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Assessing the use of marine protected areas by loggerhead sea turtles (*Caretta caretta*) tracked from the western Mediterranean

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A R T I C L E I N F O

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A B S T R A C T

Up to date 264 Marine Protected Areas (MPAs) have been declared in the western Mediterranean Sea. The management plans of 25 of these MPAs include the loggerhead sea turtle (*Caretta caretta*) as a priority species to protect. However, the actual use of these MPAs by the species remains unknown. Therefore, it is important to assess their contribution to loggerhead conservation in the area. To this end, satellite tracking data of 103 loggerhead turtles of varying sizes and life stages released in Spanish Mediterranean waters and Southern Tyrrhenian Sea over the 2003–2018 period were herein used. Home range and use of MPAs by tracked loggerhead turtles were analysed using post-processed state-space model locations. The tracked turtles visited several Mediterranean MPAs, but barely used them (mean percentage of monitoring time $= 12.6 \pm 18.2$ %). There was very little overlap between turtle's core areas and tracks with the protected areas. Indeed, most of the core areas and high-density areas estimated (>85 %) were not included within any of the MPAs. Furthermore, less than 5 % of the Mediterranean MPAs were used by any tracked loggerhead sea turtles. Most of these MPAs have no protection measures that focus on this species. Loggerheads mainly use wide oceanic zones and international waters, which are difficult to protect. A high-use core area was identified for loggerhead turtles, located at the western waters of the Algerian Basin, an important fishing area outside any designated MPA and with no

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protection measures that focus on marine turtle conservation. We conclude that existing MPAs in the western Mediterranean may not contribute enough to loggerhead turtle conservation. We propose potential MPAs designations to be considered for loggerhead sea turtle conservation in the Mediterranean Sea at the Alboran Sea, the Algerian basin, the Northern area of the Strait of Sicily, Northeast Tunisian waters, waters around Malta, waters at the Tyrrhenian Sea and at the Ionian Sea.

1. Introduction

The Mediterranean Sea is recognised as a hotspot of marine biodiversity because it comprises around 9 % of the planet's marine species diversity (MedPAN and UNEP-MAP-SPA, 2016). However, it faces many conservation challenges, like pollution, marine traffic, exploration and extraction of hydrocarbons, severe overexploiting of marine resources by fisheries - including bycatch-, and impacts of both climate change and invasive species (Halpern et al., 2008; Coll et al., 2012). All these threats result in the decline and loss of the populations and habitats of marine species (FAO, 2018; MedPAN and UNEP-MAP-SPA, 2016). One of the measures currently at the forefront of marine conservation is to establish marine protected areas (MPAs). In recent decades, the number of proposed and designated MPAs increased in the Mediterranean Basin as a result of Aichi Biodiversity Target 11 of the Convention on Biological Diversity (CBD), whereby signature countries agreed to protect and effectively manage 10 % of coastal and marine areas by 2020 (CBD, 2010; Boonzaier and Pauly, 2016). To date, there are 1,233 MPAs and other effective area-based conservation measures (OECMs) in the Mediterranean that cover 236,713 km^2, which means that 9.4 % of the Mediterranean surface is legally designated as protected. These MPAs are not evenly distributed; they occur mainly (90 %) in northwest, coastal European waters (MedPAN and UNEP-MAP-SPA, 2016). There are also a strong biases both for the geographic distribution of protected areas in the Mediterranean, mainly in the northwest, and for the type of protected ecosystems, mainly coastal (Micheli et al., 2013b; Amengual and Alvarez-Berastegui, 2018). This distribution seems to poorly protect oceanic species or species with a large distribution range and broad mobility (Micheli et al., 2013a). In fact, there is a general lack in connectivity between Mediterranean MPAs. An interconnected MPA network is especially relevant when considering wide-ranged species with a complex life cycle involving different areas, including those beyond the boundaries of designated sites (Gabrié et al., 2012; Pendoley et al., 2014; Amengual and Alvarez-Berastegui, 2018). The use of MPAs to protect highly mobile marine species can prove difficult as their ranges may encompass large areas, and even entire ocean basins (Block et al., 2011; Fortuna et al., 2018). Nonetheless, many mobile marine megavertebrates display high site fidelity to specific regions on a seasonal or yearly basis, which allows the protection of key areas (Pendoley et al., 2014).

Marine turtles may use distant areas in their different life stages (Bolten, 2003). Given their long life cycle and their late reproductive maturity age (Bolten, 2003; Casale et al., 2011), they are particularly vulnerable to threats, such as fisheries bycatch, boat strikes, seismic surveys, debris ingestion and climate change effects (Cardona et al., 2009; Carreras et al., 2004; Tomás et al., 2008a; Casale and Margaritoulis, 2010; Witt et al., 2010; Báez et al., 2013; Camedda et al., 2014; Domènech et al., 2015 Rees et al., 2016; Casale and Heppell, 2016; Nelms et al., 2016 Casale et al., 2018; Báez et al., 2019; Domènech et al., 2019). Consequently, marine turtle protection is challenging because their movements may span vast distances and cross international maritime borders (Mazor et al., 2016; Harrison et al., 2018).

The loggerhead sea turtle (*Caretta caretta*) is a priority species listed in Annexes II and IV of the Habitats Directive (European Comission, 2007) and is considered 'Vulnerable' by the IUCN (Casale and Tucker, 2017). Species listed in Annex II should be protected in the core areas of their habitat, that must be designated as Sites of Community Importance (SCIs) and included in the Natura 2000 Network (European Comission, 2007). Species listed in Annex IV should be strictly protected across their natural range by ensuring that other activities will not lead to incidental killing or specimens being captured (European Comission, 2007).

In the Mediterranean, the loggerhead is catalogued as Least Concern, but this status should be considered to be conservation-dependent as the current population in this sea is the result of decades of intense conservation programmes, especially at nesting sites (Casale et al., 2018), and cessation of these programmes could be followed by a declining population (Casale and Tucker, 2017).

The western Mediterranean, which comprises the waters from the east Gibraltar Strait up to the west Sicilian Channel, is an important foraging area for Mediterranean and Atlantic management units of loggerhead sea turtle (Clusa et al., 2014). Furthermore, in the last decade, nesting events have been recorded in this basin, out of the nesting range of the species (Tomás et al., 2008b, 2015; Báez et al., 2020). These nesting events are probably the result of an incipient colonization process guided by global warming (Tomás et al., 2008b; Maffucci et al., 2016; Carreras et al., 2018; Hochscheid et al., 2022).

Despite management plans of 40 Mediterranean MPAs mention the loggerhead turtle as a priority species to protect, few studies about the suitability and use of Mediterranean MPAs by this species have been published, and those that exist have focused on specific regions and life stages (Schofield et al., 2010b). Thus, far from the nesting protected areas in eastern Mediterranean, MPAs contribution to loggerhead conservation remains unknown and should be assessed in order to protect important areas for this species that might remain unprotected and, thereby, contribute to reach MPAs stated goals.

For this assessment, complete knowledge of the life history stages and understanding how loggerhead turtles use space is essential (Hazen et al., 2012; Maxwell et al., 2013; Edgar et al., 2014; Fortuna et al., 2018). MPAs contribution to conservation depends on the quality and level of enforcing the management measures undertaken to reduce the impact of threats on loggerhead turtles in their habitats (Agardy et al., 2011; Hooker et al., 2011; Di Franco et al., 2018; Dureuil et al., 2018). One methodology to assess the use of

MPAs by loggerhead turtles involves computing the overlap of their high-use areas and the current MPAs by using data acquired in tracking studies (Casale et al., 2013; Schofield et al., 2013b; Revuelta et al., 2015; Casale and Simone, 2017; Snape et al., 2018). Home range estimations and relative density maps are frequently used tools to reveal the distribution patterns and space-use hotspots of marine animals (Queiroz et al., 2019) and to assess conservation management measures of loggerhead sea turtles (Schofield et al., 2010a, 2013a; Gredzens et al., 2014). Thus,both methods can be used for identifying loggerhead sea turtle core areas of activity and underscoring hotspots that can be incorporated into conservation management strategies for their protection if they are not already protected (Casale et al., 2012a; Schofield et al., 2013a; Levy et al., 2017; Hays et al., 2019).

