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Aerial survey abundance estimates of the loggerhead sea turtle *Caretta caretta* in the Pelagos Sanctuary, northwestern Mediterranean Sea

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ABSTRACT: Aerial line transect surveys, totalling 16 590 km, were performed in winter and summer 2009 in the Pelagos Sanctuary, NW Mediterranean. A total of 207 loggerhead sea turtles were sighted, with only 9 sightings during the winter. In this season average raw 'surface' density (i.e. animals at or near the surface) was 0.002 turtles km^{-2}, and on the basis of line-transect analysis, we estimated 237 specimens (CV = 34.33%; 95% CI = 122–461). The summer estimate resulted in 4083 animals at surface (CV = 14.59%; 95% CI = 3061–5466) in the study area, with a density of 0.046 km^{-2}. Results indicated strong seasonal differences and lower densities than those found in comparable surveys in Spanish Mediterranean waters. Nevertheless, the ecological and oceanographic features of the Pelagos Sanctuary, established primarily for the protection of marine mammals, render it an important area also for Mediterranean loggerhead sea turtles. The potential for human-induced mortalities of turtles summering in the Pelagos Sanctuary is high. In this context, it is vital to obtain reliable estimates of absolute and relative abundance over time, monitor the status of loggerhead sea turtles and inform the development of effective conservation actions. This study illustrates the ability of aerial surveys to provide such data in this area.

KEY WORDS: Loggerhead sea turtle · *Caretta caretta* · Pelagos Sanctuary · Aerial survey · Abundance · Seasonal distribution · Distance sampling

INTRODUCTION

The loggerhead sea turtle *Caretta caretta* is the most common sea turtle species in the Mediterranean Sea (Margaritoulis et al. 2003) and is listed as Endangered in the IUCN Red List of Threatened Species (www.iucnredlist.org). The Mediterranean Basin hosts 2 Regional Management Units (RMU) of loggerhead sea turtles: the Mediterranean and the northwest Atlantic (Wallace et al. 2010). The most recent status review (Conant et al. 2009) concluded that although there were insufficient data to reliably assess the status of the Mediterranean discrete population segments of *C. caretta*, the potential for future decline was high. Notwithstanding the uncertainties in the available data, bycatch is considered to be the main anthropogenic threat (Tomás et al. 2008, Casale & Margaritoulis 2010, Casale et al. 2010). In addition, there is increasing evidence of the importance of vessel strikes as a source of mortality (Hazel et al. 2007, Panigada et al. 2008, Casale et al. 2010); other potential threats include the degradation of nesting habitats due to coastal development (Casale & Margaritoulis 2010).

Loggerhead sea turtles prey upon several epipelagic and benthic animal taxa in a variety of habitats during their lifetime. Apart from young animals that have limited diving capacity, loggerhead sea turtles can shift

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between oceanic and neritic zones and between pelagic and benthic prey, although their foraging strategies are not yet fully understood (Hawkes et al. 2006, McClellan & Read 2007, Casale et al. 2008a, Frick et al. 2009, Mansfield et al. 2009, Reich et al. 2010). In the oceanic zone, where the sea bottom is inaccessible to them, loggerhead sea turtles feed upon epipelagic animals, often in aggregations with floating *Sargassum* (Bjorndal 1997, Bolten 2003), and can disperse over wide areas and even entire oceans (Bowen et al. 1995, Bolten et al. 1998). In the neritic zone, they have access to the entire water column and thus can also feed on benthic animals (Bjorndal 1997).

In the Mediterranean Sea, the presence of both neritic and oceanic areas within short distances enhances the intrinsic opportunistic foraging strategy of the species (Casale et al. 2008a). Loggerhead sea turtles originating from the Atlantic enter the Mediterranean and can be found in the western and the eastern part of the basin, at least as far as the central Mediterranean (Laurent et al. 1998, Carreras et al. 2006, Casale et al. 2008b).

Foraging areas can be found all over the basin (Margaritoulis et al. 2003, Casale & Margaritoulis 2010), whereas reproductive areas are largely restricted to the eastern Mediterranean Sea, in particular Greece, Turkey, Cyprus and Libya, with less important areas in Egypt, Israel, Italy, Syria, and Tunisia (Conant et al. 2009, Casale & Margaritoulis 2010). Mark-recapture and satellite tracking studies have revealed wide-ranging movements between reproductive and foraging areas, as well as amongst different foraging grounds (Margaritoulis et al. 2003, Broderick et al. 2007, Casale et al. 2007b, Revelles et al. 2007, Zbinden et al. 2008). Evidence of long-term neritic and oceanic foraging areas for adults and juveniles have been provided by mark-recapture programmes (Casale et al. 2007b). Telemetry and flipper tagging data also reveal consistent migrations of females to and from nesting areas (Margaritoulis et al. 2003, Broderick et al. 2007, Zbinden et al. 2008).

