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Conservation notes

An emerging hazard to nesting sea turtles in the face of sea-level rise

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ABSTRACT

Climate change poses a significant threat to sea turtles. In particular, beach erosion due to sea-level rise endangers sea turtle nests and can hinder the inland movement of nesting females. This study highlights an overlooked indirect hazard in the context of sea-level rise, namely the risk of nesting turtles to lethal falls from rocky cliffs exposed by beach erosion. We provide evidence of mortality of nine nesting green turtles (*Chelonia mydas*) found upside-down on the base of cliff ledges in Breem Island (locally known as جزيرة بريم), located along the northern Saudi Arabian Red Sea coast. One additional turtle was found flipped over but still alive. Our observations suggest that in areas where there is a continuum from the beach to the rocky cliffs (contrary to very steep cliffs bordering beaches), these structures pose a substantial hazard to nesting sea turtles when they attempt to return to the sea. Moreover, mean daily air temperatures of 31 ℃ (max. 44 ℃) in the northern Red Sea likely exacerbate heat exhaustion of turtles that fall off the cliffs, providing a very narrow window for the animals to be rescued. This study underscores the need to integrate these indirect effects of sea-level rise into sea turtle vulnerability assessments, as well as the importance of implementing timely mitigation measures. Such steps are essential to meet the goals of the Kunming-Montreal Global Biodiversity Framework and support the survival of breeding sea turtles amidst climate change challenges.

1. Introduction

Climate change is recognized as a significant threat to sea turtles, primarily due to the effects of warming on the sex definition and viability of hatchlings, sea-level rise and altered storm patterns (Booth, 2017; Hamann et al., 2013; Hays et al., 2017). Sea-level rise in particular poses risks to sea turtle nesting beaches by increasing the probability of beach erosion and flooding, while also affecting the reproduction of turtles. Beach erosion can lead to a higher risk of washout or inundation of nests laid in low beach areas, resulting in many cases in turtle embryo mortality from suffocation and lower hatching success (Patino-Martinez et al., 2014; Pike et al., 2015). Recent assessments of the nesting success of olive ridley sea turtle (*Lepidochelys olivacea*) “arribadas” (mass nesting events) identified

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loss and/or erosion of the nesting sites due to cyclones as the main driver of nesting failure and early egg mortality (Mishra et al., 2021). Such erosive events are likely to accelerate in the future with combined sea-level rise and intensified storm strength and frequency, reducing the availability of suitable nesting sites (Gammon et al., 2023; Maneja et al., 2021) and thereby posing a risk to sea turtles that deserves further attention.

Erosive processes also alter the profile and physical attributes of the beach, potentially affecting turtle nesting behavior (Wood and Bjorndal, 2000; Long et al., 2011). Nesting site preferences and selection vary among species, but nesting turtles typically crawl to elevated areas (Bustard and Greenham, 1969; Hays et al., 1995; Kamel and Mrosovsky, 2004; Miller et al., 2003), and depending on the geomorphology of the beach, they may successfully nest above or near rocky cliffs (i.e., rocky outcroppings fringing sandy beaches). Consequently, adult nesting turtles are also at risk when they return to the sea, as they are vulnerable to falling from these cliffs, which can lead to injuries or even fatalities.

Instances of sea turtle interactions with rocky cliffs are scarcely documented in the scientific literature (but see Limpus et al., 2003; Mortimer and von Brandis, 2013), however they have been mentioned in social media and news outlets in Oman (Bennett, 2019), Bonaire (Sea Turtle Conservation, 2022), Ascension Island (Machin, 2022), Cape Verde (Cabo Verde Natura 2000, 2024) and Florida, USA (Ortiz, 2022). Similar rocky cliff structures are also common along the Red Sea, where they have been historically exposed as a result of sea-level rise during the last interglacial transgression in the late Pleistocene (Manaa et al., 2016). The Red Sea's isolation and extreme environmental gradients, including high salinity and temperature, have shaped the adaptability of its marine species (Berumen et al., 2019), including sea turtles, making it a key area for studying climate resilience.

