



Spatio-temporal patterns and diversity of sea turtle strandings in the Moroccan exclusive economic zone (1980–2024)

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Abstract. This study provides the first long-term, national-scale assessment of sea turtle strandings in the Moroccan Exclusive Economic Zone (EEZ) over 44 years (1980 to 2024). We analysed species composition, spatial and seasonal patterns, life stage distribution, and potential mortality causes. Loggerhead sea turtles (*Caretta caretta*) dominated strandings (71%), followed by leatherback sea turtles (*Dermochelys coriacea*; 27%), while green sea turtles (*Chelonia mydas*) were rare. Most strandings occurred along the northern and central Atlantic and Mediterranean coasts, with peaks in spring and autumn. Adult and subadult sea turtles comprised the majority of strandings, indicating a higher vulnerability of these life stages to anthropogenic threats. Although the cause of death was undetermined in most cases, collisions with boats and fisheries interactions seem to be the most frequently identified factors. Our findings highlight Morocco's EEZ as an important migratory and developmental habitat for sea turtles and underscore the need for improved monitoring, standardized necropsy protocols, targeted conservation actions, and regional cooperation to mitigate threats and support population recovery.

Key words. Testudines, *Caretta caretta*, *Dermochelys coriacea*, anthropogenic threats, conservation.

Introduction

Sea turtles are iconic marine chelonians with a wide global distribution, occupying diverse habitats across ocean basins. They play a crucial role in marine ecosystems, make an essential contribution to maintaining the balance of the ocean's trophic web contributing significantly to the structure and function of oceanic trophic webs (BJORNDALE & JACKSON 2002, LEÓN & BJORNDALE 2002), and act as sentinel species that reflect the health of marine environments (HANNAN et al. 2007). Recognized as flagship and umbrella species, sea turtles have become central to global conservation initiatives (AGUIRRE & TABOR 2004, MATIDDI et al. 2017, FLINT et al. 2019).

According to the IUCN Red List, sea turtles exhibit contrasting global conservation status, ranging from Least Concern (*Chelonia mydas*) to Vulnerable (*Caretta caretta*, *Dermochelys coriacea*, *Lepidochelys olivacea*) and Critically Endangered (*Lepidochelys kempii*, *Eretmochelys imbricata*), reflecting a combination of natural and anthropogenic pressures. While natural threats such as disease and predation persist (HAWKES et al. 2009, HEITHAUS 2013), anthropogenic impacts represent a far greater challenge, including bycatch from intensive fishing activities (BENHARDOUZE et al. 2012, PUTMAN et al. 2020, DE LA HOZ

SCHILLING et al. 2023, EL ARRAF et al. 2024) and plastic pollution, which results in entanglement and ingestion of debris such as single-use plastics and abandoned fishing gear (WILCOX et al. 2018, BENHARDOUZE et al. 2021, SOLOMANDO et al. 2022).

Morocco occupies a strategic geographical position at the interface between Europe and Africa, encompassing a rich diversity of marine habitats from the Mediterranean Sea to the Atlantic Ocean. This unique geographical setting supports high biodiversity (MASSKI & DE STÉPHANIS 2015), including populations of sea turtles that use Moroccan waters as feeding areas and migration corridors (BENHARDOUZE et al. 2012, VARO-CRUZ et al. 2016, BELLIDO et al. 2018, MGHILI et al. 2023). Despite this ecological significance, scientific research on marine turtles in the Morocco's Exclusive EEZ remains limited. Data on sea turtles are notably scarcer than for terrestrial reptiles (BOUAZZA et al. 2021), and lack of reliable information on abundance, distribution, and conservation status impedes the development of effective management strategies. This knowledge gap also constrains our understanding of the interactions between sea turtles and anthropogenic pressures such as bycatch (BENHARDOUZE et al. 2012, EL ARRAF et al. 2024), plastic pollution (BENHARDOUZE et al. 2021) and collisions with boats (MGHILI et al. 2023).

