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The effects of substrate temperature on the reproductive success of *Caretta caretta* on a volcanic beach in the Mediterranean Sea

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Abstract: A five-year of monitoring (2018–2022) of the loggerhead sea turtle *Caretta caretta* nests in "Pozzolana di Ponente" beach on Linosa Island (Pelagie Archipelago, Italy) is here reported. To explore how temperatures affect the hatching success and the possible occurrence of any malformation in hatchlings, incubation temperature values were recorded using data loggers positioned at depths of 5 and 35 cm (for each nest) from the surface, approximately 0.5 m from the nest chamber. The obtained results highlighted important issues related to the success of hatching and the incidence of body anomalies. The temperatures recorded at different depths near the nests (5 and 35 cm) in some periods of incubation of the eggs were above optimal development temperature (i.e., ~33°C), causing high mortality rates, especially during the first two years of the survey (2018–2019). In the next three years (2020–2022), the implementation of shading cover cloths of the nests increased the survival rate and decreased the incidence of malformed individuals. Furthermore, atmospheric temperature data were extrapolated from the "Copernicus Climate Change" web service and included in our analyses to assess any changes over the timeframe analysed. Over five years (2018–2022), the average atmospheric temperature increased slightly by 1.7°C. In light of global warming, the implementation of effective and low-cost mitigation activities, such as the use of shade cloth covers to protect the nests from overheating, should be considered a suitable conservation action.

Keywords: conservation strategies, hatching success, loggerhead sea turtles, shade cloth covers, Sicily

INTRODUCTION

It is documented that temperature is one of the most important environmental parameters influencing nest hatching, sex ratio, embryo development as well as the correct formation of the dermaskeleton (carapace and plastron) in sea turtles (Girondot and Kaska, 2015; Wyneken and Lolavar, 2015; Caracappa *et al.*, 2016; Laloë *et al.*, 2017; Jensen *et al.*, 2018; Lolavar and Wyneken, 2020; Bentley *et al.*, 2021; Maurer *et al.*, 2021). In addition, the moisture contained in the substrate seems to play a role during embryonic development (Lolavar and Wyneken, 2020 and references therein); if the nest contains a water amount above 25%, such a condition will hinder or even stop the development of the embryos, thus determining a low hatching success. Furthermore, Visconti *et al.* (2022) have suggested that the nature of the substrate (in terms of colour, grain size, mineralogical composition, etc.) can affect its ability to absorb or reflect heat from solar radiation and retain water, and consequently influence the hatching success (see also Hays *et al.*, 2001).

Volcanic sand beaches, such as those occurring on the island of Linosa, the site of our study, are dark, have a low albedo, and generally have coarse granulometry (Visconti *et al.*, 2022). Conversely, the sedimentary ones, such as those found on the nearby island of Lampedusa, where the loggerhead turtle *Caretta caretta* lays its eggs, are light coloured, have a rather fine grain size and a high albedo (see Visconti *et al.*, 2022). All these aspects are crucial in determining the success of sea turtle hatching, and even more so in a future perspective, where temperatures are predicted to increase progressively in the coming decades (Almpanidou, Markantonatou and Mazaris, 2018; Antonioli *et al.*, 2020).

Recently, Almpanidou, Markantonatou and Mazaris (2018) have used *Caretta caretta* as a model species and compared its phenological changes related to temperature and pluviometry regimes in 45 nesting sites of the eastern part of the Mediterranean during the period 1971–2015 and in a 2016–2060 forecast. The 2016–2060 forecast model highlighted how the change in the environmental parameters will influence the incubation times and the hatching success of the species. In addition to such a prediction, the rise of sea level and the consequent changes in the profile of the coasts also through erosion or their disappearance must also be taken into account. In fact, as reported by Antonioli *et al.* (2020) the sea level in the Mediterranean is rising and forecast models estimate that in 2100 the level could rise by 50–140 cm. This increase will affect coastal areas which will be partly covered or eroded by waves. These changes will have a huge impact not only on turtle nesting sites but in general on the coastal profiles and on the human activities concentrated along the coastal areas.

To the effects of climate change on sea turtle nest success must be added those caused by human activities such as the construction of buildings along the coasts, the construction of ports and/or artificial breakwater barriers, the diversion and/or overbuilding of watercourses (resulting in a reduced input of sediments that reach the sea), and the occurrence of pollutants (e.g., Savoca *et al.*, 2021; Savoca *et al.*, 2022). This description concerns a large portion of the Italian sandy shorelines (Borzì *et al.*, 2021) and has direct implications for *Caretta caretta* management (Vecchioni *et al.*, 2022a). The loggerhead sea turtle *Caretta caretta* is the most common and studied species among the sea turtles present in the Mediterranean Sea. It is certainly the species with the highest number of casualties due to accidental catches with fishing gear or accidents with boats (Caracappa *et al.*, 2018 and references therein). It is included in the International Union for Conservation of Nature and Natural Resources (IUCN) red list and is considered globally vulnerable under criteria "A2b" and in continuous decline (Casale and Tucker, 2017). The Italian population of loggerhead sea turtles is instead considered endangered (EN) under criterion "D", which indicates a very restricted distribution or a very small population size (Rondinini, Battistoni and Teofili, 2022).

