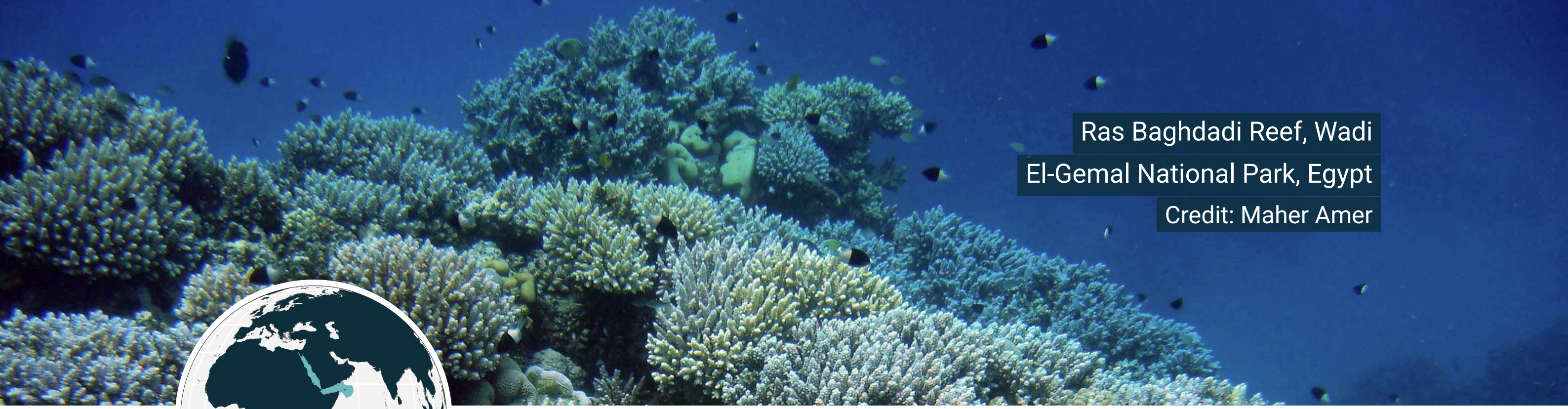
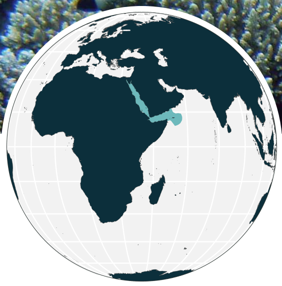




RED SEA AND GULF OF ADEN

Authors

Maher **Amer**[1], Tamer **Atalla**[2], Swaleh Ali **Aboud**[3], Mohammed **Dosoky**[3], Khaled **El-Haddad**[3], Emily K. **Fobert**[3], Jessica **Stella**[3], Mohammed **Elsayed**[3], Mohammed **Al-Tawaha**[4]

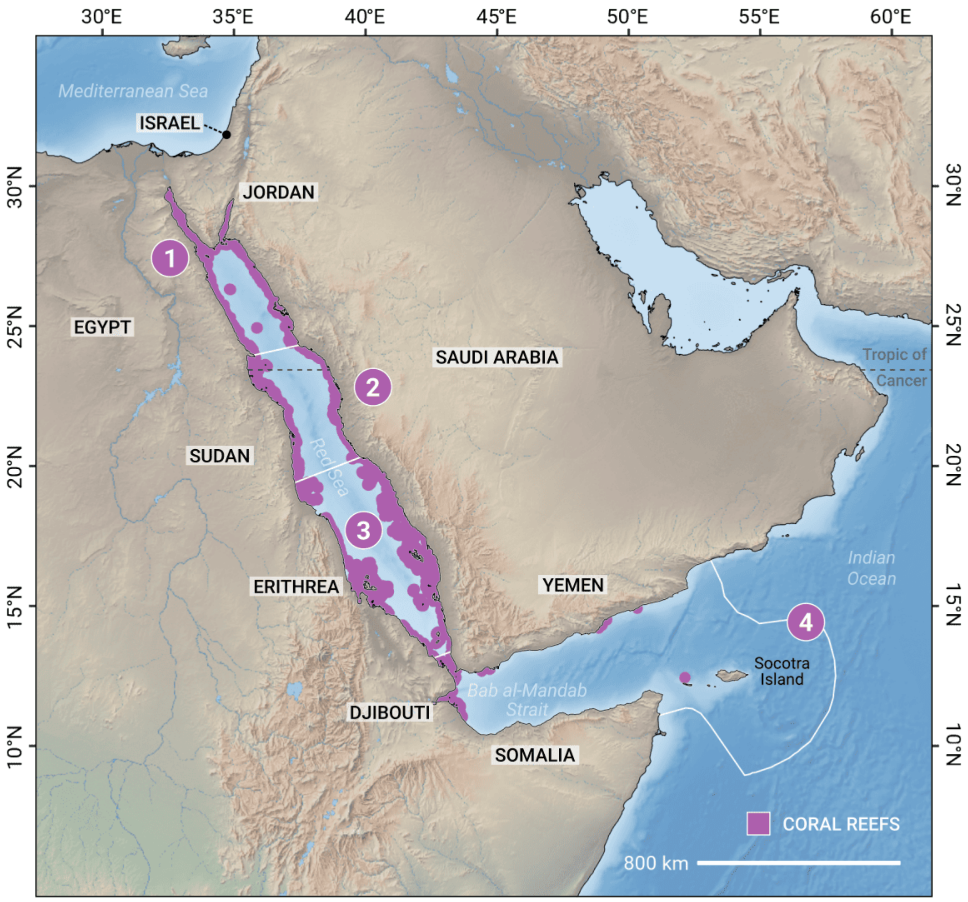
[1]The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA), | [2]Egyptian Environmental Affairs Agency (EEAA), Red Sea Protectorates, Egypt | [3]The General Organization for the Conservation of Coral Reefs and Turtles in the Red Sea (SHAMS), Saudi Arabia | [4]United Nations Development Programme, Aqaba, Jordan