However, current knowledge of loggerhead sea turtle distribution and abundance in the Mediterranean Sea is still primarily qualitative, and is largely based on opportunistic data (e.g. bycatch reports) restricted to few areas (Tomás et al. 2008, Casale et al. 2010, Casale & Margaritoulis 2010). Relative abundance can be inferred by standardized catch rates from bycatch studies (Casale 2011); however, these data are collected opportunistically and are potentially biased.

The absence of key data, and the uncertainties in the current knowledge of distribution and abundance in Mediterranean waters, emphasises the need for reliable and quantifiable information. Such data are needed to inform a full assessment of threats at population level, an improved understanding of the possible effects of climate change (Hawkes et al. 2009, Witt et al. 2010), and the development of adequate, targeted mitigating actions (e.g. Braun-McNeill et al. 2008, Howell et al. 2008).

Obtaining reliable measures of absolute and relative abundance is also considered to be of high priority for sea turtle research worldwide (Hamann et al. 2010). It is thought that 'distance sampling' (Buckland et al. 2001) is the preferred method to estimate turtle abundance and density (Shoop & Kenney 1992, Epperly et al. 1995, Braun & Epperly 1996, Davis & Fargion 1996, Preen et al. 1997, Davis et al. 2000, Gómez de Segura et al. 2003, 2006). However, only a few studies have actually applied this approach for sea turtles, either through boat-based (Eguchi et al. 2007) or aerial surveys (Witt et al. 2009). The only reliable estimate of sea turtle abundance in the Mediterranean, prior to the present study, was obtained from an aerial survey undertaken in Spanish Mediterranean waters along the Valencia coast in 2001–2003 (Gómez de Segura et al. 2006).

One of the areas where loggerhead sea turtle occurrence remains poorly described is the northernmost part of the western Mediterranean Basin; the only available information comes from fishery surveys (Di Natale et al. 1995, Orsi Relini et al. 1999). However, from a stock structure perspective, the picture is somewhat clearer and the available genetic data suggest that the Liguro-Provençal current is frequented mainly by turtles of Mediterranean origin, with little contribution from the North Atlantic (Carreras et al. 2006). Hence, assessing sea turtle abundance (and ultimately trends) in this area would be of great benefit for the conservation of the Mediterranean Sea loggerhead sea turtle population.

The study area lies within the Pelagos Sanctuary for Mediterranean Marine Mammals. This was established by Italy, France and the Monaco Principality in 2001 and represents the world's first high seas marine protected area (Hoyt 2005). It encompasses almost 90 000 km^2 of both pelagic and coastal waters between the Italian, Monegasque and French coasts of the Ligurian Sea and the north of Sardinia Island. The area is recognized for its high productivity and notably high cetacean concentrations, especially in summer (Notarbartolo di Sciara et al. 2008). In order to provide information for the management of the Pelagos Sanctuary, the Italian Ministry of the Environment funded a series of research programmes aimed at estimating cetacean abundance throughout the year in the seas around

Italy. In this context, 2 aerial distance sampling surveys (winter and summer) were carried out in 2009 (Lauriano & Panigada 2010, Panigada et al. 2011). Although the surveys were targeted at cetaceans, data were also collected for other species, including the loggerhead sea turtle. A number of authors have suggested that aerial surveys provide a reliable approach to estimating the density and abundance of turtles (Shoop & Kenney 1992, Epperly et al. 1995, Braun & Epperly 1996, Davis & Fargion 1996, Preen et al. 1997, Davis et al. 2000, Gómez de Segura et al. 2003, 2006).

This study presents, for the first time, seasonal abundance estimates for the loggerhead sea turtle in the Pelagos Sanctuary and quantitative information on distribution within the area, at least at the time of the aerial surveys. We compare our results with a similar study conducted in Spanish Mediterranean waters and demonstrate the utility of conducting aerial surveys to assess sea turtle abundance. The results contribute to the conservation of the species, providing information on the potential value of the Pelagos Sanctuary for the conservation of large marine vertebrates other than cetaceans.