Sea turtles are long-lived species with late reproduction, and adult females hold the highest reproductive value among all life stages (Bolten et al., 2011). Thus, prioritizing conservation actions to protect this vital population segment is crucial and highly recommended to reduce mortalities. In this context, addressing direct and indirect risks to endangered sea turtles arising from beach erosion due to sea-level rise, including rocky cliff exposure, is essential to achieve the goals of the Kunming-Montreal Global Biodiversity Framework of halting and reversing biodiversity loss. Here, we highlight an emerging threat to nesting sea turtles due to the extension of rocky cliffs caused by beach erosion in the Red Sea —a yet unrecognized hazard in the context of sea-level rise.

2. Methods

Breem Island (locally known as [1](جزيرة بريم) is home to the Red Sea's second largest population of nesting green turtles (*Chelonia mydas*). Recent estimates suggest that the annual nesting abundance of green turtles at Breem Island averages between 60 (Vilela and Hardenstine, 2023) and 146 females per year, with an increasing population trend over the last 40 years (Shimada et al., 2021). Hawksbill turtles (*Eretmochelys imbricata*) also nest on this island but are less common, with an average of 16–20 nesting females per year. In this region, the nesting season for green turtles typically spans from April to November, with peak nesting occurring from July to September (Shimada et al., 2021; Vilela and Hardenstine, 2023).

The island, located in the Al-Wajh lagoon, is composed primarily of limestone, forming raised coral terraces (or rocky cliffs) along the shoreline, separated by gently sloping sandy beaches (Fig. 1A). The northwestern edge of Breem Island features a continuous rocky cliff approximately 6 km long and over 3 m high. Sea turtle nesting is concentrated along the southern and southwestern coasts. Along this area, there are three smaller rocky cliffs, ranging from 1 to 2 m in height and stretching between 100 and 900 m along the shore, with sandy beaches interspersed between them. The high-water mark typically reaches the rocky cliffs, with some small pockets of 1–2 m of backshore. However, at the central cliff, the backshore is considerably wider (5–12 m) with sandy areas at its base, which occasionally leads to turtles attempting to nest at the foot of the cliff. In most cases, however, nesting sea turtles lay their eggs above the dunes on the sandy beaches between the rocky cliffs.

Fallen sea turtles were encountered opportunistically and documented by trained staff during monitoring patrols in the nesting season between 2019 and 2023. Survey efforts varied across years due to logistical constraints, and differences in methodology and patroller expertise may have contributed to variability in detection rates, thus likely introducing detection bias to our dataset. Patrols consisted of walking a transect of approximately 6 km along sandy beaches and rocky cliffs and were generally conducted during the day. Tracks were inspected for species (i.e., hawksbill or green turtle) and activity (i.e., whether tracks indicated a false crawl, nest attempt, or actual nest), geo-referenced and crossed after recording. For this study, we focused on track count, rather than nest count, to better reflect where turtles emerged and potentially interacted with rocky cliffs. Survey efforts included: 3 survey days in September 2019, no surveys in 2020 due to the COVID-19 pandemic, 12 survey days over 6 months in 2021, 9 survey days over 6 months in 2022, and 9 survey days over 8 months in 2023.

To visualize the turtle track density patterns across the island, we created a heatmap of the cumulative tracks across years using the Heatmap renderer symbology with a 5-meter radius in QGIS 3.38.3. We then overlaid the location of sea turtle/rocky cliff interactions on the map for visual comparison and identify key areas for planning mitigation measures. In addition, we determined the extent of the rocky cliff along the south-western coast of Breem Island through on-site visits and satellite imagery of 2022 captured by the CNES/Airbus satellite constellation and accessed through the Google Earth Pro software (Fig. 1A).

[1] Also reported in the literature as Jazirat Mashabah, Mashabih, Birrim, or Birema.