In this context, stranding networks are increasingly recognized worldwide as low-cost but powerful ecological observatories, capable of revealing mortality drivers, habitat use, and population structure when analysed over long-time scales. Stranding data provides critical insights into sea turtle occurrence, life stage composition, and causes of mortality and are increasingly recognized as important indicators of population health and human impacts. However, no study has yet conducted long-term examination of strandings across Morocco's EEZ. Addressing this gap is essential to understand the role of Moroccan coastal waters as developmental habitats and migratory pathways and to support evidence-based conservation strategies planning.

The present study provides the first comprehensive, multi-decadal (44 years) spatio-temporal analysis of sea turtle strandings along the Moroccan EEZ (1980 to 2024). Specifically, we aim to: (1) assess species composition and relative frequencies of stranded individuals, (2) examine seasonal and regional variations in strandings, (3) characterize the life stages of stranded turtles, and (4) identify potential sources of mortality. These findings will help inform national monitoring and conservation programs tailored to Morocco's specific ecological and anthropogenic contexts.

Materials and methods

Study area

The study area encompasses the entire Moroccan Exclusive Economic Zone (EEZ, Fig. 1), which extends 200 nautical miles (approximately 370 km) from the baseline and covers an area of 564506 km² (Flanders Marine Institute 2023). Situated in the northwest of the African continent, this maritime zone includes the Moroccan coasts along both the Mediterranean Sea and the Atlantic Ocean. The area is recognized for its exceptional biodiversity and rich fish stocks (BELHABIB et al. 2012).

Data collection

Data on stranded sea turtles were collected along the Moroccan coastline from 1980 to 2024, using multiple complementary sources (Table 1): published data, GBIF (www.gbif.org) and original records compiled in this study, including reports from fishermen, citizen data, and records from the Moroccan Fisheries Observatory platform (OHM) maintained by the National Institute for Fisheries Research (INRH).

