Estuarine, Coastal and Shelf Science 319 (2025) 109293

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Turtle bycatch from trawlers: What modelling is telling us in the southern Adriatic sea

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ARTICLE INFO

Keywords:
Bycatch
Loggerhead turtle
GAM
GLM
Bottom trawlers
South adriatic sea

ABSTRACT

The Southern Adriatic Sea (Geographical Sub-Area GSA18) is intensively exploited by bottom trawling and it is also an important foraging ground for both juvenile and adult loggerhead sea turtles (*Caretta caretta*). The risk of unwanted catches of sea turtles with trawling is therefore high in this area, demanding tailored insights on this issue. In this study, we investigated the patterns and potential drivers of loggerhead sea turtle bycatch in this area, using generalized linear and generalized additive models. We analyzed data collected by observers onboard and logbooks. Results indicated that the likelihood of turtle bycatch is significantly higher during the day, likely due to the turtles' diel foraging patterns. Seasonal variations revealed an increased bycatch rate in summer and autumn, coinciding with the turtles' southward migration to warmer waters. Additionally, the generalized additive model provided spatiotemporal insights, identifying two bycatch hotspots around the Gargano promontory and off the coast of Brindisi, areas recognized for their high suitability as foraging habitats. Depth and distance from the coast were also significant key factors, with most bycatch occurring in shallow and coastal waters. The drivers of bycatch identified in this study provide crucial insights for shaping initiatives to reduce bycatch of loggerhead sea turtles. These findings emphasize the need for tailored conservation measures to mitigate bycatch, such as temporal and spatial fishing restrictions.

1. Introduction

Fisheries bycatch, which refers to the unintended capture of non-target species during fishing activities, ranks among the most pressing global fisheries issues (Lewison et al., 2014; Gray and Kennelly, 2018). Particularly concerning is the incidental capture and subsequent discarding of endangered, threatened and protected (ETP) species in both commercial and artisanal marine fisheries, amounting to over 20 million specimens annually, including seabirds, mammals, elasmobranchs, and sea turtles (Gray and Kennelly, 2018). The Mediterranean Sea is one of the globally most intensely fished areas, which results in high bycatch of ETP species. Carpentieri et al. (2021) conducted a comprehensive review of bycatch involving different groups of vulnerable species in the Mediterranean and Black Sea, highlighting the severity of the issue while also pointing out the shortcomings in monitoring efforts and the need to intensify these efforts.

ETP species, typically characterized by long lifespans, late maturation, and low reproductive rates (Lewison et al., 2004), are particularly vulnerable to fishing pressure, with interactions from fisheries contributing to substantial population declines (Meyer et al., 2017; Brownell

This article is part of a special issue entitled: The Adriatic blue growth published in Estuarine, Coastal and Shelf Science.

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https://doi.org/10.1016/j.ecss.2025.109293
Received 29 October 2024; Accepted 3 April 2025
Available online 3 April 2025

et al., 2019; Luck et al., 2022). Sea turtles are considerably impacted by various fishing gears, including longlines, nets, and trawlers, especially in the Mediterranean Sea. Three species of sea turtles are present in the Mediterranean Sea: the leatherback turtle (*Dermochelys coriacea*), the green turtle (*Chelonia mydas*), and the loggerhead turtle (*Caretta caretta*). Leatherback turtles rarely enter the Mediterranean Sea and do not breed there (Casale et al., 2003), whereas green and loggerhead turtles face substantial bycatch pressures (Encalada et al., 1996; Casale, 2011). Loggerhead turtles are predominantly found in the western and central Mediterranean, while green turtles are more common in the eastern Mediterranean (Casale, 2010). The complex life cycle of loggerhead turtles involves extensive migrations between juvenile, subadult, and adult habitats (Bolten, 2003; Casale et al., 2007; Revelles et al., 2007; Scales et al., 2016). The Gulf of Gabès, the Adriatic Sea, the southern coast of Turkey, the Egyptian coast of the Mediterranean with their extensive shallow waters and rich benthic communities are considered as the most important feeding habitats for sea turtles in the Mediterranean, especially for juveniles and subadult specimens (Carpentieri et al., 2021). However, these areas are also among the most heavily exploited by trawl fisheries in the World due to the extensive continental shelf (Eigaard et al., 2017). When an area heavily populated by sea turtles overlaps with an area heavily exploited by bottom trawling, as is the case in the Adriatic, the risk of bycatch is very high (Lucchetti et al., 2016a). The Adriatic Sea is a critical area for loggerhead dispersal and aggregation, especially for specimens nesting in the western Ionian Sea (Casale and Mariani, 2014). Furthermore, the south Adriatic Sea has recently become a significant nesting area, reflecting a broader trend of northward expansion of the nesting range in the Mediterranean basin (De Silva, 2022; Hochscheid et al., 2022).

The signs of fishing-induced mortality in sea turtles in several Mediterranean areas is evident from the high number of stranded turtles showing signs of fishing gear interactions (Casale, 2011; Tomás et al., 2008). Casale (2011) identified trawls as the second most important gear in terms of number of turtles captured after pelagic longlines, particularly in the Adriatic Sea where bottom trawls have a notable impact on sea turtles (Carpentieri et al., 2021; Casale, 2011; FAO, 2019; Lucchetti et al., 2016b; Lucchetti et al., 2019). Carpentieri et al. (2021), more recently estimated that over 28,000 capture events may occur in the entire Adriatic basin, most of them (over 18,000) by trawling, with likely more than 8000 dead turtles. The direct mortality reported for bottom trawling is around 18 %. However, post-release mortality remains a significant concern (Casale, 2011). Franchini et al. (2021) found that over 40 % of turtles caught by trawling, although alive at the time of release from the nets, showed signs of gas embolism in a study conducted in the Southern Adriatic Sea. These turtles presented significant positive correlations between the presence of gas-embolism and duration, depth, ascent rate of trawl, turtle size and temperature. Therefore, the impact of trawling on the sea turtle population could be considerably greater than indicated by the number of dead individuals observed on board during fishing operations. Recent studies (Lucchetti et al., 2017a, 2017b) have even suggested that the impacts of bottom trawls may be comparable to or greater than those of drifting longlines.

