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Uncovering Sea Turtle Strandings in the Greek Seas (Eastern Mediterranean Sea): Spatiotemporal Patterns and Signs of Anthropogenic Interaction

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ABSTRACT

The Mediterranean Sea is frequented by local populations of loggerhead turtle *Caretta caretta* and green turtle *Chelonia mydas*. Greek waters host both nesting sites and foraging grounds for the loggerhead turtle, whereas only foraging grounds for the green turtle. Both species face threats in their marine environment sourcing from anthropogenic activity. Here, stranding data, spanning from 2010 to 2021, were used to shed light on the main drivers underneath these threats and to identify seasons and areas of high number of stranding events. Stranding events showed an increasing trend over the years for both species. The majority of the strandings were categorized as “unknown,” while those showing signs of anthropogenic interaction (i.e., strandings related to marine litter ingestion, oil pollution, fishing gear entanglement, and injuries) held a significant part, representing ~25% and ~35% for the loggerhead and green turtle, respectively. The present work identified seasons and areas of concern with emphasis on areas that indicate fishery interaction, providing information that can support the designation of conservation measures in marine Greek waters.

1 | Introduction

Sea turtles are slow-growing, long-lived, highly migratory animals that travel hundreds or even thousands of miles performing migrations between their natal nesting sites and foraging grounds (Bolten 2003; Casale and Mariani 2014; Hays et al. 2010; Luschi and Casale 2014; Scott, Marsh, and Hays 2014). Over the course of their life, they face threats throughout their distribution range and at every stage of their life cycle (Casale et al. 2018). Apart from the natural challenges that they face, nowadays, anthropogenic activities pose a major source of threats to their survival, which are primarily attributed to the loss and degradation of nesting habitat due to coastal development, marine litter and pollution, vessel strikes, entanglement, and incidental capture by fishing gears (Casale et al. 2018).

Sea turtles spend most of their life at sea, with only adult females coming ashore to nest at their natal sites (Casale et al. 2010). However, sea turtles’ interaction with commercial, recreational, or fishing vessels can result to animals being injured by ship collision (Pasanisi et al. 2022) or entangled in fishing gears (Belmahi et al. 2020; Casale et al. 2010; Marisaldi, Torresan, and Ferrari 2023; Sönmez 2018; Tomás et al. 2008; Türkozan et al. 2013) that may end up stranded. Fishery interaction is acknowledged as one of the main threats for the sea turtles in the Mediterranean Sea (Carpentieri et al. 2021; Casale and Margaritoulis 2010). Marine litter is also considered an important threat, as marine litter ingestion can damage or block the digestive tract, causing animals to be unable to digest food and, ultimately, starve to death (Casale et al. 2016; Margaritoulis, Koutsodendris, and Panagoloulou 2007).

Stranded sea turtles can also be found on the coastline due to parasitism and disease (Chaloupka et al. 2008; Tagliolatto et al. 2020). Moreover, examples, mainly from the Atlantic Ocean, underline the fact that sea turtles can find themselves trapped in unfavorable areas (e.g., areas with temperatures lower than their optimal thermal range) due to unusual weather conditions or the inter-annual variability of oceanographic events (Báez et al. 2011; Hays and Marsh 1997; Kettemer et al. 2022; Witt, Penrose, and Godley 2007).

Understanding the reasons behind sea turtle mortality and identifying sensitive areas for protection is essential for the management and conservation of these charismatic species. Developing action plans to protect them, though, necessitates information on sea turtle population size and structure, spatial/temporal distribution, foraging, mating and nesting areas, and the migratory corridors they use to travel between these habitats (Bolten et al. 2011; Cantor et al. 2020; Rees et al. 2017; Tagliolatto et al. 2020). Stranding data can provide information on mortality rates (Hart, Mooreside, and Crowder 2006), abundance (Báez et al. 2011), spatial/temporal distribution (Cantor et al. 2020; Casale et al. 2010; Tagliolatto et al. 2020; Türkozan et al. 2013), and important habitats of sea turtles (Mghili et al. 2023). Additionally, stranding events can improve our understanding of the mortality causes (Mghili et al. 2023; Tagliolatto et al. 2020), being a source of evidence of how anthropogenic activities (e.g., vessel strikes or fishery interactions) affect marine megafauna (Tomás et al. 2008).

In Greek waters, the vast majority of the stranded sea turtles are loggerhead turtles *C. caretta*, accounting for over 90% of all events, while the remaining events concern green turtles *C. mydas* and a small percentage of leatherback turtles *Dermochelys coriacea* (Corsini-Foka, Kondylatos, and Santorinios 2013; Dimitriadis et al. 2022; Kopsida, Margaritoulis, and Dimopoulos 2002; Panagopoulos et al. 2003; Papazekou et al. 2024). The first two species have local populations that nest and feed in the Mediterranean Sea, whereas the leatherback turtle is a visitor from the Atlantic Ocean that does not breed in the basin (Casale et al. 2018). The loggerhead turtle is the most common, abundant, and studied species in the area, nesting mainly in the eastern part of the basin (Margaritoulis, Koutsodendris, and Panagoloulou 2007; Casale and Margaritoulis 2010). Greece hosts about 46% of the total documented nesting sites for the loggerhead in the Mediterranean (Casale et al. 2018; Margaritoulis, Lourenço, and Rees 2023). Known important foraging grounds for the species are the Adriatic Sea, Tunisia waters, the Amvrakikos Gulf in eastern Ionian Sea, and the North and Central Aegean Sea (Casale et al. 2018; Chatzimentor et al. 2021). The green turtle is encountered mainly in the eastern part of the Mediterranean basin, nesting in Turkey, Cyprus, and Syria (Casale et al. 2018; Türkozan et al. 2023). The species is known to use Greek waters as foraging grounds (Casale et al. 2018; Casale and Margaritoulis 2010), and it has been observed to nest at least twice on Cretan beaches (Archelon 2019).

Mediterranean populations of both species have been identified as Regional Management Units (RMUs) (Wallace et al. 2023, 2010). Although the global status of the loggerhead turtle is listed as vulnerable in the IUCN (International Union for the Conservation of Nature) Red List of Threatened Species (www.iucnredlist.org), the status of the Mediterranean population is positive; it is listed as least concern in the IUCN Red List. The positive status is due to conservation measures that have been taken in the past decades, and any cessation of all these efforts will jeopardize its existing conservation status (Casale et al. 2018; Mazaris et al. 2017). Contrary, the status of green turtle, globally, is of concern, as it is listed as endangered in the IUCN Red List.

