

REGIONAL REPORT V.0

Red List of Ecosystems assessment of Red Sea and Gulf of Aden coral reefs

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Red List of Ecosystems; coral reefs; ecosystem collapse; risk assessment; Red Sea; Gulf of Aden

ABSTRACT

The Red Sea and Gulf of Aden constitute a complex and globally significant tropical marine ecosystem characterized and long recognized by exceptional biological diversity and a high degree of endemism. Overall, the region contains an estimated 13,118 km² of coral reefs, representing around 7% of the photic coral reef area assessed globally in the Red List of Ecosystems (5.0% of global coral reef extent according to GCRMN 2025). These exceptional coral reefs are facing increasing pressure from marine heatwaves, coastal development, overfishing, pollution, tourism and recreation, and biological disturbances, though their risk status has not previously been evaluated.

Here, we present the first regional IUCN Red List of Ecosystems (RLE) assessment of coral reef collapse risk in this system, integrating biological observations spanning 1969 – 2025 to estimate change in functioning reef distribution (Criterion A) and biotic condition (Criterion D), combined with mapped reef distribution (Criterion B), historical thermal stress (Criterion C1), and future climate projections (Criterion C2). Current ecosystem risk varied spatially, with the Northern Red Sea (NRS) and Gulf of Aden (GoAden) classified as Vulnerable, and the Central Red Sea (CRS) and Southern Red

Sea (SRS) as Endangered. In the NRS, risk based on observed change was driven primarily by thermal-related environmental degradation, whereas change in reef distribution and biotic condition remained least concern; this favorable condition is consistent with documented coral thermal resilience. The Endangered status of the CRS reflected greater biotic degradation alongside continued environmental pressure, while the SRS showed greater change in both reef distribution and biotic condition. GoAden's overall risk was derived from Criteria B and C, with Criteria A and D assessed as Data Deficient; its classification may be revised upward as additional biological data become available. Despite these differences in risk based on observed change, projected increases in extreme thermal stress resulted in all four ecoregions being classified as Critically Endangered under future climate-driven decline. The spatial differences in current ecosystem risk highlight the importance of protecting reefs that remain in comparatively good condition and supporting recovery where ecological change is more evident, while the shared future climate risk emphasizes the need to strengthen climate adaptation, reduce locally manageable pressures, and accelerate global action to limit climate change.

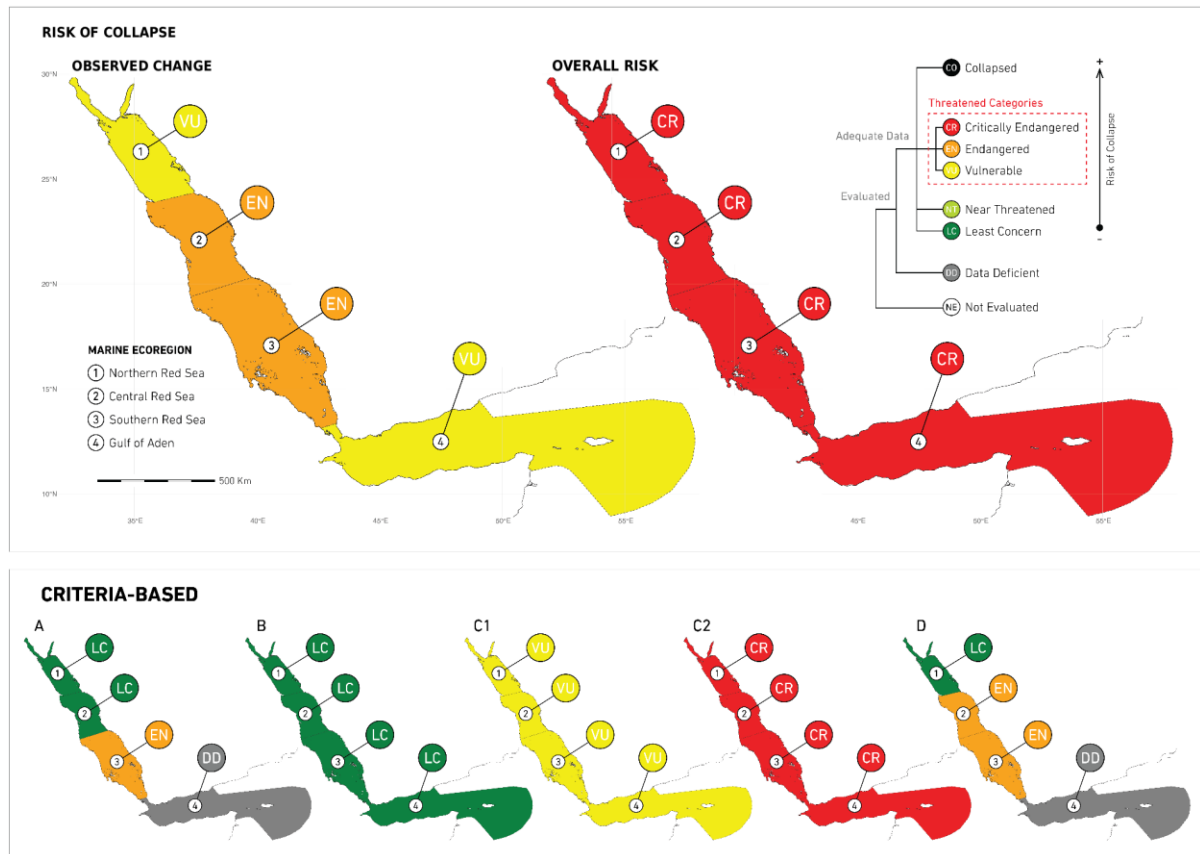


Figure 1. Overall and criteria-based RLE risk status of coral reef ecoregions in the Red Sea and Gulf of Aden. The upper panels show observed change (past 50 years; Criteria A, B, C1 and D) and overall risk status, including projected heat stress (Criterion C2) under the SSP2-4.5 climate scenario. The lower panels show the individual classifications for Criteria A–D across the four ecoregions.

1. Study Area

This Red List of Ecosystems (RLE) assessment evaluates the risk of collapse for coral reefs across the Red Sea and Gulf of Aden as of 2025. The Red Sea and Gulf of Aden coral reefs (IUCN Global Ecosystem Typology M1.3 - photic coral reefs) extend across over 2,250 km from the tips of the Gulfs of Suez & Aqaba (30°N) to the Bab al-Mandab strait in the south (~12.38°N) and out into the Indian Ocean extending eastward to approximately 54°E and southward to 10°N (Fig 2). The region is bounded by nine countries: Djibouti, Egypt, Eritrea, Israel, Jordan, Saudi Arabia, Somalia, Sudan, and Yemen (Fig. 2). The Red Sea and Gulf of Aden constitute a complex and globally significant tropical marine ecosystem characterized and long recognized by exceptional biological diversity and a high degree of endemism (Pilcher & Alsuhaibany, 2020). Overall, the region contains an estimated 13,118 km² of coral reefs,

representing around 7% of the photic coral reef area assessed globally in the Red List of Ecosystems (5.0% of global coral reef extent according to GCRMN 2025) (Amer et al., 2026; Wild et al., 2011). (Pilcher & Alsuhaibany, 2020)(Amer et al., 2026; Wild et al., 2011)

Coral reefs of the Red Sea and Gulf of Aden were previously classified into three ecoregions under the Marine Ecoregions of the World (MEOW) framework (Spalding et al., 2007) and have since been updated in the GCRMN 2026 regional chapter to four ecoregions: Northern Red Sea (NRS), Central Red Sea (CRS), Southern Red Sea (SRS), and Gulf of Aden (GoAden) (Amer et al., 2026). These boundaries were refined using published research (Cerutti et al., 2025) and local expert knowledge. These coral reef ecoregions capture ecological variation in coral reef biodiversity (e.g., DiBattista et al., 2016; Macrina et al., 2025; Oury et al., 2025; PERSGA, 2010), environmental variables (e.g., salinity, temperature, chlorophyll; Ngugi et al., 2012; Raitso et al., 2013), and exposure to threats (e.g., destructive fishing practices, development, tourism, climate change; Amer et al., 2026; Bruckner et al., 2012; Hilmi et al., 2025; PERSGA, 2010; Sarant, 2020; Tilot et al., 2008), and are equivalent to level 4 of the IUCN Global Ecosystem Typology (regional sub-groups). Coral reefs in each ecoregion were independently assessed using the IUCN Red List of Ecosystems criteria (details on data collection/ monitoring in annex 1).

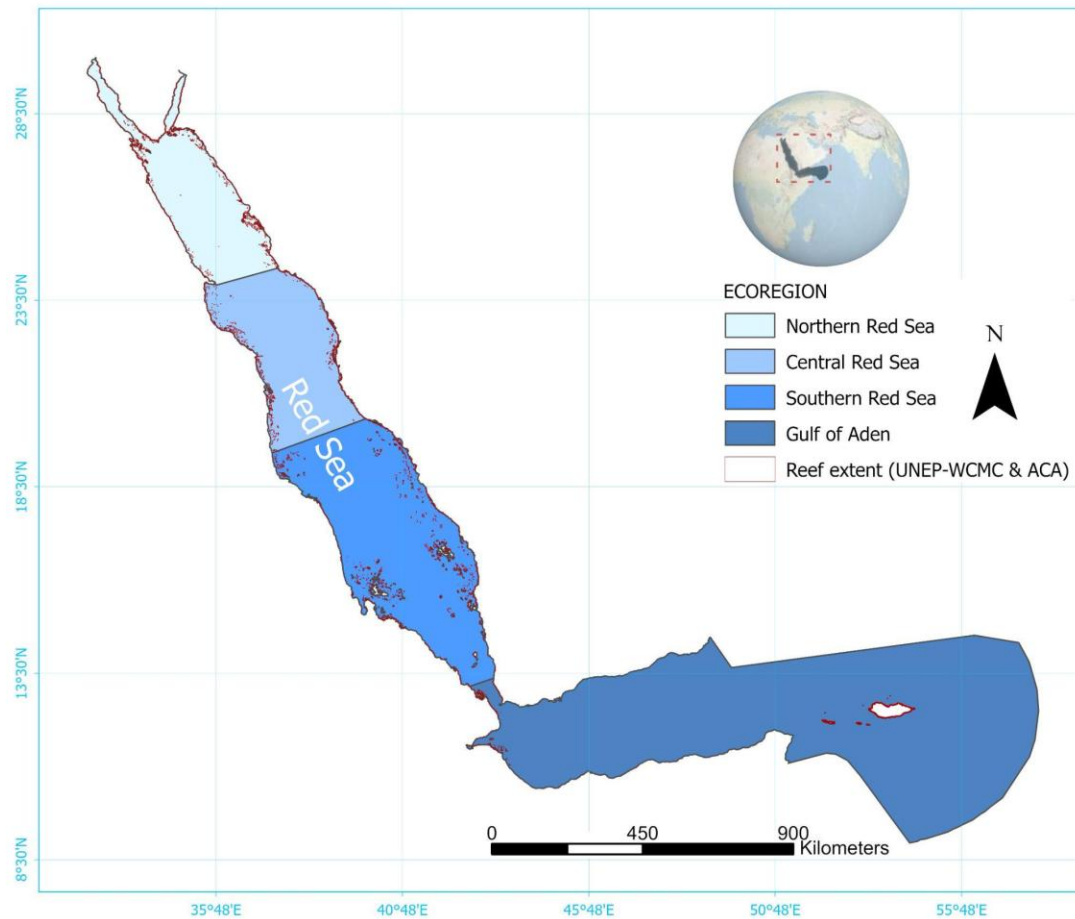


Figure 2. Coral reefs of the Red Sea and Gulf of Aden, grouped within coral reef ecoregions (Units of Assessment) evaluated under the IUCN Red List of Ecosystems criteria and corresponding to Level 4 of the IUCN Global Ecosystem Typology.

2. Ecosystem Description

2.1. Overview

Reef-building Scleractinia corals form the structural foundation of coral reef ecosystems, including those of the Red Sea and Gulf of Aden, providing the primary framework that underpins habitat complexity and associated biodiversity (Wild et al., 2011). The region's reef systems are highly diverse in form and origin, reflecting its unique geological history as a relatively young, tectonically active basin. All major reef types occur in the region, including barrier reefs and extensive fringing reefs and patch reefs bordering the coasts and islands of Djibouti, Egypt, Eritrea, Jordan, Saudi Arabia, Sudan, and Yemen. There is one atoll, Sanganeb, and pinnacle reefs in the central and southern Red Sea (Kotb et al., 2004). Coral reef development is limited by cold seasonal upwelling in the Gulf of Aden off Djibouti, northern

Somalia and Yemen. Many fringing reefs in clearer water have high coral cover close inshore and around islands away from the shore. The most abundant reef type in the Red Sea is a fringing reef (Kotb et al., 2004).

The Red Sea represents a key region of coral communities, with both endemic and widespread species throughout the tropical Indo-Pacific area (Berumen et al., 2019). Within these frameworks, benthic communities are highly complex and dynamic as they are throughout most of the tropics, comprising diverse coral assemblages alongside macroalgae, turf algae, crustose coralline algae (CCA), and invertebrate and microbial components that collectively structure reef functioning. However, recent evidence indicates a gradual shift in community composition towards increased dominance of macroalgae, turf algae, and CCA in some areas (Gonzalez et al., 2024), reflecting changing ecological balances across the region. These responses are not uniform spatially, with coral communities in southern regions typically showing more rapid and pronounced changes compared to northern and central reefs (Gonzalez et al., 2024). In addition, coral assemblage structure also varies with depth and distance from shore, with inner shelf reefs showing lower coral abundance and diversity but higher macroalgal cover, likely driven by nutrient gradients, while adjacent soft sediments show higher inshore diversity indicative of mild disturbance (Ellis et al., 2017).

2.2. Key Biotic Components

The region supports approximately 94 genera and more than 350 species of Scleractinia corals, alongside over 1,250 fish species, highlighting its high biological richness (Arrigoni et al., 2019; Berumen et al., 2019; Golani & Fricke, 2026; Oury et al., 2025; Ryanskiy, 2022; Terraneo et al., 2019). At the genus level, diversity is largely shared across ecoregions, with ~56 genera occurring throughout the system, including *Porites* and *Acropora* (Berumen et al., 2019; Voolstra & Berumen, 2019). In contrast, within the Red Sea and Gulf of Aden region, around 10 genera are restricted to the Red Sea, such as *Podabacia* and *Ctenactis*, and 3 to the Gulf of Aden, including *Isopora*, *Heteropsammia*, and *Cyathelia* (Berumen et al., 2019; Voolstra & Berumen, 2019). This biodiversity is further characterized by high levels of endemism, with fish endemism reaching around 14.7% in the Red Sea and 4.6% in the Gulf of Aden (Bogorodsky & Randall, 2018), reflecting long-term isolation and strong biogeographic structuring across the region. These patterns are driven by restricted exchange through the Bab el-Mandeb Strait into the Gulf of Aden, environmental gradients

along the basin, and constricted conditions in the northern Gulf of Aqaba, all shaped by the region's unique geological history (DiBattista et al., 2016).

Benthic assemblages build on this coral framework including crustose coralline algae, turf algae, macroalgae, soft corals, and associated invertebrates. These communities are diverse and highly varied in the Red Sea, reflecting strong habitat heterogeneity across reef zones (e.g., flats, slopes, lagoons, and deeper reef zones), with benthic mosaics varying along environmental gradients such as depth (Carvalho et al., 2023; Ellis et al., 2017). In addition, shifts in benthic dominance between coral-, algal-, and mixed assemblages are commonly observed across reef zones (Gonzalez et al., 2024), highlighting the dynamic balance between biogenic calcification and algal proliferation within Red Sea reef ecosystems (Isaak et al., 2024).

Reef fish communities are a critical component of coral reef ecosystems, playing key functional roles in maintaining ecosystem processes and resilience. However, studies on reef fish abundance in the Red Sea remain relatively limited (Angulo-Preckler et al., 2024). Similar to other coral reef systems, herbivorous fishes, particularly parrotfishes (Scarinae) and surgeonfishes (Acanthuridae), play a central role in regulating algal growth and mediating coral-algal interactions, thereby facilitating coral recruitment and recovery (Jessen & Wild, 2013; Khalil et al., 2013; Tietbohl, 2022), with parrotfishes often reported as among the most abundant functional groups (Hoey et al., 2016). In contrast, piscivorous fishes, including top predators, have been recorded at relatively low abundance across many parts of the Red Sea (Syafuruddin et al., 2024; C. T. Williams et al., 2024).

Beyond corals, benthic assemblages, and reef fishes, Red Sea coral reef biota extends to a diverse range of associated organisms that support ecosystem structure and functioning. Macrobenthic communities show high small-scale heterogeneity, low dominance, and a large proportion of rare species, with assemblage structure driven mainly by species turnover (Carvalho et al., 2023). The region also supports diverse megafauna, including at least 17 cetacean species (Costa et al., 2018), as well as elasmobranchs and sea turtles, with over 75% of recorded species of conservation concern (Garzon et al., 2022). Sea turtles are dominated by hawksbill (*Eretmochelys imbricata*) and green (*Chelonia mydas*) turtles, with records of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) (Mancini et al., 2015). In addition, reef-associated calcifiers such as giant clams contribute to reef building, accounting for an estimated 0.7% on average and up to 9% of the Red Sea coral reef calcium carbonate

budget (Rossbach et al., 2021), highlighting their role in sustaining reef framework development.

