Biological Conservation 322 (2026) 112078

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

From patchy records to basin-wide insight: Integrating six decades of Mediterranean sea turtle nesting data

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ARTICLE INFO

Keywords:
Data integration
Regional policy
Sea turtle conservation
Long-term trends
Mediterranean Sea

ABSTRACT

Transboundary conservation of migratory marine species is frequently constrained by fragmented and locally isolated biodiversity data, limiting the detection of large-scale ecological change. In the Mediterranean Sea, one of the world's most politically complex and environmentally pressured basins, decades of sea turtle nesting observations have remained dispersed across countries and organizations, preventing a holistic assessment of population trends. Here, we integrate over sixty years of nesting records for *Caretta caretta* and *Chelonia mydas* into the first standardized, basin-wide database for the Mediterranean (MedSTN), harmonizing 2290 validated records spanning 1960–2023. By integrating this database into Generalized Additive Models (GAMs), we reveal coherent regional patterns invisible in local assessments. Our results show a fundamental structural disparity in population dynamics: while the Eastern Mediterranean remains the primary reproductive stronghold with stable nesting core areas, for both species, we detect a significant northward range expansion for *C. caretta* in the Western Mediterranean. This emerging nesting trend is characterized by an exponential increase in unique nesting sites following a distinct temporal breakpoint circa 2010, suggesting a potential northward range expansion that is consistent with climate-mediated thermal suitability and may be influenced by trans-oceanic immigration. Conversely, *C. mydas* nesting remains almost entirely confined to its Eastern strongholds, exhibiting long-term latitudinal stasis despite localized increases. By transforming a fragmented legacy into a policy-relevant evidence base, MedSTN demonstrates how basin-scale data integration can uncover regional ecological signals and support proactive conservation prioritization. Our framework provides a replicable model for unifying long-term datasets to guide the transboundary management of wide-ranging species under accelerating global change.

1. Introduction

Efficient biodiversity conservation requires a thorough understanding of the biogeographical and ecological processes operating across multiple spatial and temporal scales. Conservation outcomes emerge from the intricate interactions among ecological dynamics, anthropogenic pressures, and management interventions, which function simultaneously at local, regional, and global levels (Bennett et al., 2009). Yet, tackling large-scale challenges, such as global biodiversity loss or the management of species across entire oceanic basins, is frequently impeded by the dominance in the literature of short-term, site-specific studies, resulting in fragmented and spatially biased datasets (Lindenmayer et al., 2022). Consequently, the formulation, evaluation, and implementation of conservation strategies that extend beyond political and administrative boundaries remain severely constrained (Bertzky and Stoll-Kleemann, 2009; Stephenson et al., 2015).

This issue is particularly evident when dealing with migratory species. In fact, these species move across vast spatial extents and different ecological contexts, exposing them to multiple threats along their routes and making their conservation heavily dependent on integrated, multi-scale data (Fujioka et al., 2014; Mattsson et al., 2020). Sea turtles are a clear example: in the Mediterranean Sea, the loggerhead turtle (*Caretta*

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https://doi.org/10.1016/j.biocon.2026.112078
Received 18 May 2026; Received in revised form 20 August 2026; Accepted 23 August 2026
Available online 28 August 2026

caretta) and the green turtle (*Chelonia mydas*) combine long-distance migrations (in the order of hundreds to thousands of kilometres) with complex, multi-stage life cycles, exposing them to pressures across multiple jurisdictions and making population assessments particularly sensitive to data gaps (Fuentes et al., 2023; Wallace et al., 2023). Both species are of high conservation and management interest (*Caretta caretta*, Mediterranean subpopulation, IUCN: Least Concern, Casale, 2015; *Chelonia mydas*, Mediterranean subpopulation, IUCN: Near Threatened, Broderick et al., 2024) and have been continuously monitored for decades. A few recent initiatives have synthesized these efforts into regional status assessments (Groombridge, 1990; Casale and Margaritoulis, 2010; Casale et al., 2018; Casale et al., 2020) providing evidence-based support to Red List evaluations (Casale, 2015; Broderick et al., 2024). However, most information is dispersed across different organizations, projects, and countries, and there is a lack of a systematic monitoring scheme, with data collected through methodologies that, while often standardized at the local level, remain non-standardized across the country and often cover only a limited temporal window. This heterogeneity limits the possibility of establishing a reliable conservation baseline, reduces the ability to detect long-term trends, obscures the drivers of population change, and undermines the effectiveness of transboundary conservation measures (Hamann et al., 2010; Wallace et al., 2010; Girard et al., 2022).

While data fragmentation is not unique to sea turtle research, strategies to foster long-term, integrated, and multidisciplinary collaborations, particularly for highly migratory species, often rely on open data sharing (Urbano et al., 2021; Grémillet et al., 2022). Publishing primary data in standardized, open-access repositories is essential to overcome the limitations of localized, short-term studies (Soranno et al., 2015; Roche et al., 2022). Therefore, we here introduce the **Med**iterranean **S**ea **T**urtle **N**esting database (MedSTN), a centralized platform that standardizes and integrates historical and contemporary nesting records for sea turtles across the Mediterranean basin. By consolidating previously fragmented and sometimes obscure datasets into an open-access framework, MedSTN enables robust, basin-wide analyses of spatial and temporal trends, favours the identification of priority habitats, and allows for the evaluation of future conservation outcomes. By providing a centralized, standardized platform, MedSTN represents a critical pivotal point for Mediterranean sea turtle research, supporting robust syntheses that transcend political and administrative boundaries and providing a foundation for sustained science, policy, and management applications.

2. Material and methods

2.1. Data compilation and data quality control

We assembled a dataset of nesting events for loggerhead and green turtles across the Mediterranean by integrating information from peer-reviewed publications, technical reports, and other digital and archival sources, including grey literature and online databases. Searches were conducted in Web of Science, Scopus, and Google Scholar using the following Boolean search string: ("sea turtle" OR "marine turtle" OR "*Caretta caretta*" OR "*Chelonia mydas*" OR "loggerhead" OR "green turtle") AND ("nest" OR "nesting") AND ("Mediterranean"). All publications retrieved were screened through a backward and forward citation tracking process (snowballing) to identify additional data sources. All documents were reviewed to extract nesting information at the highest possible spatial and temporal resolution. All records explicitly classified as false crawls (i.e., tentative nesting events eventually leading to the female returning to the sea without laying eggs) were removed to retain only confirmed clutch deposition events (we herein use the term 'nest' for each successful clutch deposition to maintain consistency with published baseline literature and regional monitoring assessments). To prevent double counting across overlapping sources, data were harmonized by cross-referencing the nesting year, beach name, and geographic coordinates for each entry. All geographic coordinates were standardized to WGS84 decimal degrees. Geographic coordinates were assigned to the centroid of each nesting beach rather than representing the exact location of individual nests. Where geographic coordinates were missing from the original source, site locations were georeferenced by identifying the midpoint of the sandy shoreline for each beach using Google Earth Pro. For each clutch deposition event, we extracted and standardized specific data fields, including country, nesting site (beach name), coordinates, species, monitoring years, abundance, beach length, monitoring method, and data source, to ensure a uniform analytical structure. Detailed definitions and descriptions of all fields are provided in the ReadMe.txt file. For each nesting beach, we calculated a categorical Nest Count Index (NCI) including the following classes: 0: no nests, 1: 1 nest, 2: 2–10 nests, 3: 11–50 nests, 4: 51–100 nests, 5: 101–500 nests, 6: 501–1000 nests, 7: 1000–5000 nests. We included in MedSTN all data available up to and including 2023. The database, to ensure its long-term relevance, is designed as a dynamic repository that will be continuously updated and maintained as new nesting data become available at the following link: [https://maioranolab.com/medstn/]. The database is publicly accessible and can be consulted and downloaded at the following DOI: [https://doi.org/10.6084/m9.figshare.32172771].

