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Satellite tracking identifies important foraging areas for loggerhead turtles frequenting the Adriatic Sea, Central Mediterranean

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Abstract

The Adriatic Sea is one of the main foraging areas for marine turtles of the Mediterranean Sea, but the specific high-use sites are poorly known, due to the scarceness of satellite tracking data available for juvenile turtles frequenting the area. In the present study, we tracked 8 juvenile and adult loggerhead turtles (*Caretta caretta*) that were released along the north-western Adriatic coast after a rehabilitation period having been equipped with Argos-linked satellite transmitters. Tracked turtles displayed quite variable movement patterns, but mostly remained in the north-western Adriatic, especially during the summer months. A marked preference for specific coastal sites was revealed in many turtles, that actively moved towards these specific locations when released south of it or having spent the winter away. Pooling these data with those obtained in previous studies on a further 10 turtles, we highlighted the presence of two main high-use areas, north and south of the Po River delta, where future conservation actions may then be focused.

Keywords: marine turtles; utilization distribution; site fidelity; water temperature; seasonal distribution.

Introduction

Thanks to its extended neritic areas, the Adriatic Sea, and especially its northern portion, offers optimal foraging opportunities to bottom-dwelling marine turtles, like the loggerhead turtle *Caretta caretta*. It is a narrow, semi-enclosed basin in the Central Mediterranean, with a major NW-SE oriented axis of about 750 km long and 200 km wide. Its northern and central portions are characterised by shallow waters, with average depths at less than 150 m, and as low as 35 m in the northernmost area. The general seawater circulation of the Adriatic is cyclonic, being composed of a northwest-directed flow along the eastern coast and a southeast flow along the western coast (Danovaro & Boero, 2019).

The Adriatic Sea is recognised as one of the most important foraging grounds for these species in the Mediterranean Sea (Casale *et al.,* 2018). It is frequented by juveniles and by adults outside the breeding season that aggregate in specific neritic feeding areas, as indicated by information obtained from various sources such as capture-mark-recapture, mixed stock and stable isotopes analyses, distribution of incidental captures, fixed line transects from ferries and satellite tracking (Lazar & Tvrtkovic, 1995; Margaritoulis *et al.*, 2003; Casale *et al.*, 2004; Casale *et al.,* 2007; Casale *et al.*, 2012a, b; Schofield *et al.,* 2013; Luschi & Casale, 2014; Tolve *et al.,* 2018; Haywood *et al.,* 2020; Baldi *et al.,* 2022; Zampollo *et al.,* 2022). Late juveniles and adults can also remain in the region to winter (Hochscheid *et al.,* 2007; Casale *et al.,* 2012a), although they often use the Adriatic foraging sites only seasonally, shifting to southern sites during cold periods (reviewed in Luschi & Casale, 2014). Satellite telemetry, in particular, allows the specific locations frequented by tracked individuals to be identified, providing basic information that, when integrated with that obtained from other sources, can lead to the development of effective protection measures against anthropogenic threats. Indeed, obtaining tracking data on turtles of different size classes, especially juveniles, has been identified as a research priority for Mediterranean turtles (Casale *et al.*, 2018).

Quite a wealth of tracking data is available for Mediterranean adult loggerheads, especially those belonging to the large rookery on Zakynthos Is., Greece, and foraging in the central/northern Adriatic Sea (Zbinden *et al.*, 2011; Schofield *et al.*, 2013). In a few other cases (Mencacci *et al.*, 2006; Casale *et al.,* 2012a; Luschi *et al.*, 2013; Casale

