

METHODS

Global Red List of Coral Reef Ecosystems: assessment methods

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Overview of the assessment

The approaches used in this global assessment of photic coral reefs under the IUCN Red List of Ecosystems (RLE) followed the Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria 2.0 (IUCN 2024), and builds from previous published coral reef RLE assessments, namely Obura et al. (2022) and Bland et al. (2017). The RLE provides a standardised framework for assessing the risk of ecosystem collapse based on 5 Criteria A to E. For coral reefs, collapse was defined as the near or complete loss of hard corals, to the point where defining processes such as carbonate accretion are absent or negligible (hard coral cover below 5%). The coral reefs within each of the 127 ecoregions were assessed against Criteria A to D (Table 1), each of which addresses a different way in which an ecosystem can be degraded or placed at risk. Criterion E was only applied in four Australian ecoregions with a suitable coral reef model.

Each criterion resulted in one of the RLE risk categories, in increasing order of risk: Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR) and Collapsed (CO). Ecoregions with insufficient data to assess a particular criterion were classified as Data Deficient (DD).

Once all applicable criteria and sub-criteria had been assessed, the overall risk status for coral reefs in each ecoregion was determined using a precautionary approach consistent with RLE principles: the final classification reflected the most severe category assigned across all criteria. This ensured that any severe risk that could drive collapse was not diluted or overlooked.

Table 1. Criteria and sub-criteria applied and the main data used.

Criterion	Aspect assessed	Main data used
A	Reduction in geographic distribution over the past 50 years (A1)	Recent hard coral cover from monitoring sites (used as a proxy for area lost)
B	Restricted geographic distribution, and vulnerability to a single threatening event (B1, B2)	Spatial layer of mapped reef extent
C	Degradation of the abiotic environment from marine heatwaves, over the past 50 years (C1) and the next 50 years (C2)	Satellite-derived and modelled Degree Heating Weeks
D	Disruption of biotic processes and interactions over the past 50 years (D1)	Monitoring data on hard corals, algae, parrotfish and groupers (where available)

Criterion	Aspect assessed	Main data used
E	Quantitative estimate of the probability of ecosystem collapse	Integrated ecosystem models linking coral cover decline, thermal stress, and ecological interactions

Criterion A: Reduction in geographic distribution

Criterion A assesses the reduction in the extent of an ecosystem over time, typically over 50 years. Sub-criterion A1 was assessed, which measures the percentage of reef area lost in each ecoregion over the past 50 years (1975–2025). Sub-criteria A2a and A2b, which require assessment into the future, were not evaluated, except for four ecoregions in Australia. A3, which requires evaluating historical decline since 1750, was not evaluated either. Historical mapped reef area spanning about 50 years is rarely available, and coral reefs can undergo functional decline without any visible change in the structural extent mapped by satellites. Mapped area reduction therefore could not be used, and recent hard coral cover was instead used as a proxy for declines in reef area (Obura et al. 2022).

Hard coral cover data from monitoring sites were compiled, and only sites with at least one survey between 2020 and 2025 were retained. Each site was classified as a functioning (net-accreting) reef or a degraded site using a threshold of either 5% or 10% hard coral cover. This threshold represents an established point below which coral abundance is too low to maintain positive carbonate accretion, and at which a reef is considered functionally collapsed (Perry et al. 2013; Obura et al. 2022). A sensitivity analysis was run across thresholds of 1–10% (Fig. 1). Each site was assumed to represent an equal portion of reef area, and all monitored sites were assumed to have been functioning reefs around 1975. The percentage of sites currently below the threshold was therefore taken as the proportion of reef area that had since degraded or been lost.

The representativeness of the monitoring data was assessed by comparing the area of a polygon enclosing all monitoring sites with the Extent of Occurrence of reefs in the ecoregion, and the proportion of 10 × 10 km grid cells containing monitoring data with the total number of reef cells (Area of Occupancy). Expert judgement was used to decide whether the data were sufficient to represent ecosystem-level decline, and ecoregions with fewer than 10 monitoring sites were classified as Data Deficient (DD). Where data were adequate, the percentage of sites below the coral cover threshold was compared with the RLE thresholds for A1: ≥80% (CR), 50–80% (EN), 30–50% (VU), 27–30% (NT) and <27% (LC) (Fig. 2).

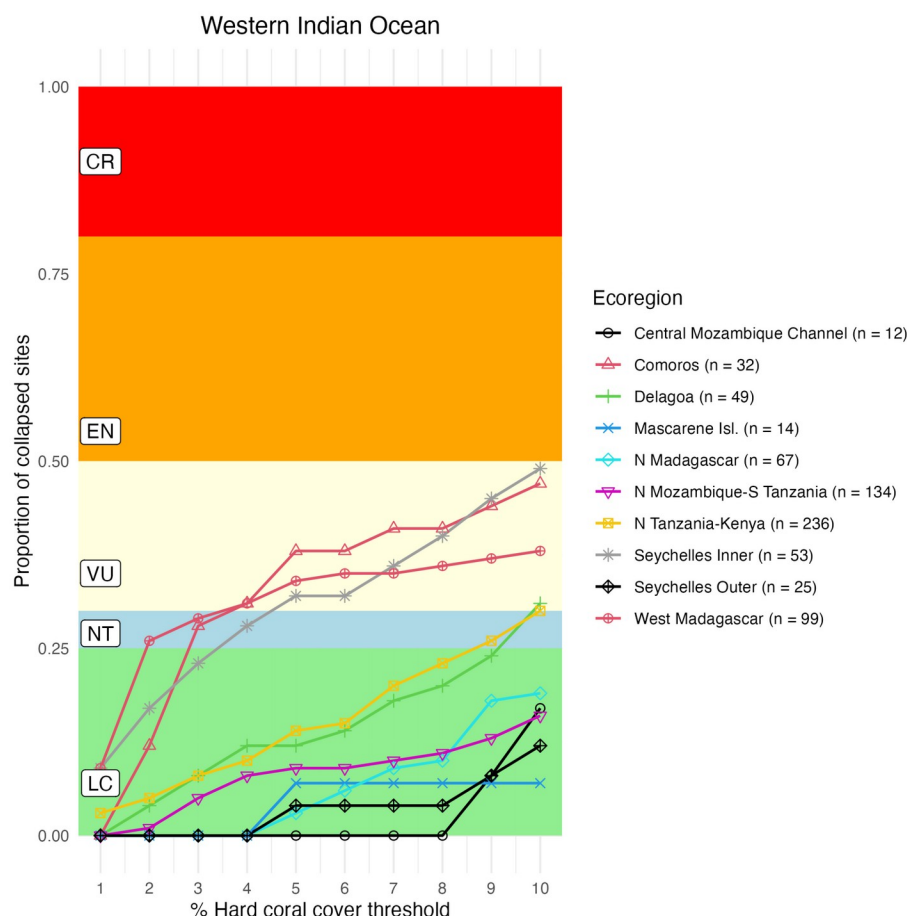


Figure 1. Sensitivity of Criterion A1 to the collapse threshold: proportion of collapsed reef sites (0–1, y axis) in 10 Western Indian Ocean ecoregions (lines) and the corresponding risk category (shaded areas), for hard coral cover thresholds of collapse from 1% to 10% (x axis). n = number of monitoring sites.