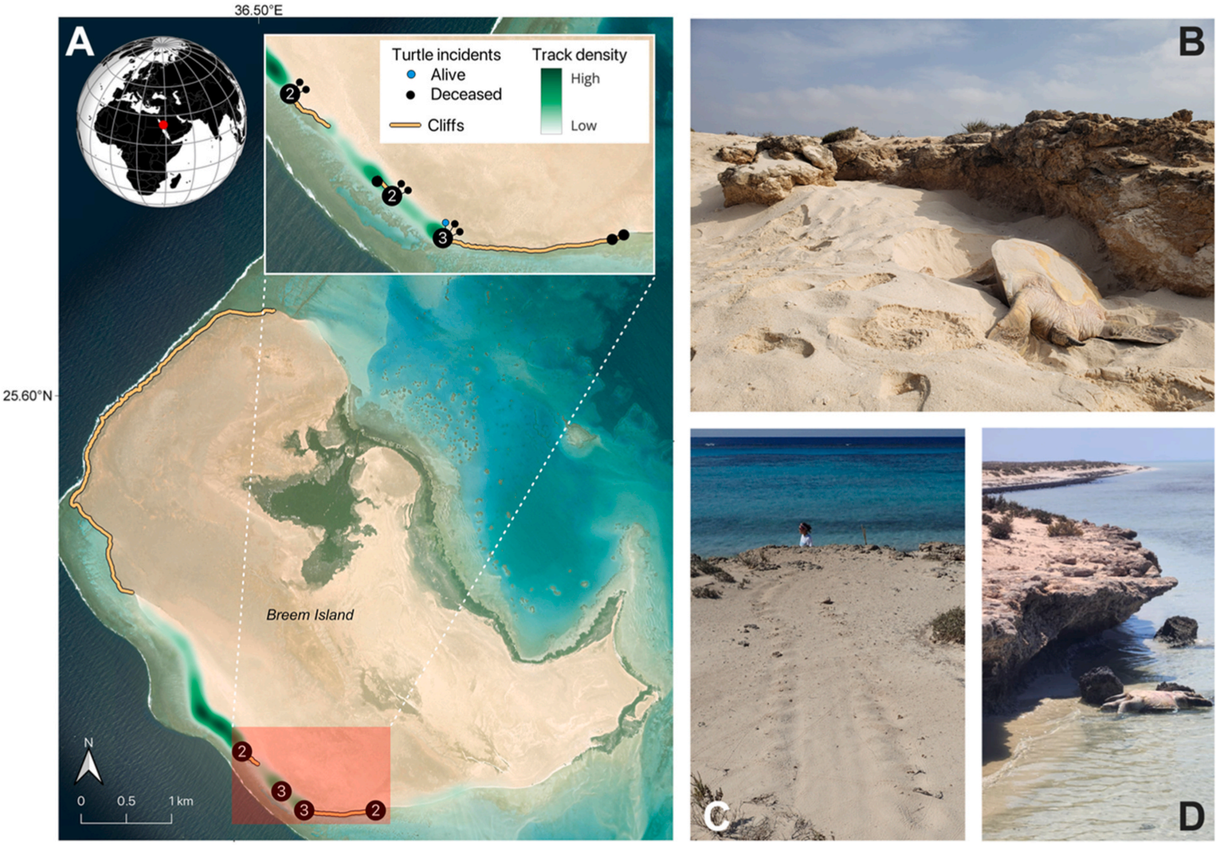

Fig. 1. (A) Satellite map indicating the areas of sea turtle tracks and the spatial distribution of incidents where nesting turtles fell off cliffs in Breem Island, in the northern Saudi Arabian Red Sea. (B – D) Images of various nesting green turtles (and tracks) after they had fallen off the cliff. Satellite image in (A) licensed by ©MapTiler ©OpenStreetMap contributors. Photos taken by Hector Barrios-Garrido (B), Takahiro Shimada (C) and Taha Boksmati (D).

3. Results

During the monitoring patrols, we documented 10 green turtles stranded on the ledge of these cliffs. The turtles were found either upside down or with apparent cervical fractures (broken neck) (Fig. 1B-D). Nine of these turtles were already deceased (Fig. 1D), while one, discovered flipped on her back, was still alive and was safely returned to the sea (Fig. 1B). Hawksbill tracks were also recorded during the patrols, but none traversed rocky cliffs.

