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Fishery Bycatch of Sea Turtles in the Moroccan Western Mediterranean Sea: An Assessment Based on Interviews with Fishermen

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ABSTRACT

Sea turtle bycatch remains a major conservation concern in the Mediterranean Sea, where interactions with fisheries continue to threaten vulnerable species. Data on bycatch along the western Mediterranean coast of Morocco remain scarce. This study aims to assess sea turtle bycatch patterns using local ecological knowledge (LEK). Structured questionnaire-based interviews were conducted with 436 fishermen across twenty coastal locations. Fishermen reported 99 bycatch events over five years, which were extrapolated to approximately 450 annual events, resulting in an estimated 40 mortalities. *Caretta caretta* was the most frequently encountered sea turtle species (79.8%), followed by *Dermochelys coriacea* (20.2%). Bottom gillnets were identified as the most detrimental fishing gear (56.5%). Bycatch was spatially concentrated in central fishing grounds and peaked during the summer (67.7%). A random forest model identified fishing gear, fishing depth (m), boat length (m) and distance to shore (km) as the key factors influencing sea turtle bycatch. These findings highlight the significant threat posed by fisheries to sea turtle populations and emphasize LEK as a cost-effective approach and innovative tool for rapidly acquiring essential data on sea turtle bycatch, particularly in the Moroccan context.

INTRODUCTION

Fishing is both a vital cultural and subsistence activity for human societies **(Díaz *et al.*, 2018)**. Moreover, it is a major extractive pressure on marine ecosystems **(Pikitch *et al.*, 2004)**. Along the western Mediterranean coast of Morocco, it plays a key socio-economic role, involving around 3,599 fishers **(Maritime Fishing Delegation of Jebha, 2024; Maritime Fishing Delegation of Mdiq, 2024)**. A major ecological concern associated with fisheries is bycatch -the unintentional capture of non-target species, which exerts a significant anthropogenic pressure on marine megafauna such as sea turtles **(Hall *et al.*, 2000; Wallace *et al.*, 2000; Lewison *et al.*, 2004; Moore *et al.*, 2010)**. Both industrial and artisanal fisheries link bycatch to one of the leading sources of mortality **(Lewison & Crowder, 2007; Wallace *et al.*, 2010; Casale, 2011; Wallace *et***

***al.*, 2013a; Attum *et al.*, 2025)**. Mortality rates remain underreported in many regions **(Lewison *et al.*, 2004a)**, yet bycatch can generate cascading ecological effects and it is a global conservation priority **(Lewison *et al.*, 2004b; Estes *et al.*, 2011; Bradai *et al.*, 2025)**.

Sea turtles play key ecological roles by transferring nutrients and maintaining the stability of marine and coastal ecosystems, including coral reefs and seagrass bed **(Bouchard & Bjorndal, 2000; Lutz *et al.*, 2003; Hays *et al.*, 2025)**. In the Mediterranean Sea, three sea turtle species are present: the loggerhead (*Caretta caretta*), green turtle (*Chelonia mydas*), and leatherback (*Dermochelys coriacea*) **(Louhichi *et al.*, 2023)**. The western Moroccan Mediterranean coast functions as a migratory corridor for loggerheads and leatherbacks moving between the Atlantic and Mediterranean **(Camiñas & Valeiras, 2001; Casale *et al.*, 2003; Revelles *et al.*, 2007)**, leading to frequent interactions with fisheries **(Benhardouze *et al.*, 2012)**. Research conducted over recent decades indicate that this coastal zone serves as an important foraging and reproductive habitat **(Casale, 2008; Benhardouze, 2009; Aksissou *et al.*, 2010)**. Strandings confirm the occurrence of both species year-round **(Benhardouze, 2004; Ocaña *et al.*, 2006; Benhardouze, 2009; Mghili *et al.*, 2023; Hamiche *et al.*, 2025)**. Notably, both *C. caretta* and *D. coriacea* are classified as “Vulnerable” by the International Union for Conservation of Nature Red List **(Wallace *et al.*, 2013b; Casale & Tucker, 2017)**.

Onboard observer programs are considered the most reliable approach for quantifying bycatch **(Oliveira *et al.*, 2015)**. However, their implementation is costly and logistically challenging, notably in small-scale fisheries within developing countries, where research budgets are typically scarce **(Lewison *et al.*, 2004a; Moore *et al.*, 2010)**. In the absence of detailed logbook or ecological surveys, interviews with fishers provide valuable insights into bycatch levels **(Moore *et al.*, 2010)**. Local ecological knowledge (LEK) has become a key tool for informing conservation actions and fisheries management, offering cost-effective guidance for mitigation strategies and policy decisions **(Brook & McLachlan, 2008; Paudel *et al.*, 2016)**. Large-scale datasets derived from LEK are commonly obtained through structured or semi-structured community-based interviews **(Zappes *et al.*, 2016)**. In particular, LEK offers alternative perspectives on the spatial and temporal dynamics of bycatch, as it constitutes experiential knowledge accumulated by resource users without formal scientific training **(Davis & Wagner, 2003; Newing, 2011)**. Such surveys enable cost-effective data collection across broad regions and record experiential evidence from fishers regarding bycatch, thereby informing assessments in areas with limited scientific monitoring **(Richman *et al.*, 2014; Lin *et al.*, 2023)**.

Several research efforts have evaluated sea turtle bycatch in the Mediterranean, including studies conducted in Spain **(Alvarez de Quevedo *et al.*, 2010)**, Italy **(Lucchetti *et al.*, 2017)**, Greece **(Panagopoulou *et al.*, 2017)** and Tunisia **(Louhichi *et al.*, 2023)**.

However, recent data from the western Mediterranean coast of Morocco remain scarce, with only a few localized investigations reported to date **(Benhardouze *et al.*, 2012; Kaddouri *et al.*, 2018; Ahannach & Aksissou, 2023; El Arraf *et al.*, 2024)**. These recent Moroccan studies, have contributed valuable insights into bycatch patterns, yet remain geographically limited in scope. However, the paucity of information is particularly problematic in countries with low and middle incomes, where high marine biodiversity coincides with limited resources for monitoring bycatch dynamics **(Pilcher *et al.*, 2017; Hines *et al.*, 2020)**. Moreover, little is known about local community awareness and attitudes toward sea turtle conservation in this region. These knowledge gaps hinder the development of effective management strategies and highlight the urgent need for a more comprehensive evidence base for conservation planning in Morocco.

To address the lack of data on sea turtle bycatch in Moroccan waters, we conducted a community-based Local Ecological Knowledge (LEK) survey along the western Mediterranean coast. The study pursues four main objectives: (1) identify sea turtle species most affected by bycatch; (2) determine which fisheries and gear types contribute most to bycatch and mortality; (3) examine spatial and seasonal patterns of bycatch; and (4) analyze the factors influencing the probability of sea turtle bycatch occurrence.

MATERIALS AND METHODS

Study area

The study was carried across 20 coastal locations within three western Mediterranean provinces of Morocco: Chefchaouen, M'diq-Fnideq, and Tetouan. The study area extended geographically from Jebha (35°12′31.2″N, 4°39′54.6″W) to Fnideq (35°50′31.6″N, 5°21′12.7″W) (Fig. 1). These provinces were selected because fishing constitutes a central component of their local economies, with high dependence on fisheries-related commercial activities **(Ministry of Agriculture and Maritime Fisheries, 2023)**. The region supports both artisanal small-scale fisheries, primarily located in rural coastal villages, and large-scale industrial fisheries concentrated in major ports. To capture this diversity, the survey encompassed 18 villages and cities as well as two major ports.