Our knowledge regarding sea turtle stranding events in Greek waters is limited to past, mainly descriptive (Kopsida, Margaritoulis, and Dimopoulos 2002; Margaritoulis 1986; Panagopoulos et al. 2003), and geographically restricted information (Corsini-Foka, Kondylatos, and Santorinios 2013; Dimitriadis et al. 2022; Papazekou et al. 2024). Here, a 12-year dataset (from 2010 to 2021) of loggerhead and green turtle stranding events was analyzed with the aim of understanding anthropogenic activities that threaten these two species and identifying areas with high density of stranding events that could facilitate the spatial management in the Greek Seas.

2 | Material and Methods

2.1 | Stranding Data

Information on stranded sea turtles derived from port authorities reports during the period 2010 to 2021, which were registered and stored at an IMBRIW-HCMR (Institute of Marine Biological Resources and Inland Waters - Hellenic Centre for Marine Research) database. Over 6000 stranding events of loggerhead and green turtles were documented in the Greek Seas (i.e., Aegean, Ionian, and Cretan seas) (Figure 1). As the Greek coastline presents highly complicated topography, 282 port authorities are employed, being responsible for inspection and surveillance. Upon a stranding event, the person who spotted the event calls and informs the corresponding port authority. For each stranding event, port authorities submit photographic material followed by a report that includes information on date and location (geographic coordinates or toponym). Information on species, sex, and morphometrics (i.e., straight carapace length (SCL) (in centimeters), straight carapace width (SCW) (in centimeters), curved carapace length (CCL) (in centimeters), and curved carapace width (CCW) (in centimeters)) is also recorded based on a specific protocol (https://ia37rg02wpsa01.blob.core.windows.net/fek/02/2023/20230203376.pdf; protocol on pages 36231–36232). Cases presenting advanced decay are also noted. Species classification was based on the report and the submitted photographic material following the examination by an expert. Clues such as external injuries, bleeding, the presence of fishing nets, or extruding fishing line were also noted. A veterinary report was also considered if available. Ambiguous cases of species

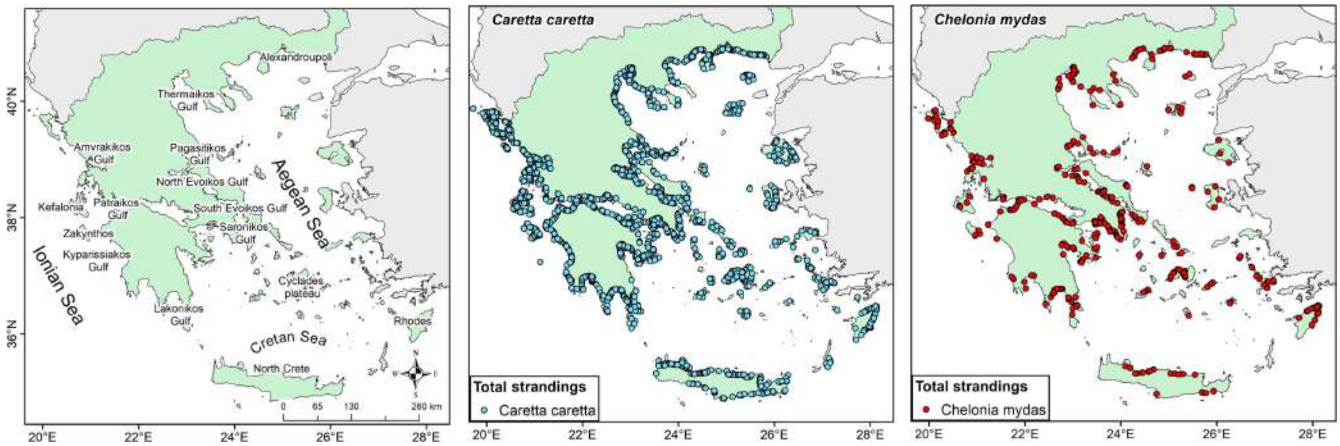

FIGURE 1 | Map of toponyms and the location of stranding events for the loggerhead turtle *Caretta caretta* and the green turtle *Chelonia mydas* for the period 2010–2021.

identification were classified as "turtle" and were excluded from analyses.

Stranded animals were initially categorized into "dead" or "alive". As veterinary reports were available in less than 5% of all cases (4.14% and 2.18% of loggerhead and green turtles, respectively) and necropsies were even rarer, understanding the cause of stranding or the cause of death was not possible. Thus, the aim of the analysis was to define the possible interaction of sea turtles with anthropogenic activities rather than the cause of stranding. For this purpose, stranding records assigned to anthropogenic-related activities were separated into the following categories:

- "Injuries" (i.e., one or more wounds clearly resulted from anthropogenic interaction such as vessel strikes based on veterinary/port authority reports).
- "Fishing gear entanglement" when remnants of a fishing gear (nets or longlines) were found on the body of the stranded animal based on photographs, veterinary and/or port authority reports. An additional small percentage of stranding events was also added in this category when entanglement in ropes was apparent or wounds by a harpoon were clearly mentioned in the port authority reports.
- "Marine litter ingestion" (when a veterinary report clearly stated that the stranded animal had swallowed a plastic item, e.g., plastic bag).
- "Oil pollution" (when a veterinary report clearly stated that the cause of death was due to oil pollution).

Additional categories, independent to anthropogenic impact, were assigned such as "predation" (when clear signs of predation of other animals were found on the body of the stranded animal based on photo identification, veterinary, and/or port authority reports), "bleeding" (when a veterinary report clearly stated that the cause of death was due to bleeding), and "disease" (when a veterinary report clearly stated that the cause of death was due to disease). All other cases that had no information available to associate the stranding event to any kind of the above categories were assigned as "unknown".

The Mann–Kendall trend test was used to assess the presence of any increasing trend in stranding events over the years. The Mann–Kendall test was performed using the MannKendal() function from the "zyp" (v0.11–1) package of R (v4.2.3; R Core Team, 2023). Analysis of variance (ANOVA) was applied to detect annual differences in the number of stranding events among seasons (i.e., spring (March to May), summer (June to July), autumn (September to November), and winter (December to February) per species and categories (i.e., total strandings, "injuries," and "fishing gear entanglement"). ANOVA was also applied to detect differences in the mean CCL of total strandings among seasons. The Kruskall–Wallis tests were used when the Shapiro–Wilkinson tests indicated a failure to meet the two assumptions of normality and homogeneity of variance. Differences were considered statistically significant at p value < 0.05. Post hoc comparisons were performed using the Tukey HSD test.