Citation

Amer, M., Atalla, T., Aboud, S. A., Dosoky, M., *et al.* (2026). Chapter 7 – Red Sea and Gulf of Aden. *In González-Rivero, M., et al. Status of Coral Reefs of the World: 2025. Global Coral Reef Monitoring Network and International Coral Reef Initiative.* https://doi.org/10.59387/LFPR6347.RSGA

INTRODUCTION

The Red Sea and Gulf of Aden GCRMN region extends over a maritime area of around 1.1 million km^2, ranging across 22° of latitude and 27° of longitude, forming one of the world's most diverse coral reef provinces [307]. Covering an estimated 12,590 km^2, or about 5.0% of global coral reef extent, it is the sixth-largest GCRMN region. There are, in addition, many other reef types that contribute to the great diversity of this system within the region and hence support an enormous reef-associated biota. Coral reefs lie within the exclusive economic zones of nine countries: Egypt, Sudan, Eritrea, Djibouti, Saudi Arabia, Yemen (including Socotra), Somalia, Jordan, and Israel. Coral reefs extend from the northern Red Sea, through the Gulfs of Suez and Aqaba, along the Red Sea coastline, and into the Gulf of Aden (Figure 2.7.1). For the purpose of this report, the GCRMN Red Sea and Gulf of Aden region was divided into four subregions: Northern Red Sea (subregion 1, 29.2% of coral reefs extent in the region), Central Red Sea (subregion 2, 26.6%), Southern Red Sea (subregion 3, 37.4%) and Gulf of Aden (subregion 4, 6.8%) (Table A.1).



▲ **Figure 2.7.1.** The distribution of coral reefs within the Red Sea and Gulf of Aden region and respective subregions. White polygons and numbers represent subregions. Subregion 1 = Northern Red Sea, Subregion 2 = Central Red Sea, Subregion 3 = Southern Red Sea, Subregion 4 = Gulf of Aden. Coral reefs are delineated with a 20 km buffer to enhance interpretation, and only coral reefs within the region are represented. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the region.

The Red Sea is one of the warmest and most saline seas in the world, creating extreme reef environments. Corals in the Red Sea therefore tolerate conditions that are lethal elsewhere, reflecting long-term selection for heat- and stress-tolerant genotypes [368], which likely underpins the reef resilience and recovery observed at some sites.

The Red Sea is a narrow, elongated basin that exhibits pronounced north-to-south environmental gradients, with cooler, less saline waters in the north and warmer, saltier conditions in the south [369–372]. Northern Red Sea reefs (subregion 1) are generally well-developed narrow fringing systems along steep slopes, while the Gulf of Suez and Gulf of Aqaba host patch reefs and narrow fringing systems. Southward, reefs broaden, diversify, and form longitudinal barrier reefs along the Saudi Arabian and African coasts, extending hundreds of kilometers, with additional patch reefs and atoll-like structures such as Sanganeb Atoll in Sudan [373]. South of 20° N, reefs from the Central Red Sea (subregion 2) are less vertically developed, often in turbid waters, with coastal fringing reefs replaced by mangroves, sand beaches, and patch reefs. In the Gulf of Aden (subregion 4), fringing reefs occur along ~25% of the Yemeni coast [374]. Seasonal macroalgae can dominate shallow substrates in turbid areas, while offshore reefs, including platform, patch, barrier reefs, coral cays, and islands such as Farasan and Dahlak, support the greatest diversity [375]. Central areas (Sudan, Eritrea) host extensive fringing and offshore complexes, whereas southern Saudi reefs extend over 1,800 km, and the Socotra Archipelago contains highly diverse reefs with Indian Ocean affinities [376]. Smaller reefs in Djibouti and northern Somalia remain ecologically connected to the Red Sea corridor (subregion 4) [376].

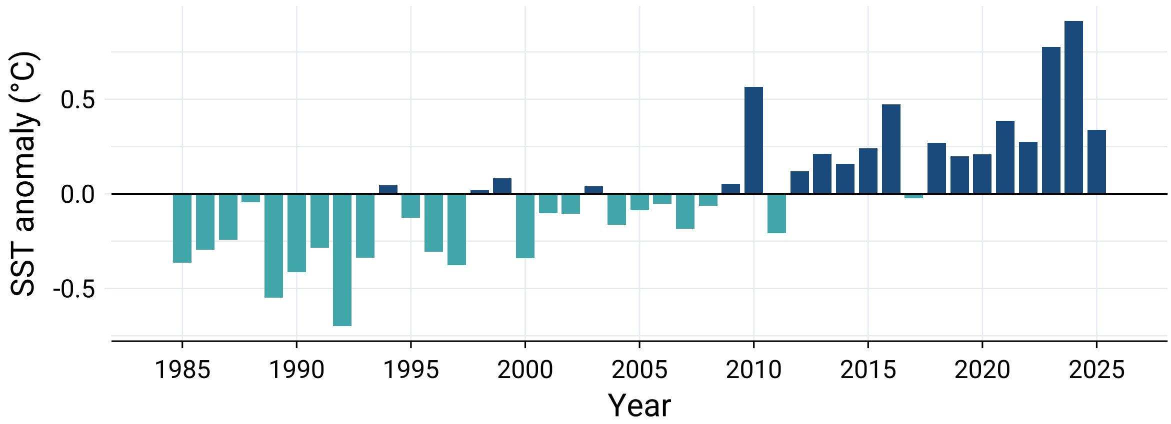
The coral reefs of the Red Sea support livelihoods for over 28 million people, contributing ~USD 230 million annually from fisheries and ~USD 6 billion from reef-based tourism globally [371, 377]. Coral reef tourism has historically accounted for nearly 2% of Egypt's gross domestic product (GDP), with similar growth anticipated in Saudi Arabia under Vision 2030 [17]. Rapid population growth near reefs (3.27 million within 5 km in 2020, a 69.4% increase since 2000), combined with coastal development, shipping, and land-based pollution, increasingly impacts reef condition, even as reefs continue to provide coastal protection from waves and sea-level rise.

