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Investigating the Distribution of Foraging Sites of Loggerhead Sea Turtles, *Caretta caretta*, in the Mediterranean Sea †

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Abstract: A better understanding on the distribution of highly migratory marine megafauna and the potential exposure of their habitats to anthropogenic activities is essential for their effective protection. Here, we deliver a comprehensive view on the distribution of foraging grounds for the representatives of marine megafauna, loggerheads, *Caretta caretta*, in the Mediterranean Sea, along with an assessment on their exposure to fisheries. Using the available published satellite tracking information on the adult Mediterranean foraging loggerheads, we built a series of distribution models to develop a map of the foraging grounds across the basin. We also assessed the exposure of the delineated foraging grounds to the cumulative risk due to different types of fisheries. Our findings revealed that the foraging grounds of adult loggerheads extended over the 9% of the Mediterranean Sea. We identified well-established areas in the central Mediterranean Sea but also sites, at the western part, for which the current knowledge was restricted. The exposure of the foraging grounds to fisheries differed across the basin, with the Adriatic Sea being under the highest level of risk. The developed approach, combining modeling techniques and risk assessment, allowed to reveal critical sites for loggerheads on which conservation actions should focus.

Keywords: bycatch; conservation planning; ecological niche models; marine turtles; risk assessment

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1. Introduction

Marine megafauna represents a key component of the marine ecosystems [1]. This iconic group of species consists of highly mobile animals, which inhabit different habitats that might be very distant [2]. Thus, they are extremely prone to various anthropogenic activities which could threaten the robustness of their populations [3]. Sea turtles, representatives of the charismatic marine megafauna, are migratory species characterized by an incredible dispersal performance, while they use distinct areas for different life-history stages, with adult individuals travelling between foraging and breeding areas [4]. Still, our knowledge regarding the spatial distribution of the foraging grounds at a wide scale and the potential exposure of these habitats to human-related pressures is rather scarce [5], especially compared to the well-studied breeding activities [6].

The Mediterranean Sea is a regional entity that encompasses a specific population of loggerhead sea turtles with distinct biogeographical, demographic and genetic characteristics [7]. Even though several local studies have been conducted at the basin focusing on foraging loggerheads (e.g., [8]), a systematic approach to consolidate the available data is still missing (but see [9,10] for baseline efforts towards this direction). Information gaps on the distribution of foraging areas at the basin scale, raise further difficulties in a better understanding on the vulnerability of the species due to anthropogenic activities at these

habitats and hamper our capacity to design proper conservation measures [11]. For example, in the Mediterranean Sea, fisheries have been considered as a major threat for loggerheads, since over 132,000 incidents of bycatch have been recorded on a yearly basis, leading to an estimation of more than 44,000 deaths per year [9,12]. Therefore, it is essential to assess to what extent the foraging grounds of the Mediterranean loggerhead population are subjected to this type of risk.

In the current study, we develop and provide a comprehensive systematic approach for elucidating the distribution of foraging grounds for loggerhead sea turtles across the Mediterranean Sea. To do so, we created a thorough database with all the available tracking data for the adult foraging animals, published in the literature for the basin. Next, based on this information, we built a series of species distribution models so as to deliver a map of the foraging grounds delineated at the region. To improve our understanding of the potential impact of fisheries to these habitats, we also conducted an assessment on their exposure to the combined risk due to different types of fishing gears, i.e., longline, trawling, fixed net and purse seine fisheries. The proposed approach could contribute to the determination of key foraging areas and "hotspots" of fisheries risk to inform management and research priorities for loggerhead sea turtles in the Mediterranean region.

2. Methods

To collect all the available information on foraging sea turtles in the Mediterranean Sea, we conducted a systematic literature review, searching Google Scholar and using the terms "sea turtles" or "marine turtles", "satellite telemetry" and "Mediterranean". From the sources identified (by July 2020), we extracted all locations of foraging adult loggerheads. We focused on sources that explicitly referred to adult animals and also retained individuals with curve carapace length >66.5 cm, as the mean lowest reported size for nesting females in the Mediterranean region [9]. We also excluded individuals that have been subjected to rehabilitation prior to release. We finally collected and digitized 119 presence locations of foraging turtles (Figure 1).

To determine current climatic conditions, we used climatic data on sea surface temperature (SST) for the Mediterranean Sea from the Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC) [14], provided on a daily basis for 1950–2100, at a 0.0625° spatial resolution. To capture the most representative time period of foraging activity in the region, we used SSTs from September to March [5]. Based on these data, we built and used for the subsequent analyses, a set of four bioclimatic variables (*sensu* [15]) over the period 1991–2020: mean diurnal range, temperature range of the seven-month studied period, temperature seasonality, minimum temperature of the coldest month.