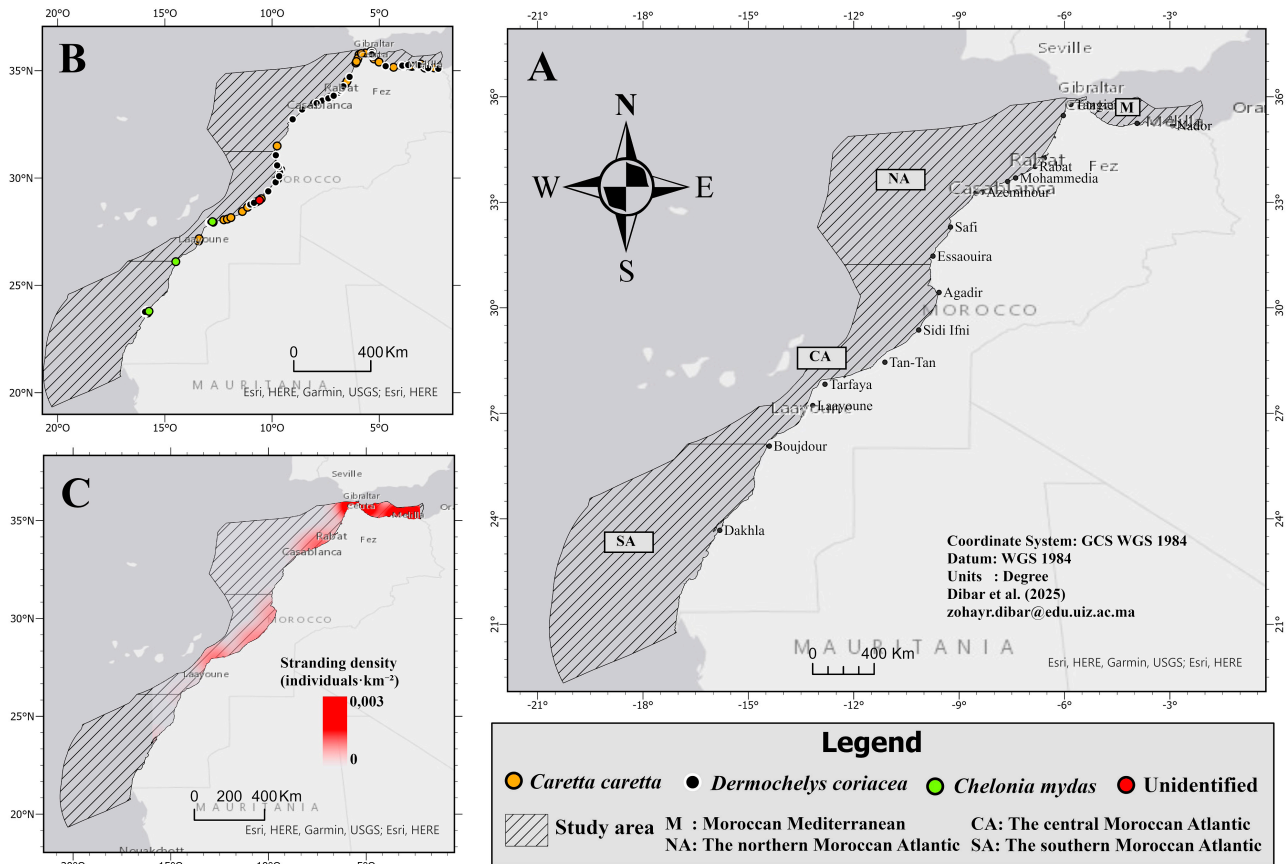


Figure 1. Map of (A) study area of the Moroccan Exclusive Economic Zone (EEZ) showing four regions: the Moroccan Mediterranean (M), the northern Moroccan Atlantic (NA), the central Moroccan Atlantic (CA), and the southern Moroccan Atlantic (SA), (B) Locations of stranded sea turtles recorded between 1980 and 2024, (C) Kernel Density Estimation (KDE) map of sea turtle strandings, expressed as individuals × km² (range: 0–0.003).

Spatio-temporal patterns and diversity of sea turtle strandings

Table 1. Annual record and regional distribution of sea turtle strandings (*Caretta caretta* and *Dermochelys coriacea*) in the Moroccan EEZ (1980–2024): the central Moroccan Atlantic (CA), the northern Moroccan Atlantic (NA), the southern Moroccan Atlantic (SA), and the Moroccan Mediterranean (M). The total number of individuals per year and bibliographic references are also indicated.

Year	<i>Caretta caretta</i>				<i>Dermochelys coriacea</i>				Total	References
	M	NA	CA	SA	M	NA	CA	SA		
1980	–	–	–	–	12	1	–	–	13	Bjorndal (1990)
1984	15	3	28	1	–	5	5	–	57	BONS & GENIEZ (1996)
1988	–	–	–	–	2	–	–	–	2	Bjorndal (1990)
1999	1	–	–	–	–	–	–	–	1	ROJO-NIETO et al. (2011)
2001	–	–	1	–	–	–	–	–	1	ELBAHI et al. (2022)
2002	6	–	–	–	–	–	–	–	6	BENHARDOUZE et al. (2009), ROJO-NIETO et al. (2011)
2003	46	1	–	–	–	–	–	–	47	BENHARDOUZE et al. (2009), ROJO-NIETO et al. (2011)
2004	2	6	–	–	1	–	–	–	9	BENHARDOUZE et al. (2009)
2005	1	–	–	–	2	–	–	–	3	ROJO-NIETO et al. (2011)
2006	2	–	6	–	3	–	–	–	11	TIWARI et al. (2006), GBIF (2024)
2009	–	1	–	–	–	–	–	–	1	RIHANE et al. (2018)
2012	–	1	–	–	–	–	–	–	1	GBIF (2024)
2013	–	–	3	–	–	1	–	–	4	ELBAHI et al. (2022), this study
2014	–	–	–	1	–	–	1	–	2	This study
2015	–	–	–	–	–	10	5	2	17	ELBAHI et al. (2022), MASSKI & TAI (2017), IZZABAHA (2016), this study
2016	–	–	–	2	1	1	–	–	4	MASSKI & TAI (2017), Izzabaha (2016), this study
2018	–	1	–	–	–	–	–	–	1	RIHANE et al. (2018), GBIF (2024)
2019	1	–	2	–	–	–	–	–	3	ELBAHI et al. (2022), GBIF (2024), this study
2020	2	1	2	–	–	2	1	1	9	ELBAHI et al. 2022, GBIF (2024), this study
2021	10	1	1	1	4	2	–	–	19	AHANNACH & AKSISSOU (2021), this study
2022	8	3	2	–	1	1	–	1	16	GBIF (2024), this study
2023	3	5	5	–	1	1	–	–	15	This study
2024	5	2	2	–	–	1	2	–	12	This study
Total	102,	25,	52,	5,	27,	25,	14,	4,	254	
(n, %)	55.4	13.6	28.7	2.7	38.6	35.7	20	5.7	–	