Subcriterion	Time frame	CR	EN	VU
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 2. Risk thresholds for sub-criteria (A1, A2a, A2b, A3) under Criterion A based on reductions in geographic distribution. Source: IUCN (2024).

Criterion B: Restricted geographic distribution

Criterion B assesses ecosystems whose distribution is so limited that they are at risk of collapse from the chance occurrence of one or a few threatening events, such as a cyclone, bleaching event or disease outbreak. Two standardised spatial metrics were used: the Extent of Occurrence (EOO; B1), defined as the area within the outer boundary of the ecosystem's known distribution, and the Area of Occupancy

(AOO; B2), defined as the area occupied by the ecosystem and measured as the number of 10×10 km grid cells containing reef.

A coral reef extent layer was compiled from multiple global sources, including the Global distribution of coral reefs, version 4.1 (UNEP-WCMC et al. 2021), which is based on the Millennium Coral Reef Mapping Project, and/or the Allen Coral Atlas (Allen Coral Atlas Team 2026). Where higher-resolution national or territorial maps were available, they were substituted for, or merged with, the global layer. The sources used in each region are described in the corresponding regional report. Analyses were carried out in R using the *redlistr* package. The merged layer was projected to the appropriate UTM zone, the EOO was generated as the minimum convex polygon around all reef features in each ecoregion (Fig. 3), and its area was calculated. AOO was calculated using a 10 km cell size (Fig. 4), counting cells containing coral reef. In line with the RLE 1% rule (IUCN 2024), all grid cells whose cumulative area of the reef ecosystem was $< 1\%$ were excluded from the AOO count.

EOO and AOO values were compared with the thresholds defined in the RLE guidelines (Fig. 5), and ecoregions with values within 10% of the VU thresholds were classified as NT. To assign a final status under B1 or B2, experts were required to justify observed or inferred declines, or the presence of current threats (e.g. ocean warming, pollution, coastal development or overfishing) presenting an ongoing risk to the reefs.

Western Indian Ocean
Criterion B1: Extent of Occurrence

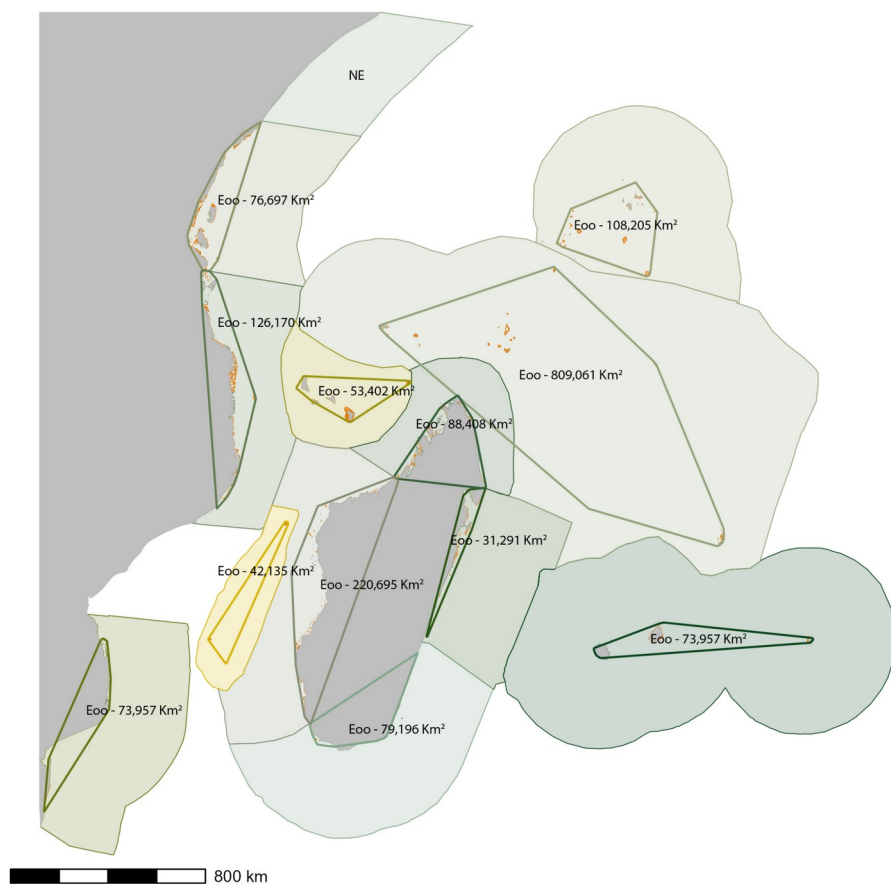


Figure 3. Extent of occurrence (EOO) of coral reefs in each Western Indian Ocean ecoregion, shown as the minimum convex polygon enclosing all mapped reefs.