2.2. Nesting trends in space and time

To investigate the spatio-temporal drivers of nesting activity, we modelled nesting intensity as a function of year and latitude. We calibrated species-specific Generalized Additive Models (GAMs) using the gam function in the mgcv package for R (Wood, 2017). This approach was selected for its robustness in handling non-linear ecological relationships and the inherent overdispersion of nesting count data (Zuur et al., 2009). To overcome the high heterogeneity and data gaps in historical records, where exact clutch numbers were frequently unavailable, the models were fitted using the discrete Nest Count Index (NCI) as a proxy for nesting intensity. GAMs were fitted using a Negative Binomial distribution with a log-link function, treating the ordinal index values as discrete, bounded integer counts (Zuur et al., 2009). The model structure integrated smooth functions for the temporal trend and the latitudinal gradient, alongside a site-specific random effect to account for local, time-invariant environmental characteristics and to partially mitigate the confounding effects of site-level differences in historical monitoring presence. For *Caretta caretta*, the model included an interaction term between Year and Region (Eastern/Western Mediterranean) to test for divergent population trajectories across the basin. For the Western Mediterranean, an additional interaction between Year and Latitude was integrated to statistically validate the observed northward range expansion. Model selection and smoothness parameters were optimized using Restricted Maximum Likelihood (REML). For *Caretta caretta*, the model formula was structured as follows:

$$\mathrm{NCI_{CC}} \sim \mathrm{Region} + s(\mathrm{Year}, \mathrm{by} = \mathrm{Region}, k = 5) + s(\mathrm{Latitude}, \mathrm{by} = \mathrm{Region}, k = 5) + s\left(\mathrm{Site}, bs = \text{"re"}\right)$$

where Region is a parametric factor (Eastern vs. Western Mediterranean), s(Year) and s(Latitude) are thin plate regression splines penalized separately for each macro-region with the basis dimension restricted to k = 5 to prevent overfitting, and s(Site, bs = "re") specifies a site-specific random intercept to control for local environmental characteristics and variability in monitoring effort.

For *Chelonia mydas*, as nesting is confined to its eastern strongholds, the model was fitted using an additive structure without regional interaction terms:

$$NCI_{CM} \sim s(\mathrm{Year}, k = 5) + s(\mathrm{Latitude}, k = 5) + s(\mathrm{Site}, bs = \text{"re"})$$

The goodness-of-fit was evaluated by calculating the percentage of deviance explained and adjusted R-squared values. Temporal dynamics were assessed by examining the effective degrees of freedom (edf) of the s(Year) term, which served to identify whether nesting trends exhibited linear, non-linear, or fluctuating trajectories over time (Zuur et al., 2009). Significance of the smooth terms was determined using the approximate Chi-square tests implemented in mgcv package. Uncertainty around the smooth curves was evaluated using 95% Bayesian credible intervals (Wood, 2017).

To estimate whether the increase in nesting records corresponds to a geographical range expansion, we analysed the "First nesting occurrence" date for each unique site. The correlation between time and the establishment of new sites was evaluated using Spearman's Rank Correlation (rho). To objectively identify the temporal breakpoint in the cumulative emergence of new nesting sites for *C. caretta* in the Western Mediterranean, we analysed the instantaneous rate of change (the first derivative) of the site-accumulation curve. We fitted a cubic smoothing spline to the cumulative site data over time. The first derivative was then numerically calculated to identify the precise inflection point where the nesting dynamics transitioned from a long-term historical baseline of sporadic records to an accelerated range expansion. The robust temporal structure of this acceleration was further evaluated using a Spearman's rank correlation analysis. Finally, we generated spatiotemporal heatmaps using Kernel Density Estimation (KDE) to visualize the evolution of 'nesting cores' across the study period (via the kde2d function in the MASS package for R).

3. Results

The final dataset includes 1950 validated nesting records for *Caretta caretta* and 340 for *Chelonia mydas* spanning 1960–2023 and encompasses 16 Mediterranean countries with documented nesting activity.

3.1. Spatial patterns in monitoring effort and nesting intensity

For *C. caretta* both nesting intensity and long-term monitoring efforts are largely restricted to the Eastern Mediterranean. Monitoring programs spanning more than 20 years are predominantly located at major rookeries in Greece, Turkey, and Cyprus, complemented by long-standing datasets in southern Italy, Tunisia and Israel (Fig. 1). Correspondingly, the highest average NCI values (> 500 nests) are almost exclusively recorded in these regions, reflecting their role as the core nesting areas for the species (Fig. 2).

For *C. mydas* the nesting activity is limited to the Eastern Mediterranean basin. Sites with the longest temporal coverage (> 20 years; Fig. 3) and highest average NCI values (101–500; Fig. 4) are in Turkey and Cyprus, confirming that the species' reproductive range remains geographically constrained despite local increases.

3.2. Model performance and basin-specific dynamics

The Generalized Additive Models (GAMs) calibrated for both species provided a robust fit to the data. The model for *Caretta caretta* exhibited high explanatory power, accounting for 80.6% of the total deviance (R^2 = 0.842, n = 1950). The analysis revealed a significant structural divergence in recorded nesting intensity between regions (Western vs Eastern) ($\beta = -0.37$, $p < 0.05$). Despite the lower intensity currently observed in the Western Mediterranean compared to the Eastern, the former is characterized by a rapid, non-linear acceleration in recorded nesting activity. This dynamic is mirrored by a distinct pattern in *Chelonia mydas*, for which the model exhibited even higher explanatory power, capturing 87.5% of the variance in documented nesting records ($R^2 = 0.919$, $n = 340$). Unlike the broader distribution of the *C. caretta*, *C. mydas* nesting remains almost entirely confined to the Levantine basin, with only one nesting event recorded in the Central Mediterranean (Tunisia in 2019) (Ben Ismail et al., 2022). The high significance of the site-specific random effect ($p < 0.001$) further confirms that *C. mydas* dynamics are driven by stable, localized loyalty to historically established rookeries.