2.3. Key Abiotic components

The Red Sea ecosystem is structured by extreme latitudinal gradients in temperature, salinity, and chlorophyll, which are primarily driven by its semi-enclosed nature and the seasonal exchange with the Indian Ocean. A defining feature is the north-south thermal gradient, where sea surface temperatures (SST) range from a winter low of 14–21°C in the northern Gulfs to summer maxima exceeding 33°C in the southern Farasan Banks (Chaidez et al., 2017; Ngugi et al., 2012; Sawall et al., 2014). This is coupled with a pronounced salinity gradient that increases from 36.5 PSU at the Bab el-Mandeb to over 41 PSU in the north, as intense evaporation occurs in the absence of riverine input (N. M. Rasul et al., 2018). These variables create a continuous but highly heterogeneous environment, making the placement of rigid ecoregional boundaries a persistent challenge for management (Cerutti et al., 2025).

A critical driver of this structure is the summertime intrusion of Gulf of Aden Intermediate Water (GAIW), which introduces relatively cool, nutrient-rich water into the southern and central Red Sea. This influx not only drives a north-south gradient in chlorophyll-a and primary productivity but also provides localized "thermal subsidies" that can temporarily decouple reef-water temperatures from regional SST trends (DeCarlo et al., 2021a). Such oceanographic complexity, including mesoscale eddies and wind-driven upwelling, ensures that while the ecosystem is longitudinally linked, local abiotic conditions can vary significantly over short distances and seasonally, further complicating basin-wide regionalization efforts (Cerutti et al., 2025; Raitsos et al., 2013).

In addition to the three ecoregions within the Red Sea (northern, central, and southern), and the Gulf of Aden represents a distinct fourth ecoregion characterized by a dynamic, monsoon-driven abiotic regime. Seasonal wind patterns drive coastal upwelling along the Arabian and Somali coasts, increasing nutrient availability and productivity (Wilson et al., 2000), while exposure and upwelling gradients strongly influence coral community structure and reef-building potential (Benzoni et al., 2003). The region also shows pronounced seasonal variability in temperature, with relatively stable but lower salinity than the Red Sea (El-Mashjary & Ali, 2010). These conditions create a transitional environment that can limit coral recruitment and distinguish the Gulf of Aden from the more stable and extreme conditions of the Red Sea (Wilson et al., 2000).

2.4. Key processes and interactions

Ecological persistence in the Red Sea is governed by a complex web of trophic interactions and responses to environmental and anthropogenic pressures, as summarized in the conceptual model (Figure 3). The model highlights key interactions among corals, algae and reef fishes, and illustrates how these relationships are influenced by major pressures including ocean warming, overfishing, coastal development, and associated nutrient and sediment inputs. The components carried forward into the regional assessment were guided by the availability and comparability of data across the region. Accordingly, the assessment focused on hard coral and algae as the major biotic components, and ocean warming as the principal pressure for which data could be consistently applied at the regional scale.

The interaction between hard corals and algae is central to reef condition and trajectories of change (Manikandan, 2025). Following disturbances or reductions in hard coral cover, benthic communities often shift toward increased dominance of macroalgae and turf algae, altering competitive interactions and ecosystem trajectories (Gonzalez et al., 2024). The balance between coral and algal dominance remains a key determinant of ecosystem condition, stability, and resilience. While specific data on Red Sea herbivory remains limited, it is functionally similar to other Indo-Pacific systems where grazing by parrotfishes (*Scarinae*) and surgeonfishes (*Acanthuridae*), among other herbivores, is key for suppressing algal growth and clearing space for corals (Bonaldo & Bellwood, 2009). However, chronic overfishing has led to the depletion of both apex predators and key herbivores, particularly in the central and southern sectors, potentially triggering top-down cascades that compromise the reef's ability to recover from acute disturbances (Kattan et al., 2017). The structural integrity of these reefs further relies on the interaction between scleractinian calcification and bioerosion, a balance that is increasingly threatened by shifting environmental baselines (Riegl et al., 2012).

A fundamental biotic process is the regional adaptation of Red Sea corals to thermal thresholds that are significantly higher than those in other ocean basins. While corals in the northern Red Sea have historically benefitted from a wide thermal safety margin, many populations in the central and southern regions are currently living at or near their physiological limits (Osman et al., 2018; Voolstra et al., 2021; Ziegler et al., 2019). Nonetheless, this system is also characterized by environmental resilience to elevated temperature, salinity, and alkalinity in a quasi-isolated basin, including potential thermal refuges that may buffer climate-driven impacts (Berumen et al., 2019; DiBattista et al., 2016;

Fine et al., 2013; Osman et al., 2018). This "thermal screening" legacy is now being tested by the trajectory of modern climate change. Recent thermal anomalies, including the 2023–2024 bleaching event, show increasing bleaching intensity and impacts (e.g., mortality) throughout the entire Red Sea; though most of the NRS may have experienced limited impacts from thermal bleaching and associated mortality, it is not immune to these effects (Ben Zion, 2025; Kochman-Gino & Fine, 2023).

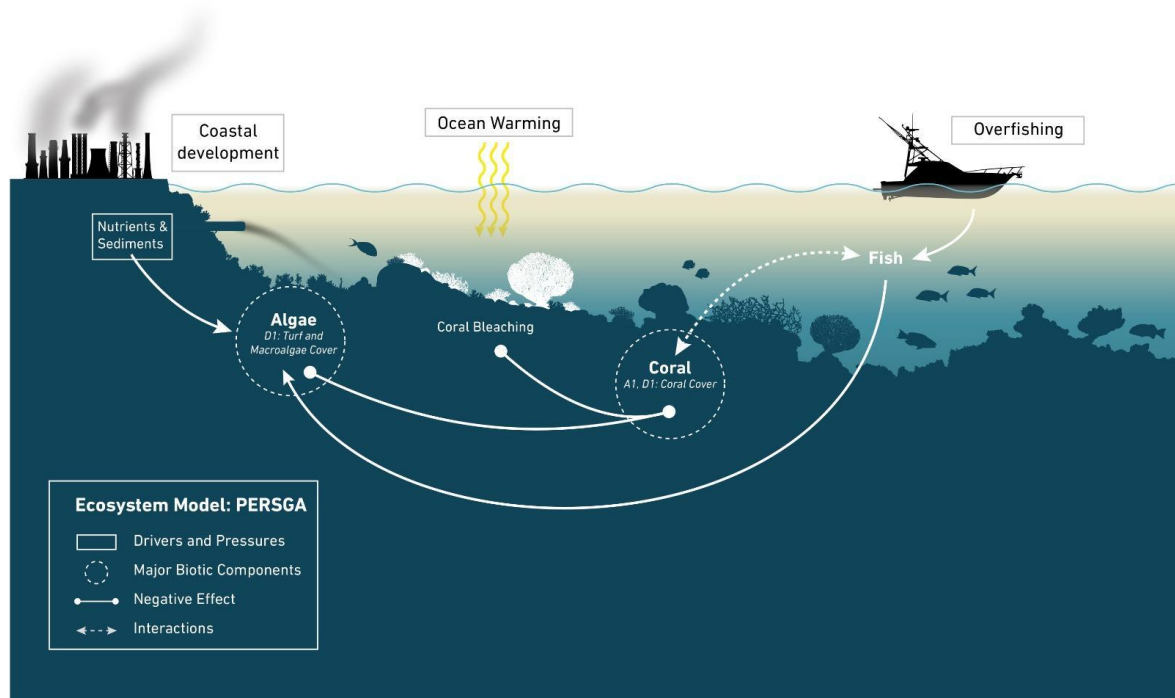


Figure 3. Conceptual model of the Red Sea and Gulf of Aden coral reef ecosystems. The model illustrates key biotic and abiotic components, as well as external drivers, threats, and the processes and interactions between them.

2.5. Main Threats

The Red Sea is unusual among major coral reef regions in having no permanent riverine discharge and, because of its narrow and enclosed configuration, generally low wave exposure and infrequent severe storms (Gladstone et al., 1999). Consequently, the threat landscape is dominated by two primary branches: global climatic stress and localized anthropogenic development (Table 1). The most immediate and severe threat is climate change-driven warming, characterized by increasingly frequent and intense marine heatwaves (MHWs, (Genevier et al., 2019; Hanafy et al., 2024, 2025b). The 2023 and 2024 bleaching events, which reached record heat stress levels across the NRS (e.g., Kochman-Gino

& Fine, 2023), have demonstrated that climatic warming is now capable of impacting Red Sea corals across the entire basin. In the Gulf of Aden, reefs also face local pressures from fishing, coastal development, and pollution, alongside rising heat stress (Table 1).

The second branch of threats involves rapid coastal development and the associated pressures of overfishing and poor resource management. The scale of these varies significantly across nations. Egyptian coral reefs bring in millions of tourists (Crawford, 2015) while large-scale tourism is completely absent or highly limited in other nations (e.g., Eritrea, Yemen). While tourism remains a vital economic driver, its associated impacts, if poorly managed, contribute to a cumulative degradation that threatens to transition the ecosystem toward a collapsed state (Riegl et al., 2012). Both planned and ongoing large-scale industrialization and giga-projects (e.g., NEOM and Red Sea Global in the north) introduce localized stressors such as dredging, or other industrialized activities, such as nearshore fish aquaculture. Furthermore, the artisanal and commercial over-extraction of key fish species may reduce the functional redundancy of the system, making reefs more susceptible to phase-shifts following bleaching or outbreaks of the crown-of-thorns starfish (e.g., *Acanthaster spp.* Doll et al., 2026). This fishing pressure has already resulted in marked alterations in fish community structure, particularly through the depletion of top predators, with potential cascading effects on trophic dynamics and overall ecosystem stability (Kattan et al., 2017).

Table 1. Occurrence of major threats impacting coral reefs in each ecoregion categorized based on the IUCN Threat Classification Scheme

Threat type	Subcategory	Ecoregion			
		NRS	CRS	SRS	GoAden
1. Residential & Commercial Development	1.1 Housing & Urban Areas	✓	✓	✓	✓
	1.2 Commercial & Industrial Areas	✓	✓	✓	✓
	1.3 Tourism & Recreation Areas	✓	✓	+	✓
2. Agriculture & Aquaculture	2.1 Marine & Freshwater Aquaculture	✓	✓	✓	✓
3. Energy Production & Mining	3.1 Oil & Gas Drilling	✓	+	✓	✓
	3.2 Mining & Quarrying	✓	✓	✓	✓
	3.3 Renewable Energy	+	+	+	+
4. Transportation & Service Corridors	4.1 Shipping Lanes	✓	✓	✓	✓
5. Biological Resource Use	5.1 Fishing & Harvesting Aquatic Resources	✓	✓	✓	✓
6. Human Intrusions & Disturbance	6.1 Recreational Activities	✓	✓	✓	✓
	6.2 War, Civil Unrest, Military Exercises	–	✓	✓	✓
	6.3 Work & Other Activities	✓	✓	✓	✓
7. Natural System Modifications	7.1 Other Ecosystem Modifications	✓	✓	✓	✓
	8.1 Invasive Non-Native/Alien Species/Diseases	✓	✓	✓	✓
	8.2 Problematic Native Species/Diseases	✓	✓	✓	✓

Threat type	Subcategory	Ecoregion			
		NRS	CRS	SRS	GoAden
8. Invasive & Other Problematic Species, Genes & Diseases	8.3 Introduced Genetic Material	+	+	+	+
9. Pollution	9.1 Domestic & Urban Wastewater	✓	✓	✓	✓
	9.2 Industrial & Military Effluents	✓	✓	✓	✓
	9.3 Agricultural & Forestry Effluents	✓	✓	✓	✓
	9.4 Garbage & Solid Waste	✓	✓	✓	✓
	9.5 Air-Borne Pollutants	✓	✓	✓	✓
	9.6 Excess Energy	✓	✓	✓	✓
10. Geological Events	10.1 Volcanoes	–	–	+	–
	10.2 Earthquakes/Tsunamis	✓	–	✓	✓
11. Climate Change & Severe Weather	11.1 Habitat Shifting & Alteration	✓	✓	✓	✓
	11.2 Temperature Extremes	✓	✓	✓	✓
	11.3 Storms & Flooding	✓	✓	✓	✓

2.6. Definition of the collapsed state of the ecosystem

Ecosystem collapse represents the final stage of degradation, signifying a transformation of the defining abiotic features or biotic communities and their subsequent contributions to functional processes (e.g., herbivory, reef accretion). This state can result from a number of pathways that reduce the capacity of an ecosystem to sustain its characteristic biota, such as disease, overharvesting, or a persistent change in environmental conditions. Collapse can occur locally, for example in a single reef, or over larger regional scales. For an ecosystem type to be classified as ‘Collapsed’, it must have fully declined or degraded across its entire distribution, although recovery may still be possible under conducive conditions (Obura et al., 2021).

For coral reefs, collapse is signaled by the near or complete loss of hard corals to levels where defining processes such as carbonate accretion are absent (or negligible). A collapsed reef would have extremely low coral richness and diversity, with communities dominated by a few weedy or stress-tolerant species. Collapsed coral reefs are often characterized by a phase shift from coral dominance to high abundances of other benthic components, such as turf and/or fleshy algae, rubble, sediments and sponges or other filter-feeding invertebrates (Goatley et al., 2016; Roff et al., 2015; Tebbett et al., 2025). This state is also associated with low abundance and diversity of other key biodiversity, including altered fish communities (Ainsworth & Mumby, 2015; Cruz et al., 2015). In some cases, collapse corresponds to a simplified topographic structure or occurs where the geomorphological structure of coral reefs permanently disappears through land reclamation or coastal development. A collapsed

reef may have an unsuitable abiotic environment due to declines in water quality, increases in temperature, as well as frequent and severe disturbance events.

Under the Red List of Ecosystems framework, collapse can be defined as when key biotic or abiotic indicators reach thresholds where the ecosystem's defining features are (or would be) lost.

For this assessment, the coral reef ecosystem of the Red Sea and Gulf of Aden is defined as 'Collapsed' if any of the following thresholds are met:

- a. complete loss of coral reef area [geographic distribution reaches zero],
- b. hard coral cover falling below 10%,
- c. sea surface temperatures exceeding critical thresholds, resulting in frequent and severe heatwaves and coral bleaching at an average return time between events of [5 years or less],

In addition, the following biotic indicators reflect severe functional degradation but not complete ecosystem collapse, and can be used to elevate risk levels:

- a. an algal-to-coral cover ratio exceeding 5:1,
- b. all 'functionally important' coral species being Critically Endangered under the RLTS including *Acropora* spp. *Pocillopora* spp. *Stylophora* spp., *Porites* spp. and other reef building scleractinian corals,
- c. severe depletion of key fish groups [e.g., herbivores and piscivores to levels well below historical baselines (Kattan et al., 2017).

Table 2. Key abiotic and biotic features and characteristics of the coral reef's ecoregions in the Red Sea and Gulf of Aden highlighting unique aspects of each ecosystem.

