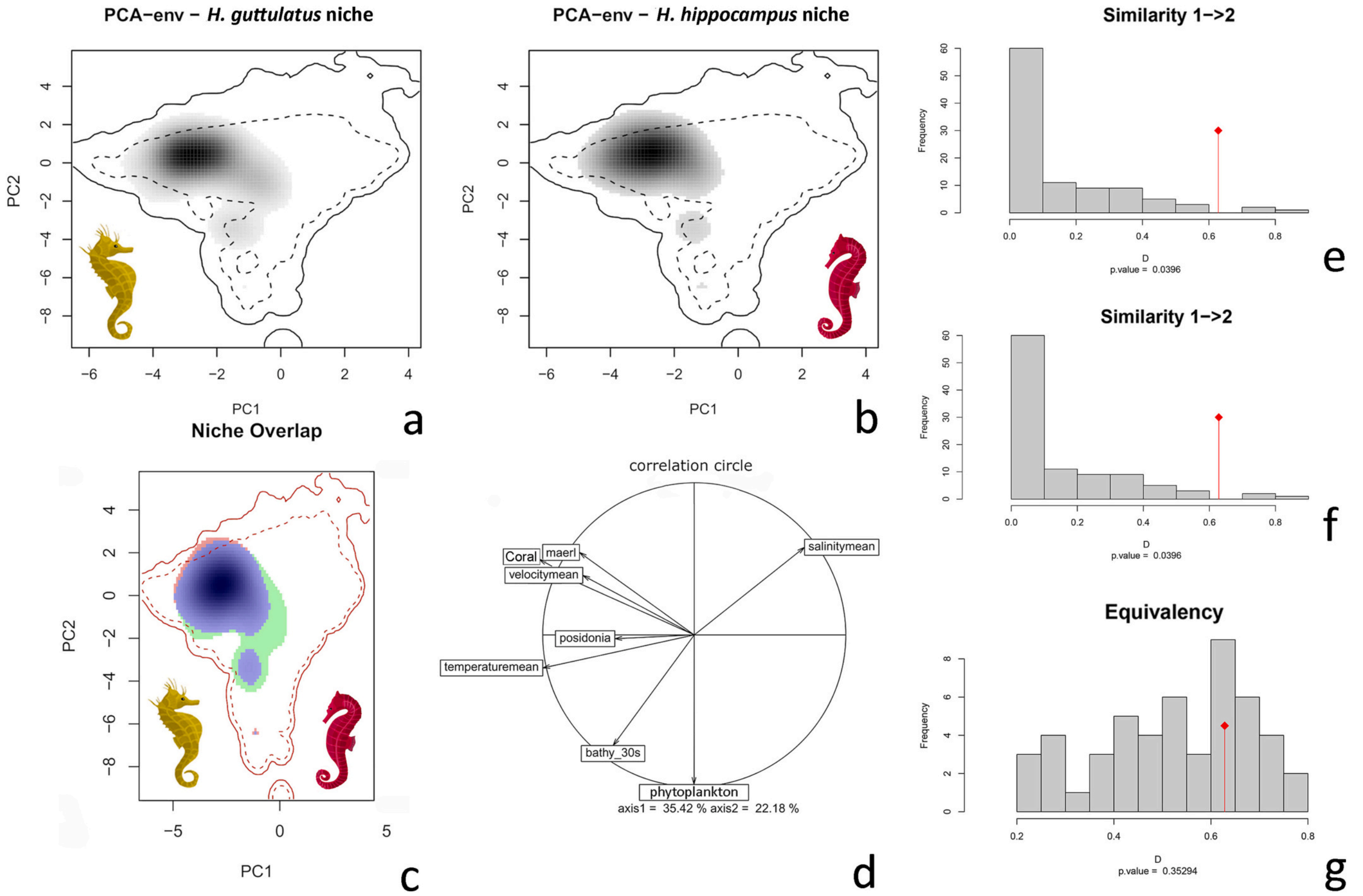

Fig. 4. Niche similarity and equivalency between *H. guttulatus* and *H. hippocampus*: a) Environmental occupancy plot along the two-first axis of the PCA-env of *H. guttulatus*; b) Environmental occupancy plot of *H. hippocampus*; c) Niche overlap (blue) between *H. guttulatus* (green) and *H. hippocampus* (red); d) PCA predictor correlation circle, labels as follows: temperaturemean = mean temperature; salinitymean = mean salinity; velocitymean = mean current velocity, phytoplankton = mean phytoplankton; bathy_30s = bathymetry; posidonia = habitat availability of *Posidonia oceanica*; maerl = habitat availability of maerl; Coral: habitat availability of coral reefs; e-g) Histograms of the simulated values for the niche similarity and equivalency tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Niche overlap metric (Shoener's D) and the equivalency and similarity tests among the species *Hippocampus guttulatus* (Sp1) and *Hippocampus hippocampus* (Sp2). Significant *P* values ($P < 0.05$) are shown in bold.

Test	*H.guttulatus - H.hippocampus*
Shoener's D	0.63
Equivalency	$P = 0.353$
Similarity 1 - > 2	$\mathbf{P = 0.039}$
Similarity 2 - > 1	$P = 0.056$

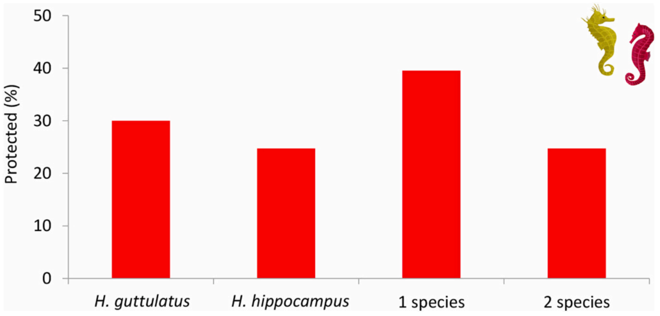

Fig. 5. Percentage of protected habitat suitable for *Hippocampus guttulatus* and *Hippocampus hippocampus* in Italy.