THREATS AND DISTURBANCES

Heat stress

From 1985 to 2025, the long-term average sea surface temperature (SST) over coral reefs within the Red Sea and Gulf of Aden region was 27.85 °C (Table A.3). SST increased by 0.9 °C over this period, at an average rate of 0.23 °C per decade (Table A.3). SST anomalies were largely negative from the late 1980s until around 2009, before shifting to positive values and rising to approximately +0.25 °C during 2020–2024 (Figure 2.7.2). While these are regional averages, variability exists. In cooler years, the northern Red Sea was occasionally warmer than the southern Red Sea, whereas in warmer years the southern Red Sea consistently recorded higher temperatures, increasing heat stress in that subregion [378].

Major heat stress events in the Red Sea and Gulf of Aden region occurred in 1998 and 2010, with prolonged heat stress during 2015–2016, and renewed warming in 2020. Extreme heat stress peaked in 2023–2024, resulting in severe bleaching before stress levels declined in 2025 (Figure 2.7.3). Coral bleaching from heat stress was confirmed by in situ observations [379]. Bleaching risk in the Red Sea increases from north to south, with central and southern reefs exposed to higher temperatures and more frequent extreme events [108].



▲ **Figure 2.7.2.** Annual mean sea surface temperature (SST) anomalies (°C) over the coral reefs of the Red Sea and Gulf of Aden region from 1985 to 2025. SST anomalies were calculated based on the long-term average over the period 1985–2025. Positive values (red bars) indicate SST warmer than the long-term average, whereas negative values (blue bars) indicate SST cooler than the long-term average. Derived from NOAA Coral Reef Watch data (Skirving *et al.* [107]; see Materials and Methods).

The year 2024 marked the warmest year on record globally, exceeding 1.5 °C above pre-industrial levels [380], coinciding with the largest SST anomalies in the region (Figure 2.7.2). Severe mass bleaching was recorded for the first time in the northern Red Sea (north of 26° N) and along the Gulf of Aqaba reefs [381].

Regional disturbances

In 2024, three physical factors intensified bleaching risk in the northern Red Sea and Gulf of Aqaba. Altered currents reduced mixing of cooler deep water with surface layers, extreme low sea levels exposed shallow corals to sunlight and air, and calm winds limited replenishment of cooler surface water, prolonging heat stress [382]. Together, these localized disturbances likely amplified bleaching severity, highlighting subregional drivers of heat stress not always evident in broader regional analyses.

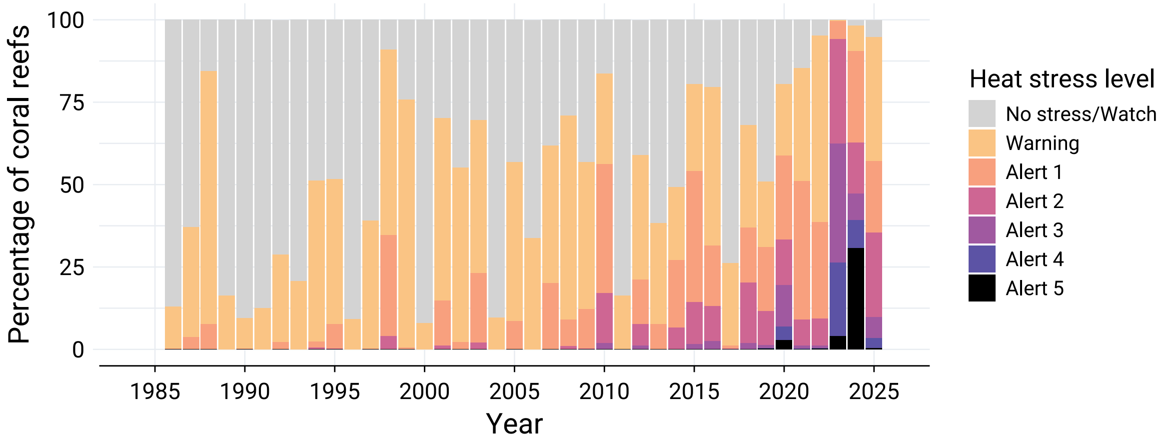
In addition to physical stressors, coral reefs in the Red Sea and Gulf of Aden are affected by localized anthropogenic stressors [371]. Coastal development and shoreline infrastructure alter water flow and increase sedimentation, while shipping operations contribute to localized pollution, anchor damage, and chemical stress [383]. These anthropogenic pressures, when interacting with natural disturbances, such as low tides, altered currents, and calm wind conditions, exacerbate bleaching risk and reduce reef resilience.