2.2 | Identifying "Hotspot Stranding Areas"

All stranding records were georeferenced based on the toponym information provided in the port authority report and a .shp file was produced using ArcGIS (ESRI 2015; v.10.4). The Kernel Density analysis tool in ArcGIS (ESRI 2015; v.10.4) was applied to identify "hotspot stranding areas", i.e. areas of high occurrences of sea turtle strandings per species. The Kernel Density analysis tool calculates the density of features in a neighborhood around those features. Specifically, a smoothly curved surface is fitted over each point with the surface value being highest at the location of the point and decreasing as the distance from the point increases, reaching zero at a specified radius distance from it. Considering the peculiar topography of the Greek Seas, the high number of islands, and the number of available records, the specified radius distance was set at 10 nm. The Kernel function is based on the quartic kernel function (Silverman 1986). The radius distance is based on Silverman's rule-of-thumb bandwidth estimation formula.

The Kernel Density analysis tool was applied separately for the two species to define "hotspot stranding areas" in the case of the following: (a) total stranding records, (b) stranding records characterized as "injuries," and (c) stranding records characterized as "fishing gear entanglement." The latter was used to visualize areas of fishery interactions.

Moreover, the Kernel Density tool was applied separately to define "hotspot stranding areas" for the different developmental stages of loggerhead and green turtles. Analysis was conducted solely in cases that CCL was recorded and stranded animals were assigned as (a) juveniles, (b) subadults, and (c) adults. For the loggerhead turtle, individuals with CCL less than 30 cm were classified as juveniles, CCL between 30 and 75 cm as subadults, and CCL greater than 75 cm as adults (Casale, Mazaris, and Freggi 2011; Margaritoulis et al. 2003). For the green turtle, individuals with CCL less than 31.5 cm were classified as juveniles, CCL between 31.5–85 cm as subadults, and CCL greater than 85 cm as adults (Türkozan et al. 2013).

TABLE 1 | Stranding category for the loggerhead turtle *Caretta caretta* and the green turtle *Chelonia mydas* in the Greek Seas for the period 2010–2021.

Stranding category I	Stranding category II	*C. caretta*	*C. mydas*
Non-anthropogenic Interaction	Disease	0.08%	0.19%
	Bleeding	0.20%	0.19%
	Predation	0.26%	0.19%
	Unknown	74.68%	64.98%
Anthropogenic Interaction	Marine litter ingestion	0.11%	0.19%
	Oil pollution	0%	0.37%
	Fishing gear entanglement	6.03%	4.31%
	Injuries	18.64%	29.58%

3 | Results

3.1 | Stranding Events Description

Totally, 6591 stranding events of loggerhead turtles were recorded from 2010 to 2021 in Greek waters (Figure 1) with 96.45% (6357 records) found dead and 3.55% (234 records) alive. A 6.5% of the dead stranded loggerhead turtles (414 out of 6357 records) were found in advanced decay. The majority of the records included stranded animals reported as "unknown" (74.68%), 18.64% of the records were related to apparent "injuries," and 6.03% were related to "fishing gear entanglement" (Table 1). The CCL was measured in 5375 individuals. The mean CCL was 71.8 cm (±17.6 SD; range: 5.5–180 cm) with juveniles and subadults (i.e., sea turtles with CCL < 75 cm) holding 66% of the stranded records (Figure 2A). Mean CCL varied among seasons (F-value = 4.24, p value < 0.01), being higher during spring (Tukey's HSD test: p value < 0.01). The Mann–Kendall trend test denoted an increasing trend of stranding events over the years (Kendall's tau = 0.545, p value = 0.016; Figure 2A). Total stranding events varied significantly among seasons (F-ratio = 50.95, p value < 0.01), being higher during summer (Tukey's test: p value < 0.01). This was also the case for the categories