risk for *H. hippocampus*, while Tuscany (28%), Friuli Venezia Giulia (20%), and Veneto (14%) were the regions at lowest risk (Fig. 7b and Table S8).

The joint risk map of both seahorse species was similar to the *H. hippocampus* one (Fig. 7b).

H. guttulatus' paths were impacted by the presence of ports (33%), dredging (27%), and discharge (27%), while discharge (30%), fishing effort (26%), and ports (21%) affected the *H. hippocampus* ones.

4. Discussion

The Mediterranean seahorses *H. guttulatus* and *H. hippocampus* are elusive species that have been assessed as Data Deficient by the IUCN Red List of Threatened Species (Pollom, 2014; Pollom, 2017). Here, we contributed to increase the urgently needed ecological knowledge on these fishes through citizen science, GIS and SDMs applications in Italy. We provided spatially-explicit information on their distribution at an unprecedented resolution on the whole national territory, aiding efforts to improve their conservation and limit detrimental anthropic impacts.

4.1. Species distribution models, niche analysis and least-cost paths

Our SDMs successfully estimated the current Italian distributions of *H. guttulatus* and *H. hippocampus*, respectively, as shown by validation with the other biodiversity platforms (Konowalik and Nosol, 2021) as well as the AUC and TSS values, which are among the highest reported in