The present study used the satellite tracking data of a large sample size of loggerhead sea turtles of different life stages, captured and released in the western Mediterranean over the 2003–2018 period, to describe the species distribution in this sea. The present study aims to analyse the overlapping of the loggerhead turtle distribution and hotspots over the MPAs in the Mediterranean Sea to assess whether current MPAs represents an effective conservation strategy for the wide-ranging transboundary loggerhead sea turtle.

2. Materials and methods

2.1. Studied turtles

The satellite tracking data of 103 loggerhead sea turtles tagged and released in the western Mediterranean over the 2003–2018 period were used here: 17 post-hatchlings (headstarted yearlings, <24 cm straight carapace length, SCL), 10 early juveniles (24–40 cm SCL), 59 late juveniles (> 40–70 cm SCL) and 17 adult-size turtles (> 70 cm SCL), four of which were nesting females (Table 1, further details in Table S1 and own dataset available at EMODNet repository [dataset] Abalo-Morla et al., 2022).

The post-hatchlings proceed from sporadic nesting activity in different regions of the Spanish Mediterranean (see Abalo-Morla et al., 2018b for further details) and were selected based on their swimming and diving activities, and the appropriate size for tagging, which ensures that tags do not hinder behaviour or turtle growth movements (Mansfield et al., 2012). Several (n = 28) juvenile and adult turtles proceeded from bycatch or entanglements and were tagged and released immediately after capture, or if needed, after full recovery in rescue centres to minimize the possibility to be compromised (Table S1). It is possible that movement patterns displayed by these turtles may have been biased by time spent in confined spaces and maintenance conditions in rehabilitation centers or by trauma, stress, and injuries inflicted during fishing operations or other human activities (Cardona et al., 2012). Otherwise, recent satellite-tracking studies about recovered turtles showed that behaviour of amputees and non-amputees turtles was similar after release (Robinson et al., 2021). Thus, we could infer that our recovered turtles could be used as a proxy for wild animals. Juvenile turtles were separated into early juveniles and late juveniles because the transition between passive drifting and active habitat selection seems to occur at an SCL of about 40 cm (Cardona et al., 2005). The turtles larger than 70 cm SCL were considered adults as 70 cm was assumed as the minimum SCL for adult loggerhead turtles from the Mediterranean or Atlantic populations inhabiting the Mediterranean Sea (Margaritoulis et al., 2003; Casale et al., 2011, and references therein). Tracking data were obtained from own tracking projects (available at data repository) and from published satellite tracking datasets (Williard et al., 2015; Cardona and Hays, 2018, Table S1). We considered that our sample size could offer an approach about loggerhead dispersal and habitat use for individuals tracked from western Mediterranean.

2.2. Location data acquisition and data processing

The location data were collected by the Argos system, which classifies seven location classes (LC) of decreasing accuracy (3, 2, 1, 0, A, B, Z). LCs 3, 2, and 1 have Argos estimated errors of less than 250 m, 500 m, and 1,500 m, respectively (CLS, 2016). State-space models (SSM) provide a general and highly flexible statistical tool that allows position estimates to be inferred from the observed data by accounting for measurement errors and variability in movement dynamics (Jonsen et al., 2005, 2007, 2013). These models have been previously applied to model the movements of marine animals, including marine turtles (Jonsen et al., 2007; Hoenner et al., 2012). A hierarchical switching state-space model (hDCRWS) was fitted to our data to provide a position estimate at regular 24-hour

Table 1
Satellite tracking data information by life stage. Sex, percent of turtles taken from bycatch events, range of deployment years, mean track duration, standard deviation of the mean (SD), maximum and minimum tracking durations in days and Economic Exclusive Zone (EEZ) of release.

Life stage	Sex	% Bycatch	Range of deployment years	Mean tracking duration (days)	SD (days)	Minimum (days)	Maximum (days)	EEZ release
Adults (n = 17)	2 male 5 female 10 unknown	24 %	2008–2018	107	115	14	394	Spain
Late juveniles (n = 59)	1 male 1 female 56 unknown	34 %	2003–2018	121	100	6	339	11 Italy 48 Spain
Early juveniles (n = 10)	All unknown	36 %	2003–2018	111	89	22	317	Spain
Post-hatchlings (n = 10)	All unknown	0 %	2016–2017	174	96	69	337	Spain

intervals (Jonsen et al., 2007; Jonsen, 2016; Christiansen et al., 2016) using the 'bsam' R-package (Jonsen et al., 2005) in R 3.4.3 (R Development Core Team 2019). Two Markov Chain Monte Carlo (MCMC) chains for 120,000 iterations were ran by dropping the first 60,000 samples as a burn-in and retaining every 10th sample from the remaining 60,000 assumed post-converge samples from each chain to reduce sample autocorrelation. Thus, the model parameters and estimated locations were calculated using 12,000 MCMC samples. A 24-hour time step was used to generate one daily location of the tracking period from the posterior means of the resultant distributions. SSM locations were post-processed to remove terrestrial locations (Hoenner et al., 2012; Arendt et al., 2012).

2.3. Home range estimation and relative density estimation

Post-processed state-space model locations were used to estimate the loggerhead turtle home ranges and relative density estimations from our data (Hoenner et al., 2012; Pendoley et al., 2014; Queiroz et al., 2019). A home range is theoretically defined as the area in which an animal conducts its daily activities, and excludes atypical migrations or unpredictable movements (Worton, 1989). We used the utilisation distribution (UD) to define the spatial extent of an animal's home range and measure the spatial intensity of use. The core areas of UDs are high-use areas defined as portions of the home range that exceed equal-use patterns (Samuel et al., 1985). Kernel Utilization Distribution (KUD) (Worton, 1989) was computed using the 'adehabitatHR' package in R (Calenge, 2006), with the reference bandwidth as a smoothing parameter (Christiansen et al., 2016; Dujon et al., 2018). Home range areas were identified using KUD up to the 95 % contour levels. Core areas were identified using KUD at two different levels, 50 % and 25 % KUD (Powell, 2000), for the whole tracking dataset and for each life stage throughout the monitoring period (Lockhart and Barco, 2015). The terrestrial area that overlaped with home ranges areas was excluded from the home range estimations using QGIS 2.18.0 (QGIS Development Team 2019). Home range and core areas were represented on maps of the Mediterranean Sea.

The habitat-use maps obtained from the tracking data are likely biased towards the tagging site. To address biases associated with variable track lengths and shorter tracks near the tagging location, we applied a time weighting procedure to compute less biased relative density estimates (Block et al., 2011; Queiroz et al., 2019). Following Queiroz et al. (2019), each daily location estimated for each individual was weighted by the inverse of the number of all individuals with location estimates for the same relative day of their track. Location weights after a threshold day of the number of tracking day (day 220) were fixed equal to the weight on the day corresponding to the 85th percentile of track lengths in order to minimize bias in lower sample sizes (Queiroz et al., 2019). In this way, individual location estimates closer to the deployment location tended to receive a lower weight than later locations. All individuals contributed equally to the described global spatial density patterns because their weights were normalized so that they summed to 1.

Hotspots were defined as areas within the upper 75 % percentile of weighted daily location density. Relative density maps were obtained at a 0.25° x 0.25° grid-cell for (1) the whole tracking dataset and (2) each life stage throughout the monitoring period.

