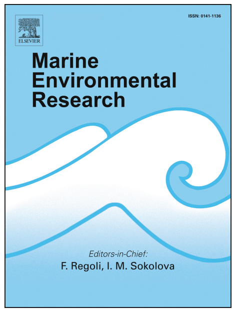

Combining methods for detection of bycatch hotspot areas of marine megafauna species in and around critical rookeries and foraging areas

Nikolaos Simantiris, Charalampos Dimitriadis, Stavros Xirouchakis, Marios-Dimitrios Voulgaris, Evangelia Beka, Martha Z. Vardaki, Georgios Karris

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The rationale

1. Collect satellite data and questionnaire surveys (local ecological knowledge) to spatially delineate habitat use by sea turtles and seabirds and identify fishing grounds
2. Conduct a spatial analysis to delineate the overlap and intensity of interaction between animal habitat use and fishing activity through a vulnerability assessment
3. Identify bycatch hotspots and implement proper mitigation measures

Bycatch impact

SEA TURTLES

- Mortality (entanglement and drowning)
- Injuries (sustained from fishing gear)
- Population decline
- Stress (bycatch survivors may have injuries and experience stress that influences their reproduction and survival probability)

SEABIRDS

- Mortality (Direct death due to entanglement)
- Population Decline
- Disruption of Ecosystem's function (Seabirds are an important indicator of the ecosystem's health and bycatch can affect their population and therefore the entire ecosystem's functioning)

MITIGATION ACTIONS

- Technical solutions (bycatch reduction devices, green LED lights on the nets, weighted lines)
- Training of fishers on safe-release
- Incentives for fishers that avoid marine protected areas
- Regulation of high bycatch fishing gear and methods
- Bycatch monitoring
- Policy/regulations to enforce the use of sustainable fishing practices

Combining methods for detection of bycatch hotspot areas of marine megafauna species in and around critical rookeries and foraging areas

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Abstract

Bycatch, the incidental catch of non-target species, threatens marine megafauna such as sea turtles and sea birds in the Mediterranean region. Identifying bycatch hotspots is essential to guide mitigation measures and target audiences. In the Mediterranean Sea, South Ionian Sea in Greece is a major marine habitat, including critical nesting areas, for sea turtles, and an important breeding and foraging habitat for sea birds. This work combined methodologies to identify bycatch hotspots through a vulnerability assessment and questionnaire surveys utilising both scientific data and local ecological knowledge (LEK). The study determined the major bycatch hotspots for sea turtles and sea birds, evaluated the potential impact on both species, and discussed mitigation measures to reduce the impact of bycatch and effectively protect this economically and ecologically important ecosystem. Our approach and outcomes may well contribute to a science-based and LEK included, adaptive management framework regarding the establishment or revision of Marine Protected Areas in the study area and elsewhere across

critical marine habitats for sea turtles and sea birds.

Keywords: Bycatch, Sea turtles, Sea birds, Satellite data, mitigation strategies, Vulnerability assessment

1. Introduction

One of the major anthropogenic threats affecting marine megafauna conservation is bycatch (i.e. unintentional catch due to excessive fishing activities) (de la Hoz Schilling et al., 2023; Putman et al., 2020; Domingo et al., 2025). Marine megafauna species encounter various types of fisheries due to their extensive geographic distribution and the use of vast marine areas across different regions (Wallace et al., 2010). The likelihood of interactions between fisheries and marine megafauna depends on the spatial and temporal overlap between essential habitats for these species and fishing operations, with the latter involving various fishing techniques and gear types. Despite considerable efforts aiming to address the vulnerability of megafauna to bycatch and identify critical areas where species are prone to bycatch (Lewison et al., 2014; Cardona et al., 2025), scarcity of information for many regions worldwide remains a challenge hindering both sustainable fisheries management and effective conservation of marine megafauna (Cook and Heath, 2018; Fuentes et al., 2023). In the Mediterranean Sea, bycatch is known to affect several marine megafauna species, with sea turtles and sea birds being amongst the most impacted (Izquierdo-Serrano et al., 2022; Karris et al., 2018; Simantiris et al., 2024).

Sea turtles are an emblematic group of reptiles broadly distributed across all oceans except polar regions, presenting great importance to marine ecosystems and the food chain (Hannan et al., 2007; Simantiris, 2024, 2025). Due to their highly mobile nature, sea turtles exploit multiple coastal, neritic, and oceanic habitats at different life stages across their long and complex life cycle (Casale et al., 2018). Yet as highly migratory species, they traverse between foraging and nesting areas which may be located thousands of kilometers apart (Dujon et al., 2018; Hays et al., 2006; Stokes et al., 2015). Therefore, sea turtles are prone to the bycatch threat deriving from many different fisheries (Casale, 2011; Lewison et al., 2014). In the Mediterranean region, bycatch appears to increase the overall mortality of sea turtle populations (Dimitriadis et al., 2022b; Papazekou et al., 2024b; Agabiti et al., 2024).

Seabirds constitute a diverse group of more than 400 species, spending part or all of their lives interacting with oceans, e.g., by foraging and migrating over them (Harrison et al., 2021). They also constitute one of the most threatened group of birds facing various ecological challenges (Croxall et al., 2012; BirdLife, 2018). These marine top predators are nowadays recognized as critically important bioindicators of marine ecosystems that are useful in assessing the environmental disruption and the impacts of climate change on marine biota (Parsons et al., 2008; Mesquita et al., 2015). Indirect mortality from bycatch in fishing gear is presently a major threat to seabirds, with longline and gillnet fishing being the most impactful fishing practices (Cortés et al., 2017; Dias et al., 2019; Courbin et al., 2024). Despite these considerations, significant gaps of knowledge for the spatial distribution and rate of seabirds' bycatch persist in the Mediterranean, including key areas such as the central and Eastern Mediterranean (Ram´ırez et al., 2024).

Identifying the strength and extent of the spatial overlap between high use areas by marine megafauna and human induced threats is often a challenging task (Dimitriadis et al., 2022b; Ferreira et al., 2023). The threat of bycatch to sea turtles and seabirds has been assessed using direct, indirect, and combined approaches aiming to identify mortality hotspots and areas with a high likelihood of species interactions with fisheries. Direct approaches to assess the bycatch and mortality rate involve data collection by observers onboard vessels from industrial fishing fleets (e.g. (Cambie et al., 2013; Cardona et al., 2025)), reporting by fishers on logbook programmes and questionnaire surveys (e.g. (Tagliolatto et al., 2020; Baldi et al., 2022; Tubbs and Berggren, 2024)). Alternatively, indirect methods for identifying bycatch hotspots and high-risk areas for marine megafauna due to fisheries focus on analyzing the overlap between areas frequently used by the animals and the distribution and intensity of fishing effort (e.g. (Pikesley et al., 2018; Almpanidou et al., 2018, 2021; Hatch et al., 2023; Saüt et al., 2024)).

This work, as other studies described above, sets a methodological framework that combines direct and indirect cost-effective approaches, incorporating both scientific data and local ecological knowledge, to identify and evaluate bycatch hotspots in a case study across a critical area for sea turtles and sea birds at the Mediterranean level, the South Ionian Sea (Greece, Mediterranean) (Issaris et al., 2012; Karris et al., 2018; Simantiris et al., 2024). In this study, the authors combine of satellite data and questionnaire surveys, and by the use of a vulnerability assessment approach, we aim to spatially delineate habitat use by sea turtles and sea birds, identify the main fishing grounds and their overlap with habitat use by the animals, and ultimately point out bycatch hotspots. Consequently, this study provides valuable information on where conservation efforts should be allocated and prioritized and suggests a suite of mitigation measures and best practices for the alleviation of bycatch impacts on marine megafauna.