& Simone, 2017; for a total of 5 individuals), tracked turtles were considered by the authors to be mature because of their large size (Curved Carapace Length, CCL > 74 cm). Conversely, only a few turtles considered juveniles (CCL < 70 cm) have been tracked in the basin (Casale *et al.,* 2012a n=6; Luschi *et al.,* 2013 n=1; Casale & Simone, 2017 n=4; Snape *et al.,* 2020 n=3; for a total of 13 individuals tracked), even though they constitute the majority of turtles frequenting the Adriatic Sea (Casale *et al.,* 2010; Vasapollo *et al.,* 2019). These data have shown that juvenile turtles dwelling in the Adriatic display variable movement patterns, ranging from residence in spatially limited sites to long distance migrations, often of a seasonal nature (Casale *et al.,* 2012a). In some cases, collected data have indicated the role of seawater temperatures in determining these movement patterns, although the overall picture is far from clear (reviewed Luschi & Casale, 2014). Most importantly, tracking results have also shown how loggerheads do not favour any special habitat or geographical area in the Adriatic, dispersing quite widely and frequenting either coastal or offshore (but still neritic) waters.

A tendency of tracked juveniles to prefer the eastern side of the Adriatic, especially in its northern portion, has been noted (Casale *et al.*, 2012a; Snape *et al.*, 2020), which corresponds to a similar tendency for adult turtles having nested in Greece (Zbinden *et al.* 2011; Schofield *et al.,* 2013). Loggerheads are, however, known to frequent the waters of the western Adriatic and show a frequency of incidental captures (Pulcinella *et al.*, 2019; Bonanomi *et al.*, 2022) or of stranding events (Casale *et al.,* 2010) in the area.

However, this information alone does not allow us to identify the specific areas that are most frequently used by juvenile turtles foraging in the northern Adriatic Sea, and the tracking data available (Casale *et al.,* 2012a) are too scant to meet this aim. To start filling this gap, we describe the movements of juvenile and adult-sized loggerheads, that were satellite-tracked for several months while moving in the northern and central Adriatic Sea after a rehabilitation period spent in a sea turtle rescue centre. The new data were additionally pooled with those obtained in other satellite-tracked turtles released in the northern and central Adriatic Sea (Mencacci *et al.,* 2006; Casale *et al.,* 2012a; Luschi *et al.,* 2013). In this way, we aimed at i) identifying the specific hotspot sites mostly used by turtles frequenting the northern Adriatic; ii) assessing the nature of the movements performed (e.g., large scale wanderings, permanence in restricted sites, seasonal migrations), also evaluating if turtles displayed fidelity to specific foraging or wintering sites; iii) determining the role of varying temperatures in prompting the onset of tracked movements and the choice of the identified hotspots.

Materials and Methods

All tracked turtles were rescued by the Fondazione Cetacea rehabilitation centre in Riccione, Italy. They had been captured along the north-western Adriatic coast (latitudes between 43.97°N to 44.68°N), five having been incidentally caught by bottom trawlers and three found stranded along the coast. They suffered from respiratory problems or had wounds on their head, eyes, and carapace due to impacts with boats. After being kept in captivity for variable periods (from four months up to four years; Table 1), they were in optimal health at the time of release. Their size ranged from 52 to 85 cm CCL (Table 1).

The eight turtles were equipped with satellite transmitters (PTT) linked with the Argos system (Table 1) and were released from various places along the west coast of the Adriatic Sea (Fig. 1). The locations were classified by Argos in different location classes (LCs) on the basis of their estimated accuracy (see also Witt *et al.,* 2010). We reconstructed the routes by using data of all the location classes but discarding the locations placed on land and those which inferred movement speeds exceeding 4 km/h (see Luschi *et al.,* 2018). Location data were also managed through STAT (Satellite Tracking and Analysis Tool *http://www.seaturtle.org*) which associated each turtle location with sea surface temperature values (Coyne & Godley, 2005), that were then used for the analysis of turtle movements in relation to temperature.

Table 1. Details of the eight turtles tracked by satellite. TAM PTTs were made by Telonics Inc. (Mesa, AZ, USA); Kiwisat ones by Lotek (Havelock North, New Zealand).