2.4. Use of MPAs

To analyse the use of Mediterranean MPAs by loggerhead sea turtles, the post-processed SSM turtle location point data were overlapped in the Marine World Database on Protected Areas (Revuelta et al., 2015; IUCN and UNEP-WCMC, 2020). To avoid MPA use

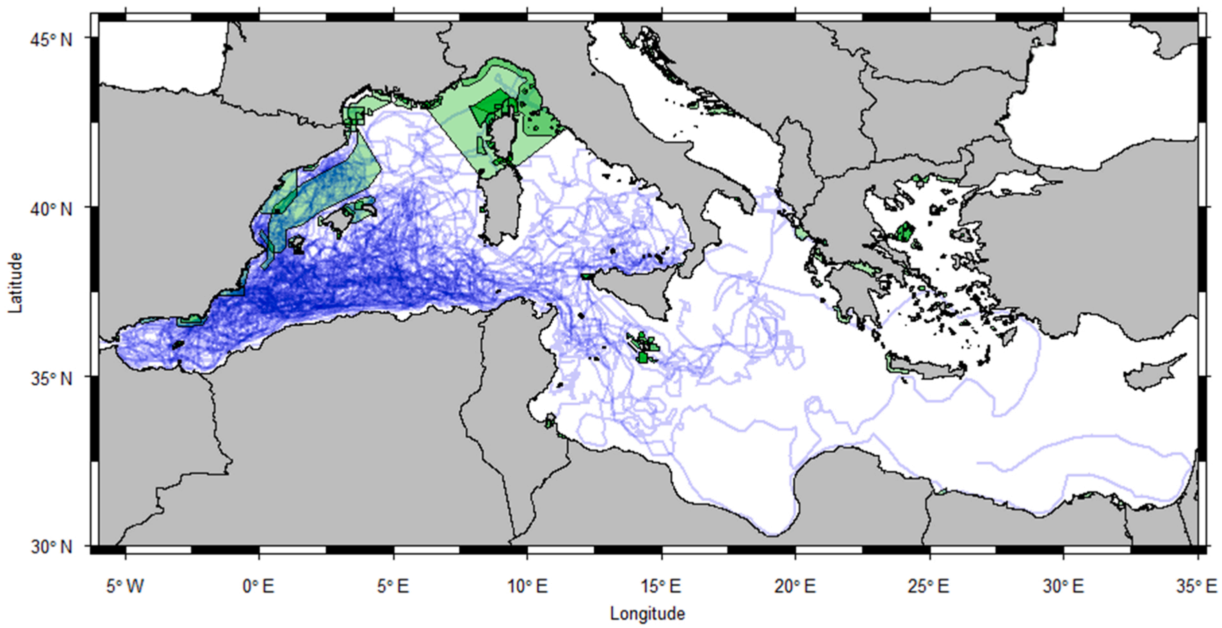

Fig. 1. Turtle trajectories (in blue) and marine protected areas (green) in the Mediterranean Sea.

overestimation that might be caused by MPAs whose areas overlap, we counted presence once in these cases. The turtle presence was assigned to the smaller area in which fell the presence point in order to observe possible important small MPAs. However, if the presence point was located in a border of a MPA which overlaps with another MPA that better englobed the presence point, the location was assigned to the last. A residency index was estimated by dividing the number of days in which a turtle was detected within MPA boundaries by the total number of days that the turtle was monitored (Mason and Lowe, 2010; Revuelta et al., 2015). The abundance (total number of individuals) and density (individuals km^2) for our monitored turtles within limits of MPAs were also calculated (Fortuna et al., 2018). The estimated relative density, home ranges and core areas were mapped for each life stage and for the whole sample of tracked turtles to compute the percentage of overlapping between turtles locations and MPAs (Schofield et al., 2013a; Revuelta et al., 2015; Fortuna et al., 2018). Weighted location data by Economic Exclusive Zones (EEZ) extension were also overlaid over EEZ (Flanders Marine Institute, 2018) in order to compare the use turtles made among countries' EEZ. Bathymetry data were obtained using the 30 arc-second resolution GEBCO global bathymetric model (GEBCO, 2014; Weatherall et al., 2015). The classification between neritic and oceanic zones was divided by the 200 m isobath. A two-way ANOVA was conducted to test if the differences in the use of neritic and oceanic zones between life stages were significant. A 5 % significance level was used in all the analyses. The considered Mediterranean regions are shown in Fig. S1.

3. Results

3.1. Tracking data

The monitored individuals travelled extensively the Mediterranean Sea, mainly throughout its westernmost part (Fig. 1). Turtle trajectories by life-stage and turtle trajectories over bathymetry data and release points are shown in Figs. S2 and S3, respectively.

The mean tracking duration (±standard deviation of the mean (SD)) was 133 days ±109 SD. The tracking duration details for each life stage of loggerhead sea turtles are reported in Table S1. After the data analysis and post-processing, a total of 13039 locations were considered. Concerning habitat use, a total of 2140 locations (16.4 %, $n = 103$ turtles) were located in neritic waters (<200 m depth). No significant differences were observed for the frequency of neritic locations among life stages (ANOVA, $F_{3,7} = 1.98$, p-value $= 0.30$). Most weighted locations by EEZ extension fell inside the Algerian (29 %) and Spain (26 %) Exclusive Economic Zones (EEZ) (Fig. 2).

3.2. Relative density, home range and core area estimates

The tracked loggerhead sea turtles generally covered large areas of the Mediterranean Sea. The individuals' 50 % KUDs ranged from 139 km^2 to 1397,226 km^2 and their 25 % KUDs ranged from 0.01 to 451,068 km^2. Core area sizes by life stages are shown in Fig. 3.

For the whole tracking dataset, core areas were observed in the Algerian Basin (Fig. 4.a). The estimated home ranges for each life stage showed a different habitat use among stages (Fig. 4.b). Post-hatchlings had the largest overall home range and two different core areas: one at the westernmost part of the Mediterranean Sea from the Alboran Sea to the Balearic Sea, and another to the southwest of the Ionian Sea (Fig. 4.b1). For early juveniles, core areas concentrated in the western Mediterranean, in the Balearic Sea and the Argelian Basin (Fig. 4.b2). Late juveniles (Fig. 4.b3) and adults (Fig. 4.b4) also had core areas in the Algerian Basin. Besides, adults were more likely to remain in the western Mediterranean basin where tagged.

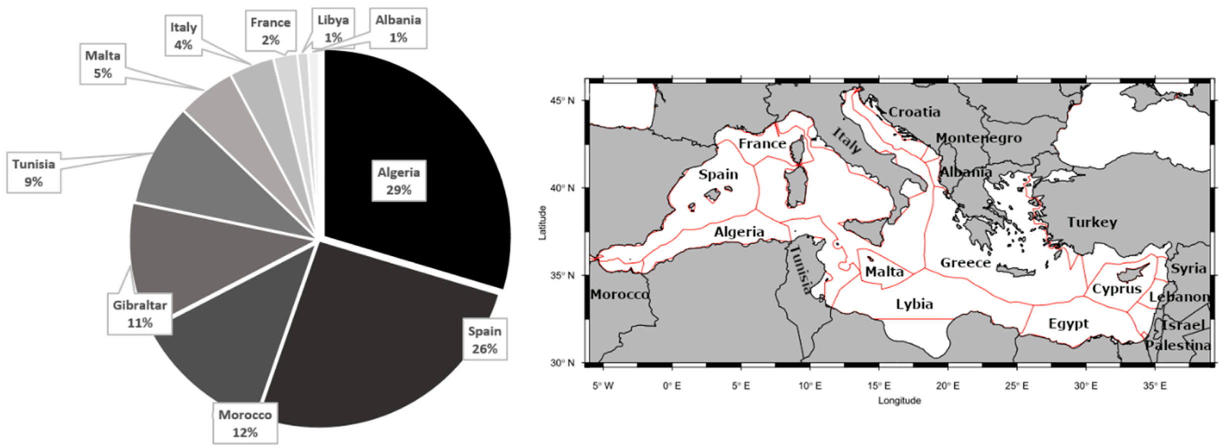

Fig. 2. Percent of daily locations weighted by Economic Exclusive Zones (EEZ) extension that fell inside EEZ per country.

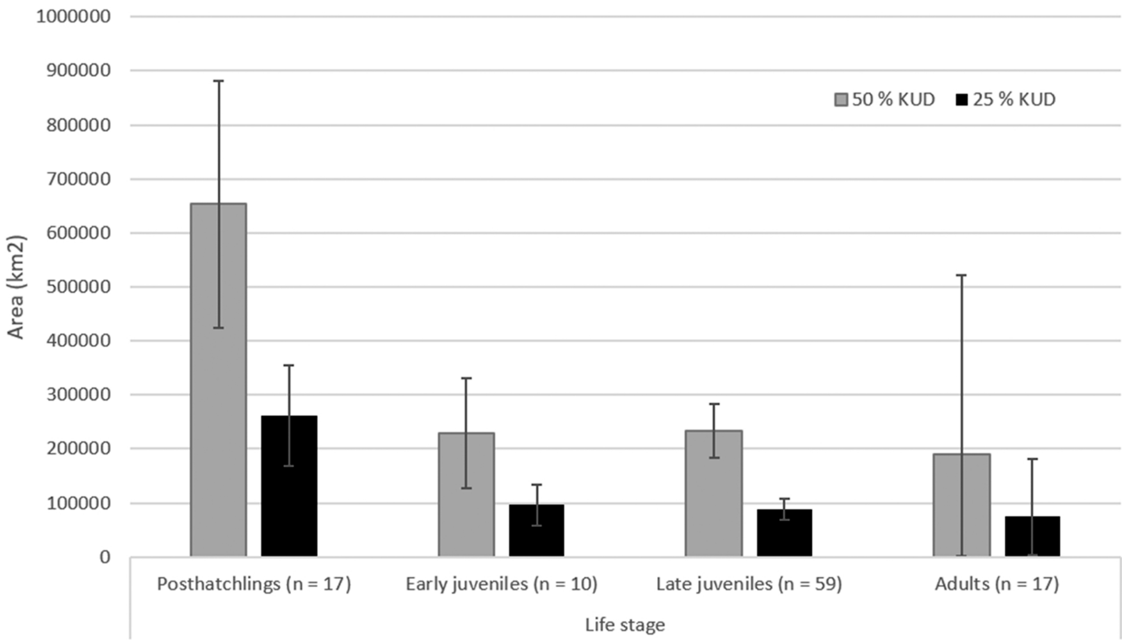

Fig. 3. Mean kernel utilization distributions (KUD) at 50 % and 25 % and standard deviation.by life stage.Sampling size is denoted by *n.*