2. Materials & Methods

2.1. Study area

Zakynthos Island (Ionian Sea, Greece) is home to the second largest nesting population of loggerhead (*Caretta caretta*) sea turtles in the entire Mediterranean region (Casale et al., 2018), with about 300 females and 100 males breading and laying an average of 1200 nests annually (Schofield et al., 2017; Margaritoulis et al., 2022). On top of that, nearby marine areas off-Zakynthos Island are systematically used by young and adult turtles (*Caretta caretta, Chelonia mydas*) year-round as foraging areas and migration corridors (Dimitriadis et al., 2022a; Papazekou et al., 2024a). At the same time, the biggest rookery at the Mediterranean level (Kyparissia Bay) and several other stable nesting sites (around the coastline of Kefalonia Island) are located a few tens of kilometers away from the study area (Casale et al., 2018; Dimitriadis et al., 2022b). The study area includes 3 protected areas of the EU habitat and birds Directives (92/43/EEC and 2009/147/EC, respectively) under the codes GR2210001, GR2210002, GR2210004, as well as the National Marine Park of Zakynthos (NMPZ) established by a Presidential Decree in 1999 (Simantiris et al., 2024). NMPZ includes the Strofades island group which is nowadays considered a European breeding population stronghold of Scopoli's shearwater (*Calonectris diomedea*) and the species' largest colony at a national level since it hosts ca. 5,550 pairs while areas around and off Zakynthos island constitute important foraging areas (Karris et al., 2017; Keller et al., 2020). Moreover, the region is a marine habitat of elasmobranchs, cetaceans, and monk seals (Frantzis et al., 2019; Giovos et al., 2021; Papazekou et al., 2024a; Panou et al., 2023). The Natural Environment & Climate Change Agency (NECCA), is the dedicated unit of the Greek government for the management of these marine and coastal areas.

2.2. Innovation of previous methodologies

Existing methodologies for identifying fishing fields include analyzing VMS (Vessel Monitoring System) data, Automatic Identification System

(AIS) data, self-reporting, questionnaires, and onboard observer data (Yan et al., 2022; Wang et al., 2024; Mesquita et al., 2024; Maina et al., 2016; Hu et al., 2016; Ram´ırez et al., 2024; Precoda and Orphanides, 2024; Maina et al., 2018; Tzanatos et al., 2005; Moutopoulos et al., 2020). However, relying solely on VMS and AIS data has several limitations as to the accessibility and reliability of the data, and the fact that VMS is not required for all fishing vessels and fisheries, and especially not for small-scale fishing activities (vessels $\leq$12 m) (Wang et al., 2024; Thoya et al., 2021; Birchenough et al., 2021). On the other hand, the onboard observer and self-reporting methodologies are often determined to be biased and/or incomplete (Gilman et al., 2019; Tubbs and Berggren, 2024). Questionnaires have proven significant for estimating the fishing grounds, although the researchers should evaluate the responses to discriminate true from biased responses (Karris et al., 2013). The innovation of this work is the combination of satellite data (proven to be extremely reliable in detecting vessel occurrence (Santamaria et al., 2017; Paolo et al., 2024)), questionnaires for the fishing community of Zakynthos, and existing telemetry data for species occurrence in the identified fishing fields.

2.3. Questionnaires

A total of 32 small-scale artisanal fishers (SSF), representing more than 90% of the overall registered fishers (N=35 with a fishing fleet of 35 vessels) of the local sector (their fishing area extends all around Zakynthos Island up to 3 nautical miles from the coast) (Bennett et al., 2020), responded positively to answering a number of predefined questions, from different fishing shelters and harbors around the island (Fig.1). The fishers had an average of 32 years of experience fishing in the area, with their active years varying between 6 and 52.

2.4. Satellite data

SSF usually consists of relatively small vessels (less than 12 meters in total length) that usually operate within the first three nautical miles from the coast and within a restricted range from their home harbor (Calò et al., 2022), without the obligation to report fishing operations through VMS and AIS systems (Regulation (EU) No 508/2014). After collecting spatial information on the fishing grounds from local fishers (questionnaire surveys), and integrating relevant information from scientific literature (Dimitriadis et al.,

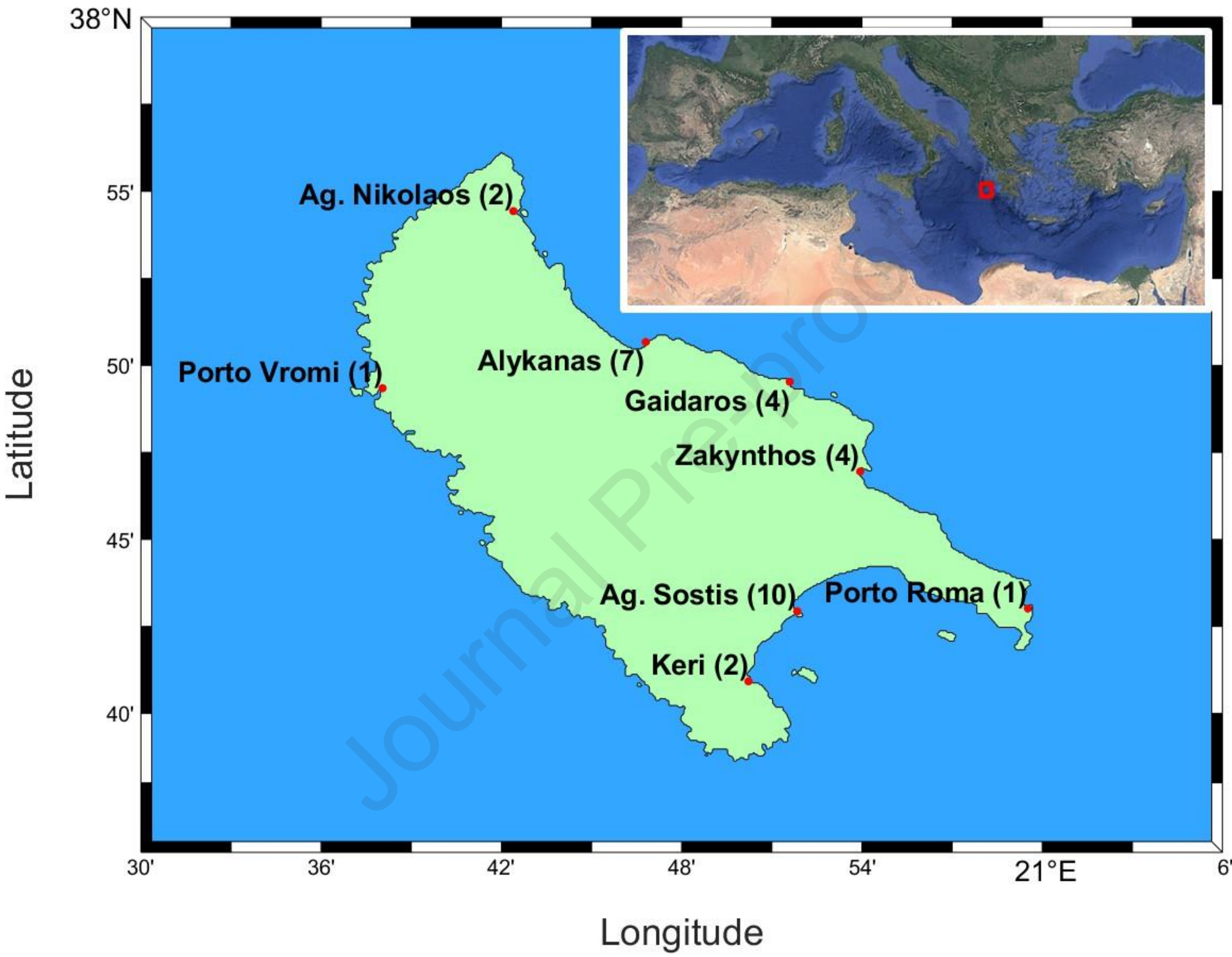

Figure 1: The harbor locations and number of fishers that responded to questionnaires in Zakynthos Island, Greece