All records were compiled into a standardized database, following established protocols (BELLIDO et al. 2018, HAMA et al. 2020), and include detailed information on species, date, geographic coordinates, sex (when determinable), condition at discovery (alive/dead), suspected causes of stranding, and life stage. The protocol was further extended to record the number of individuals, photographs, and data sources associated with each stranding event. A sea turtle was considered stranded when found ashore (alive or dead). To avoid duplication, records were systematically cross-checked by date and location.

The probable cause of stranding was assessed conservatively by trained scientists at the INRH, notably through the national stranding monitoring network. Assessments were based on standardized field observations supported by photographs and on-site field notes, and a cause was recorded only when diagnostic evidence was clear; otherwise, cases were classified as undetermined.

Data analyses

Stranding data was analysed to examine variations in the number of individuals across regions and seasons. Tests for

normality (Shapiro–Wilk test) and homogeneity of variances (Levene’s test) indicated that the dataset did not meet the assumptions for parametric statistical tests ($p < 0.05$). Therefore, non-parametric methods, specifically the Kruskal–Wallis test, were employed to assess differences among groups, with a significance threshold set at $p < 0.05$. All statistical analyses were conducted using R software (version R-4.4.2). Maps illustrating stranding locations and distribution patterns were produced with ArcGIS Pro (Advanced version, Named User Advanced License, Esri Inc., Redlands, California, USA).

For analytical purposes, we subdivided the EEZ into four regions: the Moroccan Mediterranean Sea (M), the northern Moroccan Atlantic (NA), the central Moroccan Atlantic (CA), and the southern Moroccan Atlantic (SA) (Fig. 1A). To visualise spatial clustering of strandings, we generated a Kernel Density Estimation (KDE) surface from the georeferenced stranding points in ArcGIS Pro using the Geodesic method. The default search radius was automatically calculated for the input dataset using a spatial variant of Silverman’s rule-of-thumb (SILVERMAN 1986), which is considered robust to spatial outliers (i.e., a few points located far from the main clusters). KDE applies a smoothing kernel around each record and sums contributions across space to produce

Table 2. Records of sea turtles stranded in the Moroccan exclusive economic zone (1980–2024). The number of dead and live individuals (N) and the percentage (%) of total observations are indicated.

Area	Area (km ²)	% EEZ	<i>Caretta caretta</i>		<i>Dermochelys coriacea</i>		<i>Chelonia mydas</i>		Unidentified		Total (N, %)
			Dead	Alive	Dead	Alive	Dead	Alive	Dead	Alive	
Moroccan Mediterranean (M)	18.260	3.2	96	6	27	–	–	–	–	–	129, 50
Northern Moroccan Atlantic (NA)	191.963	34	22	3	24	1	–	–	–	–	50, 19.4
Central Moroccan Atlantic (CA)	96.093	17	51	1	14	–	–	1	1	–	68, 26.3
Southern Moroccan Atlantic (SA)	258.190	45.8	5	–	3	1	1	1	–	–	11, 4.3
Total (n, %)	564.506	100	184, 71.3		70, 27.1		3, 1.2		1, 0.4		258, 100

a continuous raster of stranding intensity. Output values were expressed as stranding density (individuals × km²).