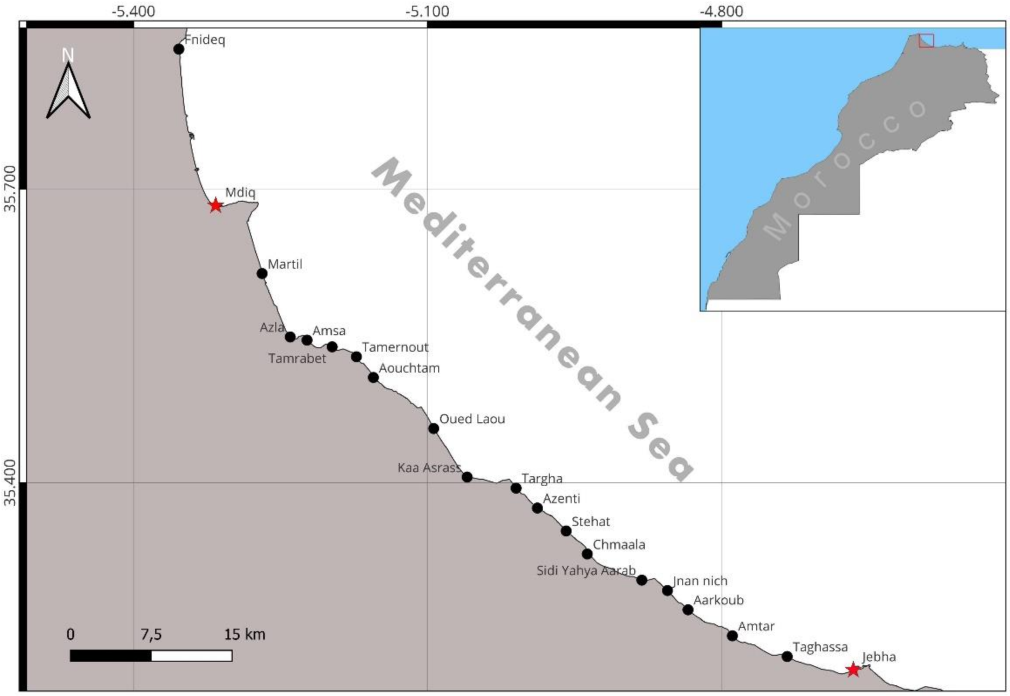

Fig. 1. Map of the 20 surveyed localities, including 2 fishing ports (red stars) and 18 fishing cities/villages (black circles), located along the western Mediterranean coast of Morocco

Survey design and data collection

Structured questionnaire-based interviews were conducted with 436 fishermen between April and September 2024. The survey included 41 mainly closed-ended questions, designed to collect quantitative and factual information. The questionnaire was divided into three sections: (i) socioeconomic characteristics (age, education, fishing experience, employment status); (ii) fishing effort and practices (annual fishing days, gear types, vessel characteristics (length, number of fishermen), approximate water depth and fishing grounds); and (iii) sea turtles interactions (bycatch events within the past five years, species involved, injuries and mortality, fate of captured turtles, and perceptions toward sea turtle conservation). Open comments on bycatch were also recorded as qualitative notes. To enhance species identification accuracy, fishermen were shown photographs of sea turtles to assess recognition ability. Interviews, lasting approximately 30-40 minutes, were conducted in fishing ports or on beaches near fishing communities.

Proportional sampling effort per port was weighed according to fleet size and activity using official statistics, based on data from the Ministry of Agriculture, Maritime Fisheries and Rural Development, local Maritime Fishing Delegations (Jebha and M’diq), and the National Fisheries Offices. These sources provided information on registered fishermen, fishing vessels, catch statistics, and fleet activities. A purposive and snowball sampling approach **(Babbie, 2013; Robinson, 2014)** was used, with experienced fishermen or gatekeeper, such as the president of the fishermen's association, facilitating access to respondents and recommending others based on expertise **(Campbell *et al.*, 2006)**. This referral process fostered rapport and participation **(Glain *et al.*, 2001)**, resulting in a robust and diverse sample. Eligible participants were professional fishers (≥18 years old) who had lived in the area for at least five years and relied on fishing as their primary income. Questionnaires were distributed during organized community events aligned to boat arrivals to optimize participation. Socioeconomic and non-sensitive questions were asked first to establish trust and encourage reliable responses. Only fully completed surveys were retained (eight incomplete interviews were excluded).

Data analysis

Twenty sites were analyzed to assess the spatiotemporal patterns of sea turtle bycatch between Jebha and Fnideq. Data were categorized by season: winter (December to February), spring (March to May), summer (June to August), and autumn (September to November). Chi-squared tests (χ^2) were used to examine spatiotemporal variations in bycatch frequency. Bycatch incidents were calculated as the proportion of respondents reporting bycatch events relative to the total number of interviews per location. The number of times respondents have caught each species over the previous five years was used to calculate the annual bycatch rate per species. In order to prevent memory problems and remove the randomness of the annual variation, we selected the last five years as the time frame. Bycatch per unit of effort (BPUE) and fishing effort were used to estimate annual bycatch and mortality levels. Fishing effort per gear type expressed as fishing days·year^{-1}, followed the workflow described in the Bycatch Data Processing and Analysis Flowchart (Fig. 2). Since each fishing vessel was associated with a single dominant main gear type, BPUE was defined as the mean number of bycatch events per boat per year (± SD) across five-year period. Mortality rate was calculated as the ratio of dead sea turtles to the total bycatch for each species, gear type and location. Total bycatch estimates were calculated by multiplying BPUE by fishing effort, whereas the estimates of mortality were derived by multiplying the bycatch estimates by the documented mortality rates per gear type. The impact of fishermen knowledge and environmental conditions on bycatch likelihood was determined by applying a Random Forest model. Eight predictor variables and one binary response variable (bycatch: yes/no) were used: gear type, depth, boat length, distance to shore, fisher age, years of fishing experience, annual fishing days, and location. Five hundred trees were generated using bootstrapped samples or in-bag, with out-of-bag estimates employed for model validation. The importance of each predictor variable was assessed by the mean decrease in accuracy and increase in mean squared error when predictors were excluded **(Biau & Scornet, 2016)**. The most influential predictors were explored using partial dependence plots (PDPs) to visualize their effects on bycatch probability **(Breiman, 2001)**. Analyses were conducted in R version 4.5.1 **(R Core Team, 2021)** using Random Forest model, and ggplot2 packages, with significance set at α = 0.05.

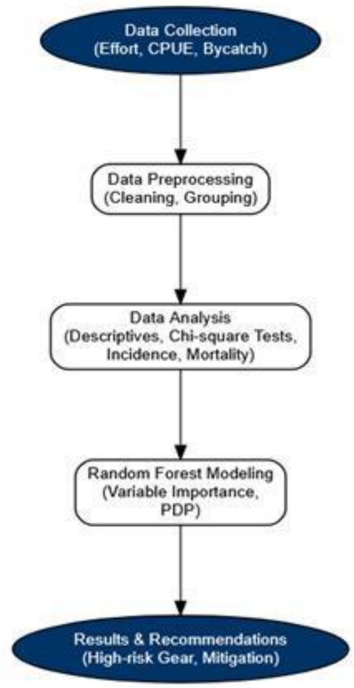

Fig. 2. Flowchart of the bycatch data processing and analysis workflow

RESULTS

Characteristics of fishers and their fishing activity

In total, 436 respondents were interviewed with the following distribution: Mdiq (n = 77), Martil/Azla (n = 64), Jebha (n = 59), Chmaâla (n = 40), Kaâ Asrass (n = 27), Amtar (n = 26), Targha (n = 22), Fnideq (n = 22), Oued Laou (n = 20), Amsa (n = 16), Aouchtam (n = 12), Jnan Nich (n = 11), Tamernout (n = 10), Sidi Yahya Aarab (n = 8), Steha (n = 6), Azenti (n = 5), Tamrabet (n = 4), Taghassa (n = 4), Aarkoub (n = 3), and all respondents were male. Women were primarily involved in the making and repair of nets, rather than in fishing activities. The mean age of respondents was 43.6 years (SD = ± 11.8, range = 22–65), with an average of 23.7 years of fishing experience (SD = ± 11.9, range = 5–48). The majority of fishermen had limited or low levels of education (n = 390, 89.45%). In terms of educational level, 6.2% (n = 27) had completed secondary school, 3% (n = 13) had completed high school, and only 1.4% (n = 6) had received higher education. The majority of respondents (n = 365, 83.7%) were full-time fishers, while 10.6% (n = 46) were part-time fishers, and 5.7% (n = 25) worked seasonally. The most commonly reported fishing gear was the bottom gillnet, typically used with small-sized vessels (n = 110, 25.23%), followed by longlines (n = 105, 24.1%), trammel nets (n = 93, 21.3%), and purse seines (n = 80, 18.34%). Other reported gear types included trawls (n = 12, 2.75%), beach seines (n = 16, 3.7%), and handlines (n = 20, 4.6%). The mean reported water depth was 49.2 meters (SD = ± 33.8). Based on the responses of fishermen, the majority of their target species have decreased over time, accounting for 70.8%, followed by 20% reporting that the numbers have stayed the same, and only 9.2% indicating that the numbers have increased.