Western Indian Ocean
Criterion B2: Area of Occupancy

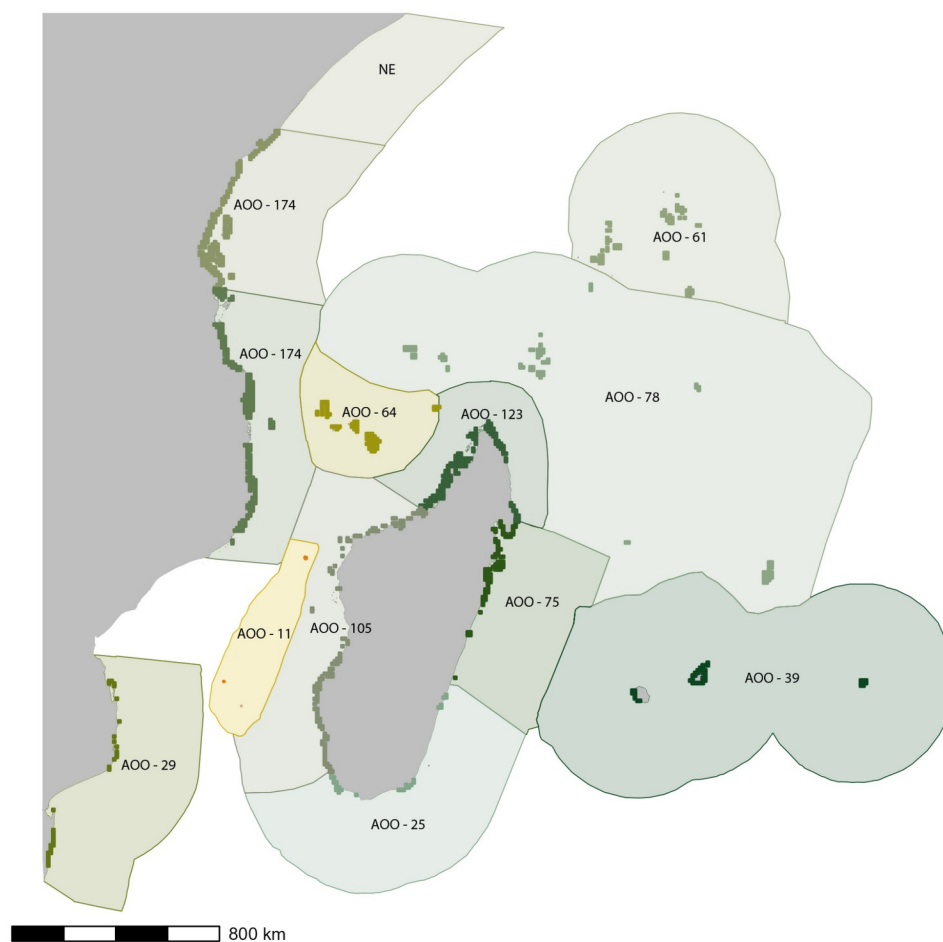


Figure 4. Area of occupancy (AOO) of coral reefs in each Western Indian Ocean ecoregion, shown as the number of occupied 10×10 km grid cells.

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

Figure 5. Thresholds and conditions for assessing ecosystems under Criterion B (restricted geographic distribution) of the IUCN Red List of Ecosystems - sub-criteria B1 (extent of occurrence), B2 (area of occupancy) and B3. Source: IUCN (2024).

Criterion C: Degradation of the abiotic environment

Criterion C evaluates whether abiotic conditions that support ecosystem functioning and persistence have changed to the extent that they pose a significant risk to the ecosystem's ability to sustain its characteristic biota and ecological processes. For coral reefs, the assessment focused on the increasing frequency of extreme marine heatwaves that cause widespread bleaching and mortality, which are among the main threats to reef persistence (Hughes et al. 2017). Sub-criterion C1 assessed change over the past 50 years (1975–2025) and C2a assessed projected change over the next 50 years (2026–2075).

Pathways to collapse and indicators

Recurrent heatwaves can reduce the suitability of the environment for reef-building corals through several pathways. Two plausible and distinct pathways were assessed, each requiring a different analytical approach (Table 2).

- The chronic (press) pathway represents 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 events become more frequent, recovery intervals

shorten, preventing meaningful recovery and leading to progressive degradation (Hughes et al. 2018; Emslie et al. 2024). Its indicator was the expected number of severe bleaching events over a 30-year period, expressed as an average return interval (years between events).

- The acute (pulse) pathway represents rapid decline following a small number of extreme heat stress events over a short period, causing widespread mortality across coral taxa, including stress-tolerant species, and near-complete coral loss. Its indicator was the number of severe mortality events within a 5-year window.

Use of Degree Heating Weeks

Degree Heating Weeks (DHW), a measure of the accumulation of heat stress over a rolling 12-week window, was used to determine marine heatwave events. DHW data are available globally since 1985, including for future climate projections (Skirving et al. 2019; Mellin et al. 2024), and have a well-documented relationship with coral bleaching across many regions (Liu et al. 2005; Heron et al. 2016a; Sully et al. 2019). $DHW \geq 4$ is associated with bleaching onset and $DHW \geq 8$ with widespread mortality (Liu et al. 2005; Kayanne 2017; Skirving et al. 2019). Although DHW may not always be the most precise predictor of bleaching at fine spatial or temporal scales, it provided a robust, scalable and comparable indicator suited to capturing broad trends in disturbance regimes and to a standardised approach across ecoregions.

DHW data

For the assessment of sub-criterion C1, satellite-measured DHW from NOAA Coral Reef Watch at 5 km resolution¹ (Liu et al. 2012) was used. Daily DHW data begin in 1985, whereas the RLE assessment period begins in 1975. Thermal conditions in 1975–1984 were therefore assumed to be broadly comparable to those of the earliest decade of the satellite record, as supported by the occurrence of the first global mass bleaching event later, in 1997–1998 (Hoegh-Guldberg 1999), and by the acceleration of ocean warming from the late 1990s (Cheng et al. 2017, 2023; Heron et al. 2016b; Merchant et al. 2025).

For the assessment of sub-criterion C2, modelled daily DHW projections for 1985–2100 at a 0.5° resolution (~55 km) (Mellin et al. 2024) were used for three climate pathways (SSP2-4.5, SSP3-7.0 and SSP5-8.5). ²The data were based on an ensemble average of five CMIP6 models ('ens5'). A pathway aligned with the Paris Agreement (SSP1-1.9) was not available. SSP5-8.5 represents an extreme case that is increasingly unlikely (Sarofim et al. 2024), so SSP2-4.5 and SSP3-7.0 were explored further, with SSP2-4.5 treated as the primary scenario that was finally retained for calculation.

For both C1 and C2, DHW values were 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 interpolation.

¹ Available at: <https://coralreefwatch.noaa.gov>

² Available at: https://adelaide.figshare.com/articles/dataset/Global_projections_of_sea_surface_temperature_and_coral_bleaching_risk_in_the_21st_century/25143128