Bycatch is influenced by various factors, including species life cycles, fishing strategies, and seasonal variations (Lucchetti et al., 2017a, 2017b; Alessandro and Antonello, 2010). The technical and operational characteristics of fishing gears play a role, as bottom trawls and set nets predominantly affect turtles during their demersal life stages, whereas drifting longlines primarily interact with turtles during pelagic phases (Carpentieri et al., 2021; Casale et al., 2007; Piovano et al., 2009; Carbonara et al., 2023). Therefore, to accurately assess sea turtle bycatch rates and impacts, it is crucial to consider various factors related to fishing activities (e.g. gear types, fishing strategies, effort, and exploited areas), as well as sea turtle habitats, biology, and migration patterns (Carpentieri et al., 2021). Bycatch is not uniformly distributed (Kindt-Larsen et al., 2023), and areas with high bycatch rates do not always coincide with zones of high fishing effort but rather with specific fishing methods that increase the likelihood of bycatch events. Therefore, analyzing the variability in fishing practices is crucial for estimating total bycatch in different fisheries and understanding the factors driving bycatch for an effective management. Given challenges and costs associated with monitoring efforts, it is crucial to concentrate monitoring effort and mitigation strategies to the conditions of highest bycatch risk, such as particular gears, areas, and seasons, where issues are known to occur. This study aimed at analyzing the potential drivers of bycatch of *Caretta caretta* caught by bottom trawls within one of the most important bycatch areas for this species, namely the Southern Adriatic Sea (Carpentieri et al., 2021; Casale, 2011). The effects of various variables, including geographic, seasonal and physical ones, were investigated.

2. Material and methods

2.1. Data collection

The data used in this study were collected during a bycatch monitoring pilot study carried out in 2018 within the European Data Collection Framework (EU-DCF) in Southern Adriatic Sea (Geographical Sub-Area GSA18 *sensu* FAO-GFCM) on the bottom trawl (OTB). The data were collected using two strategies: by observers onboard and by logbooks filled out voluntarily by fishers. The fishers were trained in advance on the data to be collected to homogenise the data acquisition process that included the geographical coordinates of hauls, their duration, time and depth, the number of sea turtles caught and the occurrence of bycatch events. In addition, the curved carapace length (CCL) of *C. caretta* specimens caught was measured. Observers onboard collected the same types of data. Specimens in good condition upon capture were released directly back into the sea after being freed from the nets, while those with injuries were transported to the nearest authorised recovery center.

2.2. Modelling

The data analysis was performed using the R software v.4.1.1 (R Core Team, 2021) with *gamlss* library (Rigby and Stasinopoulos, 2005). The analysis of bycatch, being a rare event, is characterized by a high percentage of zeros and high variability. In fact, the percentage of zeros can be, according to the literature, greater than 80 %, and can exceed 95 % in studies involving marine mammals (Thompson et al., 2013; Cruz et al., 2018). In order to model bycatch satisfactorily, robust techniques that account for this high percentage of zeros are necessary (Feng, 2021). For this reason, in this study, we modelled bycatch using two-stage models, also called "hurdle models", previously applied in other bycatch studies (Thompson et al., 2013; Christensen-Dalsgaard et al., 2019; Kroetz et al., 2020; Puente et al., 2023). In the first stage, the presence/absence of bycatch was modelled using a logistic Generalized Linear Model (GLM) (with Bernoulli distribution and logit link function), from which an estimate of the probability of bycatch per set was obtained. In the second stage, given that bycatch occurred, the expected number of sea turtle bycaught was estimated using a GLM with a distribution appropriate to the type of data, which in this case was a Poisson distribution. This approach provided an estimate of the average number of individuals caught incidentally.

As explanatory variables, we used data collected both onboard and geographic/physical variables obtained from public data infrastructure. Among the data collected onboard or by logbook, the variables have been grouped in two categories. The first category included variables related to the fishing operation (operational variables), such as geographic position (longitude, latitude), depth of the haul/operation (mean depth), time of the day (day or night) and season (autumn, spring, summer, winter). For geographic position and depth, we estimated the midpoint of longitude and latitude (in decimal degrees) of the setting/hauling phases of the net. Due to convergence issues in the model fitting, factorial variables such as year, month, or season could not be included in the model along with the remaining variables, therefore all variables' effects were explored in a univariate manner. The second category included physical variables like distance to coast and depth, which were extracted from 3D monthly Copernicus Mediterranean reanalysis products (Copernicus Marine Environment Monitoring Service, CMEMS). The depth data used to generate the grid was derived from the EMODnet Bathymetry portal (EMODnet, 2022).

In a second step, Generalized Additive Models (GAM (Wood, 2017);) were applied to investigate and statistically test the impact of variables that showed a significant effect on loggerhead sea turtle bycatch. GAM models were preferred over classical linear models due to their flexibility to model nonlinear relationships when investigating both factors and numeric explanatory variables (Venables and Dichmont, 2004; Hastie and Tibshirani, 1986). The bycatch rate data, in terms of the number of *C. caretta* per trawl haul on duration in hour (bycatch index; BI), were modelled using the Tweedie family error distribution with a log link function. The BI data were modelled using distance from the coast, depth, longitude, and latitude as numeric explanatory variables and day/night, season and month as categorical variables. In the forward inclusion approach, variables are added to the model one at a time. At each step, variables not yet included in the model are tested for inclusion to avoid multicollinearity issues. Variables with a high Pearson's correlation coefficient ($r > 0.5$, absolute value) was considered correlated and, consequently, only one of the two was retained in the analysis. The model fit evaluation was carried out by computing the proportion of the null deviance explained, Akaike information criterion (AIC), the adjusted R^2 (Wood, 2011), significance of the smoothers on explanatory variables (p-value) and the reasonability of the partial effects described by splines. AIC was preferred as the performance metric because it accounts for both the goodness of fit and the complexity of the model, allowing to select the best model based on the lowest value while accounting for the risk of overfitting by down weighting models with a higher number of parameters (Anderson and Burnham, 2002; Weakliem, 2016). GAM fitting was carried out using the *mgcv* R package 1.8–36 (Wood, 2017). Once the best model was selected, a map of the BI was generated using a regular grid of points with a resolution of 0.01°.