Fishing effort by gear type

According to records from the Maritime Fishing Delegation of Jebha and Mdiq, a total of 1,015 artisanal boats operated in the two surveyed provinces in 2024, representing 44.8% of the whole Mediterranean fishing fleet. Additionally, seining vessels accounted for 23.3% (n = 24) of the fleet, trawling vessels for 8.9% (n = 16), and longlining vessels for 4.6% (n = 6). Annual fishing effort varied significantly across different gear types. The highest efforts were recorded for trawls, with an average of 175.71 ± 38.23 days/year, followed by purse seines at 170.85 ± 42.62 days/ year. Bottom gillnets (154.08 ± 40.76 days/ year) and longlines (142.17 ± 48.94 days/ year) exhibited intermediate fishing efforts, while trammel nets had the lowest effort, with only 122 ± 28.64 days/ year.

Bycatch per unit of effort (BPUE) by species and gear type

Analysis of the bycatch per unit effort (BPUE) over five years revealed that *C. caretta* was caught more frequently than *D. coriacea* across all gear types. For *C. caretta*, the highest number of bycatch events was recorded in bottom gillnets (n = 46), trawls (n = 16) and purse seines (n = 10), with average BPUE values of 0,44 turtles/vessel/year (SD = ± 0.23), 0.53 turtles/vessel/ year (SD = ± 0.3) and 1 turtle/vessel/ year respectively. In contrast, trammel nets and longlines had fewer bycatch events (5 and 2, respectively), with slightly lower BPUE values of 0.5 turtle/vessel/ year (SD = ± 0.14) and 0.4 turtle/vessel/year respectively. For *D. coriacea*, bottom gillnet (n = 10) recorded an average BPUE at 0.67 turtle/vessel/year (SD = ± 0.12). Other gear type, such as purse seines (0.4 turtle/vessel/year, SD = ± 0.23), also contributed to bycatch, though with slightly lower BPUE values. The number of vessels involved in bycatch events was generally higher for *C. caretta* than for *D. coriacea*. BPUE variability (standard deviation) remained moderate for both species, suggesting a relatively consistent catch rate per vessel.

Bycatch estimates of sea turtle species and the impact of fishing gear

A total of 99 bycatch events were recorded over the past five years. Analysis of the bycatch distribution revealed a significant interspecific imbalance (Fig. 3): *C. caretta* accounted for 79.8% (n = 79) of the bycatch, while *D. coriacea* comprised 20.2% (n = 20). Bottom gillnets were the most common gear type associated with bycatch events of

C. caretta, reported by 46 respondents, and accounting for 58.2% of the 99 events. Bycatch was also reported in purse seines (12.7%, n = 10) and trawls (20.3%, n = 16). In contrast, *C. caretta* bycatch in trammel nets accounted for only 6.3% (n = 5), and in longlines, it represented 2.5% (n = 2). For *D. coriacea*, the bycatch distribution varied across different gear types: bottom gillnets accounted for 50% (n = 10) of the incidents and purse seine represented also 50% (n = 10). While trammel nets, trawls and longlines were not associated with any bycatch of this species (Fig. 4). The fishing fleet operating in Morocco's western Mediterranean coast is therefore estimated to cause 449.6 annual bycatch of *C. caretta* and 171.6 of *D. coriacea* (Table 1).

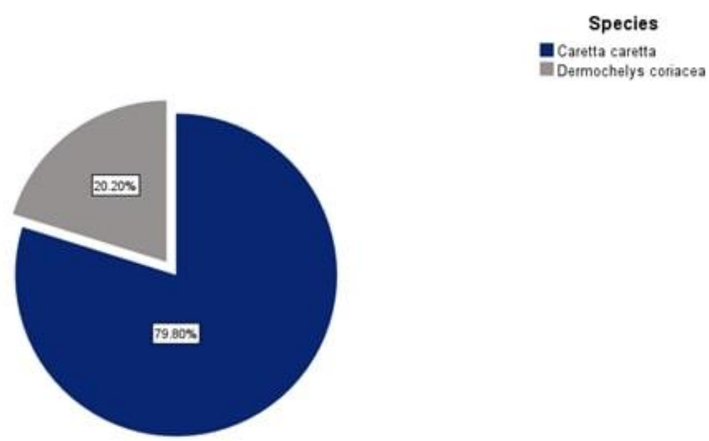

Fig. 3. Species composition of sea turtle bycatch

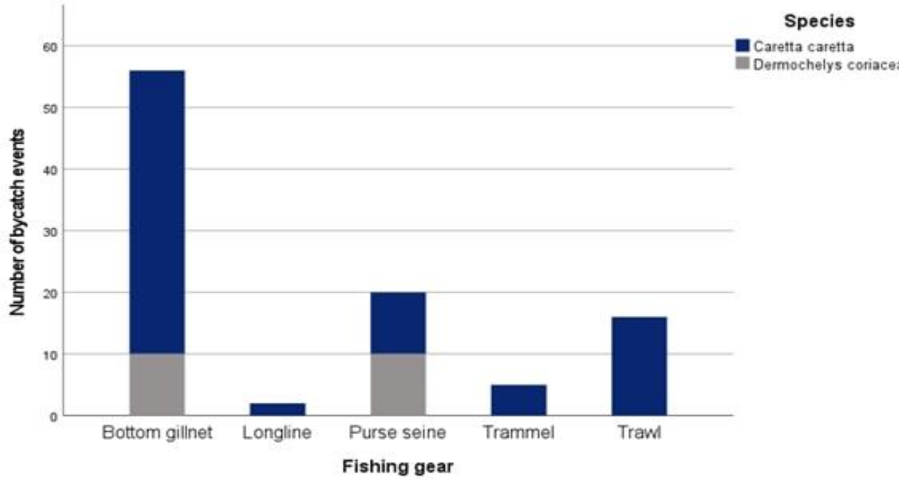

Fig. 4. Species-specific composition of *Caretta caretta* and *Dermochelys coriacea* bycatch across different types of fishing gears

Table 1. Total number of bycatch events, mean BPUE (expressed as events per boat per year), and estimated bycatch and mortality of *Caretta caretta* and *Dermochelys coriacea* across different fishing gears, recorded over the last five years in the Moroccan western Mediterranean coast

Sea turtle species	Fishing gear	Total events	Per/year	Mean BPUE ± SD	Median CPUE	Bycatch estimate	Mortality estimate
Caretta caretta	Bottom gillnet	46	9.2	0.44 ± 0.23	0.4	67.79	33.89
	Longline	2	0.4	0.4	0.4	56.86	0
	Purse seine	10	2	1	1	170.85	0
	Trammel	5	1	0.5 ± 0.14	0.5	61	0
	Trawl	16	3.2	0.53 ± 0.3	0.4	93.12	46.65
Dermochelys coriacea	Bottom gillnet	10	2	0.67 ± 0.12	0.6	103.23	0
	Purse seine	10	2	0.4 ± 0.24	0.4	68.34	0

CPUE = Bycatch Per Unit Effort; SD = Standard Deviation

Spatio-temporal variation in sea turtle bycatch

Spatiotemporal variation was observed in the reports of the most recent bycatch events for both sea turtle species. Seasonal variation in sea turtle bycatch was highly significant ($\chi^2 = 110.74$, df = 3, $P< 0.001$), with the majority of events occurring in summer (n = 67, 67,7%) and spring (n = 26, 26.3%). Fewer events were recorded in autumn (n = 5, 5.1%) and winter (n = 1, 1%). *C. caretta* was the dominant species year-round, comprising 68.4% (n = 54) of catches in summer, 25.3% (n = 20) in spring, and 6.3% (n = 5) in autumn (Fig. 5). In contrast, *D. coriacea* was also recorded in summer (65%, n = 13), spring (30%, n = 6) and winter (5%, n = 1). The distribution of sea turtle bycatch varied significantly across locations ($\chi^2 = 242.52$, df = 18, $P < 0.001$), with some areas exhibiting much higher capture rates than others. Sea turtles were recorded in the most of locations, with the highest number of bycatch events occurring in Martil (n = 18, 18.2%), followed by Mdiq (n = 12, 12.1%), Oued laou (n = 10, 10.1%), Jebha (n = 10, 10.1%), and Amtar (n = 9, 9.1%). Other locations with notable bycatch included Amsa and Fnideq (n = 7, 7.1%), Targha (n = 6, 6.1%), Kaa Asrass (n = 5, 5.1%), Aouchtam and Chmaala (n = 4), Jnan nich, Sidi Yahya Aarab (n = 3) and Azenti (n = 1). The remaining locations, including Azenti, Sidi Yahya Aarab and Jnan nich together accounted for 7% of the total bycatch (Fig. 6A).