3.3. Overlap of turtles' home ranges and density maps over MPAs

Overall, tracked turtles visited 60 Mediterranean MPAs, which comprised a total protected area of 222,040 km^2 (Table S2). Tracked individuals spent only a mean of 12.6 % ± 18.2 SD of their monitored days inside the limits of MPAs (range: 0–76 %). Only nine turtles (8.7 %) of all the monitored individuals spent more than 50 % of their tracked days inside MPAs (Fig. S4). The use of MPAs seemed to decrease with turtle development as the percentage of turtles that spent more than 50 % of their time inside MPAs lowered among developmental stages (post-hatchlings: 17.7 %, early juveniles 10 %, late juveniles 6.8 %, and adults 5.9 %). Twenty-two turtles (22 %) visited at least one MPA during their monitoring period. However this percent decreases as the number of MPAs which overlapped with the core area of each turtle increases (Fig. S5). Moreover, 31 (30 %) of the monitored individuals did not frequent any location inside the limits of MPAs (Fig. S5).

Also, we observed that 5.9 % of post-hatchlings, 10.0 % of early juveniles, 51.0 % of late juveniles and 23.5 % of adults never used an MPA.

The residency indices of turtles by life stage are shown in Table 2. Post-hatchlings used 25 different MPAs, of which 17 were used immediately after they were released from the Spain's Mediterranean coasts. The highest residency index was observed in early juveniles, followed by post-hatchlings, late juveniles and adults, which spent less time in MPAs. A significative positive correlation was observed between the residency index in MPAs and frequency of neritic locations (correlation = 0.52, t-statistic = 2.1686, df = 13, p-value < 0.04926) as most MPAs are coastal.

The MPA with most turtles using it and with the highest residence index, even when considered different life stages, was the SPAMI (Special Protected Area of Mediterranean Importance) "Mediterranean Cetacean Corridor" (Table 2), though on average the use was concentrated mainly in the southernmost part (Fig. 5). The second most used was the Delte de l'Ebre and Columbretes Islands.

According to the low residence indices recorded, the other MPAs seemed to be used only during transit. Fig. 5 shows homerange areas and relative density maps overlapped with MPAs. Between 9.2 % and 15.7 % of the global estimated core areas fell within protected areas, depending on whether we consider the 25 % or the 50 % KUD (Fig. 5a). Estimated core areas at 25 % KUD overlapped with only 1.5 % (18 out of 1233) Mediterranean MPAs (Fig. 6a). It is relevant to note that 10 out of 18 MPAs which overlapped home ranges were small areas (<50 km2). However, small protected areas (< 50 km2) were underused by tracked turtles, as only 0.2 % of locations that fell on a protected area were in a small protected area.

Regarding density areas, between 8.3 % and 11.1 % of the hotspots fell into protected areas, depending on whether we consider areas upper 75 % percentile or 50 % percentile of weighted daily location density, respectively (Fig. 5b). Estimated density at 75 % percentile overlapped with 3.7 % (46 out of 1233) Mediterranean MPAs (Fig. 6b).

Different use of MPAs by life stages was observed. Post-hatchlings most visited area was the Mediterranean Cetacean Corridor. The Platform Cabo de la Nao, Almería – Seco de los Olivos, Submarine valleys of Mazarrón and MPAs between the Balearic Islands and the Spanish coastline, including the Menorca Channel, were visited only during transit or migratory movements during the first months after release. After crossing the Sicilian Channel the MPA most visited by posthatchlings was Il-Bahar tal-Lvant, inside the 25 % KUD hotspot (Fig. 4 b1).

Early juveniles showed the higher residency index in the Mediterranean Cetacean Corridor, Northwest Ibiza, Delte de l'Ebre –

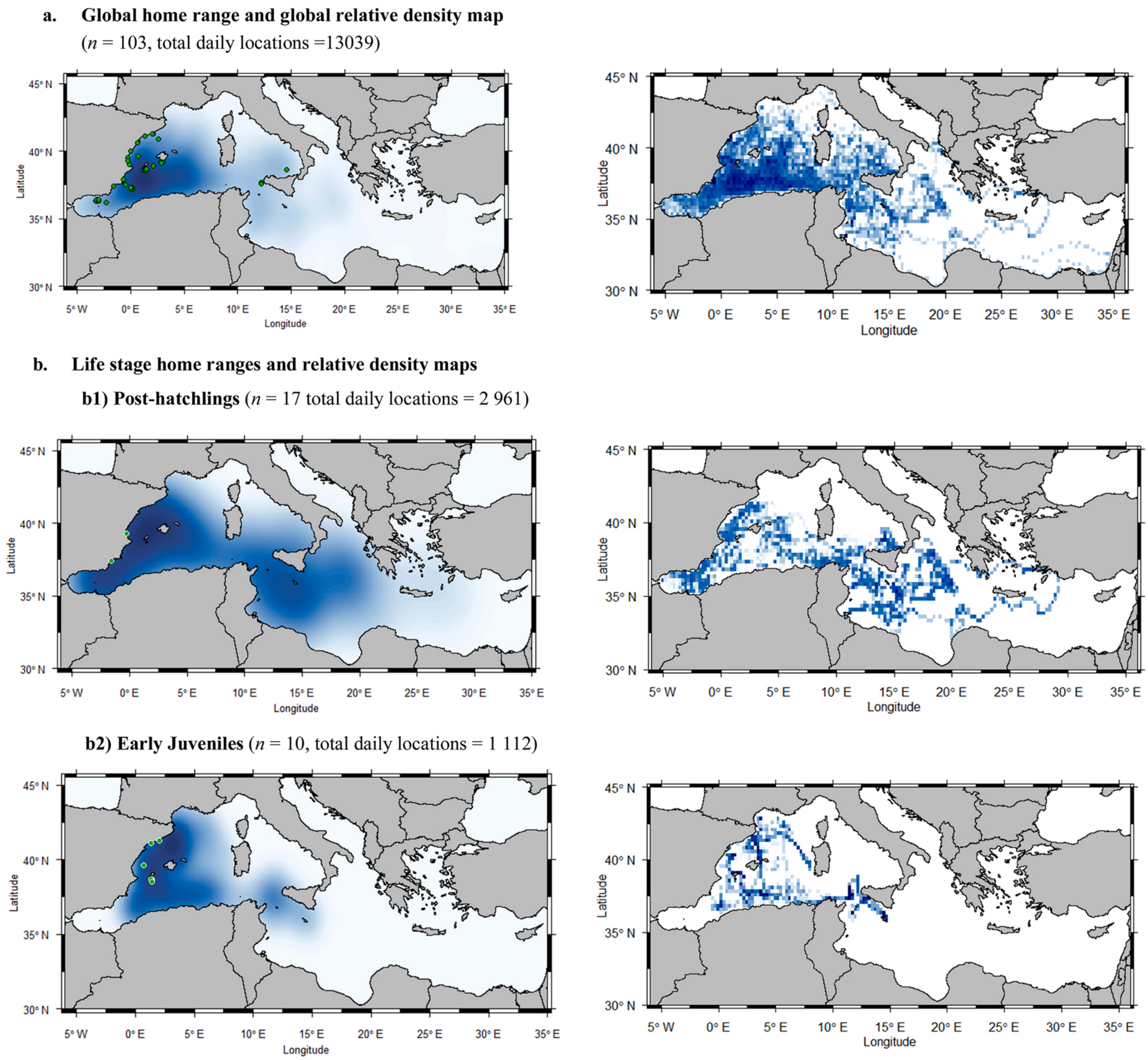

Fig. 4. The home range estimates (on the left) and relative density maps (on the right) for loggerhead sea turtles in the Mediterranean Sea. Blue dark areas are high-density areas (25 % KUD and percentile 75, respectively). Fig. 4a. The global home range and relative density for all the tracking data. The home ranges and relative density by life stage are shown in Fig. 4b; b1: post-hatchlings, b2: early juveniles, b3: late juveniles and b4: adults. Release points are shown in green at the home range estimate map.