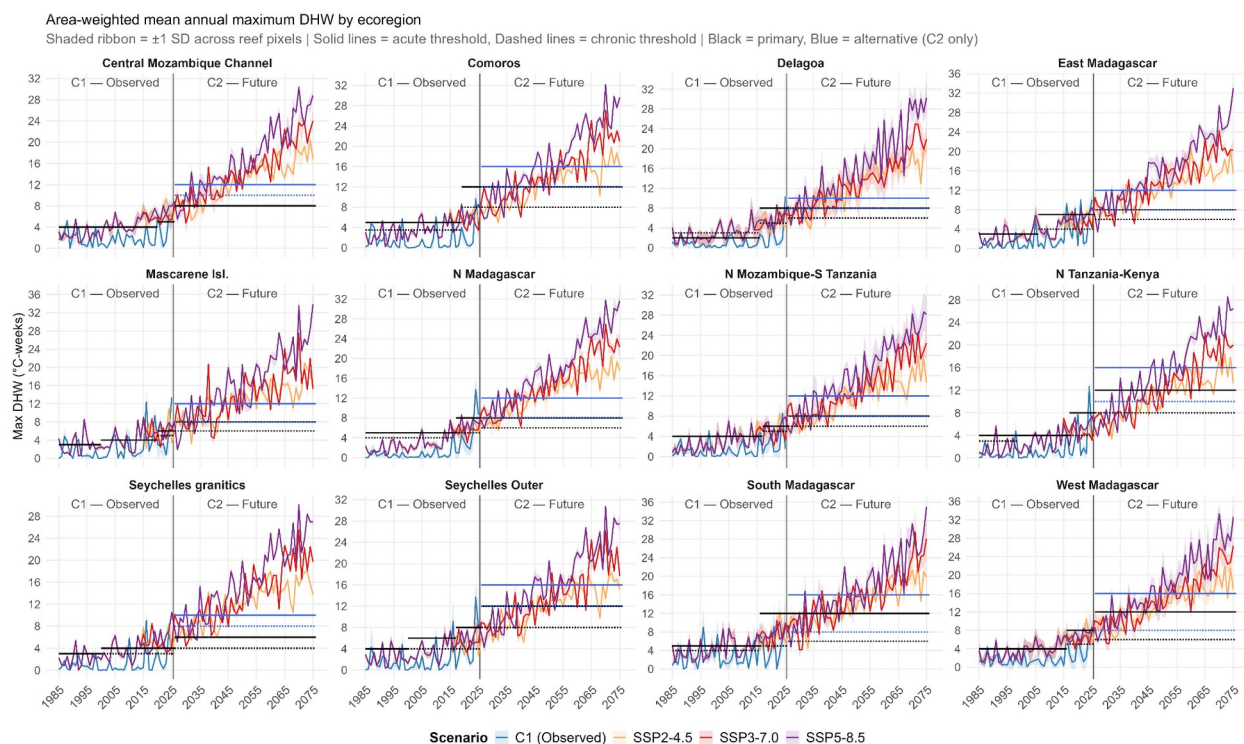


Figure 6. Annual maximum Degree Heating Weeks (DHW) averaged across coral reefs within each ecoregion from 1985–2075 for four trajectories: observed data used to assess sub-criterion C1 from 1985–2025 (blue line), and projections under three Shared Socioeconomic Pathways — SSP2-4.5 (orange), SSP3-7.0 (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.

Annual maximum values

Daily DHW data (C1 and C2) were converted to an annual maximum for each reef pixel by calculating the monthly maximum and then extracting the highest value recorded in the local summer season. Where the summer season straddled two calendar years, the seasonal maximum was attributed to the year in which the stress began. This produced an annual time series of maximum DHW for each reef pixel.

DHW thresholds for each ecoregion

To convert DHW data into ecologically meaningful values related to heatwaves that can cause coral bleaching or significant coral mortality, regional experts established ecoregional DHW thresholds corresponding to two event types. The chronic pathway threshold was the DHW level estimated to lead to a severe bleaching event (widespread bleaching affecting more than about 50% of colonies). The acute pathway threshold was the DHW level estimated to lead to a severe mortality event (mortality of more than 50% of colonies across all taxa, including stress-tolerant species).

Thresholds were informed by historical observations of reef responses to global and local bleaching events (e.g. 1998, 2010, 2016 and 2024) (Fig. 7). They were identified by contrasting years in which widespread bleaching occurred against years of comparable or lower stress without such a response. The lowest DHW consistently associated with a widespread response, below which no non-response was recorded, was taken as the lower limit. Where DHW substantially exceeded this value, bleaching was assumed to have begun at the threshold, with additional accumulated heat stress contributing to greater severity and mortality rather than indicating a higher onset threshold. Mortality thresholds were the same as, or consistently higher than, bleaching thresholds.

Accounting for coral adaptation to heat stress over time

DHW thresholds were not treated as fixed, because the DHW required to trigger a given response is expected to change over time. In the 1980s and 1990s, lower DHW values may have caused severe bleaching and mortality (Hoegh-Guldberg 1999), whereas present and future coral communities may be altered or acclimated and require higher values for comparable responses (Pratchett et al. 2013; Heron et al. 2016b; Sully et al. 2019). For C2, thresholds were informed by responses in the most recent years of the satellite record (about 2020–2025) and, where appropriate, were adjusted upwards to account for species filtering and potential adaptation or acclimation. Where required, a range of plausible threshold values was applied to account for uncertainty. Where appropriate, thresholds were aligned with the NOAA Coral Reef Watch Bleaching Alert levels of 4, 8, 12, 16 and 20 DHW.

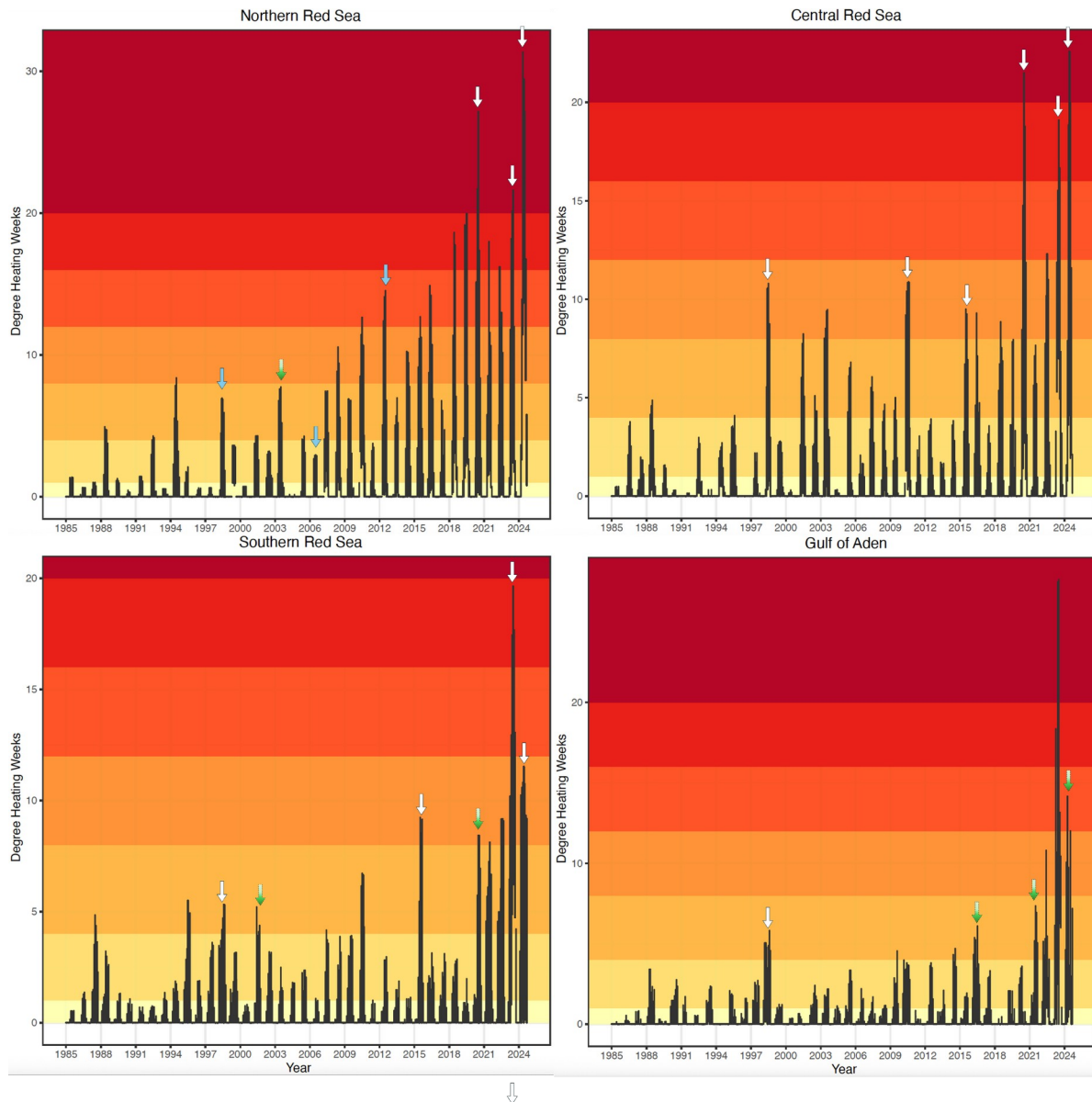


Figure 7. Accumulated thermal stress on coral reefs of the Red Sea and Gulf of Aden, 1985–2025, shown separately for each of the four coral reef ecoregions (ordered north to south). Black shapes are violin plots showing the distribution of Degree Heating Weeks (DHW, °C-weeks) across reef pixels within 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.