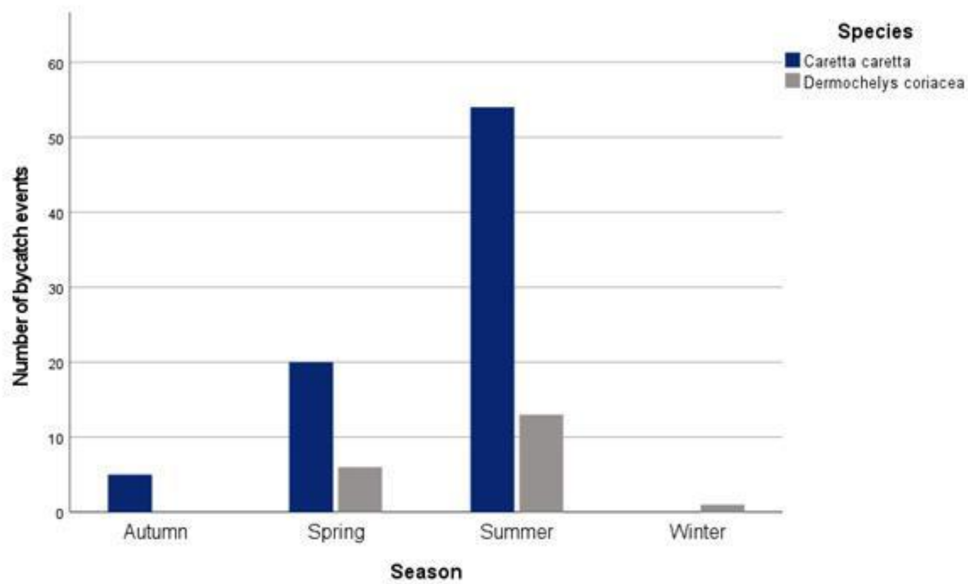

Fig. 5. Seasonal variation in the species composition of sea turtle bycatch

Status of sea turtle bycatch

The results demonstrate differences in the distribution of bycatch based on both the type of gear used and the condition of the turtles at the time of capture. Of the recorded bycatch, 38.38% (n = 38) were alive and uninjured, 29.29% (n = 29) were alive but injured, and 32.32% (n = 32) were dead. A total of 56 bycatch events in bottom gillnets revealed that the proportion of injured live turtles remained high (41.1%, n = 23). However, 17 sea turtles were alive and uninjured (30.4%), and mortality reached 28.57% (n = 16). In longlines bycatch, only one status was displayed, with 2 injured turtles. Purse seines had a high proportion of uninjured live turtles (80%, n = 16), followed by live, injured turtles (20%, n = 3). Trammel nets showed only uninjured live turtles (n = 5), with no observed mortality. Finally, trawls recorded 16 mortalities, with no observed live, injured and uninjured sea turtles (Table 2). The majority of respondents (72%, n = 72.7) indicated that they would take action to release the live individual, while 20% (n = 19.19) would opt to inform the local fisheries administration. A smaller proportion (8%, n = 8) would choose to discard the deceased individual.

Table 2. Status of bycaught sea turtles (*Caretta caretta* and *Dermochelys coriacea*) by fishing gear type

Sea turtle species	Fishing gear	Sea turtle status	N	%
Caretta caretta	Bottom gillnet	Alive injured	19	24
		Alive not injured	11	13.9
		Dead	16	20.3
	Longline	Alive injured	2	2.5
	Purse seine	Alive not injured	9	11.4
		Alive injured	1	1.3
	Trammel	Alive not injured	5	6.3
	Trawl	Dead	16	20.3
Dermochelys coriacea	Bottom gillnet	Alive injured	4	20
		Alive not injured	6	30
	Purse seine	Alive injured	3	15
		Alive not injured	7	35

Sea turtle mortality

Across all gear types, the overall mortality rate was 32.3% (n = 32). Mortality rates depend on the fishing gear type utilized. The mortality of *C. caretta* and *D. coriacea* was analyzed for each fishing gear type. *C. caretta* accounts for the entirety of the mortality rate. Both bottom gillnets (n = 16) and trawl (n = 16) recorded the same number of incidents, with an overall mortality rate of 16.2% of each of them. No mortality was recorded in longlines, purse seines and trammels. In contrast, no mortality was observed for *D. coriacea*. The fishing fleet operating in Morocco's western Mediterranean coast is therefore estimated to cause an annual mortality estimates of 80.5 events for *C. caretta* (Table 1). The mortality rate of captured sea turtles exhibited notable spatial heterogeneity, with the highest rate observed in Amtar and Fnideq (18.75%, n = 6 for each location), followed by Aouchtam, Oued laou, Jebha (12.5%, n = 4 for each location), and Kaa Asrass (9.37%, n = 3). The lowest mortality rate was observed in Amsa, Martil (6.25%, n = 2 for each location), and Chmaala (3.12%, n = 1). In contrast, certain areas, including M'diq, Stehat, Sidi Yahya Aarab, and Aarkoub, Azenti, Jnan nich, Targha, Taghassa, Tamrabet and Tamernout reported no mortality (Fig. 6B).

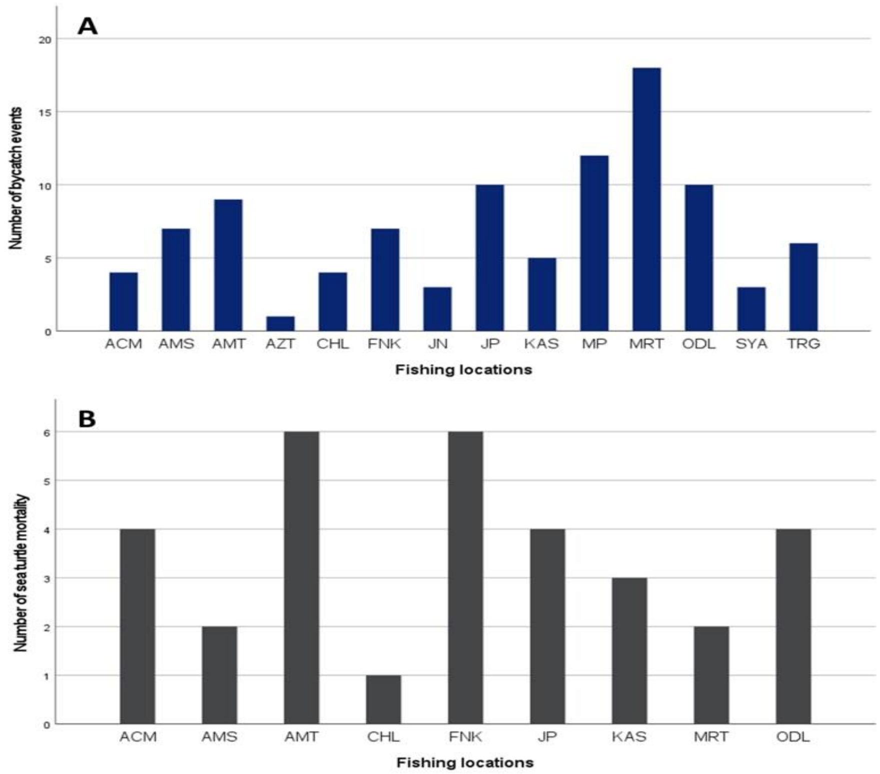

Fig. 6. Variation in the number of sea turtle bycatch events (A) and mortalities (B) across surveyed fishing locations. (ACM: Aouchtam, AMS: Amsa, AMT: Amtar, AZT: Azenti, CHL: Chmaala, FNK: Fnideq, JN: Jnan nich, JP: Jebha port, KAS: Kaa Asrass, MP: Mdiq port, MRT: Martil, ODL: Oued laou, SYA: Sidi Yahya Aarab, TRG: Targha)