Columbretes Islands, Gulf of Lion, Menorca Channel and Maltese MPAs (Il-Bahar tal-Lvant and Il-Bahar tal-Grigal). All these MPAs fell inside home range and/or relative density hotspots (Fig. 4b2).

Late juveniles mostly visited the Cetacean Mediterranean Corridor, followed by the Delte de l'Ebre – Columbretes Islands, northwest Ibiza, Tabarca – Cabo de Palos, submarine valleys of Mazarrón and the Platform Cape de la Nao. Although these areas were the most used by late juveniles, the residency indexes were low compared to other life stages, as the hotspot was located in the Algerian basin (Fig. 4b3). Adults visited a few areas as the core area was at the Algerian basin (Fig. 4b4). In decreasing residency index the areas visited by adults were: Mediterranean Cetacean Corridor, Platform Cape de la Nao, Tabarca – Cabo de Palos, Delta de l'Ebre – Columbretes Islands, South Almería – Seco de los Olivos and submarine valleys of Mazarrón.

3.4. MPAs proposal for loggerhead sea turtle conservation in the Mediterranean Sea

According to the core areas and the relative density maps obtained, the areas to be considered for protection of the loggerhead sea turtle in the western and central Mediterranean would be located in open waters more than in coastal areas. As important areas

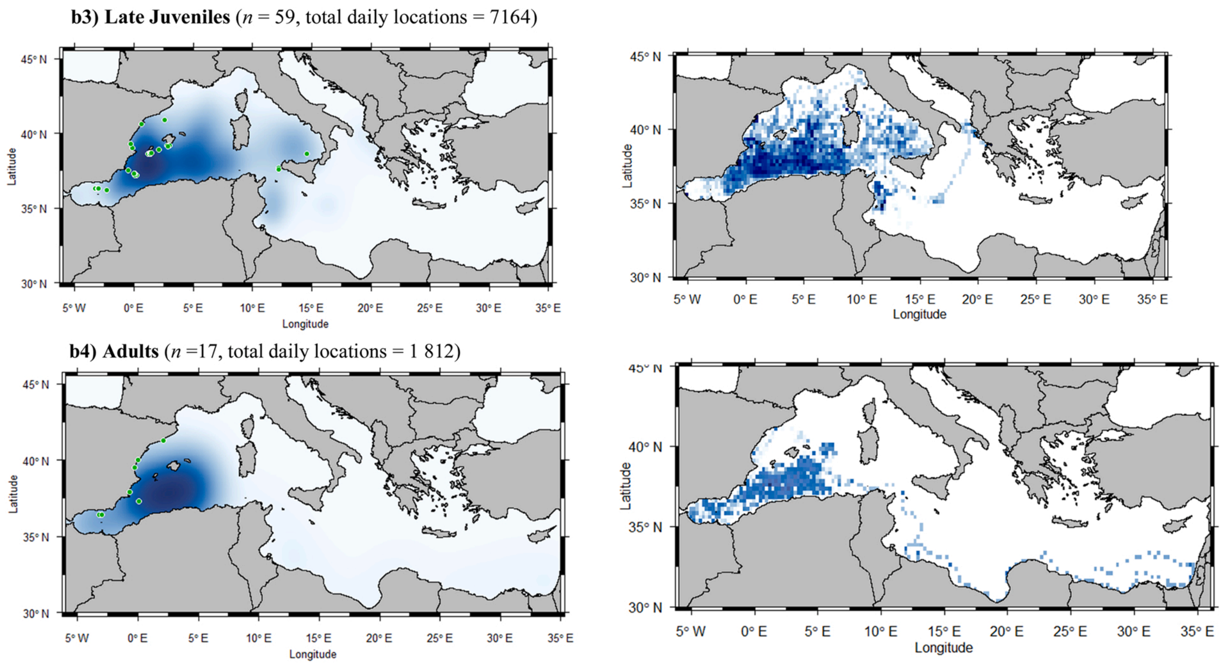

Fig. 4. (*continued*).

Table 2
Most widely used MPAs by monitored loggerhead sea turtles. MPA size is shown in squared kilometres and density in number of the monitored individuals that used the MPA per squared kilometre. The residency index is the number of locations inside the limits of MPAs versus the total location number. The Residence index is shown as a percent for all the stages and separated by stage. The percent of individuals is the number of individuals that used MPAs versus the total number of monitored individuals. MPA designations are: SPAMI (Specially Protected Areas of Mediterranean Importance), SPA (Special Protection Area, Birds Directive) and SCI (Site of Community importance, Habitats Directive). Global residency index considering all dataset are shown in the last row.

MPA	MPA Area (km^2)	Designation	Density (indv/ km^2)	Individuals (%)	Residency index (%)				
					All	Adults	Late juveniles	Early juveniles	Post-hatchlings
Mediterranean Cetacean Corridor	60965	SPAMI	0.001	33.0	6.8	1.1	4.6	18.2	2.6
Marina area Delta de l'Ebre - Columbretes Islands	9017	SPA	0.001	11.7	0.7	0.6	0.8	1.0	0.1
Northwest Ibiza	472	SPA	0.017	7.8	0.6	0.0	0.8	1.3	0.0
Marine plataform Cabo de la Nao	2681	SPA	0.007	19.4	0.6	0.7	0.5	0.1	0.2
Marine area Tabarca - Cabo de Palos	1260	SPA	0.008	9.7	0.6	0.7	0.7	0.0	0.1
Submarine valleys of Mazarrón	1540	SCI	0.016	23.3	0.4	0.4	0.5	0.2	0.1
South Almería "Seco de los Olivos"	2829	SCI	0.005	13.6	0.4	0.5	0.2	0.0	0.2
Pelagos Sanctuary For The Conservation Of Marine Mammals	87500	SPAMI	0.00001	1.0	0.3	0.0	0.6	0.0	0.0
Menorca Channel	3354	SCI	0.002	7.8	0.2	0.1	0.1	1.1	0.1
All MPAs				69.9	12.7	4.9	11.1	26.2	16.3

obtained from our analysis comprises large areas across the Mediterranean basin, we suggested several candidates to be protected areas, whose shape was computed taking into account the minimum area which includes the closest cells of upper 75 % percentile of relative density estimates: in first place of global estimates and in second place to completely define these areas taking into account life stage. Those proposed areas should be considered as the minimum area of interest that could be protected as no buffer area was added to MPAs proposal.

Here, we propose candidate areas to be considered as marine protected areas in the following zones: the west of the Algerian basin, the waters at the Northern Ionian Sea, waters at the Northern Strait of Sicily, areas at the Tyrrhenian Sea and waters at the Northeast Tunisia (waters in front of Hammamet Gulf in Tunisia) (Fig. 7). Also, we propose an enlargement and a connection of the already existing Maltese MPAs (MPAs Il-Bahar tal-Lvant and Il-Bahar tal-Grigal), as the Maltese EEZ waters close to these areas seemed to be important, at least for early juveniles tracked from western Mediterranean and post-hatchlings from Spanish Mediterranean nests.