In recent years, efforts have been made to estimate the reproductive success of this species by monitoring the number of nests along the coasts of several countries. Unfortunately, to date, the numerous attempts to monitor nests are not sufficient, due to the lack of a shared network and the exchange of information among countries to increase knowledge on the distribution of nesting sites and the general state of conservation of the species. In most cases, just a census of the nests was made, without monitoring them using data loggers or without recording information relating to the nests themselves, e.g., distance from the sea, nature of substrate, the success of hatching, possible anomalies present in the carapaces, presence of parasites, the vitality of hatchlings, etc. As far as the Italian coast is concerned, several online reports made by private citizens on amateur blogs, social networks, environmental associations and, occasionally, local newspapers, are available. Unfortunately, such information is not very useful as it is often unreliable and lacking essential information. Conversely, scientific papers dealing with this topic appear to date rather limited (e.g., Blasi *et al.*, 2022; Denaro *et al.*, 2022; Vecchioni *et al.*, 2022a; Vecchioni *et al.*, 2022b). Recently, Hochscheid *et al.* (2022) have shown that from 2010 to 2023 in the western sector of the Mediterranean *Caretta caretta* has shown a progressive expansion of the nesting area, as evidenced by the occurrence of a high number of nests in areas where the females had never been known to lay eggs before. The authors ascribe this increase to i) a greater awareness of citizens reporting the occurrence of the species, ii) the general increase of human activities along the coasts, and iii) climate change, (i.e., the rising of the temperatures which has contributed to the expansion of nesting sites). A very similar pattern has been described for Sicily by Prato *et al.* (2022). It is likely that this expansion represents a response linked to the increase in water temperature, which, paradoxically, could be positive for the species in terms of expansion of the nesting area.

The aim of this study was to compare the five-year monitoring of loggerhead sea turtle *Caretta caretta* nests on Linosa Island (Italy, Sicily) using data loggers to explore how temperatures can affect the hatching success and the presence of malformations in hatchlings. In addition, temperatures were recorded near the nests and at the same depths in the investigated beaches in Linosa and on the nearby island of Lampedusa, which have a different geological origin. Lastly, atmospheric temperature data were also extrapolated from the web service "Copernicus Climate Change" (C3S, no date a) and included in our analyses to evaluate any possible changes in the timeframe analysed. This allowed us to provide some intuitive, but effective, strategies to mitigate the negative effects of high incubation temperatures.

MATERIALS AND METHODS

STUDY AREA

The study took place in the Pelagie Archipelago located off the southwestern coast of Sicily (Fig. 1) and consists of three islands, i.e., Lampedusa, Lampione and Linosa. This last one is a volcanic island, which, unlike the other two (Lampedusa and Lampione), is not part of the African continental plate which resulted from a fracture of the African continent. This is reflected in the terrestrial fauna diversity of Lampedusa and Lampione, which is rich in typically North African species and poor of European taxa (Massa, 1995; Stöck *et al.*, 2008; Harris *et al.*, 2009; Faraone *et al.*, 2020; Faraone *et al.*, 2022). Linosa has an area of 5.43 km^2 and is part of the "Pelagie Archipelago" Marine Protected Area (MPA). In Linosa the only beach present is "Pozzolana di Ponente" (Fig. 1), where *Caretta caretta* has been laying its eggs for several years (Mingozzi *et al.*, 2007 and reference therein). The "Pozzolana di Ponente" beach has an extremely small extent (it is about 200 m long and about 7 m wide) with small variations over the years even if strong storm surges in some cases have completely submerged it (Visconti *et al.*, 2022). The mineralogical and granulometric features of the beach are described in Visconti *et al.* (2022).

ENVIRONMENTAL PARAMETERS OF THE NESTS

In the frame of our five-year survey (2018–2022), the beach of "Pozzolana di Ponente" was monitored (throughout the daily surveillance activities of MPA operators and volunteers) between June and September to observe the occurrence of any turtle activity as laying eggs and emerging newly hatched turtles (see Tab. 1 for further details). After the first two years of monitoring, each nest was permanently equipped with a shade cloth cover (150 × 150 cm cover on top and side cover 20 × 150 cm, placed all around the nesting chamber) mounted on an aluminium frame placed at 160 cm heights from the surface. In addition, when needed sandbags and tarpaulin covers were placed around the nest chambers protecting the nests mainly from climatic factors (e.g., high irradiance, flooding caused by intense rains and storm surges). During the five-year survey, all the nests were also protected with a circular wire mesh against potential predators of the eggs, such as the ghost crab *Ocypode cursor* (which has been reported in Sicily and is constantly expanding its range (see Vecchioni *et al.*, 2019 and reference therein), rats, dogs, or anthropic disturbance (e.g., accidental trampling by bathers or the use of beach umbrellas).