Turtle ID	CCL (cm)	Time in captivity (mo)	PTT model	Release date	Last fix date	Tracking duration (d)
T1	65	50.6	TAM-4525	26/09/2010	08/06/2011	255
T2	68	9.3	TAM-4410	21/10/2010	23/12/2010	63
T3	58	24.0	Kiwisat 202	04/09/2011	01/02/2012	150
T4	85	3.9	Kiwisat 202	09/10/2011	05/08/2012	301
T5	74	5.5	Kiwisat 202	05/09/2015	12/05/2016	250
T6	52	7.6	TAM-2640	31/07/2016	24/02/2017	208
T7	72	5.8	TAM-2638	03/09/2016	27/01/2017	146
T8	62	5.2	TAM-2638	28/05/2017	29/07/2017	62

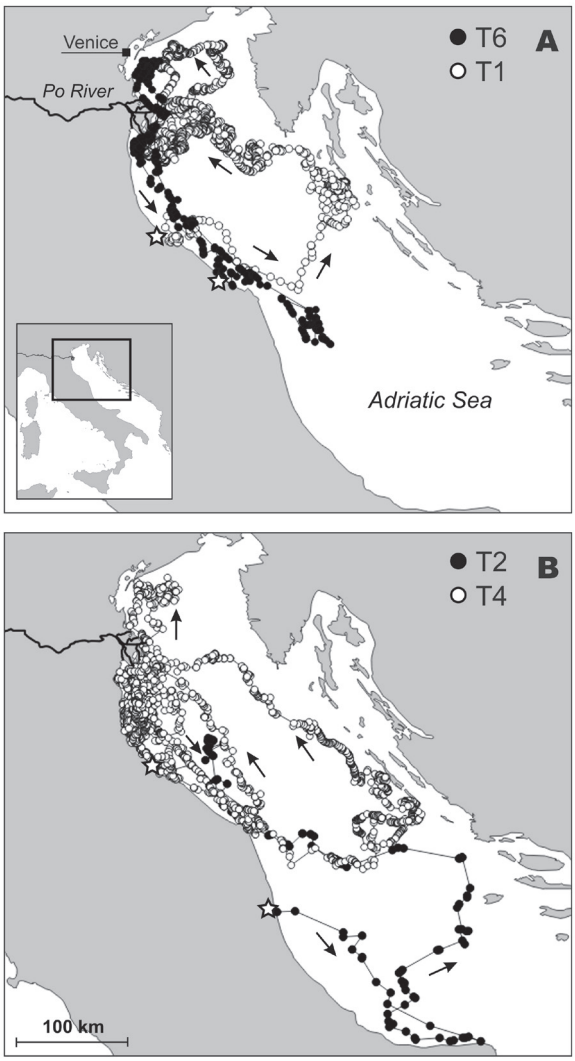

Fig. 1: Reconstructed routes of A) Turtles T6 (black circles) and T1 (empty circles); B) of turtles T2 (black circles) and T4 (empty circles). Stars indicate release locations.

To identify the areas mostly frequented by tracked turtles, a Utilization Distribution (UD, Worton, 1989) was calculated on all the locations collected in the northern and middle sub-basins of the Adriatic Sea, defined as the area north of a line connecting Vieste, Italy and Split, Croatia (Artegiani *et al.*, 1997). The same procedure was repeated by also considering the locations obtained in the three satellite-tracking studies published so far that involved turtles released in the northern and central Adriatic Sea (Mencacci *et al.,* 2006; Casale *et al.,* 2012a; Luschi *et al.*, 2013), for a total of a further 10 turtles tracked for 11-313 days while remaining in the study area.

Moreover, we estimated the seasonal home ranges for three turtles of this study that were tracked both in the winter (defined as the period January-March) and the summer (period July-September). For each season, the density of each turtle's UD was estimated using the fixed kernel technique (Kernel Utilization Distribution, KUD) with a reference smoothing parameter (Worton, 1989). The 95% and 50% volume contours (KUD95% and KUD50% respectively) were used to delineate the individual home range and core areas polygons. These analyses were made using the package "adehabitatHR" (Calenge, 2006) in R 4.1.2 (R Core Team, 2021).