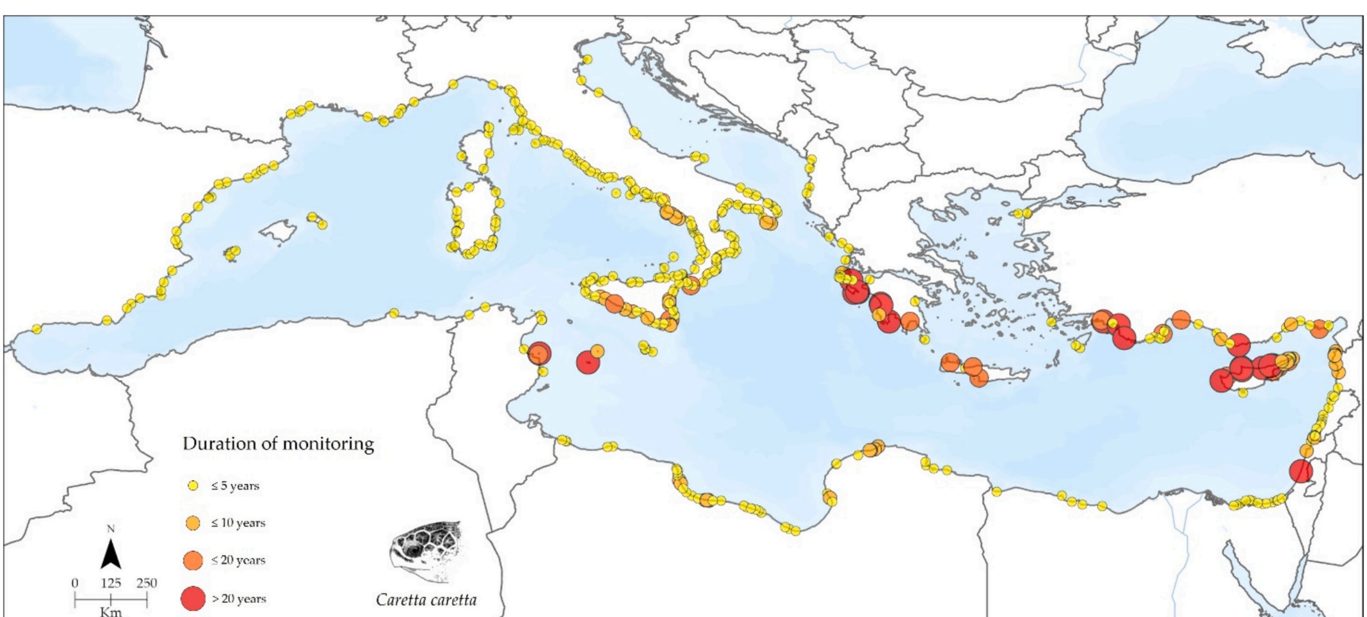

Fig. 1. Monitoring duration for *Caretta caretta* nesting sites in the Mediterranean Sea.

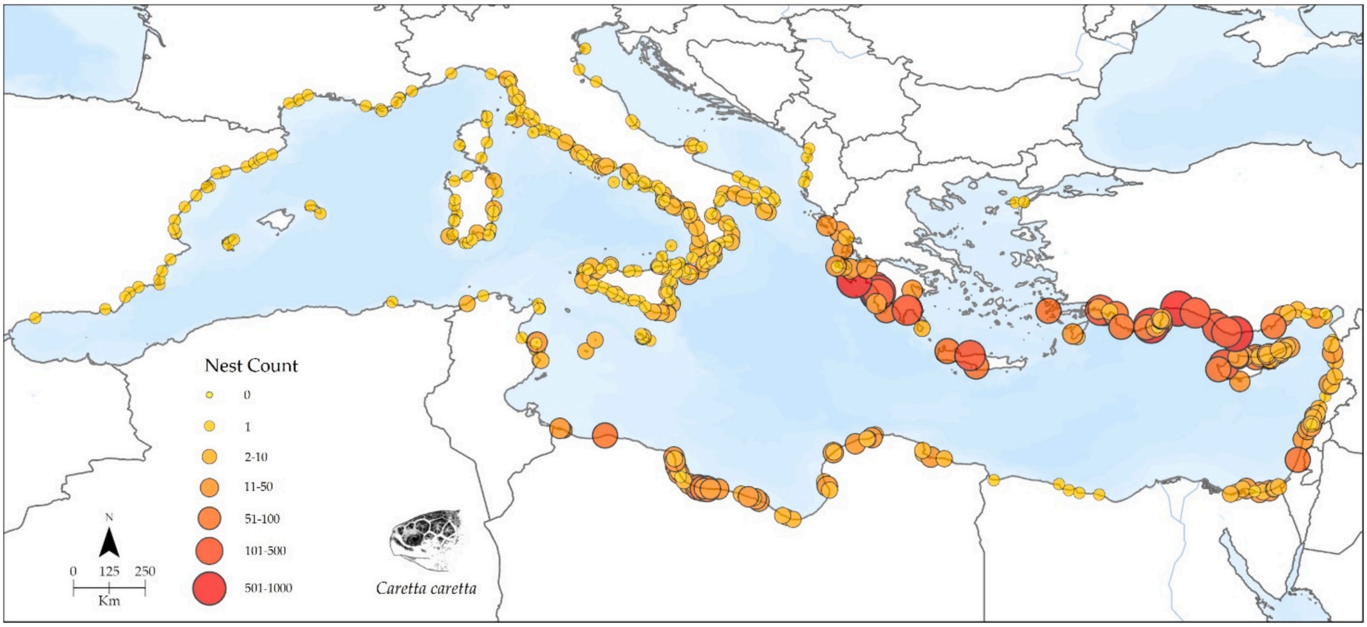

Fig. 2. Spatial distribution of the Nest Count Index (NCI) classes for *Caretta caretta* nesting sites across the Mediterranean Sea.

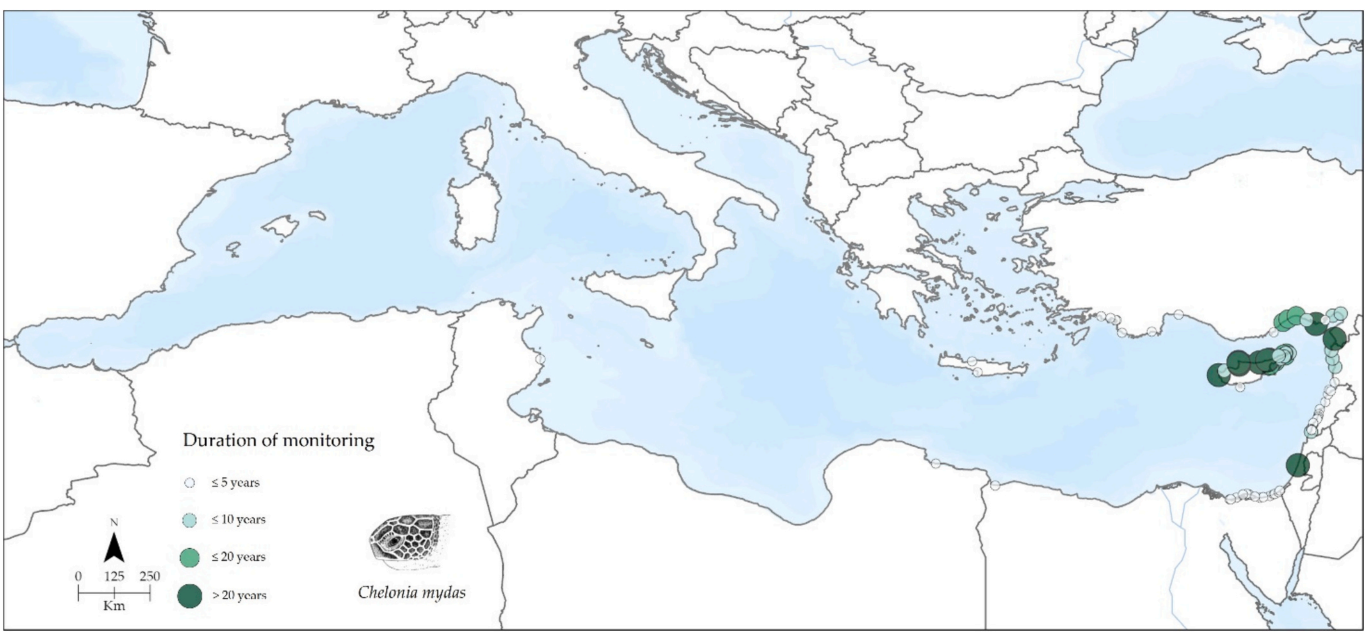

Fig. 3. Monitoring duration for *Chelonia mydas* nesting sites in the Mediterranean Sea.