To monitor the nest temperature and the egg incubation period, small data loggers (iButton® Data Logger "DS1923+F5", Analog Device, 1.3 cm diameter, 0.01°C precision) were used. In order to minimise the disturbance of the nest chambers, the temperature was recorded near the monitored nests from 2019 to 2022, using a data logger positioned at the depth of 5 and 35 cm (for each nest) from the surface, approximately 0.5 m from the nest chamber. Data loggers were programmed to record a reading every 20 minutes. In addition, since the two major islands of the Pelagie Archipelago (i.e., Lampedusa and Linosa) have different geology, the temperatures of the sand between these two islands were compared, positioning data loggers (with the same settings as those in Linosa) in a beach of Lampedusa, i.e., in "Cala Croce" in 2021. A three-day temperature trend has been produced in each year following the method described by Visconti *et al.* (2022).

Furthermore, as the air temperature can be a proxy of the substrate temperature, and the latter affects the development of the eggs, we compared and included in our analyses satellite-based data (hourly gap-free gridded data with 0.25° × 0.25° of spatial resolution) recorded at 2 m above the ground. In particular, the fifth generation of climate ECMWF reanalysis (ERA5) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach *et al.*, 2020) and distributed by Copernicus Climate Change Service (C3S, no date a) was used for this study.

BIOMETRICS MEASUREMENTS AND MULTIVARIATE ANALYSIS

Biometric parameters were promptly measured from each emerged turtle, using a standardised fieldwork sheet, recording weight (*WT*, 0.01 g), carapace length and width (*CL* and *CW*, respectively) using a calliper 0.01 mm. In addition, the incidence of morphological anomalies was recorded. In order to compare the biometric parameters of the hatchlings, born before and after the shading cover of the nests, our dataset was checked for

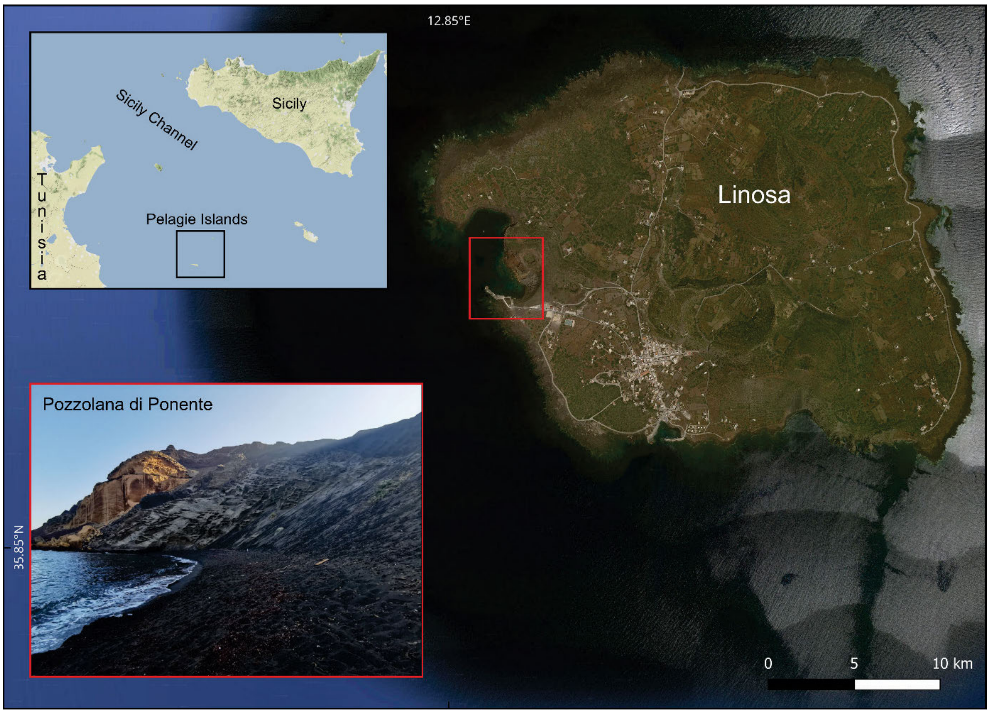

Fig. 1. Linosa Island (Sicily, Italy) and "Pozzolana di Ponente" beach; source: own elaboration and the photo therein (phot.: *A. Citarrella*)