Instances of fallen turtles were recorded between June and December, with the majority occurring during the peak nesting season. Specifically, five turtles were recorded in September (two in 2019, two in 2021, and one in 2022), three in August (all in 2021), and one each in June (2021) and December (2019). Extrapolating from recent estimates of annual nesting abundance (Shimada et al., 2021; Vilela and Hardenstine, 2023), the nine recorded turtle deaths over four seasons amount to a mortality rate of approximately 1.5–3.75 % of the nesting population during the study period.

4. Discussion

In this study, we report incidents of nesting sea turtles falling off rocky cliffs while returning to the sea, often resulting in lethal outcomes. This hazard to nesting females is most likely an indirect effect of sea-level rise, a factor previously overlooked when assessing sea turtles' vulnerability to climate change. By raising awareness of these incidents within the scientific community, we aim to shift focus towards systematically detecting this hazard, rather than relying only on opportunistic encounters, and implementing targeted conservation measures to reduce sea turtle interactions with rocky cliffs and its associated mortality.

The reports from citizens and NGOs (Bennett, 2019; Cabo Verde Natura 2000, 2024; Machin, 2022; Ortiz, 2022; Sea Turtle Conservation, 2022) highlight the prevalence of sea turtle-rocky cliff interactions around the world, which might also be occurring unnoticed on beaches with comparable geomorphology elsewhere. A potential reason for the lack of scientific reports may be the logistical challenges in consistent and frequent beach monitoring, as the likelihood of encountering a recently fallen turtle is low. Decomposition processes cause deceased turtles to float and drift with tides and currents, often leading to stranding elsewhere. This makes the window for detection narrow, especially in warm environments like the Red Sea, where a carcass can decompose within 1–2 weeks (Hector Barrios-Garrido, pers. comm.). Given this scenario and the time between surveys in our study (typically one month or more), it is likely that the estimated green turtle mortality rate due to rocky cliff falls (between 1.5 % and 3.75 % of the nesting population) is an underestimation and may be a contributing factor to overall turtle deaths in the region. In this context, citizen science and unmanned aerial technologies, such as drone surveys, could support beach monitoring efforts across larger areas by improving the timely detection of turtles that fall from coastal rocky cliffs.

Although both green and hawksbill turtles nest on Breem Island, only green turtles were found to interact with the rocky cliffs, likely due to differences in their nesting behavior. Hawksbills typically make shorter crawls, nest just above the dune, and return directly to the sea (Nasiri et al., 2022). In contrast, green turtles tend to nest on uneven topography and can crawl longer distances in search of suitable habitat (Hays et al., 1995). In addition, sea turtles at Breem Island encounter various challenges during nesting, including high nest density, marine debris, and the presence of unsuitable areas like the coastal rocky cliffs we describe. As expected, some areas with the highest track density are located close to these cliffs, increasing the likelihood of sea turtles wandering over the terraces. Additionally, elevated air temperatures during the peak nesting season in the northern Red Sea (mean 31 $\pm$ 1.3 °C, with highs reaching 44 °C; Meteostat.. 2024) likely contribute to the mortality of turtles that fall, as prolonged exposure to extreme temperatures can lead to heat exhaustion and lethal body core temperatures for sea turtles (above 39 °C) (Limpus et al., 2003).

The present-day cliffs in the Red Sea are very stable and less prone to modifications, in contrast to the sandy beaches which are unconsolidated and highly vulnerable to erosion (Al-Hashim et al., 2021). This is a problem, considering that the rate of sea-level rise in the northern Red Sea is estimated to be twice the global average (Abdulla and Al-Subhi, 2021), because the retreat of the coastline could potentially expose new parts of the coral terraces which commonly extend a few hundred meters inland on islands and up to 5 km on the mainland (Manaa et al., 2016). Predicting the precise long-term impact of sea-level rise on these nesting beaches however is complex. It remains uncertain to which degree cliffs could become further exposed as beach recession advances, or if sand accretion could provide new nesting habitat for turtles in some areas. Moreover, as sea level increases, the shorter distance between cliff edges and the water, especially during high tides, may reduce turtle mortalities by making it more likely that a falling turtle will land in the water rather than on the sand. Developing predictive models for the impact of different sea-level rise scenarios on sea turtle nesting habitat would be invaluable to identify areas vulnerable to further erosion in Breem Island and other nesting beaches in the region such as Ras Al Baridi and Farasan Islands.