3.3. Temporal trends in nesting intensity

Temporal nesting dynamics exhibited distinct trajectory differences both between regions and species. For *Caretta caretta*, the Eastern Mediterranean displayed long-term stability with no significant directional trend (edf $= 1.07$, $p = 0.49$) (Fig. 5a). Conversely, the Western Mediterranean exhibited a significant increasing trend (edf $= 1.37$, $p < 0.05$). This divergent trajectory suggests a recent and significant intensification of nesting efforts within the basin. The temporal pattern for *Chelonia mydas* mirrors the long-term latitudinal consistency of the Eastern *C. caretta* population, exhibiting a weak and statistically non-significant temporal trend in nesting intensity over the six-decade study period (edf $= 1.00$, $p = 0.07$) (Fig. 5b).

3.4. Spatiotemporal colonization and site occupancy

The spatiotemporal distribution of nesting activity highlights a profound divergence in the range expansion dynamics of the two species across the Mediterranean basin. For *C. caretta*, Spearman's rank correlation identified a robust and highly significant positive relationship between time and the emergence of new nesting sites in the Western Mediterranean (rho $= 0.73$, $p < 0.001$). Analysis of the first derivative of the cumulative site-accumulation curve mathematically identified a distinct temporal breakpoint in 2010. This year marks the exact inflection point where the system transitioned from historical, sporadic nesting events to a phase of rapid, exponential increase in unique nesting sites (Fig. 6a). The spatiotemporal heatmaps, visualized through KDE, provide definitive evidence of a latitudinal shift in the nesting

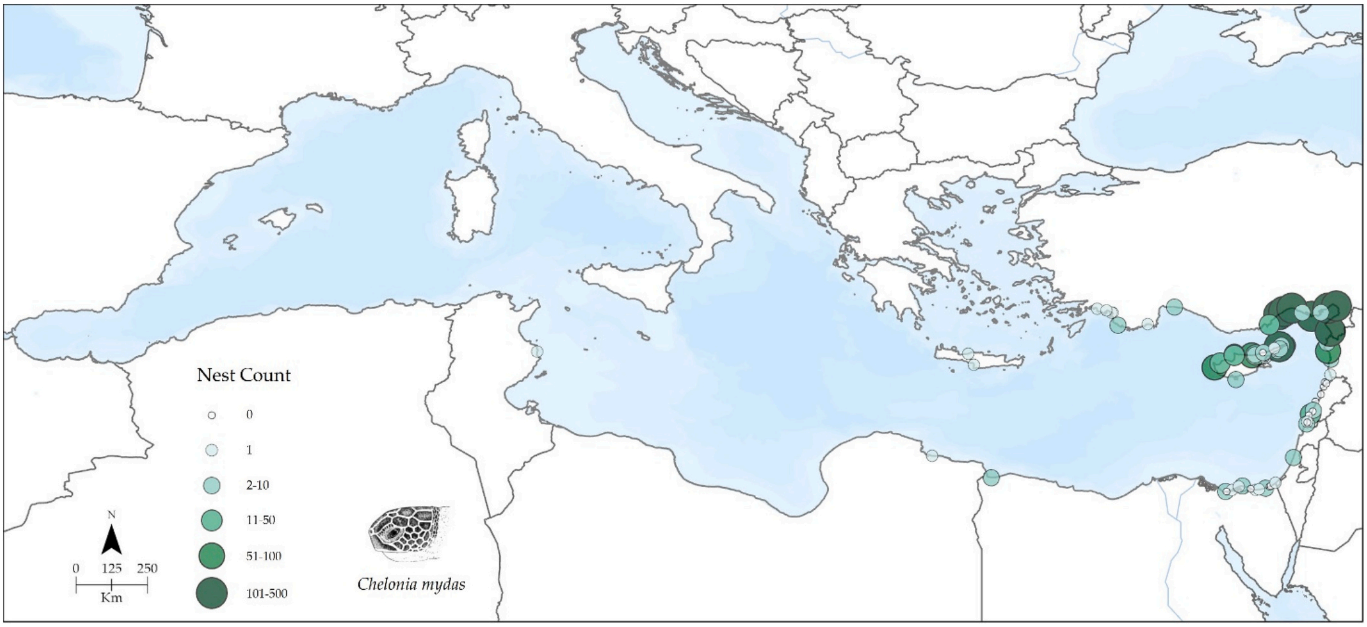

Fig. 4. Spatial distribution of the Nest Count Index (NCI) classes for *Chelonia mydas* nesting sites across the Mediterranean Sea.