Patterns and factors influencing sea turtle bycatch

The Random Forest model (500 tree; OOB error = 0.21; AUC = 0.83) identified fishing gear, boat length (m), fishing depth (m), distance to shore (km) and location as the main predictors of bycatch probability (Fig. 7). Sociodemographic and operational factors, including the fishermen's age, contributed secondarily. In contrast, fisherman's experience and the number of fishing days per year had a minimal impact on bycatch patterns. The effect of the tree explanatory variables (boat length, water depth and distance to shore) was examined using partial dependence plots to identify the optimal values associated with increased sea turtle bycatch probability. The analysis shows that the probability of bycatch varies non-linearly according to these variables. In terms of boat length, the probability of catching turtles is relatively high for smaller vessels, then decreases for intermediate lengths (approximately 5 to 10m), before stabilizing at around 0.53–0.55 for larger boats. This suggests that smaller boats present a slightly increased risk of bycatch. With regard to fishing depth, the probability of bycatch is initially moderate, increases sharply at intermediate depths, and then stabilizes at higher values (Fig. 8). This profile indicates that certain depth ranges, possibly corresponding to habitats frequented by sea turtles, are associated with a higher risk of accidental capture. Finally, in terms of distance to shore, the risk of bycatch remains relatively low for short distances, then increases almost exponentially beyond 10km, reaching probabilities greater than 0.65. This result could reflect the fact that fishing operations further from the coast, in areas more frequented by turtles or less monitored, increase the probability of bycatch.

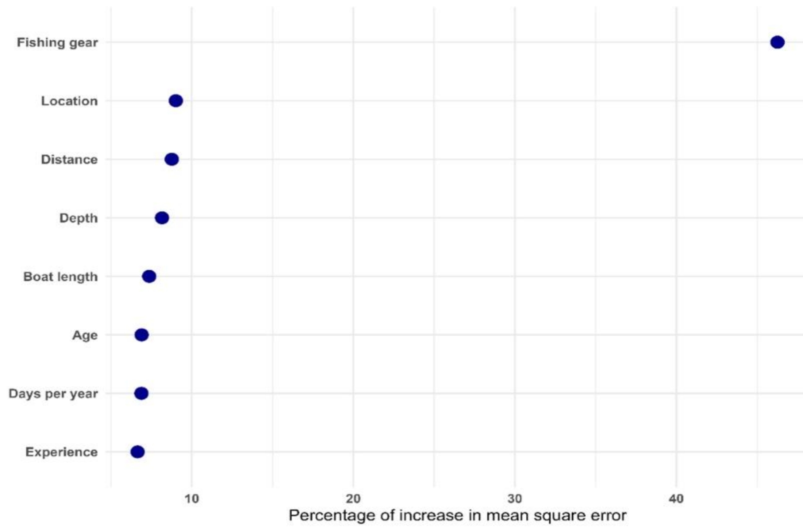

Fig. 7. Importance ranking of explanatory variables used to investigate sea turtle bycatch events, measured by the percentage increase in the mean squared error (MSE) of the Random Forest (RF) model after permuting each variable

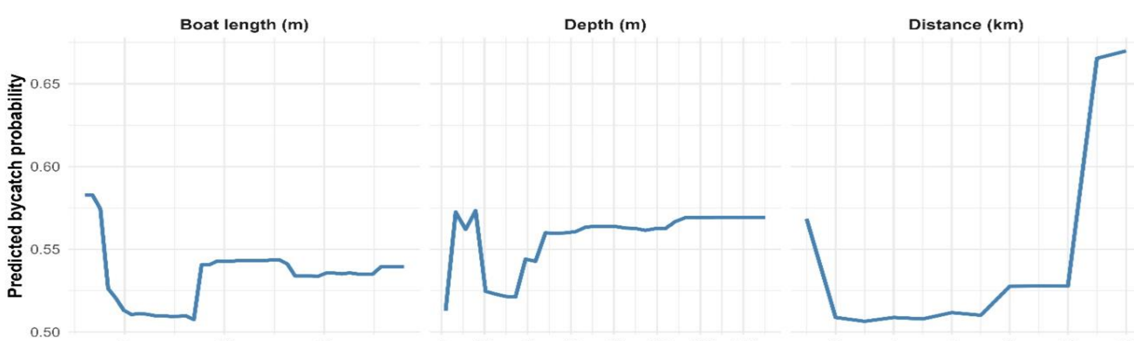

Fig. 8. Univariate partial dependence plots of three explanatory variables (boat length, water depth, and distance to shore) estimated using the Random Forest (RF) model for sea turtle bycatch

`The results indicate a significant variation in the probability of bycatch depending on the type of fishing gear used. The random forest model predicted that longlines have the highest probability of bycatch (0.4), suggesting that nearly 40% of fishing operations with this gear result in an interaction. However, this metric of probability must be interpreted alongside fishing effort to assess overall impact. While, bottom gillnets have the lowest probability, at only 0.15, indicating a much lower risk of catching sea turtle species. Other gear types showed intermediate probabilities: trammel net (0.33), trawl (0.28) and purse seine (0.22) (Fig. 9). This analysis reveals a critical distinction: longlines pose the highest unit risk, but the extensive use of bottom gillnets makes them the source of the greatest cumulative impact on sea turtles in the region.

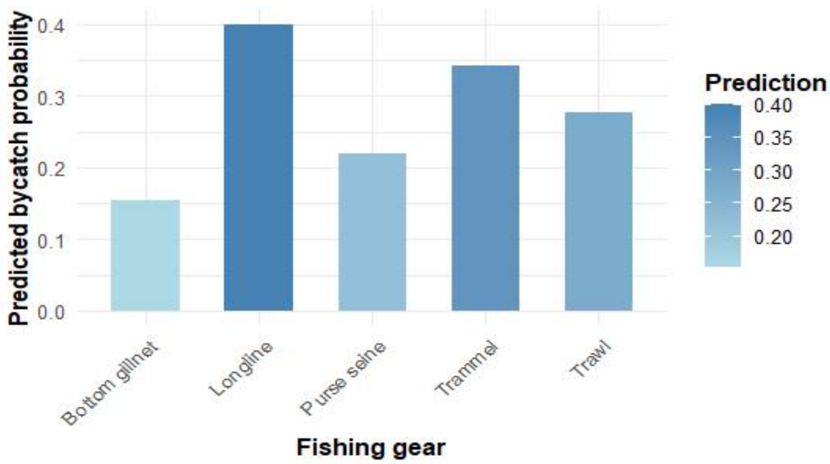

Fig. 9. Model-predicted bycatch probabilities for sea turtles according to fishing gear type

DISCUSSION

The study aimed to gather datasets concerning sea turtle bycatch, the risks associated with fishing gear, and the seasonal and spatial patterns of bycatch through questionnaire-based interviews with fishermen. The goal was to establish new baselines for conservation priorities, enhancing the understanding of sea turtle bycatch in Morocco's western Mediterranean, a region known for its rich marine biodiversity and significant anthropogenic pressure.

Interest and uncertainty in the LEK approach for assessing sea turtle bycatch

Our study illustrates that in systems combining social and ecological factors, where data from alternative sources is scarce, immediately surveying fishers has the potential to be an effective method to gather sufficient information for estimating bycatch rates, identifying spatiotemporal patterns, and pinpointing high-risk gears **(Domènech *et al.*, 2014; Lin *et al.*, 2023)**. These data are essential for evaluating potential population-level impacts on threatened species and for developing strategies to mitigate bycatch through fisheries management. The interview method, endorsed by the FAO for fisheries assessments **(FAO, 2019)**, proves to be a quick and efficient approach for initial evaluations of fisheries and their interactions with sea turtles. The observers onboard have been widely applied in fishing investigations to accurately evaluate bycatch **(Carreras *et al.*, 2004; Alfaro Shigueto *et al.*, 2008)**. In Morocco, however, bycatch evaluations face logistical challenges due to limited data collection periods, small sample sizes, and restricted coverage. Information gaps on bycatch remain significant in many regions that are rich in biodiversity, as few fisheries implement observer programs for marine data on bycatch catches **(Kelleher, 2005)**, and several areas deficient in reports of anecdotal evidence through coastal assessment or marine resources evaluations **(Hines *et al.*, 2020)**. These issues lead to the disparate distribution of bycatch standards, emphasizing the imperative for enhanced surveillance and study efforts.