Table 1. Nest parameters, temperatures (*T* – range at the depth of 5 and 35 cm), weight (*WT*), carapace length (*CL*), and carapace width (*CW*) of the hatchlings based on the five-year survey (2018–2022) made in "Pozzolana di Ponente", Linosa (Sicily, Italy)

Year	Nest	Period of incubation	Days of incubation	Range *T* at 5 cm (°C)	Range *T* at 35 cm (°C)	Laid eggs	Emerged turtles	Hatching success (%)	Mean *WT* (g)	Mean *CL* (cm)	Mean *CW* (cm)
2018*	A	7 July–24 August	48	–	–	64	4	6.25	14.20 ±0.50	3.30 ±0.04	2.60 ±0.06
	B	15 July–24 August	43	–	–	80	30	37.5	14.40 ±0.70	3.61 ±0.07	2.60 ±0.05
	C	18 August–2 October	44	–	–	70	10	14.3	13.10 ±0.70	3.80 ±0.06	2.80 ±0.07
2019*	A	22 June–8 August	47	28.53–44.50	26.60–34.95	103	10	9.7	13.40 ±0.70	3.92 ±0.04	3.02 ±0.05
	B	8 July–21 August	44	28.53–44.50	29.60–37.20	96	35	36.5	13.90 ±0.40	3.80 ±0.05	2.90 ±0.06
2020	A	12 June–1 August	50	24.17–52.76	25.18–33.67	75	63	84	14.20 ±0.85	4.00 ±0.16	3.00 ±0.18
	B	24 June–9 August	46	26.12–48.48	26.18–35.52	89	87	97	14.70 ±1.40	4.20 ±0.40	3.10 ±0.64
	C	1 August–19 September	49	27.17–34.66	25.18–33.17	79	75	95	15.00 ±1.25	4.20 ±0.14	3.20 ±0.18
2021	–	–	–	–	–	–	–	–	–	–	–
2022	A	4 June–23 July	49	26.62–41.08	26.12–33.61	118	97	82	12.80 ±1.70	3.63 ±0.25	2.70 ±0.20
	B	1 July–17 August	47	26.62–41.08	29.17–32.16	94	81	86	13.95 ±1.24	4.00 ±0.14	2.63 ±0.14

Source: own study and * Visconti *et al.* (2022).

parametric assumptions using the Shapiro–Wilk test. Since our data have a normal distribution, the independent T-test (T), with a level of significance at 0.05, was conducted on each variable (i.e., *CL*, *CW*, and *WT*). Statistic univariate tests were performed through the statistical software "R" v. 4.3.2 (R Foundation, 2023). Moreover, principal coordinate analysis (PCoA) was performed to visualise the possible variation among samples, based on the total number of eggs occurring within each nest, days of incubation, hatching success (% determined as the proportion of hatched turtles with respect to the total number of laid eggs) and number of emerged individuals. This multivariate analysis was implemented through the software package PRIMER & PERMANOVA (Clarke and Gorley, 2006), based on the normalised Euclidean distance matrix. The percentage reported in each axis of the PCoA refers to the eigenvalue whose magnitude indicates the amount of variation captured in that axis.

RESULTS

Overall, between 2018–2022 a total of ten nesting events occurred in "Pozzolana di Ponente" beach in Linosa, recording 492 hatchings; no records of deposition activities were detected in 2021 only (see Tab. 1). An increase in hatching success over time coupled to a decrease of the detected morphological anomalies was observed.

During the studied timeframe (2018–2022), and specifically between June 1 and August 31, the atmospheric temperatures recorded on the island (2 m a.s.l.) showed a constant increase over time (Fig. 2). In fact, the average temperature during the study period rose from 24.6°C in 2018 to 26.3°C in 2022, thus a 1.7°C temperature increment in 5 years. Moreover, if only the maximum temperatures during the same period are considered, the increase is even higher, i.e., in 2018 and 2019

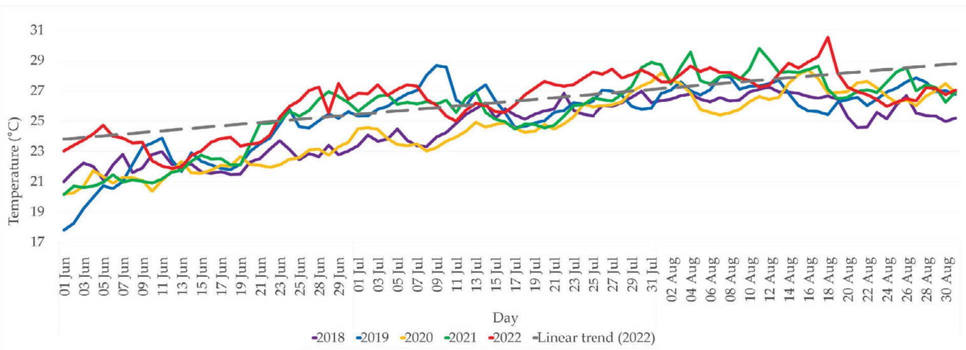

Fig. 2. Average daily atmospheric temperature trend 2018–2022 in Linosa at 2 m a.s.l. climatic data are compared to the linear trend (2022), i.e., dotted grey line; source: own study, linear trend (C3S, no date b)