STATUS OF CORAL REEFS IN THE REGION

Long-term modeled benthic cover estimates for the Red Sea and Gulf of Aden region from 1997 to 2024 reveal alternating periods of stability, decline, and recovery in coral reef condition. These patterns reflect the combined influence of localized human impacts, including coastal development, tourism, fishing, and sedimentation, together with episodic thermal stress events that have driven repeated coral bleaching across the region.

Hard coral cover

Hard coral cover has consistently remained the dominant benthic component in the Red Sea and Gulf of Aden region, with median cover ranging from 20.1% to 37.8% between



▲ **Figure 2.7.3.** Percentage of the coral reefs within the Red Sea and Gulf of Aden region experiencing heat stress levels per year, from 1986 to 2025. No stress/Watch (DHW = 0); Warning (possible bleaching, $0 < \text{DHW} < 4$); Alert 1 (reef-wide bleaching, $4 \leq \text{DHW} < 8$); Alert 2 (reef-wide bleaching and mortality of heat-sensitive corals, $8 \leq \text{DHW} < 12$); Alert 3 (multi-species mortality, $12 \leq \text{DHW} < 16$); Alert 4 (severe multi-species mortality, $16 \leq \text{DHW} < 20$); and Alert 5 (near-complete mortality, $\text{DHW} \geq 20$). Derived from NOAA Coral Reef Watch data (Skirving *et al.* [107]; see Materials and Methods).

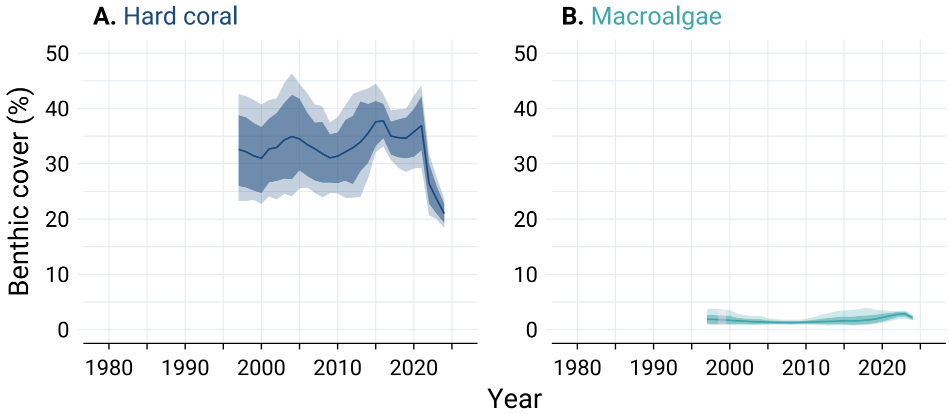
1997 and 2024 (Figure 2.7.4A).

Coral reefs in the region were exposed to elevated thermal conditions prior to the global coral bleaching event of 1998 (Figure 2.7.3). Despite this early heat stress, median hard coral cover remained relatively high, at 32.1% during 1997–1999 (Figure 2.7.4A). This stability during a period when widespread bleaching occurred globally suggests that reefs in the Red Sea and Gulf of Aden possess notable thermal tolerance. This resilience is likely supported by long-term exposure to naturally high and variable temperatures, as well as the presence of heat-tolerant coral genotypes in the northern basin [368].

From 2000 to 2008, hard coral cover remained relatively stable, with median values ranging between 31.0% and 34.9% (Figure 2.7.4A). Several years within this period, particularly 2003–2005, recorded upper credible intervals approaching or exceeding 45%, indicating that many reef sites maintained strong coral dominance despite environmental variability.

The early 2010s were marked by another period of heat stress associated with bleaching events, although modeled median hard coral cover remained relatively stable at around 31.5% between 2009 and 2011 (Figure 2.7.4A). Following this disturbance, reefs showed a clear recovery phase, and by 2016, median hard coral cover had increased to 37.8%; the highest values observed in the modelled time series. This recovery likely reflects favourable post-disturbance conditions, successful coral recruitment, and ecological controls such as herbivory that limit algal growth.

From 2017 to 2021, coral reefs in the region experienced a period of relative stability. Median hard coral cover remained consistently high, ranging from 34.6% to 36.9% (Figure 2.7.4A). This pattern suggests a period of relatively minor disturbance impacts, during which reefs have retained the capacity to recover hard coral cover to maintain historical levels. At the same time, human pressures along the Red Sea coastline were gradually increasing. Expanding coastal development, tourism infrastructure, and associated activities contribute to localized coral stress through sedimentation and physical disturbance [384]. Despite these pressures, hard coral cover



▲ **Figure 2.7.4.** Modeled temporal trends of benthic cover in the Red Sea and Gulf of Aden region from 1980 to 2024 for hard coral (A) and macroalgae (B). The solid line represents the estimated median benthic cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.

remained relatively stable during this period, indicating that reefs were able to withstand chronic but sub-threshold stress without major losses in benthic cover.

The year 2021, however, marked a clear turning point in reef condition. Renewed ocean warming beginning in 2021, consistent with global increases in SST, preceded one of the most intense heat stress periods recorded for the region. Summer heat stress intensified further during 2023–2024 (Figure 2.7.3), leading to widespread and severe bleaching across many reef areas. From 2021 to 2024, median hard coral cover declined rapidly, from 36.9% to 21.0% (Figure 2.7.4A). This represents an absolute loss of 15.9 percentage points, corresponding to a relative decline of 43.1% within only a few years. Lower credible intervals in 2024 approached 18%, indicating that some reef sites experienced particularly severe localized impacts, while other reef sites retained relatively higher levels of hard coral cover. This rapid decline contrasts sharply with the slower fluctuations observed in earlier decades and suggests the frequency and intensity of heat-stress events may now be exceeding frequencies that prevent full recovery [369].