Ecoregion	Key Biotic	Key Abiotic	Key Threats
NRS	Reef communities are characterized by high hard coral cover, creating structurally complex habitats that support diverse reef fish assemblages (Kleinhaus et al., 2020; PERSGA, 2010). Corals in this region exhibit exceptional thermal tolerance, making the northern Red Sea a potential global climate refugium under future ocean warming (Fine et al., 2013; Hanafy et al., 2024, 2025a; Kleinhaus et al., 2020; Osman et al., 2018). Both turf algae and macroalgae interact with corals, but turf algae are the dominant competitors and cause the greatest tissue damage, while herbivorous fishes regulate algal growth and help maintain coral dominance (Haas et al., 2010; Jessen & Wild, 2013).	The northern Red Sea is characterized by warm, oligotrophic waters with pronounced seasonal variability in temperature, salinity, and nutrient availability (Haas et al., 2010; N. M. A. Rasul et al., 2019). Winter cooling promotes nutrient enrichment and seasonal phytoplankton bloom despite generally low chlorophyll- <i>a</i> concentrations (Acker et al., 2008). Although sea surface temperature is a key driver of coral bleaching, the northern Red Sea experiences comparatively lower thermal stress than the central and southern regions, contributing to its lower bleaching susceptibility and recognition as a potential climate refugium (Cerutti et al., 2025; Kleinhaus et al., 2020).	Fishing and expanding aquaculture, shipping, and coastal/industrial development dominate human pressures, with additional impacts from pollution and localized tourism. The system remains relatively less industrialized in some areas but is highly sensitive to disturbance. Marine heatwaves are increasingly stressing coral reefs through bleaching and mortality, despite the region's role as a potential coral refugia.
CRS	Reef communities retain structurally complex frameworks built by hard corals that continue to support diverse reef fish assemblages, despite widespread reductions in live coral cover following the 2015–2016 and 2023–2024 mass bleaching events (Amer et al., 2026; Dunn et al., 2025; Gonzalez et al., 2024). Repeated thermal stress has increased bleaching-related mortality and reduced skeletal growth of massive reef-building corals by approximately 30% since 1998, indicating declining reef-building capacity under continued ocean warming (Cantin et al., 2010). Declining coral cover has increased benthic space for both turf algae and macroalgae, with turf algae emerging as the dominant competitors on degraded reefs (Gonzalez et al., 2024). Despite these disturbances, coral disease prevalence remains relatively low, suggesting that thermal stress remains the primary driver of coral decline in the central Red Sea (Aeby et al., 2021).	The central Red Sea exhibits strong cross-shelf environmental gradients, with nutrients, chlorophyll- <i>a</i> , turbidity and sedimentation varying substantially from coastal to offshore reefs (Roik et al., 2016). Summer temperatures can exceed 30°C, exposing reefs to substantial thermal stress and making marine heatwaves an important environmental driver of bleaching and coral mortality (Krokos et al., 2019).	This is the most intensively used section, where urban and industrial development, shipping, and pollution are strongly concentrated. Fishing and aquaculture pressures continue to rise, alongside invasive species and localized disturbance. Marine heatwaves act as the dominant ecological stressor, compounding already high cumulative human impacts.
SRS	Southern Red Sea reef communities show high spatial variation, with inner-shelf reefs supporting lower abundance and diversity of hard corals and higher macroalgal cover than offshore reefs (Ellis et al., 2017). Coral and algal community structure varies with location and depth, reflecting strong cross-shelf ecological gradients (Ellis et al., 2017). Herbivory is also an important ecological process, with parrotfishes dominating the species richness and biomass of roving herbivorous fishes and their distribution changing	The southern Red Sea is characterized by high water temperatures and stronger seasonal oceanographic variability than regions farther north. Summer monsoon winds drive seasonal upwelling, particularly around the Farasan Banks, temporarily cooling reef waters and influencing local thermal conditions. The timing and strength of this upwelling can modulate maximum summer temperatures and consequently coral exposure to thermal stress (DeCarlo et al., 2021b).	A combination of expanding infrastructure (ports, tourism, mining) and growing fishing and aquaculture activity shapes human pressure, with additional influence from conflict-related disturbance and variable governance. Ecosystem modification and development are emerging concerns. Marine heatwaves remain a major driver of coral stress alongside these human pressures.

Ecoregion	Key Biotic	Key Abiotic	Key Threats
	seasonally in association with algal availability and extreme summer temperatures (Afeworki et al., 2013).		
GoAden	Coral communities in the Gulf of Aden are highly spatially variable, ranging from high-cover coral assemblages and diverse coral and fish communities in Djibouti to more restricted and locally dominated coral communities along the Yemeni coast, with community structure strongly influenced by exposure and upwelling (Benzoni et al., 2003; Cowburn et al., 2019; PERSGA, 2010).	The Gulf of Aden is strongly influenced by monsoon-driven upwelling, producing pronounced seasonal variation in water temperature and nutrient conditions that strongly influence coral community structure and reef development (Benzoni et al., 2003; El-Mashjary & Ali, 2010).	Shipping corridors and conflict-related disturbance are the most distinctive human pressures, alongside fishing, aquaculture, and coastal development. Impacts are spatially patchier than in the Red Sea but strongly influenced by geopolitical instability. Pollution and invasive species add further stress, while marine heatwaves intensify coral bleaching and mortality.

3. Criterion Assessment

Coral reefs in four ecoregions within the Red Sea and Gulf of Aden were assessed using IUCN Red List of Ecosystems (RLE) Criteria A–D. The assessment criteria, indicators and data used are summarized in Table 3. The following section briefly describes the approach used for each criterion, with detailed methods presented in the Annex.

1.1. Criterion A — Decline in Distribution

Decline in distribution of coral reefs over the past 50 years was assessed using hard coral cover data and was calculated as the proportion of reef sites currently with less than 10% hard coral cover, which is an estimated minimum threshold for net accretion (Perry et al., 2013). Coral reefs in each ecoregion were classified as Vulnerable (VU) if they experienced a 30–50% decline, Endangered (EN) if the decline was 50–80%, and Critically Endangered (CR) if the decline exceeded 80%. Reefs with declines of 27–30% were classified as Near Threatened (NT), and all others were considered Least Concern (LC).

1.2. Criterion B — Restricted Geographic Distribution

Criterion B assesses the extent of occurrence (EOO) and area of occupancy (AOO) of the current distribution of coral reefs. EOO is the total area within the outer limits of the ecosystem's distribution, while AOO is the area occupied by the ecosystem, measured as the number of 10 by 10 km grid cells. Both were derived using both the Millennium Coral Reef Layer and Allan Coral Atlas datasets and validated by regional experts. For both metrics, the thresholds from the RLE guidelines were applied to assess risk, and additional conditions on continuing decline were evaluated using threat and biotic data from Criteria C and D.

1.3. Criterion C — Environmental Degradation

Under Criterion C, we evaluated the most pertinent threat to the persistence and survival of coral reefs, thermal stress caused by ocean warming, assessing both historical changes over the past 50 years (sub-criteria C1) and projections (sub-criteria C2) for the next 50 years. For C1, we examined trends in sea surface temperature (SST) over the past 50 years, while C2 considered projected increases in thermal stress over the next 50 years, based on annual maximum Degree Heating Weeks (DHW). For both C1 and C2, the relative severity of environmental degradation was calculated by comparing the magnitude of past and projected

changes against established thresholds for coral reef collapse. Risk categories are triggered when the extent of reefs exposed to declines according to this matrix.

1.4. Criterion D — Disruption of Biotic Processes and Interactions

Criterion D assesses the disruption to two key biotic components over the past 50 years. Four indicators were initially considered, including live hard coral cover, algae-to-coral ratio, parrotfish and grouper. However, fish data were limited across ecoregions and inconsistently aggregated into functional groups with different families, and were therefore excluded. Criterion D was consequently assessed using two key biotic components: live hard coral cover and algae-to-coral ratio derived from in-situ monitoring data. For each reef site, the decline in each indicator is measured relative to both the state of the reef 50 years ago and a hypothetical collapse threshold, representing the point at which that biotic component is no longer functional. The proportion of sites experiencing varying degrees of decline is then evaluated, and a risk matrix is used to determine the risk status for each indicator. Finally, a heuristic, stepwise approach across all indicators is applied to derive the overall risk status under Criterion D for each ecoregion.

Table 3. Methodology, parameters and collapsed thresholds used to assess Coral Reefs ecosystems in the Red Sea and Gulf of Aden under the Red List of Ecosystem criteria.

Criterion	Sub-criterion	Indicator(s)	Data Sources	Collapse Threshold(s)	Criterion Assessed? (Yes/No)	Comments
A	A1 – (Past 50 years)	Reef habitat extent from monitoring data	Hard coral cover	80% loss of extent over 50 years Threshold of 10% of coral cover	Yes	Based on regional contributed data and the literature compiled data
B	B1 –Extent of Occurrence (EOO)	Extent of Occurrence (EOO) + ongoing decline or number of threats defined locations	Regional reef maps, expert knowledge	EOO < 50,000 km ² + ongoing decline or threats	Yes	Calculated per eco-region using minimum convex polygons
	B2 -- Area of Occupancy (AOO)	Area of Occupancy (AOO) + ongoing decline or number of threats defined locations	Grid-based reef presence (10×10 km), monitoring data	AOO < 50 + ongoing decline or threats	Yes	Fluctuation data limited; AOO estimates incomplete
C	C1 – Environmental degradation	Degree Heating Weeks (DHW))	NOAA Coral Reef Watch, HadISST	Return interval of ≤ 3 years between bleaching events or 3 severe marine heatwave events occurring within 5 years	Yes	

Criterion	Sub-criterion	Indicator(s)	Data Sources	Collapse Threshold(s)	Criterion Assessed? (Yes/No)	Comments
	C2 – Projected future degradation	Projected Degree Heating Weeks (DHW)	Global Climate Projections	Return interval of ≤ 3 years between bleaching events or 3 severe marine heatwave events occurring within 5 years	Yes	Eco-region average
D	D1 – Disruption of biotic processes	Hard coral cover, Algae-coral ratio (ACR)	Benthic cover from UVC surveys	Hard coral cover $< 5\%$, ACR = 0.833	Yes	Based on regional contributed data and the literature compiled data

4. Risk Status

Seventy-five percent of the coral reef ecoregions assessed in the Red Sea and Gulf of Aden were classified within threatened categories under current conditions, with three of the four ecoregions assessed as Vulnerable or Endangered (Table 4). Under current conditions, risk was lower in the NRS (Vulnerable) than in the CRS and SRS, which were both classified as Endangered. This regional difference reflected comparatively low estimated decline in functioning reef distribution and biotic degradation in the NRS, while biotic degradation contributed more strongly to risk in the CRS and both estimated decline in functioning reef distribution and biotic degradation contributed to the Endangered status of the SRS. In contrast, geographic distribution remained Least Concern across all ecoregions, indicating that restricted distribution was not a major contributor to risk based on observed change. Environmental degradation associated with extreme thermal stress was Vulnerable across all the four ecoregions, representing a shared source of risk based on observed change. The GoAden was classified as Vulnerable based on criteria C, with criteria B assessed as least concern. Under future conditions, this spatial variation was replaced by a common regional pattern, with all four ecoregions classified as Critically Endangered under Criterion C2 due to projected increases in the frequency and spatial extent of extreme thermal stress.

Table 4. Summary of Red List of Ecosystems (RLE) assessment results for the Red Sea and Gulf of Aden coral reef ecoregions. Current overall status is the highest risk category under Criteria A, B, C1 and D. Future overall status is based on projected thermal stress under the IPCC SSP2-4.5 scenario (Criterion C2). DD indicates insufficient evidence to assign a current overall status.

Ecoregions		Criteria					Overall	
		A	B	C1	C2	D	Observed change	Overall risk
1	Northern Red Sea	LC	LC	VU	CR	LC	VU	CR
2	Central Red Sea	LC	LC	VU	CR	EN	EN	CR

Ecoregions		Criteria					Overall	
		A	B	C1	C2	D	Observed change	Overall risk
3	Southern Red Sea	EN	LC	VU	CR	EN	EN	CR
4	Gulf of Aden	DD	LC	VU	CR	DD	VU	CR

4.1. Criterion A: Reduction in Geographic Distribution

Criterion A identified differences in estimated decline in coral reef distribution among the assessed ecoregions. The SRS showed the greatest decline, with 53% of reef sites currently below the 10% hard coral cover threshold used as a proxy for decline in reef distribution over the past 50 years (Table 5). This exceeded the 50% threshold for an Endangered (EN) classification. The SRS has also experienced pronounced changes in coral community structure, including declines in branching reef-building corals (Hammerman et al., 2022), providing additional evidence of ecological deterioration in this ecoregion.

In contrast, estimated declines were substantially lower in the NRS and CRS, where 4% and 25% of reef sites, respectively, were below the critical hard coral cover threshold. Both ecoregions were therefore classified as Least Concern (LC) under Criterion A. In the CRS, sustained coral calcification across seasons and multiple coral genera further indicates continued reef-building activity (Roik et al., 2016, 2018). Overall, the results indicate increasing decline from north to south, with the SRS showing the greatest level of concern. The GoAden was classified as Data Deficient (DD) because available data were insufficient to assess decline under this criterion.

Table 5. Risk status of the Red Sea and Gulf of Aden coral reef ecoregions under Criterion A, determined from estimated declines in coral reef area over the last 50 years.

Coral Reef Ecoregion	Proportion of reef sites below critical hard coral cover threshold	Risk status
NRS	0.04	LC
CRS	0.25	LC
SRS	0.53	EN
GoAden	-	DD

4.2. Criterion B: Restricted Geographic Distribution

Under Criterion B, all four coral reef ecoregions were classified as Least Concern (Table 6). Extent of Occurrence (EOO) ranged from 151,103.1 km² in the CRS to 344,739.1 km² in the GoAden, while Area of Occupancy (AOO) ranged from 112 in the GoAden to 680 in the SRS, with both B1 and B2 supporting the same classification across all ecoregions. These results demonstrate the broad geographic distribution of coral reef ecosystems across the Red Sea and

Gulf of Aden and indicate that restricted geographic distribution is not currently a major contributor to ecosystem risk.

Table 6. Risk status of Red Sea and Gulf of Aden coral reef ecoregions under Criterion B, determined from distribution of coral reefs measured as the Extent of Occurrence (EOO) and Area of Occupancy (AOO).

Coral Reef Ecoregion	Extent of Occurrence EOO (km ²)	Area of Occupancy AOO	B1	B2	Risk Status
NRS	157,316.6	321	LC	LC	LC
CRS	151,103.1	265	LC	LC	LC
SRS	263,220.0	680	LC	LC	LC
GoAden	344,739.1	112	LC	LC	LC

4.3. Criterion C: Environmental Degradation

Based on the frequency and spatial extent of extreme thermal stress, all of the four coral reef ecoregions, the Northern, Central and Southern Red Sea and the Gulf of Aden, were classified as Vulnerable under Criterion C1 (Table 7). Under Criterion C2, projected increases in the frequency and extent of extreme thermal stress resulted in all four ecoregions being classified as Critically Endangered. The importance of thermal stress across the region is also evident from recent marine heatwaves and associated coral bleaching, including events affecting Red sea and Gulf of Aden (Darmaraki et al., 2025; Kochman & Fine, 2025). The shift from Vulnerable under C1 to Critically Endangered under C2 indicates a substantial increase in ecosystem risk from extreme thermal stress under future climate conditions.

Table 7. Risk status of the Red Sea and Gulf of Aden coral reef ecoregions under Criterion C, determined from estimated declines in abiotic conditions, specifically changes extreme heat events.

Coral Reef Ecoregion	Risk Status Criterion C1	Risk Status Criterion C2
NRS	VU	CR
CRS	VU	CR
SRS	VU	CR
GoAden	VU	CR

4.4. Criterion D: Disruption of biotic processes or interactions

Criterion D showed clear spatial differences in the disruption of key biotic components across the Red Sea (Table 8). The NRS showed comparatively lower biotic degradation, with both hard coral cover and the algae-to-coral ratio classified as Least Concern. In contrast, the CRS and SRS shared an overall Endangered classification, although the contribution of the two indicators

differed: in the CRS, hard coral cover was Vulnerable and the algae-to-coral ratio Endangered, whereas both indicators were Endangered in the SRS. This pattern indicates greater disruption of coral and coral–algal conditions in the CRS and SRS compared with the NRS and is consistent with reported spatial differences in coral - algal states across the Red Sea, including greater algal dominance in parts of the southern Red Sea (Gonzalez et al., 2024). In the GoAden, limited spatial coverage, with available biological data concentrated primarily around Djibouti, resulted in a Data Deficient classification for both indicators.

Table 8. Risk status of the Red Sea and Gulf of Aden coral reef ecoregions under Criterion D, determined from estimated historical declines in critical biotic components. Risk status for each indicator and the overall status across all indicators. Ranges in risk e.g. EN-CR, represents uncertainty in the outcomes, and where relevant the most likely category is presented (outside of the parentheses) in addition to the range.

Coral Reef Ecoregion	Hard corals	Algae-coral ratio	Overall
NRS	LC	LC (LC-NT)	LC
CRS	VU	EN (VU-EN)	EN
SRS	EN (VU-EN)	EN	EN
GoAden	DD	DD	DD

5. Conclusion and recommendations

This first regional Red List of Ecosystems assessment provides a baseline for understanding coral reef ecosystem risk across the Red Sea and Gulf of Aden, integrating evidence of changes in functioning reef distribution, geographic distribution, environmental degradation and key biotic components across the four ecoregions. Reefs remain geographically extensive across all four ecoregions, but their current condition and degree of ecosystem change vary spatially. The NRS retains comparatively favorable biotic conditions, whereas greater biotic degradation is evident in the CRS and SRS, with the SRS also showing greater estimated change in functioning reef distribution. In the GoAden, limited spatial coverage of in-situ biological data resulted in an overall Data Deficient classification. Thermal stress, however, represents a shared pressure across the region. Under Criterion C2, projected increases in the frequency and spatial extent of extreme thermal stress under the intermediate SSP2-4.5 climate scenario resulted in all four ecoregions being classified as Critically Endangered. This indicates substantial future ecosystem risk even under an intermediate emissions pathway and emphasizes the importance of strengthening regional climate adaptation alongside global efforts to limit future warming.