MATERIALS AND METHODS

Study area

The area surveyed was the Pelagos Sanctuary (Fig. 1), a semi-basin with a widely extended bathyal plain at approximately 2500 m depth, associated with a narrow continental shelf in the west (~5 km) and a more extended (>10 km) shelf in the east. A highly dynamic frontal system, caused by the interaction of oceanographic, climatic and geomorphologic factors, leads to a biologically productive area. It represents one of the most highly variable ecosystems in the Mediterranean Basin (Estrada 1996, Salat 1996, Arnau et al. 2004, Notarbartolo di Sciara et al. 2008). Its importance for cetaceans was first described in the early 1990s (Notarbartolo di Sciara et al. 1993, Forcada et al. 1995). In 2001, under a high seas agreement established under the Barcelona Convention, the Pelagos Sanctuary was added to the list of Specially Protected Areas of Mediterranean Importance, which, at least officially, conferred protection by all signatory Mediterranean countries in both national waters and in the high seas (Hoyt 2005, Notarbartolo di Sciara et al. 2008).

Survey design

This paper reports on 2 aerial surveys. The survey design and methods (and subsequent analyses) were in accordance with line-transect distance sampling methodology (Buckland et al. 2001). The platform used was a 2 engine high-wing aircraft (Partenavia P-68) equipped with bubble windows (to allow direct observation of the trackline below the plane) flying at a constant altitude of 750 feet (229 m) with a ground speed of approximately 100 knots (185 km h^{-1}). The survey height was designed to be optimal for the major target species: the fin whale *Balaenoptera physalus* and the striped dolphin *Stenella coeruleoalba* (Panigada et al. 2011). Three experienced researchers were on board: 2 were seated in the rear seats searching for animals through the bubble windows and the third observer was in the co-pilot seat, recording the data (see below) directly onto a laptop. The aircraft flew along 82 parallel transects, equally spaced at 10 km, designed using the software Distance 5.0 (1www.ruwpa.st-and.ac.uk/distance/; Thomas et al. 2009) to provide equal coverage probability (Fig. 1). The total planned survey distance was 8852.56 km. The area was subdivided in 3 sub-regions, primarily based on bathymetry: (A) east (30 907 km^2), (B) southwest (23 208 km^2) and (C) northwest (34 153 km^2).

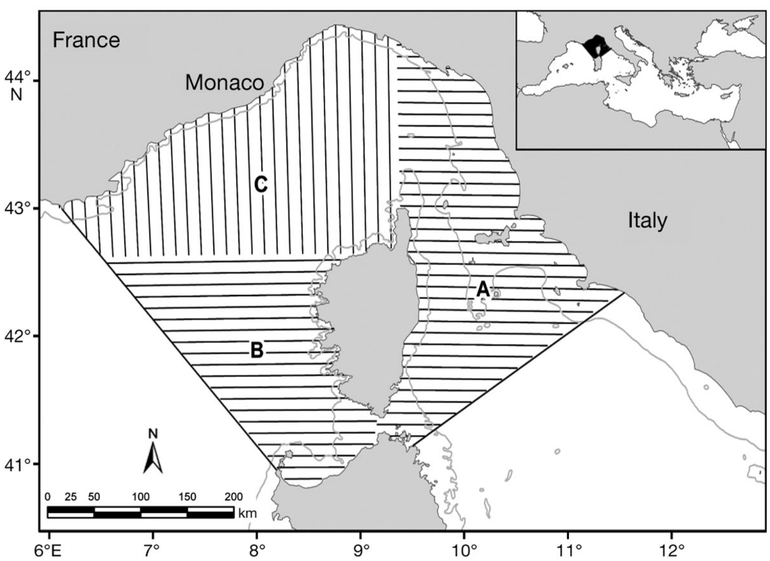

Fig. 1. Study area (Pelagos Sanctuary), showing the 82 transects (lines) in 3 sub-regions (A, B and C) used to estimate loggerhead sea turtle abundance and density in the present study

At each sighting, data collected included GPS position (latitude, longitude), group size, declination angle when the sighting was estimated to be abeam and observer. Primary search effort data (distance flown in acceptable conditions) and altitude were recorded directly from the GPS. Data were recorded directly onto a laptop with data logging programs. Acceptable conditions were defined as Beaufort state 3 or less. Additional relevant information such as sea state, glare, cloud cover and subjective sighting condition (the observers' view as to their ability to see an animal at the surface if present on a 3-point scale) was recorded at the beginning of each transect and/or whenever changes occurred. Declination angle to the sighting was measured with Suunto clinometers that, together with the plane altitude, allowed the perpendicular distance from the track line to the sighting to be measured, according to the formula $X = h \times \tan(90 - \alpha)$, where h is the plane altitude and α is the declination angle.