3. Results

3.1. Data collection

In total, 374 fishing trips were monitored (42 by observers onboard and 332 by logbook) with a total of 1415 hauls (165 by observers onboard and 1250 by logbook), from which 69 were positive to the sea turtle catch (4.8 % of total hauls). Table 1 reports the monitoring effort by month in 2018. Fig. 1 shows the location of the monitored hauls and the hauls where *C. caretta* was caught.

Table 1
Number of fishing trips and hauls monitored by month in 2018. The number of positive hauls corresponds to the number of hauls with *Caretta caretta* bycatch.

Month	Number of fishing trips	Number of hauls	Number of positive hauls	Number of loggerhead turtles
January	43	140	5	5
February	5	18	2	2
March	8	38	2	2
April	6	29	4	4
May	5	17	4	4
June	10	43	0	0
July	36	138	8	11
August	24	89	1	2
September	13	59	1	1
October	63	260	11	15
November	75	254	14	20
December	86	330	17	23
Total	374	1415	69	89

In total during the monitored fishing hauls, data were collected on 89 loggerhead turtles with CCL ranging between 35 and 92 cm. Fig. 2 shows the CCL frequency distribution of *the C. caretta* specimens caught in the monitored fishing hauls.

3.2. GLM modelling: univariate approach

The results of the GLM analysis are reported in Table 2 and the model convergence was satisfied for all variables tested.

Fig. 3 reports the probability of *C. caretta* catch in relation to time of the day (day *vs* night), season, mean depth of the hauls, distance from the coast, latitude and longitude.

Autumn and summer appeared to be the seasons with a higher catch probability of *C. caretta* by trawler (Fig. 3A). Time of the day (i.e. day/night) was also a driver of the bycatch rate for loggerhead sea turtles caught by bottom trawl. During the day, the probability to catch loggerhead sea turtles was higher than during the night (Fig. 3B; Table 2). The first 50 m of depth (Fig. 3C) and the 30 km of distance from the coast (Fig. 3D) showed the highest probability of loggerhead sea turtle catch in the South Adriatic. The variables latitude (Fig. 3E) and longitude (Fig. 3F) showed a significant increasing (North-South) and decreasing trend (West-East) in the probability of catch respectively (Fig. 3).

3.3. GAM modelling: multivariate approach

The Pearson correlation test conducted for numerical variables revealed that latitude and longitude were highly negatively correlated ($r > 0.5$ as absolute value). Depth was also positively correlated with distance from the coast and longitude (Table 3), as expected given the topography of the area.

In Table 4, the results of the GAM analysis for the BI are reported. Following the forward inclusion approach, the final model (in bold in Table 4) included depth (D), day/night (D/N) and the interaction between latitude and longitude (Long, Lat) as explanatory variables. The BI index decreased with increasing depth (Fig. 4; and, therefore, increasing distance from the coast) until about 250 m, depth. The BI index was also significantly higher during the day than during the night (Fig. 4). The BI index also tended to increase with latitude but to decrease with longitude (Fig. 4).

A map of the BI generated by the selected GAM model is represented in Fig. 5. Two main areas were identified as zones with a higher bycatch probability: one located around the Gargano promontory (north area), and another off the city of Brindisi (south area) (Fig. 5).

4. Discussion

Caretta caretta is the most abundant sea turtle species in the Mediterranean Sea (Casale, 2011). It is a long-lived species with late sexual maturity, nesting mainly in the eastern part of the basin, particularly in Greece, Turkey, Cyprus and Libya (Broderick et al., 2002; Margaritoulis et al., 2003; Mingozzi et al., 2006). However, in the last decade, the loggerhead turtle has expanded its nesting range in the context of climate warming, with new colonies emerging further north and west in the Mediterranean basin (Hochscheid et al., 2022; Mancino et al., 2022; Pietroluongo et al., 2023). Loggerhead turtles occupy various ecosystems (nesting beaches, coastal, neritic and open sea, as well as pelagic and demersal areas) throughout their lifetimes. Previously classified as "endangered" (Casale and Tucker, 2017), *Caretta caretta* is now assessed by the IUCN Red List of threatened species as "least concern" due to the effectiveness of protection efforts in the Mediterranean basin over the last decades, particularly for nesting sites (Hochscheid et al., 2022; Mancino et al., 2022; Casale et al., 2015). Information on its ecology, biology, and behaviour, gained from various sources, including stranding data, tagging programs, and satellite telemetry studies (Maffucci et al., 2006; Luschi and Casale, 2014), show that it occurs throughout the entire Mediterranean basin, with a preference for some areas (e.g.