Data on monthly mean seawater surface temperature provided by Copernicus Marine Service Information (MEDSEA_MULTIYEAR_PHY_006_004, monthly data, spatial resolution 0.042°), were used to compare the temperature at the eastern Adriatic wintering sites of three turtles with those that were recorded at a location at the same latitude in the western Adriatic along the Italian coast. For each turtle, the comparison was made for the two coldest months of the tracking period (February 2011 for turtle 1; March 2012 for turtle 4 and January 2012 for turtle 3). The temperature was extracted for the centroids of the KUD50% for each turtle that showed a movement between two sites.

Results

The eight turtles of the present study were mostly released in late summer/early autumn and were tracked for 62-301 days, thus covering in most cases the following winter and spring months as well (Table 1). Tracked turtles displayed quite variable movement patterns, that were however mostly confined to the northern Adriatic (Figs 1, 2). A major exception is represented by turtle T5 (Fig. 2B), which moved south soon after release in early September, leaving the Adriatic Sea in October to reach the Peloponnese coast (Greece), where it passed the winter. Its last locations in May indicate that it was moving northward again, apparently returning to the Adriatic.

The remaining seven turtles frequented the waters of the north-western Adriatic, and especially those close to the coast around and south of the Po River delta and offshore Venice lagoon (Fig. 1, 2). Turtles moved actively towards these areas even if released south of it or after having spent the winter away, as is the case of turtles T1 and turtle T4 wintering in the eastern Adriatic or turtle T2 in the southern Adriatic (Figs 1, 2). This is well represented in the UD of the present data pooled with those released in the northern Adriatic in previous studies (see above), which clearly reveals two main high-use areas in the region (Fig. 3), north and south of the Po River delta.

Six turtles (T1, T3, T4, T6, T7, T8) remained in the area for at least one month during the summer and/or the autumn, experiencing warm water temperatures, and five were tracked (T8 ended in Aug.) as they left the area later in the season: three in November/December (T4, T6, T7), with mean temperature 13.0 (SE=0.5)°C, and two (turtles T1, T3) already in mid-Oct., with mean temperatures 19.4 (SE=0.6)°C. Turtles T1, T3 and T4 crossed the northern Adriatic to reach localised wintering sites on the eastern Adriatic coast (Figs. 1A, 4), where they remained during the winter months, with turtles T1 and T4 (turtle T3 tracking ended on 1 Feb) returning again to north-western waters from late April onward. Overall, turtles resided in a more restricted site during summer months than in the winter, when they tended to use a larger foraging area spread along the Croatian coast. The mean monthly seawater temperature at these wintering sites was 0.8-3.4 °C higher than that at of the same latitude site along the Ital-