Results

Species diversity and mortality rates

Between 1980 and 2024, a total of 258 sea turtles were recorded within the Moroccan Exclusive Economic Zone (EEZ). Loggerhead sea turtles (*Caretta caretta*) dominated these records, representing 71.3% of observations (N = 184, Table 2), followed by leatherback turtles (*Dermochelys coriacea*) at 27.1% (N = 70). The Green turtle (*Chelonia mydas*) was exceptionally rare, with only three stranded specimens recorded in the southern Moroccan coasts, and one additional stranding record could not be identified.

Most of the stranded turtles were dead at the time of discovery (N = 244; 94.6%), while only a small proportion were alive (N = 14; 5.4%), underscoring the severity of mortality pressures in Moroccan waters.

Spatial and temporal patterns of strandings

A Kruskal-Wallis test revealed significant differences in the number of strandings among regions (H (3) = 9.81, p = 0.020, Table 2). The Mediterranean region, despite being the smallest area, accounted for 50% of strandings. In contrast, the southern Moroccan Atlantic, which covers over 45% of the Moroccan EEZ, represented only 4.3% of recorded strandings. These patterns should be interpreted with caution due to likely differences in survey effort across regions.

No significant trend was detected in annual stranding numbers across the entire study period (p > 0.05). However, loggerhead strandings were particularly frequent from 2001 to 2014 (N = 77), while leatherback strandings increased during 2015–2024 (N = 35). Notably, a general rise in strandings has been observed since 2015. However, the post-2015 increase indicates improved reporting efficiency, changing oceanographic conditions, or escalating anthropogenic pressures, and warrants targeted future investigation.

Seasonal analyses showed that loggerhead strandings occurred throughout the year, with pronounced peaks in

spring (N = 40) and winter (N = 26; Fig. 2). Leatherback strandings were most frequent along the Mediterranean coast (38.6%; N = 27) and the northern Moroccan Atlantic coast (35.7%; N = 25), with a pronounced annual peak in 2015 (N = 17). Leatherbacks were observed in all seasons but were most common in autumn (N = 27), with December alone accounting for 18 strandings.

Life stages and seasonal variation

Of the stranded turtles for which sex could be determined, loggerhead records included 15 females and five males, while leatherback records included 10 females and three males. The sex of many individuals could not be identified due to juvenile status or incomplete information.

Among 96 individuals measured, subadults represented the most common life stage (42.7%, N = 41), followed by adults (40.6%, N = 39) and juveniles (16.7%, N = 16, Table 3). The predominance of subadult and adult turtles suggests that larger individuals are disproportionately exposed to threats in Moroccan marine waters.

Seasonally, adult strandings were most frequent in winter (N = 16) and autumn (N = 9), while subadult strandings peaked in spring (N = 12) and summer (N = 10). Juvenile strandings were rare but slightly more frequent in winter (N = 6) and spring (N = 5). Loggerheads predominated in all seasons and life stages. Leatherbacks, although fewer overall, were more commonly stranded during autumn and winter, particularly in the subadult stage.

These seasonal patterns may reflect increased vulnerability of adults during winter, possibly linked to migratory movements, harsher environmental conditions (including thermal stress due to low sea surface temperatures, increased exposure to storm-induced turbulence, persistent winds blowing towards the coast that promote drift, and reduced trophic availability during winter), or increased interactions with fisheries. The dominance of subadult strandings during spring and summer may suggest seasonal use of Moroccan EEZ as developmental habitats. These patterns support the hypothesis that Moroccan marine waters function as a transitional developmental habitat, particularly for subadult loggerheads.

Table 3. Seasonal and developmental stage distribution of stranded sea turtles (*Caretta caretta* (CC) and *Dermochelys coriacea* (DC)) in the Moroccan EEZ (1980–2024).