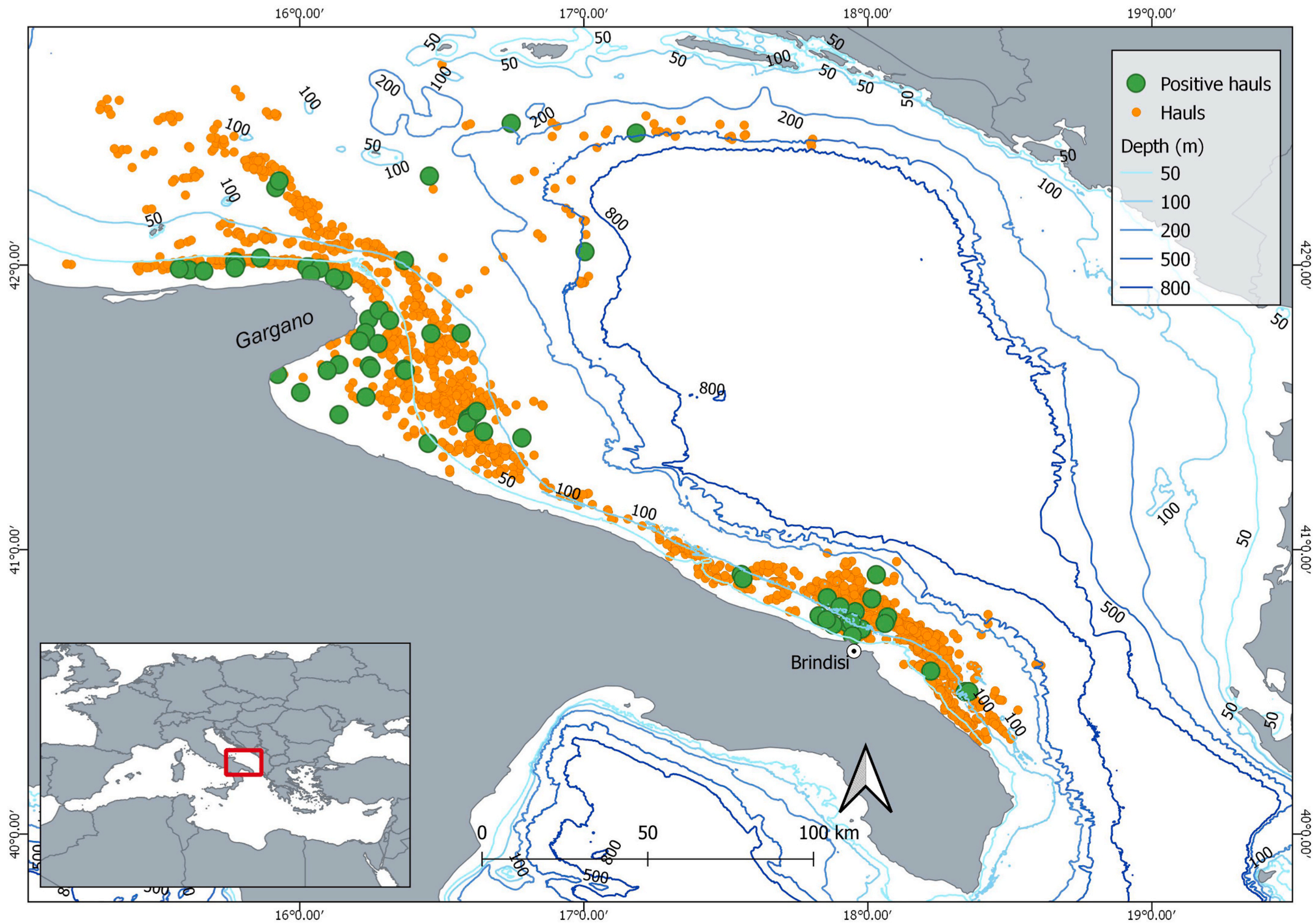

Fig. 1. In the bottom-left rectangle the position of the study area within the Mediterranean basin is highlighted (red square). The main map shows the location of the bottom trawl fishing hauls monitored (orange points) with a focus on positive ones (green points) for the catch of loggerhead turtles (*Caretta caretta*) in 2018. Bathymetry layer source: (EMODnet, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

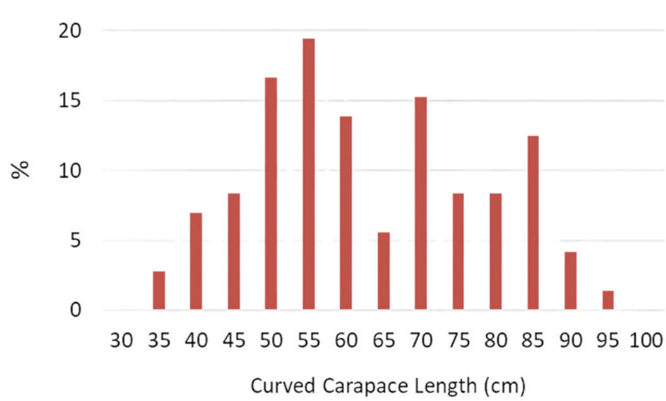

Fig. 2. Percentage histogram of the curved carapace length frequency distribution in 5 cm intervals for *C. caretta* specimens bycaught (total of 89 individuals). Observations were collected in the Southern Adriatic Sea during the 2018 pilot study of bycatch monitoring within the European Data Collection Framework.

Tunisia, Libya, Egypt and south-east Turkey), including the Adriatic Sea (Casale, 2010; Luschi and Casale, 2014), which are important foraging areas (Luschi and Casale, 2014; Mariani et al., 2023; Casale and Simone, 2017). In the Mediterranean basin, sea turtles are subject to cumulative and synergistic effects of natural phenomena and human activities. These include the ingestion of marine litter, collisions with vessels, destruction of nesting beaches, as well as incidental interaction with commercial fisheries (bycatch), which is considered as one of the main threat to their conservation (Carpentieri et al., 2021; Casale, 2011; Lucchetti et al., 2016b). This study therefore contributes to gather additional insights to improve the effectiveness of conservation measures.

Table 2
Results from the GLM analysis. AIC: Akaike Information criterion.

Variable	AIC	Convergence
Longitude	163.278	TRUE
Haul depth	163.920	TRUE
Day/Night	163.945	TRUE
Latitude	163.959	TRUE
Distance to coast	164.685	TRUE
Season	166.892	TRUE

Accurately determining the level, nature, seasonality, and geography of interactions between different fishing activities and vulnerable species groups through monitoring plans on incidental catch rates is crucial to: a) to focus monitoring efforts; and b) to define technical conservation measures, such as adopting mitigation devices (BRDs), implementing spatial or temporal closures, or deciding where to establish new