2022b; Karris et al., 2013), which however refers to a lower spatial resolution than the one needed herein, we employed a complementary approach for the detection of small scale fishing boats at finest spatial scale by using satellite Synthetic Aperture Radar (SAR) images (Mahdavifard et al., 2022;

Satya et al., 2023; Ouchi, 2016). The pros of using satellite data to monitor maritime activity are the ability to cover vast areas, the process is successful regardless of cloud cover conditions, and most importantly, the vessels do not need to cooperate. The process relies on the fact that radar signal is differently reflected by the sea and the vessels, and hence the satellite sensor will receive different signals (Chaturvedi, 2019; Bioresita et al., 2018). Therefore, detecting vessels in the sea becomes possible.

In this study, SAR data from the sensors onboard the Sentinel-1 satellites were used to detect fishing vessels in the area near Zakynthos Island, Greece. The data were used from the Copernicus Collection data on the Google Earth Engine (GEE) following an approach suggested by previous studies as well (Rodr´ıguez-Benito et al., 2021; Gascoin, 2019). The approach is based on the creation of a map composite in GEE from the Sentinel-1 image collection provided by Copernicus (Gorelick et al., 2017). After carefully selecting the area of interest, a few modifications were made to the original script provided by Gascoin (2019) in order to acquire the data on the occurrence of ships in the study area (Fig.2). The GEE script was used to detect ship occurrence within the study area for a time-series between 2014 and 2024. Due to the difference in the scattering signal of sea and vessels, the script provided a map of the study area, created from the Sentinel-1 images (Sentinel-1 Image Collection: COPERNICUS/S1-GRD), with black pixels representing the sea surface and white pixels representing vessels (Fig.2). The data were filtered to get images collected in interferometric wide (IW) swath mode and VH (transmitter-receiver) polarization at both ascending and descending orbit passes. Finally, the images were filtered to acquire images from the same angles of view and the generated map was exported as GeoTIFF to be further analyzed in Matlab.

In Matlab, the GeoTIFF images were imported and the data points with values greater than zero were determined. The values equal to zero were assumed to correspond to the reflectance of the sea surface. The land was masked to avoid adding bias to our results. To assess the size of vessels, all the connected points were assigned a polygon to estimate their size. To identify the small-scale vessels and discriminate them from other types of vessels (e.g. cargo) we used the size of the vessels (between 2-12 m in length).

2.5. Telemetry data for species

Data on the occurrence of sea turtle species within the study area were extracted from the OBIS-SEAMAP database, the largest data center for sea

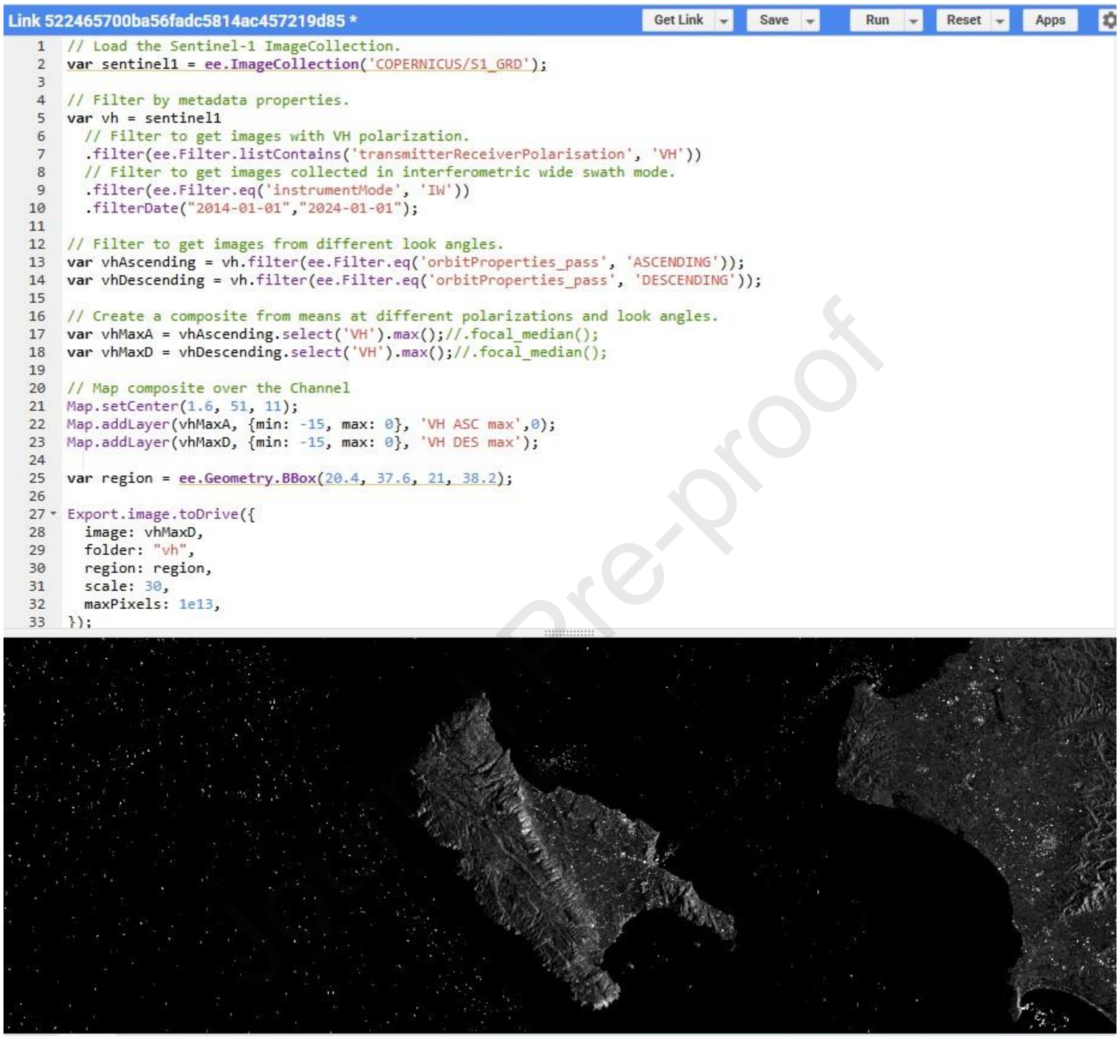

Figure 2: The analysis used in GEE to geographically define and extract the vessels' data