the maximum temperatures did not exceed 30°C, whereas in 2022 reached 30.5°C, with an average increase equal to 2.25°C. During our study, only two concerning marine-weather events (i.e., intense storm surges) and a few intense rains occurred; despite this, no harm was reported to the nest chambers since they were promptly protected with sandbags and tarpaulin covers. After analysing the sand temperatures, we observed a constant pattern year by years; therefore, we have here reported the three-day trends for each year analysed.

In 2018, during the first year of our survey, three different nesting events were recorded: on July 7, July 15, and August 18; the observed hatching success ranged between 6 and 37% (about 20% on average, see also Tab. 1). In addition to the low hatching rate a significant presence of hatchlings with various malformations in the carapace or beak was observed (Visconti *et al.*, 2022). Unfortunately, that year there were no data loggers to record the temperatures of the sand near the nests.

During 2019, only two nesting events occurred, i.e., on June 23 and July 8 with a hatching success between 9.7 and 36.5% (with an average hatching rate of 22%). As with 2018, several malformations (e.g., abnormalities of the number of inframarginal scutes in the carapaces or irregular beaks, around 67% (see Visconti *et al.*, 2022) were observed in the newly emerged turtles, mostly related to a difference in the numbers of marginal scutes and deformed flippers (Visconti *et al.*, 2022). In this second year, we had the chance to include data loggers; therefore, the temperatures at 35 cm depth near the nests, were between a maximum of 37.2°C and a minimum of 26.6°C, with an average daily temperature of the sand around 32.4°C. We can observe the trend of atmospheric and sand temperatures at the two different depths (i.e., 5 and 35 cm) over three days in detail in Figure 3.

Observing these trends, appears clear that the maximum temperatures of the sand, at 5 cm depth, were not recorded in the hottest hours of the day, but in the evening, around 09:00 p.m. Instead, as regards the temperatures recorded at 35 cm depth, the maximum peak was recorded in the early hours of the morning, between 1:00 and 2:00 a.m. Similarly, the minimum temperatures of the sand at 5 cm depth were recorded in the late morning, around 11:00 a.m., while at 35 cm was recorded between 02:00 and 04:00 p.m., thus in the hottest hours of the day (see Visconti *et al.*, 2022 for explanations of this trend).

The third year of the survey, 2020, was characterised by the occurrence of three nests, two of which were made in June (12 and 24) and one on August 1. Based on the experience of the previous two years (2018–2019), the nests were covered with shade cloth cover placed about 1.50 m from the sand. In sharp contrast to what was observed in the first two years of the survey, the hatching rate in 2020 was on average 92% (see Tab. 1 for further information). Only 2% of newly hatched turtles showed carapacial malformations. Analysing the data from the data loggers, at 35 cm depth, the average daily temperature of the sand was about 31.21°C, with values ranging in the entire incubation period between a minimum of 25.18°C and a maximum of 35.52°C. The data showed that the daily average temperature of the sand at a depth of 35 cm, during the incubation period, was lower than the previous year, reaching a temperature of 1.21°C lower than the daily average of the previous year. This is recorded even though the average atmospheric temperature, calculated for the same period, i.e., from June 1 to September 30, had increased slightly: in 2019, in fact, it was 25°C while in 2020 the average was 25.50°C, then 0.50°C higher. The trends of temperature variations in the different nests at different depths, correlated to the atmospheric temperature can be observed in a Figure 4. Also in this case, as in 2019, the maximum temperatures of the sand, unlike the atmospheric one, are reached during the night hours; conversely, the minimum temperatures of the sand are reached during the day, in the hottest hours.

In 2022, after the summer of 2021 during which no egg-laying had occurred, two nesting events took place, namely on June 4 and July 1, with a hatching success of 82 and 84%, respectively. Only one specimen out of 178 emerged turtles showed beak malformation. Also, in 2022 the nests were covered with shade cloth canvas. Similar to what was observed in the previous years, Figure 5 shows the details of the three-day trends. Data loggers present near the two nests recorded an average daily temperature of the sand (at 35 cm depth) of about 30.31°C, with a minimum temperature of 26.12°C and an average maximum of 33.61°C.