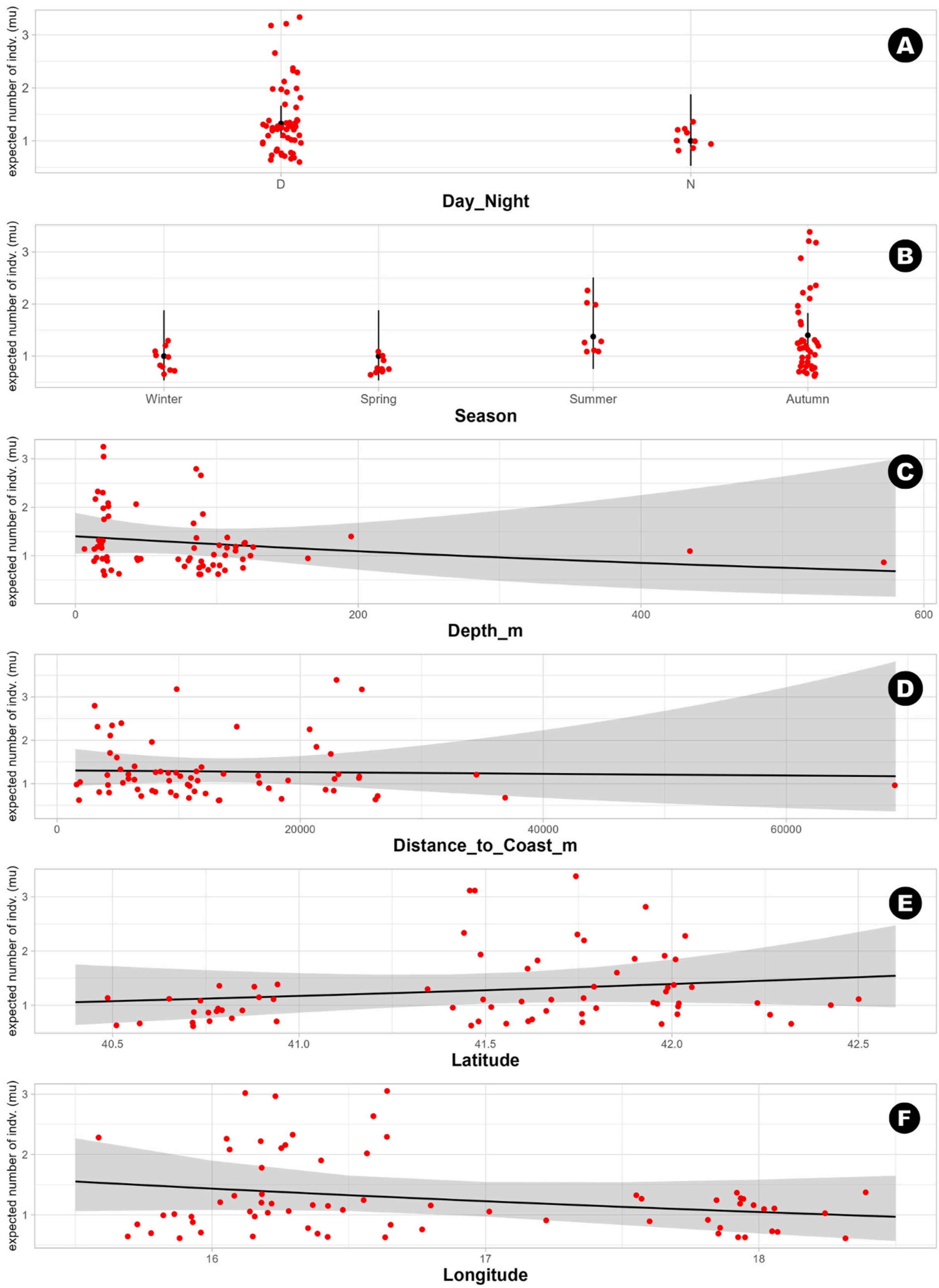

Fig. 3. Predicted number of loggerhead sea turtles (*Caretta caretta*) bycaught in bottom trawls by A) time of the day (day *vs* night), B) season, C) mean depth of the haul (m), D) distance from the coast (m), E) latitude (°) and F) longitude (°). Black dots are the predicted value for categorical factors, grey shaded regions indicate the 95 % confidence intervals, red dots are the observed number of sea turtles without zeros. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Pearson Correlation matrix of the numerical explanatory variables, distance from the coast, depth, latitude and longitude. Correlated variables (r > 0.5 as absolute value) are highlighted with an asterisk (*).

	Distance from the Coast	Depth	Latitude	Longitude
Distance from the coast	1.000			
Depth	0.549*	1.000		
Latitude	0.072	−0.298	1.000	
Longitude	0.066	0.625*	−0.896*	1.000

recovery facilities. However, in several countries of the Mediterranean basin, data on the incidental catch of vulnerable species are either absent or not fully available, and in general, the systematic collection of these data is poorly implemented (Carpentieri et al., 2021). Incidental captures are not consistently recorded or reported (e.g. (ICES, 2019; ICES, 2020)), and observer programs often cover only a small portion of the fleet in terms of number of vessels, time and location. For these reasons, despite bycatch being one of the most important threats to marine ecosystems and biodiversity — particularly in the Mediterranean basin, a biodiversity hotspot (Coll et al., 2010; Ligas, 2019; Costello et al., 2010; Granger et al., 2015) —, studying incidental catch rates of ETP in this region is particularly challenging (Carpentieri et al., 2021; Ligas, 2019).

The primary reasons for these shortcomings are the complexity and high costs associated with monitoring. Typically, data on the incidental catch of vulnerable species, along with some biological information, is gathered through on-board observers. However, observer programs can be inconvenient for fishers. They require an extra person (or people) on the vessel, taking up valuable deck space. In some artisanal vessels, there is simply no room for an on-board observer. Furthermore, the observer's activities, such as measuring, weighing, and recording information, are outside the scope of normal fishing practices, interfering with and taking time from the fishing activity. These factors result in limited willingness from the fishers in participating and collaborating with observers' programs. Due to these factors, fleet observer programmes can only guarantee relatively low coverage in terms of fishing days. Therefore, to increase the number of observations and improve bycatch estimates, complementary strategies have been proposed and applied to supplement the data obtained through on-board observers with other observation methods. These include fishery dependent (self-sampling monitoring or logbook, interviews) or fishery independent methods (surveys with research vessel or chartered vessel, stranding data). The combination of multiple sources of observations is crucial to achieve a wider spatial/temporal coverage, a minimum level of monitoring and to obtain a more complete and robust picture of the bycatch situation (FAO, 2019; Coll et al., 2010).

Given that monitoring these capture events is complex and costly, especially since bycatch events are generally rare, it is essential to concentrate sampling efforts on the specific gears, areas, and seasons where issues are known to exist.

The statistical models adopted in this study made it possible to characterize the bycatch problem in the region, both temporally and spatially, identifying two bycatch hotspots in the west-south Adriatic. These areas are likely to become increasingly important bycatch hotspots in the context of climate warming that is driving an expansion of the species north and west in the Mediterranean basin (Hochscheid et al., 2022; Mancino et al., 2022; Pietroluongo et al., 2023). New nesting sites (more than 50 nests; https://tartapedia.it/) have been recently reported precisely in the areas covered by this study. In more detail, the drivers examined by GLM that showed significant correlations with the probability of bycatch occurrence included time (day/night), season, distance from the coast, depth, and geographic factors such as latitude and longitude, which are further discussed hereafter.