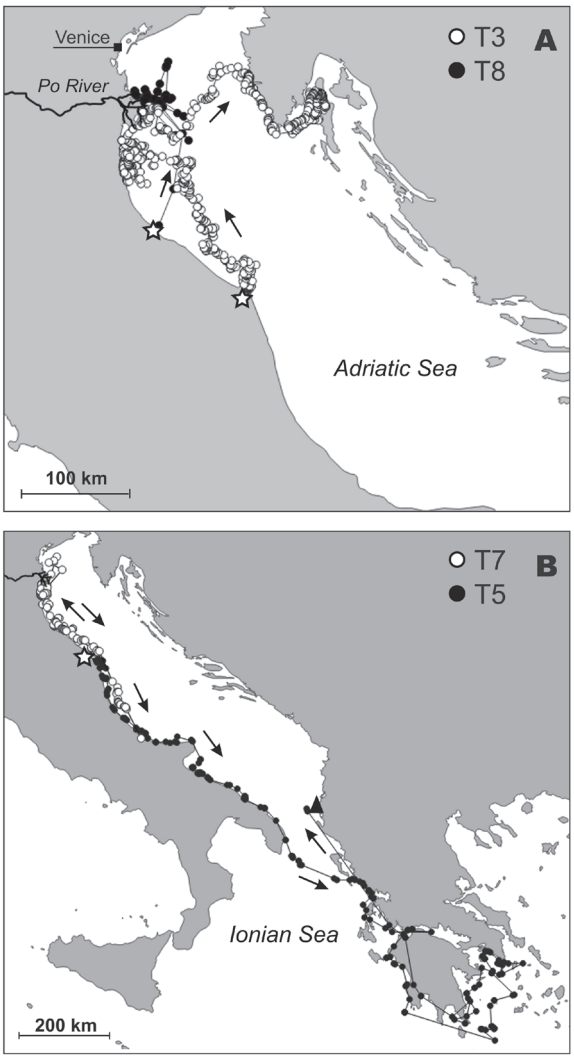

Fig. 2: Reconstructed routes of A) Turtles T8 (black circles) and T3 (empty circles); B) of turtles T7 (empty circles) and T5 (black circles). Stars indicates release locations; the black triangle indicates the last location for turtle T5.

ian coast. Turtle T6 also frequented two distinct areas but always resided in the north-western Adriatic Sea, moving at lower latitudes during the winter months (Fig. 1A, 4), where it experienced temperatures 5°C higher than those recorded during winter in the area they frequented in the summer.

Discussion

The present results allowed us to identify the specific locations most frequented by turtles foraging in the northern Adriatic Sea, documenting the importance of its north-western side, and thus contributing to filling a major gap in the scientific knowledge of the ecology of Mediterranean turtles. Tracked turtles remained over the wide continental shelf of the region for large part of the year, while displaying a marked preference for the westernmost waters of the basin, close to the Italian coast, especially during the warmer months. While this pattern may be partly due to the uneven distribution of capture and release sites (that were all along Italian coast), it is clear that turtles chose to remain in this area for several weeks after release, moving away only when seasonal conditions changed but returning there after spending the coldest months in other areas (see also below). Indeed, the UD obtained for the 18 turtles tracked in the region so far, clearly highlights the relevance of the coastal waters north of 44°N latitude (Fig. 3). Therefore, these may represent high-use areas that should be considered most relevant for the conservation of the species.

Most tracked turtles were probably immatures in the late phase of their developmental period, except for turtle T4 whose size (85 cm CCL) was above the range of size at maturity estimated for Mediterranean loggerheads (Casale *et al.*, 2018). These findings thus nicely complement previous data for juvenile and adult turtles tracked in the region, which were mostly found to preferentially stay in the eastern Adriatic, even when released from the Italian coast (Casale *et al.,* 2012a; Snape *et al.,* 2020). Specifically, of the two areas especially frequented by tracked turtles (Figs. 1-3), the one offshore from the Venice Lagoon was shown to be targeted by a few adult females migrating from Zakynthos Is. that established their foraging sites there (Zbinden *et al.*, 2011; Schofield *et al.,* 2013). Similarly, only two juvenile turtles were previously found to stay for some time along the coast south of the Po River delta (Casale *et al.*, 2012a), where nearly all tracked turtles resided for long time.