LEK is particularly useful for studying bycatch in situations where there is a need for rapid assessment of bycatch patterns over large special extent, particularly in cases in which onboard observer programs are limited in scope as well as coverage, often focusing on specific fisheries that may not reflect the broader region. Additionally, LEK allows for the collection of both past as well as current data in a one attempt, enabling the reconstruction of past bycatch baselines and the examination of changes in dynamics and contributing factors over time. However, several sources of error and uncertainty must be considered when deriving bycatch estimates. Decline in memory accuracy and response bias is able to lead to substantial inaccuracies in data from structured interviews **(Gomm, 2004; Fowler, 2009)**. Additionally, sea turtle bycatch may be either underestimated or overestimated, influenced by contributors including fear of negative repercussions from accurate reporting **(Walsh *et al*., 2002)** or, on the contrary, the desire to influence interviewers favorably or attract external investment to the community **(Gomm, 2004)**. Fishermen who have targeted species for catch, whichever intentionally or as bycatch, may had exhibited diminished inclination to participate in interviews, potentially leading to an underestimation of levels of the catch **(Moore *et al.*, 2010)**. National statistics in relation to fishing vessels, which had become accustomed to estimate bycatch stages through the Mediterranean, may as well be biased due to variations in data collection methods across different Maritime Fisheries Delegations and National Fisheries Offices. Consequently, interview-based bycatch estimates for the region, as presented in this and similar studies, should be interpreted with caution underscoring the need for more comprehensive research to offer impartial confirmation. Fishermen's Ecological Knowledge (FEK) plays a valuable complementary role in scientific research, offering new insights and ideas, while scientific studies can test hypotheses derived from FEK **(Panagopoulou *et al.*, 2017)**. FEK is particularly useful for researchers and policymakers, providing rich contextual information that can enhance fish population management and ecosystem restoration **(Johannes *et al*., 2000)**. Given their extended time at sea, fishermen gain extensive proficiency in marine ecosystems, comprising untargeted species **(Zappes *et al.*, 2010; Silva *et al.*, 2014)**.

Bycatch patterns and influencing factors

Our interview survey facilitated a broad spatio-temporal analysis across the western Mediterranean Sea, highlighting areas where fisheries and sea turtles overlap. This allowed for the discovery of species-specific variations in the parameters affecting the incidence of bycatch. Across every species, incidents of bycatch were more frequent in summer and spring, alongside fewer incidents declared in winter and autumn. Given that fishing tends to decline in the winter due to unfavorable sea conditions, this tendency might reflect seasonal fluctuations in fishing intensity **(Li *et al.*, 2021)**. Additionally, some marine megafauna reduce activity and migrate toward profound oceanic regions throughout colder months **(Jefferson *et al.*, 2015)**, potentially reducing their exposure to fishing interactions.

Sea turtles are able to cover miles distances because of ecological and physiological variables like temperature of the ocean, resource abundance, and reproductive phases **(Louhichi *et al*., 2023)**. Seasonal and reproductive migrations **(Broderick *et al.*, 2002)** likely contribute to variations in turtle abundance and bycatch rates. However, further research is required to confirm these seasonal trends. Previous studies have identified location as a key variable impacting bycatch **(Alvarez Perez & Wahrlich, 2005; Du Fresne *et al.*, 2007)**, with other potential influences including bait type and depth of gear setting **(Macías López *et al.*, 2012)**. Increased fishing effort likely leads to more interactions between sea turtles and fishermen, with these interactions potentially causing substantial loss of income for fishermen **(Panagopoulou *et al*., 2017)**. Our results indicate that the interaction between fishermen and sea turtles is extremely changing, affected by outside influences including the condition of marine fish reserves. Declining fish stocks may drive fishermen to intensify their efforts, which consequently increases the likelihood of sea turtles becoming entangled in fishing gear.

Our random forest (RF) modeling approach indicates that sea turtle bycatch is primarily influenced by boat length, distance from the shore and water depth. Similarly, **Lin *et al.* (2023)** found that bycatch patterns are more strongly affected by boat length and distance from shore. Their study also showed that a higher bycatch probability is linked with deep-water areas and bigger maritime vessels, which are typically employed in these environments **(Lin *et al.*, 2023)**. The intricate biological cycle of sea turtles that reproduce in the open sea and move extensively among feeding and resting locations, is probably reflected in these patterns **(Wang, 1993)**. Another factor influencing sea turtle bycatch is the depth at which fishing gears are deployed. We reported that almost the majority of captures with fishing gear set deeper than 50 meters. Despite this depth variation, gillnets are typically placed in coastal waters, which overlap with the foraging and resting habitats of sea turtles, particularly loggerhead sea turtle **(Lutz *et al.*, 2003)**. C. caretta generally stay less deep than 200 meters **(Lutcavage & Lutz, 1997; Houghton *et al.*, 2002)** and tend to be susceptible to fishing gear utilized in shallow coastal waters as opposed to the ones on the higher incline **(Casale *et al.*, 2004)**. Various factors, such as fishing gear size, haul duration, speed, and time of day, vary across fisheries, vessels within the identical sea resources, and yet among different trips or operations of the identical maritime boats. These variables can influence different features of sea turtle bycatch and mortality **(Casale, 2011)**. Additionally, factors related to sea turtle ecology, including developmental stages, size of the body and temperature, also play a significant role in determining catch rates and associated mortality **(Louhichi *et al.*, 2023)**.

Vulnerability of sea turtle species to bycatch

During the investigated period, only two sea turtle species; *C. caretta* and *D. coriacea* were recorded as bycatch. Most of these captures engaged loggerhead turtles, with fewer instances of leatherback bycatch. *C. caretta* has the greatest number of individuals, particularly in the western Mediterranean Sea **(Broderick *et al.*, 2002; Casale & Margaritoulis, 2010; Lucchetti & Sala, 2010; Casale *et al.*, 2018)**, and utilizes both oceanic and neritic zones **(Jribi *et al.*, 2007; Casale, 2008)**. This region serves as a crucial foraging, developmental habitat **(Aksissou *et al.*, 2010; Clusa *et al.*, 2013)** and a migration pathway for subadult and juvenile loggerhead sea turtles **(Rees *et al.*, 2008; Stokes *et al.*, 2015)**. As a result, the occurrence of bycatches and strandings among these age groups is widespread **(Hamiche *et al.*, 2025)** and concerning, as they are vital to population dynamics **(Ocaña *et al.*, 2006)**. The technology of satellite monitoring data showed that juvenile loggerheads with a CCL greater than 57cm prefer inhabit the waters of Moroccan Mediterranean Sea **(Eckert *et al.*, 2008)**. The disappearance of both juveniles and adults measuring over 30cm in CCL in loggerhead populations has a more significant influence compared to the disappearance among juvenile turtles, such as eggs, hatchlings, and smaller juveniles **(NRC, 1990)**. Accidental capture in northwestern African waters may also negatively impact various nesting populations across the broader Atlantic and Mediterranean **(Monzón-Argüello *et al.*, 2010)**. The region primarily hosts juveniles and subadults of loggerhead sea turtle **(Tiwari *et al.*, 2001; Tomas *et al.*, 2001; Ocaña *et al.*, 2006)**. This region remains crucial for population movements **(Crouse *et al.*, 1987)**. As such, bycatch in Moroccan marine environment might have major effects at the population level across the broader Mediterranean.

Bycatch risk from fishing gears on sea turtles

It is acknowledged that the Mediterranean Sea is a global hotspot for marine biodiversity **(Rodríguez-Rodríguez & Abdul Malak, 2022)**. However, it is also one of the most heavily fished regions worldwide, driven by a large human population and the rapid growth of fisheries industries in bordering countries **(Ortega *et al.*, 2023)**. Morocco was listed by **Casale (2011)** as one of the Mediterranean countries having the largest yearly bycatch, estimating over 10,000 turtle captures per year, indicating the significant impact of Moroccan fisheries. Sea turtles get regularly caught in fishing gear along Morocco's coast **(Tiwari *et al.*, 2001; Benhardouze, 2012; Kaddouri *et al.*, 2018; Ahannach & Aksissou, 2023; El Arraf *et al.*, 2024)**, yet bycatch estimates for many fisheries remain unavailable. The existing studies suggests that bycatch of sea turtles in the Mediterranean remains substantial, estimated at around 132,000 annually **(Casale, 2008; Casale, 2011; Casale & Heppell, 2016; Casale *et al.*, 2018)**. While no fishery or gear specifically targets sea turtles, their behaviors, such as breeding and feeding migrations, lead to interactions with various fishing gear types **(Wallace *et al.*, 2008; Alessandro & Antonello, 2010)**.