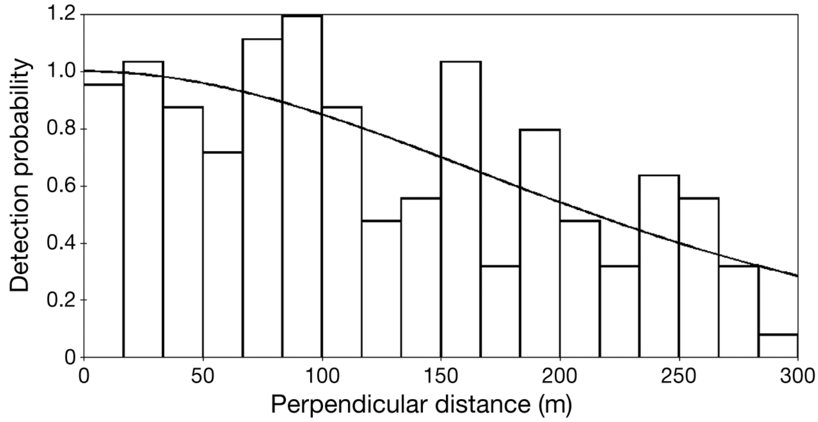

Fig. 2. Pooled detection function (winter and summer sightings), using the 300 m truncation. Bars represent the detection probability and the curve shows the detection probability trend according with the distance from the line (transect)

Data analysis

Distance analyses of the sightings data were performed using the dedicated software Distance 6.0; multiple covariate distance sampling (MCDS) methods were applied (Buckland et al. 2001, Thomas et al. 2007, 2010). In MCDS, additional explanatory variables (z) are considered along with perpendicular distance in the estimation of the detection function and hence the effective strip width. The potential covariates considered were observer, Beaufort sea state and glare (all as factor variables with 3 levels each). The best model fit, selected using the minimum Akaike's information criterion (AIC) value (Akaike 1974, Buckland et al. 2001), indicated that the variable 'observer' should be included in the detection function (Table 1, Fig. 2).

Table 1. Akaike's information criterion (AIC) values for the multiple covariate distance sampling. All covariates are fitted as factors with 3 levels each

Model	AIC	Delta AIC	No. parameters
Observer	1850.18	0	3
Sea state	1854.09	3.91	4
Glare	1853.22	3.04	4
Sea state + Glare	1856.75	6.57	7
Sea state + Observer	1855.21	5.04	6
Observer + Glare	1854.04	3.86	6

Abundance was estimated using a Horvitz-Thompson-like estimator formula, according to Marques et al. (2007):

$$\widehat{N} = \frac{A}{2wL}\sum_{i=1}^{n}\frac{1}{\widehat{P_a}(z_i)} \quad (1)$$

where A is the area of the study area, n is the number of sightings, L is the total search effort (total transect length), w is the half strip width, $2wL = a$ is the covered area, $\hat{P}_a$ is the estimated probability of detecting the ith object within the covered area a, and z is the covariate. Variance of n was empirically estimated from stratified samples with overlapping sub-regions (Estimator O2) (Fewster et al. 2009).

A simple power analysis was performed to explore the 80% power of the survey results to detect changes in abundance in a monitoring programme such as the one presented; based on the results from the summer survey, a coefficient of variation (CV) of 15% was chosen using TRENDS software (Gerrodette 1993). The following parameters were also selected: significance level $\alpha = 0.05$; 1-tailed test; linear model of rate of change; CV proportional to the square root of the abundance estimate; standard normal distribution.

RESULTS

The first aerial survey was conducted in winter 2009 between 11 to 31 January and 18 to 22 February (the interval due to poor weather conditions and essential aircraft maintenance). The second survey, with identical sub-areas, track-lines and methods as the first, was undertaken in summer 2009 between 21 July and 2 August.