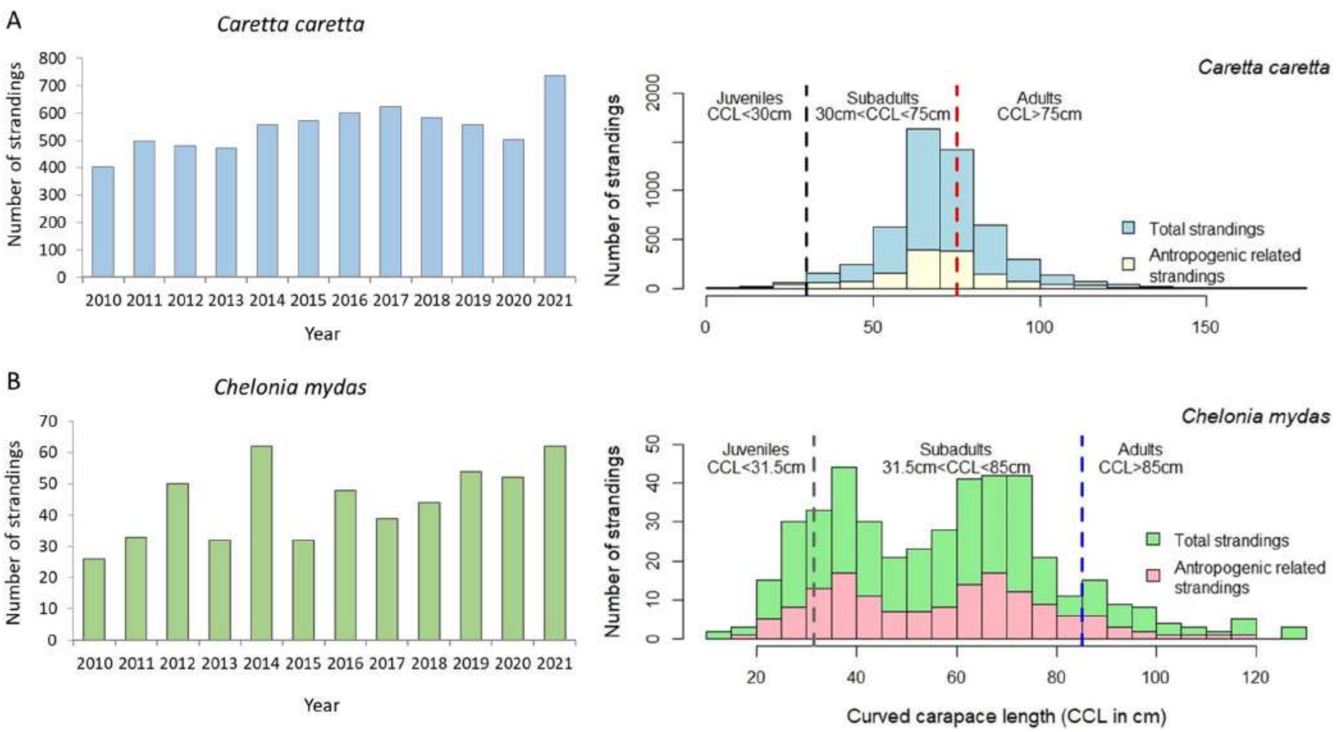

FIGURE 2 | Annual variability of total stranding events and frequency distribution of curved carapace length (CCL) (in centimeters) of (A) loggerhead turtle *Caretta caretta* and (B) green turtle *Chelonia mydas* for the period 2010–2021 in the Greek Seas.

"unknown," "injuries," and "fishing gear entanglement" (F-value = 31.52, p value < 0.01; F-value = 24.20, p value < 0.01; F-value = 14.17, $p < 0.01$, respectively), being higher during summer (Tukey's HSD test: p value < 0.01).

In the case of green turtles, 534 stranding events were recorded from 2010 to 2021 in Greek waters (Figure 1) with 94.9% (507 records) found dead and 5.1% (27 records) alive. A total of 18.5% of the dead stranded green turtles (94 out of 507 records) were found in advanced decay. The majority of the records involved stranded animals reported as "unknown" (64.98%), 29.58% of the records were related to "injuries," and 4.31% were related to "fishing gear entanglement" (Table 1). The CCL was measured in 435 individuals. The mean CCL was 58.3 cm (± 23.1 SD; range: 10–130 cm) with juveniles and subadults (i.e., sea turtles with CCL < 85 cm) holding 87% of the stranded records (Figure 2B). Mean CCL varied among seasons (ANOVA: F-ratio = 2.70, p value = 0.05), being higher during summer compared to winter (Tukey's HSD test: p value = 0.03). The Mann–Kendall trend test denoted an increasing trend of stranding events over the years (Kendall's tau = 0.492, p value = 0.033; Figure 2B). Total strandings varied among seasons (F-value = 7.42, p value < 0.01), being higher during summer (Tukey's HSD test: p value < 0.05). This was also the case for strandings reported as "unknown" and "injuries" (F-value = 4.90, p value < 0.01; F-value = 3.114, p value < 0.05, respectively), whereas in the case of "fishing gear entanglement," no significant difference was found (F-value = 1.76, p = 0.17).

3.2 | Identifying "Hotspot Stranding Areas"

Density maps (Figure 3) showed that certain areas presented higher number of strandings and were considered as "hotspot stranding areas" of the loggerhead turtle. In the Ionian Sea, areas with high densities of strandings were the Amvrakikos, Kyparissiakos, and Lakonikos Gulfs, as well as Zakynthos Island. In the Aegean Sea, higher densities were noted over a series of gulfs such as Saronikos, Thermaikos, and North and South Evoikos Gulfs. Moreover, the analysis highlighted areas such as the coastline of the Thracian Sea (i.e., Alexandroupoli wider area) and the north–central coast of Crete. The analysis of "fishing gear entanglement" strandings underlined the importance of areas in the Ionian Sea, such as Zakynthos Island, Patraikos, and Amvrakikos Gulfs in the Ionian Sea, followed by Alexandroupoli wider area, Saronikos Gulf, and Cyclades plateau in the Aegean Sea (Figure 3).

Further, analysis revealed that the "hotspot stranding areas" differentiated among the developmental stages of the loggerhead turtle (Figure 4). For the juveniles, the areas with the highest number of stranding events were Zakynthos Island, Saronikos Gulf, the north–central part of Crete, and the Cyclades plateau. For the subadults, the Amvrakikos Gulf, Alexandroupoli area, and the Thermaikos Gulf were identified as "hotspot stranding areas". Finally, for the adult turtles, the importance of Amvrakikos Gulf was highlighted.

For the green turtle, density maps (Figure 3) revealed areas with a high number of total strandings such as Thermaikos, Saronikos and South Evoikos Gulfs, Alexandroupoli area, and Cyclades plateau in the Aegean Sea. The analysis of "fishing gear entanglement" strandings underlined the importance of Thermaikos, Pagasitikos, and Saronikos Gulfs in the Aegean Sea and Patraikos Gulf in the Ionian Sea. The analysis also revealed differences in the "hotspot stranding areas" when considering the developmental stages of green turtles (Figure 4). For the juveniles, areas presenting a higher number of stranding events were the Cyclades plateau and the northern part of Rhodes Island in the Dodecanese complex. For the subadults, the analysis revealed the importance of the wider area of Alexandroupoli and Thermaikos Gulf in the North Aegean Sea, South Evoikos Gulf and Saronikos Gulf in the central Aegean Sea, and the northern part of Rhodes Island in Dodecanese complex. Finally, North Evoikos and Saronikos Gulfs were the areas presenting the higher number of stranding events of adult green turtles.

3.3 | Fishery Interaction: Stranding Events Related to Fishing Gear Entanglement

Fishing gear entanglement was observed in 345 stranding events for the loggerhead turtle (193 longlines, 141 nets, 10 longlines and nets, and 1 bottom trawl, respectively) and in 23 stranding events for the green turtle (6 longlines and 17 nets) for the study period. For the loggerhead turtle, this means an average of 16.1 (± 6.63) animals per year entangled in longlines and an average of 11.8 (± 4.83) animals per year entangled in nets. For the green turtle, this equals to an average of 0.5 (± 0.67) entanglements per year in longlines and 1.42 (± 1.44) entanglements per year in nets. The spatial distribution of the entangled sea turtle strandings underlined the importance of Zakynthos Island in the Ionian Sea for longlines, whereas several areas were highlighted for nets (e.g., Zakynthos Island and Amvrakikos Gulf in the Ionian Sea and Saronikos and Thermaikos Gulfs in the Aegean Sea) (Figure 5).