Gillnetting, however, is the predominant fishery method in the area, and further small-scale artisanal gears remain similarly frequently utilized **(Teh *et al.*, 2017; Grimm *et al.*, 2025)**. Gillnets potentially attract sea turtles attempting to feed on targeted species, increasing their likelihood of capture **(Louhichi *et al.*, 2023)**. Our study highlights that the high bycatch associated with gillnets mostly results from the large number of operating boats and the socio-economic dependence of small-scale fishers on low-cost gear. These findings align with global patterns and support concerns raised by previous studies **(Lazar *et al.*, 2006; Marcovaldi *et al.*, 2006; Echwikhi *et al.*, 2012; López-Barrera *et al.*, 2012)**, which have reported significant incidental loggerhead bycatch in gillnets. **Moore *et al.* (2010)** questioned over 6,000 artisanal fishermen from Malaysia, Jamaica, Tanzania, Comoros, Cameroon, Nigeria and Sierra Leone, identifying gillnets as the primary threat to sea turtles. While a single small gillnetting vessel has a lower bycatch efficiency than bigger vessels used for seining or trawling **(Lin *et al.*, 2023)**, thus further research is needed.

Purse-seines pose a comparatively low threat to sea turtles, accounting for only 2% of total bycatch **(Levy *et al.*, 2015)**. In contrast, seining exhibits the greatest bycatch and CPUE rates ever recorded **(Lin *et al.*, 2023; Domingo *et al.*, 2025)**. This method involves netting schooling fish instantly upon sighting, with short soak times, which allows for the immediate release of any captured sea turtles, significantly reducing entanglement and drowning risks. Contrary to our findings, longlines seem to represent the greatest efficient gear regarding bycatch **(Lucchetti *et al.*, 2017)**. The risk of bycatch is increased when pelagic longlines are used, as *C. caretta* individuals are more commonly found below 50 meters in depth **(Louhichi *et al.*, 2023)**. Usually, longline bycatch happens in wide waters when loggerhead turtles are in pelagic stage, with high incidence areas identified in Spain **(Báez *et al.*, 2007; Clusa *et al.*, 2016)**, Northern African region **(Jribi *et al.*, 2008; Benhardouze *et al.*, 2012)**, the Italian southern maritime zones **(Piovano *et al.*, 2012)**, Greece **(Snape *et al.*, 2013)** and in the Adriatic Sea **(Armienti *et al.*, 2025)**. **Valeiras and Camiñas (2001)** found that at least two species of sea turtles, *C. caretta* and *D. coriacea*, are unintentionally captured by the Spanish surface longliner fleet.

Because of their greater efficiency and utilization of bigger vessels, purse seines and trawls account for the majority of fisheries captures **(Pauly & Liang, 2020; Carbonara *et al.*, 2025)**. Trawls are regarded as the most threatening fishing gear for sea turtle bycatch **(Casale *et al.*, 2004; Wallace *et al.*, 2011)** which is consistent with our results. Other research has similarly emphasized the significance of sea turtle interactions with static net fisheries, considering them as impactful as those with trawl fisheries **(Casale *et al.*, 2005)**. According to **Casale *et al.* (2004)**, trawlers in the Mediterranean capture over 39,000 sea turtles annually. Our study identified bottom gillnets and trawl nets as the primary threats to sea turtles in the study area, with a number of 56 and 16 sea turtle caught, respectively. In contrast, **Levy *et al.* (2015)** found that trawl vessels had a higher bycatch per vessel (48.9 turtles) compared to gillnet vessels (20.9 turtles). Hooks and lines are a notable cause of sea turtle bycatch **(Bugoni *et al.*, 2008)**, with handlines accounting for the majority of turtle captures **(Pusineri & Quillard, 2008)**. Other studies have also highlighted hook and line fisheries as a significant threat to turtles, indicating that their bycatch is widespread **(Bugoni *et al.*, 2008)**. Aligned with our results, trammel nets are another major source of bycatch, particularly in Northern Cyprus and southern Turkey **(Carreras *et al.*, 2004)**. Although other fishing gear may exhibit increased bycatch proportions though are functioned occasionally, resulting into lower overall bycatch.

The bycatch values estimated in our study may not fully reflect the actual situation, as they could be either underestimated or overestimated. Nonetheless, it is more plausible that the figures are underreported, particularly in the Moroccan Mediterranean region, where the capture of sea turtle is legally forbidden. Moreover, some fishers who accidentally caught these species may have avoided interviews due to the sensitive nature of the issue, which likely resulted in a further underrepresentation of true bycatch rates **(Moore *et al.*, 2010)**. Such biases may stem from unreliable information given by fishers, gaps or omissions in data collection, and possible recording errors made by data analysts. Consequently, bycatch estimates based on interviews should be interpreted carefully. These uncertainties emphasize the necessity for more comprehensive investigations to independently verify the reported figures.

Although the Random Forest model identified longline as the fishing gear with the highest predicted probability of sea turtle bycatch and bottom gillnet as the lowest, this result contrasts with fishermen’s perceptions, who reported higher turtle captures in bottom gillnets. This may be explained by differences in fishing effort, target catch volume or spatial distribution of non-target species. Additionally, this discrepancy may reflect differences between perceived and observed bycatch patterns. The model’s prediction is driven by the statistical relationships within the dataset, which may be influenced by unbalanced sampling effort, spatial and temporal fishing distribution, or confounding factors such as depth, season, and fishing area. In contrast, fishers' responses are based on experiential knowledge that may be localized or influenced by recent events. Therefore, the observed divergence does not necessarily indicate an error in the model but highlights the complexity of bycatch dynamics and the importance of integrating both empirical data and FEK for a comprehensive understanding of sea turtle–fisheries interactions.

Mortality concurrent with bycatch

In addition to bycatch rates, the effect of fisheries on sea turtle mortality should be evaluated, considering both direct bycatch-related deaths and potential post-release survival reductions. While previous Mediterranean studies estimated mortality rates via interviews **(Moore *et al.*, 2010; Domènech *et al.*, 2014)**, our data show a 32.3% mortality rate, primarily in trawl and bottom gillnets, with zero mortality for the remaining fishing gears. This highlights the need for gear-specific mitigation strategies. However, the fate of marine turtles released in the Moroccan Mediterranean Sea remains unknown **(Benhardouze *et al.*, 2012)**. While some marine megafauna, including sea turtles, are often released alive and tend to survive **(Poisson *et al.*, 2014)**, their long-term survival is still uncertain. In the Moroccan Mediterranean Sea, approximately 12% of vulnerable specimens captured incidentally are released alive **(El Arraf *et al.*, 2024)**. However, 72% among the fishers that we conducted a survey with indicated that releasing caught turtles directly which significantly lowers their chances of survival **(MAP-UNEP, 1999)**. Sea turtles may experience injury after capture, leading to death after several weeks **(Casale *et al.*, 2007; Domènech *et al.*, 2014)**. Additionally, 47% of sea turtles captured during a typical haul (3.5–5.75 hours) die during the process **(MAP-UNEP, 1999; Nada & Casale, 2011)**. Bycatch-related mortality risks can be categorized based on gear types and fishing practices. Sea turtles captured by trawl nets may survive, be in a comatose condition or be dead upon being taken onboard **(Nada & Casale, 2011)**. Previous studies indicate that drowning due to forced apnea, caused by prolonged net submersion during trawling, nets, and longlines, is a primary cause of sea turtle mortality **(Alessandro & Antonello, 2010)**. Supporting our findings, the totality of the sea turtles captured in trawls in our study were dead. Turtles in a comatose state which can be discarded when are dead, released to the waters, typically do not survive **(Norton, 2005)**. In contrast, turtles subjected to resuscitation methods frequently survive **(Casale *et al.*, 2004)**. Still, even though a turtle is released, delayed mortality may occur if the fisherman fails to remove all net ropes, which can lead to severe injuries and necrosis **(Gerosa & Casale, 1999)**.