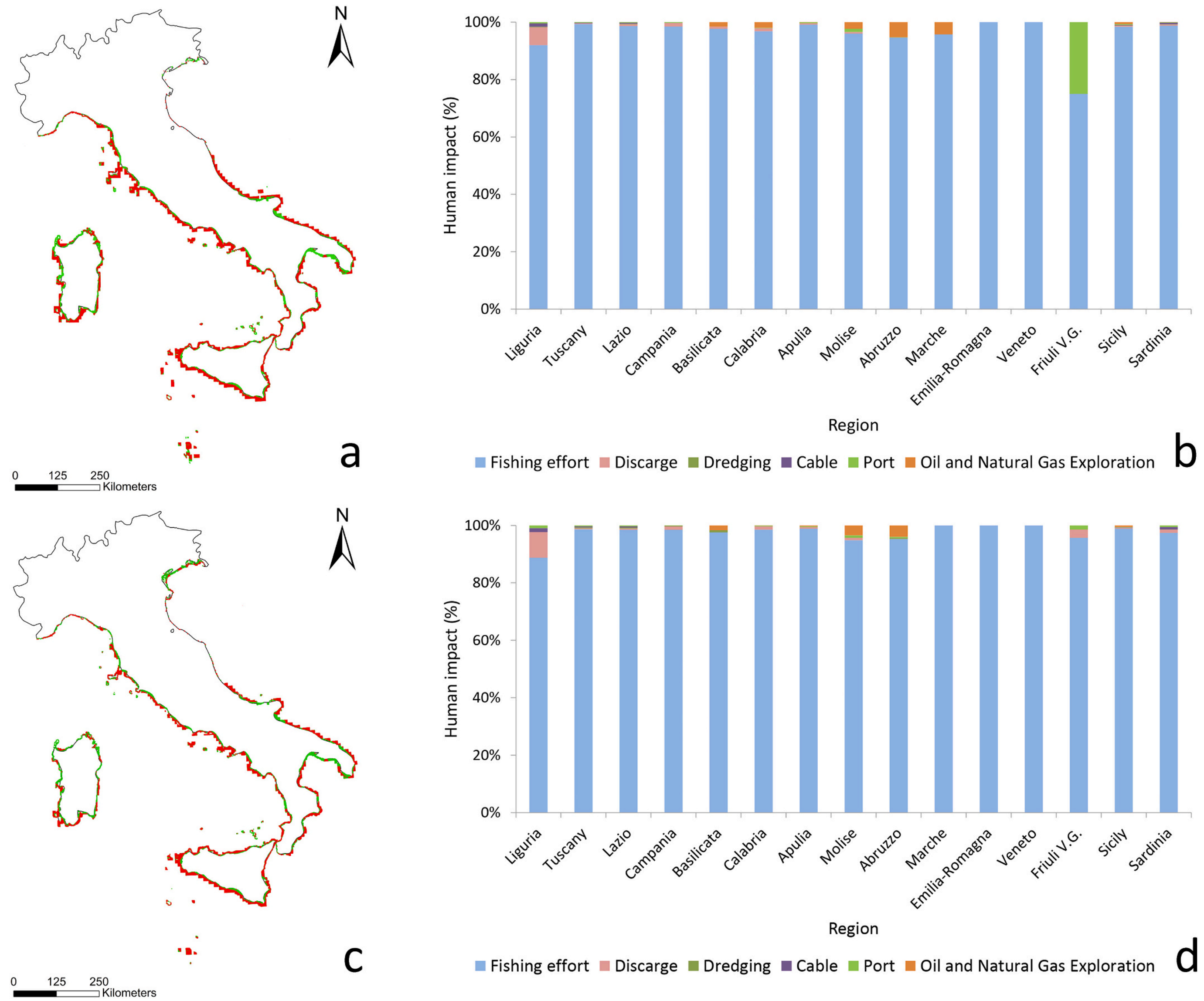

Fig. 6. Overlap between binary maps (green) and human activities (red), and details on anthropic impact in each Italian region in *Hippocampus guttulatus* (a and b) and *Hippocampus hippocampus* (c and d).

published models (e.g., Ahmadi et al., 2023; Buonincontri et al., 2023; Di Febbraro et al., 2023; Rubanschi et al., 2023). Our results indicated that Italy hosts highly suitable areas for both species, consistent with earlier research (Monteiro et al., 2023; Ready et al., 2010; Zhang and Vincent, 2018). Specifically, our maps showed a greater amount of habitats in Italy that are suitable for both species close to the coasts of the Tyrrhenian Sea and Southern Italy than previous SDMs for seahorses in the Mediterranean basin. Here, previous analyses did not show suitable zones in areas where the presence of both seahorses has been confirmed, such as in the Mar Piccolo in Taranto (Southern Italy, Apulia, Pierri et al., 2022), the Messina Strait (data collected from our Citizen Science survey), and the Tyrrhenian coast from Campania to Sicily. Our models highlighted a potential distribution gap in both species from Abruzzo to Emilia-Romagna, in line with the current knowledge on these species, while Monteiro et al. (2023) considered the whole Northern Adriatic Sea as suitable. The discordance among our and previous findings is likely the result of differences in geographic scale and resolution, which were improved in our study. Additionally, we considered benthic predictors linked to bathymetry, while Zhang and Vincent (2018) and Monteiro et al. (2023) used the surface layers (a constant 0.5 m depth, Assis et al., 2018), which are less representative of benthic species associated to the sea bottom such as *H. guttulatus* and *H. hippocampus* (Correia et al., 2018). The accurate selection of predictors is a major methodological concern affecting model performance and needs to be highly representative of the biology of the target species when using SDM outputs in conservation prioritization (Franklin, 2023).