Life stage Species	Adult		Juvenile		Subadult		Total (N, %)
	CC	DC	CC	DC	CC	DC	
Autumn	7	2	2	2	3	8	24, 25.00
Spring	3	3	4	1	11	1	23, 23.96
Summer	5	3	1	-	5	5	19, 19.80
Winter	13	3	5	1	4	4	30, 31.25
Total (N, %)	39, 40.6		16, 16.7		41, 42.7		96, 100.00

Potential causes of strandings

We identified three main types of threats potentially affecting sea turtles within the Moroccan EEZ: boat collisions, fisheries interactions, and other or unclear causes (e.g., marine pollution, disease). For most stranded individuals, the cause of death could not be determined due to advanced decomposition or insufficient diagnostic information. Of the 258 cases recorded, a cause of stranding could be established for only 34 individuals (13.4%), comprising 24 loggerheads and 10 leatherbacks.

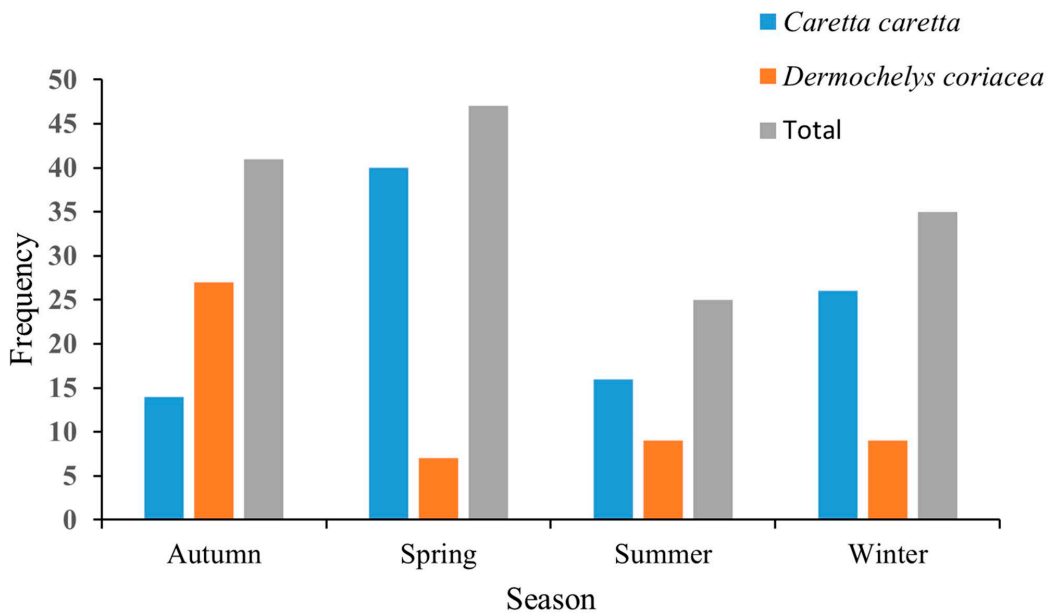


Figure 2. Seasonal distribution of sea turtle strandings (*Caretta caretta* and *Dermochelys coriacea*) recorded in the Moroccan EEZ between 1980 and 2024.