Tracking data additionally allowed us to characterise the kind of movements performed by the turtles, as well as to evaluate the role of temperature changes. Besides remaining for long time in circumscribed neritic/coastal areas, tracked turtles performed some extended movement that led them away from the region, either to cross the Adriatic and reach its east coast (turtles T1, T3, T4; Fig. 4) or make southward migrations towards lower latitudes (turtles T5 and T7; Fig. 2B). Similar movements aiming at southern wintering sites have already been observed in adult and juvenile loggerheads frequenting the northern Adriatic waters (Mencacci *et al.*, 2006; Zbinden *et al.,* 2008, 2011; Casale *et al.,* 2012a; Luschi *et al.,* 2013). Such prolonged, and likely active, movements between different areas are comparable to those recorded in non-rehabilitated turtles (e.g., Schofield *et al.,* 2013; Snape *et al.,* 2020) and this indicates that the turtles in the study turtles were not affected by the rehabilitation period they spent in the rescue centre, which was sometimes prolonged (Table 1). Indeed, several other studies have not recorded major anomalies in the behaviour after release of rehabilitated individuals (e.g., Mestre *et al.,* 2014; Luschi *et al.*, 2018; Robinson *et al.,* 2020). Both movement patterns shown by tracked turtles were likely prompted by the decreasing temperatures at the northern foraging sites and led turtles to spend the coldest months in thermically more favourable areas that guaranteed them temperatures five degrees higher than if they had remained in western Adriatic waters. The importance of water temperature in prompting or directing seasonal movements of loggerhead turtles has been shown in many other cases (e.g., Luschi & Casale, 2014; Evans *et al.*, 2019), but our tracking data allowed us to quantify

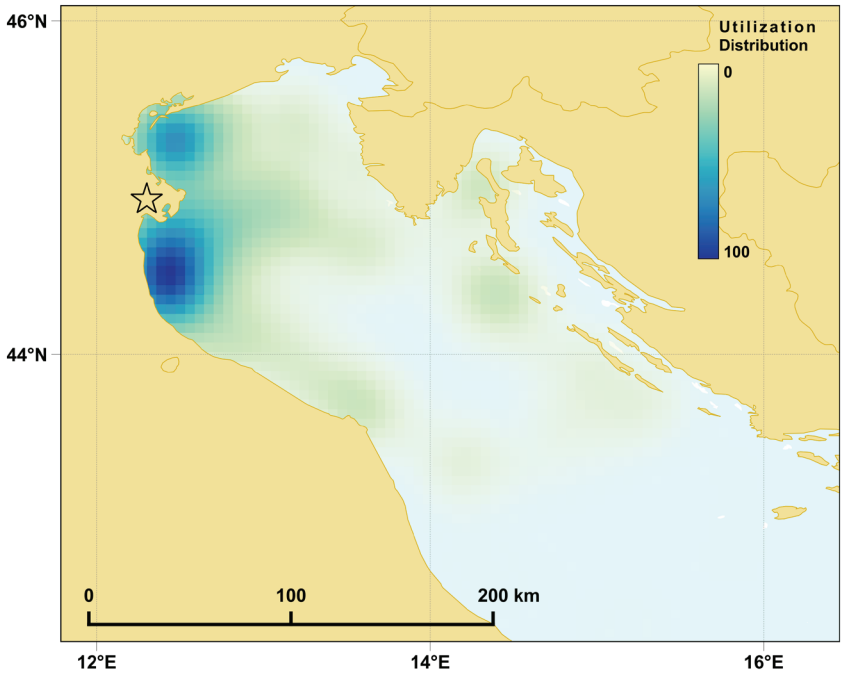

Fig. 3: UD for the turtles of the present study and those published in previous papers (total n=18). The colours show the probability density to find the turtles in each cell. Further details in the text. The star indicates Po River delta.