Conversion of heat stress to events

Each year at each reef pixel was classified as an event (1) or non-event (0) by applying the thresholds, producing a binary event time series for each pathway (chronic using bleaching thresholds, and acute using mortality thresholds).

Relative severity of decline

Criteria C and D shared a common approach to quantifying decline. The current state of each indicator was compared with both a historical baseline (the initial value) and a hypothetical collapse threshold.

Current values. For the chronic pathway, a binomial (logistic) regression was fitted to the event series of each reef pixel to model the probability of a severe bleaching event as a function of time (DeCarlo & Whitaker 2025). This provided a smoothed estimate of annual event probability, reducing sensitivity to interannual variability and describing the underlying trajectory of the disturbance regime, which suits assessment of chronic stress. For C1 the model was fitted to observed data (1985–2025), and for C2 to projected data (1985–2100). Annual probabilities were summed across every 30-year window in the assessment period to give the expected number of events, which was converted to a return interval (30 years ÷ expected events) (Fig. 8). For C1 and C2, the shortest return interval across the respective windows was used as the current value for each reef polygon. Return interval was used as the indicator because recovery from disturbance is slow, typically requiring 10–15 years for fast-growing corals and considerably longer for the full range of coral life histories (Gilmour et al. 2013; Robinson et al. 2019). For the acute pathway, a 5-year moving window was applied across the assessment period, and the maximum number of severe mortality events in any window was used as the current value for each reef polygon (Fig. 9). This event-based approach preserves temporal variability and captures the clustering of extreme events that characterises acute collapse.

Initial values. For the chronic pathway under C1, baseline conditions around the 1970s were taken as bleaching events occurring at most once every 10–15 years (about 2–3 events per 30 years), a natural regime allowing sufficient time for meaningful recovery (Baker et al. 2008; Graham et al. 2011; Gilmour et al. 2013; Hughes et al. 2018; Robinson et al. 2019). For C2, the initial value was calculated from projected DHW for the 30 years preceding 2026 (1996–2025) using the same probabilistic framework. For the acute pathway under C1, a uniform initial value of 0 events was applied to all reefs, assuming major widespread bleaching events began only from 1982/83. A sensitivity test using an initial value of one event resulted in ecoregions with known bleaching impacts being classified incorrectly as LC, and was therefore not applied in the final calculations. For C2, the initial value was the maximum number of severe mortality events in any 5-year window in 2016–2025.

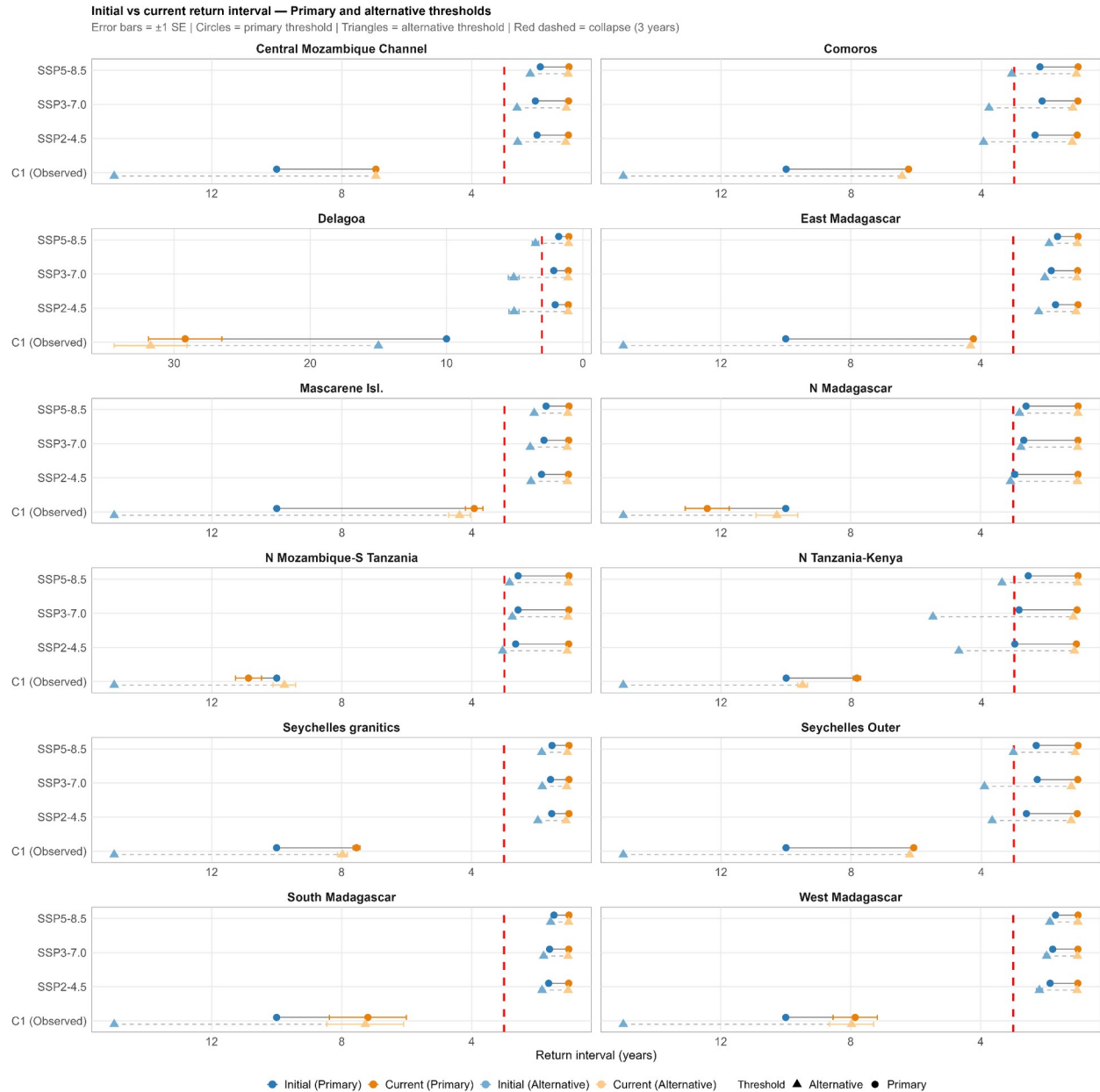


Figure 8. Change in the average return interval between severe bleaching events (years) for each ecoregion in the Western Indian Ocean (x-axis), comparing initial conditions (blue) to current or projected future conditions (orange) across four trajectories (y-axis): observed data (C1) and projections 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.