Macroalgal cover

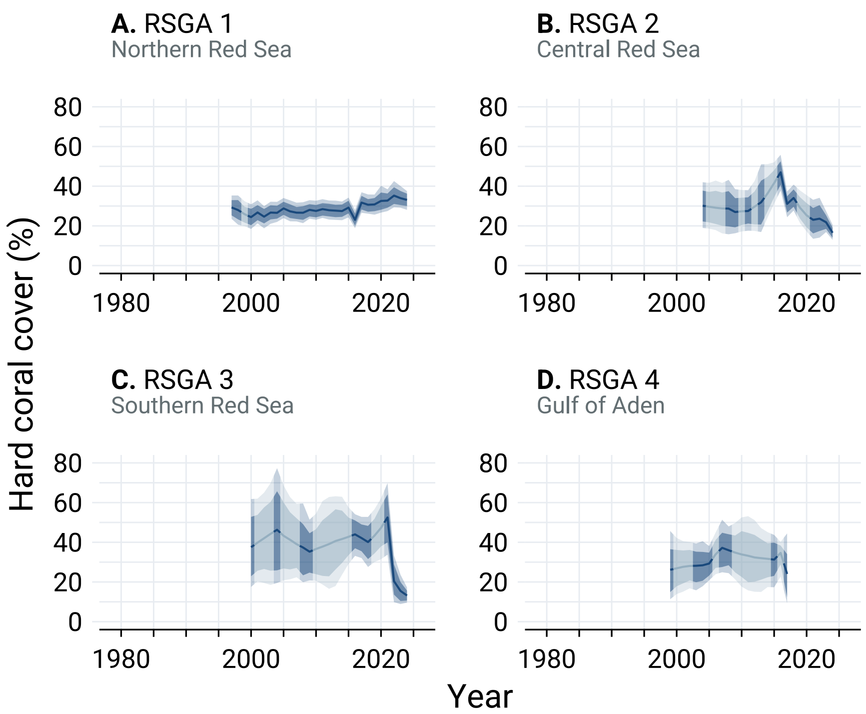
Despite the substantial loss of hard coral cover during the study period, macroalgal cover did not increase proportionally. Median macroalgal cover rose only slightly, from approximately 1.5% in 1997–2009 to 2.5% in 2020–2024 (Figure 2.7.4B). This limited response reflects the long-standing pattern of relatively low macroalgal dominance across Red Sea reefs [385, 386]. Environmental conditions such as limited nutrient input, high salinity, intense solar radiation, and strong herbivory pressure may restrict large-scale macroalgal proliferation and moderate competitive interactions with corals [83, 387].

The absence of a clear macroalgal phase shift suggests that other opportunistic benthic groups may be occupying space made available by coral mortality. In particular, turf algae are increasingly recognized as potential competitors on degraded reefs. Increased turf algal growth has been documented in parts of the Central Red Sea under conditions of nutrient enrichment and environmental disturbance, where it can expand rapidly and occupy available substrate [388]. Monitoring these benthic groups is therefore important for detecting early changes in reef community structure that may not be visible when examining macroalgal cover alone.