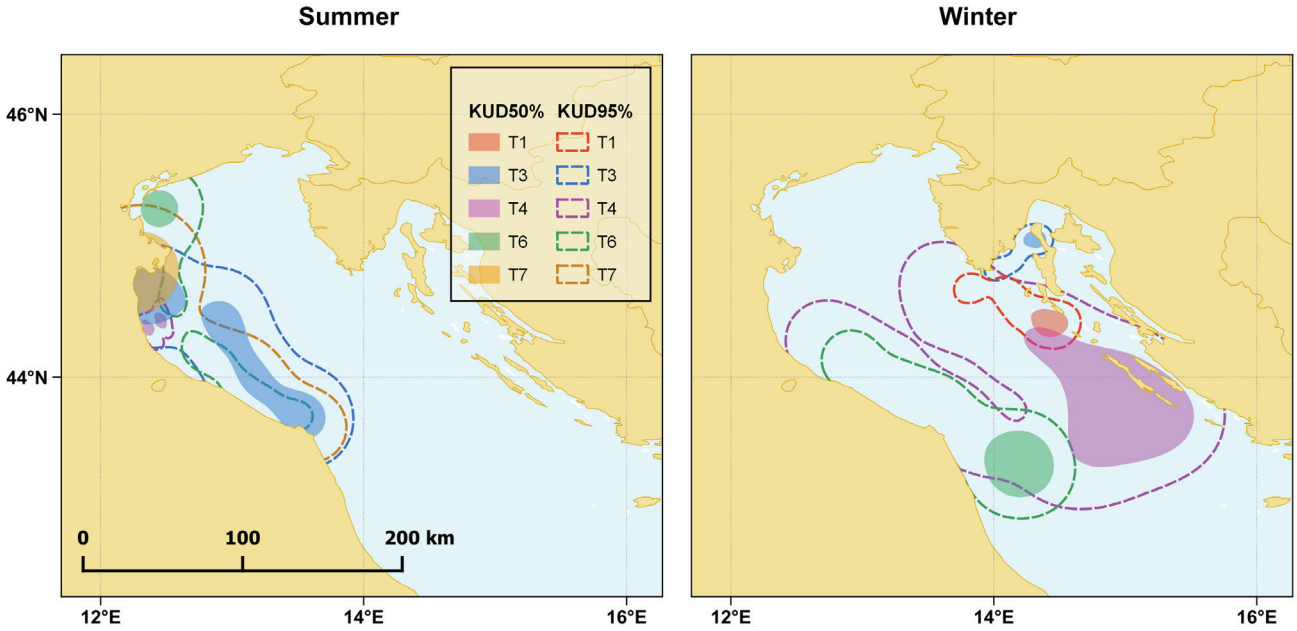

Fig. 4: Seasonal KUD95% (dashed lines) and KUD50% (colour filled areas) for the five turtles that were tracked during the winter (Jan-Mar) and/or the summer (Jul-Sept) months.

the thermal advantages gained by turtles moving in different areas during the coldest months.

Tracking data also documented the turtles' tendency to return to the western foraging area in successive seasons after having spent the winter months away, thus displaying a fidelity for their foraging area (Shimada *et al.,* 2020). In the Mediterranean, such multi-season fidelity has already been demonstrated in satellite-tracked adult male and female loggerheads (Broderick *et al.,* 2007; Casale *et al.,* 2013; Mingozzi *et al.*, 2016). Fidelity of juvenile loggerheads has been reported in other areas (Mansfield *et al.,* 2009; Gonzales Carman *et al.,* 2016). This fidelity further highlights the relevance for these turtles of the locations they frequented, which are likely to offer the most profitable foraging opportunities. It is known that molluscs largely contribute to the diet of northern Adriatic Sea loggerheads, which search this prey using a mining strategy that results in bioturbation, a fundamental process in nutrient transport in marine ecosystems (Lazar *et al.*, 2011).

The present results have some conservation implications. The estimated loggerhead distribution (Fig. 3), which derives from the largest sample of tracking data assembled so far for the region, could provide novel indi-

cations about potential hot-spot areas, where turtles concentrate in high numbers. These results complement turtle bycatch data collected in the area (Casale *et al.*, 2004; Lucchetti *et al.,* 2017; Pulcinella *et al.*, 2019) and call for special attention to be paid to the waters north and south of the Po River delta, where specific conservation measures, like the implementation of turtle excluder devices (Vasapollo *et al.*, 2019), could be applied to mitigate the mortality induced by trawlers. The tracking information provided in the present study can then be combined with that on the abundance of turtles of different size classes and on the connectivity across sites, allowing us to select key areas in the region where protection measures may produce the highest conservation benefits.

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