Collapse thresholds. The same thresholds were applied to C1 and C2, because similar environmental conditions should lead to similar ecological outcomes regardless of when they occur.

- For the chronic pathway, the collapse threshold was established at severe bleaching on average every 3 years over 30 years (about 10 events), at which recovery intervals are insufficient and cumulative mortality drives progressive degradation (Hughes et al. 2018; Emslie et al. 2024; DeCarlo & Whitaker 2025). A sensitivity test used one event every 5 years (about 6 events per 30 years), as even these recovery windows do not allow full recovery over multiple decades (Hughes et al. 2018). Annual severe bleaching, often cited in reef outlooks (van Hooidonk et al. 2016; De Clippele et al. 2023; Zeng et al. 2025), was considered overly conservative because collapse is likely to occur before such conditions are reached (Bland et al. 2017; Obura et al. 2022).
- For the acute pathway, the collapse threshold was established at 3 severe mortality events within any 5-year window, with 2 events tested as a sensitivity analysis. Previous assessments used two severe bleaching events per decade (Bland et al. 2017; Obura et al. 2022), but several reefs experienced two or more within a decade between 2015/16 and 2025 without clear evidence of collapse (Pratchett et al. 2021; Emslie et al. 2024; Henley et al. 2024). This suggested greater resilience to moderate clustering than previously assumed, and that a higher frequency was needed to reliably indicate collapse conditions.

For each reef polygon, and for each pathway and sub-criterion (C1, C2), the relative severity of decline was calculated as:

$$\text{Relative severity of decline (\%)} = (\text{initial value} - \text{current value}) \div (\text{initial value} - \text{collapse threshold}) \times 100 \quad (1)$$

A value of 0% indicates no change from the initial value and 100% indicates that the collapse threshold has been reached or exceeded.

Table 2. Summary of parameters used to assess Criterion C under the chronic and acute pathways. DHW, Degree Heating Weeks; SSP, Shared Socioeconomic Pathway. Sub-criterion C1: 1975–2025; Sub-criterion C2: 2026–2075.

Component	Sub-criterion	Chronic (press) pathway	Acute (pulse) pathway
Rationale	–	Cumulative effects of recurrent bleaching events; as events become more frequent, recovery intervals shorten, preventing meaningful recovery and leading to progressive degradation (Hughes et al. 2018; Emslie et al. 2024)	Rapid decline following a small number of extreme heat stress events over a short period, causing widespread mortality across coral taxa, including stress-tolerant species, and near-complete coral loss
Indicator	–	Expected number of severe bleaching events over a 30-year period, expressed as an average return interval (years between events)	Number of severe mortality events within a 5-year window
DHW data	C1	Daily DHW from NOAA Coral Reef Watch, 5 km resolution, 1985–2025 (Liu et al. 2012)	
	C2	Modelled daily DHW projections, 1985–2100 (Mellin et al. 2024); SSP2-4.5 as the primary scenario, with SSP3-7.0 also explored	

Component	Sub-criterion	Chronic (press) pathway	Acute (pulse) pathway
DHW thresholds	C1	Ecoregional DHW at which severe bleaching events occur (widespread bleaching affecting more than about 50% of colonies), identified from historical bleaching responses; time-varying	Ecoregional DHW at which severe mortality events occur (mortality of more than 50% of colonies across all taxa, including stress-tolerant species); equal to or higher than the bleaching threshold; time-varying
	C2	Informed by responses in the most recent years of the satellite record (about 2020–2025) and, where appropriate, adjusted upwards to account for potential adaptation; aligned with NOAA Coral Reef Watch alert levels (4, 8, 12, 16, 20 DHW) where appropriate	
Current value	C1, C2	Logistic regression of annual event probability against time for each reef polygon (C1: 1985–2025; C2: 1985–2100); probabilities summed over each 30-year window to give expected events, converted to return interval (30 years ÷ expected events); shortest return interval across windows in the assessment period	Maximum number of severe mortality events in any 5-year moving window across the assessment period, for each reef polygon
Initial value	C1	Return interval of 10–15 years (Baker et al. 2008; Gilmour et al. 2013; Hughes et al. 2018)	0 events in a 5-year window, as major widespread bleaching began only from 1982/83; an initial value of 1 event was tested
	C2	Return interval calculated from projected DHW for 1996–2025 using the same logistic regression	Maximum number of severe mortality events in any 5-year window between 2016–2025
Collapse threshold	C1, C2	Severe bleaching on average every 3 years over 30 years (about 10 events)	3 severe mortality events within any 5-year window



Figure 9. Mean number of severe mortality events per 5-year period, averaged across coral reef pixels within each ecoregion of the Western Indian Ocean, 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.

Relative extent and risk assignment

Risk was assigned from the combination of severity of decline and the proportion of the ecosystem affected (relative extent). For each ecoregion, the proportion of reef area that had declined by at least 20%, 30%, 50%, 70%, 80% and 100% was calculated, and these values were compared against the severity–extent risk matrix of the RLE guidelines (Fig. 10). The highest risk category triggered was assigned. For example, if 50% of reefs in an ecoregion had declined by more than 50%, the ecoregion was classified as VU.