Conservation priorities should therefore respond to both current ecosystem conditions and future climate risk. Management should seek to maintain reefs that remain in comparatively favorable condition while supporting recovery where greater ecological change has already occurred. Across the region, reducing locally manageable pressures, including overfishing, declining water quality, damaging coastal development and direct physical disturbance, can help maintain ecological functions under increasing thermal stress. Conservation planning should also recognize spatial differences in ecosystem condition, allowing management and restoration efforts to be targeted according to the ecological condition, pressures and recovery needs of individual ecoregions. These priorities can be advanced through existing regional cooperation under the Jeddah Convention and its Regional Action Plan, coordinated through PERSGA, and can contribute to broader commitments under the Convention on Biological Diversity and the Kunming–Montreal Global Biodiversity Framework.

Continued regional monitoring should particularly address Data Deficient biological components in the Gulf of Aden, improve spatial and temporal comparability of monitoring, and progressively incorporate additional ecological indicators as consistent regional datasets become available. Greater harmonization of monitoring methods and indicators among countries and institutions would strengthen the ability to detect ecosystem change consistently across the region and provide comparable evidence for future assessments. Periodic reassessment using the RLE framework should build on this first regional baseline to track changes in ecosystem risk and determine whether conservation and management actions are maintaining or improving reef condition. Together, sustained monitoring, coordinated regional conservation and repeated ecosystem risk assessment can provide an adaptive framework for responding to both emerging local pressures and the increasing challenge posed by climate change.

6. References

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8. Peer review

This report was reviewed by the IUCN Red List of Ecosystems global team and by members of other regional coral reef assessment teams under the Global Red List of Coral Reef Ecosystems initiative.

9. Disclaimer

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11. Annex

11.1. Boundary definitions

The Red Sea and Gulf of Aden are characterized by environmental and ecological variation across their geographic extent. To ensure that this variation was appropriately represented in the assessment, the Units of Assessment were defined using established marine biogeographic frameworks, supported by regional environmental and ecological evidence and expert knowledge. The resulting delineation builds on existing ecoregional classifications while incorporating regional refinements considered necessary to represent ecologically meaningful differences among coral reef systems.

Basis for ecoregion categorization: The delineation of coral reef ecoregions in the Red Sea and Gulf of Aden was based primarily on the Marine Ecoregions of the World (MEOW) framework (Spalding et al., 2007), which originally recognizes three ecoregions within the assessment area: North - Central Red Sea, Southern Red Sea, and Gulf of Aden. These ecoregions represent areas of relatively homogeneous species composition that are distinct from adjacent systems, reflecting broad biogeographic patterns shaped by environmental and oceanographic conditions. Other biogeographic assessments broadly support regional differentiation within the Red Sea and Gulf of Aden, although the number and positioning of boundaries vary among approaches. Veron et al., (2015), for example, distinguished the NRS, SRS, and GoAden based on coral diversity and biogeographic affinities. More recent analyses have demonstrated strong environmental gradients across the Red Sea basin and shown that alternative regionalizations comprising two to five ecoregions can be identified depending on variables such as sea surface temperature, connectivity, wind and sea-level variability (Cerutti et al., 2025).

Regional expert decision: Regional evidence indicates that the broad Northern and Central Red Sea ecoregion defined by MEOW encompasses substantial environmental and ecological

heterogeneity. Analyses of temperature, circulation and connectivity reveal pronounced latitudinal structuring of the basin into northern, central and southern domains (Cerutti et al., 2025), while ecological studies indicate spatial variation in reef community composition and condition that may not be adequately represented by broader biogeographic boundaries (Roberts et al., 2016). Drawing on this evidence and direct expert knowledge of reef conditions across the region, regional experts recommended subdividing the MEOW North – Central Red Sea ecoregion into separate Northern Red Sea (NRS) and Central Red Sea (CRS) units. This refinement was further supported by the recently published GCRMN *Status of Coral Reefs of the World: 2025* regional assessment, which similarly assessed the Northern and Central Red Sea as separate subregions, reflecting their distinct environmental conditions and ecosystem characteristics (Amer et al., 2026). The regional expert groups therefore endorsed this refinement, resulting in the four-ecoregion framework used in this assessment: NRS, CRS, SRS, and GoAden (Table 9).

Table 9. Geographic characteristics and ecological basis of the four ecoregions used as Units of Assessment for the Red Sea and Gulf of Aden coral reef ecosystem assessment.

Ecoregion	Country	Coral Reef Area (km ²)	Boundary Description	Justification
NRS	Egypt, Saudi Arabia, Jordan and Israel,	3,076	Extends from the Gulf of Aqaba and northern Red Sea (~30.00°N) southward to ~23.95°N, between ~32.34°E and ~34.86°E; redefined from the former MEOW North–Central Red Sea boundary through the introduction of a northern subdivision	Cooler thermal regime, higher coral cover, and relative environmental isolation compared to central Red Sea
CRS	Egypt, Saudi Arabia and Sudan	2,994	Extends from ~23.95°N to ~19.95°N, between ~35.40°E and ~39.11°E; corresponds to the central portion of the former MEOW North–Central Red Sea ecoregion	Transitional zone with strong gradients in temperature, productivity, and oceanographic exposure
SRS	Saudi Arabia, Sudan, Yemen and Eritrea,	5,900	Extends from ~19.95°N southward to Bab el-Mandeb (~13.95°N), between ~37.49°E and ~42.56°E; corresponds to the southern MEOW Red Sea ecoregion	Influenced by upwelling and nutrient enrichment; higher productivity and distinct benthic structure
GoAden	Djibouti, Somalia, and Yemen	1,148	Extends from the Bab el-Mandeb region (~13.95°N) eastward to ~8.95°N, between ~42.34°E and ~57.86°E, bordering the western Indian Ocean and adjacent to the ROPME Sea Area	Monsoon-driven oceanographic system with strong upwelling, seasonal variability, and distinct biotic and abiotic conditions

11.2. Methods description (detailed)

Geophysical and environmental data

The datasets used to derive the coral reef extent layers included the Millennium Coral Reef Mapping Project layer curated by the UNEP World Conservation Monitoring Centre ([UNEP-WCMC](#)), and the Allen Coral Atlas ([ACA](#)) global reef map. Both layers were used given the lack of widespread regional high resolution habitat maps throughout the entire PERSGA region. The entire Millennium layer was used with a subset of all available ACA layers including coral/algae layer (benthic) and the following geomorphic layers: reef slope, reef crest, outer reef flat, plateau, and sheltered reef slope. The two layers were merged by projecting both to a common coordinate reference system (WGS 84 / UTM zone 37N), dissolving each into a single reef footprint, and taking their spatial union, so that areas mapped by either or both datasets were retained and overlapping areas were counted only once. The combined layer was then intersected with the four ecoregions of the PERSGA region (Northern, Central and Southern Red Sea, and Gulf of Aden), dissolved by ecoregion, and reprojected to WGS 84 for analysis. These outputs were visually confirmed by technical and regional experts to confirm they accurately represented the extent of coral reef habitats throughout the region.

Monitoring data

Monitoring data used to assess Criteria A and D consisted primarily of percentage benthic-cover observations, particularly hard coral, turf algae and macroalgae. Turf and macroalgal records were aggregated into a single algae category for consistency among datasets and support calculation of the algae-to-coral ratio indicator. Although reef-fish indicators were initially considered, fish abundance data were insufficiently consistent within ecoregions and time periods and were therefore excluded from the assessment. Benthic-cover data were collected mainly using line-intercept transects and photoquadrats, including permanent photoquadrats at some long-term monitoring sites.

The compiled hard-coral dataset comprised 34 data sources spanning 1969–2025, with observations available for 37 individual years rather than as a continuous annual record. Temporal coverage varied among ecoregions: 1969–2025 in the NRS (35 years with observations), 1980–2025 in the CRS (25 years), 1997–2025 in the SRS (16 years) and 1997–2023 in the GoAden (8 years). As shown in Figure 6, monitoring was sparse during the earlier

decades and became more frequent from the late 1990s onward, although sampling effort varied among years and ecoregions. The datasets were compiled through PERSGA, the regional node of the Global Coral Reef Monitoring Network (GCRMN), and included long-term governmental and institutional monitoring programmes, PERSGA-coordinated regional assessments and projects, Reef Check surveys, university and other research initiatives, peer-reviewed publications, theses, and unpublished or directly contributed monitoring data.

Reef typology

To determine which coral reef systems were included in this assessment, the IUCN Global Ecosystem Typology (GET) was used to provide a consistent and globally aligned definition of coral reef ecosystems (Keith et al., 2022). Within the GET, true photic coral reefs were classified under the ecosystem functional group M1.3 Photic Coral Reefs (<https://global-ecosystems.org/explore/groups/M1.3>) and are characterized by active carbonate accretion and the development of a biogenic reef framework built by scleractinian corals over millennial timescales. Coral communities may also occur in marginal environments where environmental conditions or substrate characteristics constrain carbonate accretion and reef-framework development. Accordingly, both true reefs (Type A) and marginal reefs (Type B) were included in the assessment, while potentially confounding ecosystem types, including mesophotic coral ecosystems and subtidal rocky reefs (Type C, <https://global-ecosystems.org/explore/groups/M1.6>), were excluded. Care was taken not to exclude degraded coral reefs that may superficially resemble rocky or other non-coral reef systems, as these represent important expressions of reef degradation relevant to assessing ecosystem collapse risk.

Within the Red Sea, the reef systems captured by this definition occur in a variety of geomorphic settings. (Head, 1987) recognized three principal reef types: fringing reefs, barrier reefs and atolls. Fringing reefs occur close to shore and represent the most widespread reef type, whereas barrier reefs develop along the margins of offshore shelves. Atolls are less extensively developed and occur as large, approximately ovoid mid-basin reef structures enclosing central lagoons. (Rowlands & Purkis (2015), further distinguished Red Sea reefs into shore-attached and shore-detached systems, with fringing reefs representing the principal shore-attached form and patch and barrier-like reefs occurring as shore-detached systems.

The distribution and development of these reef types vary across the basin. Fringing reefs are particularly well developed in the northern and central Red Sea and also occur around southern island groups, while barrier and other offshore reef systems reach their greatest development in parts of the central Red Sea. Atoll-like reefs occur mainly along the Red Sea axis, where their formation is associated with tectonic ridges produced by faulting and salt uplift. The southern Red Sea also contains algal reefs, which occur in low-energy environments and are characterized by dense brown algal growth that provides consolidated substrate within otherwise sandy areas (N. M. Rasul et al., 2015).

For this assessment, the global RLE Type A and Type B definitions determined the coral reef ecosystems considered in scope, while the regional classifications described the different reef forms represented within the assessment area. In-scope reef systems included fringing, patch, barrier and atoll reefs (Head, 1987; N. M. Rasul et al., 2015; Rowlands & Purkis, 2015).

Criterion A: Reduction in geographic distribution

Criterion A assesses the reduction in the extent of an ecosystem over time, typically over a 50-year period. We focused on assessing Criterion A1, which measures the percentage of coral reef area lost across each ecoregion over the past 50 years (1975–2025). Criteria A2a, A2b or A3, requiring assessment into the future, were not evaluated. For coral reefs, historical mapped reef area data spanning ~50 years are rarely available. In addition, coral reefs can undergo functional decline, without any visible change in the structural extent mapped by satellites. For that reason, using mapped area reduction is not possible for coral reefs. Our method uses recent hard coral cover estimates from monitoring data between [2020 – 2025] as a proxy for declines in reef area (Obura et al., 2021).

Each reef site was classified as either a functioning, net-accreting reef site or a degraded site, based on a threshold of approximately [10%] hard coral cover. This threshold represents an established point where coral abundance is too low to maintain positive carbonate accretion on a reef (Perry et al., 2013). A sensitivity analysis was conducted across a range of thresholds (1–10%) to assess how results varied (Figure 4). Each site was assumed to represent an equal portion of reef area, and the overall decline in coral reef area was estimated by calculating the percentage of monitoring sites below the coral cover threshold. We assumed that all monitored sites represented functioning coral reefs around 1975; coral reef sites already recorded to have been degraded at that time were excluded from analysis (to assess change over the past 50

years). In addition, to account for potential data gaps, coral reef sites recorded to have collapsed or been permanently lost due to anthropogenic or environmental pressures, such as cyclones, dredging, sedimentation, port development, or severe bleaching, were also included, even if they are no longer part of ongoing monitoring programs. Including these sites ensured that historical losses were adequately captured.

Current and historical monitoring data were reviewed to assess their adequacy for representing ecosystem-level decline within each ecoregion. However, because precise coordinates were not available for all sites, the proportion of reef EOO or AOO represented by monitoring sites could not be quantified. Data representativeness was therefore evaluated based on the number and distribution of available sites within each ecoregion, temporal coverage, and expert judgement. Where the available observations were considered insufficient to reliably represent ecosystem-level decline across an ecoregion, Criterion A was classified as Data Deficient (DD).

Where data were adequate, risk categories were assigned according to the Red List of Ecosystems thresholds for Criterion A1, corresponding to declines of >80% (Critically Endangered), 50–80% (Endangered), 30–50% (Vulnerable), 27–30% (Near Threatened), and <27% (Least Concern) (see Table 10).

Table 10.

<i>Subcriterion</i>	<i>Time frame</i>	<i>CR</i>	<i>EN</i>	<i>VU</i>
A1	Past (over the past 50 years)	≥ 80%	≥ 50%	≥ 30%
A2a	Future (over the next 50 years)	≥ 80%	≥ 50%	≥ 30%
A2b	Any 50-year period (including past, present and future)	≥ 80%	≥ 50%	≥ 30%
A3	Historical (since approximately 1750)	≥ 90%	≥ 70%	≥ 50%

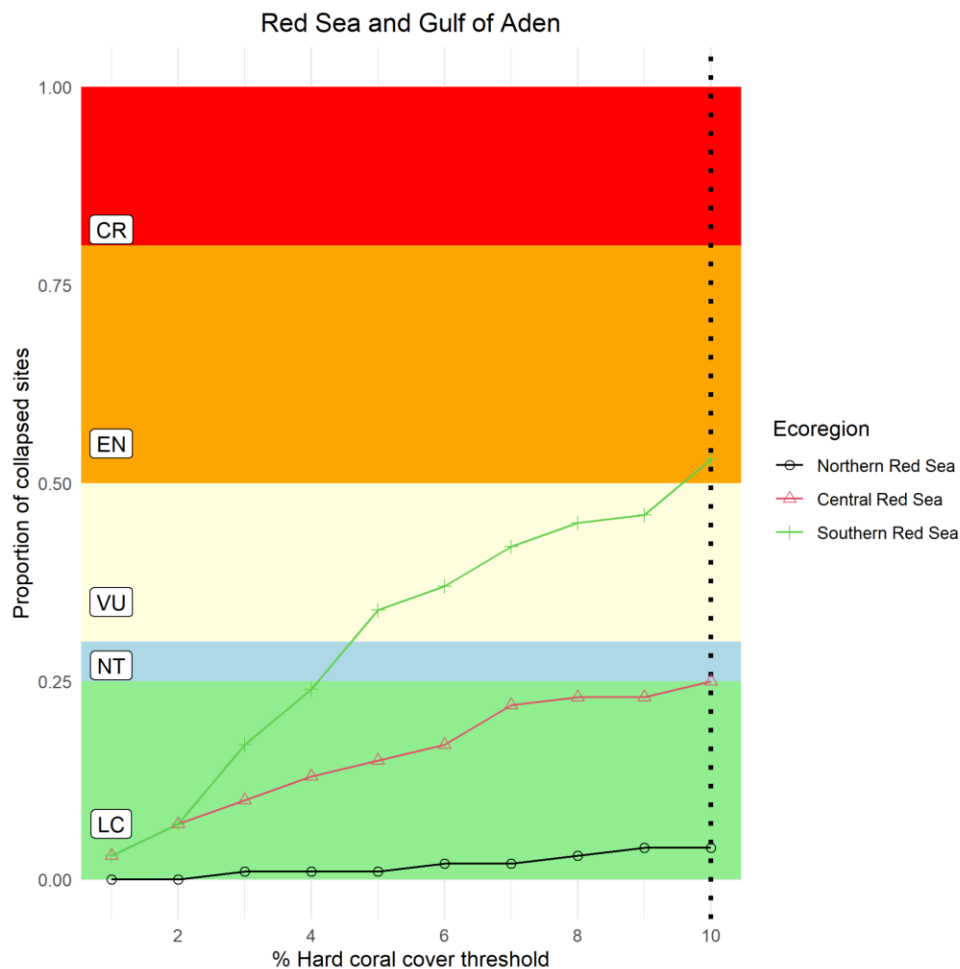


Figure 4. Sensitivity of criteria A risk classification to hard coral cover collapse thresholds (1 - 10%) across the three ecoregions assessed with sufficient data. Lines show the proportion of sites classified as collapsed at each threshold, with background colours representing RLE risk categories. The dashed line indicates the selected 10% hard coral cover threshold used in the assessment.

Criterion B: Restricted Geographic Distribution

Criterion B assesses ecosystems whose geographic distribution is so limited that they are at risk of collapse due to the chance occurrence of one or a few threatening events, such as a cyclone, bleaching event, or disease outbreak.

To assess Criterion B, the RLE uses two standardised spatial metrics:

- (i) Sub-criterion B1: Extent of Occurrence (EOO) – the area within the outer boundary of the ecosystem’s known distribution;
- (ii) Sub-criterion B2: Area of Occupancy (AOO) – the area occupied by the ecosystem, measured using 10 by 10 km grid cells.