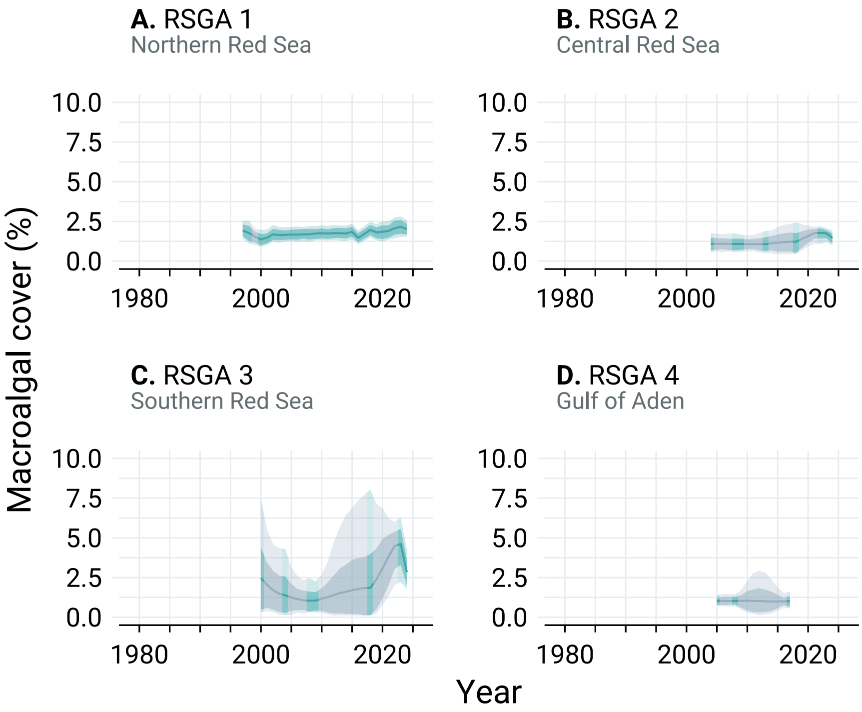
STATUS OF CORAL REEFS IN THE SUBREGIONS

RSGA 1 - Northern Red Sea

Coral reefs from the Northern Red Sea (subregion 1) showed consistent hard coral cover throughout 1997–2024, ranging from 23.0% to 35.3%. Hard coral cover declined after the 1998 coral bleaching event to 24.4% in 2000 (ranging from 18.5% to 30.9%). The 2016 mass bleaching event was the most significant event impacting this region, with the lowest recorded values reported (23.1%, ranging from 18.8% to 28%). However, after the 2016 mass bleaching event, hard coral cover has notably increased to 33.5% in 2020–2024, indicating long-term persistence and recovery potential (Figure 2.7.5A). Even during the 2010 and 2023–2024 heat stress events, declines were modest, and coral remained the dominant benthic component on Northern Red Sea reefs. Macroalgal cover remained very low at around 1.7% over the study period, suggesting limited phase shift potential. This sustained stability likely reflects naturally moderated SSTs, lower local disturbance, and adaptive traits in the coral assemblages that enhance tolerance to episodic heat stress, supporting the concept of a northern refugia [389].



▲ **Figure 2.7.5.** Modeled temporal trends of hard coral cover in Red Sea and Gulf of Aden (RSGA) subregions from 1980 to 2024. The solid line represents the estimated median hard coral cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.



▲ **Figure 2.7.6.** Modeled temporal trends of macroalgal cover in Red Sea and Gulf of Aden (RSGA) subregions from 1980 to 2024. The solid line represents the estimated median macroalgal cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.

RSGA 2 - Central Red Sea

Coral reefs in the Central Red Sea (subregion 2) experienced fluctuations over the 2004–2024 study period. Heat stress events in 2015–2016 and 2023–2024 led to a decline, with hard coral cover dropping by 15.9 and 5.3 percentage points, respectively (Figure 2.7.5B). However, macroalgal cover remained low at around 1.3% throughout the study period despite coral loss, suggesting that other benthic components, such as turf algae, may have occupied the newly available substrate [390]. The variability in coral cover likely reflects a combination of higher exposure to heat stress, localized human pressures, and site-specific ecological differences that influence recovery potential, emphasizing the vulnerability of these central coral reefs to recurrent stress.

RSGA 3 - Southern Red Sea

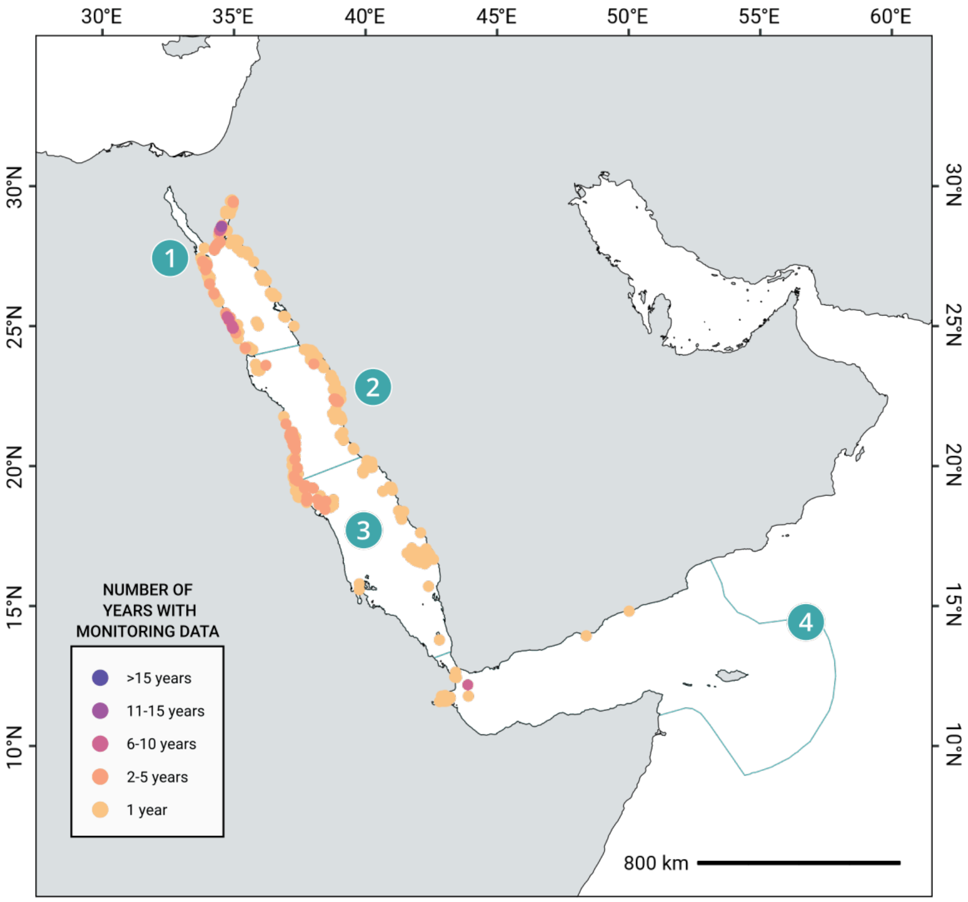
Coral reefs in the Southern Red Sea (subregion 3) are geographically isolated and less connected to neighbouring subregions [389]. The Southern Red Sea consistently had the highest median hard coral cover of all subregions, with an average of 38.5% from 2000 to 2024, with some years exceeding 45% (Figure 2.7.5C), highlighting strong coral dominance. Nonetheless, the extreme heat stress event of 2023–2024 caused severe declines in hard coral cover, which fell to 13.1% in 2024, highlighting the sensitivity of these reef habitats to prolonged and extreme warming. Macroalgal cover increased by 0.9% from 2018 to 2024, averaging at 2.8% in 2024 (ranging between 1.8% and 4.3%), but hard corals continued to dominate benthic cover. The Southern Red Sea region's prior high hard coral cover and subsequent sharp declines suggest that while favourable environmental conditions supported recovery after earlier bleaching events, extreme heat stress can override historical resilience, suggesting potential limits of coral persistence in the southern basin [390].