In contrast, in the Adriatic Sea, only 9.4% of turtles incidentally captured by bottom trawlers were dead, although the potential mortality rate was estimated to reach up to 43.8% if all comatose turtles did not survive after release **(Casale *et al.*, 2004)**. In line with our findings, turtles freed from gillnets have been shown to exhibit post-release mortality **(Snoddy & Southwood Williard, 2010)**. For aquatic biodiversity, bycatch death rates in gillnets are a major worldwide challenge **(Alfaro-Shigueto *et al.*, 2018; Dewhurst-Richman *et al.*, 2020; Mustika *et al.*, 2021)**. The **MAP-UNEP (1999)** revealed that the Mediterranean Sea turtle death rate from trammel net varied depending on the type of net and water depth, ranging from 94.4% in Corsica, in Croatia (83%), to with intermediate rates in France (53.7%), and 5.2% in Tunisia. While certain gears, such as gillnets, cause high mortality, not all bycatch results in mortality, along with many sea turtles are set free in a living state **(Mangel *et al.*, 2010)**.

The likelihood concerning sea turtle mortality is higher in nets compared to other fishing gears **(Pusineri & Quillard, 2008)**. **Jribi *et al.* (2008)** reported a mortality rate of 12.5% in Tunisian longlines, while our study found no mortality in Moroccan longlines, possibly due to variations in turtle density or fishing methods. Because of lesions or ingested hooks, interaction involving surface and bottom longlines may lead to a significant mortality after release **(Casale *et al.*, 2007; Dapp *et al.*, 2016)**. An analysis of the Atlantic Ocean purse seine fishery in Europe found that only 2% of turtles die as a result of bycatch **(Amandè *et al.*, 2011)**, with no reported mortality in the eastern Atlantic French purse-seine fishery **(Chassot *et al.*, 2009)**, which is aligned with our results. In contrast, small-scale fishing gear, such as gillnets and trammel nets, results in high mortality rates (60–70%), likely due to prolonged soak times **(Camiñas & De Málaga, 2004; Snape *et al.*, 2013)**.

Cryptic bycatch refers to animals caught or trapped in fishing gear and later navigate the water farther, often accompanied by severe traumas **(Reeves *et al.*, 2013)**. Mortality rates would likely increase significantly if fishermen did not release these animals promptly or correctly **(Finkbeiner *et al.*, 2011; Zollett & Swimmer, 2019)**. Water temperature also influences survival, with colder sea surface temperatures potentially prolonging the time before drowning in air-breathing poikilotherms, while warmer waters may shorten this period **(Hart *et al.*, 2006)**. Thus, high summer temperatures combined with long haul times may reduce survival rates. Further research on mortality after releasing of sea turtle is necessary **(Alessandro & Antonello, 2010)**.

Suggestions for mitigation and environmental awareness

Our findings highlight the concerning extent of sea turtle bycatch in this region. Several bycatch mitigation approaches have been implemented to reduce bycatch and avoid irreversible ecological impacts **(Lucchetti *et al.*, 2019; FAO, 2021; Wade *et al.*, 2021)**. For prolonged population restoration or stabilization, these strategies should promote collaboration and transition toward the fishing community's involvement in collaborative governance **(Espinosa-Romero *et al.*, 2014; Di Franco *et al.*, 2016; Truchet *et al.*, 2022)**. Fishers could be incentivized to self-report bycatch through government assistance for routine reporting. Strategies for regular monitoring should be implemented to track negative interactions **(Yan *et al.*, 2024)**, identifying the species and number of sea turtle involved. Although the majority of sea turtles survive incidental capture, we highly advise fisheries authorities to launch awareness campaigns encouraging immediate release of sea turtles after being captured (Fig. 10). Additionally, we suggest educating fisherman about resuscitation methods **(Domènech *et al.*, 2014)** and facilitating the transfer of turtles to rescue centers.

Fig. 10. A fisherman releases a juvenile sea turtle unintentionally caught in the Moroccan western Mediterranean Sea

Additionally, rescue organizations should be founded in various locations to ensure prompt response to bycatch incidents **(Zollett & Swimmer, 2019; Hamer & Minton, 2020)**. Actually, a rescue center in Mdiq is in the process of being implemented. Compensation for conservation has been shown to enhance the financial sustainability of artisanal fishermen **(Varjopuro, 2011)** and offer financial support for those interacting with species of conservation concern **(Wagner *et al.*, 1997; Nyhus *et al.*, 2005; Martins *et al.*, 2025)**. Strategies up to compensation hold significant potential as a mitigating action for the negative impacts of interactions between fisheries and endangered species. Given the highly migratory nature of these species, the creation of cooperative initiatives with surrounding nations countries is crucial. The results indicate that limiting or modifying gear characteristics could minimize sea turtle bycatch in the Moroccan Mediterranean Sea. This should include: spatial and temporal restrictions on gillnet use, testing adjustments to the trawl vertical opening, and incorporating turtle excluder devices (TEDs) created regarding trawlers **(Domènech *et al.*, 2014; Bhowmik *et al.*, 2025)**. Additionally, evaluating deterrent technologies, such as green LED lights attached to large-mesh trammels and gillnets, along with phosphorescent plates **(Girard *et al.*, 2025)**, and exploring innovations like solar-powered lights that harness energy from the sun and optimize power consumption under varying fishing durations **(Senko *et al.*, 2025)**, should be considered. Such approaches suggest that fisheries bycatch could be mitigated through the sustainable use of solar energy.

Alternative, more selective gear types, like small purse seines, hooks, pots and traps, should be considered. Following **Brownell *et al.* (2019)**, environmentally sustainable fishing practices should be developed to minimize bycatch in Morocco. Using biodegradable lines and circle or J-hooks, which have fewer possibilities for turtles to ingest them **(Stokes *et al.*, 2015)**, is also recommended. In high bycatch areas, fishing should be restricted to gear that poses no threat to sea turtles. We suggest restricting fishing areas at least 50m deep, as *C. caretta* primarily inhabit shallower areas **(MAP-UNEP, 1999)**. Establishing vast Marine Protected Areas (MPAs) alongside a complete fishing restriction is a highly effective measure **(Lotze *et al.*, 2011)**. Additionally, new technologies such as drones, underwater cameras, and low-cost hydrophones attached to nets could aid in creating a comprehensive network for maritime detection **(La Manna *et al.*, 2013; Buscaino *et al.*, 2021; De Marco *et al.*, 2022)**. As these mitigation techniques have reduced bycatch, they frequently ignore the ecological and socioeconomic consequences **(Wu *et al.*, 2022)**. Addressing socioeconomic factors is therefore essential when developing approaches for decreasing the bycatch of sea turtles **(Lewison *et al.*, 2018; Suuronen, 2022; Báez *et al.*, 2024)**.

CONCLUSION

Our findings establish the first quantitative baseline for sea turtle bycatch in Morocco's western Mediterranean Sea and provide a framework for designing targeted mitigation measures and policy interventions. Data on sea turtle bycatch, gathered through questionnaire-based interviews, possess significant potential for informing the development of effective conservation strategies in the Mediterranean Sea, facilitated through collaborative efforts between fishermen, authorities, and research institutions. The present study addresses a critical data gap regarding sea turtle bycatch in the western Mediterranean coast of Morocco, providing a valuable baseline that enables the formulation and execution of future mitigation measures. Nevertheless, while understanding the impacts of fisheries bycatch remains a challenging research endeavor, it is equally important to assess and prioritize the fishery-related threats to sea turtles by evaluating and comparing the effects of various fishing gear types commonly used in the Mediterranean Sea of Morocco. Quantifying bycatch rates is inherently challenging due to the lack of systematic logging or reporting of such captures, coupled with the limitations of observer programs, which often fail to cover the entire fleet and tend to be geographically and temporally inconsistent. As a result, the full extent of the issue remains poorly understood, despite its significance. To address this, the implementation of robust monitoring systems, the collection of reliable data and reporting, the development of technical solutions, and the active involvement of stakeholders could provide scientists and policymakers with a more comprehensive understanding of the problem, enabling the establishment of informed priorities for management and conservation efforts.

Ethics statement

Given the low-risk nature of the study, oral consent was deemed sufficient and was confirmed at the start of each interview. Participants were informed of the study's purpose, assured of their anonymity and confidentiality, and told they could withdraw at any time or decline to answer any question and that their responses would remain confidential and used solely for scientific research. The questionnaire excluded personal questions or sensitive items, and demographic variables (age, gender and ethnicity) were not used as selection criteria. To maintain comfort and trust, no audio recordings were made. Data were handled confidentially under the university's data protection policy.

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