turtle occurrence and distributions in the world (Halpin et al., 2009). As expected, the greatest number of occurrences is noticed in the Laganas Bay in Zakynthos where several thousands of sea turtles are gathered each year during the nesting period (Simantiris et al., 2024; Simantiris, 2024) (Fig.3). In accordance with previous studies (Schofield et al., 2013a), several presences are seen in the surrounding areas proving that sea turtles are present on the island year-round. In addition, data on the use of the pelagic and coastal zones of the study area were also used for the Scopoli's Shearwater breeders in the Strofades colony. The spatial data were based on the use of waterproofed GPS data loggers storing tracking information on 30 different breeders. The loggers were attached to the four central tail feathers using TESA tape and configured to record positions every 15 min. Weighing a total of 20–23 g, the loggers (45 $\times$ 32 $\times$ 18 mm) comprised slightly more than 3% of the mean body mass, which constitutes the recommended threshold for ensuring the elimination of any possible effect on their movement behavior (Phillips et al., 2004; Passos et al., 2010). Data collection was implemented during different breeding seasons between 2009 and 2018. The tracked birds were removed from their breeding burrows between mid of July and early August when the majority of the chicks had hatched and were about 1–2 weeks old. On returning to their nests over the following days, the birds fitted with GPS loggers were recaptured after food provision to chicks; the loggers were removed and data were downloaded and stored. Generally, some of the main foraging grounds according to GPS data are located in coastal areas around Zakynthos Island and off the north-western Peloponnese (Karris, 2014; Karris et al., 2018) (Fig.4). The high density of GPS locations found in the vicinity (within 2-3 nm) of the Strofades colony is not considered an indication of a core foraging area but as bird aggregations just before visiting their nesting sites to feed the chicks during the night. It is known that Procellariiform seabird species such as Scopoli's Shearwater exhibit nocturnal behaviour as an adaptation strategy to avoid terrestrial predators. As a response to that threat, they tend to form flocks or "rafts" during dusk, just before coming ashore to their nesting sites at night (Karris et al., 2018; Rubolini et al., 2015).

2.6. Vulnerability assessment

A vulnerability assessment was carried out in an effort to identify the bycatch threat level for sea turtles and sea birds within the study area. In order to evaluate the vulnerability of each location to bycatch, the methodological approach described by Cuevas et al. (2019) was followed. This approach calculated the ecological vulnerability of selected species based on quantified sensitivity data (degree of impact from specific threat), expected threat (occurrence of a specific threat), and a stability factor (environmental and/or anthropogenic features that influence the effect of the threat). The pixel dimensions used that represent the spatial resolution of the dataset were 50x50 m. The following equations were used for the estimation of the cumulative vulnerability:

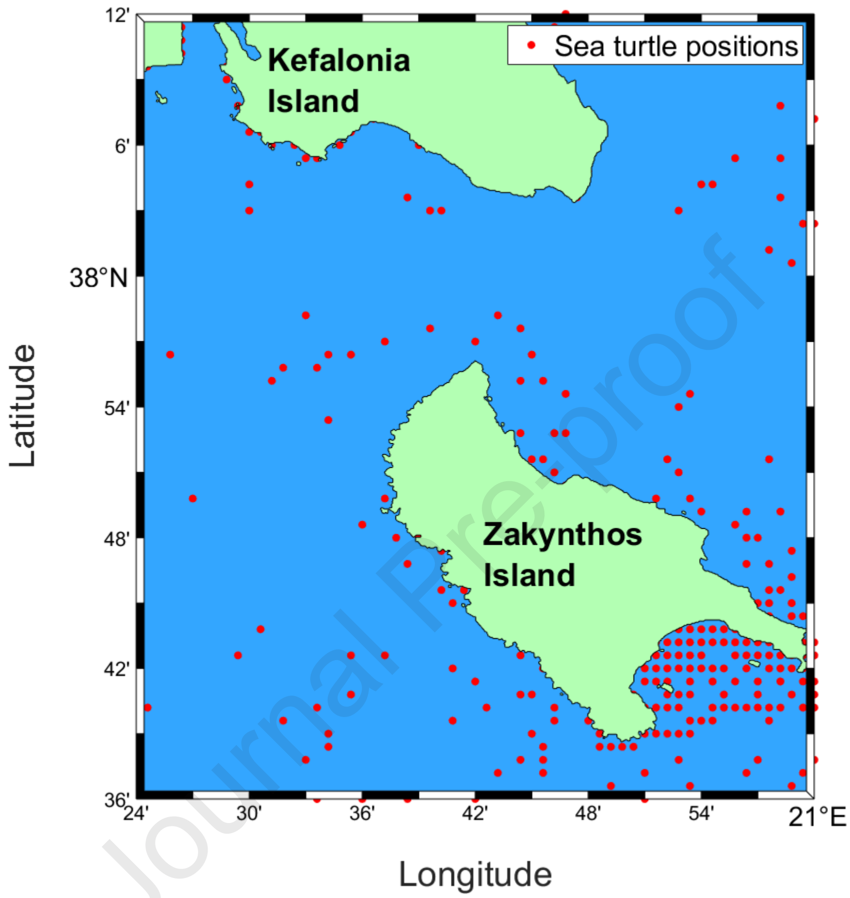

Figure 3: The occurrence of sea turtles in the study area from satellite tag data

$$V = Sens * E_{Th} - SC \tag{1}$$

where V is the vulnerability for each species, *Sens* is the sensitivity to a specific threat, E_{Th}, is the expected threat, and *SC* is the stability factor. The expected threat was given a value between 0 and 1 based on the fishing effort from the satellite data (1 being a high occurrence of fishing vessels and 0 a low occurrence derived from a density spatial interpolation based on the satellite telemetry data for vessel occurrence), and the stability factor was 0 for regions outside marine protected areas (MPAs) and 1 for MPAs.