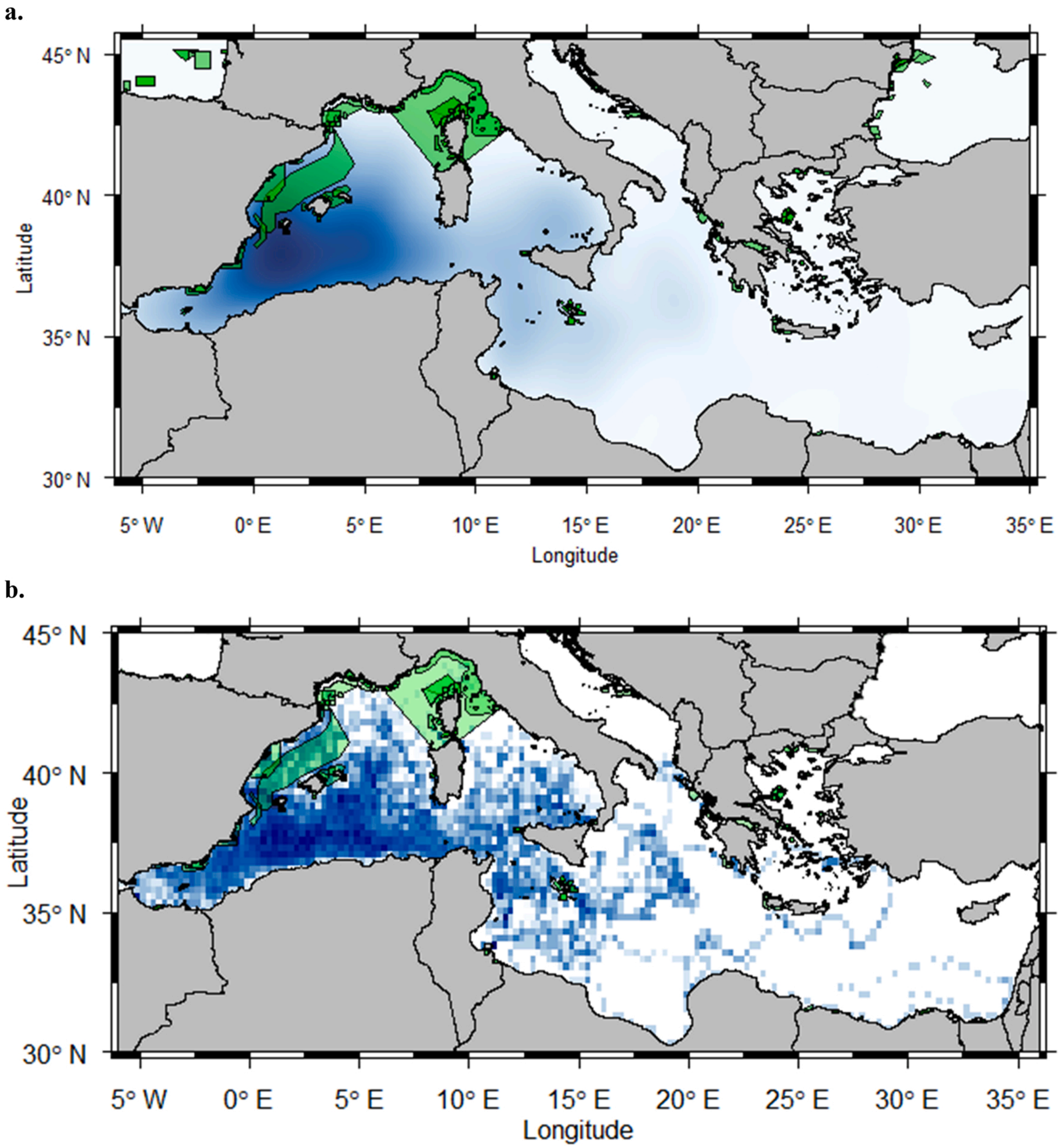

Fig. 5. Overlapping of the kernel utilization distributions (KUD) and the relative density estimations of the monitored individuals with marine protected areas (green) in the Mediterranean Sea. a) Overall home range b) Relative density map. Blue dark represents high density areas (25 % KUD and percentile 75, repectively).

Finally, we propose to protect the waters located at the Alboran Sea, which also would imply an enlargement and connection of the already existing areas: South Almeria – Seco de los Olivos, Marine Reserve of the Alboran Island and Marro – Cerro Gordo Cliffs (Fig. 7).

High-use areas identified in the Balearic Sea are in their most part already under several figures of protection, so therefore, we do not propose any candidate to this area.

4. Discussion

The present study provides home range estimations, descriptions of core areas and relative density estimations for loggerhead sea turtles tracked from western Mediterranean, by relating them to the current MPAs' network in this sea to ascertain their effectiveness to protect this species in this sea.

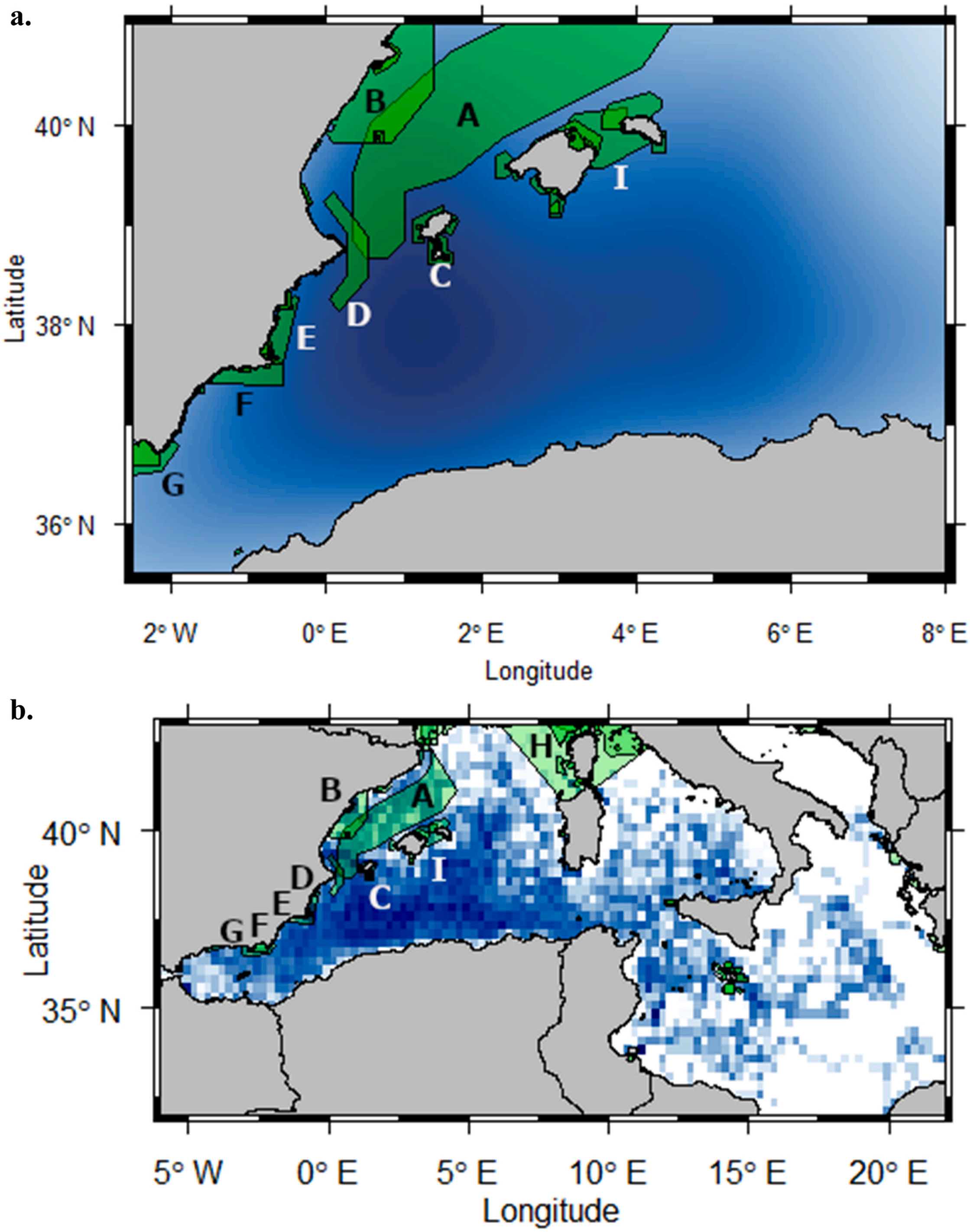

Fig. 6. Overlapping of the kernel utilization distributions (KUD) and the relative density estimations of the monitored individuals with marine protected areas (green). Results zoomed in core areas: a) Home range maps zoomed over the 25 % and 50 % KUD core areas; b) Density map zoomed over percentile 75. The MPAs which overlapped turtles core areas with a higher residency index and listed decreasingly were: A. Mediterranean Cetacean Corridor; B: Delta de l'Ebre and Columbretes Islands; C: Northwest Ibiza; D: Marine plataform Cabo de la Nao; E: Marine area of Tabarca - Cabo de Palos; F: Submarine valleys of Mazarrón; G: South Almerica – Seco de los Olivos; H: Pelagos Sanctuary For The Conservation Of Marine Mammals; I: Menorca Channel.