The frequency of bycatch events seemed significantly higher during the day than at night. This result could be linked to the higher fishing activity during the day and the sea turtle's vertical movement pattern during the stationary foraging period characterized by prolonged immersion during the day (Storch et al., 2003). A daily pattern of activity and use of the seabed has already been described both inside (Houghton et al., 2002) and outside the Mediterranean Sea (Storch et al., 2003). These studies reported different sea turtle behaviour movements between nighttime resting on the surface or mid-water and daytime foraging on the bottom (Houghton et al., 2002; Ogden et al., 1983). Measurements of energy expenditure during immersion confirmed a different daily pattern with diel feeding activity and nocturnal resting (Storch et al., 2003). Additionally, loggerhead turtles benefit from spending time on the seabed to seek foraging opportunities. By adjusting the amount of air inhaled to the depth to which they intend to dive, a turtle may remain neutrally buoyant for much of the dive time (Houghton et al., 2002). This explains the positive relationship between depth and duration of dives observed for *C. caretta* (Houghton et al., 2002). However, this behaviour, whereby turtles remain on the bottom for a longer time during the day, maximizes the possibility of capture by bottom trawling, which is generally carried out during daytime in the

Table 4
Main results of the GAM tested models. The numerical explanatory variables used are distance from the coast (DC), depth (D), latitude (Lat) and longitude (Long). The factorial explanatory variables are season (S) and day/night (D/N). Significance of the smoothers (sign.) on explanatory variables, explained deviance (in percentage), the adjusted r-squared (R^2) and Akaike Information Criterion (AIC) as performance metrics are reported. The final best model is indicated in bold.

Tested Model	Formula	D/N sign	S sign.	DC sign.	D sign.	Long/Lat sign.	Deviance explained	R^2	AIC
family = Tweedie log link function	BI ~ factor (D/N)	<0.05	–	–	–	–	17.1	0.068	31.757
family = Tweedie log link function	BI ~ factor (S)		<0.05	–	–	–	25.5	0.117	28.105
family = Tweedie log link function	BI ~ s(DC)	–	–	<0.05	–	–	14.8	0.089	35.08
family = Tweedie log link function	BI ~ s(D)	–	–	–	<0.05	–	39.6	0.262	12.224
family = Tweedie log link function	BI ~ s(Long,Lat)	–	–	–	–	<0.05	38.7	0.336	28.591
family = Tweedie log link function	BI ~ s(D) + s(Long,Lat)	–	–	–	<0.05	<0.05	39.6	0.262	12.224
family = Tweedie log link function	BI ~ s(D) + factor(S)	–	>0.05	–	<0.05	–	46.5	0.291	9.255
family = Tweedie log link function	BI ~ s(D) + factor(D/N)	<0.05	–	–	<0.05	–	47.8	0.3	3.842
family = Tweedie log link function	**BI ~ s(D) + factor(D/N) + s(Long, Lat)**	<0.05	–	–	<0.05	<0.05	53	0.313	2.424

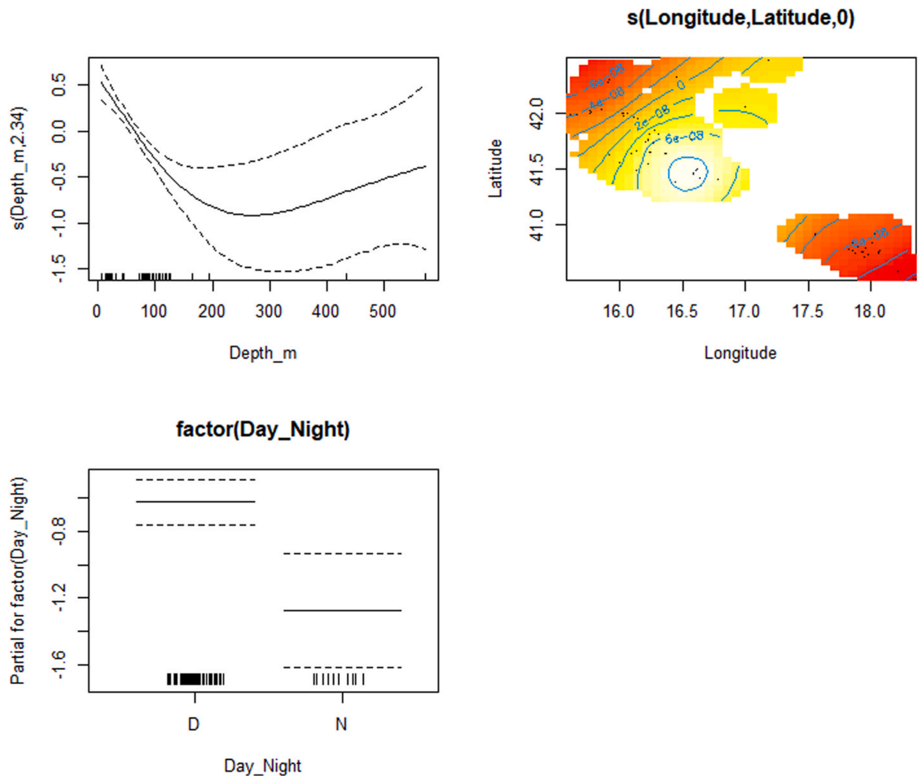

Fig. 4. On the left, splines of the Tweedie GAM model used to describe the partial effects of depth and day/night factor on the bycatch index (number of specimens/durations of the trawl haul). Dotted lines designed an area representing the 95 % confidence intervals, while notches on x axis are the observations. On the right, bidimensional splines of the Tweedie GAM model used to describe the spatial distribution of bycatch index (number of specimens/durations of the trawl haul). The continuous colour ranges from red (lower values) to yellow (highest values). Latitude and Longitude are expressed in decimal degrees. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Mediterranean Sea and in particular in the Adriatic basin (Coro et al., 2023; Maiorano et al., 2019).