4 | Discussion

This is the first large-scale analysis of sea turtle (i.e., loggerhead and green turtles) stranding events over the entire Greek Seas addressing the impact of anthropogenic activities on sea turtles, the occurrence of seasonality patterns, and the spatial distribution of stranding events. For both species, stranding events showed an increasing trend over the years. The increasing trend in the stranding events can be attributed to a plethora of reasons, such as possible increases in sea turtle population, in anthropogenic pressure, or even in reporting effort (Mghili et al. 2023). The latter could be the result of public awareness activities paying off, resulting in more calls reaching the port authorities. In the same line, the recently observed increase of the nesting activity in the Mediterranean Sea (Casale et al. 2018; Margaritoulis, Lourenço, and Rees 2023) is often considered as an index of population status.

Identifying the reason behind a standing event is constrained by the state of the animal's decomposition and the lack of necropsy (Dimitriadis et al. 2022; Hart, Mooreside, and Crowder 2006). Here, the small number of necropsies, the advanced decay of the carcass, especially in green turtles, and the absence of apparent visible evidence on the stranded animals resulted into the high

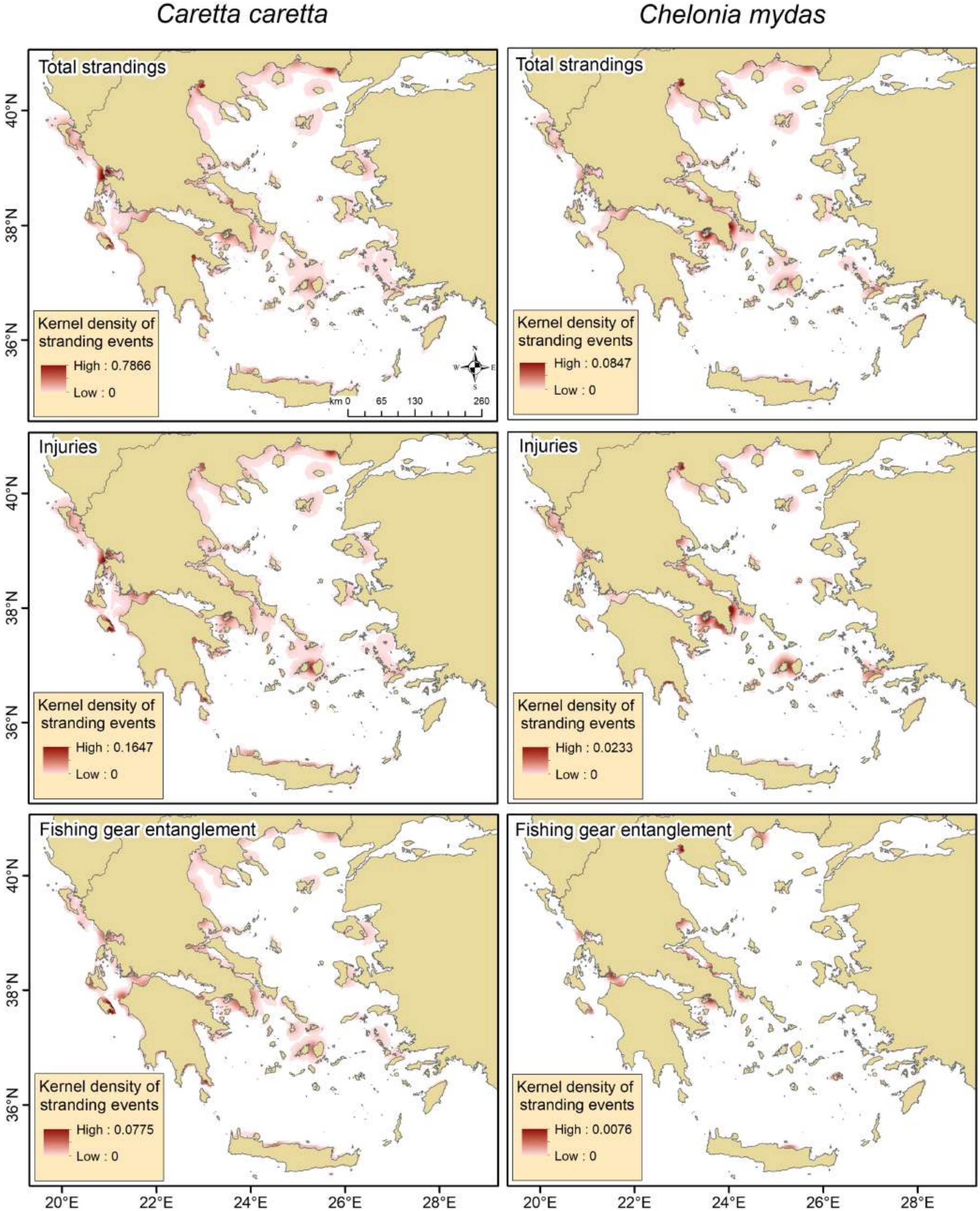

FIGURE 3 | Kernel density of total strandings, "injuries", and "fishing gear entanglement" strandings of loggerhead turtle *Caretta caretta* and green turtle *Chelonia mydas* for the period 2010–2021 in the Greek Seas.

percentage of "unknown" strandings. Special focus was given on the stranded sea turtles that showed signs of interaction with anthropogenic activities involving marine litter ingestion, oil pollution, fishing gear entanglement, and injuries, representing ~25% and ~35% of the total strandings for the loggerhead and the green turtle, respectively.