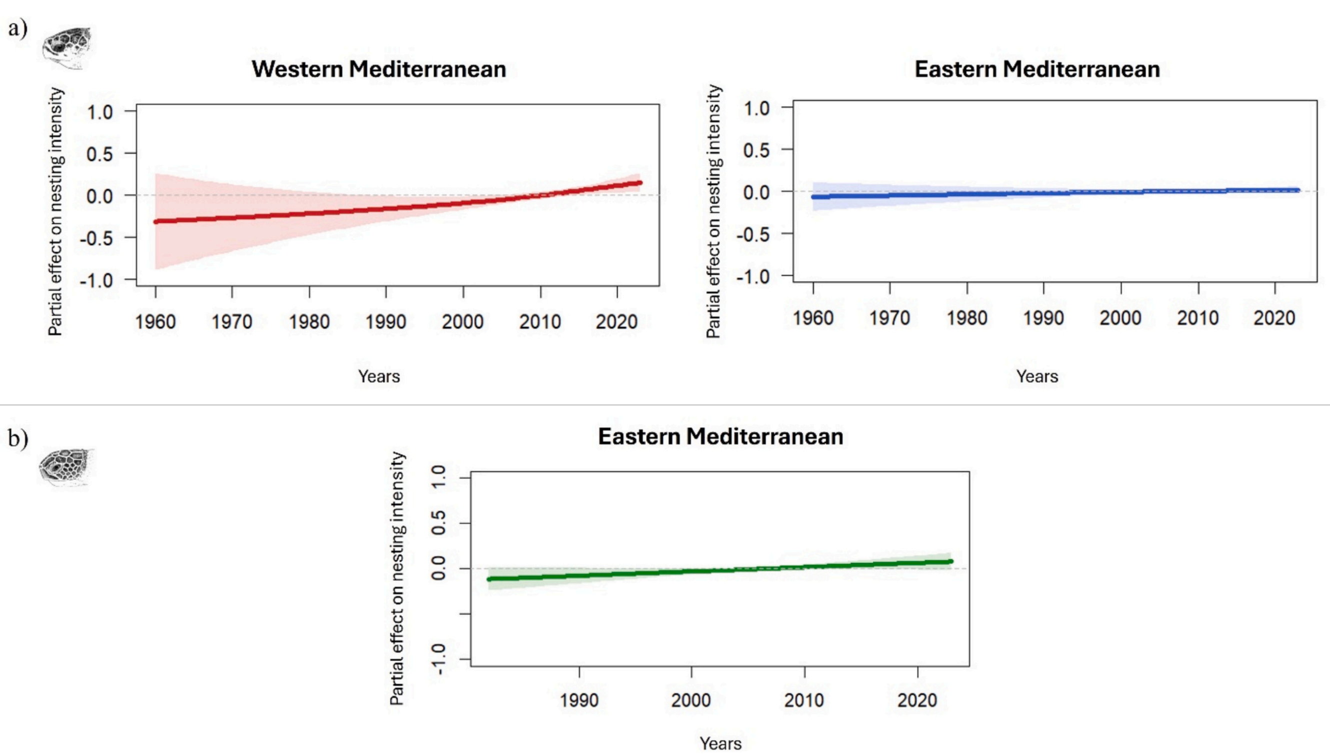

Fig. 5. Temporal trends in nesting intensity for *Caretta caretta* and *Chelonia mydas*. The plots illustrate the GAM smooth functions (solid lines) with 95% Bayesian credible intervals (shaded areas) for: (a) *C. caretta* in the Western (red) and Eastern (blue) Mediterranean, and (b) *C. mydas* in the Eastern Mediterranean (green). The y-axis represents the partial effect of the smooth term on the log-transformed nesting intensity, where a value of zero indicates the mean intensity over the study period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

range of *C. caretta*. Statistical modeling via GAMs (Table S1 in Supplementary material) confirms that while the Eastern Mediterranean core has remained latitudinally stable over the six-decade study period ($p < 0.001$), the Western Mediterranean exhibits a dynamic and accelerating northward shift in recorded nesting activity ($p < 0.05$). This northward progression, increasingly occurring above 38°N, is visually confirmed by the density shift toward the KDE heatmap (Fig. 6b). This latitudinal extension of documented nesting in the West contrasts sharply with the spatial stability observed for *C. mydas*. Spearman's correlation identified a weak and non-significant relationship between time and the emergence of new sites (rho = 0.186, $p = 0.38$). Instead of a gradual or accelerating expansion, the cumulative curve for *C. mydas* is characterized by a sudden influx of records in the early 1990s (Fig. 6c). This abrupt increase reflects a well-documented sampling artifact,

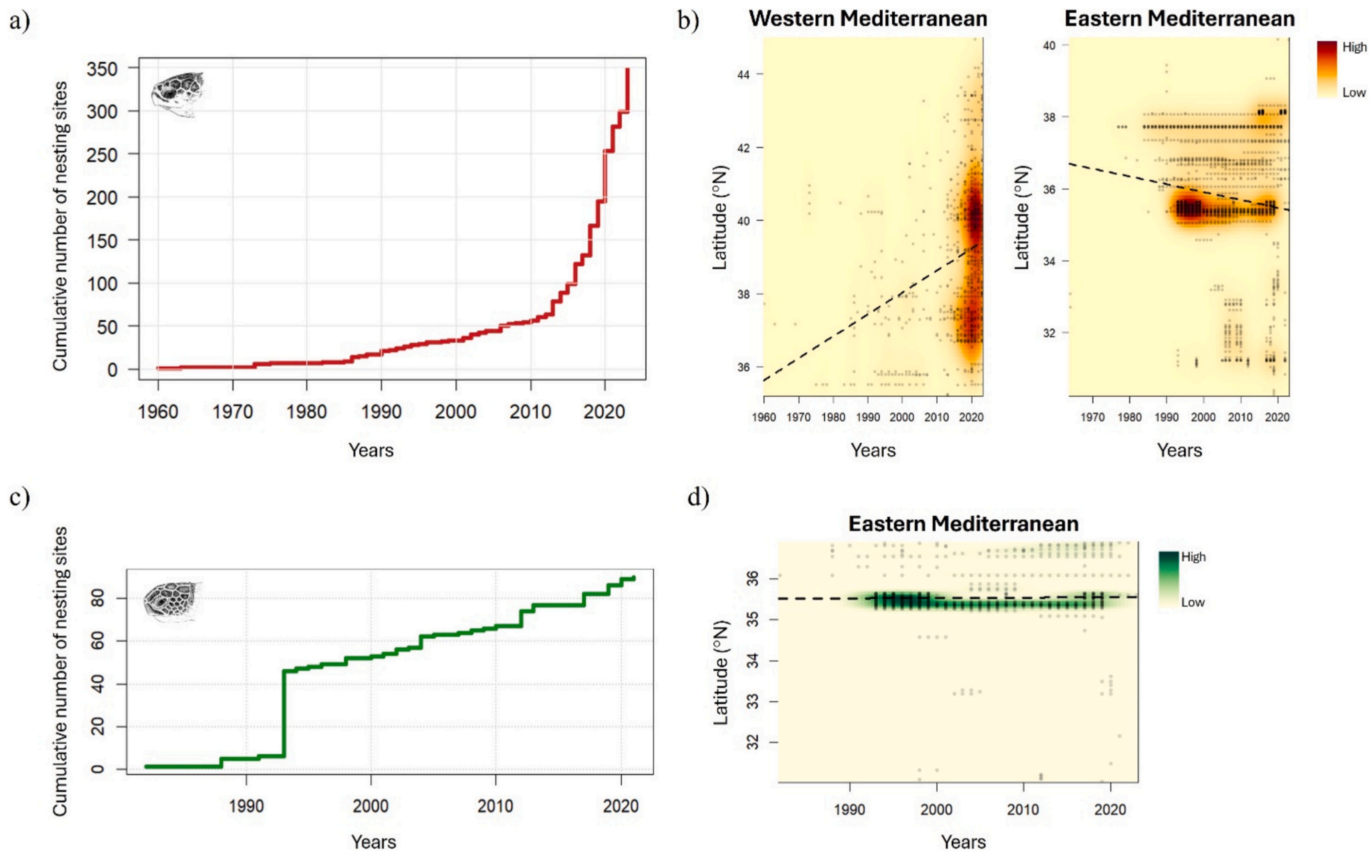

Fig. 6. Comparative spatiotemporal colonization and nesting intensity dynamics for *Caretta caretta* and *Chelonia mydas*. (a) Cumulative number of *C. caretta* nesting sites, showing a sharp temporal breakpoint around 2010 followed by exponential growth. (b) Spatiotemporal recorded nesting intensity heatmaps for *C. caretta*. In the Western basin (left), a significant northward shift indicates an active range expansion ($p < 0.05$), whereas the Eastern basin (right) shows a latitudinally stable distribution core ($p < 0.001$). (c) Cumulative number of *C. mydas* nesting sites, exhibiting a prominent step-like increase in the early 1990s, reflecting the historical onset of systematic regional monitoring programs, followed by a steady, linear accumulation without evidence of recent exponential acceleration. (d) Spatiotemporal nesting intensity heatmap for *C. mydas*, showing long-term stasis with nesting activity anchored in the southern Levantine basin.

specifically the formal initiation of systematic, large-scale beach surveys in Turkey and Cyprus. Following this initial monitoring pulse, the addition of unique green turtle nesting sites has remained essentially static and linear, with no signs of recent range extension. Furthermore, spatiotemporal heatmaps (Fig. 6d) confirm that the 'heat core' of *C. mydas* remains geographically anchored in the south-eastern Levantine basin, exhibiting a long-term latitudinal stasis.