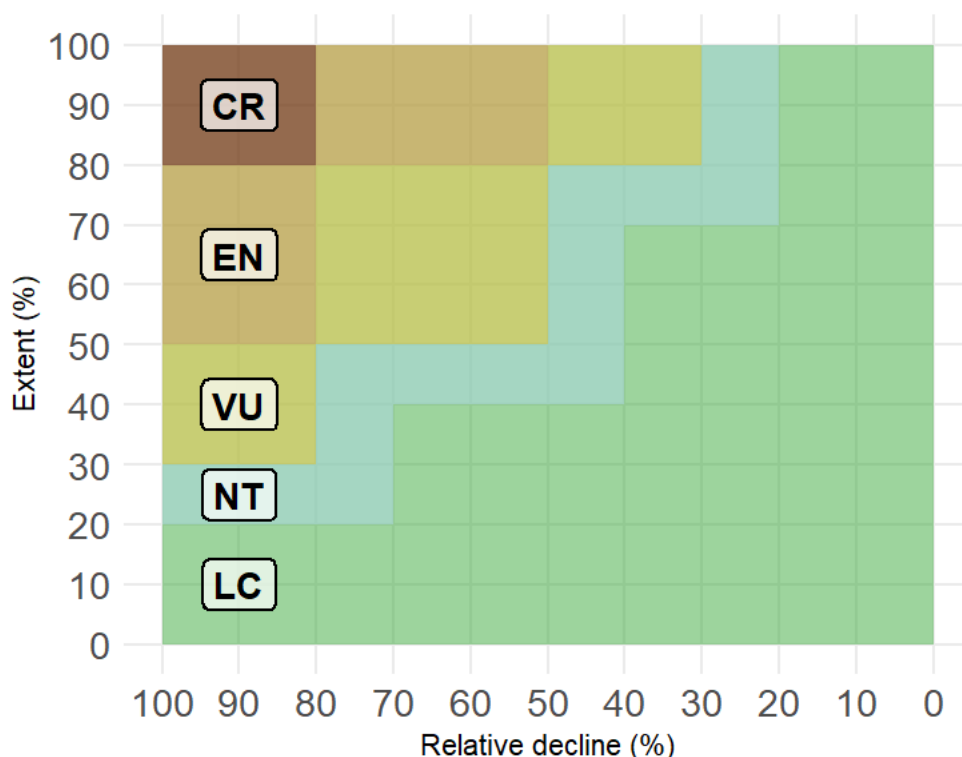


Figure 10. Risk matrix used to assign risk categories under Criteria C and D: relative extent of the ecosystem affected (y axis) versus relative severity of decline (x axis).

Uncertainty and risk category

The analysis was repeated across all plausible combinations of DHW thresholds, collapse thresholds and initial values, producing a range of risk outcomes. Where the chronic and acute pathways differed, the category from the pathway with the greatest confidence (best estimate) was reported, or a range of outcomes was presented. The most severe status across pathways and sub-criteria was taken as the final status for Criterion C.

Criterion D: Disruption of biotic processes and interactions

Criterion D identifies ecosystems experiencing severe disruption to biotic organisms, processes and interactions, including declines in characteristic species, shifts in community structure and loss of

ecological functions. Sub-criterion D1 assessed degradation over the past 50 years, estimating how close each ecosystem component was to collapse.

Indicator selection

Two to four biotic components were assessed, following previous RLE assessments (Bland et al. 2017; Obura et al. 2022), using indicators calculated from standard underwater survey data (e.g. point intercept and belt transects). Indicators were selected for ecological relevance, data availability, spatial coverage, sensitivity to ecosystem condition, and the ability to define both a reference state and a collapse threshold. The most common indicators were: (i) hard coral cover, the keystone taxon responsible for habitat structure and accretion and a key measure of reef health used consistently over several decades; (ii) the algae-to-coral ratio ($\text{algae cover} \div [\text{algae} + \text{coral}] \text{ cover}$), which represents benthic competition and captures the balance between coral and algal dominance, with turf and fleshy algae combined in some cases to account for inconsistent taxonomic resolution among monitoring programs; (iii) herbivore biomass or density, a proxy for herbivory and the top-down control of algae, most often measured using parrotfishes but also including surgeonfishes and other herbivores; and (iv) piscivore biomass or density, a proxy for piscivory that helps regulate the food web, most often represented by groupers but also potentially including snappers and other large carnivorous fishes. Biomass or density was used for fish depending on data availability within each ecoregion.

Relative severity of decline

The current state of each indicator was compared with both a historical baseline (the initial value) and a hypothetical collapse threshold, so that decline was expressed as a percentage of the distance between the two. Expressing decline in this way allowed indicators measured in different units (e.g. return interval, percentage cover, fish abundance) to be assessed on a common scale.

Current values

Current values were calculated for each site, defined as a monitoring location at which sampling units are aggregated, using data from 2020–2025. Where multiple records existed for a site in this period, the mean was used.

Initial values (about 1975)

Standardised monitoring began in the 1990s, so baselines for each indicator were reconstructed from empirical data, literature and expert knowledge. Estimates represented conditions across the whole ecoregion and were derived as distributions (mean and standard deviation) to incorporate natural variability and uncertainty. Reef condition in the mid-1970s was first considered for each ecoregion (better than present, relatively pristine, or already degraded), and initial values were estimated to reflect this.

Two methods were used to estimate benthic baselines. In the literature-derived method, regional experts assumed that reef condition in the 1970s was generally better than at present and that 1997/98, the year of the first widespread global bleaching event, marked a major turning point; reefs surveyed before 1998 were therefore considered broadly representative of 1970s conditions (Obura et al. 2022; Gudka et al. 2023). Benthic data from early surveys (primarily 1980s–1990s) at relatively healthy and representative

sites were aggregated to estimate ecoregional means and variances. In the maximum-value method, sites with long monitoring time series (≥ 10 years) were assumed to have experienced good conditions at some point, and the maximum recorded value of each indicator at each site was extracted; the distribution of these maxima within an ecoregion provided the baseline distribution, compared with published historical data (1960s–1990s) where available. For hard coral cover, a hierarchical decision process supported by expert consultation selected between the two estimates: published estimates were preferred when based on adequate sample sizes ($n \geq 10$) and considered spatially representative, and the monitoring-derived estimate was used when no published estimate existed or when it provided stronger spatial representation. For the algae-to-coral ratio, limited pre-1998 data meant that a regional baseline was applied to most ecoregions (Obura et al. 2022), with independent estimates used only for ecoregions with sufficient data (Gudka et al. 2023).

Fish baselines were estimated using space-for-time substitution. Fishing pressure was assumed to have been lower in the 1970s, so that the abundance of exploited groups was expected to have been higher, but comparable surveys from that period were unavailable. Contemporary fish assemblages at well-managed, no-take marine protected areas with at least 10 years of protection were therefore used as proxies for pre-fishing conditions (Obura et al. 2022, Gudka et al. 2024). Data from approximately the most recent five years were excluded to maintain a distinction from the current window (2020–2025) and because habitat decline following recent bleaching events would have begun to affect fish populations despite protection. Reference sites were selected for each ecoregion, with baselines shared across neighbouring ecoregions where few reference sites were available.

Collapse thresholds

Collapse thresholds represented the point at which ecosystem function or identity is lost and were based on previous RLE assessments (Obura et al. 2022, Gudka et al. 2024). For benthic indicators, this was a transformation in state away from a coral-dominated system. Hard coral cover was set at 5%, the minimum level required to sustain positive carbonate accretion. The algae-to-coral ratio was set at 0.833 (algae cover five times coral cover), indicating a persistent shift to algal dominance from which recovery is unlikely. For fish, thresholds represented loss of ecological function (insufficient herbivory or piscivory to influence ecosystem dynamics) and were set at 10% of baseline abundance for parrotfish and 20% for groupers.

For each indicator, the relative severity of decline at each monitoring site with current data was calculated using equation (1). Initial values were represented as a normal distribution defined by the estimated mean, standard deviation and observed range, and a value was randomly sampled from this distribution and assigned to each site.