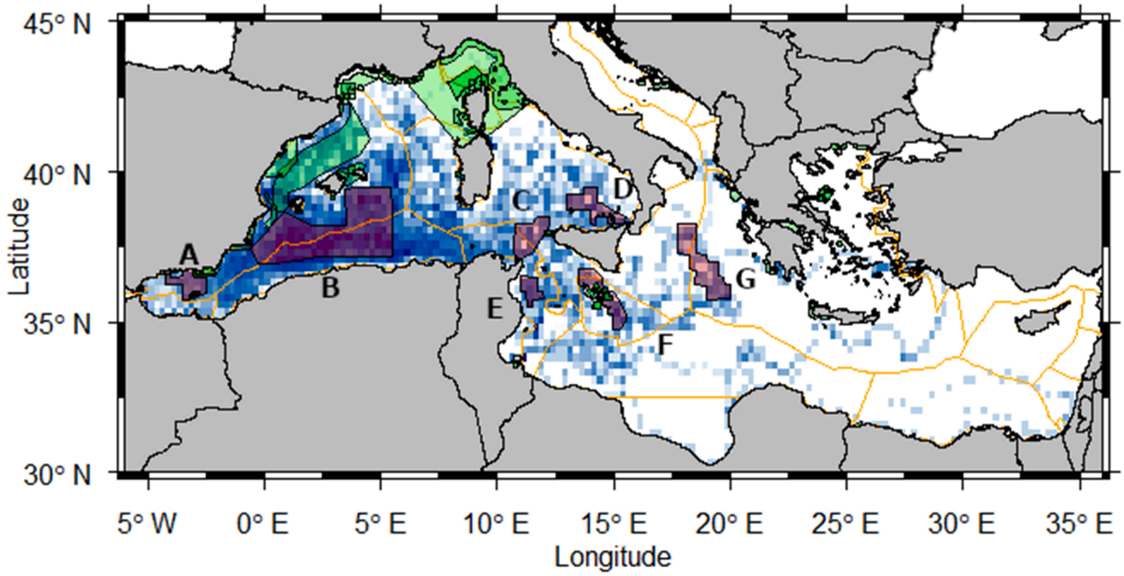

Fig. 7. Specially Protected Areas of Mediterranean Importance (SPAMIs) proposed for loggerhead sea turtle conservation in the Mediterranean Sea and extension in km^2: A) Alboran Sea (13,064 km^2), B) Algerian basin (116,032 km^2), C) Northern Strait of Sicily (17,140 km^2), D) Tyrrhenian Sea (17,579 km^2), E) Northeast Tunisia (7,709 km^2), F) Malta (17,713 km^2), and G) Northern Ionian Sea (29,257 km^2). Current Marine Protected Areas are shown in green. Relative density estimates are shown in blue. Delimitation of countries Exclusive Economic Zones are shown in orange.

4.1. Spatial distribution

Our results should be considered for satellite-tracked loggerhead sea turtles tracked from western Mediterranean because despite tag bias was addressed in our methodology, it cannot be fully corrected. Most of the monitored individuals moved long distances and had wide home range areas that apparently decreased with life stage development, with post-hatchlings having the widest home ranges probably to dispersal movements. Early juveniles show more reduced home ranges probably because they move around feeding habitats. This coincides with the proposed model of ontogenetic reduction in home ranges, and agrees with previous literature (Carr, 1987; Bolten, 2003; Schofield et al., 2010a; Casale et al., 2012a). No transitions by late juveniles and adults to neritic areas were observed, as proposed in other areas (Scott et al., 2014), because they remained in oceanic waters. In fact, long term studies on diet, debris ingestion, and epibionts suggest that the ontogenetic habitat shift in the loggerhead sea turtle are very flexible in the Spanish Mediterranean, with temporary exploitation of oceanic resources regardless of size (Tomás et al., 2001; Domènech et al., 2018; Domènech et al., 2019; Ten et al., 2019).

The main identified core areas were located in the Algerian Basin, the southern Balearic Sea, the Alboran Sea, the Sicilian Channel, the Northeast Tunisia, Maltese Sea, Tyrrhenian Sea and the Ionian Sea, depending on life stage. Our results support previous studies that have pointed out the Algerian Basin and the southern Balearic Islands as an important area for loggerhead sea turtle conservation in the western Mediterranean for juveniles and adults (Cardona et al., 2005; Revelles et al., 2007a,b,c; Casale et al., 2012a,b; Hays et al., 2014). The core areas observed for late juveniles and adults along the Algerian Basin may be related to the highly productive eddies of the Algerian current (Millot, 1999; Obaton et al., 2000; Pinardi and Masetti, 2000; Bosc et al., 2004; Balbín et al., 2014; Cardona and Hays, 2018). Also, a strong current as the Algerian current may act as a physical barrier in loggerhead dispersal movements by retaining some individuals in the Algerian basin (Revelles et al., 2007b; Revelles et al., 2007c). Besides, adults tracked from western Mediterranean were more likely to remain in the same basin where tagged (Luschi et al., 2017). This could be related, for instance, to the turtle's Mediterranean or Atlantic genetic origin (Carreras et al., 2018), or to a possible adult fidelity to a foraging or breeding area (Casale et al., 2012c).

The Algerian basin and the Alboran Sea are also important areas for post-hatchlings, and probably also for hatchlings, of nests laid in the western Mediterranean (Abalo-Morla et al., 2018a and present study). Regarding post-hatchlings, the core area observed off the Spanish Mediterranean coast would be an important developmental area for hatchlings only immediately after entering the sea, before entering in the influence of currents that may transport them to the Eastern Mediterranean, although we cannot discard a potential effect of release locations from the coast of Spain. The Tyrrhenian Sea could be an important area for post-hatchlings and juveniles for foraging (Chimienti et al., 2020). This sea presents robust cyclonic and anticyclonic gyres that change seasonally affecting sea productivity and turtle distribution (Blasi and Mattei, 2017; Luschi et al., 2018). The Sicilian Channel, Northeast Tunisia, Malta and the Ionian Sea seem to be also important developmental areas for post-hatchlings coming from nesting events in the western Mediterranean, as has been proposed also for hatchlings from eastern Mediterranean nesting beaches (Hays et al., 2010; Casale and Mariani, 2014), and also for juveniles and adult loggerhead tagged in other Mediterranean areas (Bentivegna, 2002; Schofield et al., 2010a; Bastari et al., 2016; Mingozzi et al., 2016; Casale et al., 2018; Luschi et al., 2018). Additionally, the identification of core areas for the loggerhead sea turtle in the Western Mediterranean results essential for the conservation of this species and the potential colonization process in the area, given the recent increase in nesting events in this basin (Tomás et al., 2008b, 2015; Carreras et al., 2018; Marco et al., 2018), possibly as result of adaptation of the species to global warming (Witt et al., 2010; Maffucci et al., 2016; Hochscheid et al., 2022).

4.2. Effectiveness of MPA for loggerhead sea turtle protection in the Mediterranean

There was very little overlapping between turtle's core areas and tracks with the protected areas, and turtles spent very little of their monitored time inside them. Indeed, most of the core areas and high density areas estimated (>85 %) were not included within any of the MPAs. Furthermore, less than 5 % of the Mediterranean MPAs were used by tracked loggerhead sea turtles.

Just one of the most used MPAs by loggerhead turtles tracked herein had a current management plan with specific conservation measures for the species (Submarine Valleys of Mazarrón). This is especially relevant because the loggerhead turtle is a priority species set out in the Habitats Directive of the European Commission (European Commission 2007). Applied conservation measures are unlikely to be enough to protect 60 % of the loggerhead turtle populations in the Mediterranean, as required by the Natura 2000 Network (European Comission, 2007; Fortuna et al., 2018). The identification of high-use areas would represent a spatial management opportunity, where specific threats could be reduced (Casale et al., 2012a; Rees et al., 2016; Fortuna et al., 2018).