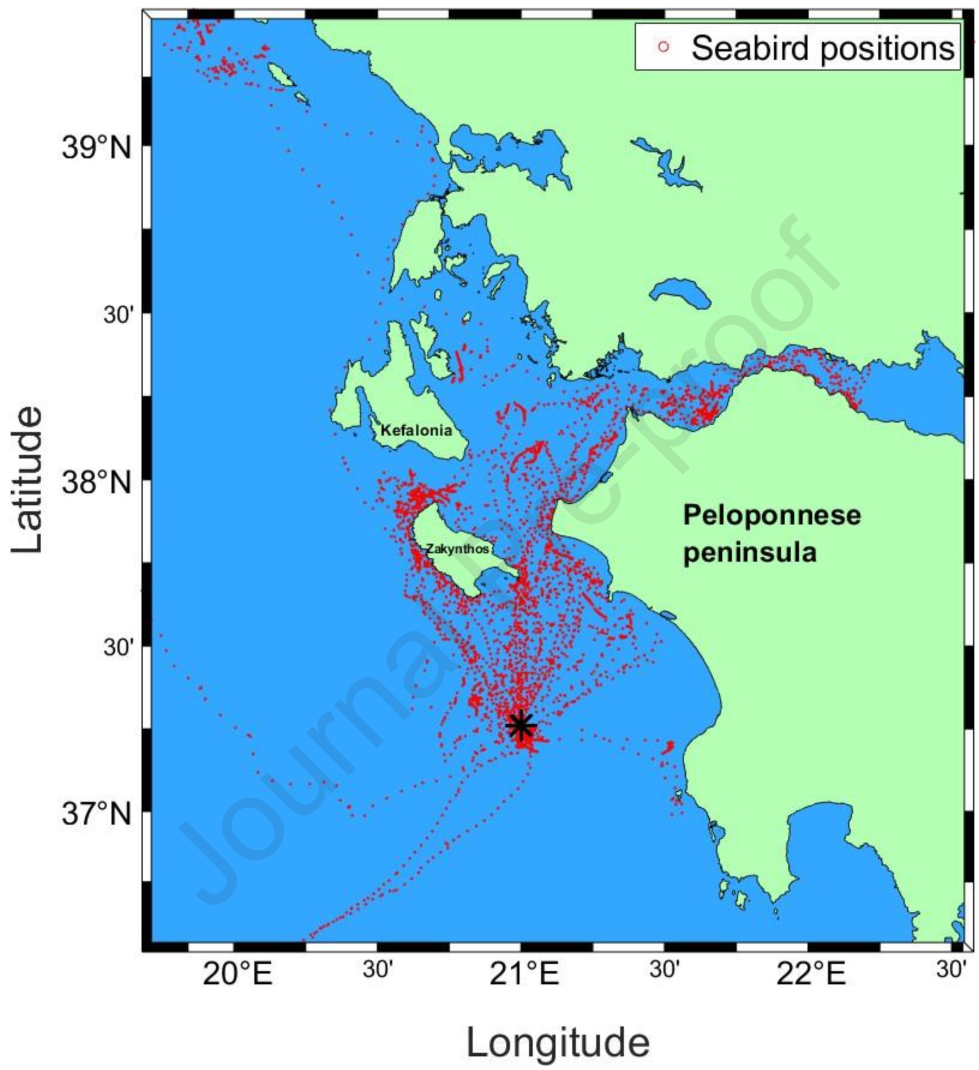

Figure 4: The occurrence of Scopoli's Shearwater breeders originating from the Strofades colony (seen with a star symbol) during their foraging distribution in the study area according to GPS data (sampling period: 2009-2018).

$$Sens = \sum (\lambda_i * Att_i) \qquad (2)$$

where λ_i is the weight of each attribute Att_i. The attributes here represent the intensity of use of different locations by each species (i.e., nesting or feeding grounds). The weights were given a value of 0.3 for nesting and 0.6 for feeding grounds according to Cuevas et al. (2019). Identification of feeding and nesting grounds for both species was based on previous research effort in the study area (Almpanidou et al., 2022; Karris et al., 2018). The attributes were given a value between 0 and 1 based on the presence of the species (1 being a high occurrence of individuals and 0 being a low occurrence derived from a density spatial interpolation based on the satellite telemetry data) from the satellite telemetry data.

$$CV = \sum (V_i) \tag{3}$$

where CV is the cumulative vulnerability for both species. The CV was rescaled to include values between 0 and 1.

3. Results

3.1. Identifying fishing grounds

According to the local fishing community of Zakynthos, 68% of the fishers reported fishing during the night, 26% during the day and night, and only 6% reported fishing during the day (Fig.8). The fishing fields for small-scale fishers include the regions of Porto Vromi, Mizithres, Laganas Bay, Tsilivi, and the channel between the islands of Zakynthos and Kefalonia.

The analysis of the GeoTIFF images showed several thousand vessel locations within the study area for the selected period (Fig.2). The analysis showed that most vessels were smaller than 50 m in length, with a small number exceeding 100 m (ferry/cargo ships). The total number of vessel occurrences between 2-12 m for the timeframe between 2014-2024 was approximately 11,000 (Figs.6,2). The projection of their location in the map revealed two regions of small-scale vessel aggregations, one on the NE coast of Zakynthos and one between the northernmost location of Zakynthos and the S Kefalonia Island (Fig.5). These locations are therefore identified as the hotspots of small-scale fishing activity in the study area in accordance with the information provided by local fishers but in a finer spatial detail.

3.2. Identifying bycatch hotspots

Considering bycatch, the questionnaires showed that more than half of the fishers have caught at least one turtle in their fishing gear, with 19% of

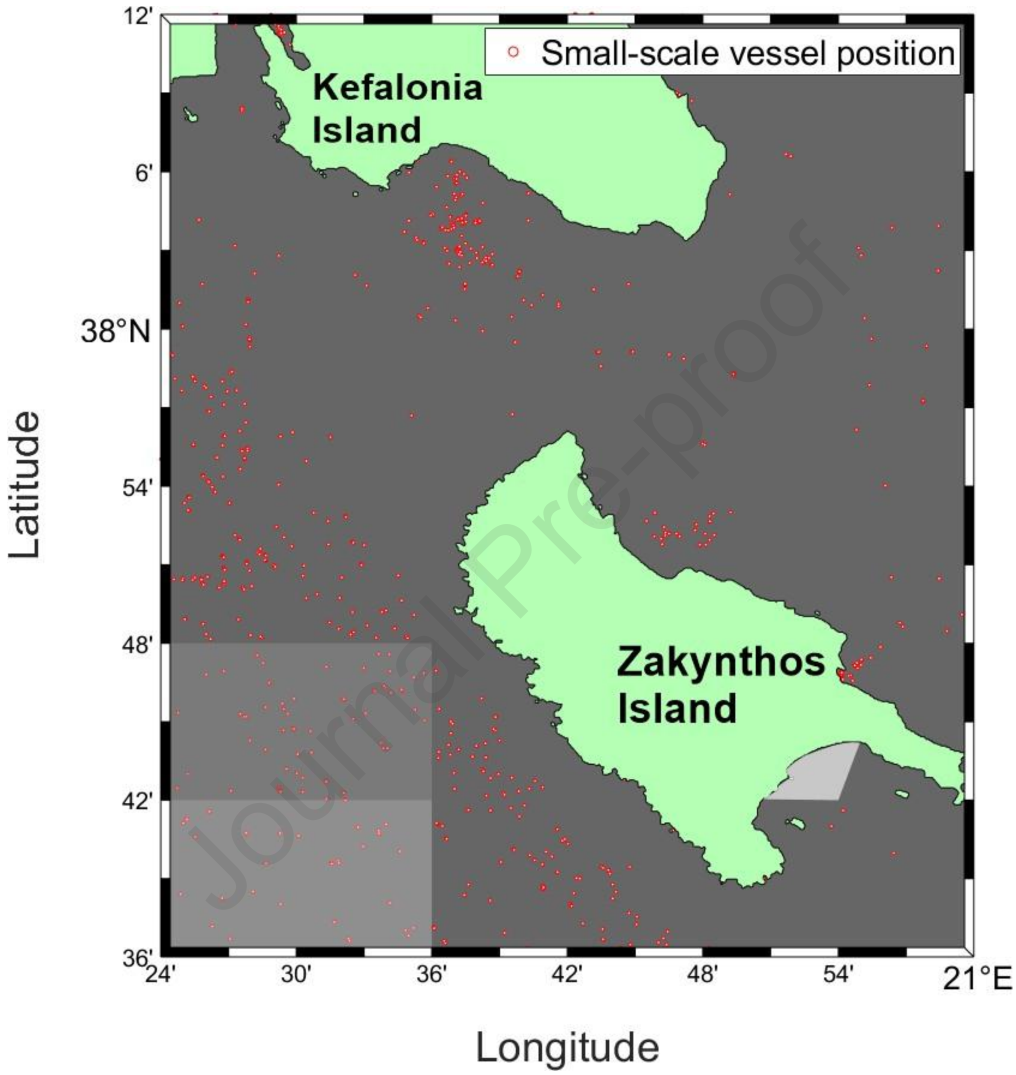

Figure 5: The identified vessel occurrence between 2014-2024 in the study area from the analysis of Sentinel-1 SAR images, Dar-grey background shows the region of known fishing activities with lighter-grey areas showing less active regions.

the fishers reporting to have caught several sea turtles during their active fishing years. A smaller amount of fishers reported 2-3 sea turtles (10 and 10% respectively). According to the fishers, bycatch usually takes place in the