4. Discussion

Large-scale ecological patterns often remain hidden until local datasets are brought together through integrated data syntheses (Zipkin et al., 2021). By harmonizing more than six decades of heterogeneous nesting records into the first standardized basin-wide platform, MedSTN enables a comprehensive reassessment of Mediterranean sea turtle dynamics. This approach moves beyond local or site-specific narratives, revealing coherent regional patterns, consistent trends and processes that emerge across the entire Mediterranean, providing a truly holistic view of population dynamics.

While the Eastern basin remains the primary reproductive stronghold, characterized by long-term population stability for both *Caretta caretta* and *Chelonia mydas* (Kasparek et al., 2001; Canbolat, 2004; Casale et al., 2020; Margaritoulis et al., 2022), despite recent documented increases in nesting sites (such as Koroni and Kyparissia Bay in Greece; Margaritoulis et al., 2023, 2025a), the Western basin has transformed into a dynamic frontier of rapid range expansion. The most salient finding of this synthesis is the exponential rapid increase in the occupancy of documented *C. caretta* nesting sites following a distinct temporal breakpoint circa 2010. This phenomenon, characterized by a significant northward shift exceeding 38°N, is consistent with the hypothesis of an ongoing, climate-driven range expansion. This acceleration aligns chronologically with the crossing of critical thermal thresholds in the basin documented in recent literature. As summer temperatures have trended upward, previously unsuitable high-latitude coastlines are hypothesized to have transitioned into viable recorded nesting niches (Pisano et al., 2020; Cos et al., 2022). While a warming Mediterranean progressively opens thermal windows suitable for successful nesting at higher latitudes (Carreras et al., 2018; Hochscheid et al., 2022; Mancino et al., 2022; Margaritoulis et al., 2025b), the provenance of these new remains a compelling question. Recent genetic evidence from independent studies suggests that this expansion may be bolstered by an influx of "pioneer" individuals from Atlantic nesting stocks (Luna-Ortiz et al., 2024). These Atlantic immigrants, entering via the Strait of Gibraltar, have been proposed to exploit newly available thermal niches in the Western basin. Consequently, the Western Mediterranean is hypothesized to be evolving into a critical biogeographic intersection where resident Mediterranean lineages and Atlantic genotypes converge (Luna-Ortiz et al., 2024).

In stark contrast to the *C. caretta* rapid colonization, *C. mydas* remains geographically anchored within its eastern strongholds. Despite localized increases in nest abundance, our GAM framework identifies a long-term latitudinal stasis, with the "heat core" of nesting activity remaining strictly confined to the Levantine and Aegean basins. This lack of a significant directional trend suggests a state of population equilibrium within its core range, likely governed by more rigid ecological requirements or stronger philopatric constraints compared to

C. caretta (Patrício et al., 2018). Such geographic concentration reinforces the species' vulnerability to localized anthropogenic threats and environmental shifts within a restricted reproductive niche (Despoti et al., 2025). However, this observed stasis may be evolving under the pressure of global environmental change. While nesting is currently restricted, climate suitability models predict a significant northward and westward expansion of potential nesting habitats as the Mediterranean continues to warm (Mancino et al., 2023). In this context, the green turtle nest documented in Tunisia in 2019 represents a pivotal biogeographic record, the westernmost for the species in the Mediterranean (Ben Ismail et al., 2022). The interpretation of this event benefits from a multi-disciplinary perspective: while warming may be increasing the availability of suitable thermal niches, recent genomic evidence reveals that this specific nest originated from the South Atlantic Regional Management Unit (RMU) rather than the Eastern Mediterranean stock (Marín-Capuz et al., 2025). Such findings suggest that the spatial dynamics of *C. mydas* are likely shaped by an interplay between environmental suitability and demographic opportunistic events. In this scenario, climatic warming may act as an environmental facilitator, rendering new sites potentially viable for trans-oceanic "pioneers" from the Atlantic.

By overcoming data fragmentation, we expose a fundamental structural disparity in population dynamics that necessitates a dual-track conservation priority. In the Eastern Mediterranean, the basin's demographic engine, the priority remains the rigorous maintenance of historical, high-density rookeries for both *C. caretta* and *C. mydas*. These core areas exhibit long-term stability but remain vulnerable to localized pressures, requiring sustained investment in standardized monitoring to detect any deviation from their current equilibrium (White, 2019). Conversely, the emerging nesting range, identified in the Western Mediterranean, redirects conservation efforts toward an anticipatory framework. In this context, it is important to note that while spatial representations of monitoring duration (Fig. 1) inherently emphasize multidecadal baseline efforts, sites characterized by shorter monitoring windows ($\leq$ 5 years) in the Western basin should not be dismissed as uninformative. Instead, they frequently catch the most recent, active nesting dynamics within these new sectors, whereas long-term monitoring durations remain predominantly anchored within stable historical strongholds. As climate change and trans-oceanic immigration reshape reproductive ranges, relying solely on historical hotspots risks overlooking emerging habitats critical for future population resilience. The detection of these "pioneer" nesting events underscores that the Western basin has transitioned from a marginal area to a focal point for transboundary cooperation (Milman et al., 2020; Urbano et al., 2021; Fuentes et al., 2023). Harmonizing these disparate records is particularly vital for highly migratory species, as regional signals of change often remain obscured until data isolation is overcome (Hostetler et al., 2025; Klaassen et al., 2026). While we acknowledge that several long-term datasets remain unpublished or only minimally described in grey literature, MedSTN centralizes existing evidence as the most comprehensive and open-access repository available. By establishing this essential baseline, the platform allows international frameworks to evaluate population trends across political boundaries, transforming fragmented records into a coherent narrative. Ultimately, such integrated systems enable managers to anticipate ecological shifts (Stephenson and Stengel, 2020; Urbano et al., 2021), ensuring that conservation efforts are as dynamic as the species they seek to protect.