Sea-level rise introduces additional challenges for coastal megafauna on beaches bordered by rocky outcroppings. For example, as more rock becomes exposed, changes in sand composition can modify the availability of suitable nesting sites for species such as coastal birds (Calabrese et al., 2024) and sea turtles (Maneja et al., 2021). Coarser particles in the sand can also hinder the emergence of sea turtle hatchlings from the nest (Saito et al., 2019). Furthermore, an extension in rock coverage alters the horizon profile for hatchlings, creating higher silhouettes that can increase the risk of disorientation or entrapment in rock crevices during their sea-finding process (Limpus and Kamrowski, 2013). These impacts illustrate the broader consequences of sea-level rise, not only for nesting females but also potentially affecting hatchling survival and performance, emphasizing the importance of addressing these indirect impacts of sea-level rise in conservation strategies.

4.1. Conservation implications

When evaluating the vulnerability of a beach to erosion, those with rocky geomorphology are typically ranked as having low vulnerability due to their evident resistance to erosion (e.g., Gammon et al., 2023). However, as we report in this study, when these formations fringe nesting beaches creating a sand-to-rock continuum with easy access, they pose a potential hazard to nesting turtles that crawl further inland. We argue that, moving forward, this risk level should be accounted for when conducting assessments and predicting sea turtle vulnerability to climate change, to more accurately reflect the indirect impact that erosion may pose on the survival of nesting sea turtles.

Finally, this study serves as an example of how monitoring and science can inform the timely implementation of management decisions. In response to the discovery of sea turtle-cliff incidents, Red Sea Global launched a pilot program in 2024 to prevent further sea turtle mortalities at Breem Island, which consisted of designing and installing environmentally safe barriers that redirect sea turtles away from the cliffs. On Raine Island in Australia, similar interventions proved highly successful, where the use of fencing reduced cliff-related sea turtle mortalities by more than 70 % (Dunstan and Robertson, 2019; Sainsbury et al., 2021). At areas of high risk of beach recession, restoration measures such as beach nourishment and dune building (Grain et al., 1995; Speybroeck et al., 2006), combined with strategic barrier positioning could help maintain the perpetuity and structure of nesting beaches contributing to the survival of future generations of sea turtles in the Red Sea. Restoration measures that consider the complete beach ecosystem will help prevent indirect effects (Speybroeck et al., 2006), safeguarding the biodiversity from further cumulative damage.

Ethics statement

All monitoring activities were permitted under the King Abdullah University of Science and Technology Institutional Animal Care and Use Committee permit No. 18IACUC11 and the National Committee of Bioethics (HAP-02-J-042).

CRediT authorship contribution statement

Natalie E. Wildermann: Data curation, Formal analysis, Validation, Visualization, Writing – Original Draft; **Hector Barrios-**

Garrido: Data curation, Investigation, Methodology, Writing – Review & Editing; **Khuld Jabby:** Conceptualization, Data curation, Investigation, Writing – Review & Editing; **Royale S. Hardenstine:** Investigation, Writing – Review & Editing; **Takahiro Shimada:** Investigation, Methodology, Writing – Review & Editing; **Ivor D. Williams:** Conceptualization, Data curation, Investigation, Project administration, Resources, Writing – Review & Editing; **Carlos M. Duarte:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – Review & Editing

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to rephrase some sentences for conciseness and readability. After using this tool the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dist. Prof. Carlos M. Duarte reports a relationship with Red Sea Global that includes: board membership. Dr. Hector Barrios-Garrido reports a relationship with Red Sea Global that includes: consulting or advisory. The authors declare that Dr. Ivor Williams and Dr. Khuld Jabby hold managing positions within Red Sea Global. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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