Our niche analyses showed that *H. guttulatus* and *H. hippocampus'* niches were similar but not equivalent. Although these two seahorses share a wide surface (> 97%) in terms of geographic extension (a bidimensional space), they occupied different niches when the multidimensionality of predictors was taken into account. *H. hippocampus* resulted to be associated with more open habitats, while *H. guttulatus* is mostly positively correlated with vegetation coverage, possibly indicating divergence in feeding opportunities and predation risk (Foster and Vincent, 2004). Our models showed that on a larger spatial scale, *H. guttulatus* and *H. hippocampus* can be found in a variety of habitats (e.g., seagrasses meadow of *Posidonia oceanica*, coral reefs, and maerl) with varying degrees of complexity in terms of their ecological requirements, for example, the presence of phytoplankton, temperature, and current velocity (Pierri et al., 2022). However, at the local scale, seahorse populations may adapt to different micro-habitats, opting for an alternative niche that eventually becomes their first choice (e.g., artificial

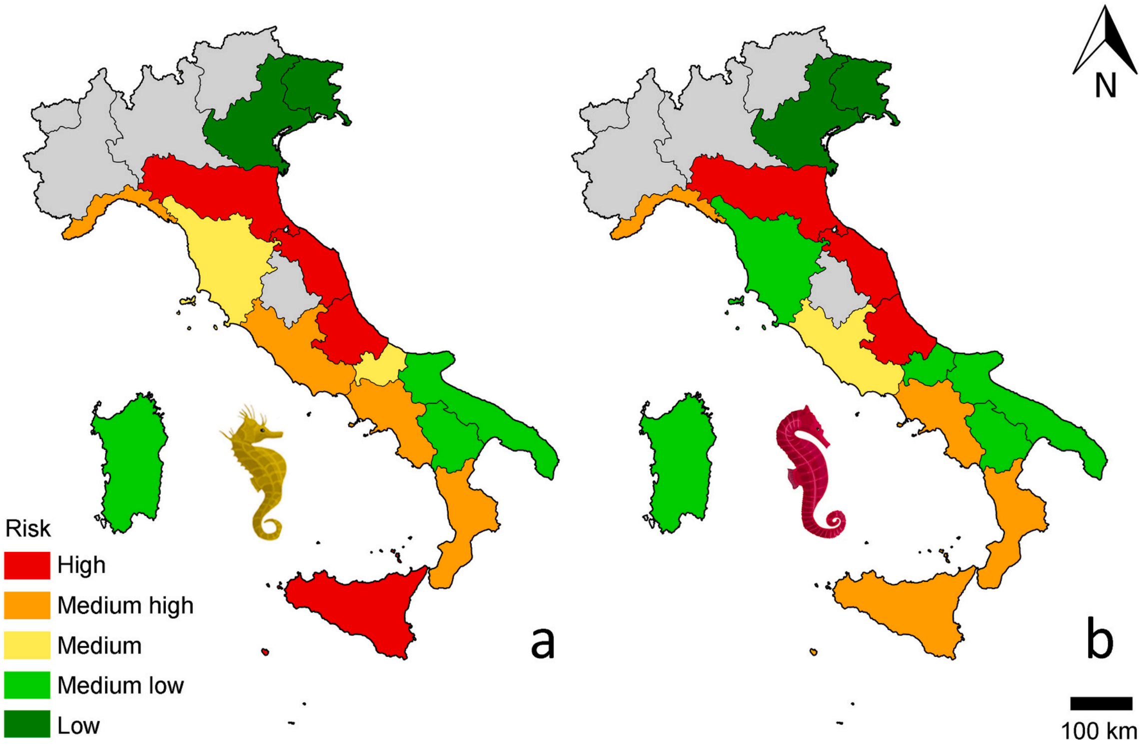

Fig. 7. Risk map for *Hippocampus guttulatus* (a) and *Hippocampus hippocampus* (b) in Italy due to human activities. Regions without access to sea are shown in grey.