4.1. Methodological considerations and data limitations

When conducting large-scale, multi-decadal macro-ecological syntheses, compiling published literature is a standard and powerful approach to capturing basin-wide dynamics. Within this framework, the compiled data inherently reflect formalized reporting trends, which are shaped by historical shifts in regional monitoring efforts and publishing accessibility across different geopolitical contexts. While localized monitoring data in some regions may be contained within national reports or non-English literature, our dataset represents the most comprehensive, standardized, and validated peer-reviewed repository currently available for Mediterranean sea turtle nesting. To ensure that these inevitable spatial and institutional variations in reporting did not bias our ecological conclusions, our statistical framework was specifically designed to be robust against heterogeneous sampling. By incorporating site-specific random effects within the Generalized Additive Models (GAMs), we effectively accounted for baseline, time-invariant differences in monitoring presence and local survey infrastructure among sectors. Crucially, while variations in historical monitoring effort cannot be directly quantified due to the lack of unpublished zero-effort data, the observed trends cannot be explained by sampling artifacts alone. A mere expansion of survey coverage would generate a random spatial distribution of new records over time. Conversely, our statistical framework identifies a highly consistent, directional northward shift ($p < 0.05$), indicating that the model is capturing a genuine macro-ecological signal rather than simple fluctuations in reporting intensity. Consequently, while absolute nest counts are bound to reporting boundaries, the highly significant non-linear temporal accelerations and latitudinal shifts identified by our models reflect robust macro-ecological signals rather than sampling artifacts, providing a reliable foundation for regional conservation planning. Furthermore, synthesized literature inevitably highlights key spatial gaps in regional survey coverage. While major nesting strongholds in the north-eastern Mediterranean have benefited from sustained, systematic monitoring programs, significant stretches of potentially suitable nesting habitat, most notably across parts of the North African coastline (e.g., sectors in Libya) and remote southern Levantine beaches, remain under-surveyed or characterized by discontinuous published reporting. Differentiating whether the lack of records in these data-deficient sectors reflects true biological absence or undetected sporadic nesting remains a critical priority. Prioritizing future standardized, transboundary monitoring in these spatial gaps will be essential to validate prospective habitat suitability under ongoing climate change and guide targeted regional conservation interventions.

5. Conclusions

The MedSTN database marks a critical pivot point for Mediterranean sea turtle research, moving from a patchwork of localized studies toward a unified, basin-wide conservation narrative. By harmonizing six decades of heterogeneous records, we have demonstrated that data integration is not merely a technical challenge but a conservation necessity. Our synthesis reveals a Mediterranean in transition. The stability of core reproductive areas in the East provides a foundation for the species' persistence, yet the rapid colonization of the Western basin by *Caretta caretta* signals a profound biogeographic shift likely driven by climate-mediated thermal suitability and trans-oceanic immigration. In contrast, the geographic confinement of *Chelonia mydas* highlights a heightened vulnerability to localized threats, demanding sustained protection of its restricted niche. For practitioners and policymakers, these results emphasize that conservation success is scale dependent. Relying on historical hotspots alone risks overlooking the emerging habitats essential for future population resilience. To be effective, transboundary governance must evolve to match the dynamic spatial scales of the species it protects. Looking forward, the long-term relevance of MedSTN depends on continued investment in open-access data, standardized monitoring and international collaboration. By bridging the gap between local observations and regional policy, this framework provides the robust evidence base required to anticipate ecological change and secure the future of marine megafauna in a rapidly warming Mediterranean.

CRediT authorship contribution statement

Chiara Mancino: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **ALan F. Rees:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Sandra Hochscheid:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Luigi Maiorano:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Acknowledgments

We sincerely thank all the researchers, scientific institutions, governmental agencies, and conservation organizations that contributed their invaluable data to the Mediterranean Sea Turtle Nesting Database (MedSTN). We especially acknowledge those who have facilitated the crucial process of data integration by making their nesting records publicly available through peer-reviewed publications and technical reports. Furthermore, the dedicated efforts of local monitoring networks and citizen science organizations were instrumental in compiling the comprehensive dataset utilized in this study.

Code availability

The R code and modeling scripts used for the Generalized Additive Models (GAMs) and statistical analyses are available from the corresponding author upon reasonable request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2026.112078.

Data availability

The data used in this study can be downloaded from the repository: [https://doi.org/10.6084/m9.figshare.32172771].

References

Ben Ismail, M., Jribi, I., Kaska, Y., Ben Nakhla, L., Ben Fradj, A., Dibej, M., Bradai, M.N., 2022. The westernmost green turtle (*Chelonia mydas*) nest recorded in the Mediterranean from Tunisia. MedTurtle Bulletin 1, 19–23.

Bennett, A.F., Haslem, A., Cheal, D.C., Clarke, M.F., Jones, R.N., Koehn, J.D., Yen, A.L., 2009. Ecological processes: a key element in strategies for nature conservation. Ecol. Manag. Restor. 10 (3), 192–199.

Bertzky, M., Stoll-Kleemann, S., 2009. Multi-level discrepancies with sharing data on protected areas: what we have and what we need for the global village. J. Environ. Manag. 90 (1), 8–24.

Broderick, A.C., Türkozan, O., Demetropoulos, S., Mastrogiacomo, A., Demetropoulos, A., Levy, Y., Leader, N., 2024. *Chelonia mydas* (Mediterranean subpopulation) (amended version of 2023 assessment). The IUCN red list of threatened species 2024:. e.T4616A259027885. Accessed on 29 January 2026.

Canbolat, A.F., 2004. A review of sea turtle nesting activity along the Mediterranean coast of Turkey. Biol. Conserv. 116 (1), 81–91.

Carreras, C., Pascual, M., Tomás, J., Marco, A., Hochscheid, S., Castillo, J.J., Cardona, L., 2018. Sporadic nesting reveals long distance colonisation in the philopatric loggerhead sea turtle (*Caretta caretta*). Sci. Rep. 8 (1), 1435.

Casale, P., 2015. *Caretta caretta* (Mediterranean subpopulation). . The IUCN red list of threatened species 2015: e.T83644804A83646294. Accessed on 29 January 2026.

Casale, P., Margaritoulis, D. (Eds.), 2010. Sea Turtles in the Mediterranean: Distribution, Threats and Conservation Priorities. IUCN.

Casale, P., Broderick, A.C., Camiñas, J.A., Cardona, L., Carreras, C., Demetropoulos, A., Türkozan, O., 2018. Mediterranean sea turtles: current knowledge and priorities for conservation and research. Endanger. Species Res. 36, 229–267.

Casale, P., Hochscheid, S., Kaska, Y., Panagopoulou, A., 2020. Sea turtles in the Mediterranean region: MTSG annual regional report 2020.

Cos, J., Doblas-Reyes, F., Jury, M., Marcos, R., Bretonnière, P.A., Samsó, M., 2022. The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. Earth Syst. Dynam. 13 (1), 321–340.

Despoti, S., Solanou, M., Tsoukali, S., Valavanis, V., Tsagarakis, K., Giannoulaki, M., 2025. Uncovering sea turtle strandings in the Greek seas (eastern Mediterranean Sea): spatiotemporal patterns and signs of anthropogenic interaction. Aquat. Conserv. Mar. Freshwat. Ecosyst. 35 (2), e70066.

Fuentes, M.M.P.B., McMichael, E., Kot, C.Y., Silver-Gorges, I., Wallace, B.P., Godley, B.J., Hays, G.C., 2023. Key issues in assessing threats to sea turtles: knowledge gaps and future directions. Endanger. Species Res. 52, 303–341.

Fujioka, E., Kot, C.Y., Wallace, B.P., Best, B.D., Moxley, J., Cleary, J., Halpin, P.N., 2014. Data integration for conservation: leveraging multiple data types to advance ecological assessments and habitat modeling for marine megavertebrates using OBIS–SEAMAP. Ec. Inform. 20, 13–26.

Girard, F., Girard, A., Monsinjon, J., Arcangeli, A., Belda, E., Cardona, L., Claro, F., 2022. Toward a common approach for assessing the conservation status of marine turtle species within the European marine strategy framework directive. Front. Mar. Sci. 9, 790733.

Grémillet, D., Chevallier, D., Guinet, C., 2022. Big data approaches to the spatial ecology and conservation of marine megafauna. ICES J. Mar. Sci. 79 (4), 975–986.

Groombridge, B., 1990. Marine Turtles in the Mediterranean: Distribution, Population Status, Conservation. No. 18-48. Council of Europe.

Hamann, M., Godfrey, M.H., Seminoff, J.A., Arthur, K., Barata, P.C.R., Bjorndal, K.A., Godley, B.J., 2010. Global research priorities for sea turtles: informing management and conservation in the 21st century. Endanger. Species Res. 11 (3), 245–269.

Hochscheid, S., Maffucci, F., Abella, E., Bradai, M.N., Camedda, A., Carreras, C., Tomás, J., 2022. Nesting range expansion of loggerhead turtles in the Mediterranean: phenology, spatial distribution, and conservation implications. Glob. Ecol. Conserv. 38, e02194.

Hostetler, J.A., Cohen, E.B., Bossu, C.M., Scarpignato, A.L., Ruegg, K., Contina, A., Hallworth, M.T., 2025. Challenges and opportunities for data integration to improve estimation of migratory connectivity. Methods Ecol. Evol. 16 (2), 362–376.

Kasparek, M., Godley, B.J., Broderick, A.C., 2001. Nesting of the green turtle, *Chelonia mydas*, in the Mediterranean: a review of status and conservation needs. Zool. Middle East 24 (1), 45–74.

Klaassen, M., Marques, T.A., Alves, F., Fernandez, M., 2026. Trends in marine species distribution models: a review of methodological advances and future challenges. Ecography 5, e07702.

Lindenmayer, D.B., Lavery, T., Scheele, B.C., 2022. Why we need to invest in large-scale, long-term monitoring programs in landscape ecology and conservation biology. Curr. Landsc. Ecol. Rep. 7 (4), 137–146.

Luna-Ortiz, A., Marín-Capuz, G., Abella, E., Crespo-Picazo, J.L., Escribano, F., Félix, G., Carreras, C., 2024. New colonisers drive the increase of the emerging loggerhead turtle nesting in Western Mediterranean. Sci. Rep. 14 (1), 1506.

Mancino, C., Canestrelli, D., Maiorano, L., 2022. Going west: range expansion for loggerhead sea turtles in the Mediterranean Sea under climate change. Global Ecology and Conservation 38, e02264.

Mancino, C., Hochscheid, S., Maiorano, L., 2023. Increase of nesting habitat suitability for green turtles in a warming Mediterranean Sea. Sci. Rep. 13 (1), 19906.

Margaritoulis, D., Lourenço, G., Riggall, T.E., Rees, A.F., 2022. Thirty-eight years of loggerhead turtle nesting in Laganas Bay, Zakynthos, Greece: a review. Chelonian Conserv. Biol. 21 (2), 143–157.

Margaritoulis, D., Lourenço, G., Rees, A.F., 2023. Update of the loggerhead sea turtle (*Caretta caretta*) population nesting in Koroni, Greece, Mediterranean. Zool. Stud. 62, e50.

Margaritoulis, D., Rees, A.F., Riggall, T.E., 2025a. Exponential increase in a loggerhead sea turtle nesting population: investigating the role of multi-decadal nest protection in Kyparissia Bay, Greece. Zool. Stud. 64, e29.

Margaritoulis, D., Fytilis, D., Manias, N., Panagopoulou, A., Theodorou, P., Rees, A.F., 2025b. Sporadic nesting events of loggerhead sea turtles *Caretta caretta* along the Greek coasts of the Ionian Sea. Herpetozoa 38, 225–230.

Marín-Capuz, G., Crespo-Picazo, J.L., Demetropoulos, S., Garrido, L., Hardwick, J., Jribi, I., Carreras, C., 2025. Incipient range expansion of green turtles in the Mediterranean. Molecular Ecology 34 (11), e17790.

Mattsson, B.J., Devries, J.H., Dubovsky, J.A., Semmens, D., Thogmartin, W.E., Derbridge, J.J., Lopez-Hoffman, L., 2020. Linking landscape-scale conservation to regional and continental outcomes for a migratory species. Sci. Rep. 10 (1), 4968.

Milman, A., Gerlak, A.K., Albrecht, T., Colosimo, M., Conca, K., Kittikhoun, A., Ziegler, J., 2020. Addressing knowledge gaps for transboundary environmental governance. Glob. Environ. Chang. 64, 102162.

Patrício, A.R., Varela, M.R., Barbosa, C., Broderick, A.C., Airaud, M.B.F., Godley, B.J., Catry, P., 2018. Nest site selection repeatability of green turtles, *Chelonia mydas*, and consequences for offspring. Anim. Behav. 139, 91–102.

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F.E., Buongiorno Nardelli, B., 2020. New evidence of Mediterranean climate change and variability from sea surface temperature observations. Remote Sens. 12 (1), 132.

Roche, D.G., O'Dea, R.E., Kerr, K.A., Rytwinski, T., Schuster, R., Nguyen, V.M., Cooke, S.J., 2022. Closing the knowledge-action gap in conservation with open science. Conserv. Biol. 36 (3), e13835.

Soranno, P.A., Bissell, E.G., Cheruvelil, K.S., Christel, S.T., Collins, S.M., Fergus, C.E., Webster, K.E., 2015. Building a multi-scaled geospatial temporal ecology database from disparate data sources: fostering open science and data reuse. GigaScience 4 (1), s13742–015.

Stephenson, P.J., Stengel, C., 2020. An inventory of biodiversity data sources for conservation monitoring. PLoS One 15 (12), e0242923.

Stephenson, P.J., Burgess, N.D., Jungmann, L., Loh, J., O'Connor, S., Oldfield, T., Shapiro, A., 2015. Overcoming the challenges to conservation monitoring: integrating data from in-situ reporting and global data sets to measure impact and performance. Biodivers. 16 (2–3), 68–85.

Urbano, F., Cagnacci, F., Euromammals Collaborative Initiative, 2021. Data management and sharing for collaborative science: lessons learnt from the Euromammals initiative. Front. Ecol. Evol. 9, 727023.

Wallace, B.P., DiMatteo, A.D., Hurley, B.J., Finkbeiner, E.M., Bolten, A.B., Chaloupka, M. Y., Mast, R.B., 2010. Regional management units for marine turtles: a novel framework for prioritizing conservation and research across multiple scales. PLoS One 5 (12), e15465.

Wallace, B.P., Posnik, Z.A., Hurley, B.J., DiMatteo, A.D., Bandimere, A., Rodriguez, I., Mast, R.B., 2023. Marine turtle regional management units 2.0: an updated framework for conservation and research of wide-ranging megafauna species. Endanger. Species Res. 52, 209–223.

White, E.R., 2019. Minimum time required to detect population trends: the need for long-term monitoring programs. BioScience 69 (1), 40–46.

Wood, S.N., 2017. Generalized Additive Models: An Introduction with R. chapman and hall/CRC.

Zipkin, E.F., Zylstra, E.R., Wright, A.D., Saunders, S.P., Finley, A.O., Dietze, M.C., Tingley, M.W., 2021. Addressing data integration challenges to link ecological processes across scales. Front. Ecol. Environ. 19 (1), 30–38.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R, 574. springer, New York, p. 574.