The CCL of loggerhead turtles caught by bottom trawlers observed in this study primarily include juvenile and subadult specimens. Considering 80 cm as the average size at maturity in the Mediterranean Sea (Casale, 2011), only 20 % of the loggerhead sea turtles bycaught by bottom trawl can be considered adults (age >20 years). Most captures involve specimens with a CCL of 50–55 cm (about 6 years of age (Casale, 2011);). In the same area, Carbonara et al. (2023) reported, for pelagic longline targeting swordfish in the summer period, similar results in terms of loggerhead turtle CCL, with a bulk of length frequency distribution around 40–50 cm (juveniles and sub-adults) and only a few adult specimens with a CCL >80 cm. The different length classes are generally also linked to different phases of the biological cycle. In fact, the loggerhead turtle has a complex life cycle with characteristic ontogenetic habitat feeding shifts (Mariani et al., 2023; Casale et al., 2008, 2012a). After the hatchlings reach the sea, the oceanic phase begins, and they head to the open sea where they spend most of their juvenile stage - with a CCL not exceeding 50 cm (Tomas et al., 2001; Bjorndal et al., 2000) - primarily feeding on pelagic prey due to their limited diving capacity (Bolten, 2003; Luschi and Casale, 2014; Casale et al., 2008). After the juvenile oceanic phase, a transitional phase to the subadult stage (CCL about 50–60 cm) follows, where sea turtles use both oceanic and neritic habitats (Palmer et al., 2021). Sea turtles then start frequenting more benthic habitats, moving closer to neritic areas and adapting their feeding strategy (Casale et al., 2008). Once they reach the adult stage and become sexually mature (CCL >80 cm), they can be found in neritic areas, feeding mainly on benthic organisms (Margaritoulis et al., 2003; Bjorndal et al., 2000; Lazar et al., 2011). Following this life cycle pattern, the sub-adults and adults, which comprise the majority of turtles caught by bottom trawl in South Adriatic (Fig. 2), mostly visit the coastal area for feeding purposes (Mariani et al., 2023; Casale and Simone, 2017).

Several authors (Coro et al., 2023; Maiorano et al., 2019; Ferrà et al., 2018), using AIS data from trawling vessels, have highlighted how trawling fishing effort in this Mediterranean area is concentrated in coastal waters and shallow depths. Moreover, considering that according to the EU reg 1696/2006 (for the Italian fleet starting from 1968), the use of towed gears is prohibited within 3 nautical miles of the coast or within the 50 m isobath where that depth is reached at a shorter distance from the coast. The distribution range of the species described above overlaps with trawling areas mostly in the areas where the shelf is large and the shallow waters (depth <50 m) are present also with distance from the coast >3 miles. As observed in the Northern Adriatic (Lucchetti et al., 2019), this overlap effectively explains the high bycatch rates observed at shallow depths and near the coast in the present study especially in the north part of study area (Figs. 3 and 5). Indeed, recently Li Veli et al. (Li et al., 2024) assessed the bycatch vulnerability of sea turtle by Productivity Susceptibility Analysis categorizing the OTB sea turtle bycatch vulnerability of whole Adriatic Sea (Northern and Southern) with a high score.

Autumn and summer are the seasons with the highest bycatch rates, which seems to correspond with the migration patterns of loggerhead turtles (Fig. 3). Casale et al. (2012a), following the migration pattern of *C. caretta* in the Adriatic Sea over a complete year cycle, observed southward migration along the western side in late summer/autumn and a northward return in spring to the same site, following a route along the eastern Adriatic coast. In the Mediterranean basin, cold winter temperatures (below 13 °C) seem to induce turtles to move southwards, where temperatures are warmer before winter (Luschi and Casale, 2014; Casale and Simone, 2017; Casale et al., 2012a). However, not all *C. caretta* follow this southward migration pattern during the winter. In