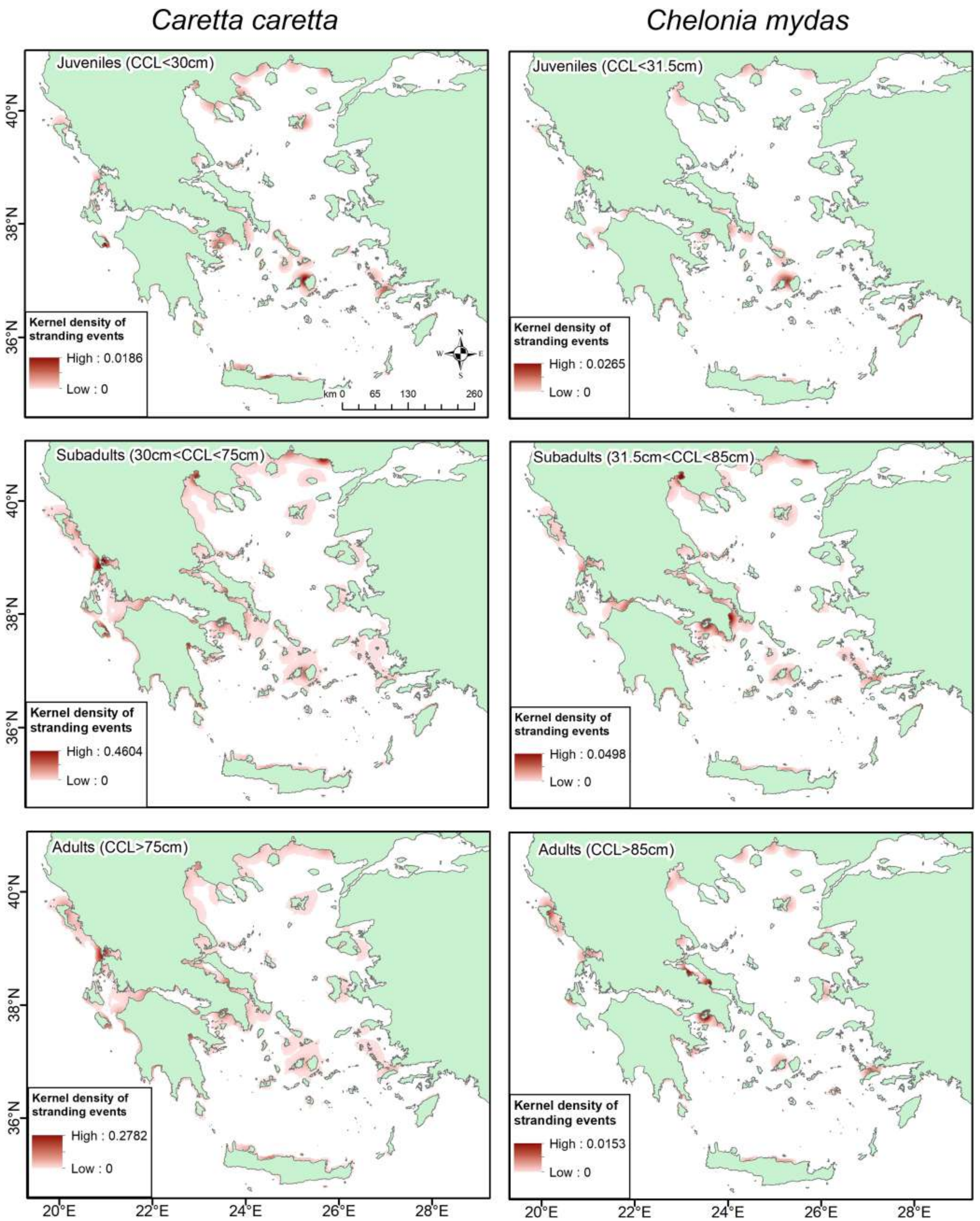

FIGURE 4 | Kernel density of total stranding events of juvenile, subadult, and adult loggerhead turtle *Caretta caretta* and green turtle *Chelonia mydas* for the period 2010–2021 in the Greek Seas. CCL, curved carapace length.

Both sea turtle species indicated significantly higher number of strandings in the summer. Seasonality in the stranding events has been also observed in other areas of the Mediterranean Sea (Bellido López et al. 2018; Casale et al. 2010; Corsini-Foka, Kondylatos, and Santorinios 2013; Marisaldi, Torresan, and Ferrari 2023; Papazekou et al. 2024; Tomás et al. 2008).