Selection and validation of coral reef extent layer:

The analysis requires a spatial layer representing the current distribution of coral reefs. Two satellite-derived global coral reef maps were considered: the Millennium Coral Reef Mapping Project layer curated by the UNEP World Conservation Monitoring Centre (UNEP-WCMC), and the Allen Coral Atlas (ACA) global reef map since region-specific benthic habitat maps are typically spatially limited or relatively old (Sullivan et al., 2025). Both layers were evaluated by regional experts to determine the most suitable layer for each ecoregion. It was found that the UNEP-WCMC layer covered the majority of reef habitats in the main Red Sea basin, but failed to capture coral reef habitats in the Socotra archipelago of the Gulf of Aden ecoregion. Further interrogation of the ACA layer found the benthic layer, specifically coral/algae, and geomorphic layers, specifically reef slope, reef crest, outer reef flat, plateau, and sheltered reef slope, best captured coral reefs throughout all ecoregions, and successfully identified coral reefs around the Socotra archipelago. Therefore, it was decided to incorporate both layers to capture the full extent of coral reefs throughout the Red Sea and Gulf of Aden region. Experts agreed the outputs of these layers accurately captured the extent of coral reefs throughout their respective ecoregions, and therefore the combined coral reef layers were used to calculate the Extent of Occurrence (EOO) and Area of Occupancy (AOO) for Criterion B1 and B2 respectively.

Once the validated coral reef extent layer was projected using the combined coordinate reference system (WGS 84 / UTM zone 37N (EPSG:32637)), the *makeEOO* function in the *redlistr* package in R was used to generate the minimum convex polygon representing the EOO of each ecoregion. The *getAreaEOO* function was then used to calculate the EOO area in km². For Criterion B2, a 10 x 10 km grid was overlaid over the reef extent layer using the *makeAOOGrid* function, and the number of grid cells containing coral reefs was counted to estimate the AOO. All grid cells whose cumulative area of the reef ecosystem was <1% were excluded from the AOO count.

To determine the risk category under Criterion B, EOO and AOO values were compared against the thresholds defined in the Red List of Ecosystems (RLE) guidelines. Ecoregions with EOO or

A00 values within 10% of the VU thresholds were classified as Near Threatened (NT). Finally, to formally assign the risk status under Criterion B1 or B2 for each ecoregion, experts were required to justify observed or inferred declines to reefs, or the presence of current threats, such as ocean warming, pollution, coastal development, or overfishing, that are presenting an ongoing risk to coral reefs (Table 11).

Table 11.

Subcriterion	Measure of geographic distribution	CR	EN	VU
B1	Area of a minimum convex polygon (km²) enclosing all occurrences (extent of occurrence, EOO) is: AND at least one of the following (a–c): (a) An observed or inferred continuing decline in ANY OF: i. spatial extent of the ecosystem; OR ii. environmental quality appropriate to the characteristic biota of the ecosystem; OR iii. biotic interactions* appropriate to the characteristic biota of the ecosystem. (b) Observed or inferred threatening processes that are likely to cause continuing declines in geographic distribution, environmental quality or biotic interactions within the next 20 years. (c) Ecosystem exists at:	≤ 2,000 1 threat-defined location	≤ 20,000 ≤ 5 threat-defined locations	≤50,000 ≤ 10 threat-defined locations
B2	The number of 10×10 km² grid cells occupied (area of occupancy, AOO) are: AND at least one of a–c above (same as for B1).	≤ 2	≤ 20	≤ 50
B3	A very small number of threat-defined locations (generally fewer than 5) AND prone to the effects of human activities or stochastic events within a very short time period, and thus capable of Collapse or becoming Critically Endangered (CR) within a very short time period (B3 can only lead to a listing as Vulnerable, VU).			VU

Criterion C

Criterion C evaluates the degradation of abiotic conditions that support an ecosystem's functioning and persistence. The goal is to evaluate whether abiotic conditions have changed to such an extent that they pose a significant risk to the ecosystem's ability to sustain its characteristic biota and ecological processes. Such changes may arise from alterations in disturbance regimes, including events such as floods, fires, or storms.

Ocean warming, and extreme heatwave events which cause widespread and severe coral bleaching (and mortality) have emerged as one of the biggest issues affecting coral reefs in many

parts of the world, and the main threat affecting their persistence into the future (Hughes et al., 2017). This analysis is designed to capture broad-scale changes in the abiotic environment associated with increasing frequency of extreme marine heatwave events that cause coral bleaching (Emslie et al., 2024; Hughes et al., 2017; Maynard et al., 2017), and determine how present and future environmental conditions threaten the survival and persistence of coral reef ecosystems.

Recurrent heat waves reduce the environmental suitability for reef-building corals through several pathways. A shift in disturbance regime increases the risk of large-scale coral mortality and affects the establishment and persistence of species (Elma et al., 2026; Mudge & Bruno, 2023). These changes can be associated with substantial declines in coral abundance, reduced structural complexity, and lower carbonate accretion rates (G. J. Williams et al., 2019; G. J. Williams & Graham, 2019). Additionally, recurrent bleaching episodes weaken coral communities, reduce reproductive output, and increase susceptibility to other stressors such as disease (Briggs et al., 2024; Byrne et al., 2025; Croquer & Weil, 2009; Levitan et al., 2014). As these events become more frequent, intervals between disturbances are shortened, preventing meaningful coral recovery and increasing the likelihood of progressive ecosystem degradation and eventual collapse (Emslie et al., 2024; Hughes et al., 2017).

Indicator selection

To assess the likelihood of recurrent heat waves driving ecosystem collapse at regional scales, we assessed two plausible and distinct pathways, each requiring a different analytical approach.

The first is a chronic (press) pathway, driven by the cumulative effects of recurrent bleaching events that weaken coral communities, reduce growth and reproductive output, and increase susceptibility to secondary stressors such as disease. As bleaching events become more frequent, recovery intervals shorten, preventing meaningful recovery between disturbances and leading to progressive ecosystem degradation over time. The second is an acute (pulse) pathway, characterised by rapid decline following a small number of extreme heat stress events occurring over a short period. These events can cause widespread mortality across coral taxa, including stress-tolerant species, leading to near-complete coral loss and triggering collapse.

We assessed the relative change in disturbance conditions over:

- the past 50 years (1975–2025) as part of sub-criterion C1, and
- 50 years into the future (2026–2075) for sub-criterion C2

For the chronic pathway, the indicator is the expected number of severe bleaching events over a 30-year period, expressed as an average return interval (years between events).

For the pulse pathway, the indicator is the number of severe mortality events within a 5-year window.

Using DHW as a proxy for bleaching events

For both pathways, Degree Heating Weeks (DHW), a measure of the accumulation of heat stress over a rolling 12-week window, was used to approximate the occurrence of severe bleaching and mortality events (Liu et al., 2014).

Although data on historical bleaching observations exist (Donner et al., 2017; Eakin et al., 2026; van Woesik & Kratochwill, 2022), they are not spatially or temporally extensive. DHW data are globally available since 1985, including for future climate projections (Mellin et al., 2024; Skirving et al., 2019), and are underpinned by a well-documented, long-term relationship with coral bleaching across many regions globally (Heron et al., 2016; Liu et al., 2005; Sully et al., 2019). Values of $DHW \geq 4$ are associated with bleaching onset, while values of $DHW \geq 8$ or more are historically linked to widespread coral mortality (Kayanne, 2017; Liu et al., 2005; Skirving et al., 2019). In addition, DHW has been widely used in recent studies assessing bleaching risk under climate change (Beyer et al., 2018; Bozec et al., 2025; Mellin et al., 2024; Obura et al., 2021), and is supported by established thresholds linking DHW levels to bleaching severity developed by the NOAA Coral Reef Watch (https://coralreefwatch.noaa.gov/product/5km/index_5km_baa-max-7d.php). While DHW may not be the most precise predictor of bleaching severity at fine spatial or temporal scales, it provides a robust, scalable, and comparable indicator of bleaching risk suitable for capturing broad trends in disturbance regimes over time, and supports a standardised approach across ecoregions.

Data

Sub-criterion C1 was assessed using satellite-measured DHW from NOAA Coral Reef Watch at a spatial resolution of 5 km (Liu et al., 2014). The standard RLE assessment timeframe is 50 years; however, satellite measurements of DHW began 40 years ago in 1985. For the period 1975–1984, thermal conditions were assumed to be broadly comparable to those observed during the

earliest decade of the satellite record (1985–1995). This assumption is supported by the fact that the first global mass bleaching event occurred later, in 1997–1998 (Hoegh-Guldberg, 1999), and that global ocean heat content has been consistently above average since the mid-1990s, with ocean warming accelerating further since the late 90s and early 2000s (Cheng et al., 2017; Heron et al., 2016; Maynard et al., 2017; Merchant et al., 2025). The 1985–1995 period is therefore the closest available proxy for late-1970s thermal stress regimes. DHW values were spatially attributed to each reef pixel using a 50 km buffer, retaining only data from pixels within this distance of mapped reef extent, and assigning values through an interpolation process.

Sub-criterion C2 used modelled climate projections of daily Degree Heating Weeks from Mellin et al., (2024) for 1985–2100, available for three climate pathways: SSP2-4.5, SSP3-7.0, and SSP5-8.5. The dataset did not include projections corresponding to the Paris Agreement pathway (SSP1-1.9; approximately 1.5–2°C warming by 2100), which is considered increasingly unrealistic given current global emissions trajectories (Tagomori et al., 2026). All three scenarios with data were assessed to explicitly demonstrate how the degree of climate mitigation affects risk outcomes for coral reefs. The highest emissions scenario (SSP5-8.5) represents an extreme case that is considered increasingly unlikely to eventuate (Sarofim et al., 2024), therefore, SSP2-4.5 and SSP3-7.0 were treated as the primary scenarios.

For both C1 and C2, daily DHW data were converted to an annual maximum value for each reef pixel by first calculating the monthly maximum, and then extracting the highest value recorded from each local summer season. In regions where the summer season straddles two calendar years (e.g. the thermal peak occurs during November–March), the seasonal maximum was attributed to the year the stress began. This produced an annual time series of maximum DHW for each reef pixel spanning the historical and future assessment periods.

Thresholds

To convert the annual maximum DHW data into a record of disturbance events, ecoregion-specific DHW thresholds were applied to classify each year as an event (value of 1) or not (value of 0). The DHW thresholds used for this classification differed between the two pathways, reflecting their distinct ecological mechanisms.

For the chronic pathway, a severe bleaching event is defined as one in which widespread bleaching occurs across approximately more than 50% of coral colonies. These events cause substantial loss of thermally sensitive species but may not typically reach the intensity required

to cause widespread mortality of stress-tolerant taxa. For the pulse pathway, a severe mortality event is defined as an extreme, high-intensity thermal stress event that causes widespread mortality (more than 50% of colonies) across all coral taxa, including stress-tolerant species. Applying the thresholds produced two binary event time series for each reef pixel which forms the basis of the chronic and pulse analyses.

DHW thresholds corresponding to severe bleaching events (chronic pathway) and severe mortality events (pulse pathway) for each ecoregion were informed by historical observations of coral reef responses to marine heatwaves, specifically the levels of thermal stress associated with widespread bleaching and coral mortality. These thresholds were not treated as fixed, as the DHW level required to trigger a given bleaching response is expected to change over time. For example, in the 1980s and 90s, relatively lower DHW values may have resulted in severe bleaching and mortality (Hoegh-Guldberg, 1999), whereas coral communities today (or in the future) may be altered or acclimated, potentially requiring higher DHW values to trigger comparable responses (Heron et al., 2016; Maynard et al., 2017; Pratchett et al., 2013; Sully et al., 2019). For C2, thresholds were informed by bleaching responses to thermal stress levels observed during the most recent years of the satellite record (2015–2025) and were adjusted upward into the future to account for anticipated species filtering, and potential thermal adaptation or acclimation. Thresholds were defined at the ecoregional level where locally relevant evidence supported this (discussed further below). To account for uncertainty in the exact level of heat stress that causes bleaching/mortality, two plausible DHW threshold values were applied for each pathway.

Thresholds were derived by cross-referencing the literature of published bleaching records for the region against satellite DHW at the time and place of each observation, and against the ecoregional distribution of annual maximum DHW (Fig. 5, Table 12-13). These values were linked to the established NOAA Coral Reef Watch (CRW) alert levels and grounded based on published observations from each ecoregion where available (Abaker et al., 2024; Awaleh et al., 2026; DeCarlo, 2020; DeCarlo et al., 2020; DeVantier et al., 2000; Dosoky et al., 2021; Dunn et al., 2025, 2026; Eladawy et al., 2022; Eyal et al., 2019, 2022; Furby et al., 2013; Gonzalez et al., 2024; Hanafy et al., 2012, 2024, 2025; Hanafy & Dosoky, 2023; Kotb et al., 2004; Mayfield, 2025; Monroe et al., 2018; Osman et al., 2018; Pilcher & Alsuhaibany, 2000a, 2000b; Turak et al., 2007). Because in-situ observations are spatially and temporally uneven, particularly in the Southern Red Sea and Gulf of Aden (Osman et al., 2018), thresholds represent expert-elicited best estimates constrained by the observational record rather than statistically fitted values. As the

Gulf of Aden was severely lacking in data and past and current observations of coral bleaching, it was decided to use the same thresholds as the Southern Red Sea which has more published data on coral bleaching (DeCarlo et al., 2020, 2021; Kotb et al., 2004). In the future, more data linking SSTs, DHWs, and coral bleaching is needed from both regions to better understand local thresholds.

Thresholds were allowed to vary between ecoregions because the Red Sea and Gulf of Aden span a steep latitudinal gradient in summer maximum temperature and in the accumulated heat stress reefs routinely experience (Raitsos et al., 2013). The regional distribution of annual maximum DHW differs markedly between ecoregions (Fig. 5), and coral assemblages differ correspondingly in composition, thermal history and proximity to their upper thermal limits (e.g., Banc-Prandi et al., 2022; Berumen et al., 2019; DeVantier et al., 2000; Evensen et al., 2022; Gonzalez et al., 2024; Macrina et al., 2025; Oury et al., 2026; Sawall et al., 2015; Terraneo et al., 2017; Vicario et al., 2024). Though all ecoregions used in this assessment reflect known environmental and biological gradients (Cerutti et al., 2025), within these broad ecoregions environmental conditions or reef communities and their thermotolerance may vary—meaning thresholds applied broadly across an ecoregion here may not accurately reflect small-scale variation in actual coral thermal limits (e.g., Rich et al., 2022; Voolstra et al., 2025). Thresholds were held constant within periods delimited by documented regional mortality events and stepped upward at those change points, on the basis that where a severe event removes thermally sensitive taxa, the surviving assemblage requires a higher level of accumulated stress to produce a comparable response.