RSGA 4 - Gulf of Aden

Coral reefs in the Gulf of Aden (subregion 4) are less structurally developed than those within the Red Sea basin [383]. Available monitoring data for this subregion are limited, spanning 1999–2017, with no recent observations. During this period, hard coral cover ranged from 24.1% to 37.2% (Figure 2.7.5D), while macroalgal cover remained consistently low, averaging 1.0% (Figure 2.7.6D). The sparse temporal coverage and absence of post-2017 data constrain the assessment of current reef condition and longer-term trends.

DESCRIPTION OF MONITORING DATA

Trends in benthic cover across the Red Sea and Gulf of Aden region were derived from 14 datasets encompassing 502 monitoring sites and 903 surveys conducted between 1997 and 2024 (Table A.4).



▲ **Figure 2.7.7.** Spatio-temporal distribution of benthic cover monitoring sites across the Red Sea and Gulf of Aden region and respective subregions. Light blue polygons and numbers represent subregions. Subregion 1 = Northern Red Sea, Subregion 2 = Central Red Sea, Subregion 3 = Southern Red Sea, Subregion 4 = Gulf of Aden. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the region.

Spatial coverage of surveys was uneven among subregions: 67% of surveys (representing 53.2% of surveyed sites) were conducted in Northern Red Sea (subregion 1), whereas only 3.8% (5.6% of surveyed sites) were conducted in Gulf of Aden (subregion 4, Table A.4). The majority of surveys focused on shallow reef areas, at depths of less than 10 m (Figure A.2). This uneven effort shapes interpretation of benthic trajectories, emphasizing more confidence in the patterns observed in the Northern Red Sea (subregion 1) compared with the sparsely sampled Gulf of Aden (subregion 4).

Temporal trends in monitoring data across the four Red Sea and Gulf of Aden subregions also reflect these regional differences. The Northern Red Sea (subregion 1) has the most complete monitoring data, with consistent monitoring from the late 1990s through 2024 (Figure 2.7.7), providing a strong basis for evaluating long-term reef dynamics, resilience, and coral responses to repeated disturbance events over nearly three decades. Monitoring in Central Red Sea (subregion 2) and Southern Red Sea (subregion 3) began later and became more consistent from the early to mid-2000s, allowing assessment of reef condition across multiple environmental stress periods, although some gaps remain where surveys were not conducted. Gulf of Aden (subregion 4) has the most limited record, with observations only from the late 1990s to the late 2010s and no recent data, restricting evaluation of current reef status or comparisons with other subregions. Despite these limitations, the available observations provide a historical context for understanding regional benthic trends, highlighting areas of resilience and vulnerability, and emphasizing the need for expanded, sustained monitoring to support effective management and conservation strategies across all Red Sea and Gulf of Aden subregions.

CONCLUSIONS

The benthic cover results across the four Red Sea and Gulf of Aden subregions reveal distinct spatial patterns in hard coral and macroalgal dynamics from 1997 to 2024. Median hard coral cover was highest in the Southern Red Sea (subregion 3) and the Central Red Sea (subregion 2) during the early 2000s, exceeding 40% and 30%, respectively, whereas the Northern Red Sea (subregion 1) and Gulf of Aden (subregion 4) maintained lower but more stable hard coral cover, generally around 25–29% (Figure 2.7.5). Notably, reefs in the Northern Red Sea (subregion 1) remained comparatively stable even during major bleaching events that affected other parts of the Red Sea. This resilience likely reflects environmental buffering, cooler baseline temperatures, or the presence of heat-tolerant coral genotypes [389].

Macroalgal cover remained low across all subregions, generally below 2% cover, with only a slight increase in the Southern Red Sea (subregion 3) during 2020–2023 (Figure 2.7.6). These patterns suggest that coral declines did not result in a widespread shift to macroalgal dominance at the regional scale.

Overall, the modelled benthic trajectories from 1997 to 2024 highlight several important ecological patterns. First, hard coral cover exhibited alternating phases of stability, recovery, and recent rapid decline, reflecting the cumulative effects of repeated thermal stress events. Second, consistently low macroalgal cover indicates that large-scale shifts toward algal dominance have not occurred, although changes in other benthic groups may still be emerging. Third, the broad credibility intervals observed in several years point to strong spatial variability in reef condition, with some reefs maintaining relatively high hard coral cover while others experienced substantial declines.

Together, these results emphasize the complex interactions between climatic disturbances and local environmental conditions shaping reef trajectories across the Red Sea and Gulf of Aden. Although reefs in the region have historically shown resilience to bleaching events, the severe coral losses recorded during 2023–2024 demonstrate that even these systems are vulnerable to increasingly frequent and intense thermal stress. Continued long-term monitoring and adaptive management will therefore be essential to support the future condition and stability of these globally important reef ecosystems.

DATA CONTRIBUTORS

Mohammad S. Al-Tawaha, Khadija Y. I. Abaker, Swaleh Aboud, Mustafa K. Altaib, Maher Amer, Tamer Attalla, Chico Birrell, Graham J. Edgar, Elamin M. Elamin, Sheikheldin M. Elamin, Mohammed Elsayed, Jan Freiwald, Matthew Fynes, Jamie Hayes, Magda M. Ismael, Gareth John, Mohammed M. Kotb, Anderson B. Mayfield, Jenny Mihaly, Karin Moejes, David Obura, Elizabeth Oh, Osama S. Saad, Rick D. Stuart-Smith, Oliver Taylor.