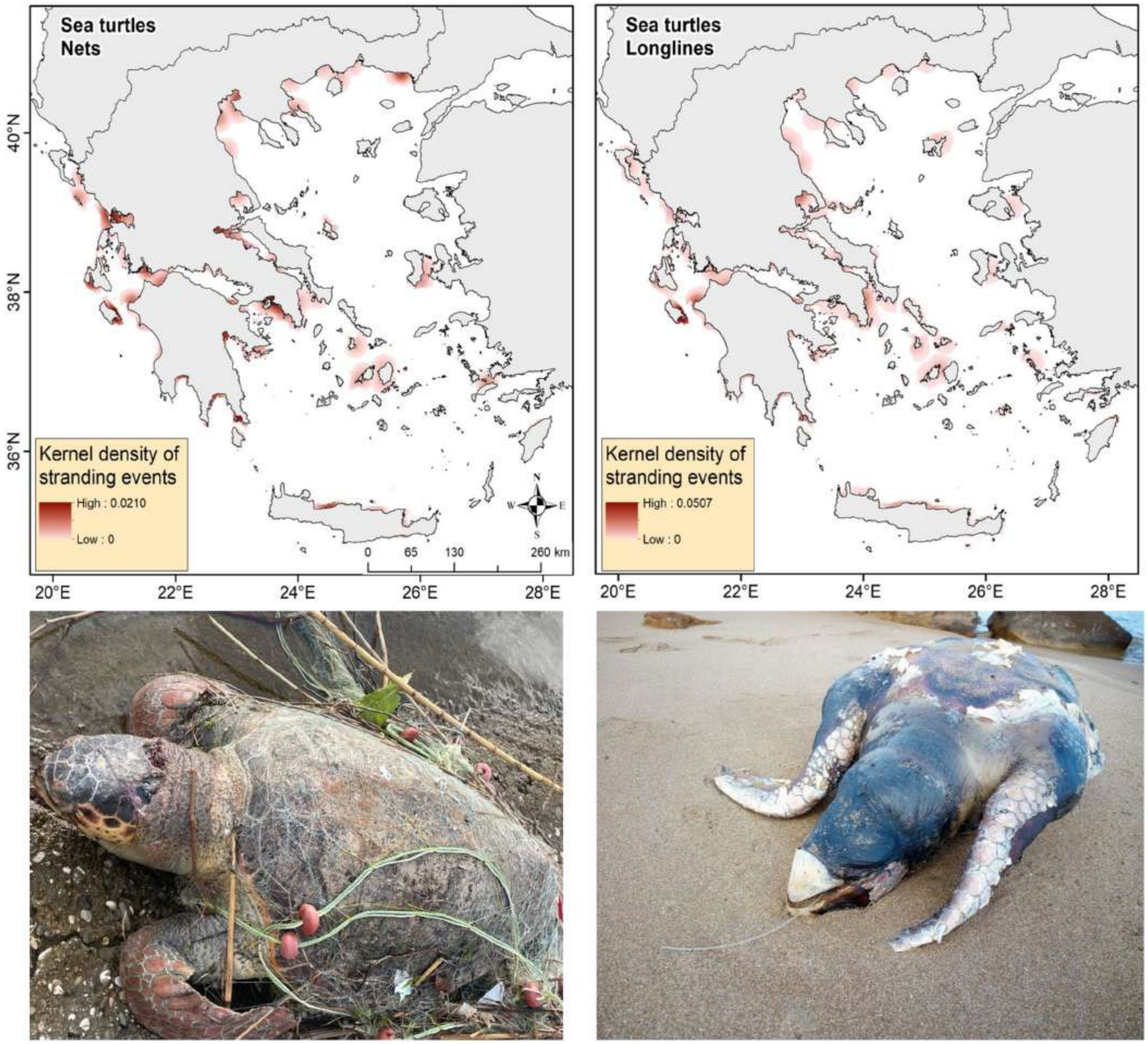

FIGURE 5 | Kernel density of stranding events of entangled sea turtles (i.e., loggerhead turtle *Caretta caretta* and green turtle *Chelonia mydas*) to fishing gears (i.e., nets and longlines) for the period 2010–2021 in the Greek Seas. Photographs of sea turtles entangled in nets and longlines.

Previous studies have reported that increased anthropogenic activity at sea during the summer has been linked to increased stranding events in the Mediterranean waters (Mghili et al. 2023; Papazekou et al. 2024; Tomás et al. 2008). In Greek waters, summer is characterized by amplified ship traffic in the coastal zone due to tourism activities (Tsiotas 2017) and increased fishing effort of the small-scale fishery (Tzanatos et al. 2005). Also, summer corresponds to the nesting period of the loggerhead turtle that lasts from mid-May to early August (Schofield et al. 2013). At this time of the year, a high number of turtles approach the coast to nest, being more vulnerable to the increased rate of anthropogenic activity. Furthermore, during the summer months, human presence on the coasts is increased, resulting in a higher likelihood of spotting a stranded animal. These conditions are likely to act synergistically, producing a higher number of stranding events during this time period (Papazekou et al. 2024).

Going a step further, the spatial distribution of stranding events was explored and discussed in terms of known nesting and foraging grounds. Greek territory hosts important terrestrial and marine habitats for the loggerhead turtle, including migratory routes between nesting and foraging areas, such as the Ionian Sea, the west Peloponnese, and the Central and North Aegean Sea (Almpanidou, Markantonatou, and Mazaris 2019; Casale et al. 2018). Kyparissiakos Gulf, Zakynthos, and Kefalonia Islands host the most important rookeries in terms of density and number of clutches in the Mediterranean Sea (Casale et al. 2018; Margaritoulis 2005). Amvrakikos Gulf and the neritic waters of the central Aegean Sea have been identified as important foraging habitats for adult loggerhead turtles (Casale et al. 2018; Rees et al. 2017; Zbinden et al. 2008). Amvrakikos Gulf is a key foraging and wintering ground that hosts not only loggerhead turtles nesting in Greece but also nesting loggerhead turtles from Turkey, Cyprus, and Libya (Rees et al. 2017). The Aegean Sea hosts the main foraging grounds for adult loggerhead turtles originating from rookeries of North Crete (Margaritoulis and Rees 2011). In addition, the North Aegean Sea hosts oceanic and neritic foraging grounds for juvenile and subadult loggerhead turtles (Chatzimentor et al. 2021).

"Hotspot stranding areas" of loggerhead turtle coincided with important foraging grounds for the species, such as Amvrakikos, Saronikos, and Thermaikos Gulfs, and certain nesting areas such as Zakynthos Island (Casale et al. 2018; Rees et al. 2017; Zbinden et al. 2008). The analysis also revealed that the hotspot areas of stranding events differentiated among the developmental stages of the loggerhead turtle. For adults and subadults, those "hotspot stranding areas" coincided with foraging grounds, such as Amvrakikos Gulf and North Aegean Sea (Casale et al. 2018; Chatzimentor et al. 2021; Rees et al. 2017). For juveniles, "hotspot stranding areas" coincided with the main nesting sites, such as Zakynthos Island (Margaritoulis 2005) and North Crete (Margaritoulis and Rees 2011). This implies that "hotspot stranding areas" per developmental stage largely coincided with their respective distribution areas. Although a stranding area is not expected to always coincide with the mortality area, as current regimes, wind direction, and oceanographic conditions play a decisive role where an animal might strand (Hart, Mooreside, and Crowder 2006), the current findings indicate that the wider stranding and mortality areas are not likely to vary much. This raises an issue for further exploration.

Furthermore, green turtle density maps showed that Thermaikos Gulf, Saronikos Gulf, and Cyclades plateau in the Aegean Sea were areas with high number of stranding events, denoting the presence of the species in these areas. When it comes to species developmental stages, the "hotspot stranding areas" were further differentiated, giving a clearer picture of green turtle potential presence in Greek waters. The species is often found in the Greek Seas, especially in the Lakonikos Gulf in the southern Peloponnese, an area considered as a developmental and foraging habitat for juvenile green turtles (Margaritoulis and Panagopoulou 2010; Margaritoulis and Teneketzis 2003). Also, the presence of green turtles is frequent in the waters of Rhodes Island in the southeast Aegean Sea (Corsini-Foka, Kondylatos, and Santorinios 2013; Margaritoulis and Panagopoulou 2010), areas that are in line with the findings of the present work.

The majority of the stranded green turtles were juveniles and subadults, which is in agreement with others' works in the Greek Seas (Corsini-Foka, Kondylatos, and Santorinios 2013; Kopsida, Margaritoulis, and Dimopoulos 2002; Panagopoulos et al. 2003). Green turtles, during the first years of their life, come to the waters of the Aegean Sea in search of food (Casale et al. 2018). During this phase, they are more vulnerable to anthropogenic activities such as fishing (Stokes et al. 2015), having a higher probability of being stranded. In addition, compared to adult green turtles that are primarily herbivores, juveniles and subadults are more susceptible to fishing activity due to their omnivorous nature (Stokes et al. 2015) leading to depredation and/or bait attraction.