The year 2021 was characterised by the lack of egg laying along the "Pozzolana di Ponente" beach in Linosa. Therefore, with no nests to protect and monitor in Linosa, a comparison of sand temperatures between Linosa and Lampedusa (i.e., "Cala Croce", where *Caretta caretta* lays sometimes its eggs) was made. In Linosa, data loggers were positioned in the portions of the beach where generally the loggerhead sea turtle lays its eggs. In

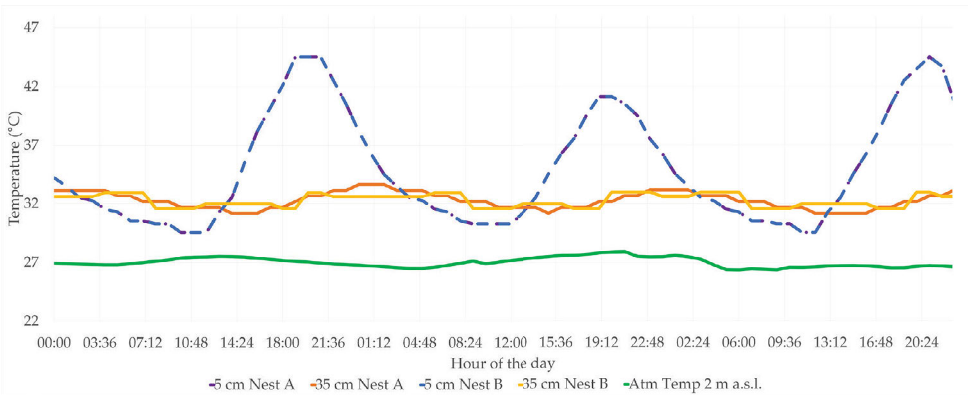

Fig. 3. Three-day temperature trends recorded in 2019 (from 26 to 28 July 2019) in "Pozzolana di Ponente" (Linosa, Sicily) between the superficial and the deep layers near the nests "A" and "B"; Atm Temp = atmospheric temperature; source: own study

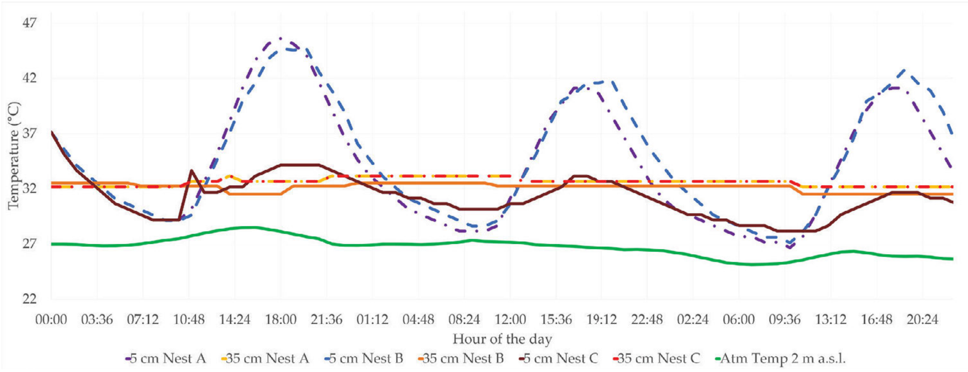

Fig. 4. Three-day temperature trends recorded in 2020 (from 3 to 5 August 2020) in "Pozzolana di Ponente" (Linosa, Sicily) between the superficial and the deep layers near the nests "A", "B" and "C"; Atm Temp = atmospheric temperature; source: own study

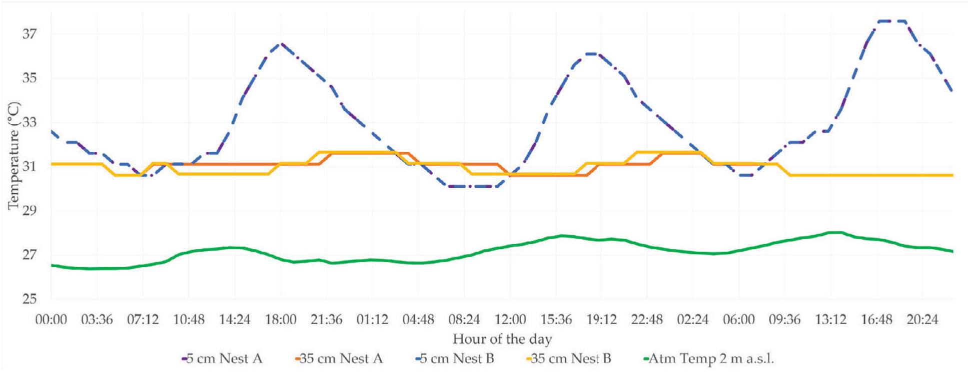

Fig. 5. Three-day temperature trends recorded in 2022 (from 4 to 6 July 2022) in "Pozzolana di Ponente" (Linosa, Sicily) between the superficial and the deep layers near the nests "A", "B"; source: own study

this case, no shade cloth covers were placed in the area above the temperature sensors.