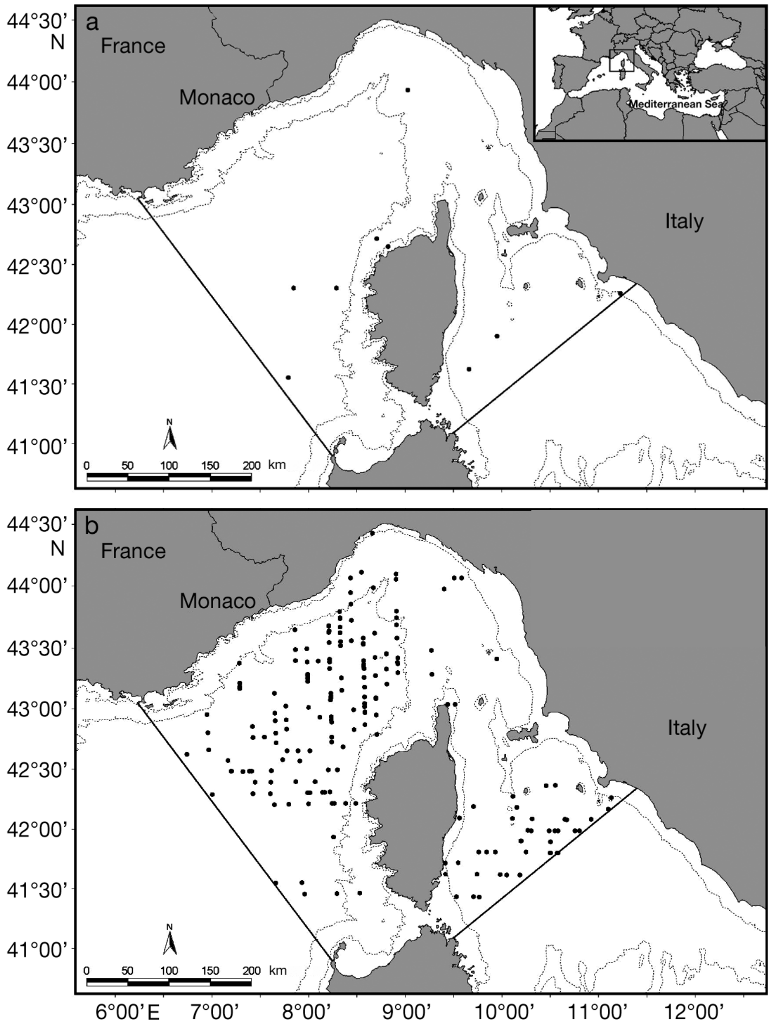

Fig. 3. Loggerhead sea turtle sightings (•) in the study area in (a) winter and (b) summer

In the winter survey, a distance of 8144 km (92% of the total projected survey distance) was flown, but only 9 turtle sightings were recorded (Fig. 3a); it is clear that the low number of sightings reflected low presence.

During the summer, even better coverage (97%) was obtained and 198 loggerhead sea turtles were sighted (Fig. 3b). However, 27 (13.6%) of these sightings lacked the declination angle (6 ind. in sub-region A, 9 in B and 12 in C). Accordingly, 165 sightings were carried forward to density/abundance analyses. All sightings of sea turtles were of single animals. Winter and summer sightings were pooled to fit a detection function, which was applied to obtain the winter and summer estimates.

To fit the detection function, the perpendicular distance to sightings was truncated at 300 m, resulting in 164 (9 in winter and 155 in summer) of the potential 174 (9 in winter, 165 in summer) sightings, which were incorporated in the final analyses. Two different functions were considered: half normal and hazard rate, together with cosine and simple polynomial series expansion. Based on the minimum AIC value, the best model was the half normal with cosine adjustment terms.

The effective strip width was 201.98 m (CV = 4.74%; 95% CI = 183.95 to 221.78), the probability of observing an object in a defined area was 0.67 (CV = 4.74%) and the probability density function evaluated at zero distance was 0.0049 (CV = 4.74%).

The overall mean winter surface density (not corrected for availability bias [animals under the water that therefore could not be seen by the observers] or perception bias [animals at the surface that were missed by the observers]) was 0.0026 turtles km^{-2} with a total surface estimate of 237 animals (CV = 34.33%; 95% CI = 122 to 461) (Table 3). In the summer survey, the mean surface density was 0.046 turtles km^{-2}, with a total surface estimate of 4083 animals in the whole study area (CV = 14.59%; 95% CI = 3061 to 5446) (Table 3). Sub-region C presented higher surface density values (by ~2.5 times) and thus abundance (by ~3 to 4 times) than sub-regions A or B (Table 2).

The power analysis results indicate that with 80% power, the time to detect a 2% range of annual declines is 18 yr, 10 yr for 5%, 7 yr for 10% and 6 yr for 15%.

DISCUSSION

This study represents the first investigation of the winter and summer abundance of loggerhead sea turtles in the Ligurian/Corsican and north Tyrrhenian Seas.

Study caveats

The analyses presented here assume that all sightings were of loggerhead sea turtles. In fact, 2 other sea turtle species occur in the Mediterranean Basin (Groombridge 1990, Casale & Margaritoulis 2010): the green sea turtle *Chelonia mydas* and the leatherback sea turtle *Dermochelys coriacea*. Fortu-

Table 2. Winter and summer loggerhead sea turtle abundance and density estimates for each study area sub-region (see Fig. 1)

Sub-region	Transect length (km)	No. transects	No. sightings	Density estimate	Abundance estimate	CV (%)	Lower 95% CL	Upper 95% CL
Winter								
A	3167.9	38	3	0.00234	72	57.18	24	222
B	2038.2	16	3	0.00364	85	77.64	17	411
C	2938.3	22	3	0.00252	86	34.31	42	179
Total	8144.4	76	9	0.0026	237	34.33	122	461
Summer								
A	3033.3	34	39	0.031	968	24.51	0.018	0.052
B	2264.8	20	23	0.024	574	36.01	265	1246
C	3148.8	25	93	0.071	2458	19.31	1634	3698
Total	8446.9	79	155	0.046	4083	14.59	3061	5446