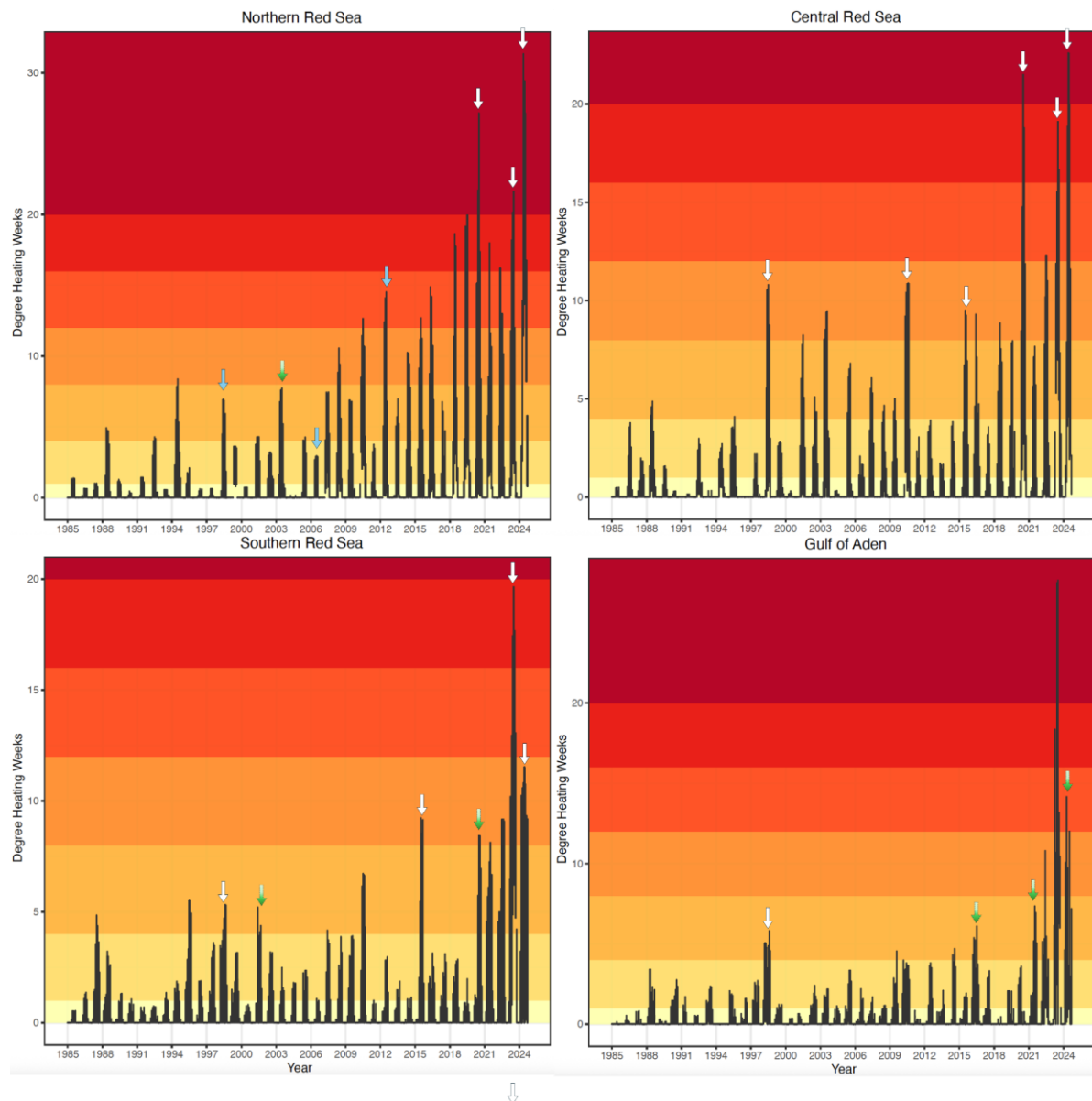


Figure 5. Accumulated thermal stress on coral reefs of the Red Sea and Gulf of Aden, 1985–2025, shown separately for each of the four coral reef ecoregions (ordered north to south). Black shapes are violin plots showing the distribution of Degree Heating Weeks (DHW, °C-weeks) across reef pixels within each ecoregion at monthly intervals, based on a random 10% subsample of pixels; width is proportional to the number of pixels at a given DHW value, so a narrow peak indicates that only part of the ecoregion experienced that level of stress. DHW data are satellite-derived from NOAA Coral Reef Watch at 5 km resolution (Liu et al., 2012), attributed to reef pixels within a 50 km buffer of mapped reef extent. Background shading denotes NOAA Coral Reef Watch bleaching alert levels: Bleaching Warning (DHW 0–4), Alert Level 1 (4–8), Alert Level 2 (8–12), Alert Level 3 (12–16), Alert Level 4 (16–20) and Alert Level 5 (>20). Arrows mark years for which bleaching was reported in the region: white = published in-situ observations of widespread bleaching, blue = moderate to mild published in-situ observations of bleaching, and green/white = unconfirmed, but likely moderate to severe bleaching. Mortality associated with these bleaching events is highly region-specific and variable.

Northern Red Sea

Shallow-water assemblages in this ecoregion show a well-documented thermal buffer. Bleaching in 1998 was patchy and limited, affecting less than 15% of colonies at any site, with little evidence of more than incidental bleaching (DeVantier et al., 2000b, 2000a), and no bleaching was recorded at eight Egyptian sites in 2015 despite DHW of 5.1–10.5 °C-weeks (Osman et al., 2018). Where bleaching did occur during this period, it was largely restricted to mesophotic depths (Eyal et al., 2022). Widespread shallow-water bleaching was not documented until 2020, with wide ranging DHWs (3.6–20.6 DHWs) reported throughout the region (Dosoky et al., 2021; Dunn et al., 2025). This occurred again in 2023, with DHWs peaking around 18 (Hanafy & Dosoky, 2024) and 2024, at more than 25–30 DHW (Hanafy et al., 2025a; Kochman & Fine, 2025; Zvuloni et al., 2024). The absence of a widespread event before 2020 means there is no observed change point within C1, so a single threshold was applied across 1985/6–2025: DHW ≥ 12 for widespread bleaching and DHW ≥ 16 for severe mortality. This is corroborated by the ecoregional DHW distribution, in which severe events cluster above 15 DHW (Figure 5). Additional testing of higher DHW thresholds was tested, with no change in data outputs.

Central Red Sea

This ecoregion has a longer and better-resolved bleaching record, with mortality documented in 1998, 2010, 2015, 2020, 2023 and 2024. In 1998, near-total mortality occurred on coastal fringing reefs at Rabigh and approximately 70% mortality on reefs 25 km offshore (Wilkinson, 2000), with coral core stress bands recorded at Thuwal at 3.6–5.4 DHW (DeCarlo et al., 2021b). In 2010, 74% of inshore colonies bleached at 10–11 DHW (Furby et al., 2013; Riegl et al., 2012). Extensive bleaching in 2020 occurred at 12.7–20.6 DHW (Dunn et al., 2025), and the 2023 and 2024 events at approximately 18–23 DHW produced high mortality across both inshore and offshore reefs (Bähr et al., 2025; Dunn et al., 2026; Mayfield, 2025). A widespread bleaching threshold of DHW ≥ 8 is consistent with the lower bound of events producing bleaching across more than half of colonies, and with the modal severe-event range of 8–10 DHW in the ecoregional distribution (Figure 5). The mortality threshold was set at DHW ≥ 8 to 2015 and raised to ≥ 12 from 2016, reflecting the loss of sensitive taxa through the 2015–2016 event and those that followed.

Southern Red Sea

Reefs here bleach at markedly lower accumulated heat stress than elsewhere in the region, because upwelling and consistently high summer temperatures appear to amplify the biological effect of a given DHW value (DeCarlo, 2020; DeCarlo et al., 2021a). For instance, stress bands were recorded in 81% of *Porites* cores across the Farasan Banks in 2015 at only approximately 2–4 DHW (DeCarlo, 2020), with 99% bleaching recorded at a nearshore site at 7 DHW (Osman et al., 2018) and extensive bleaching to 20–30 m depth (Lozano-Cortés et al., 2016); unpublished survey data indicate more than 25%, and locally up to 90%, mortality throughout the Farasan Banks in the same year (A. Monroe et al., pers. comm.). By contrast, no stress bands were recorded in 67 cores from the same reefs in 1998 (DeCarlo, 2020), and heat stress of approximately 7 DHW in 2002 produced only limited bleaching in the absence of upwelling. Loss of coral cover following 2015–2016 was greatest in this ecoregion (Gonzalez et al., 2024). Initial thresholds were therefore set lower than other regions, at $\text{DHW} \geq 4$ for widespread bleaching and ≥ 5 for severe mortality, with 2015 treated as the change point after which the assemblage is assumed to have shifted, raising the thresholds to ≥ 8 and ≥ 10 respectively.

Gulf of Aden

This is the most data-poor ecoregion in the assessment. The available record indicates substantial impact in 1998, with 20–30% hard coral mortality across Djiboutian waters (Obura, 1999) and near-total mortality reported at some sites in the eastern Gulf of Aden (Kotb et al., 2004; Turak et al., 2007), and further mortality attributed to bleaching in 2016 (Cowburn et al., 2019). In 2023, spatially variable bleaching affecting up to approximately 23% of benthic cover was recorded in Djibouti at ~ 13 DHW (Awaleh et al., 2026). Given the oceanographic similarity to the Southern Red Sea and the absence of any basis for distinguishing the two on the available data, the same threshold values were applied, with the change point set at 2016 to match the documented event. This assumption should be treated as a source of uncertainty in the Gulf of Aden result.

Primary and alternative threshold sets

Two threshold sets were carried through the analysis for each pathway, bracketing uncertainty in the DHW level at which a given response occurs. The two sets serve a different purpose in the historical and future periods, and the direction of the offset differs accordingly.

For the historical and current periods (C1), the alternative set tests the possibility that the thresholds inferred from the observational record are set too high for a given ecoregion. That is, that widespread bleaching or mortality began at lower accumulated stress than the documented events imply; this is plausible given the lack of widespread monitoring or tourism throughout most of the region. In the pulse pathway the alternative mortality thresholds for these periods are therefore set below the primary values (for example, 12 rather than 16 DHW in the Northern Red Sea to 2025), which tests whether the C1 result is sensitive to a more conservative reading of the historical record. In the chronic pathway the observational constraint on the bleaching threshold is tighter, so the alternative values are equal to or above the primary values throughout.

For the future period, the alternative set instead represents a degree of thermal adaptation or acclimatisation beyond the shifts already documented at each change point, and is therefore set above the primary values in both pathways. The increment is scaled by the thermal buffer available in each ecoregion: larger in the Northern Red Sea, where summer temperatures remain furthest below the assemblage's upper limit, and smaller in the Southern Red Sea and Gulf of Aden, where taxa already live close to their thermal limits and the scope for further adaptation is correspondingly reduced. Neither set is presented as a prediction; together they define the range within which the risk status is reported.

Table 12. Ecoregional DHW thresholds representing thermal stress levels resulting in widespread bleaching (chronic pathway). Values are annual maximum DHW in °C-weeks.

Ecoregion	C1 – observed, past 50 years (1975–2025)			C2 – predicted, future 50 years (2026–2075)		
	Timeframe	Primary	Alternative	Timeframe	Primary	Alternative
Northern Red Sea	1985/6–2025	12	12	2026–2075	12	14
Central Red Sea	1985/6–2015	8	8	2026–2075	8	12
	2016–2025	8	10			
Southern Red Sea	1985/6–2015	4	4	2026–2075	8	10
	2016–2025	8	8			
Gulf of Aden	1985/6–2016	4	4	2026–2075	8	10
	2017–2025	8	8			

Table 13. Ecoregional DHW thresholds representing thermal stress levels resulting in severe mortality (pulse pathway). Values are annual maximum DHW in °C-weeks.

Ecoregion	C1 – observed, past 50 years (1975–2025)			C2 – predicted, future 50 years (2026–2075)		
	Timeframe	Primary	Alternative	Timeframe	Primary	Alternative
Northern Red Sea	1985/6–2025	16	12	2026–2075	16	18
Central Red Sea	1985/6–2015	8	8	2026–2075	12	16
	2016–2025	12	10			
Southern Red Sea	1985/6–2015	5	4	2026–2075	10	12
	2016–2025	10	8			
Gulf of Aden	1985/6–2016	5	4	2026–2075	10	12
	2017–2025	10	8			

Calculation of decline and risk

Current values

To apply Criterion C, the RLE assesses the level of risk based on the severity of decline and the proportion of the ecosystem affected. Analyses were conducted independently for each pathway (chronic and pulse). The relative severity of decline for both sub-criteria C1 and C2 was calculated for each reef pixel using the formula:

$$\text{Relative severity of decline} = \frac{\text{current conditions} - \text{initial conditions}}{\text{collapse thresholds} - \text{initial conditions}} \times 100$$

The chronic pathway is assessed in terms of the average return interval of severe bleaching events over a 30-year period (DeCarlo & Whitaker, 2025; Hughes et al., 2018). Return interval is an ecologically meaningful indicator because recovery from disturbance is a slow process, typically requiring 10–15 years for fast-growing species and considerably longer for the full complement of coral life histories and morphologies (Gilmour et al., 2013; Robinson et al., 2019). As bleaching events become more prevalent and frequent, the combined effect of repeated mortality and shortened intervals between disturbances limiting recovery, drives cumulative coral loss and increases the likelihood of ecosystem-level collapse (Eakin et al., 2026; Hughes et al., 2017; Pratchett et al., 2021).

Return intervals were estimated by fitting a binomial (logistic) regression model to the binary bleaching event time series for each reef pixel, where the probability of a severe bleaching event in any given year is modelled as a function of time (DeCarlo & Whitaker, 2025). This probabilistic approach provides a continuous, smoothed estimate of annual event probability. This reduces sensitivity to interannual variability and characterises the underlying trajectory of disturbance regimes, making it well suited to assessing chronic, long-term stress. The modelled annual probabilities were summed across all possible 30-year windows within the assessment periods of C1 (1985/6-2025) and C2 (2026-2075) to determine the expected number of severe bleaching events, which was then converted to an average return interval by dividing 30 years by the expected number of events. The current condition value was based on the shortest return interval (highest disturbance) over all 30-year periods. For C1, the model was fitted using observed DHW data (1985–2025), and for C2, the models were fitted using projected DHW data (1985–2100).

For the pulse pathway, current conditions were assessed using a 5-year moving window, applied across the full assessment periods of C1 and C2 for each reef pixel. The number of severe mortality events within each window were counted, with the maximum count across any 5-year period, representing the highest observed or projected clustering of extreme events, used as the current condition value. This event-based approach preserves temporal variability and is specifically designed to capture the clustering of extreme events that characterises the acute collapse pathway.

Initial values

To calculate relative severity of decline, initial values reflecting the baseline disturbance regime of each assessment period (C1 and C2) must be established.

For the chronic pathway, under C1, historical baseline conditions (circa the 1970s) are characterised by bleaching events occurring at most once every 10–15 years, equivalent to approximately 2–3 events per 30-year period. This reflects a natural disturbance regime in which sufficient time elapsed between events for meaningful coral recovery (Baker et al., 2008; Gilmour et al., 2013; Graham et al., 2011; Hughes et al., 2018; Robinson et al., 2019). For C2, the initial value is calculated from projected DHW data over the 30-year period immediately preceding 2026 (1996–2025), using the same probabilistic framework applied to the rest of the C2 analysis.

For the pulse pathway, under C1, the initial value is the maximum number of severe mortality events within any 5-year window at the start of the satellite time series (1985/86–1990/91). For C2, the initial value is the maximum number of severe mortality events within any 5-year window during the decade immediately preceding 2026 (2016–2025).

Collapse thresholds

To complete the calculation of relative severity of decline, it is necessary to define a collapse threshold, when the frequency of damaging heat waves creates a high likelihood of collapse. For coral reefs, collapse is defined by the near or complete loss of hard corals, corresponding to a hard coral cover below 5%. The same collapse thresholds are applied to both C1 and C2 because conceptually similar environmental conditions should lead to similar ecological outcomes regardless of when they occur.

For the chronic pathway, the collapse threshold is defined as severe bleaching events occurring, on average, every 3 years over a 30-year period (approximately 10 events per 30-year window) (DeCarlo & Whitaker, 2025). At this frequency, recovery intervals are considered insufficient to permit meaningful coral recovery between disturbances, and the cumulative, iterative mortality caused by several events drives progressive and significant ecosystem degradation (Emslie et al., 2024; Hughes et al., 2017). As a sensitivity test, a threshold of one event every 5 years (~6 events per 30-year window) was also assessed as even these narrow recovery windows do not allow for full recovery, and will lead to substantial decline after multiple decades (Hughes et al., 2017). Annual severe bleaching is a commonly cited when predicting future reef outlooks (De Clippele et al., 2023; van Hooidek et al., 2016; Zeng et al., 2025), however it is considered overly conservative as collapse will likely occur before we reach conditions conducive to yearly bleaching (Bland et al., 2017; Obura et al., 2021).

For the pulse pathway, the collapse threshold is defined as 2–3 severe mortality events occurring within any 5-year window. This formulation was adopted in response to evidence that the collapse threshold used by (Obura et al., 2021) for the Western Indian Ocean, and Bland et al. (2017) for the Meso-American Reef of two severe bleaching events per decade (equivalent to approximately one event every 5 years), may be insufficient to drive collapse under current conditions. Several reefs, including the Great Barrier Reef and Little Cayman, have experienced two or more severe bleaching events within a decade between 2015/16 and 2025 without clear evidence of ecosystem collapse (Emslie et al., 2024; Henley et al., 2024; Pratchett et al., 2021).

This suggests that reefs may be more resilient to moderate clustering of events than previously assumed, and that a higher frequency, specifically 2–3 extreme mortality events within a 5-year window, is required to reliably indicate conditions conducive to collapse.

The 2023 and 2024 events in the Central and Northern Red Sea provide a regional analogue for the mechanism this threshold is intended to capture: successive years of high accumulated stress produced mortality of up to 100% in *Acropora* and *Millepora* and a 65% relative loss of hard coral cover across depths (Bähr et al., 2025; Dunn et al., 2026; Mayfield, 2025) affecting offshore reefs that had been comparatively spared in 2010 and 2015.

Role of initial values in distinguishing C1 and C2

Although the collapse thresholds are identical for the two sub-criteria, the reference states against which they are evaluated are not, and this distinction is material to interpretation. Reefs across the region in the mid-1970s were, so far as the record allows us to judge, largely undisturbed by thermal stress: the first documented regional bleaching occurred in 1997–1998. Reefs entering the C2 period are in a substantially altered state, having passed through mortality events in 1998, 2010, 2015–2016, 2020, 2023 and 2024 in at least part of the region, and the C2 initial values calculated from the 1996–2025 window reflect this. A given increase in event frequency projected forward from 2026 therefore represents a proportionally larger step toward collapse than the same increase would have represented in 1975. This is captured through the initial values rather than through the collapse threshold, and should be stated explicitly when C1 and C2 results are compared.