Conversely, in Lampedusa, the data loggers were positioned near the known nesting sites, at a depth of 5 and 35 cm. Considering the same period (i.e., between July 29 and August 25), the analysed data highlighted how in Lampedusa the average daily temperatures of the sand, at both depths, were significantly lower compared to those recorded on Linosa (see Fig. 6 and Tab. 1).

The univariate analyses based on biometric parameters, showed that *CL* (T-test = 4.78; degrees of freedom (df) = 490; probability value (p-value) < 0.0001) and *CW* (T-test = 3.46; df = 490; p-value = 0.0006), as well as number of hatched eggs, during the first two years of monitoring, were lower than those obtained in 2020–2022, when the shading of the nests was implemented (see Tab. 1). Conversely, for *WT* no significant differences were observed (T-test = 0.66; df = 490; p-value < 0.5089).

The PCoA, based on the available data recorded during the period 2018–2022, showed a clear separation of the nesting sites, in different years, in two different clusters (see Fig. 7). Specifically, we can observe two groups: the first one on the right of the graph represented by nests of 2018 and 2019 without protective covers, and the second on the left by nests of 2020 and 2022 with protective covers.

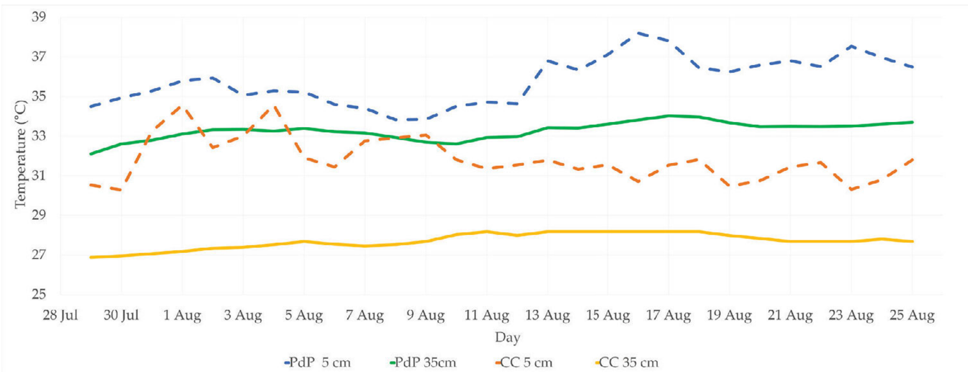

Fig. 6. Temperature trends (from 29 July to 25 August 2021) between the most superficial layer near the nest (5 cm) and the deeper one (35 cm) in Linosa – "Pozzolana di Ponente" (PdP) and Lampedusa – "Cala Croce" (CC); source: own study

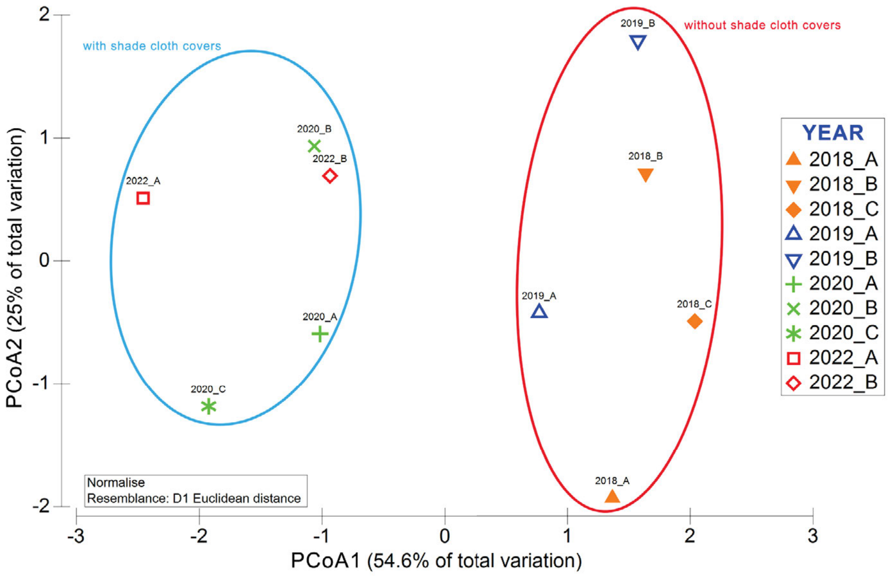

Fig. 7. Principal coordinate analysis (PCoA) plot highlighting the clustering of nesting sites during the period 2018–2022; A, B and C refer to different nesting sites that occurred during the same year; source: own study

DISCUSSION

Among the main challenges faced by sea turtles and specifically the Mediterranean populations of *Caretta caretta* during the terrestrial phases of their life cycle (egg-laying) are: i) the incubation temperatures of the eggs, coupled with its mineralogical composition; and ii) a constant and progressive reduction and/or disappearance of suitable sites for nesting (beaches), mainly caused by excessive anthropisation and coastal erosion (Borzì *et al*., 2021).

