

Advancing Sea Turtle Monitoring at Nesting and Near Shore Habitats with UAVs, Data Loggers, and State of the Art Technologies

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This supplementary file includes information on:

- Monitoring nesting beach habitat selection and use (Section S1.1), monitoring nesting beach macro-environmental properties and changes in beach profile (Section S1.2) and monitoring human presence and impacts from anthropogenic activities (Section S1.3)
 - Relevant pilot case studies (Section S2)
- Monitoring thermal variations in nesting habitat and deriving sex ratio estimates (Section S3)
 - Methodology
 - Case study/application
- Monitoring marine turtle habitat utilization and behavior in nearshore habitats (Section S4)
 - Methodology
 - Case study/application

Section S1.1

Monitoring nesting beach habitat selection and use

A. Methodology

Field survey techniques

Equipment: Unmanned Aircraft System (UAS), high-resolution RGB sensors

Optimal temporal coverage: Daily daytime UAS surveys throughout the nesting and hatching period

Spatial coverage: Nesting habitat of marine turtles, including both primary nesting sites and sporadic nesting locations

Optimal monitoring time: Early in the morning to capture clear tracks of nesting females

Methodological background: Proficient understanding of UAV operation and safety procedure's ability to design and execute automated flight plans using UAS software; manual UAV control.

Data processing

- Retrieve image and video footage from UAV flights and identify nests and nesting tracks and/or individuals
- Create a digital spatio-temporal database to organize and store collected data, enabling retrieval and visualization of temporal and spatial patterns associated with nesting and habitat use.

Expected outputs/Applications for adaptive management

- Map habitat selection and usage patterns.
- Analyze emergence patterns and detect spatiotemporal dynamics in habitat utilization.
- Investigate the correlation between abandoned nesting attempts and macro/micro-features of the beach.

- Adapt management and conservation actions in real-time based on observed nest counts, habitat use and nesting location selection patterns.
- Assess long-term habitat alterations and quantify potential shrinkage in nesting areas.

Section S1.2

Monitoring nesting beach macro-environmental properties and changes in beach profile

A. Methodology

Field survey techniques

Equipment: Unmanned Aircraft System (UAS), high-resolution RGB sensors and/or multispectral sensors

Optimal temporal coverage: Depending on the specific monitoring objectives, the extent of the nesting beach, and local factors such as vegetation, weather conditions and landscape dynamics, we propose three alternative monitoring schemes:

Baseline Conditions: Conduct seasonal monitoring, repeated for a minimum of two years, to validate the boundaries of the vegetation zone and identify changes in nesting site boundaries.

Highly Dynamic Coastal Environment: Conduct annual monitoring at least once each season to adapt management actions to the dynamic coastal environment.

Extreme Rainfalls or Storms: In the event of extreme rainfalls or storms occurring a few weeks before or during the nesting season, additional UAV flights would be necessary.

Furthermore, we recommend additional daily monitoring throughout the breeding and incubation period to identify and address potential impacts of erosion and vegetation on nesting and hatching success.

Spatial coverage: Nesting habitat of marine turtles and adjacent areas, targeting sites with plant species that may adversely affect clutch development and hatching success and areas behind the sandy shore, particularly when steep slopes are present.

Optimal monitoring time: Conduct UAV flights during midday to ensure optimal visibility and detect signs of erosion and vegetation structure without shading. If clusters of tall plants (>20 cm) are present, consider repeating measurements four times daily to capture circular patterns of generated shadow.

Methodological background: Basic understanding of UAV operation and safety procedures, design and execution of automated flight plans using UAS software and manual UAV control, allowing for flexibility to environmental conditions or unexpected events.

Data processing

- Retrieve image and video footage from UAV flights.
- Create a georeferenced orthophoto map of the study area using specialized photogrammetry software, such as Pix4Dmapper.

For vegetation monitoring

- Conduct in situ data collection to identify plant species, inspect root systems etc.
- Calculate vegetation indices (e.g., NDVI, SAVI, EVI, VDVI) to gain insights into vegetation conditions.

For erosion monitoring

- Conduct in situ measurements to assess slopes created by erosion, utilizing specialized topographic equipment, sample sand and mineral deposition locations to analyze erosion effects etc.

Expected outputs/Applications for adaptive management

- Identify dynamic changes in erosion along the sandy coast through time series monitoring and identify areas requiring regular monitoring or direct management actions to mitigate erosion.
- Measure the width and the length of the beach each time.
- Identify stony detritus, larger rocks, or pebbles that may disturb nesting and hatchling emergence.
- Determine seasonal and interannual shrinkage of the core nesting habitats.
- Detect changes in the structure and expansion of vegetation communities.
- Assess vegetation density and properties and direct management measures to eliminate potential impacts on reproduction processes and outcomes.
- Define areas for potential relocation, steering clear of plant species with roots prone to growing on nests.
- Detect and map seasonal streams.
- Determine measures to reduce fluvial sediment supply and design channels to minimize the flow of clay onto the beach.

Section S1.3

Monitoring human presence and impacts from anthropogenic activities

A. Methodology

Field survey techniques

Equipment: Unmanned Aircraft System (UAS), high-resolution RGB sensors

Optimal temporal coverage: Adapting our monitoring approach to specific objectives, nesting beach size, and local factors like visitation rates and nearby infrastructure, we propose alternative monitoring schemes to pinpoint intervention sites and implement control measures effectively. For areas with high visitor density or permanent structures near the nesting beach (e.g., beach bars, hotels) and those experiencing significant boating tourism activity, we recommend daily monitoring to regulate visitation patterns and flow. Sites with lower visitor density could benefit from weekly monitoring.

Additionally, we advocate for seasonal monitoring to establish a comprehensive time-series database, crucial for identifying inter-annual variations in tourism intensity and associated impacts, especially in response to legal or unauthorized development projects.

Spatial coverage: Nesting habitat and nearshore marine areas, targeting sites with high visitor density or recreational boating.

Optimal monitoring time: We recommend conducting UAV flights in the late morning, midday, late midday, afternoon, and night to comprehensively monitor human presence throughout the day.

Methodological background: Basic proficiency in UAV operation and safety procedures; ability to design and execute automated flight plans using UAS software; manual UAV control.

Data processing

- Retrieve image and video footage from UAV flights.
- Create a georeferenced orthophoto maps of the study areas using specialized photogrammetry software.
- Develop a digital spatio-temporal database to organize and store collected data, facilitating retrieval and visualization of temporal and spatial patterns associated with human use and infrastructure.

Expected outputs/Applications for adaptive management

- Analyze the types and coverage of beach furniture and their influence on the nesting area, as well as the density of boats in the nearshore environment.
- Identify impacted sites, i.e. areas with extensive beach furniture cover, hotspots of increased boat density.
- Record number of tourists and their location in the nesting area.
- Develop, parameterize, and carry out risk assessments pertaining to human-induced activities.
- Determine thresholds for the maximum number of visitors (carrying capacity) allowed within nesting sites and the number of boats allowed in the vicinity of nesting sites.
- Identify areas requiring ongoing monitoring or immediate management interventions.
Determine zones of protection where strict measures or spatio-temporal restrictions on specific activities should be applied

Section S2. Case studies/applications

Case study #1

Study site: Emergence patterns of loggerhead marine turtle in Gerakas beach, located in Zakynthos Island, Greece, eastern Mediterranean

Equipment: UAV DJI Phantom 4 Pro with integrated RGB sensor

Management purpose: Detection of habitat use and emergence patterns

Methodology: The UAV flights over Gerakas nesting beach were strategically conducted in the early morning, benefiting from favorable weather conditions and minimal touristic presence on the beach. Given the large extent of the nesting site, three separate flight missions were required to cover the entire area. Operating at an elevation of 30 meters, the flight extended over approximately one and a half hours. The flight operations were executed by a certified UAV operator, adhering to relevant civil aviation regulations. Necessary permissions were secured from the National Marine Park of Zakynthos to ensure compliance with local guidelines. An additional operator was on-site to visually supervise and ensure the safe execution of the flight. The flight mission operated autonomously, managed through the Pix4Dcapture Pro application on a mobile phone. A total of 175 drone images were captured during the mission, which were used to create a detailed orthophoto map of the nesting site, using Pix4Dmapper photogrammetry software. This map was used for detecting and analyzing habitat use and nesting site distribution patterns as part of the monitoring protocol.