Risk status assignment

For C2, analyses were conducted under three emissions scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5), with SSP2-4.5 treated as the primary scenario.

To assign the risk status under Criteria C1 and C2 for each ecoregion, relative severity of decline was interpreted in conjunction with reef extent using the severity–extent matrix. The relative extent of decline for each ecoregion was approximated from the cumulative proportion of reef area experiencing different levels of decline ($\geq 20\%$, $\geq 30\%$, $\geq 40\%$, $\geq 50\%$, $\geq 70\%$, $\geq 80\%$, and 100%).

Where results differ between the chronic and pulse pathways, the risk category was reported based on the pathway with the greatest confidence, or a range of outcomes presented across

both pathways. Uncertainty across DHW thresholds, collapse thresholds, and initial values was incorporated by repeating the analysis across all plausible combinations of these parameters, producing a range of possible risk outcomes. The final reported risk status for each ecoregion for C1 was based on the mean decline across all combinations, while for C2, the final status corresponded to the best-case scenario of an intermediate climate pathway (SSP2-4.5) with coral adaptation (higher future DHW thresholds).

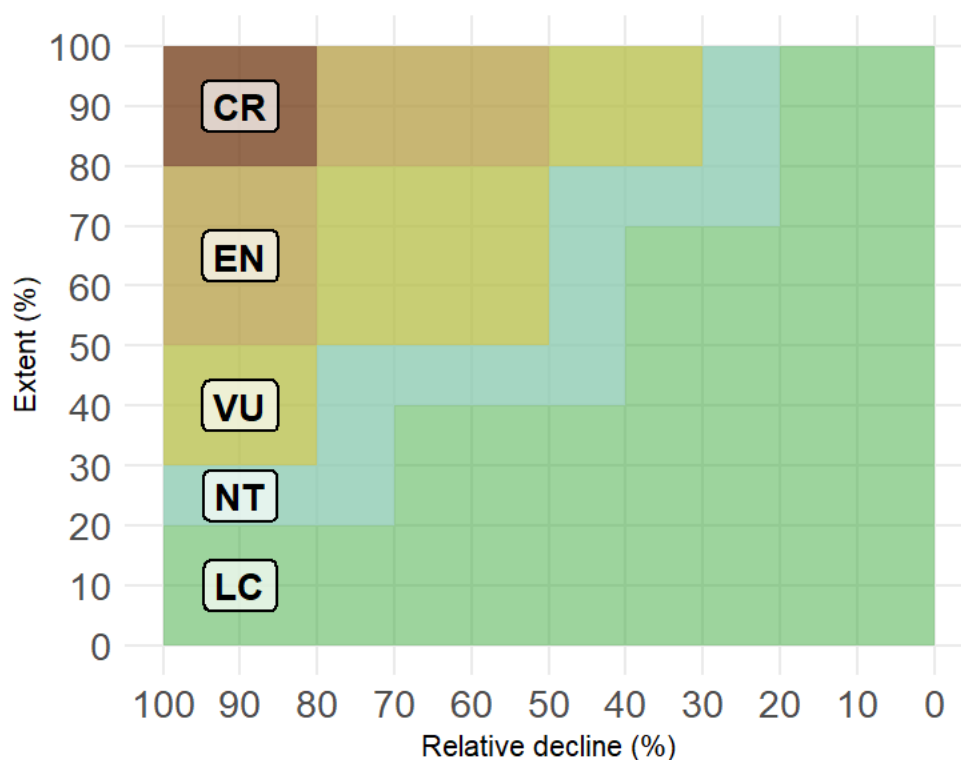


Figure 6.

Criterion D: Disruption of Biotic Processes and Interactions

Criterion D was evaluated to identify ecosystems experiencing severe disruption to biotic organisms, processes and interactions. This includes declines in characteristic species, shifts in community structure, and the loss of ecological functions necessary for maintaining ecosystem identity. The approach enables identification of the most degraded ecosystem components and how this degradation contributes to the overall risk of collapse. This assessment evaluated the

degradation over the past 50 years (sub-criterion D1), estimating how close each ecosystem component was to collapse or severe functional disruption.

Indicator selection

In the Red Sea and Gulf of Aden, two key biotic components were assessed based on past RLE assessments (Bland et al., 2017; Obura et al., 2021) and using data derived from standard underwater survey methods [e.g. point intercept transects, line intercept transect and photoquadrats]. These components include:

- Hard corals, as the keystone ecosystem taxa responsible for forming the habitat structure and accretion processes.
- Algae, as the principal competitive taxa to hard corals;

For each component, indicators were selected based on ecological relevance, data availability, spatial coverage, sensitivity to ecosystem condition, and the ability to define both a reference state and a collapse threshold.

Hard coral cover was selected as the indicator of coral state, as it has been consistently used as a key measure of reef health over several decades.

The algae-to-coral cover ratio was used to represent benthic competition, rather than algae cover alone, as this directly captures the dynamic balance between coral and algal dominance. Algae included turf algae, fleshy macroalgae, and calcifying macroalgae such as *Halimeda*, reflecting differences in how monitoring programs classified algae. Crustose coralline algae (CCA) were excluded. The ratio was calculated as the total algae cover divided by the sum of algae and coral cover.

Calculation of risk

Biotic degradation under Criterion D was assessed using the relative severity of decline. This metric compares the current state of each indicator to both a historical baseline (level approximately 50 years ago) and a hypothetical collapse threshold.

Current values

Current values for each indicator were derived from the most recent monitoring data available, using a five-year period spanning 2020–2025 (table 14). This period was selected to provide a

contemporary representation of reef condition while retaining sufficient observations to account for variation in monitoring effort among years and ecoregions. A *site* refers to the smallest surveyed spatial unit reported in the contributed datasets, representing the finest spatial level at which observations were provided, and may comprise observations aggregated from replicate sampling units, such as transects or photoquadrats. Where a site was surveyed more than once during the five-year period, values were averaged across all available surveys to obtain a single current value for that site and avoid giving greater weight to more frequently monitored locations. The resulting site-level values were then used to characterize the distribution of current conditions within each ecoregion.

The temporal and spatial coverage of recent monitoring data varied among ecoregions (Figure 6). Sufficient contemporary data were available to estimate current conditions for the Northern, Central and Southern Red Sea, although monitoring intensity and spatial coverage differed among them. For the Gulf of Aden, however, current data were limited to a 2023 dataset from a single country, providing insufficient representation of the wider ecoregion. Large areas of the Gulf of Aden, including reefs along Yemen and the Socotra Islands, were not represented in the current dataset. The available observations were therefore considered insufficient to reliably characterize current reef condition across the ecoregion or quantify change relative to the historical reference state. Consequently, the Gulf of Aden was classified as Data Deficient (DD) rather than extrapolating conditions from the limited available sites to the entire ecoregion.

Table 14. Mean current value of each indicator per ecoregion (n – number of sites).

Ecoregion	Indicator	n	Mean	Std. dev	Min value	Max value
NRS	HC	135	36.97	16.54	2.50	80.70
CRS	HC	60	17.97	13.71	0.29	59.2
SRS	HC	76	18.61	21.84	0.59	80.89
GoAden	HC	16	48.02	6.46	38.11	58.50
NRS	ALG	131	19.82	16.93	0.00	57.71
CRS	ALG	53	37.40	16.68	1.09	69.51
SRS	ALG	76	34.11	20.55	0.00	81.09
GoAden	ALG	16	13.49	5.72	4.99	25.10



Figure 7. Temporal trends mean hard coral cover and survey effort across the Red Sea and Gulf of Aden ecoregions. Grey bars show the number of surveyed sites, and red dashed lines delimit the historical (≤ 1998 and recent (2020 - 2025) reference periods

Initial values

An ecoregional reference state representing conditions of each indicator approximately 50 years ago (circa 1975) was established to quantify long-term change. Historical observations close to this reference period were limited, with only 13 hard-coral-cover observations representing 11 sites and 2 published sources available up to 1975. These observations were collected in 1969, 1973, and 1974 and were confined to the Northern Red Sea. By 1998, the historical record had increased to 238 observations representing 230 sites and 12 data sources, although coverage remained spatially and temporally uneven. Most observations were from the Northern Red Sea (112 observations), followed by the Gulf of Aden (69), Southern Red Sea (38), and Central Red Sea (13). Baseline conditions could therefore not be estimated directly from observations

around 1975 and were instead reconstructed using empirical monitoring data, published literature, and regional expert knowledge. Initial conditions were represented as distributions, defined by a mean and standard deviation, rather than as single values to account for natural spatial variability and uncertainty in historical conditions (Obura et al., 2021).

Given these limitations, three alternative approaches were evaluated to estimate initial conditions for each ecoregion. Each approach used the available historical and monitoring data differently, allowing the resulting estimates to be compared and the most appropriate approach to be selected for each ecoregion.

Method 1 – Pre-1998 inclusive: Regional experts assumed that reef condition in the 1970s was generally better than at present, and that 1997/8, the year of the first widespread global bleaching event, represented a major turning point in reef condition. Several reefs prior to 1998 were considered broadly representative of earlier (1970s) conditions, with only localised degradation in places. The primary approach used all available observations collected in or before 1998 (Gudka et al., 2024; Obura et al., 2021). The dataset combined nine published sources contributing 45 observations from 41 sites and three regional monitoring sources contributing 193 observations from 190 sites. Overall, it comprised 238 observations from 230 sites spanning 1969–1998 and included coverage of the Northern, Central and Southern Red Sea and the Gulf of Aden. Nevertheless, coverage remained uneven, with nearly half of the observations coming from the Northern Red Sea.

Method 2 – Pre-1998 filtered: Some historical datasets lacked sufficiently precise sampling dates to distinguish confidently between observations collected before and after the 1998 bleaching event. A filtered version of the pre-1998 dataset was therefore evaluated by excluding unusually low coral-cover values relative to surrounding observations that could represent already disturbed reef conditions. The observations identified for exclusion were all from the Northern Red Sea, while no comparable low-cover observations requiring exclusion were identified in the other ecoregions.

Method 3 – Maximum-value approach: A third approach used long-term monitoring records to estimate the best observed condition of individual reefs. Sites with at least two surveys spanning ≥ 10 years were selected. From each site's monitoring history, we extracted the maximum recorded hard coral cover and the minimum recorded algal cover. These hard coral site-level maxima were treated as proxies for relatively good observed reef conditions rather than as

direct estimates of conditions in 1975. The distribution of maximum values across sites within each ecoregion was then aggregated to derive an alternative initial-condition distribution, expressed as a mean and standard deviation.

Expert elicitation and final selection: Estimates from Methods 1 and 2 differed only slightly, whereas Method 3 produced more variable estimates. Outputs from all three approaches were presented to regional experts for evaluation, taking into account data coverage, spatial representativeness, and knowledge of historical reef conditions. For the Northern Red Sea, Central Red Sea and Gulf of Aden, the pre-1998 inclusive approach (Method 1) was considered the most appropriate representation of initial conditions, drawing on the combined published and monitoring records spanning 1969–1998 (Figure 5). For the Southern Red Sea, however, the available historical observations disproportionately represented offshore reefs and a limited subset of locations, some of which may already have experienced degradation, while inshore reef systems were poorly represented. To reduce this spatial bias and provide a more representative approximation of historical conditions, regional experts recommended using a broader Red Sea-wide pre-1998 dataset to derive initial values for the Southern Red Sea (table 15).

Table 15. Mean initial values with variance measures for live hard coral and algae cover for each ecoregion (n – number of sites).

Ecoregion	Indicator	Mean	Std. dev	Min value	Max value	n
NRS	HC	34.88	14.60	5.0	82.2	112
CRS	HC	33.95	10.43	20.0	50.2	13
SRS	HC	28.97	17.27	5.0	82.2	163
GoAden	HC	26.15	19.14	5.0	80.0	69
NRS	ALG	11.90	9.29	0.0	48.8	60
CRS	ALG	9.32	9.09	0.0	25.0	11
SRS	ALG	18.30	17.30	0.0	85.0	107
GoAden	ALG	23.90	22.20	0.0	85.0	69
NRS	ACR	0.25	0.17	0	0.50	60
CRS	ACR	0.21	0.20	0	0.70	9
SRS	ACR	0.40	0.31	0	0.94	107
GoAden	ACR	-	-	-	-	-

Collapse thresholds

Collapse thresholds were defined for each indicator to represent the degradation point at which ecosystem function or identity is completely lost, and the ecosystem is fundamentally changed.

For benthic indicators, thresholds reflect a transformation in state, for example away from a coral-dominated ecosystem to one that is algae-dominated. For hard coral cover, a threshold of

[5%] was applied, representing the minimum level required to sustain positive carbonate accretion on a reef. For the algae-to-coral ratio, a threshold of [0.833] (i.e. algae cover five times greater than coral cover) was used, indicating a persistent shift to algal dominance where recovery becomes unlikely.

Calculating relative severity of decline

Relative severity of decline was calculated for each site with current data using the formula:

$$\text{Relative severity of decline} = \frac{\text{initial value} - \text{current value}}{\text{initial value} - \text{collapse threshold}} \times 100$$

Uncertainty in initial conditions was incorporated by applying a bootstrapping approach. For each ecoregion and indicator, initial values were represented as a normal distribution defined by the estimated mean, standard deviation, and observed range (min and max). Initial values were randomly sampled from this ecoregional distribution and assigned to each site.

The highest risk category was determined from the decline-extent matrix, with the ecosystem extent calculated as the proportion of sites exceeding decline thresholds ($\geq 20\%$, $\geq 30\%$, $\geq 50\%$, $\geq 70\%$, $\geq 80\%$, and 100% decline). This process was repeated [1000] times, and each time the resulting highest risk category for the iteration was recorded. To determine the final risk category for each indicator, the distribution of outcomes across all iterations was considered. Where $\geq 80\%$ of iterations produced the same category, this was assigned as the final status. When a dominant result was not returned, an appropriate category or range of categories was applied, e.g. if 50% of iterations were LC, and 50% VU, then the overall risk was NT.

The analysis assumed that monitoring sites broadly reflect conditions across the entire ecoregion. Where spatial coverage was uneven or limited, we assessed whether observed patterns were representative of the unsampled areas based on the distribution of pressures and environmental conditions. If the available data were considered insufficient to reliably characterize ecosystem-wide patterns, the ecoregion was classified as *Data Deficient*.

Determining final risk class for Criterion D

The overall risk category for Criterion D for each ecoregion was determined by integrating results across all indicators using a stepwise approach, following previous coral reef RLE assessments.

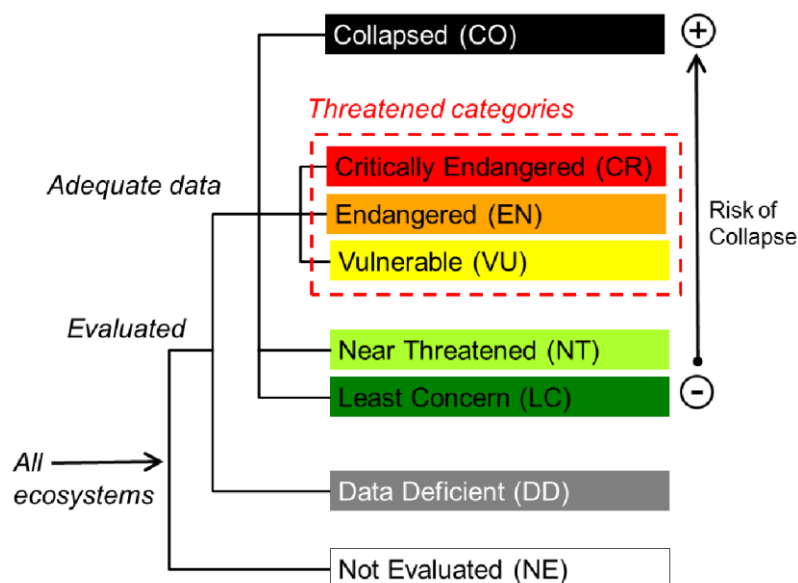
Indicators were evaluated in sequence according to their ecological role and interactions:

1. Hard corals (reef engineers);
2. Algae (competitive dynamics);

The assessment used the coral condition as the baseline classification. At each subsequent step, the overall risk category was increased by one level if the next indicator was classified at a higher risk level than the cumulative status to that point. This approach ensures that hard coral, as the foundational component of reef ecosystems, had the greatest influence on the final classification, while still accounting for the contribution of other biotic components. It also prevented the overall assessment from being disproportionately driven by secondary indicators (e.g. algae).

Overall risk status

Once all applicable RLE criteria and sub-criteria had been assessed, the overall risk status for coral reefs in each ecoregion was determined. A precautionary approach, consistent with the principles of the Red List of Ecosystems framework was applied whereby the final classification reflected the most severe risk category assigned across all evaluated criteria. This approach ensures that any severe risk which may drive collapse is not diluted or overlooked in the final assessment.