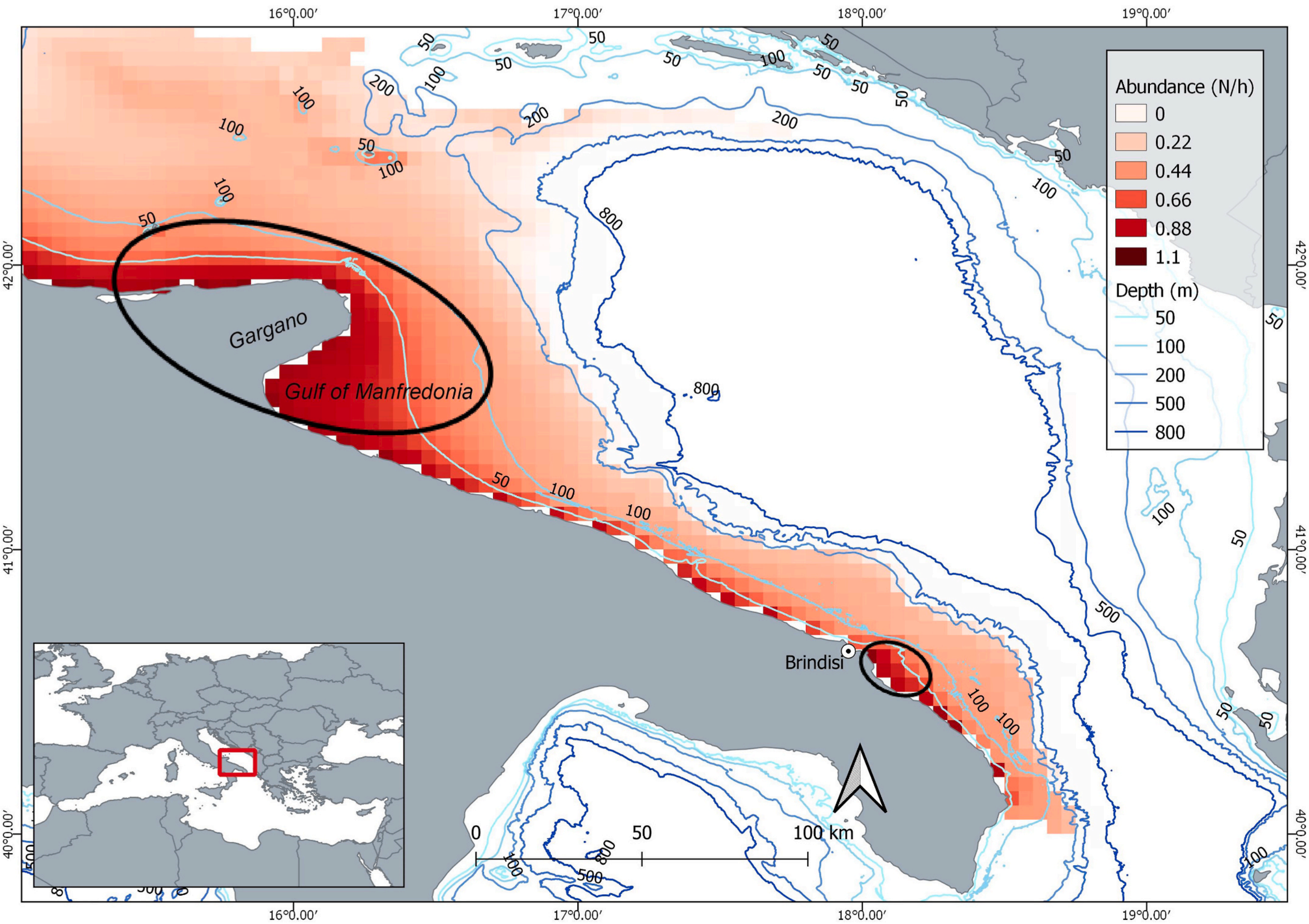

Fig. 5. In the bottom-left rectangle the position of the study area within the Mediterranean basin is highlighted (red square). The main map represents the spatial distribution of the bycatch index (number of *Caretta caretta* individuals [N] per duration of the trawl haul [h]; i.e. abundance). The black circles indicate the areas with the highest bycatch indices: one located around the Gargano promontory (upper black circle), and another off Brindisi (lower black circle). Bathymetry layer source: (EMODnet, 2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

some cases, adult specimens have been observed maintaining activity at temperatures around 11 °C, adopting a behavioural strategy known as overwintering (Hochscheid et al., 2007). The Adriatic hosts sub-adult and adult loggerhead turtles migrated from nesting sites in Greece, Turkey and Cyprus after egg deposition (Hays et al., 1991; Lazar et al., 2004; Zbinden et al., 2008, 2011). Moreover, in the Adriatic, not only adults but also juveniles, likely arriving from these rookeries, are permanent or at least seasonal residents, mostly in late summer/autumn (Casale and Simone, 2017; Casale et al., 2012a). Thus, our results appear to be supported by the migration pattern of turtles across the Adriatic Sea, indicating a seasonal concentration of both sub-adults and adults in the southwestern part of the Adriatic during the autumn.

The mapping of bycatch event (GAM analysis) highlighted two areas with a higher bycatch rate: one around the Gargano promontory and one to the south off Brindisi (Fig. 5). The area around the Gargano promontory is already recognized as an important foraging area for both juvenile and adult loggerhead turtles (Casale and Simone, 2017). It is interesting to note that juvenile sea turtles in this area show a higher resident behaviour compared to other Mediterranean locations (Casale and Simone, 2017). There is a general tendency for a progressive reduction of home ranges with a gradual shift from a pelagic juvenile phase to a benthic sedentary lifestyle typical of the adult phase (Zbinden et al., 2011). The very small home ranges observed in that area seem to be associated with local conditions, such as very shallow coastal waters with probable availability of benthic preys (Casale and Simone, 2017; Casale et al., 2012b). Moreover, the two areas identified in this study with higher bycatch rates coincide with areas previously identified as suitable habitats for *C. caretta*, considering several environmental parameters (e.g. sea surface temperature, chlorophyll concentration, particulate organic carbon) (Zampollo et al., 2022).

5. Conclusion

The two-stage models (GLM - hurdle models) applied in this study have proven to be a useful tools for modelling bycatch-related factors in the Mediterranean context. The modelling of loggerhead turtle bycatch data showed that bycatch in bottom trawl is mainly concentrated in shallow waters and coastal areas, is significantly higher during the day (corresponding to prolonged immersion for feeding) than during the night, and that autumn and summer appear to be the seasons with significantly higher numbers of sea turtle bycaught (likely due to migration patterns). The GAM modelling approach allowed for the identification of areas with higher bycatch indices, which could be very useful for effective protective actions. Indeed, the identification of these areas, as well as the identification of the part of the daytime (day) and the depth (within 50 m) that most affect the catch of loggerhead turtles, can be used to propose mitigation measures. Other factors should be further investigated and integrated in the analyses in order to better identify bycatch conditions, such as density of loggerhead turtle's preys or environmental variables or by considering inter-annual data.

As a conclusion, we believe that the statistical approach adopted can be applied to other regions to make the best use of collected data and characterize the bycatch problem. Given the rarity of bycatch events and the challenges and costs associated with monitoring efforts, this approach could prove beneficial in focusing sampling efforts on the particular gears, areas, and seasons where issues are known to occur.

CRediT authorship contribution statement

Pierluigi Carbonara: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, Formal analysis, Funding acquisition, Project administration, Resources, Validation. **Matteo Chiarini:** Formal analysis, Visualization, Writing – review & editing, Investigation, Methodology, Software, Validation. **Giovanni Romagnoni:** Writing – review & editing, Formal analysis. **Lola Toomey:** Writing – review & editing, Writing – original draft. **Alessandro Lucchetti:** Writing – review & editing, Validation. **Cosmidano Neglia:** Data curation, Investigation, Visualization, Writing – review & editing. **Maria Teresa Spedicato:** Writing – review & editing, Funding acquisition. **Walter Zupa:** Formal analysis, Methodology. **Amaia Astarloa:** Conceptualization, Formal analysis, Methodology, Writing – review & editing, Software, Supervision, Validation.

Funding

This research has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement number 101000318 (SEAwise). Moreover, the data used in this study were collected according to the Data Collection Framework (DCF), which is supported by the Italian Ministry of Agriculture, Food Sovereignty and Forestry (MASAF) and the European Commission (EU Regulations 1004/2017).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank all fishers from the ports of Manfredonia, Molfetta, Monopoli and Brindisi who collaborated in the data collection.

Abbreviations

AIC	Akaike Information Criterion
AIS	Automatic Information System
BI	Bycatch Index
BRDs	Bycatch Reducing Devices
CCL	Curved Carapace Length
EU-DCF	European Data Collection Framework
GAM	Generalized Additive Model
GLM	Generalized Linear model
GSA18	Geographical Sub Area 18
OTB	Bottom Otter Trawl
ETP	Endangered, Threatened and Protected

Data availability

Data will be made available on request.

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