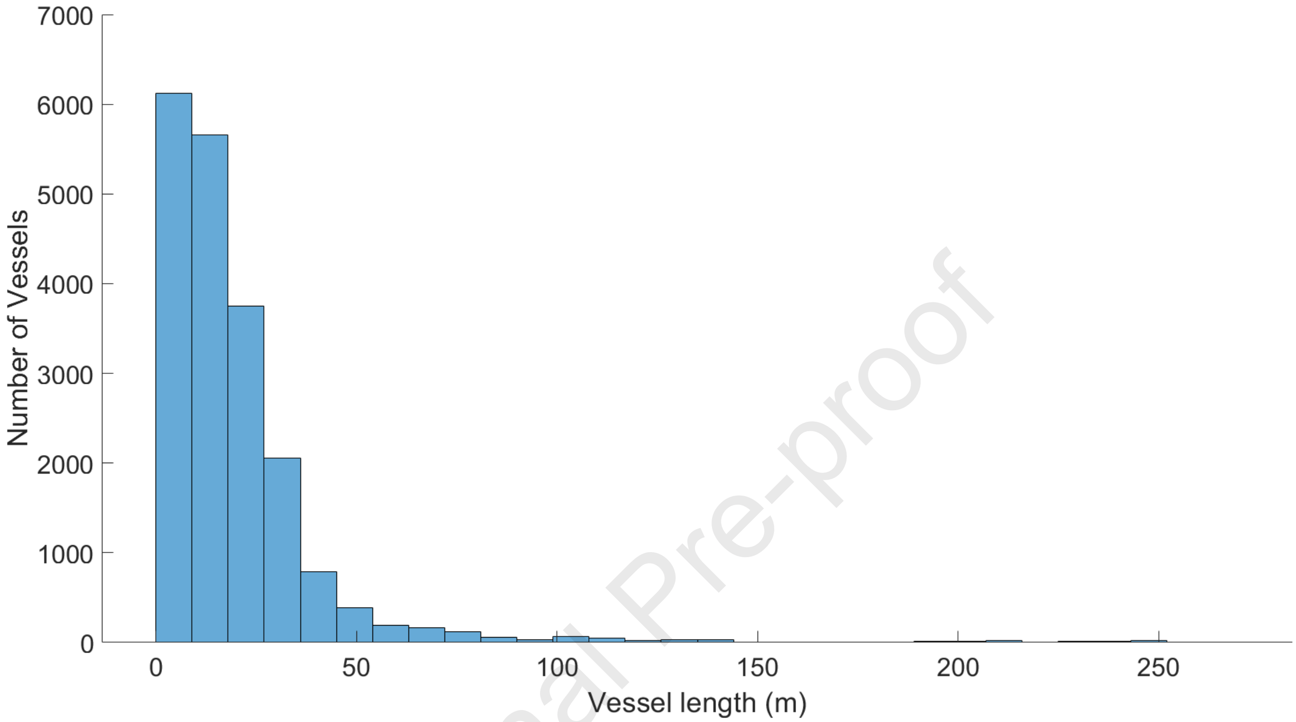

Figure 6: The length of identified vessels in the study area between 2014-2024

summer months, and between May and October (Fig.7). The areas of high bycatch as reported by the local fishermen are shown in Fig.8. According to the analysis of Sentinel-1 SAR images, the occurrence of vessels in the study area occurs in aggregations in two locations (Fig.5). The first location is near Zakynthos on the northern side of the island near the Alykanas harbor. The second and larger one is located between Zakynthos and Kefalonia in the Lourdas Bay. Considering the overlap of the presence of sea turtles and sea birds in these regions, as identified by telemetry data, and the fishing grounds, as identified by the satellite data and the questionnaires, the two areas can be considered significant hotspots for bycatch of the aforementioned marine species (Figs.3,4).

3.3. Vulnerability map

Based on equations:1,2,3, the total cumulative vulnerability was assessed for the impact of bycatch on sea turtles and sea birds in the study area

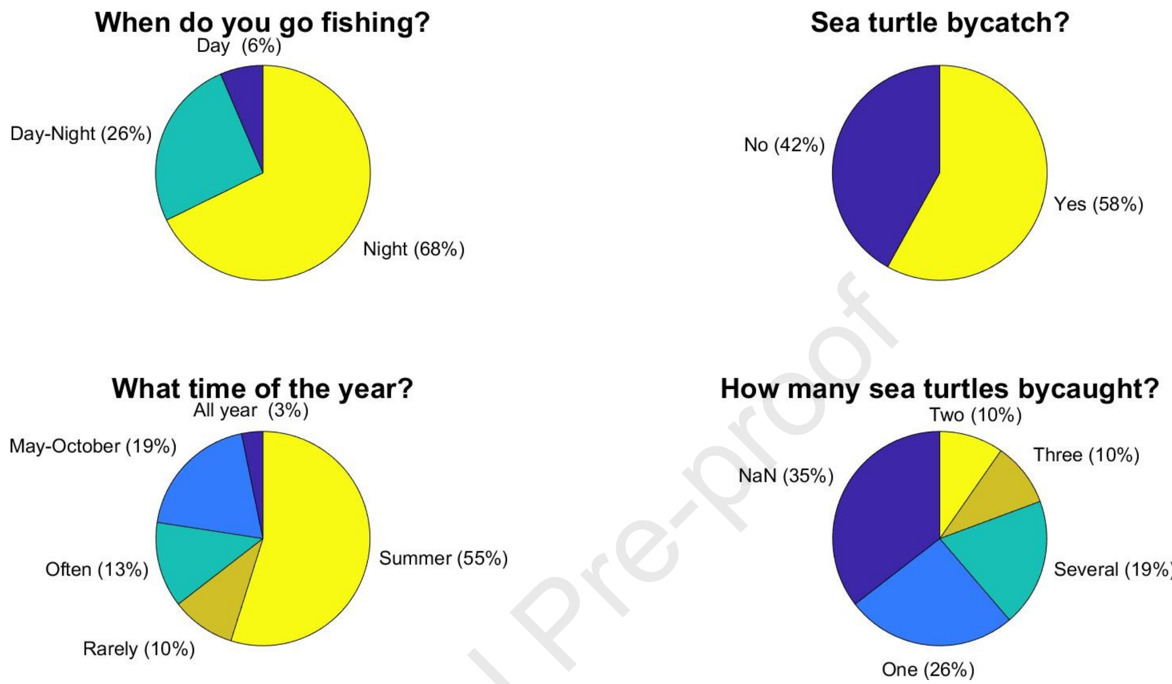

Figure 7: Answers of fishers in main questions involving bycatch in Zakynthos Island, Greece

(Fig.9). The most vulnerable region was identified to be in the area between the islands of Zakynthos and Kefalonia, an area that is experiencing high fishing activity and the occurrence of both sea turtles and sea birds, with some other areas in the coasts of Zakynthos island exhibiting slightly higher values than the other regions.