We applied an ensemble modelling approach [16] to develop a distribution map of the foraging grounds across the Mediterranean region, using sdm package for R [17] and fitting four different algorithms (i.e., Generalized Linear Models, Generalized Additive Models, Random Forest, Multivariate Adaptive Regression Spline). We generated ten different sets of 1000 pseudo-absences and applied a 10-fold cross-validation procedure to examine the predictive accuracy of the models. We also used two alternative evaluation metrics for the final ensemble, the Area under the Curve (AUC; [18]) and the True Skill Statistics (TSS; [19]).

To transform the continuous model output to binary distribution map, with 0 representing absence and 1 presence, we used as a cut-off value the threshold that maximizes TSS [20]. Given that the majority of the Mediterranean adult loggerheads forage within the neritic zone [21], we intersected the developed distribution map with the areas with depth less than 200 m, based on bathymetry data derived from the General Bathymetric Chart of the Oceans—GEBCO [22]. To further examine the distribution of foraging grounds across the Mediterranean Sea, we calculated the proportion of foraging area that was included within the seven marine ecoregions (*sensu* [13]) found in the basin (Figure 1).

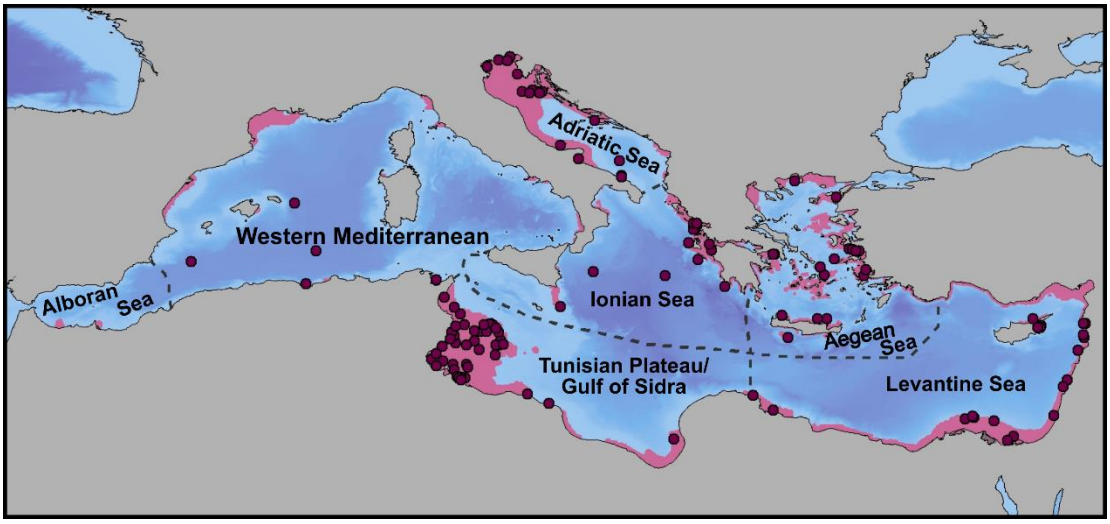

Figure 1. The distribution of the foraging grounds (pink polygons) of adult loggerhead sea turtles, *Caretta caretta*, under current climatic conditions (1991–2020) across the Mediterranean Sea. The locations (red points) that represent foraging adult loggerhead sea turtles, derived from the available published satellite tracked data, based on which the distribution map of foraging grounds was delineated, are also presented. Marine ecoregions (*sensu* [13]) comprising the Mediterranean Sea are delineated by black dashed lines.

To evaluate the exposure of loggerhead foraging grounds to risk due to fisheries, we considered fishing effort from four types of fishing gears, for which sea turtles have been reported as susceptible to bycatch incidents [12], i.e., longline, trawling, fixed net and purse seine fisheries. We obtained data on global fishing effort from the Global Fishing Watch (GFW) website [23,24], provided at 0.01° spatial resolution, on a daily basis for 2012–2016, by gear type and flag state, based on Automatic Identification System (AIS) used by industrial fishing vessels. We calculated the annual fishing effort (fishing hours per year) for the most recent available year (2016) by estimating the sum of all the daily information for each gear type within a cell of resolution 0.0625° × 0.0625°, to be compatible with the output of the distribution model. It should be noted that data might be limited at specific regions, e.g., Northern Africa, Western Asia due to poor coverage of AIS while small, artisanal vessels were not included in the dataset [24].