Most of the MPAs are designed to protect waters near or not far from the coasts, and we have seen that tracked turtles barely used the waters included in many of them in the western Mediterranean. Small and coastal MPAs (<50 km^2) were not used often. Similar results have been observed elsewhere. For instance, very little use of coastal MPAs has been observed by loggerhead turtle nesting females in Cyprus (Snape et al., 2018). On the other hand, large MPAs are difficult to manage given the diverse range of economic, political and legal obstacles that may impede the establishment and enforcement of large reserves, especially transnational ones (Badalamenti et al., 2000; Agardy et al., 2011; Singleton and Roberts, 2014; Gruby et al., 2016). Moreover, the lack of an inter-connected Mediterranean MPAs' network was pointed out as a main constraint for the conservation of wide-ranged species with complex life cycles (Gabrié et al., 2012; Amengual and Alvarez-Berastegui, 2018). For all these reasons, current MPAs may offer unsuccessful protection for loggerhead sea turtles in the Mediterranean Sea, as proposed in previous studies at smaller geographical scales (e,g,. Revelles et al., 2007b, Snape et al., 2018).

Previous sea turtle conservation efforts in the Mediterranean have primarily focused on protecting nesting sites (Casale and Margaritoulis, 2010), although population models have indicated that only preserving sea turtle nesting areas is insufficient without considering other key habitats (Casale and Heppell, 2016; Casale et al., 2018). Conservation planning for sea turtles must consider these species' ecological and ontogenetic developmental requirements (Hamann et al., 2010; Venter et al., 2014; Rees et al., 2016) and should explicitly protect all life stages (Bentivegna, 2002; Beger et al., 2015) with large-scale conservation plans that explicitly incorporate their habitat needs and migratory behaviours (Mazor et al., 2016; Harrison et al., 2018). According to Art. 4.1 of the Habitats Directive, the core areas used by the species, and now identified in the present study, should be protected (European Comission, 2007; Fortuna et al., 2018).

According to our results, the areas to maximize protection for the conservation of the loggerhead sea turtle tracked from western Mediterranean were identified in the western and central Mediterranean. Therefore, we propose several areas as potential candidates to be protected in the Mediterranean. If protected, over 18 % of the Mediterranean Sea would be under legal conservation figures of protection. This proposal will help to achieve the goal of the "High Ambition Coalition for Nature and People" (https://www.hacfornatureandpeople.org/home) of protecting at least 30 % of world's land and ocean by 2030.

The most effective type of MPA in these basins depends on the distribution and extension of the areas which are intended to protect. On the one hand, SPAMIs could be an option for those areas which include waters of the Economic Exclusive Zone (EEZ) of two countries. On the other hand, areas that fell in a country EEZ in the European Union (Alboran Sea and Tyrrhenian Sea) could be declared protected marine areas in the 2000 Nature Network framework, as the loggerhead sea turtle is a priority species under the Habitat Directive (European Comission, 2007).

Both, existing protected areas and proposed areas to be protected should include the implementation of specific measures to enhance loggerhead sea turtle conservation. In the Mediterranean Sea there are 1,233 MPAs declared, of which 118 consider the loggerhead sea turtle as a priority species to protect. However, only 40 have current management plans including specific conservation measures focused on the loggerhead sea turtle. For example, in the Balearic Sea, the MPA "Mediterranean Cetacean Corridor" includes protection measures for cetacean species but do not include any conservation measures focused on sea turtles. We observed that the Balearic could be an important area for post-hatchlings and juveniles of loggerhead sea turtle. Therefore, our proposal is to include specific protection measures for loggerhead conservation in the already existing MPAs in the Balearic Sea.

The MPA we propose in the Alboran Sea could contribute to the protection for post-hatchling and adult loggerhead sea turtles. The MPA in the Algerian basin could be of interest for the protection of juvenile and adult loggerhead turtles (Cardona et al., 2005; Casale et al., 2012b). The proposed MPAs Northern Strait of Sicily, Northeast Tunisia, Maltese waters, and Tyrrhenian Sea could be also important areas to be protected, particularly for juveniles tracked on western Mediterranean and post-hatchlings from clutches laid in the Spanish Mediterranean and probably also for post-hatchlings from western Mediterranean in general. Traditionally, a limited exchange between the two Mediterranean basins has been estimated for hatchlings and post-hatchlings originating in the western Mediterranean, and turtles would be expected to be retained in the South Tyrrhenian Sea (Maffucci et al., 2016), which is considered an important foraging and overwintering area (Blasi and Mattei, 2017; Luschi et al., 2018; Chimienti et al., 2020). Northeast Tunisia was also identified an important foraging areas adults and subadults of loggerheads tracked on the western Mediterranean basin The proposed MPA in the Northern Ionian Sea could also act as a key area for loggerhead post-hatchlings, at least, from western

Mediterranean nests, since similar research about post-hatchlings from eastern Mediterranean is still a gap knowledge. Increasing nesting events in the western Mediterranean basin during last decades could be a consequence of global warming (Tomás et al., 2008a; Maffucci et al., 2016; Carreras et al., 2018), therefore our results could be important for post-hatchlings conservation. Furthermore, proposed MPAs include important areas for other species of cetaceans, sharks and sea turtles, which could be benefited from conservation measures taken in this areas.

Our results agree with previous studies that pointed out the waters at the southwest of Balearic Islands, the west of the Algerian basin, the Alboran seamounts in the Alboran Sea, the northern side of the Strait of Sicily, the Tunisia Plateau and the northern Ionian Sea as potential SPAMIs (Notarbartolo di Sciara and Agardy, 2009; Micheli et al., 2013a,b). Previous studies also proposed the northern part of the Mallorca and Menorca Channel as Site of Community Importance (pSCI) for seabirds, cetaceans and loggerhead sea turtle conservation (Barberá et al., 2014), and this area partially overlap with the early juvenile loggerhead core areas estimated herein. Proposed areas to be protected in the Central Mediterranean are based on the results showed in this paper and for turtles tracked from western Mediterranean. However, further research and collaboration among researchers from both basins is needed to define important areas to be protected accurately, especially for juveniles and post-hatchlings, gathering satellite-tracking data from both eastern and western Mediterranean. For instance, similar research with satellite-tracked loggerhead post-hatchlings from eastern Mediterranean is still a gap knowledge and further research is needed. Nonetheless, managers and conservation stakeholders from Central Mediterranean could use this research as a starting-point to define adequate protected areas for loggerhead post-hatchlings conservation.

5. Conclusions

The present study has revealed that the current distribution and coverage of Mediterranean MPAs seem to be insufficient to protect the loggerhead sea turtles in this sea. Core areas for the loggerhead turtles observed in the Algerian Basin, the Sicilian Channel and the Ionian Sea are currently beyond the limits of MPAs and, hence, remain unprotected. Moreover, most MPAs in the western and eastern Mediterranean lack of explicit management measures focusing on minimize threats that undermine sea turtle conservation. Therefore, conservation measures that focus directly on loggerhead turtle survival would be most beneficial if they were to include in the core areas described in this paper. The MPAs we propose in the Alboran Sea, Algerian basin, Northern Strait of Sicily, Northeast Tunisia, Malta, Tyrrhenian Sea and Northern Ionian Sea, could be interesting areas to be implemented for loggerhead sea turtle conservation in the western and central Mediterranean.

Compliance with ethical standards

The authors declare that there is no conflict of interest and that consent was obtained from all the involved parties. The authors declare that animals were treated according to all applicable international, national, and/or institutional guidelines for the care and use of animals. Animal ethics approval was granted by the Universitat Politècnica de València. The tagging of post-hatchlings was done after obtaining a permit from the regional and national Spain's Environmental Authorities (Generalitat Valenciana, Generalitat de Catalunya, Consejeria de Medio Ambiente y Ordenación del Territorio de la Junta de Andalucía, Ministerio de Medio Ambiente y Medio Rural Marino).

CRediT authorship contribution statement

There is no conflict of interest with any of the authors. Each author contributed to the manuscript as follows: SA-M, EB, JT and OR conceived the study, SA-M, EB and JT prepared the material, performed the data analysis and wrote the manuscript. OR and DM provided tracking data and also provided inputs to the manuscript. RS, YS, JC-P, AM, MM, AC and SH provided tracking data. All authors have agreed to be listed and approved the submitted version of the manuscript.

Declaration of Competing Interest

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2022.e02196.

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