4. Discussion

Small-scale fisheries in the Mediterranean comprise more than 80% of the fishing vessels, 50% of employment onboard vessels, and around 30% of revenues (FAO, 2020), while it is crucial for the welfare of the coastal population of developing countries (Teh and Sumaila, 2013). According to Fao et al. (2018), in the last 7 decades, the global consumption of fisheries products has increased exponentially and is expected to keep increasing by 1.5%

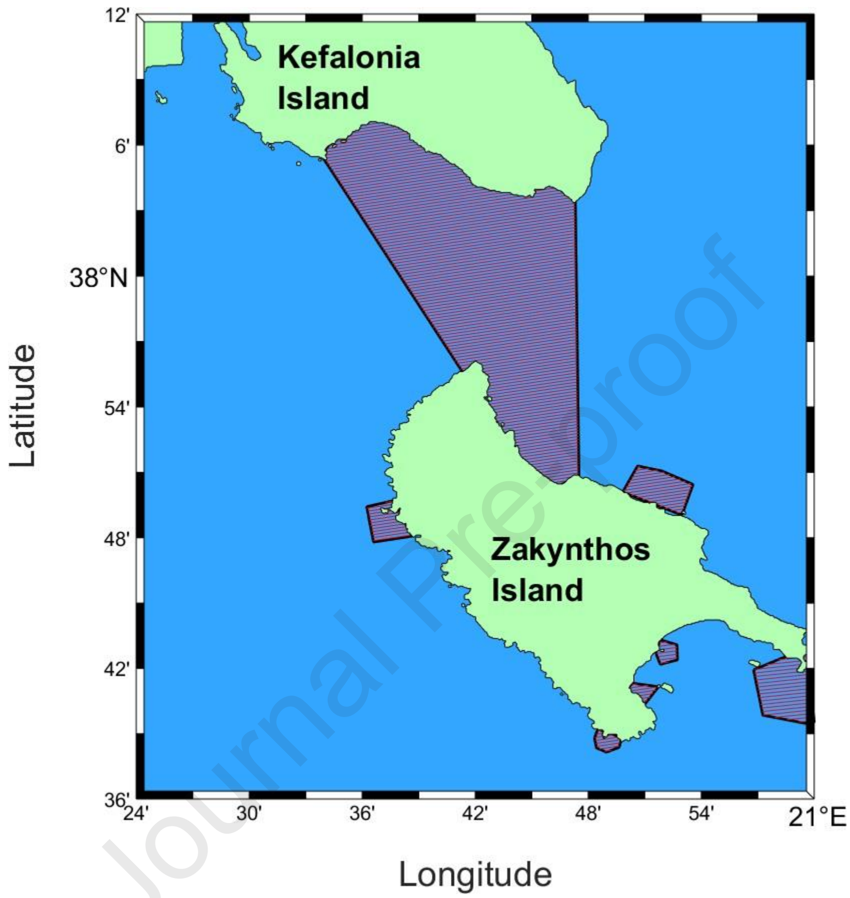

Figure 8: Bycatch hotspots according to the local ecological knowledge of the fishers in the study area

annually. In the Mediterranean region, most fishing activities occur by small vessels using various types of fishing gear (Lleonart and Maynou, 2003). Due to the intensive needs of the population of the Mediterranean region for the consumption of seafood products, the fishing industry is expanding leading to the overexploitation of resources and the degradation of the marine environment (Colloca et al., 2017; Lotze et al., 2011). Due to the extensive fishing activities, marine organisms such as sea turtles, elasmobranchs, cetaceans, and sea birds are impacted due to bycatch (Virgili et al., 2024). Bycatch is caused by the overlapping of fishing grounds with the species' marine habi-

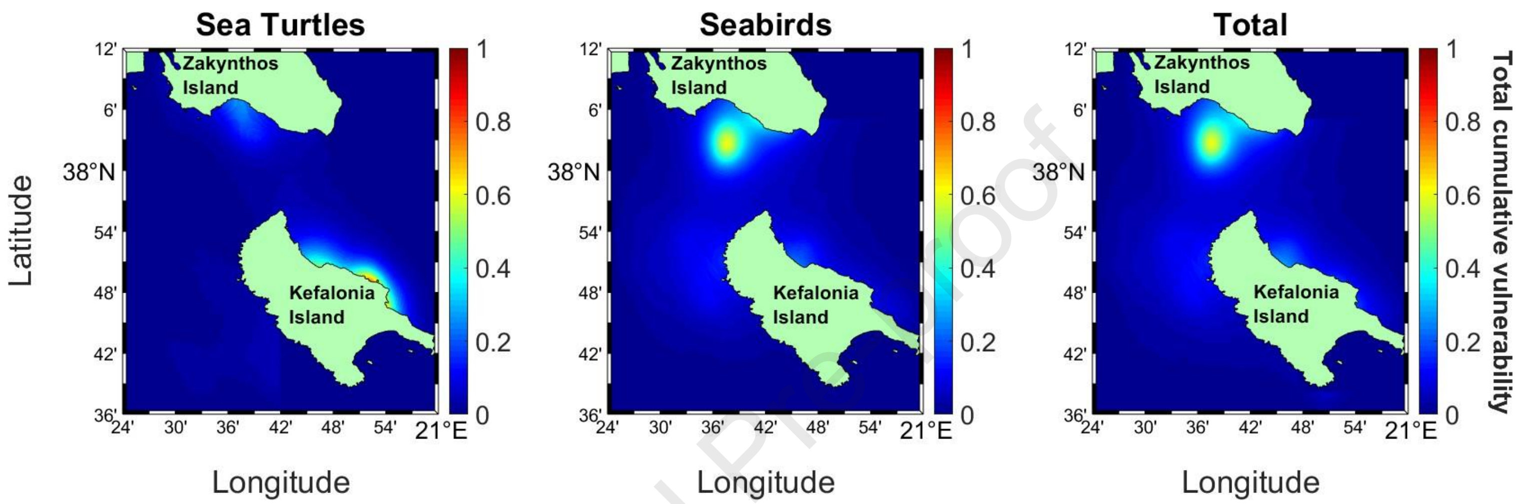

Figure 9: The spatial representation of the total cumulative vulnerability assessment for bycatch for sea turtles, sea birds, and the total cumulative vulnerability for both species in the study area

tats, leading to high mortality rates, especially for sea turtles (*Caretta caretta*, *Chelonia mydas*), monk seals (*Monachus monachus*), whales (*Ziphius cavirostris*, *Physeter macrocephalus*, *Megaptera novaeangliae*), dolphins (*Stenella coeruleoalba*, *Tursiops truncatus*, *Delphinus delphis*) and seabirds (*Calonectris diomedea*)(Papazekou et al., 2024a; Li Veli et al., 2024; Virgili et al., 2024; Tomás et al., 2008; Karris et al., 2018). Bycatch can account for up to 40% of the fishing activity's product, with a smaller percentage comprising of megafauna species (McCauley et al., 2015; Allman et al., 2021; Wallace et al., 2011; Dulvy et al., 2021). Hence, bycatch mitigation measures are essential to ensure the conservation and sustainability of the marine environment and ecosystem of our planet.

4.1. Impact on Sea turtles

According to the telemetry data, sea turtles are present in every region around the island, with higher densities reported within Laganas Bay due to the nesting activity (Fig.3). The areas around the island and between the islands of Kefalonia and Zakynthos are considered mating and foraging areas (Casale et al., 2018; Papazekou et al., 2024b,a) in close proximity to the nesting beaches of Mounda Bay, at the southeast part of Kefalonia island. Sea turtles are most commonly reported between early spring when mating starts (Schofield et al., 2013b), and till the end of October. As commented by the fishers (Figs.7,8) and verified by the satellite data (Fig.5), the fishing grounds with higher intensity include the regions between the northern Zakynthos and the southern Kefalonia islands. The questionnaires also showed that in these regions, sea turtle bycatch is frequent, especially at night, between May to October. Considering the increasing trend of fishing activities (Fao et al., 2018), the increasing nesting activity on Zakynthos island (Margaritoulis et al., 2022), and the movement of Mediterranean sea turtles from the eastern basin towards the central and western due to the impact of climate change (Simantiris, 2024), the identified hotspots for bycatch in Zakynthos island may pose a significant threat for the species as bycatch will also increase accordingly, leading to higher numbers of stranded sea turtles and other species in the region (Papazekou et al., 2024a).