In the Mediterranean basin, fishing activity has been recognized as one of the most important sources of anthropogenic mortality for sea turtles (Carpentieri et al. 2021; Marisaldi, Torresan, and Ferrari 2023; Margaritoulis, Koutsodendris, and Panagoloulou 2007; Tomás et al. 2008). Sea turtles are by-catch of both medium-scale (e.g., bottom trawls) and small-scale fisheries (e.g., set nets and longlines) (Carpentieri et al. 2021). The bottom trawl is the fishing gear with the highest number of captures per year, though the set net is the fishing gear with the highest direct mortality rate reaching up to ~ 50% (Carpentieri et al. 2021). Stranding analysis has shown that clear evidence of fishing gear entanglement was less than 10% for both species.

Here, the longline was the fishing gear presenting the highest number of sea turtle entanglements, predominantly the loggerhead turtle. This was especially the case in the Ionian Sea, an area including key foraging grounds and nesting sites of the species (Casale and Margaritoulis 2010). The number of entangled sea turtles in the stranding incidents is below the 2500 sea turtle entanglement estimates on annual basis in set nets at Greek waters (Carpentieri et al. 2021 and references therein), but not far from the 98 animals mentioned as incidental catch by set longlines in 2008 in the Aegean Sea (Carpentieri et al. 2021 and references therein). Depredation on fishing gears is known for sea turtles (Casale and Margaritoulis 2010). It is inevitably associated with fishing gear damage and catch loss and often results to incidental catch or detrimental injuries and, consequently, stranded animals (Carpentieri et al. 2021; Panagopoulou et al. 2017). Mortality due to fishing gear entanglement can either be direct or indirect. The small percentage of clear evidence of fishing gear entanglement in the present study could be related to multiple reasons. Entangled sea turtles can die directly from hypoxia as they remain entangled for a long time underwater. If, after dying, they sink, they remain on the seafloor for days until the gas produced by decomposition makes them float to the surface (Nero et al. 2022). This process can make it difficult to determine whether a stranded animal is a result of incidental catch (Vassallo et al. 2024). In addition, indirect mortality induced after an interaction with a fishing gear can occur from a few hours to months later (Margaritoulis, Koutsodendris, and Panagoloulou 2007).

Especially for the longlines, associated strandings might reflect more the direct mortality caused by the gear, which is generally low, rather than the actual entanglement rate, as the hooked loggerhead turtles have the capacity and strength to rise to the surface, even when entangled, and breathe (Carpentieri et al. 2021). The hooked turtles are usually released with an ingested hook and a piece of nylon line that can cause severe damage in their intestines, rendering the animals unable to digest food (Margaritoulis, Koutsodendris, and Panagoloulou 2007). As death after an interaction with a fishing gear can occur many days, weeks, or even months after (Margaritoulis, Koutsodendris, and Panagoloulou 2007), it is clear that only a big number of necropsies could have enlightened the last part. Indeed, the number of hook entanglement could be seriously underestimated since necropsy is a prerequisite to reveal the presence of a hook. Despite the small percentage of entanglement, here, spatial analysis underlined the importance of certain areas as recurrent sites of sea turtle entanglement. Zakynthos Island was the single area highlighted for longlines, whereas for nets the recurrent areas were Zakynthos

Island, Amvrakikos and Lakonikos Gulfs in the Ionian Sea, and Saronikos and Thermaikos Gulfs in the Aegean Sea. These areas largely coincide with areas of increased fishing effort of the small-scale fishery (Solanou et al. 2024). Taking into account the number of stranding events along with the presence of recurrent sites of entanglement, further investigation should be done to explore the potential of applying mitigation measures focusing on such specific areas. Moreover, identifying seasonality patterns along with spatial patterns can aid managers to develop more accurate temporal and spatial measures (Hart, Mooreside, and Crowder 2006).

As fishing activity poses a major threat, the protection of sea turtles' key marine habitats has been acknowledged as a high priority for the Mediterranean basin (Casale et al. 2018). The present work has shed light on the interaction of sea turtles with anthropogenic activities in the Greek Seas based on strandings, identified seasonal patterns, and underlined "hotspot stranding areas". Management strategies could be more effective focusing on these "hotspot stranding areas" either by strengthening public awareness campaigns locally or through technical measures like specialized hooks to reduce bycatch and sea turtle mortality.

Nevertheless, the identified spatial and temporal patterns must be considered under the prism of certain limitations. The identified "hotspot stranding areas" could be partly related to the proximity to foraging or nesting grounds and/or changes in the species' population density. Moreover, differences in the monitoring effort have also an impact. For example, stranding events in populated coastlines are more likely to be detected compared to remote or poorly resourced locations (Clarke et al. 2021). Also, the existence of local environmental organizations in some places may also promote activities that can increase public awareness, coast surveillance, and the likelihood of reporting a stranding event. In addition, monitoring effort is not standardized across months and years which makes it challenging to interpret seasonal patterns. Seasonal changes in the fishing pressure by certain gears can also have an impact. These limitations underline the need for an organized monitoring stranding network (Clarke et al. 2021). One more issue is related to the degree that stranding and mortality grounds may overlap. For this, the application of drift models, which are based on local water circulation and wind regimes (Allen 2005) or backtracking models, is needed. The latter takes into account the time needed for a submerged carcass to float from a specific depth to the surface (Nero et al. 2013; Nero et al. 2022). Such modeling approaches would also contribute to more accurate estimations of the number of dead animals at sea that are unlikely to strand (Hart, Mooreside, and Crowder 2006). Future work on fishery interactions could involve overlapping with the spatial distribution of fishing effort.

Author Contributions

Smaragda Despoti: conceptualization, methodology, formal analysis, writing – original draft. **Maria Solanou:** methodology, formal analysis, data curation, investigation. **Stavroula Tsoukali:** data curation. **Vasilis Valavanis:** data curation. **Konstantinos Tsagarakis:** writing – review and editing. **Marianna Giannoulaki:** conceptualization, methodology, formal analysis, writing – review and editing, supervision.

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Disclosure

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Sea turtle stranding data were obtained from port authority reports, and according to the restrictions imposed by Greek legislation (Ministerial Decree 3376, Vol. B/19 May 2023), they cannot be disclosed to the public.

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