Access to online supplementary materials

The modelled benthic cover data, detailed outputs from the data analyses, and the CRediT author contribution statement are available on Zenodo.

REFERENCES

17. Spalding, M. *et al.* Mapping the global value and distribution of coral reef tourism. *Marine Policy* **82,** 104–113 (2017).

83. Fabricius, K. E., Crossman, K., Jonker, M., Mongin, M. & Thompson, A. Macroalgal cover on coral reefs: Spatial and environmental predictors, and decadal trends in the Great Barrier Reef. *PLoS ONE* **18,** e0279699 (2023).

107. Skirving, W. *et al.* CoralTemp and the coral reef watch coral bleaching heat stress product suite version 3.1. *Remote Sensing* **12,** 3856 (2020).

108. Puotinen, M. *et al.* Towards modelling the future risk of cyclone wave damage to the world's coral reefs. *Global Change Biology* **26,** 4302–4315 (2020).

307. Veron, J., Stafford-Smith, M., DeVantier, L. & Turak, E. Overview of distribution patterns of zooxanthellate Scleractinia. *Frontiers in Marine Science* **1,** 81 (2015).

368. Fine, M. Gulf of Aqaba as a thermal refuge: Insights from four years of intensifying marine heatwaves. *Science of the Total Environment* **1000,** 180463 (2025).

369. Eladawy, A. *et al.* Appraisal of coral bleaching thresholds and thermal projections for the northern Red Sea refugia. *Frontiers in Marine Science* **9,** 938454 (2022).

370. Evensen, N. R., Fine, M., Perna, G., Voolstra, C. R. & Barshis, D. J. Remarkably high and consistent tolerance of a Red Sea coral to acute and chronic thermal stress exposures. *Limnology and Oceanography* **66,** 1718–1729 (2021).

371. Kleinhaus, K. *et al.* Science, diplomacy, and the Red Sea's unique coral reef: It's time for action. *Frontiers in Marine Science* **7,** 90 (2020).

372. Fine, M., Gildor, H. & Genin, A. A coral reef refuge in the Red Sea. *Global Change Biology* **19,** 3640–3647 (2013).

373. Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA). *State of the marine environment, report for the Red Sea and Gulf of Aden: 2006* (2006).

374. Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA). *Regional action plan for the conservation of marine turtles and their habitats in the Red Sea and Gulf of Aden* (2004).

375. Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA). *The status of coral reefs in the Red Sea and Gulf of Aden: 2009* (2010).

376. Pilcher, N. & Alsuhaibany, A. *Regional status of coral reefs in the Red Sea and the Gulf of Aden — Middle East — 2000* (2000).

377. ResourceWatch. *Coral reefs: Red Sea and Gulf of Aden: Importance, status and outlook for coral reefs in the Red Sea and Gulf of Aden region*

378. Hamdeno, M., Alvera-Azcárate, A., Krokos, G. & Hoteit, I. Investigating the long-term variability of the Red Sea marine heatwaves and their relationship to different climate modes: Focus on 2010 events in the northern basin. *Ocean Science* **20,** 1087–1107 (2024).

379. Darmaraki, S., Krokos, G., Genevier, L., Hoteit, I. & Raitsos, D. E. Drivers of marine heatwaves in coral bleaching regions of the Red Sea. *Communications Earth & Environment* **6,** 120 (2025).

380. Foster, G. & Rahmstorf, S. Global warming has accelerated significantly. *Geophysical Research Letters* **53,** e2025GL118804 (2026).

381. Hanafy, M. H. & Dosoky, M. Y. *Coral bleaching event of 2023: Exploring distribution, sensitivity, and recovery potential on the Egyptian coast of the Red Sea* (2024).

382. Hanafy, M. H. *et al. Red Sea coral bleaching event, the 2024 coral bleaching event and recovery along the Egyptian Coast* (2025).

383. El-Naggar, H. A. in *Natural Resources Management and Biological Sciences* (eds Rhodes, E. R. & Humood, N.) chap. 5 (IntechOpen, 2020).

384. Rashed, A. & Ibrahim El-Belkasy, M. Sustainable development, tourism and heritage in Red Sea regions: Blue growth and value chain between competition and integration. *International Journal of Multidisciplinary Studies in Architecture and Cultural Heritage* **5,** 280–303 (2022).

385. Lei, X. *et al.* The impact of macroalgae on reef-building corals depends on their species, density, and contact status. *Global Ecology and Conservation* **54,** e03201 (2024).

386. Aeby, G. S. *et al.* in *Coral Reefs and Associated Marine Fauna around the Arabian Peninsula* 1st, 60–76 (CRC Press, 2024).

387. Adam, T. C. *et al.* Priority effects in coral-macroalgae interactions can drive alternate community paths in the absence of top-down control. *Ecology* **103,** e3831 (2022).

388. Karcher, D. B. *et al.* Nitrogen eutrophication particularly promotes turf algae in coral reefs of the central Red Sea. *PeerJ* **8,** e8737 (2020).

389. Osman, E. O. *et al.* Thermal refugia against coral bleaching throughout the northern Red Sea. *Global Change Biology* **24** (2018).

390. Gonzalez, K. *et al.* Differential spatio-temporal responses of Red Sea coral reef benthic communities to a mass bleaching event. *Scientific Reports* **14,** 24229 (2024).