Results

Habitat use patterns: In Figure S1, the spatial configuration of nests in Gerakas is presented. Notably, a number of nests are located in areas where umbrellas and sunbeds are permitted, with some laid just a few meters from these umbrellas, raising concerns about the sand quality surrounding the egg chamber. Given that sand composition and compaction are pivotal factors influencing oxygen flow to the eggs and, consequently, the proper development of embryos, a thorough study comparing the hatching success of these nests with those laid at the upper part of the beach would be recommended.

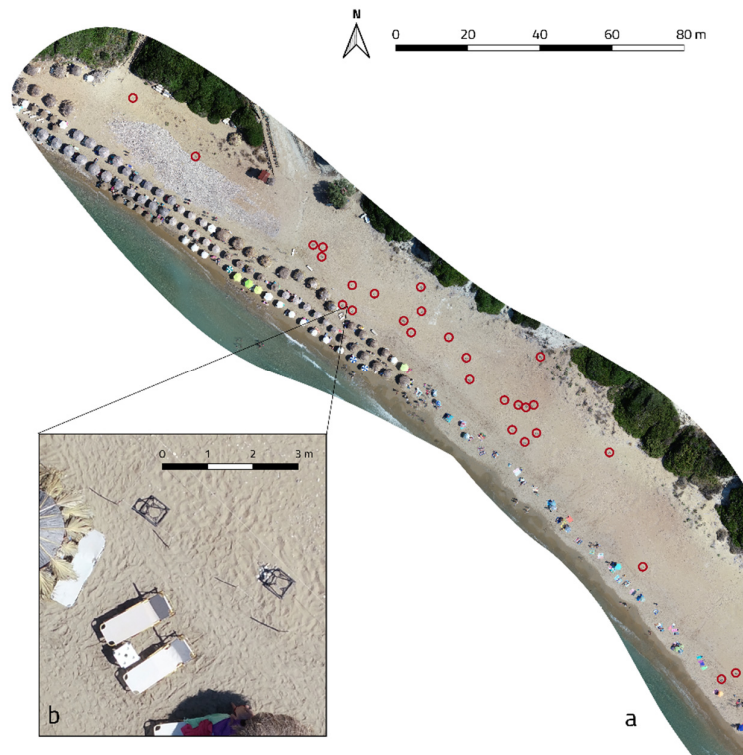


Figure S1. Spatial configuration of nests in the northern part of Gerakas beach. In panel (b), a detailed view of nests situated near beach furniture is provided.

Emergence patterns: In Figure S2, we showcase two tracks of nesting females, both confirmed as successful nesting attempts through field surveys. The aerial monitoring of tracks proves particularly valuable for extensive nesting sites, areas with high nesting density, or in cases of practical field constraints (e.g. limited personnel). The analysis of emergence patterns from aerial images can be conducted simultaneously with assessments of additional characteristics of the nesting site e.g. the thermal profile of the beach, the spatial distribution of beach furniture, vegetation etc. This integrated approach could provide an improved understanding of the habitat selection process by nesting females.



Figure S2. Tracks of nesting females in Gerakas beach. Both emergences resulted in successful nesting.

Case study #2

Study site: Loggerhead marine turtle nesting site of Gerakas beach, located in Zakynthos Island, Greece, eastern Mediterranean

Equipment: UAV DJI Phantom 4 Pro with integrated RGB sensor

Management purpose: Estimating the risk of nesting habitat loss due to erosion and vegetation expansion and directing measures to control and mitigate coastal squeeze

Methodology: The UAV flights over Gerakas nesting beach were strategically conducted in the early morning, benefiting from favorable weather conditions and minimal touristic presence on the beach. Given the large extent of the nesting site, two separate flight missions were required to cover the entire area. Operating at an elevation of 30 meters, the flight extended over approximately one and a half hours. The flight operations were executed by a certified UAV operator, adhering to relevant civil aviation regulations. Necessary permissions were secured from the National Marine Park of Zakynthos to ensure compliance with local guidelines. An additional operator was on-site to visually supervise and ensure the safe execution of the flight. The flight mission operated autonomously, managed through the Pix4Dcapture Pro application on a mobile phone. A total of 175 drone images were captured during the mission, which were used to create a detailed orthophoto map of the nesting site, using Pix4Dmapper photogrammetry software. This map was used to assess the risk of nesting habitat loss due to erosion and vegetation expansion.

Results

In Figure S3, the core nesting area of Gerakas beach alongside the vegetation zone behind the sandy shore are depicted. The red polygon marks the transition zone between the sandy beach and the vegetation area, with identified individual plants and clusters. Figures S3(b-d) reveal evidence of seaward expansion in the vegetation zone (highlighted in the orange polygon). This expansion, as seen in Figure S3(c-d), is driven by the transfer and deposition of organic material facilitated by a stream. Consequently, some individual plants are now evident in the center of the nesting zone.

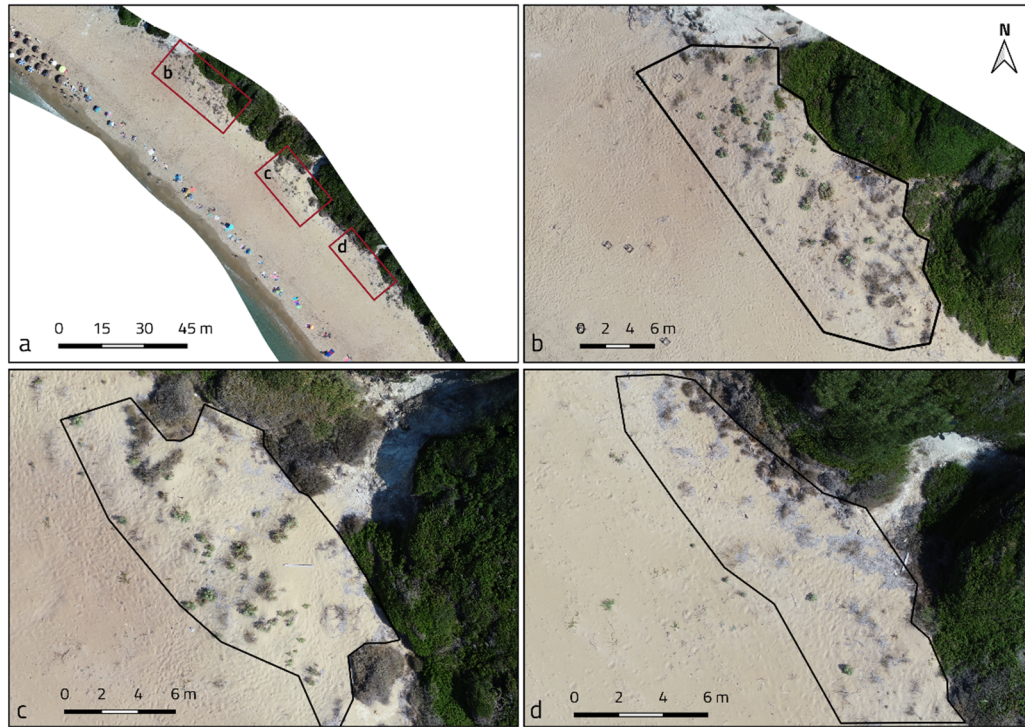


Figure S3. An image from Gerakas beach, showing the full extent of nesting area (a). The red polygons demonstrate the surface of the nesting beach where clear insights on vegetation expansion/cover are detected. In panels b-d, examples of a seaward expansion of the vegetation; in panels c and d vegetation expansion seems to be the facilitated by the organic material transferred by streams.

In Figure S4, areas of clay formation are evident on the exposed beach, and stony detritus, along with larger rocks, have been deposited on the sandy shore (Figure S4). The consistent erosion of the clayey cliff has reduced the height of the Gerakas cliff barrier, resulting in increased clay deposition, forming a thick layer above the sandy surface. Figure 5 illustrates a nest situated in a section of the beach experiencing moderate erosion. Due to the imminent threat of coverage by rocks, soil, or thick layers of sand, this nest serves as an indicative case for relocation. Thick clay layers, resulting from increased runoff, can diminish water holding capacity, potentially causing nest flooding and compounding the effects of erosion.



Figure S4. An impacted by erosion area in Gerakas beach, showcasing increased clay deposition, forming a thick layer above the sandy surface.

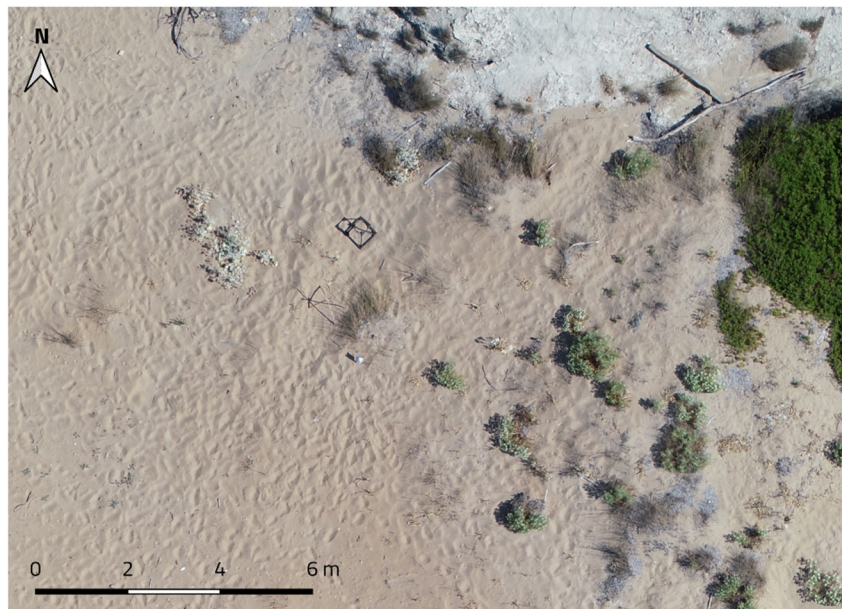


Figure S5. A nest situated in a segment of the beach experiencing moderate erosion.

Study site: Loggerhead marine turtle nesting site of Marathonisi Islet, located in the bay of Laganas, Greece, eastern Mediterranean

Equipment: UAV DJI Phantom 4 Pro with Parrot Sequoia multispectral sensor

Management purpose: Evaluate the risk of root penetration of existing nests and determine vegetation density and properties

Methodology: UAV flights over Marathonisi Islet nesting beach were conducted in the early morning, benefiting from favorable weather conditions and minimal touristic presence on the beach. One flight mission was required to cover the entire area. Operating at an elevation of 30 meters, the flight extended over approximately 20 minutes. The flight operations were executed by a certified UAV operator, adhering to relevant civil aviation regulations. Necessary permissions were secured from the National Marine Park of Zakynthos to ensure compliance with local guidelines. An additional operator was on-site to visually supervise and ensure the safe execution of the flight. The flight mission operated autonomously, managed through the Pix4Dcapture Pro application on a mobile phone. A total of 151 drone images were captured during the mission, which were used to create a detailed orthophoto map of the nesting site, using Pix4Dmapper photogrammetry software. This map was used to assess the effects of vegetation expansion on nesting potential and success as part of the monitoring protocol.

Results

Shaped by topographic factors, the nesting area forms a diverse mosaic of bare sand, rocks, and vegetation cover, including typical communities such as sand dunes, plant clusters, and individual plants (Figure S6). In Figure S7, using photos from the UAV flight, we identified nests situated in close proximity to plants. These nests are at high risk of root penetration, posing a significant threat to their hatching and emergence success. Employing NDVI classification, we pinpointed the seaward-expanding vegetation zone, delineated by a black polyline (Figure S8).

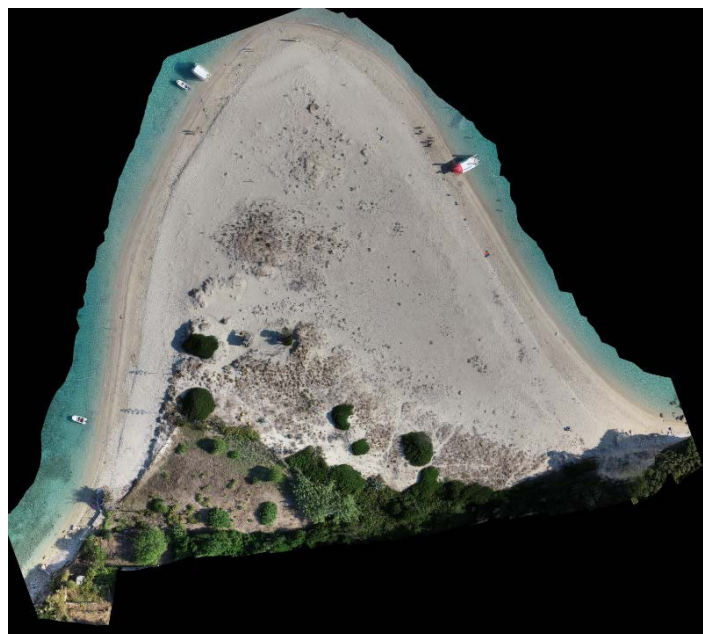


Figure S6. Orthophoto of the nesting site in Marathonisi Island

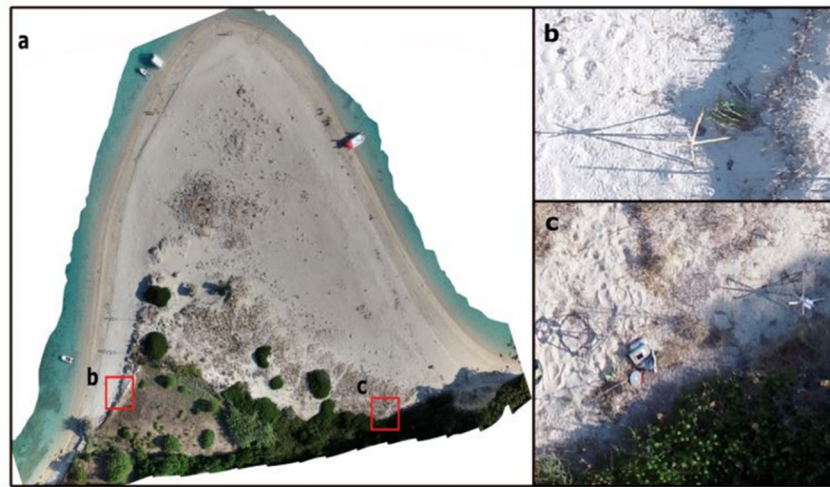


Figure S7. Marathonisi nesting beach map (a) with two cases (b and c) of nests that are in close vicinity to plants and their penetrating rooting system.

The normalized difference vegetation index (NDVI) is one of the most widely used vegetation indexes. It typically shows the ‘greenness’ i.e. the index is a measure for green biomass or canopy chlorophyll content. The index gets values from -1 up to 1, with lower values (illustrated by green in Figure S9) being indicative of water bodies) and higher values being indicative of dense, green, leafy vegetation (illustrated by red in Figure S9). The output of the NDVI clearly demonstrates the actual cover type and density within our study area.

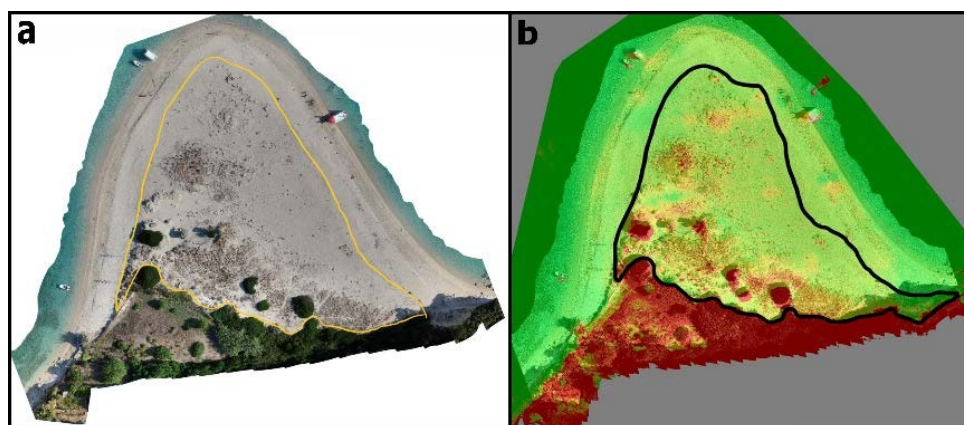


Figure S8. Expansion of the vegetation zone in Marathonisi Island. In panel (a), the vegetation zone (enclosed within the yellow polyline) was delineated through visual inspection of the orthophoto of the site; in panel (b), the vegetation zone (black polyline) was defined based on the information generated by the NDVI image (see Figure S9)

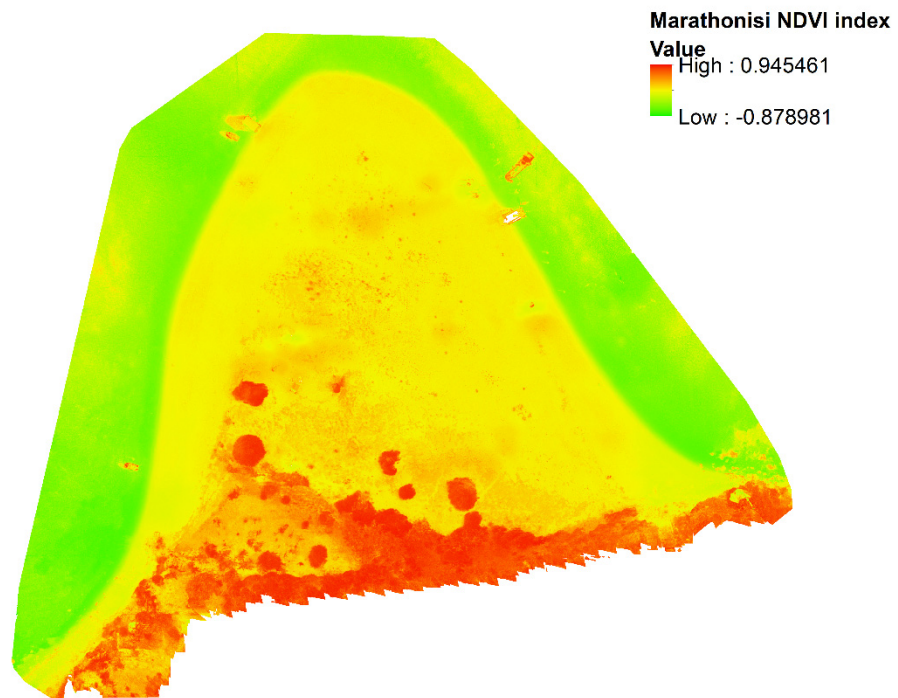


Figure S9. A map of the NDVI values for Marathonisi Island. Higher values (red) are indicative of dense, green, leafy vegetation cover with water body getting lower values (green).

Case study #3

Study site: Loggerhead marine turtle nesting site of Gerakas beach, located in Zakynthos Island, Greece, eastern Mediterranean

Equipment: UAV DJI Phantom 4 Pro with integrated RGB sensor

Management purpose: develop a baseline map of touristic infrastructure along the nesting beach and estimate the beach's carrying capacity.

Methodology: To develop a baseline map for Gerakas nesting beach, the UAV flights were conducted at the beginning of the nesting season, during early morning to depending on favorable weather conditions. Given the large extent of the nesting site, two separate flight missions were required to cover the entire area. Operating at an elevation of 30 meters, each flight extended over approximately one and a half hours. The flight operations were executed by a certified UAV operator, adhering to relevant civil aviation regulations. Necessary permissions were secured from the National Marine Park of Zakynthos to ensure compliance with local guidelines. An additional operator was on-site to visually supervise and ensure the safe execution of the flight. The flight mission operated autonomously, managed through the Pix4Dcapture Pro application on a mobile phone. A total of 175 drone images were captured during the mission, which were used to create a detailed orthophoto map of the nesting site, using Pix4Dmapper photogrammetry software.

Indicative outputs: A number of structures have been identified in the western part of Gerakas beach, accommodating visitor facilities within a designated area near the sea (Figure S10). The beach spans a total length of 540 meters, with 135 meters occupied by beach furniture. The remaining 405 meters are open for visitor use, allowing sunbathing within a 5-meter distance from the sea, while in the upper section of the beach, the use of the beach space by visitors is prohibited to safeguard the nesting habitat of sea turtles (Figure S10).

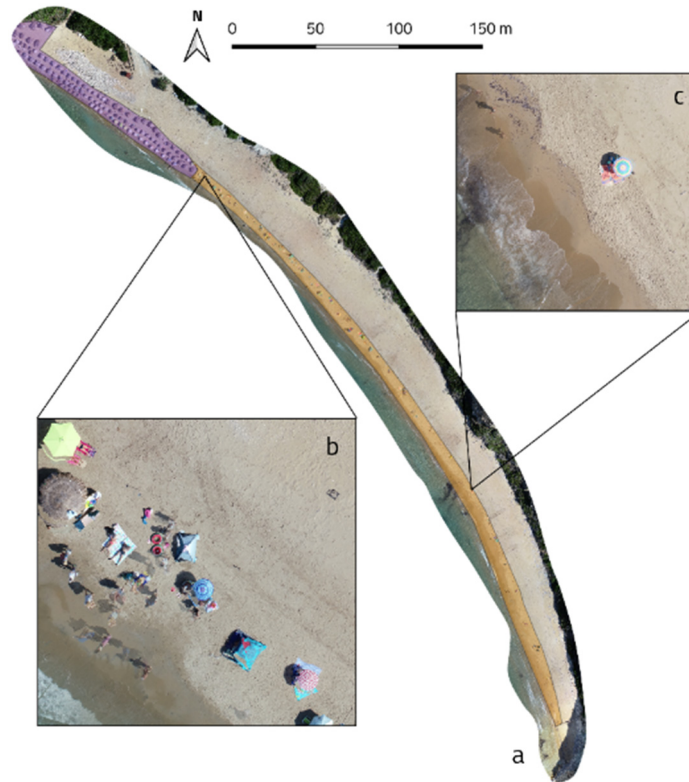


Figure S10. Spatial allocation of beach visitors regulations in Gerakas beach. Purple shading indicates the area where umbrellas and sunbeds are allowed and yellow shading spans the part of the nesting beach where visitors can use but sunbeds are not permitted. In panel (b), a cluster of beach visitors is presented. In panel (c), an area characterized by increased sand compression is depicted.

To establish a measurable benchmark for evaluating the influence of human activity on sea turtle breeding habitats, our aim was to further determine Gerakas beach's carrying capacity in terms of the number of visitors. Carrying capacity, in this context, refers to tourism development that does not disturb or alter the natural environment, such as sand compression, nest destruction, or changes in physico-chemical properties and micro-environmental characteristics.

To determine Gerakas beach's carrying capacity, we computed the area needed for each sunbather, considering items like beach towels, umbrellas and tents, with an upper limit set at 30 square meters per person to allow movement. Initially, we excluded the section with organized structures (Figure S10) from the analysis as the number and occupied area are predetermined. By assessing digital images, we determined the total size of the beach (16,030 square meters) and the available seaward zone (2,025 square meters). Employing the 30 square meters threshold, we concluded that the simultaneous presence of visitors should not surpass 68 persons. We also explored alternative scenarios for the seaward zone space required, using upper limits of 40, 20, and 10 square meters per visitor, calculating the carrying capacity for each (see Table S1). Even in the most conservative scenario, with one visitor per 10 square meters of available beach space, the actual daily tourist influx at Gerakas beach far exceeds this estimate, as confirmed by officers from the National Marine Park of Zakynthos. Notably, Gerakas beach has experienced a peak of 1,044 simultaneous visitors.

Aerial digital images revealed the spatial layout of umbrellas, sunbeds, and differences in the beach substratum (see Figure S10). Despite limited nesting attempts in the seaward part of the beach, a notable compression of sand was detected, raising concerns about the number and density of visitors in this zone. Detailed information on beach furniture locations, extent, and clustering can be found in Figure S10. Recognizing that even dispersed human structures may impact micro-environmental conditions, this monitoring protocol suggests the potential implementation of a rotational visitation system to mitigate constant or continuous impact on specific areas.

Section S3.

Monitoring thermal variations in nesting habitat and deriving sex ratio estimates

A. Methodology

Field survey techniques

Equipment: Data loggers with temperature sensor, Unmanned Aircraft System (UAS), thermal sensor

Optimal temporal coverage: Placement of temperature data loggers prior to the onset of the nesting season until the initiation of hatching in the vicinity of nests as well as various locations around the nesting site. The aerial thermal profiling of nesting sites may follow alternative monitoring schemes based on the monitoring targets.

Macro-scale monitoring: Conduct high-altitude UAV flights every four days at specified times (at least four flights per day) throughout the day to study the overall thermal profile of the sand.

Micro scale monitoring: Employ low-altitude UAV flights to detect smaller scale temperature changes across the micro-habitat of the sand. We propose repetitions every four hours for at least 20 days over the nesting period, ensuring a sufficient amount of data for analysis using statistical tools.

If monitoring involves both UASs and data loggers, we recommend conducting UAV flight repetitions every four hours over a minimum period of 10 days to establish a correlation between surface and in-sand measurements.

Spatial coverage: Nesting habitat of marine turtles, including both primary nesting sites and sporadic nesting locations

Optimal monitoring time: To study the thermal profile of nesting sites, we recommend conducting UAV flights in the late morning, at midday, during late midday, and in the afternoon before sunset.

Methodological background: Basic proficiency of UAV operation and safety procedures, design and execution of automated flight plans using UAS software and manual UAV control, allowing for flexibility to environmental conditions or unexpected events, basic proficiency in the use of monitoring equipment and safety procedures related to in situ placement of data loggers.

Analysis

- Conduct a preliminary assessment to identify suitable locations within the nesting site for placing the data loggers.

* To monitor in-nest temperatures and derive sex ratio estimates, install additional data loggers at a depth of 50 cm (depth may vary based on the species and nesting location) in the sand next to the egg chamber. Set the recording time interval to capture temperature variations throughout the day; configure other necessary settings.

- Record additional information related to the topography of the data logger locations, such as distance from the sea, distance from the vegetation zone, presence of plants, trees, or any other silhouette in the close vicinity.
- Conduct UAV flights equipped with thermal sensors to capture thermal imagery.
- Create georeferenced orthophoto maps of the study area using specialized photogrammetry software, such as Pix4Dmapper
- Analyze thermal variations between different locations in the nesting site and between nest areas and the surrounding space.

* To monitor in-nest temperatures and derive sex ratio estimates, ensure the proper operation of temperature data loggers throughout the nesting season. Uninstall data loggers during the excavation of the nest and collect the recorded information.

* Estimate the sex ratio of hatchlings and assess the correlation between in-nest temperatures provided by data loggers and surface temperatures derived from UAV flights.

Expected outputs

- Identify temporal and spatial temperature fluctuations to understand the overall thermal dynamics of the nesting site.
- Associate surface and in-nest temperatures to improve monitoring efficacy.
- Track in-nest temperature changes and identify pivotal temperatures affecting the sex determination and survival of marine turtle embryos.
- Determine potential relocation zones with optimal thermal conditions for nesting
- Implement strategies to avoid hatchling mortality by mitigating exposure to temperatures that could be lethal.
- Estimate the sex ratio of hatchlings and evaluate the potential risks it poses to population recruitment.

B. Case study/application

Study site: Loggerhead marine turtle nesting sites of Gerakas beach and Marathonisi Islet, located in the bay of Laganas, Zakynthos, Greece, eastern Mediterranean

Equipment: HOBO MX2304 temperature data loggers

Management purpose: Monitor in-nest thermal variations and estimate the sex ratio of hatchlings

Methodology: We installed 29 data loggers (HOBO MX2304) at a depth of 50 cm, in a number of locations across the nesting sites of Gerakas (n=20) and Marathonisi Island (n=9). In Gerakas beach, we placed eight data loggers next to laid nests. Additionally, twelve more data loggers were placed at both the upper and lower segments of the beach, with their locations determined by a straight line extending from the sea to the vegetation zone, passing over the nests. Six out of the data loggers were situated at the upper part of the nesting zone and the remaining six were placed at the lower part of the beach. The recording time interval was set to 30 minutes. In Gerakas, the total recording period lasted from August 6th until October 1st. In Marathonisi Island, we monitored three nests and employed three extra loggers in both the upper and lower parts of the nesting zone. The recording time interval was also set at 30 minutes and data collection spanned from July 26th until August 25th. All data loggers were removed two weeks after the last hatchling emergence.

Indicative outputs

First, we grouped the temperature records into groups, each group consisting of the records next to the nest and the records in the upper and lower part of the nest. In the majority of cases, temperatures at the site nearest to the vegetation zone exhibited higher temperatures compared to those recorded at other locations. However, one nest in Gerakas and one nest in Marathonisi, both situated within the vegetation zone, exhibited lower mean temperatures than the other samples in their group. In General, average nest temperatures in Marathonisi spanned from 25.4 to 29.6 °C (Figure S11).

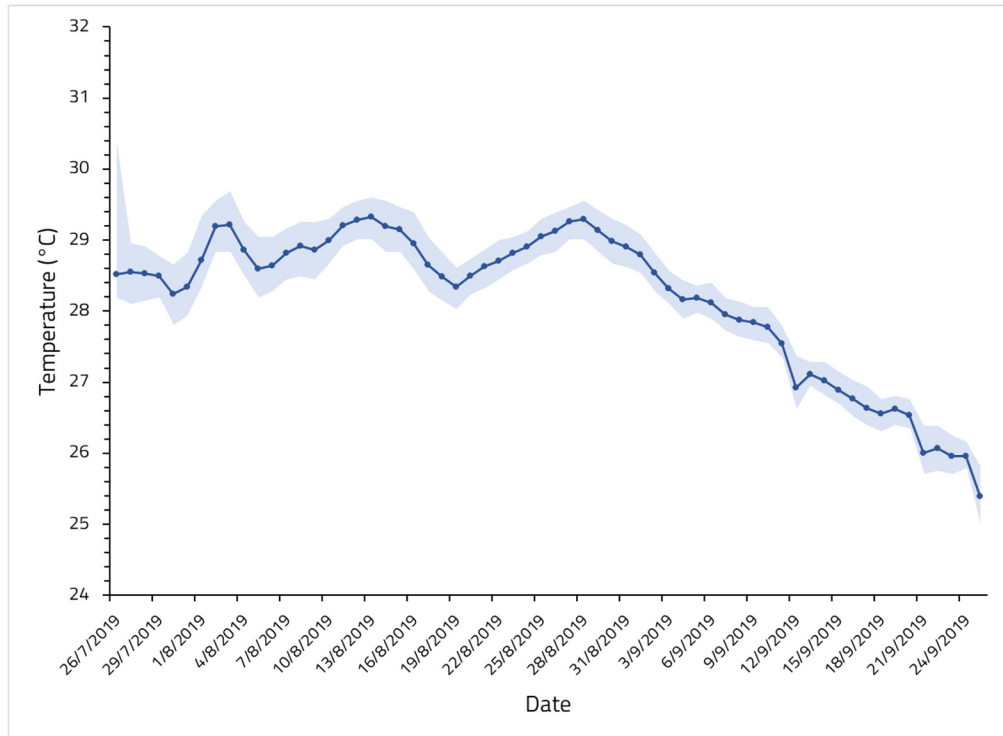


Figure S11. Variation of temperature of a nest in Marathonisi during the incubation period.

To determine the sex ratios of hatchlings, we employed a widely used model for estimating loggerhead sea turtle sex ratios in the Mediterranean. The conversion curve linking incubation duration to hatchling sex ratio was established based on measurements from artificially incubated eggs originating from Kyparisia, Greece (Mrosovsky et al., 2002, Can J Zoolog 80(12):2118-2124). The equation is as follows:

$$Y = \frac{100.06}{1 + (+188.78 - 6.37 * X)},$$

where Y represents the expected sex ratio, and X corresponds to the mean temperature during the middle third of incubation.

It is important to note that, as the data loggers were positioned near the nest (outside the egg chamber), we also considered metabolic heating – a slight temperature increase that could significantly influence sex ratio determination. Previous studies at the Zakynthos nesting site in the Mediterranean found that the metabolic heating of *Caretta caretta* averaged about 1.6 °C and occurred primarily during the final third of the incubation period (Zbinden et al., 2006, J Exp Mar Biol Ecol 334(1):151-157).

A considerable variation was observed in the estimates of sex ratios for the studied nests at the two beaches (see Table S1). While the majority of nests in Gerakas nesting sites exhibited a female-biased hatchling sex ratio, assuming the underlying conversion leads to unbiased estimates, two of the examined nests primarily produced males. In Marathonisi, two out of the three nests yielded a notably high proportion of male hatchlings.

Table S1. Estimates of sex ratio generated by using mean temperature during the middle third of the incubation period (mean T).

Nest ID	Mean T	Sex ratio (females) from T
G138Cb	30.26	98.22
G140	30.48	99.60
G142Cb	31.47	100.0
G143	30.39	99.25
G144Cb	30.10	95.12
G145	29.67	55.46
G146	29.48	27.06
G147	29.63	49.11
M029cb	29.76	68.85
M031cb	28.96	1.33
M032cb	28.94	1.18

Section S4

Monitoring marine turtle habitat utilization and behavior in nearshore habitats

A. Methodology

Field survey techniques

Equipment: Unmanned Aircraft System (UAS), high-resolution RGB sensors

Optimal temporal coverage: To tailor our monitoring strategy to specific objectives, we suggest several monitoring schemes that align with the inter-annual cycle of marine turtles.

At the start of the breeding season, we recommend weekly monitoring in the vicinity of nesting sites to explore habitat use. As the nesting season progresses, the monitoring frequency may increase, reaching daily monitoring during the peak breeding or nesting period. For foraging or over-wintering grounds, we suggest monthly or seasonal monitoring to identify inter-annual variations in habitat utilization patterns.

Spatial coverage: Marine habitats, including breeding sites in the vicinity of nesting beaches, foraging and over-wintering grounds.

Optimal monitoring time: Conduct UAV flights during the early hours after sunrise and a few hours before sunset to mitigate heightened sea water reflectance in peak daylight, thereby enhancing the detectability of animals.

Methodological background: Basic proficiency in UAV operation and safety procedures; ability to design and execute automated flight plans using UAS software; manual UAV control.

Data processing

- Retrieve image and video footage from UAV flights, identify marine turtle individuals, and document their in-water behavior when feasible.
- Develop a digital spatio-temporal database to organize and store collected data, facilitating retrieval and visualization of temporal and spatial patterns associated with marine habitat utilization.
- Report additional information collected during UAV flights, such as boat traffic, fisheries activities, seabed vegetation, pollution) that will be collected under images.

Expected outputs/Applications for adaptive management

- Analyze the spatio-temporal distribution of marine turtles in nearshore breeding and foraging areas.
- Identify hotspots of in-water sea turtle presence and activity.
- Identify favorable habitats and potential seasonal or interannual shifts in usage patterns.
- Assess the influence of anthropogenic or environmental variables on marine turtle behavior and distribution.
- Determine zones of protection where strict measures or spatio-temporal restrictions on specific commercial or recreational activities should be applied

B. Case study/application

Study site: Marine habitats of Kefalonia Island, Greece, eastern Mediterranean

Equipment: UAVs DJI Phantom 4 Pro and eBee X with integrated RGB sensors

Management purpose: Detect and analyze the spatio-temporal distribution of sea turtles in potential nearshore foraging habitats.

Methodology: To validate this monitoring protocol, we conducted on-site visits to marine and coastal sites of Kefalonia Island. Preliminary scans of these areas of interest were carried out, and flight plans for UAV missions were prepared. We utilized two distinct types of UAVs (i.e. an adaptable multirotor and a fixed-wing UAV) to perform scans at different altitudes, employing two separate cameras to cover different spectrums/bands of light in an effort to secure the most accurate visual identification of existing sea turtles in the scanned areas. To optimize visual identification, flights were scheduled from early morning (8 am) to early evening (8 pm), aligning with periods of the day when sea water reflectance was minimal. The flight operations were executed by a certified UAV operator, following all relevant civil aviation regulations. In total, 25 flights were conducted. The flight mission operated autonomously, managed through the Pix4Dcapture Pro application on a mobile phone. To enhance accuracy, the photos captured by the UAV underwent a verification process, independently reviewed by two researchers to maximize the identification of marine turtles.

Indicative outputs: In one-third of the UAV surveys, we successfully spotted sea turtles in their marine habitat (Figures S12-16). The majority of these sightings were reported in Koutavos gulf. Conversely, no evidence of sea turtle presence was observed during our flights in the southern shores of the island.

Our findings offer insights into the distribution of foraging grounds for sea turtles in the vicinity of Kefalonia. Results emphasize the importance of known areas like Koutavos gulf, while also shedding light on sites where our understanding of their significance as potential foraging grounds was less clear. Our analyses indicated that foraging sea turtles may be found in areas with increased maritime traffic, posing potential risks to their survival.

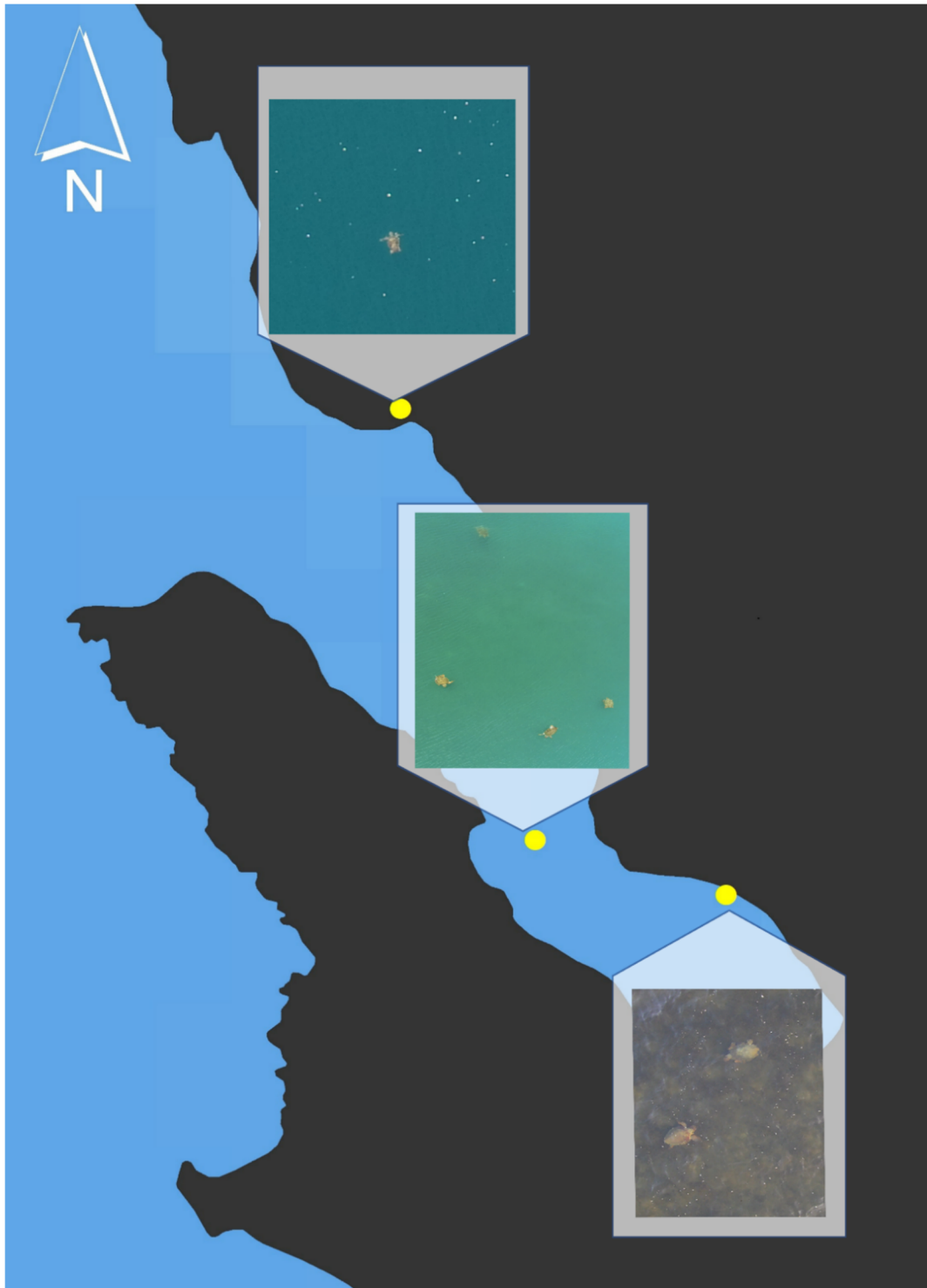


Figure S12. *Caretta caretta* sea turtle identified in the sea of Agios Konstantinos (top). Four sea turtles waiting for fish scraps near the fish market of Argostoli (middle) (Photo provided by the organization Wildlife Sense). Two sea turtles at the Koutavos lagoon about to interact (bottom) (Photo provided by the organization Wildlife Sense).



Figure S13. Male turtle at the north fish farms foraging for bivalves (top) and a loggerhead sea turtle swimming near Argostoli in the Koutavos lagoon (bottom) (Photos provided by the organization Wildlife Sense).

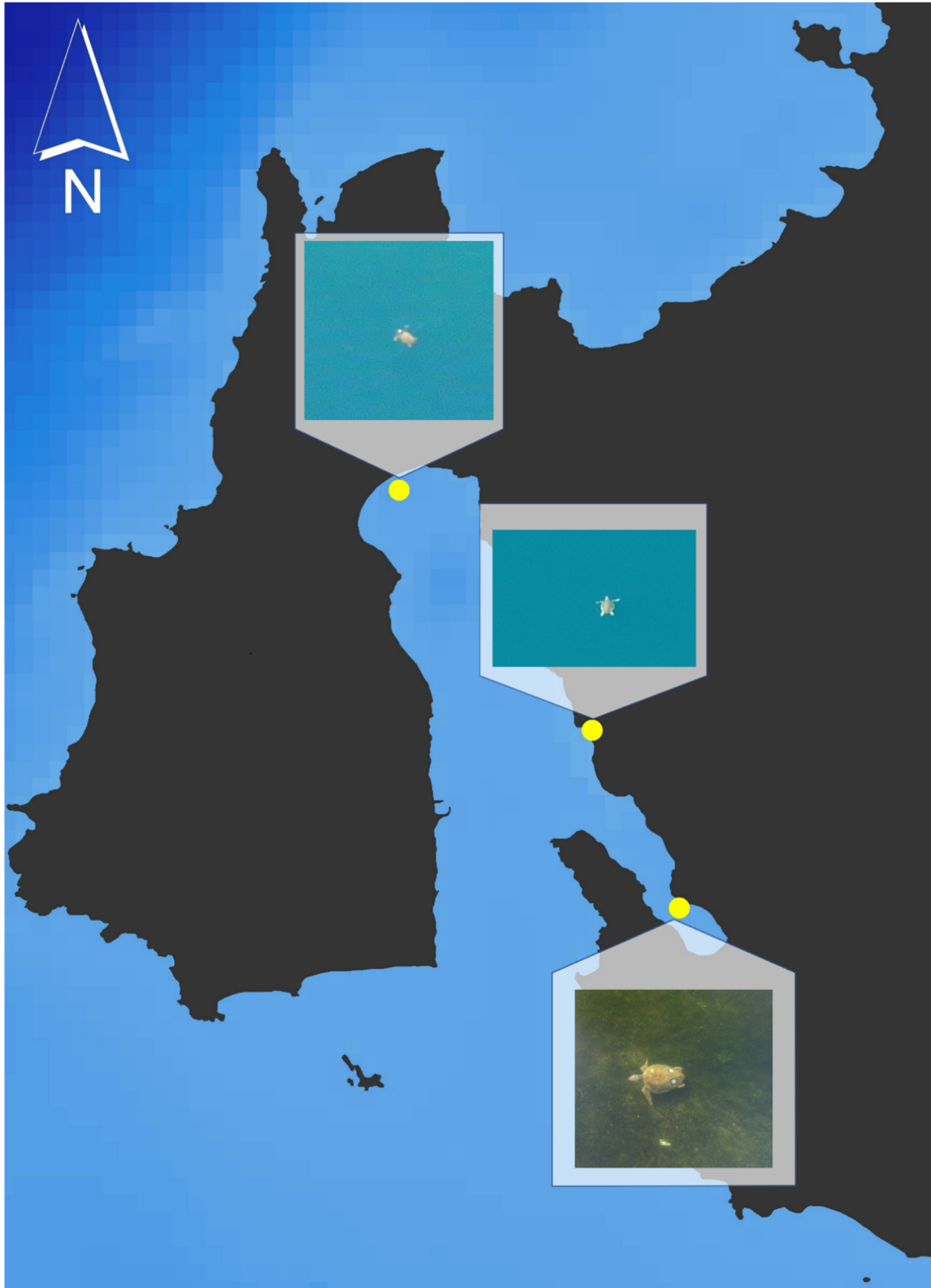


Figure S14. Loggerhead marine turtle in Livadi beach (top), another in Farsa (middle) and another tagged and number-marked loggerhead sea turtle in the Koutavos lagoon (Photo provided by the organization Wildlife Sense).

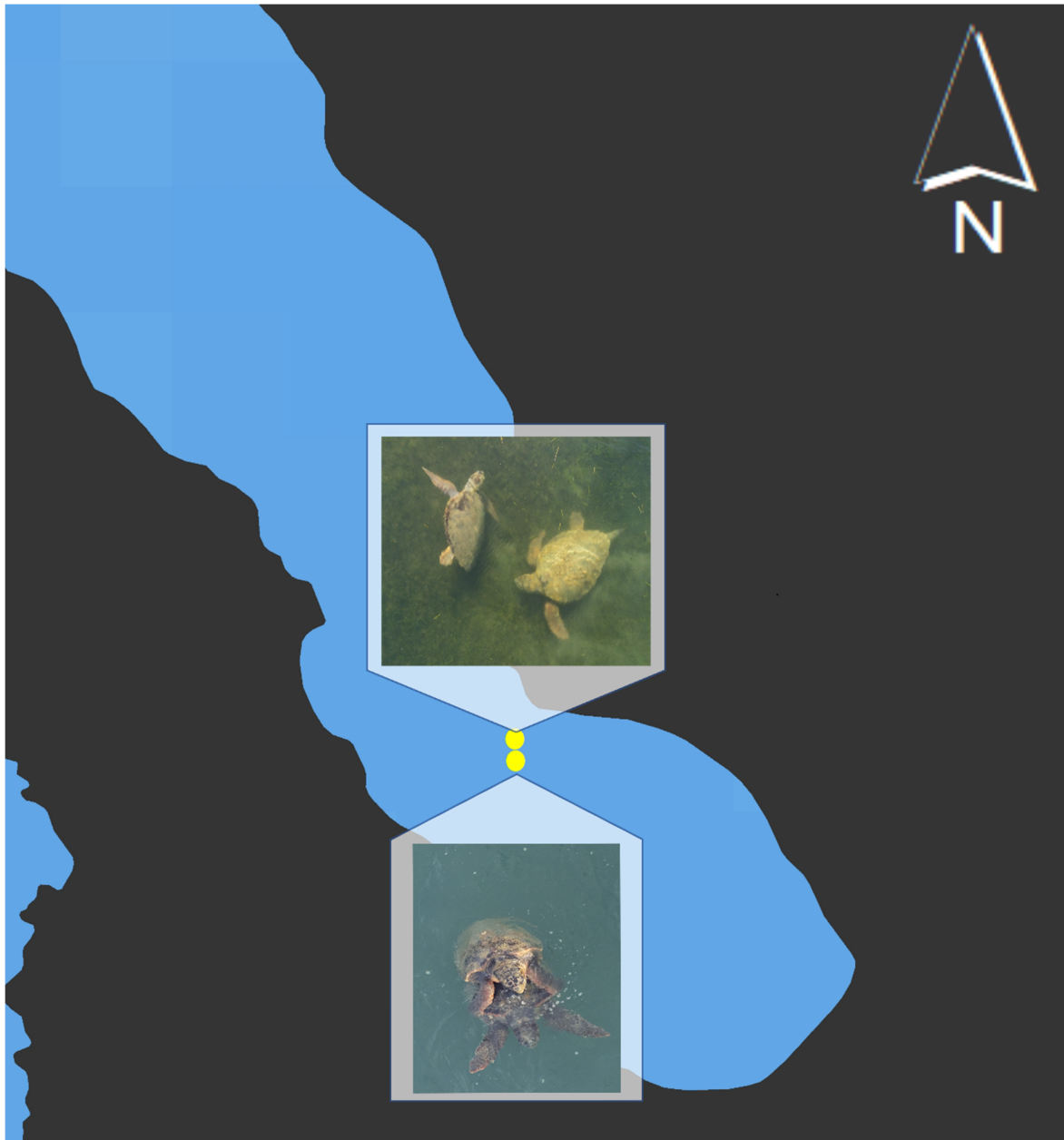


Figure S15. Male and female loggerheads initiate a (failed) mating interaction near the DeBosset bridge of Argostoli (top). Mating between two loggerhead sea turtles (bottom) (Photos provided by the organization Wildlife Sense).

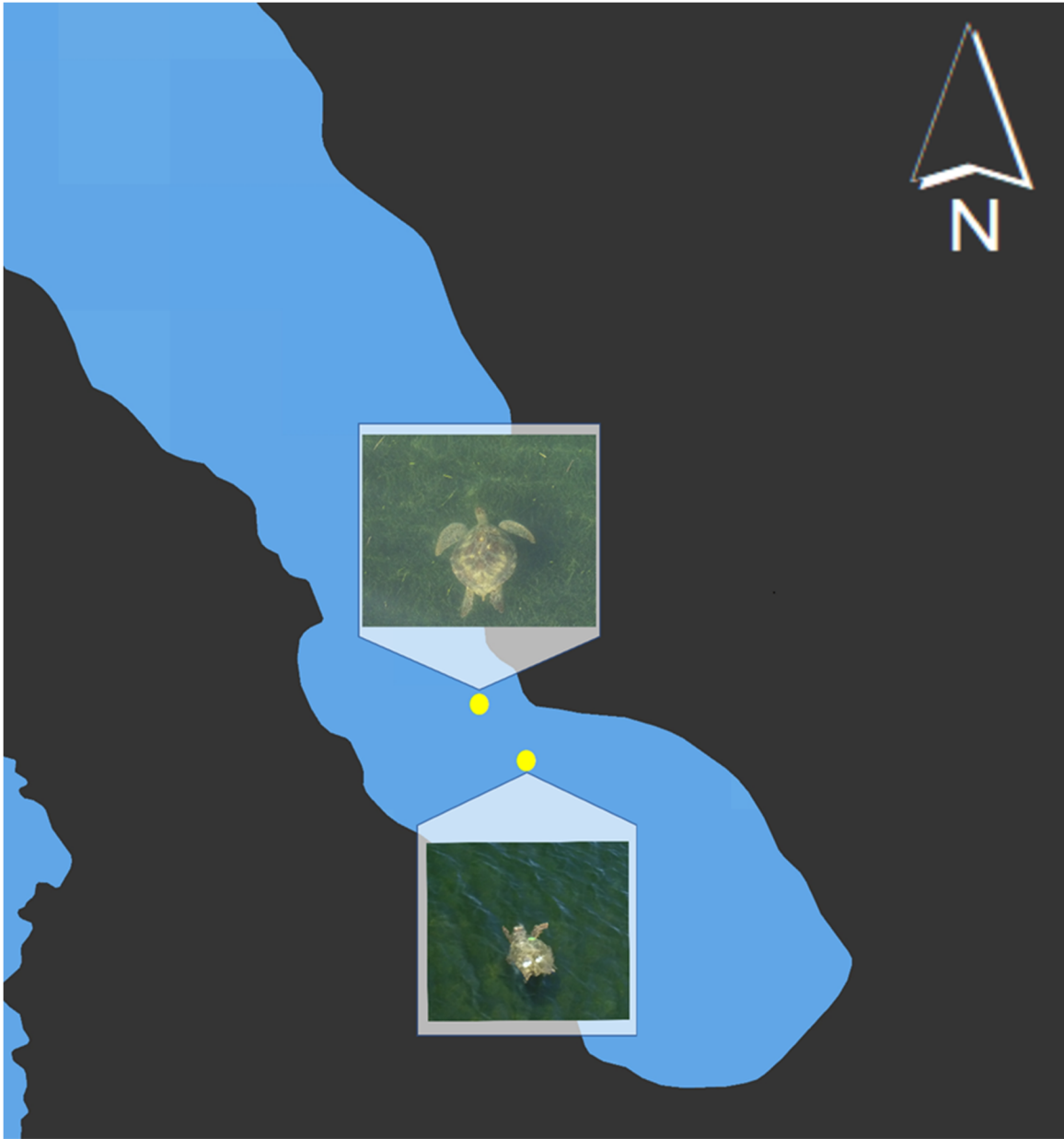


Figure S16. A young green sea turtle foraging in the bay of Argostoli (top) and a tagged loggerhead in the Koutavos lagoon heading towards the DeBosset footbridge (bottom) (Photos provided by the organization Wildlife Sense).