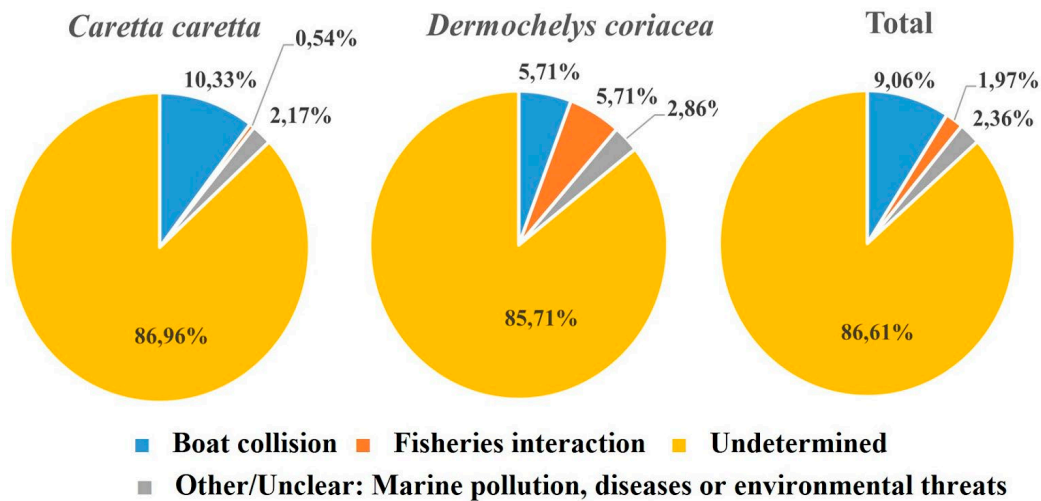


Figure 3. Identified causes of sea turtle strandings in the Moroccan EEZ (1980–2024) for *Caretta caretta* and *Dermochelys coriacea*.

Among loggerheads with an identified cause, boat collisions (documented by carapace fractures and linear or arcuate cut marks consistent with propeller contact) were the most frequently observed factor (10.3%), followed by fisheries interactions (0.5%) and other or unclear causes (2.2%). Notably, approximately 87% of loggerhead strandings remained of undetermined cause (Fig. 3).

For leatherbacks, both boat collisions and fisheries interactions each accounted for 5.7% of strandings, while 2.9% were attributed to other or unclear causes. As with loggerheads, a high proportion of leatherback strandings (85.7%) lacked a determinable cause.

These findings suggest species-specific differences in exposure to anthropogenic threats: loggerheads, which inhabit coastal waters, appear particularly vulnerable to vessel strikes, whereas leatherbacks, being more oceanic, may have greater exposure to pelagic fishing gear. However, the substantial proportion of undetermined cases underscores critical gaps in current monitoring efforts. This highlights the urgent need to enhance stranding response protocols through systematic necropsy, detailed injury assessment, and standardized data collection, to improve understanding of mortality drivers and inform effective conservation strategies.

Discussion

This study provides the first long-term, national-scale synthesis of sea turtle strandings across the Moroccan Exclusive Economic Zone (EEZ) and establishes a baseline for assessing spatio-temporal variation in observed mortality along Moroccan coasts. Overall, the marked predominance of the loggerhead turtle *Caretta caretta* in stranding records is a robust pattern and is consistent with trends reported from neighboring Mediterranean regions (JRIBI et al. 2007, NICOLAU et al. 2016, BELLIDO et al. 2018, BELMAHI et al. 2020).

Importantly, stranding records should not be interpreted as direct measures of population density. The number of carcasses documented onshore reflects only a (often small) fraction of at-sea mortality and is shaped by multiple filters acting between death at sea and detection on land, including winds, currents, and temperature, as well as decomposition/scavenging processes that can prevent carcasses from reaching the coast or remaining detectable (EPPERLY et al. 1996, HART et al. 2006). Moreover, shoreline geomorphology, beach accessibility, human presence, and the effectiveness of detection and reporting strongly influence whether a stranded turtle is recorded, meaning that spatial clustering can partly reflect observation effort rather than true abundance (COOK et al. 2021, PRADO et al. 2023). Consequently, hotspots in the stranding dataset are more appropriately interpreted as areas where mortality becomes detectable along the coastline and/or where pressures are concentrated, rather than as evidence of high local abundance (HART et al. 2006, KOCH et al. 2013).