Table 3. Estimates of sea turtle bycatch in the Mediterranean Sea

Fishing gear	Area	Catch rate	Source
Long line	Pelagos Sanctuary	0.00062 turtles 1000 hooks^{-1}	Orsi Relini et al. (1999)
	Spanish waters	0.1–4.48 turtles 1000 hooks^{-1}	Báez et al. (2007)
	Sicily channel	0.977 turtles 1000 hooks^{-1}	Casale et al. (2007c)
	Ionian Sea	0.128–0.446 turtles 1000 hooks^{-1}	Deflorio et al. (2005)
Driftnet	Ligurian Sea	0.05 turtles d^{-1}	Di Natale et al. (1995)
	Spanish waters	0.968 turtles d^{-1}	Silvani et al. (1999)
	Ionian Sea	3–50 turtles d^{-1}	De Metrio & Megalofonou (1988)

nately, both show distinct morphological and ecological characteristics that render species misidentification unlikely. The leatherback sea turtle has a unique leathery black carapace and only large individuals (>110 cm carapace length) enter the Mediterranean Sea (Casale et al. 2003). Green sea turtles, although potentially more likely to be confused with loggerhead sea turtles given their appearance, almost exclusively frequent the easternmost part of the Mediterranean Sea; only a few have been recorded from the western basin (Casale & Margaritoulis 2010).

A fundamental assumption of line transect methodology is that all animals on the track line are always detected (Buckland et al. 2001). As noted above, our estimates were not corrected for the 2 main biases that result in a violation of this assumption: availability bias and perception bias. Both of these result (perhaps substantially) in negatively biased abundance estimates. It is possible to correct for availability bias provided that there are reliable data on the proportion of time animals are unavailable to be seen (and the uncertainty around any estimated proportion). To provide an idea of the possible order of magnitude of the underestimate, the closest region to our study area where such information is available is the southwestern Mediterranean Sea. There, in July, loggerhead sea turtles were reported to spend an average of 40% of time at the surface (Revelles et al. 2007). A full analysis (including appropriate estimates of uncertainty) would require an examination of the raw data, but if we assume that this result was also representative of the animals in our study area, a corrected point estimate of abundance would have been approximately 600 and 10 000 turtles in the Pelagos Sanctuary in winter and summer 2009, respectively. Perception bias, in contrast, is usually corrected for by an independent observer approach, i.e. some or all of the surveys are undertaken with more than one observer independently searching the same area and recording data separately, known as the 'double platform' approach (see Buckland et al. 2001). However, the size of our aircraft precluded the additional persons needed to apply this approach in the present survey.

Another source of perception bias for sea turtles is the difficulty or impossibility of detecting very small specimens such as hatchlings, which are approximately 4.5 cm (straight-line carapace length, Dodd 1988) and which can frequent open waters. However, the known nesting sites are far from the study area and Casale et al. (2010) reported the mean (±SD) curved carapace length (CCL) of loggerhead sea turtles found along the north Tyrrhenian coast to be 47.6±11.8 cm (n = 175), with a minimum CCL of 25 cm. Nevertheless, when flying at an altitude of 750 ft (ca. 230 m), we are likely to have missed some smaller specimens.

Large-scale abundance patterns

The present estimate of sea turtle abundance in the Pelagos Sanctuary contributes to a better picture of the relative importance of different Mediterranean areas as foraging grounds for sea turtles. However, to advance this understanding, aerial surveys in other areas are required (Panigada et al. 2011). Although some estimates have been provided in various areas on the number of adult females (e.g. Broderick et al. 2002), e.g. the annual number of nests in several major nesting beaches (Casale & Margaritoulis 2010) and some demographic parameters such as sex ratio, survival rates and duration of the juvenile stage (Casale et al. 2006, 2007a, 2009), a comprehensive estimate of population size is not yet available. Moreover, an important gap of information about nesting level is present in Libya (Casale & Margaritoulis 2010). All of the above considerations prevent a meaningful comparison of our results, which concern sea turtles in all size classes, i.e. both adults and juveniles, the latter representing the majority of the population.

Evidence for migration

Absolute abundance estimates are important for assessing the importance of anthropogenic mortality at the population level. However, trends can also be examined using relative abundance, if data collection methods are comparable. Accounting for biases when examining trends in relative abundance is much less important if they can be assumed to be consistent across surveys (e.g. Donovan 2005). Such an assumption is clearly true for the present surveys. Indeed, the very low numbers of sightings (and hence density and abundance in the area) in winter compared with summer clearly represent a true phenomenon, at least for 2009, and indicate seasonal migrations in and out of the study area.

From a physiological perspective, loggerhead sea turtles have been reported as 'active' above 15 to 17°C (Laurent & Lescure 1994) and, to some extent, even at temperatures as low as 12°C (Hochscheid et al. 2007). Below 8°C they can experience serious problems (Spotila et al. 1997). Low temperatures have been suggested as a factor in seasonal migrations of this species. For example, seasonal (north–south) migrations have been described for the northwestern Atlantic (Musick & Limpus 1997), where juvenile and adult female turtles foraging along the coast were found to move to the south when temperature decreased below 20°C in winter (Hawkes et al. 2007, Mansfield et al. 2009). However, not all juveniles and females tracked during these studies showed such a seasonal southerly migration, as some specimens frequented other foraging areas in the north. Therefore, north–south seasonal migrations cannot be considered a general pattern for all individuals in a population, nor are observed in all populations (e.g. Limpus & Limpus 2001).

The evidence for migration in the western Mediterranean Sea is somewhat equivocal. For example, no clear seasonal patterns were suggested from some of the available satellite tracking data (Cardona et al. 2005) or capture–recapture data (Casale et al. 2007b). However, regular seasonal movements of at least adult females have been reported from other telemetry studies (reviewed in Conant et al. 2009). Lazar et al. (2003) provided evidence of seasonal migration from a small area in the northernmost sector of the Adriatic Sea, where temperatures in winter drop below 11 to 12°C. They recorded high densities in summer and low densities in winter. Gómez de Segura et al. (2006) also inferred seasonal migration for Spanish waters. During our winter study in the Pelagos area, the sea surface temperature was approximately 12 to 13°C (Fig. 4) and it may be that this induced most of the turtles to move to warmer (southern) waters. Low temperatures represent the most likely reason for a reduction of the observed low number of turtles at the surface occurring in the area in winter. However, low temperatures can also decrease the time turtles spend at the surface (Bentivegna et al. 2003, Broderick et al. 2007, Hochscheid et al. 2007) and, consequently, the number of turtles observed at the surface during aerial surveys. The sea surface temperature was approximately 12 to 13°C in winter and 23 to 25°C in summer (Fig. 4) (www.seaturtle.org).

In summary, our data show that loggerhead turtles were scarce in the northern part of the western Mediterranean Sea during January and February

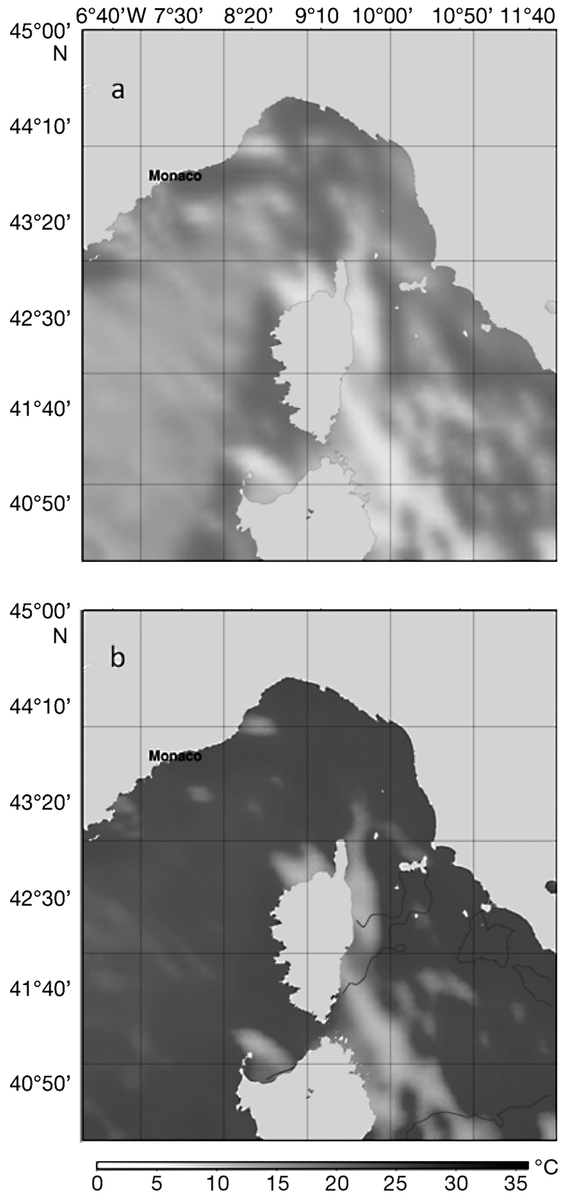

Fig. 4. Sea surface temperature (SST; °C) in the study area in (a) winter and (b) summer

2009 (the time of the winter survey), probably due to low temperatures (Fig. 4a). By contrast, they frequented the area in considerable numbers during summer.