4.2. Impact on Seabirds (Scopoli’s Shearwater breeders)

Similarly to this study, Karris et al. (2013) surveyed Zakynthos, Greece, to identify bycatch rates in the southern Ionian Sea. The authors distributed a questionnaire to the majority of small-scale fishers in the harbors of the island and reported significant incidental catches of Scopoli’s Shearwater and in a lesser extent of Mediterranean Shag due to commercial longline and gillnet fishery gears. Also, the fishers provided direct information on the fishing grounds where incidental catches of seabirds mainly occurred (e.g., coastal regions of Zakynthos Island and southern coastal area of Kefalonia Island) that matched the findings of the current study. Moreover, temporal analysis of the incidental bird mortality showed that seabirds were more susceptible to being trapped in fishery gears set around sunrise during spring and summer. According to Karris et al. (2013) the estimated annual incidental mortality of Mediterranean Shags in bottom longlines and nets represents approximately

3.0-5.1% of the pairs breeding in Southern and Central Ionian Sea (HOS unpublished data). Similarly, 495 Scopoli's shearwaters were estimated to be caught in longlines which represents 1.7-2.0% of the local population. Although bycatch of the shearwaters during the pre-breeding period in early May could affect birds that migrate via the Southern Ionian Sea, the highest bycatch rates occur during summer months, when it can be assumed that the caught birds mainly originated from the Strofades colony. Consequently, bycatch mortality of Scopoli's shearwater could be considered a potential risk for the local colony by taking into consideration that this marine top predator shows long-term mate fidelity as well as biparental care during the incubation of the single egg per nest and the chick-rearing duties.

4.3. Mitigation measures

Bycatch is a major threat to both the conservation and sustainability of marine life, and the fishing gear used by fishers around the globe (Agyekumhene et al., 2014; Gautama et al., 2022; Cardona et al., 2025). Hence, several approaches have been used in an attempt to reduce the impact of bycatch on marine megafauna. The best practices to mitigate bycatch depend on the geographical area, fishing gear types, bycaught species, importance for the local population, existing legislation, and regional management authorities (Squires et al., 2021). Especially in the case of small-scale fisheries, as in Zakynthos Island, mitigating bycatch can be very challenging.

Existing approaches involve the following methods: i) the combination of bycatch reduction devices (BRD) on board fishing vessels with the training/education of fishers on good practices, technical solutions, and eco-labeled to achieve bycatch mitigation (Virgili et al., 2024), ii) the use of green LED lights on the nets to reduce the bycatch of sea turtles and weighted lines to reduce the bycatch of sea birds (Gautama et al., 2022; Løkkeborg, 2011), iii) awards as incentives for fishers that reduce the bycatch of marine mammals and avoid marine protected areas (Lent and Squires, 2017; Macedo et al., 2019), iv) the closure of specific areas (Squires et al., 2018), v) the ban of specific fishing gear (Sala, 2016), vi) the alterations of existing fishing gear and methods (Senko et al., 2017; Squires et al., 2018; Fitzgerald, 2013; Atkins et al., 2013; Virgili et al., 2018; Lyle and Tracey, 2016; Henry et al., 2024), vii) the use of technological approaches with innovative devices for monitoring bycatch (Wakefield et al., 2018; Bartholomew et al., 2018) and alienating specific species from the fishing gear (Duarte et al., 2019; Jefferson and Curry, 1996; Wang et al., 2010), viii) the implementation of awareness and training campaigns targeting local fishing communities (Squires et al., 2018; Senko et al., 2017; Bretos et al., 2017), ix) the introduction of eco-labeling (Selden et al., 2016; Lent and Squires, 2017; Bellchambers et al., 2014; Christian et al., 2013; Berninsone et al., 2018), x) the use of dynamic ocean management methods (DOMs) where fishers, NGOs, authorities, and managers collaborate to evaluate the movement and distribution of pelagic species to adjust the spatiotemporal fishing grounds (Dunn et al., 2016; Lewison et al., 2015; Siders et al., 2024), x) and the implementation of observer programs (Bellchambers et al., 2014; Lent and Squires, 2017), among others.

In Zakynthos, the most common approach to avoid bycatch is the onboard release of bycaught organisms such as sea turtles and sea birds, a common practice that is taking place due to the training of the fishers by local NGOs and the fishers' awareness. According to the fishers' responses (Fig.7), more than 60% have caught a sea turtle in their fishing gear and have released it. They disclosed that if the sea turtle was alive, the release would take place even if it meant causing damage to their gear, while if the sea turtle was already dead, they would release it later in order to cause as less as possible to their gear. On board release is a common practice that, although voluntary, is highly significant for the conservation of marine organisms, but differentiates between species (Wosnick et al., 2023). Nevertheless, combined with education and workshops, best practices for the release of bycatch products can be communicated to the majority of fishers around the globe (Wosnick et al., 2023). The authors suggest that studies involving the use of streamer (tory) lines in longline vessels to evaluate the protective effect of this setup on seabirds are critical for finding the effectiveness of this bycatch mitigation measure for seabirds. This will allow evaluating its effectiveness towards the reduction of the loss of seabirds in longline fishery following other relevant studies (e.g. (Cortes and Gonzalez-Solis, 2018)). Moreover, the need to include more marine megafauna species data in the vulnerability assessment for bycatch is important to define specific bycatch hotspots and assist in informing conservation plans. The information presented here supports the need for conservation, education, and engagement actions in the region of the Ionian Islands for the preservation of the marine environment and the mitigation of bycatch, especially considering the high ecological and economic importance of the region due to its biodiversity and the role in fisheries.

5. Conclusions

In the Mediterranean region, bycatch is a major threat to marine life. In Zakynthos Island, Greece, bycatch is known to have a significant impact on sea turtles and seabirds, among other species. This work combined satellite data, questionnaires, and GPS data to identify the fishing fields and evaluate the interaction with sea turtles and seabirds. The current work reports one important marine area with systematic fishing activities, which is also a marine habitat for sea turtles and sea birds, and verified through the local fishing community and a vulnerability assessment as a bycatch hotspot. It also provides a useful methodological tool for researchers using different data sources to identify bycatch hot spot areas of marine protected species that are susceptible to incidental mortality on fishery gears. At a national level, the findings of the current study will also serve the need to advise conservation planning in MPA designation in the study area and elsewhere.

6. Declaration of Competing Interest

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

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8. CRediT author statement

Nikolaos Simantiris: Conceptualization, Methodology, Software, Resources, Investigation, Data Curation, Writing-Original Draft, Visualization, Formal analysis, Project administration. **Charalampos Dimitriadis:** Data Curation, Writing, Review & editing. **Stavros Xirouchakis:** GPS data collection for seabirds, Writing-Original Draft. **Marios-Dimitrios Voulgaris:** GPS data collection for seabirds, Writing-Original Draft. **Evangelia Beka:** Resources, Write, Review & editing. **Martha Z. Vardaki:** Writing, Review & editing **Georgios Karris:** GPS data collection for seabirds, Writing-Original Draft, Supervision.

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- Combining satellite data and questionnaires assist in determining fishing grounds
- Bycatch hotspots for sea turtles and sea birds in Zakynthos, Greece were determined
- There is a need for conservation, education, and engagement actions
- This work contributes to the establishment of a new national marine park

Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: