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Technical Note

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

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Abstract: In the face of environmental change, high-quality and fine-scale information is essential in order to monitor the highly dynamic environments on land and sea. While traditional approaches to data collection face a number of practical limitations, advanced technologies could supplement and further improve our efforts. Taking sea turtles as a modeling organism, we present a novel methodological framework for monitoring species by means of advanced technologies, including Unmanned Aerial Vehicles coupled with image and temperature sensors. Diverse monitoring protocols were refined through pilot studies conducted in both terrestrial and nearshore sea turtle habitats. Our approach focuses on the collection of information for critical biological parameters concerning species reproduction and habitat use, following the complex life cycle of the species. Apart from biological information, our framework encompasses also the collection of information on crucial environmental factors that might be changing due to current and future human-derived pressures, such as beach erosion and temperature profile, as well as highly important human activities such as recreational use within nesting beaches that could undermine habitat quality for the species. This holistic and standardized approach to monitoring using advanced technologies could foster our capacity for conservation, resolving difficulties previously addressed and improving the collection of biological and environmental data in the frame of an adaptive management scheme.

Keywords: marine megafauna; advanced technology; monitoring; climate change; human pressures

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1. Introduction

Coastal and marine ecosystems, along with their biodiversity, are undergoing rapid changes and significant degradation in many regions. Given the escalating global and local anthropogenic stressors, including the fast-evolving climate crisis, innovative approaches can complement standard monitoring programs, enhancing our capacity to support regional conservation planning [1]. These approaches should acknowledge the dynamic and variable nature of coastal and oceanic environments [2]. Enhancing conservation effectiveness demands precise measurement, mapping, and monitoring of biodiversity across diverse temporal and spatial scales to uncover potential recovery opportunities or failures. Success hinges on advancing cost-effective methodologies and tools to overcome the complexity, capacity building, and expense of these processes.

Positive signs of global population recoveries among sea turtles are now evident, supported by the results of extensive, long-lasting monitoring programs [3]. However, information on the number of nests or nesting individuals is missing for hundreds of nesting sites, indicating a significant gap in our knowledge. This lack of data also extends to assessments of habitat quality, highlighting the need for standardized monitoring and mapping approaches that could facilitate the development and implementation of adaptive management and recovery plans [4]. Information on the marine nearshore or offshore habitats specifically used by male and juvenile turtles, which never venture onto the sandy coasts, is particularly scarce for this charismatic marine megafauna. While a plethora of traditional monitoring tools and protocols have been developed and widely used for sea turtles (e.g., [5]), challenges and limitations still persist, mainly linked to practical constraints such as effort, personnel, time, physical access to monitoring sites, and cost. The complexity of existing monitoring schemes is heightened by climate change and associated extreme events, which introduce additional challenges and stochasticity in setting priorities, conducting monitoring efforts, and implementing measures for protection and restoration.

Advanced monitoring and computer technologies, including airborne remotely operated vehicles, as well as sophisticated optical and acoustic surveillance tools, have reached a level of maturity that enables their integration with traditional approaches. This integration can pave the way for next-generation assessments of population and habitat status. However, to fully leverage this potential, standardized protocols are necessary to ensure coherent and systematic data collation across scales and regions. Based on previous concerns, we present a novel methodological framework for monitoring sea turtles by means of advanced technologies, that could foster our capacity for conservation in the face of the environmental crisis. Our framework is organized around three fundamental axes: (i) identification of the reproduction potential of nesting sites, (ii) exploration of habitat use and pressures as well as (iii) early-warning detection of changes. As hatchlings are identified as the most vulnerable life stage of the sea turtle lifecycle [6], our proposed framework focuses on inland and nearshore applications of novel technologies that could support the collection of time series, the monitoring of changes, and the delineation of a systematic but also adaptive conservation strategy in the face of climate change.

2. Materials and Methods

2.1. Rationale

Ideally, the development of monitoring protocols should aim at enhancing the efficiency and ease of adaptive management in marine turtle nesting and nearshore habitats. Utilizing standardized procedures and modern technological equipment facilitates long-term monitoring across the species' habitat continuum, enabling the observation of pressures and impacts, and detecting changes over time. The key objectives of the monitoring protocols presented herein include: (1) characterizing nesting beaches in terms of their potential to sustain reproductive output; (2) identifying habitat use patterns and pressure drivers across different life and reproductive stages of marine turtle species; and (3) observing temporal changes to provide early-warning recommendations for adaptive management. The use of modern technologies, combined with smart survey design and post-processing guidelines, ensures the collection of high-resolution spatial data, contributing to a robust and informed monitoring and management strategy. In this framework, six distinct protocols were formulated, each tailored to address a different monitoring objective.

2.2. Monitoring Objectives

2.2.1. Monitoring Nesting Beach Habitat Selection and Use

Utilizing nest numbers and/or counts of female sea turtles is a common practice to infer population trends and to assess extinction risk [3,7,8], considering the challenges involved in counting individuals in the sea or on remote nesting beaches [9]. Traditional estimates of sea turtle abundance involve foot patrols on nesting beaches, requiring considerable time, effort, and personnel. The quality of monitoring outputs largely depends upon these factors, especially when dealing with extensive nesting beaches or in areas with particularly high nesting densities [10,11].

The main goal of this protocol is to facilitate the monitoring of habitat selection and use by nesting individuals. The integration of UAVs offers the potential to investigate and monitor extensive and heavily frequented sites efficiently, leading to significant reductions in survey time and enhancing the quality of data [12]. Anticipated outputs include the identification of emergence patterns and the provision of estimates regarding the location and the number of nests. By detecting spatiotemporal patterns of habitat use, it becomes possible to link abandoned nesting attempts with macro and micro-features of the beach [13]. Valuable insights from habitat use monitoring can contribute to extracting population trends, developing spatial models for estimating beach carrying capacity, and facilitating management actions to mitigate the negative effects of stressors on successful nesting in space and time.

2.2.2. Monitoring Nesting Beach Macro-Environmental Properties and Changes in Beach Profile

Prolonged periods of wind and wave action, mineral deposition, rising sea levels, climate variations, and human interventions collectively contribute to the alteration of nesting sandy shores [14,15]. Severe erosion and coastal squeeze can diminish the available habitat area for sea turtles, potentially leading to increased nest density, exceeding the nesting site's carrying capacity, and elevating the overall risk of egg mortality [16]. Erosion may create steeper slopes, rendering a nesting site less suitable [17] while clay/slits deposits increase embryonic mortality [18]. Additionally, vegetation surrounding the nest chamber may result in egg destruction, nutrient or moisture absorption, reduced ventilation of the egg chamber, and could adversely affect hatchling survival by causing entanglement or impeding their emergence from the nest [19–21].

This protocol was designed to provide information on the dynamics, temporal variations, and spatial patterns of macro-environmental characteristics of nesting sites, influenced by erosion, surface runoff, and vegetation zone changes. By integrating UAVs into surveys, the expected outputs encompass the detection of changes in beach morphology, identification of seasonal and interannual erosion or habitat loss, delineation of areas of mineral deposition, and configuration of the spatial structure of vegetation and stability of the sand dune systems. The results obtained could inform the development of a response strategy aimed at addressing and preventing beach erosion, mitigating coastal squeeze, managing sediment supply, and identifying suitable areas for nest relocation and vegetation control [22].

2.2.3. Monitoring Thermal Variations in Nesting Habitat and Deriving Sex Ratio Estimates

As ectothermic animals, the biology of sea turtles is closely related to temperature conditions, not just during their marine life, but also in their nesting habitats. There is evidence to suggest that both nesting site selection and nesting crawl may be influenced by sand temperatures [23,24]. Incubation conditions (e.g., temperature, moisture) affect offspring characteristics, i.e., egg survival, embryonic development, and hatchling robustness [25,26]. High temperatures in the egg chamber could be lethal for eggs/hatchlings [27,28] while sex determination of offspring is temperature-dependent, with higher temperatures favoring female production [29,30]. The ability to estimate the sex ratio of hatchlings and prevent hatchling mortality is essential for population recruitment [31].

The purpose of this protocol is to monitor temperature-related aspects affecting the reproductive biology of marine turtles in nesting habitats. The use of UAVs and temperature data loggers provides an overall approach to mapping the thermal profile of nesting sites and detecting pivotal temperatures affecting offspring production [32,33]. Recording optimal incubation temperatures and extreme thermal events could help identify thermally suitable areas for relocation of nests (i.e., hatcheries) or direct mitigation measures, e.g., clutch splitting and clutch shading [34,35].

2.2.4. Monitoring Human Presence and Impacts of Recreational Activities

The industrialization of coastal zones, with the expansion of recreational activities, is contributing to deteriorating environmental conditions, raising a series of conservation issues for marine turtles [36]. Permanent beach structures and recreational equipment can disrupt nesting activities, by limiting beach access to nesting females and increasing nesting abandonment [37]. The growing presence of tourists can result in stress-related diseases in turtles [38] or in the accumulation of litter, subsequently prolonging the time it takes for hatchlings to reach the sea and reducing hatchling survival [39]. In the marine environment, recreational boating can affect the persistence and behavior of marine turtles, mainly manifested through an increased risk of collision [40] and additionally by decreasing the duration of foraging or surfacing [41].

This protocol was developed to detect and spatially delineate recreational use and activities within the coastal zone that could potentially impact reproductive processes and outcomes. UAVs are employed to scan extensive nesting sites, assess beach structure types and cover, and estimate the carrying capacity of visitors. Aerial marine surveys contribute to pinpointing risk areas for collisions by identifying high-density zones of recreational boats and individuals. The information gathered serves as a foundation for implementing measures, such as establishing visitor limits on nesting beaches, formulating policies regarding coastal development and beach structure placement, and introducing spatiotemporal restrictions and regulations for boats within breeding and foraging grounds [42–44].

2.2.5. Monitoring Marine Turtle Habitat Utilization and Behavior in Nearshore Habitats

While nesting grounds of marine turtle species are well-documented, the identification of habitat utilization in their marine habitats is an ongoing scientific endeavor [45,46]. Direct observations and remote tracking studies have provided valuable insights into movement patterns, foraging aggregations, and in-water behavioral variations among individuals [47,48]. Nevertheless, these methods typically restrict the tracking to only a small number of animals at a given site and might overlook the least prevalent species or least accessible life stages in certain areas [49]. Considering that local stressors such as fisheries, marine traffic, predation, etc., can influence population viability at sea [50,51], enhancing our comprehension of marine turtle habitat use becomes crucial for effectively planning management and conservation actions.

This protocol was refined to capture fine-scale details regarding habitat use, breeding, and foraging ecology of sea turtles in nearshore marine environments. Leveraging UAVs facilitates the acquisition of time series data with high resolution, enabling the identification of temporal and spatial patterns in the in-water behavior of animals [52]. It allows for the monitoring of local foraging and breeding aggregations [53,54], as well as the documentation of responses to both natural and anthropogenic stressors and habitat attributes [55]. Understanding the influencing factors and the evolving structure of aggregations and behavioral variations, within and across seasons, holds the potential to inform conservation management interventions [56], such as the implementation of activity zoning and fisheries regulations.

2.3. Equipment

Protocols I, II, III, and V were implemented using the DJI Phantom 4 Pro multirotor (DJI; https://www.dji.com/gr/phantom-4-pro/info; accessed on 30 January 2024). Weighing 1388 g, it facilitates effortless transportation to field locations and requires only one or two operators in the field. The realistic maximum flight duration is approximately 20 min, allowing comprehensive coverage of all nesting beaches through one to three flights. Phantom 4 Pro comes equipped with a gimbal-controlled high-resolution RGB sensor, and all surveys were recorded in maximum image quality (5472 × 3648 pixels).

For Protocol VI, we utilized the AgEagle eBee X UAV system (AgEagle; https://ageagle.com/drones/ebee-x/; accessed on 30 January 2024). The eBee X is a fixed-wing mapping drone weighing 800 g without any payload, featuring a wingspan of 116 cm. Paired with the S.O.D.A sensor, a high-resolution RGB sensor (5472 × 3648 pixels), offers a realistic maximum flight duration of approximately 50 min. Unlike the Phantom 4 Pro, the eBee X is hand-launched and requires a linear path against the wind for landing, presenting challenges in specific locations.

Additional equipment includes the HOBO MX2304 (Onset; https://www.onsetcomp.com/products/data-loggers/mx2304; accessed on 30 January 2024) data logger and the Parrot Sequoia multispectral sensor (Parrot; https://www.parrot.com/assets/s3fs-public/2021-09/sequoia-userguide-en-fr-es-de-it-pt-ar-zn-zh-jp-ko_0.pdf; accessed on 30 January 2024). The HOBO MX2304 is a weatherproof data logger with one external temperature sensor that was used to record nest temperatures for the application of Protocol IV. The Parrot Sequoia features four narrow-band monochrome sensors capturing images of 1280 × 960 pixels in the green, red, red-edge, and near-infrared wavelength bands and was employed in Protocol I to monitor vegetation patterns.

For more detailed specifications of the monitoring equipment and their applications in the protocols, please refer to the Supplementary Materials provided in this study.

2.4. Survey Design and Post-Processing

To put the protocols to the test, aerial drone surveys were conducted at selected nesting sites of loggerhead sea turtles on Zakynthos Island (Greece), one of the largest nesting rookeries in the eastern Mediterranean [57] and in the vicinity of Kefalonia Island (Greece). All surveys were conducted in August, a period coinciding with heightened nesting activity and increased tourism on nesting beaches. Preliminary flights were executed to determine the optimal elevation for UAV flights in each scenario. For nesting beaches, the UAV was operated at an elevation of 30 m, ensuring comprehensive coverage of the study area and a detailed depiction of beach characteristics and marine turtle markings (nests, crawl tracks). In contrast, marine surveys were conducted in different elevations to enable a broader coverage of the surveyed area while still enabling the identification of individuals. UAV control was managed through the PIX4Dcapture Pro app (Pix4D; https://www.pix4d.com/product/pix4dcapture/; accessed on 30 January 2024) on a mobile phone from the ground control station. PIX4Dcapture Pro facilitated flight plan creation, ground-truthing, and real-time monitoring of flight conditions during aerial surveys. Flights were strategically scheduled early in the morning to minimize human interference on the nesting site and reduce reflectance from the sea. The UAV Forecast app was consulted before each flight to ensure optimal weather conditions for safe operations. During the aerial survey, a second observer, in addition to the operator, was deployed to maintain the visual line of sight with the UAV. Post-processing of the UAV-captured images was facilitated by Pix4Dmapper (Pix4D; https://www.pix4d.com/product/pix4dmapper-photogrammetry-software/; accessed on 30 January 2024). Pix4Dmapper is an advanced photogrammetry software that transforms drone images into georectified maps by superimposing the images using GPS coordinates. This approach enabled the comprehensive depiction of the entire nesting beach, facilitating accurate spatial pattern analyses.

Details regarding individual flights and additional monitoring techniques employed in each protocol are elaborated in the corresponding Supplementary Materials.

3. Discussion

In this work, we have proposed a methodological framework for the monitoring of sea turtles and their habitats in the face of environmental change, using novel technologies such as UAVs, data loggers, and sensors. Our approach was organized around the record and monitoring of already existing anthropogenic pressures such as coastal development, but could also be applied to new ones such as temperature increase and sea level rise, as species are predicted to be exposed to cumulative impacts resulting from the combined pressure of already existing and new human-induced activities. The use of novel technologies could be an important tool for the collection of crucial on-field information, that either wise would be difficult to collect for a limited number of scientists, managers, or volunteers. Methodological frameworks such as the one presented here could assist in a more automated and easy collection of data, that could support a more integrated and systematic monitoring of protected areas, which may suffer from a lack of funding for research and personnel for the realization of conservation fieldwork [58]. As ecosystems are currently under change, it is essential to make use of any technological advancement that offers the possibility of recurrently collecting new information and enables the systematic monitoring of changes in the long term.

The use of technological advances is nothing new, as there is already certain research devoted to their application, not only for sea turtles but also for other marine taxa such as marine mammals [59–61], marine fish, and reptiles [62–64]. Publications have provided valuable data on the interaction of animals with their environment by monitoring the movements, abundance, and behavior of marine animals [65,66]. Research on sea turtles, particularly, has been focused massively on the assessment of population abundance and density, as well as distribution across the breeding grounds by different technological means [12,63,67,68]. Estimation of certain sea turtles' indices (i.e., the sex ratio of hatchlings [69] and habitat parameters (i.e., the thermal profile of nesting beaches [70] could support monitoring of their trends and a collection of both important time series. Collection of both biological information and environmental parameters [71,72] could offer the opportunity to monitor species and their respective habitats under rapidly changing conditions.

In a dynamic and increasingly changing sea- and landscape, management decisions are often supported by limited background information. The lack of data and unsystematically collected information could be overcome by the practice of animal monitoring in the field by means of novel technological applications [73,74]. This could ensure the provision of accurate, high-quality, and real-time monitoring data ensuring less disturbance to the animals being monitored [75,76]. In front of a climatic and environmental crisis, the collection of fine-scale data offers the opportunity to gain insights into species' adaptive capacity and intraspecific variation of vulnerable species in response to environmental changes as well as habitats under change [77,78]. For instance, as hatchlings have been identified as the most vulnerable life stage in front of climate change [6], the use of in-nest data loggers could provide records of extreme temperature values which could jeopardize reproductive output or drive nest temperatures to lethal limits [27,79]. Following an adaptive cyclical process of data collection and evaluation, these systematic on-field records could inform climate-smart conservation strategies in front of the changing climate.

Since the monitoring approaches demonstrated in this study can be used in various locations with different environmental characteristics, animal concentrations, and levels of human activity, it is possible that they may encounter distinct challenges in terms of ease of implementation. Our primary focus was monitoring a single species within a de-limited study area, distinguished by nesting beaches extending up to 600 m in length. To maximize efficiency, we employed multiple UAV batteries and optimized flight parameters, such as timing and elevation, to facilitate the concurrent collection of data on multiple variables, including environmental properties and habitat utilization. Flight time constraints may pose challenges for UAS surveys particularly in long nesting sites where a single flight may not cover the entire beach. To address the limitation of monitoring ex-tensive areas, a well-designed survey could optimize results and streamline reporting by dividing extensive nesting sites into discrete segments and employing multiple batteries or UAVs, contingent on funding and equipment availability. Such monitoring schemes can prove feasible for large-scale environmental monitoring and population assessments, even in the context of mass-nesting events [68]. Moreover, as drones continue to advance with longer flight times and improved sensor technologies, the advantages of such surveys will continue to evolve, providing rapid and reliable species detection [12].

The flexibility of the monitoring approaches presented here reflects the key advantages of UAS in marine wildlife research. Monitoring techniques can vary greatly depending on the monitoring context and the unique characteristics of nesting or nearshore sites. Refining monitoring protocols for different locations or species may require experimentation, but this endeavor can yield regional and fine-scale time-series datasets, enabling the continuous monitoring of specific parameters over time.

These efforts can ultimately pave the way for the implementation of specialized measures, fully harnessing the potential of adaptive management. A long-term understanding of the spatial configuration of biotic and abiotic parameters can enhance our comprehension of coastal interactions and facilitate the detection and early warning of spatially dependent interactions. For instance, on beaches with high tourist activity, documenting visitation patterns and conducting surveys during periods of varying visitation intensity can aid in identifying management priorities and advocating for the enhancement of regulatory measures.

Although limitations exist for monitoring with advanced technological applications [80], these efforts could feed into the designation of our conservation efforts [73,81,82] and bring a significant transformation in our capacity to collect data on the biology and behavior of marine animals. Similarly, traditional monitoring approaches, which have proven critical and very informative over time [83], could be further supported by innovative monitoring schemes, enhancing our conservation capacity. By integrating advanced technologies into sea turtle monitoring programs, researchers and conservationists can gain a comprehensive understanding of sea turtle populations, migration patterns, and the threats they face, knowledge crucial for the effective conservation and management of these endangered marine species.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d16030153/s1, Section S1.1: Monitoring nesting beach habitat selection and use; Section S1.2: Monitoring nesting beach macro-environmental properties and changes in beach profile; Section S1.3: monitoring human presence and impacts from anthropogenic activities; Section S2: Relevant pilot case studies; Section S3: Monitoring thermal variations in nesting habitat and deriving sex ratio estimates; Section S4: Monitoring marine turtle habitat utilization and behavior in nearshore habitats.

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