Factors affecting habitat use

Within our study area during summer, there was a clear difference in density between the highest-density sub-region C and the other 2 sub-regions. In terms of temperature (Fig. 4b), all sub-regions were well above the threshold for activity indicated by Laurent & Lescure's (1994) study; sub-region C presented the lowest temperature between the 3 sub-regions (23°C). It is not surprising that above a certain value, absolute temperature alone does not explain sea turtle density and distribution. Depth is known to affect sea turtle distribution, because in shallow waters sea turtles have access to benthic prey. However, all 3 sub-regions have seafloor depths that are comparable and in most of the sub-regions depth is well beyond the diving capacity of loggerhead sea turtles (Fig. 1) (Lutcavage & Lutz 1997). Moreover, most sea turtles were observed in deep water (Fig. 3), thus a direct effect of depth on distribution seems unlikely. It seems much more probable that sea turtle distribution is related to prey density and accessibility or even to a passive concentration by currents (Hawkes et al. 2007, Revelles et al. 2007, Mansfield et al. 2009, Mencacci et al. 2010). Other studies have shown that sea turtles tend to concentrate in water fronts with sharp temperature and chlorophyll gradients, where a convergence of phytoplankton and zooplankton occurs, the latter representing a trophic resource for turtles (Polovina et al. 2000, Kobayashi et al. 2008, Mansfield et al. 2009). Sub-region C in our study area is known to be an important area for phytoplankton blooms (D'Ortenzio & Ribera d'Alcala 2008).

The only other area of the Mediterranean Sea with a data set similar to that of the present study is the Spanish Mediterranean waters covered by Gómez de Segura et al. (2006). Although direct comparisons of the abundance and density estimates between the Spanish study and the present study are not appropriate, particularly because of differences in study area size, the time elapsed between the surveys and possible natural variation in distribution and abundance amongst years, the results suggest that there may be significantly lower densities of sea turtles during the summer in the Pelagos Sanctuary (overall 0.046 km^{-2}, Sub-region C 0.071 km^{-2}) than in Spanish waters (0.21 km^{-2}; Gómez de Segura et al. 2006).

With similar provisos about survey and/or study timing, and notwithstanding the uncertainties surrounding bycatch data, a similar inference can be drawn from the estimated bycatch rates (both for pelagic longliners and driftnets) for the Pelagos Sanctuary compared with Spanish waters and the Ionian Sea (Table 3), if it is assumed that, in general, higher bycatch rates equate to higher sea turtle abundance.

The reasons for this difference in densities remain unclear. Temperature is an unlikely explanation, as the temperatures in the 2 areas are similar (23 to 25°C in July 2009 in the Pelagos Sanctuary and 25 to 26°C in the Spanish Mediterranean waters). Hence, other factors related to prey and/or currents seem more likely to influence sea turtle occurrence (Bentivegna et al. 2007). In addition, as reported by Carreras et al. (2006), the waters of southern Spain are frequented by high numbers of Atlantic loggerhead sea turtles, whereas the northern coast of Spain and the Tyrrhenian Sea are frequented mostly by sea turtles of Mediterranean origin, which probably distribute also along the Liguro-Provençal current.

Conservation implications

Pertinent to the data and discussion that we have presented, to assess population-level effects and monitor the success of mitigation measures, both population structure and movements, in addition to abundance must be understood. Genetic and telemetry studies are required to investigate whether the animals surveyed within an area, including those bycaught or vessel struck, belong to the Mediterranean RMU or incorporate animals from the northwest Atlantic RMU (Wallace et al. 2010), as well as to verify the appropriateness of those RMUs. In this context, the Pelagos Sanctuary appears to include only Mediterranean animals.

The presence of sea turtles in the Pelagos Sanctuary during summer exposes them to high levels of maritime traffic, including fishing, pleasure and recreational boats, leading to death from bycatch and boat collisions (Panigada et al. 2008, Casale et al. 2010). The effects of intense human activities must be evaluated at the population level and, if necessary, targeted mitigation measures for sea turtles should be considered within the Pelagos Sanctuary.

The present study shows that a well-designed long-term aerial survey programme can form part of an efficient and effective strategy to monitor species of conservation concern. These long-term monitoring programmes should be planned according to the power analysis results, which can also help to calculate the number of replicates needed to detect biologically significant abundance declines. Long-term monitoring programmes represent the only way to understand population status, evaluate the effect of human-induced mortality and provide an index of the effectiveness of suggested and applied conservation measures and mitigation policies (e.g. Donovan 2005).

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