11.3. Discussion

This assessment demonstrates the continued ecological importance and conservation value of coral reefs across the Red Sea and Gulf of Aden, while identifying important spatial differences in ecosystem risk. Reefs remain widely distributed across all four ecoregions, but risk based on observed change varies from Vulnerable in the NRS and GoAden to Endangered in the CRS and SRS. For GoAden, Criteria A and D were Data Deficient owing to limited spatial coverage of in-situ biological data; its current classification should therefore be regarded as a minimum estimate of risk and may be revised upward as additional monitoring data become available. Despite these differences, projected increases in extreme heat events result in a Critically Endangered classification across all ecoregions, consistent with global projections under C2. This combination of contrasting current conditions and shared future climate risk highlights the importance of considering ecoregional differences in conservation planning.

At present, extreme marine heatwaves represent a shared pressure across the Red Sea and Gulf of Aden, alongside overfishing, coastal development, pollution, tourism and recreation, and biological disturbances. Ecosystem change nevertheless differs across the region: the NRS showed comparatively lower estimated change in functioning reef distribution and biotic components, the CRS showed greater biotic degradation, and the SRS showed greater change in both distribution and biotic condition. This pattern is consistent with reported spatial differences in coral community structure and coral–algal states across the Red Sea (Gonzalez et al., 2024; Hammerman et al., 2022), occurring along regional gradients in temperature, nutrients and productivity (Kürten et al., 2014; Raitos et al., 2013). These patterns are supported by biological observations spanning 1969–2025. Although earlier records were sparse, reference conditions were reconstructed from monitoring data, literature and regional expertise, with uncertainty explicitly accounted for by representing initial conditions as distributions rather than single values. Despite this broadly shared exposure to thermal stress, ecosystem change appears spatially uneven across the region.

These regional patterns show both similarities and contrasts with coral reef RLE assessments elsewhere. Geographic distribution was similarly associated with relatively low risk at the regional scale in the Western Indian Ocean (WIO) (Obura et al., 2021), whereas restricted distribution contributed more strongly to risk in continental reefs of the Colombian Caribbean (Uribe et al., 2021). Biotic condition in the NRS was broadly comparable to many WIO ecoregions, notable given that this assessment incorporates observations following the 2023–2024 bleaching event, whereas the WIO assessment predates it, in 2019. Greater biotic

degradation in the CRS and SRS is consistent with findings from oceanic reefs of the Colombian Caribbean, where biotic degradation was also an important driver of ecosystem risk (Uribe et al., 2021). Projected warming was a major driver of overall risk in both the Red Sea and Gulf of Aden and the WIO (Obura et al., 2021), marking a clear point of convergence across regions.

Marine heatwaves are already an important source of bleaching risk in the Red Sea, with evidence of increasing occurrence of extreme warming events in parts of the region (Genevier et al., 2019). Responses to thermal stress nevertheless vary among reefs owing to differences in thermal environments, coral communities and thermal histories (e.g., (Bellworthy & Fine, 2017; Fine et al., 2013; Osman et al., 2018). Accordingly, ecoregion-specific DHW thresholds were applied, with plausible alternative thresholds used to account for uncertainty in thermal responses. The projected high risk does not imply inevitable ecosystem collapse but rather increasing exposure to conditions capable of driving substantial ecological change.

The comparatively favorable current condition of the NRS, particularly the Gulf of Aqaba, is consistent with documented coral thermal resilience. NRS corals are hypothesized to have been thermally pre-selected during postglacial recolonization, as populations passing through the warmer southern Red Sea filtered out thermally sensitive genotypes (Fine et al., 2013). Experimental studies similarly demonstrate high thermal tolerance in Gulf of Aqaba corals (Bellworthy & Fine, 2017; Osman et al., 2018; Savary et al., 2021), while regional projections indicate lower warming in the NRS than the CRS and SRS (Eladawy et al., 2022). Low bleaching and mortality during the exceptional 2023–2024 heatwave further support the favorable biotic condition estimated in this region (Kochman & Fine, 2025). This relative resilience, however, does not imply immunity from climate change or local pressures: maintaining water quality, effective coastal planning and marine protected area management remains important for sustaining these conditions under increasing climate pressure.

Ecosystem risk across the Red Sea and Gulf of Aden thus reflects different combinations of environmental pressure and ecological change, supporting conservation priorities tailored to individual ecoregions. Climate-related pressure is increasingly important region-wide, but differences in ecosystem response point to two complementary priorities: maintaining reefs currently in comparatively favorable condition and strengthening recovery and management of locally manageable pressures where change has been greater. The assessment also identifies opportunities for further research, particularly to improve the spatial coverage of in-situ biological monitoring in the Gulf of Aden and address its Data Deficient status, and to expand the

range of ecological indicators as comparable regional data become available. As the first regional RLE assessment, it provides a baseline for continued monitoring and periodic reassessment to track ecosystem trajectories, changes in risk and conservation effectiveness, and to guide adaptive conservation as conditions change.

Criterion C – Environmental Degradation: supplementary figures

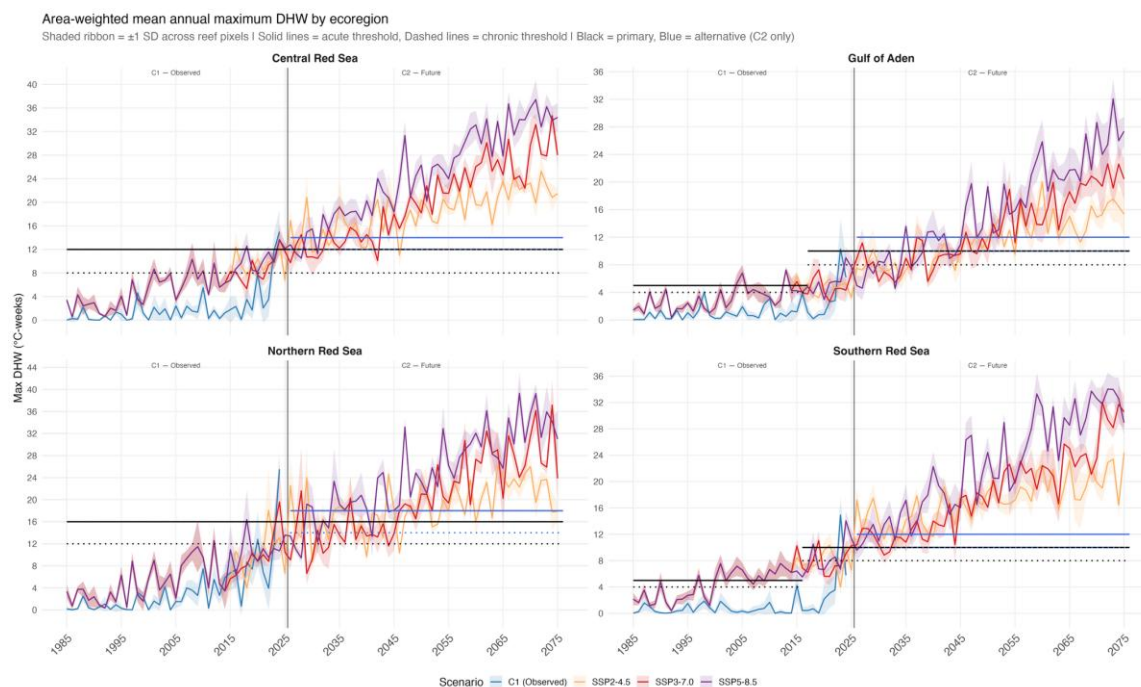


Figure S1. Annual maximum Degree Heating Weeks (DHW) averaged across coral reefs within each ecoregion from 1985–2075 for four trajectories: observed data used to assess sub-criterion C1 from 1985–2025 (blue line), and projections under three Shared Socioeconomic Pathways — SSP2-4.5 (orange), SSP3-7.0 (red), and SSP5-8.5 (purple). Shaded ribbons represent ± 1 SD in DHW across reef pixels within each ecoregion, reflecting spatial variability in thermal exposure. Horizontal lines show ecoregion-specific DHW thresholds at various points in time corresponding to severe bleaching events (chronic stress pathway; dashed lines) and severe mortality events (acute stress pathway; solid lines). Black lines indicate primary thresholds, and blue lines indicate alternative thresholds (C2 period only, 2026–2075). The vertical grey line marks the boundary between the observed (C1 - 1985–2025) and projected (C2 - 2026–2075) assessment periods.

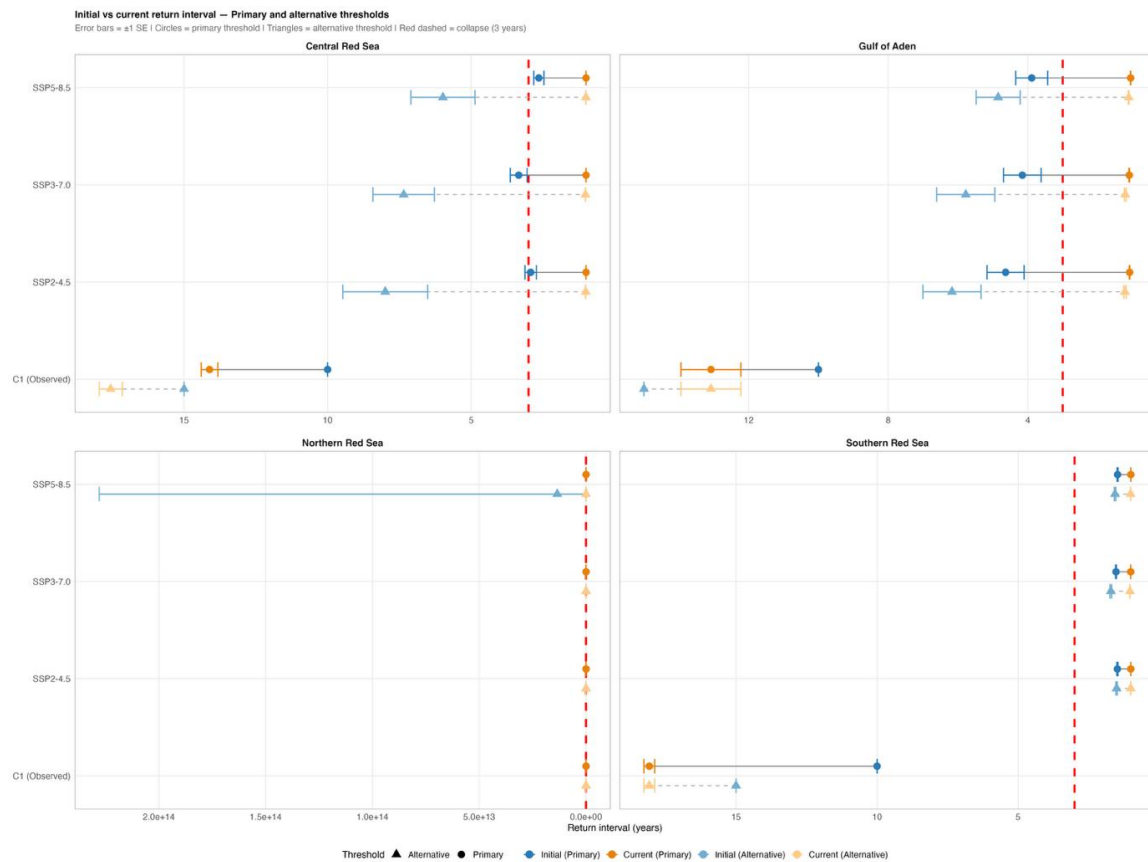


Figure S2. Change in the average return interval between severe bleaching events (years) for each ecoregion (x-axis), comparing initial conditions (blue) to current or projected future conditions (orange) across four trajectories (y-axis): observed data (C1) and projections under SSP2-4.5, SSP3-7.0, and SSP5-8.5. Connecting lines indicate the direction and magnitude of change between initial and current conditions. Return intervals were estimated for the chronic pathway by fitting a binomial regression model to the binary bleaching event time series for each reef pixel, with values representing the shortest return interval identified over each assessment period (C1: 1985–2025; C2: 2026–2075). Results are shown for both primary (filled circles) and alternative (filled triangles) DHW thresholds. For C1, initial conditions are assumed to reflect historical disturbance regimes prior to the satellite record, corresponding to a return interval of 10 years (primary threshold) and 15 years (alternative threshold). For C2, initial conditions are calculated from projected DHW data over 1996–2025 using the same probabilistic model. Error bars represent ± 1 SE across reef pixels within each ecoregion. The red dashed vertical line marks the collapse threshold of a 3-year return interval, below which disturbance frequency is considered sufficient to prevent meaningful coral recovery and drive progressive ecosystem degradation. Note that the x-axis is reversed such that movement from left to right represents a shortening return interval and worsening conditions.

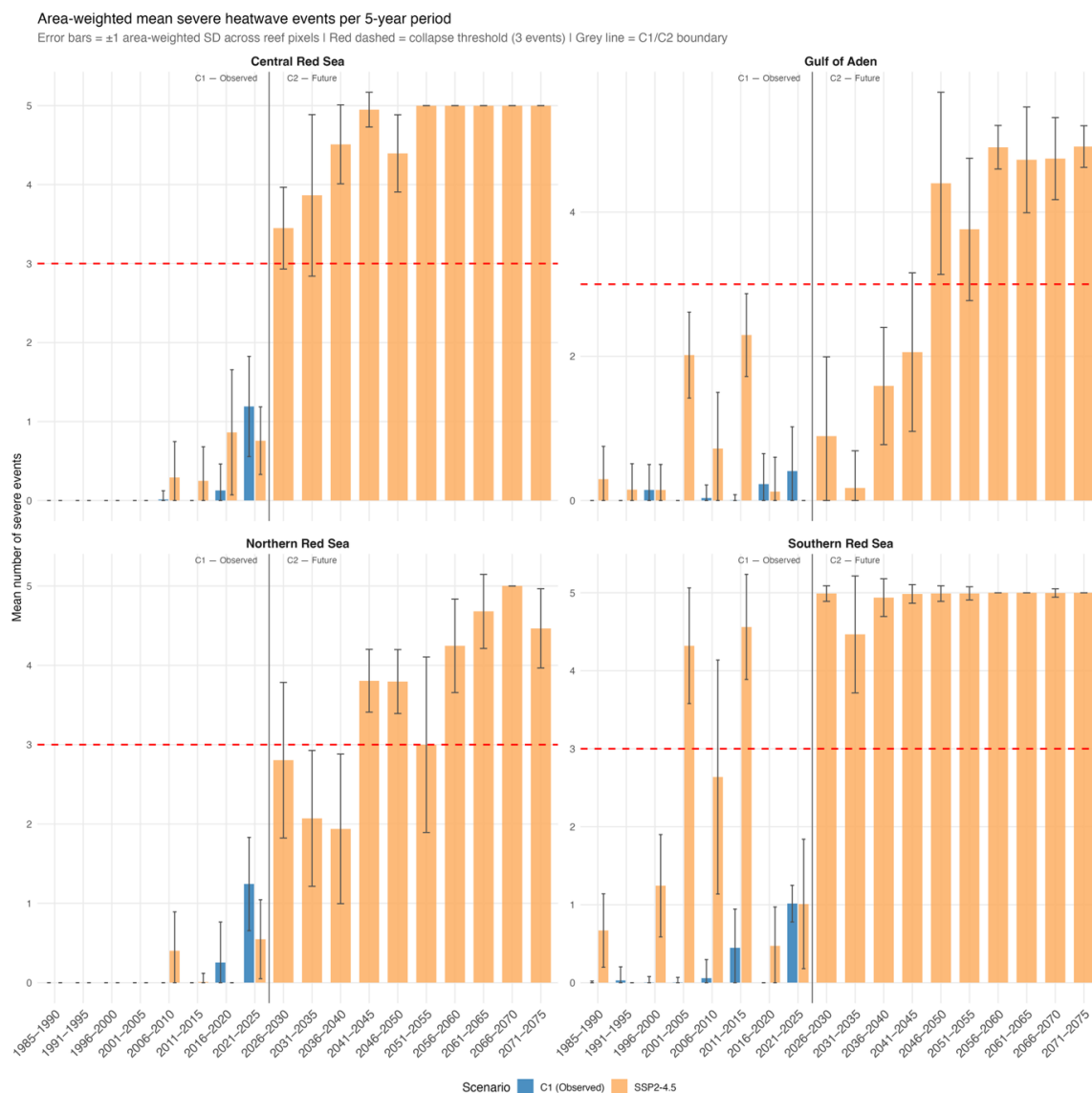


Figure S3. Mean number of severe mortality events per 5-year period, averaged across coral reef pixels within each ecoregion, under two trajectories: observed data used to assess sub-criterion C1 (blue bars, 1985–2025) and projections under SSP2-4.5 (orange bars, 1985–2075). Severe mortality events are defined as years in which annual maximum DHW exceeded ecoregion-specific acute stress thresholds associated with widespread coral mortality. Error bars represent ± 1 SD across reef pixels within each ecoregion, reflecting spatial variability in the frequency of severe thermal exposure. The red dashed horizontal line indicates the collapse threshold of 3 severe mortality events within a 5-year window. The vertical grey line marks the boundary between the observed (C1, 1985–2025) and projected (C2, 2026–2075) assessment periods.