To assess the cumulative risk from the different types of fishing gears, at the Mediterranean foraging grounds, we relied on the approach proposed by Sequeira et al. [25]. Thus, we first calculated the risk for each threat separately and then, we estimated the cumulative risk by adding the values of all the threats for each cell. We ranked the risk values across the Mediterranean within five classes with equal number of features (i.e., very low, low, medium, high, very high), based on their probability distribution. Finally, we estimated to what extent the foraging grounds were exposed to cumulative risk of fisheries at the entire basin and at the different marine ecoregions.

3. Results

The developed model was considered to exhibit a very good predictive capacity for the determination of the foraging grounds for the adult Mediterranean loggerheads, based on the estimated evaluation metrics (i.e., AUC = 0.83, TSS = 0.7).

We found that the delineated foraging grounds covered about 9% of the entire Mediterranean basin (i.e., ~217,000 km^2; Figure 1). The largest percentage of this area was located at the Central and Eastern Mediterranean. More specifically, at the Central Mediterranean, the Tunisian Plateau and the Adriatic Sea hosted the 31.75% and 24% of the total foraging area of the basin, respectively. At the Eastern Mediterranean, the Levantine Sea and parts of the Aegean Sea encompassed notable percentages of foraging grounds for

loggerhead turtles (19.19% and 13.05% of the total area, respectively). The extent of foraging grounds was found to be more limited at the Western Mediterranean (7.13% of the total foraging area), mainly located along the French and Spanish coasts.

Assessing the combined risk due to different types of fishing gears, we found that more than 40% (i.e., 40.94%) of the foraging grounds were exposed from medium to very high levels of threat, with variations being detected across the Mediterranean Sea (Figure 2).

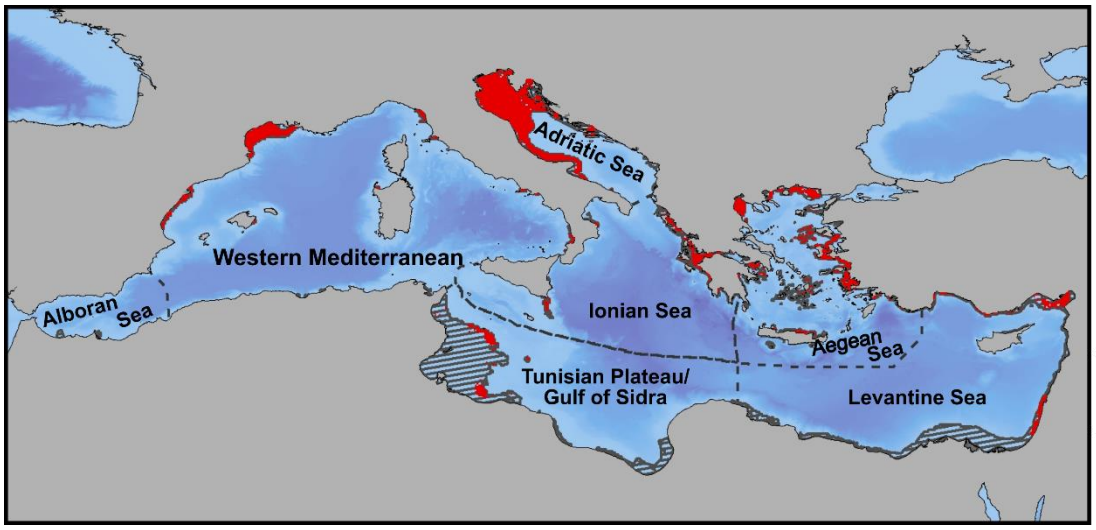

Figure 2. The sites (red polygons) of increased cumulative risk due to different types of fisheries (i.e., from medium up to very high exposure to longlines, trawlers, fixed nets and purse seines fisheries) within the distribution of foraging grounds (striped polygons) of adult loggerhead sea turtles, *Caretta caretta*, under current climatic conditions (1991–2020) across the Mediterranean Sea. Marine ecoregions (*sensu* [13]) comprising the Mediterranean Sea are delineated by black dashed lines.

The foraging area enclosed within the Adriatic Sea, in the Central Mediterranean, was more seriously affected by fisheries, with 73.47% of its extent being subjected to high and very high risk. The 57.51% of the foraging grounds hosted within the Western Mediterranean were also found to be under high and very high levels of threat. More than 50% of the foraging area hosted within the Aegean and Ionian Sea was exposed from medium to very high levels of risk (54.38% and 51.52% of the foraging area, respectively), with lower percentages being detected at the Levantine Sea and the Tunisian Plateau/Gulf of Sidra. Still, we would like to mention that the results within the Levantine Sea and the Tunisian Plateau/Gulf of Sidra should be interpreted with caution because of the poor coverage of fisheries data.

4. Discussion

Here, we delivered an integrated picture of the distribution of foraging grounds for adult loggerhead sea turtles across the Mediterranean Sea. Our findings demonstrated well-established foraging areas, which are located at the Central Mediterranean, such as the Northern Adriatic Sea and the Gulf of Gabes, in Tunisia. The significance of these areas for the Mediterranean loggerhead population, as their main foraging sites, has been previously supported, with high abundance of individuals being detected at these regions (e.g., [26,27]). We also found remarkable coverage of foraging grounds at the eastern part of the basin, in the Aegean and Levantine Sea, which are known to be frequently inhabited by loggerhead sea turtles [9]. Still, our findings highlighted foraging areas at the Western Mediterranean, such as those located at the Gulf of Lion, in France, and at part of Spanish coasts, for which satellite telemetry data from adult loggerheads are missing. However, evidence derived from other sources (e.g., aerial surveys [28], bycatch data [29]) have implied the potential important role of these areas as alternative or complementary foraging

grounds for adult loggerheads across the Mediterranean Sea, further supporting our findings. Therefore, we suggest that research and conservation initiatives should be also directed towards these sites so as to ensure the persistence of the Mediterranean loggerhead population.

Our findings also revealed that loggerhead sea turtles might be subjected to increased cumulative risk from the different types of fishing gears at the Mediterranean foraging grounds, raising doubts on the robustness of the population across the basin. Such results are in accordance with the incredible number of captures per year that have been conservatively estimated for the basin [9,12]. At the Adriatic Sea, more than 24,000 bycatch incidents and about 4500 deaths occur on a yearly basis, rendering the region a hotspot of risk for loggerhead turtles [30], as it was also highlighted by our analyses. Notably large numbers of capture events (~20,000) have been also recorded in Spain, at the Western Mediterranean and at the Aegean Sea, at the Eastern part of the basin [12]. Recent studies revealed an extensive effect of fishing activities on sea turtles that are located at Spanish waters [31] while increased frequency of interactions between fishermen and sea turtles have been observed both in Greece [32] and Turkey [33], with all of the above-mentioned regions being identified as the most exposed to risk due to fisheries. The ecoregions of Tunisian Plateau/Gulf of Sidra and Levantine Sea were found to be under lower risk due to fisheries; still, poor data coverage for countries at northern African coasts and Western Asia [24] could have resulted in downgrading the problem at these regions and thus, we recommend that these results should be interpreted with caution. Bycatch has been also recognized as a major problem worldwide for all the sea turtle species [34]. For example, trawl fishery has been identified as the main source of mortality for neritic adult loggerheads in the southwest Atlantic region [35] and the top-ranked threat for all the sea turtle species hosted in Mozambican waters [36]. Even though many attempts to mitigate the consequences of fisheries bycatch have been made (e.g., through awareness campaigns for fishermen or adaptations to fishing tools; [12]), the problem still persists, highlighting the necessity to enhance trans-boundary and multidisciplinary collaborations towards the establishment of the appropriate measures and strengthening the conservation efforts for sea turtles.

5. Conclusions

The current study, compiling a consolidated database with published satellite tracking data and applying an ensemble distribution modeling approach, provided a profound knowledge on the distribution of key foraging sites for loggerhead sea turtles across the entire Mediterranean basin. In addition, the development of a risk index that incorporated several types of fisheries, allowed us to assess the exposure of the foraging grounds to different levels of threat and identify critical regions for which potential interventions should be considered. Therefore, we suggest that, building on the spatial information derived from our analyses, additional fine-scale assessments should be conducted so as to provide specific guidelines for an effective protection and conservation of the habitats of loggerhead sea turtles.

Author Contributions: V.A. and A.D.M. conceived the study; V.A. and A.D.M. developed the data-analysis approach. V.A. and V.T. collected the data; V.A., A.C. and V.T. performed the analyses; V.A led the writing of the paper with contributions from all authors. All authors have read and agreed to the published version of the manuscript.

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