structures), thereby increasing the seahorse's plasticity to habitat changes (Correia et al., 2018). The existence and abundance of seahorses are directly influenced by habitat availability; hence, it is crucial to undertake protective measures (such as Marine Protected Areas) in order to maintain healthy habitats and high standards for biodiversity. Our habitat results of the citizen science survey are consistent with the current seahorse ecological knowledge in Italy; however, we noted that the majority of the respondents sighted a few specimens of *H. guttulatus* and *H. hippocampus* during the diving. Beyond a possible oversight on the divers' part due to mimetic capacity of the seahorses, it could means which there is a currently decline of the Italian *Hippocampus* populations, mainly due to habitat loss and degradation caused by coastal development and destructive fishing gears such as trawls and dredges, in accordance with IUCN analysis (e.g., Pollom et al., 2021).

In both species, the Least-Cost paths were found mainly in three Italian regions: Apulia, Calabria, and Sicily, in line with the higher number of observations reported in these areas in our citizen science survey. In fact, this spatial analysis is strongly related to the number of presence records and the biology of the target species (Lazic et al., 2023). Our results highlighted that monitoring and research efforts on the two Italian seahorse species have focused on these areas, and this local data is particularly informative (e.g., Pierri et al., 2022). Additionally, *H. guttulatus* and *H. hippocampus* are characterised by a sparse distribution, low mobility, and small home ranges, similarly to all the *Hippocampus* species (Foster and Vincent, 2004); thus, a larger amount of presence data at low spatial resolution (<1 km) is needed throughout their distribution range to increase monitoring and conservation actions in seahorses. To this aim, citizen science surveys, social media, diving centers, fishing events, and questionnaires, together with joint research efforts and improved scientific data sharing, can help to cost- and time-effectively obtain and analyse a large amount of solid information on species occurrences (Kelly et al., 2019, 2020).

The assessment of conservation status has largely focused on terrestrial species and involved only few marine organisms, which are often classified as Data Deficient (Luypaert et al., 2020). Our findings indicated that citizen science is a solid source of occurrence data that can directly inform the distribution, niche composition and paths of elusive species such as seahorses and facilitate the evaluation of their risk of extinction. Our *H. guttulatus* and *H. hippocampus* maps can be used to plan new citizen science surveys in Italy to improve detailed knowledge of local distributions. Our study emphasizes how reliable citizen science data can help to derive more accurate SDMs, and in turn, these spatial ecology approaches can help extrapolating spatially-restricted information at a larger geographic scale, i.e., from local observation of single divers to national maps of habitat suitability.

4.2. Conservation gap analysis and risk map

Protecting seahorses has a cascade effect across local ecosystems and contributes to preserving many other marine species and habitats (Monteiro et al., 2023; Tabugo et al., 2023; Ternes et al., 2023).

Our conservation gap analysis highlighted the need for improved management and conservation planning in *H. guttulatus* and *H. hippocampus*, particularly in the face of ongoing climate change and anthropic impact. In fact, only 30% and 25% of the potential distribution of *H. guttulatus* and *H. hippocampus*, respectively, is under different levels of protection in Italy within marine protected areas, national parks, special areas of conservation and specially protected areas of Mediterranean importance. The amount of protection granted in Italy is in line with the worldwide seahorses' average (Zhang and Vincent, 2019a). Previous studies on the whole distribution showed similar (*H. guttulatus* = 25% and *H. hippocampus* = 30%, Zhang and Vincent, 2019b) or substantially lower values of granted protection (5% in both seahorses, Monteiro et al., 2023), possibly due to the lower spatial resolution. Contrarily to marine species with large distributions and extended migratory routes, adult seahorses typically show low mobility and small home range (Foster and Vincent, 2004). Therefore, their protection is aided mostly by spatial analyses at high resolution ($\leq$ 1 km), as the ones shown in this study. Our results can guide more efficient monitoring plans and conservation actions such as increasing the extension of protected areas and/or creating a more inter-connected network (e.g., Franklin, 2023). In fact, preserving ecological corridors or *refugia* could assist range shifts and support species' persistence in the face of climate change or to avoid human activities impact.

Limited economic and human resources require careful prioritization and management of conservation efforts; risk maps such as the ones provided in this study can identify areas that require special attention and assist local stakeholders and policymakers in the decision-making processes directly. We provided the first quantitative assessment of the potential detrimental effects of human activities on *H. guttulatus* and *H. hippocampus*'s suitable habitat. Fishing emerged as the main anthropic threat in Italy, similarly to field observations in other species Vincent et al. (2011) and Cohen et al. (2017). This factor includes direct and indirect fishing activities such as intentional fishing aimed at the use of *Hippocampus* spp. specimens as food or medicine, and unintentional fishing as bycatch, which needs to be mitigated urgently (Cohen et al., 2017; Vincent et al., 2011). Biodiversity managers are advised to allocate more resources to address this stressor in Italy. Pollution is the second predictor known to affect seahorses globally. However, its negative impact on the Italian populations of *H. guttulatus* and *H. hippocampus* is less clear. In fact, conspicuous groups of these species have been reported repeatedly in the Mar Piccolo (Taranto, Apulia), a heavily polluted area with trace metals, hydrocarbons, pesticides, and organic wastes affecting both biotic and abiotic matrices (Cotecchia et al., 2021; Gristina et al., 2015; Tiralongo and Baldacconi, 2014). In the central Adriatic Sea, our findings suggested that Emilia-Romagna, Marche and Abruzzo host few suitable areas that are strongly impacted by human activities for both the seahorses. Here, we recommend a close and continuous monitoring of these smaller populations that could potentially be critically endangered.

5. Conclusions

Our findings highlight the importance of taking advantage of citizen science and SDMs based on biologically informative layers in marine species assessed as Data Deficient to achieve the sufficient level of information needed to correctly assess their conservation status. We used *H. guttulatus* and *H. hippocampus* in Italy as study models to show how such an approach can substantially boost the ecological knowledge of elusive species such as seahorses. In turn, the use of charismatic species such as seahorses in citizen science or outreach activities can enhance public engagement, reduce potential conflicts with socioeconomic activities (e.g., fishermen), and facilitate successful conservation initiatives for the marine ecosystems. Furthermore, our maps can be used to identify areas of research interest where to deepen knowledge on presence, abundance, habitat preference, impact of human activities, and status of seahorses as well as also to validate future Italian seahorse datasets. The risk maps may help conservationists and landscape planners to identify zones of conservation concern to be prioritised in Italy. Further high-resolution citizen campaigns, SDM analyses and risk maps at population-level and in other countries and for other species will provide a more comprehensive view of distributions and threats in endangered, data deficient species.

Declaration of generative AI in scientific writing

The authors have no used generative artificial intelligence (AI) and AI-assisted technologies in the writing process.

CRediT authorship contribution statement

Luciano Bosso: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Raffaele Panzuto:** Data curation, Investigation, Writing – original draft, Writing – review & editing. **Rosario Balestrieri:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Sonia Smeraldo:** Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Maria Luisa Chiusano:** Writing – original draft, Writing – review & editing. **Francesca Raffini:** Supervision, Visualization, Writing – original draft, Writing – review & editing. **Daniele Canestrelli:** Supervision, Visualization, Writing – original draft, Writing – review & editing. **Luigi Musco:** Conceptualization, Data curation, Investigation, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Claudia Gili:** Conceptualization, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Data availability

Seahorses are highly sensitive species of high biological significance and under severe threat from detrimetal anthropic activities; the provision of precise locations could subject them to threats such as disturbance, illegal trading and exploitation. Detailed data may be made available upon request after careful consideration.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2023.102402.

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