Regarding the atmospheric temperatures, a slight increase in them occurred in the studied period in the studied area (i.e., Linosa Island). In fact, as shown in Figure 2, the average external temperatures went from 24.6°C in 2018 to 26.3°C in 2022, showing an average increase of 1.7°C in 5 years. This worrying and progressive increase in the atmospheric temperature is also evident through the progressive reproductive expansion of the species in areas never used before for oviposition (Hochscheid *et al*., 2022; Prato *et al*., 2022). However, it must be noted that the response to a possible expansion of the deposition sites can be seen in a positive way by highlighting how the species always tries to compensate for potentially destructive events.

Our results, obtained during the 2018–2022 period, might have highlighted a possible cost-effective strategy to reduce mortality and malformation incidence. An easy-to-do mitigation activity might be performed by covering the nests with the use of simple shade cloth covers. In fact, as already observed in previous studies (Patino-Martinez *et al*., 2012; Wood, Booth and Limpus, 2014; Reboul, Booth and Rusli, 2021) such artificial shading systems efficiently mitigate detrimental effects caused by rising temperatures. Our results showed that the recorded values (e.g., number of hatched eggs, *CL* and *CW*) during the first two years of monitoring (2018 and 2019), where nest protection from high temperatures had not been adopted, were lower than those obtained in 2020–2022 when the shading of the nests was implemented. This difference is clearly shown in Figure 7 (see also Tab. 1).

Furthermore, it has been observed that the few hatches of the first two years (2018–2019) produced some individuals with reduced motor activity (vitality) both on the beach and in the water with poorly coordinated movements and often moving without a precise direction (Visconti *et al*., 2022). Some hatchlings had to be helped to reach the sea and, in some cases, they returned to the shore. These observations have previously been described by several authors mainly in areas outside the Mediterranean (Booth, 2017 and references therein) highlighting the negative effects of high temperatures on the size and locomotor performance of the hatchlings (Read, Booth and Limpus, 2012; Booth, Feeney and Shibata, 2013) and in general on the vitality of populations (Booth, Feeney and Shibata, 2013; Fisher, Godfrey and Owens, 2014; Wood, Booth and Limpus, 2014).

The analysis of the PCoA, as well as the values obtained from the temperatures recorded near the incubation chamber at different depths (5 and 35 cm), seem to highlight how the temperature represents a major critical issue for this species. Temperature is important both for the determination of sex and for the physiological responses of the embryo in oxygen consumption, carbon dioxide production and growth rate (Booth, 2017). Our data seem to suggest that temperatures are of paramount importance in hatching success and are in agreement with what was observed by Sifuentes-Romero *et al.* (2018), Gatto, Matthews and Reina (2021), Tello-Sahagún *et al.* (2023). Furthermore, it should be taken into account that the actual temperature of the nests might be higher than those detected by data loggers positioned near the studied nests, due to the metabolic heating produced directly by the clutch itself that might increase the nest temperature by about 1.5 ±0.05°C (DeGregorio and Southwood Williard, 2011).

CONCLUSIONS

Unfortunately, in the Mediterranean area, there are few studies aimed at investigating the possible correlation between environmental parameters, the success of the hatching of the eggs, and information on the nature of the substrate characteristic (e.g., its mineralogical composition). It is now evident even at a global level that if we want to reduce the direct and indirect impact of climate change, we need to take immediate action. It is noteworthy that in the span of 5 years (2018–2022), there has been an increase in atmospheric temperatures of 1.7°C. At this point, following this trend, the forecast model predicted so far would be underestimated. Furthermore, it is also obvious that at the moment we can only consider the phenological shifts observed (e.g., hatching success) without being able to predict the degree of possible long-term adaptive response of *Caretta caretta*. However, in the meantime, the implementation of effective and low-cost mitigation activities, such as the use of shade cloth covers to protect the nests from overheating, should be considered a suitable conservation action to be performed synergically with broader management activities aimed at the long-term conservation of sea turtles and their nesting and feeding grounds.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

INSTITUTIONAL REVIEW BOARD STATEMENT

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