A key strength of this study lies in its broad temporal coverage and its inclusion of both Atlantic and Mediter-

anean coasts, synthesising records from multiple sources over four decades. This scope enables a comprehensive overview of occurrence and threats in Moroccan marine waters. However, spatial reporting biases likely persist, including underrepresentation in parts of the Moroccan southern Atlantic where monitoring effort and coastal accessibility are lower. In addition, cause-of-death assignment was frequently not possible because many carcasses were found in a state of advanced decomposition, and systematic necropsies were not consistently available, a limitation commonly reported in stranding-based studies (BELLIDO et al. 2018, MGHILI et al. 2023). The integration of heterogeneous data sources over four decades demonstrates the feasibility of reconstructing historical baselines even in data-poor regions, a model that could be replicated elsewhere in Northwest Africa.

Our patterns are consistent with regional evidence supporting the ecological importance of Moroccan marine waters as feeding and migratory habitat for loggerheads (BENHARDOUZE et al. 2012, MGHILI et al. 2023). Seasonal peaks in loggerhead strandings in spring and autumn resemble those reported in neighbouring areas of the western Mediterranean and adjacent Atlantic, suggesting shared drivers such as seasonal movements, environmental variability, and overlap with fisheries activity (JRIBI et al. 2007, TOMÁS et al. 2008, BELMAHI et al. 2020). Leatherback strandings occurred year-round but were more frequent in autumn and winter, which may be linked to seasonal prey availability and oceanographic conditions (NICOLAU et al. 2016, MGHILI et al. 2022, BELMAHI et al. 2020). These comparisons support the interpretation that Moroccan marine waters form part of a wider Atlantic–Mediterranean continuum of habitat use by *Caretta caretta*.

The predominance of subadult and adult individuals among the measured turtles may reflect higher exposure of older life stages to anthropogenic threats and/or greater detectability of larger carcasses. Species-specific differences are also plausible. Loggerheads, which frequently use neritic and coastal habitats, are more likely to overlap with nearshore vessel traffic and coastal fishing activity, whereas the more oceanic ecology of leatherbacks may increase exposure to pelagic fishing gear while reducing the probability that carcasses drift ashore and are detected. Similar contrasts have been noted in adjacent regions of the Mediterranean and Northeast Atlantic (BELLIDO et al. 2018, MGHILI et al. 2023).

The very high proportion of strandings with undetermined causes highlights critical gaps in current response capacity and limits inference about the relative contribution of specific mortality drivers (e.g., fisheries interactions, vessel strikes, pollution, disease). Nonetheless, the subset of well-documented cases indicates that anthropogenic factors are likely important contributors to mortality. In addition, necropsy-based investigations from Morocco have documented ingestion of anthropogenic debris, including plastics, among the gastrointestinal contents of stranded turtles (BENHARDOUZE et al. 2021), highlighting marine pollution as an additional pressure that may con-

tribute to morbidity and mortality. To strengthen interpretation and directly address potential confounding by shipping intensity, future analyses should integrate AIS-derived vessel density (where available) and compare traffic hotspots with stranding concentrations, while acknowledging that AIS coverage can be incomplete for smaller vessels.

Future work should prioritise improving spatio-temporal coverage of monitoring, particularly in under-surveyed areas of the southern Atlantic EEZ, and strengthening diagnostic capacity through standardized protocols (including decomposition scoring), systematic photo documentation, and targeted necropsies. Satellite telemetry has already been widely used to quantify movements, migratory connectivity, and foraging areas of loggerhead turtles (*Caretta caretta*) (VARO-CRUZ et al. 2013, 2016). Extending such tracking efforts in Moroccan waters would help refine seasonal habitat use and support spatially targeted risk mitigation when integrated with anthropogenic pressure layers, such as fisheries effort and AIS-derived vessel traffic. In line with international best practices (JONES et al. 2011, DE CARVALHO et al. 2016), a strengthened national stranding network would transform opportunistic observations into a structured ecological surveillance system, enabling Morocco to contribute actively to international marine turtle conservation frameworks. We recommend strengthening Morocco's national stranding network through additional training, harmonised data collection, and enhanced necropsy capacity, alongside awareness actions with fishers and coastal communities. Effective conservation will require integrating biological monitoring with fisheries management, maritime traffic regulation, pollution control, and public awareness.

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