Relative extent and risk assignment

Risk was assigned from the combination of severity of decline and the proportion of the ecosystem affected (relative extent). For each ecoregion, the proportion of monitoring sites that had declined by at least 20%, 30%, 50%, 70%, 80% and 100% was calculated, and these values were compared against the severity–extent risk matrix (Fig. 10). The highest risk category triggered was assigned.

Each risk assignment was repeated 750–1000 times (see Fig. 11 as an example of results for the hard coral cover indicator for the Western Indian Ocean). Where at least 80% of iterations returned the same category, it was assigned as the final status for the indicator. Otherwise, an appropriate category or range was applied (e.g. a 50:50 split between LC and VU gave NT).

Data representativeness

The analysis assumed that monitoring sites broadly reflected conditions across the ecoregion. Where spatial coverage was uneven or limited, representativeness was assessed using the distribution of pressures and environmental conditions. Ecoregions with insufficient data to characterise ecosystem-wide patterns were classified as DD.

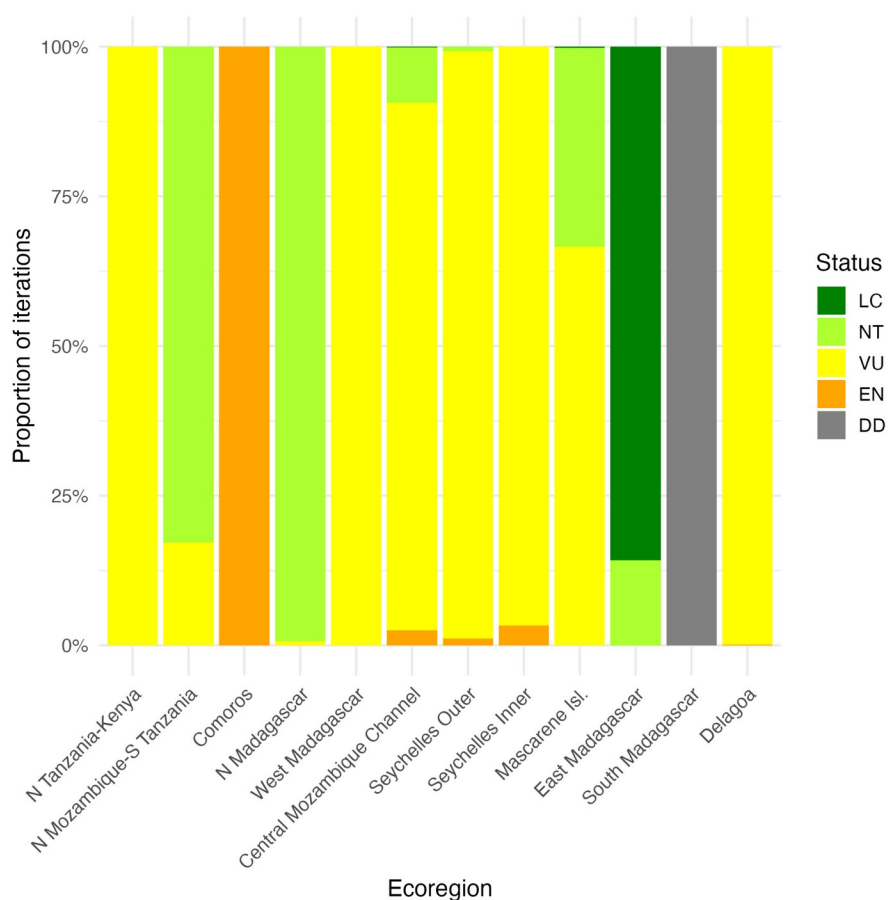


Figure 11. Percentage of 1,000 iterations returning various risk levels based on declines in hard coral cover across 12 ecoregions in the Western Indian Ocean

Combining the indicators

Indicators were combined stepwise, following previous coral reef RLE assessments (Obura et al. 2022), in order of ecological interaction: hard coral, algae, herbivorous fish, then piscivorous fish. The hard coral status was the starting classification. At each subsequent step, the overall category was increased by one level only if the next indicator was at higher risk than the cumulative status. This gave hard coral, as the

foundational structural component, the greatest influence, while still accounting for other biotic components and preventing secondary indicators such as fish from disproportionately driving the result.

References

- Allen Coral Atlas Team (2026). The Allen Coral Atlas: A High Resolution Mapping and Monitoring Observatory for Global Shallow Coral Reefs. Arizona State University Center for Global Discovery and Conservation Science, Hilo HI USA. URL: <https://allencoralatlas.org>
- Baker, A. C., Glynn, P. W., & Riegl, B. (2008). Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, 80(4), 435–471. <https://doi.org/10.1016/j.ecss.2008.09.003>
- Bland, L. M., Regan, T. J., Dinh, M. N., Ferrari, R., Keith, D. A., Lester, R., Mouillot, D., Murray, N. J., Nguyen, H. A., & Nicholson, E. (2017). Using multiple lines of evidence to assess the risk of ecosystem collapse. *Proceedings of the Royal Society B: Biological Sciences*, 284(1863), 20170660. <https://doi.org/10.1098/rspb.2017.0660>
- Cheng, L., Abraham, J., Trenberth, K. E., Fasullo, J., Boyer, T., Mann, M. E., Zhu, J., Wang, F., Locarnini, R., Li, Y., Zhang, B., Yu, F., Wan, L., Chen, X., Feng, L., Song, X., Liu, Y., Reseghetti, F., Simoncelli, S., ... Li, G. (2023). Another year of record heat for the oceans. *Advances in Atmospheric Sciences*, 40(6), 963–974. <https://doi.org/10.1007/s00376-023-2385-2>
- Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., & Zhu, J. (2017). Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, 3(3), e1601545. <https://doi.org/10.1126/sciadv.1601545>
- De Clippele, L. H., Díaz, L. A., Andradi-Brown, D. A., Lazuardi, M. E., Iqbal, M., Zainudin, I. M., Prabuning, D., van Hooideonk, R., Hakim, A., Agung, F., Dermawan, A., & Hennige, S. J. (2023). Evaluating annual severe coral bleaching risk for marine protected areas across Indonesia. *Marine Policy*, 148, 105428. <https://doi.org/10.1016/j.marpol.2022.105428>
- DeCarlo, T. M., & Whitaker, H. V. (2025). Coral bleaching projections for the Great Barrier Reef throughout the 21st century. *Geophysical Research Letters*, 52(23), e2025GL119834. <https://doi.org/10.1029/2025GL119834>
- Emslie, M. J., Logan, M., Bray, P., Ceccarelli, D. M., Cheal, A. J., Hughes, T. P., Johns, K. A., Jonker, M. J., Kennedy, E. V., Kerry, J. T., Mellin, C., Miller, I. R., Osborne, K., Puotinen, M., Sinclair-Taylor, T., & Sweatman, H. (2024). Increasing disturbance frequency undermines coral reef recovery. *Ecological Monographs*, 94(3), e1619. <https://doi.org/10.1002/ecm.1619>
- Gilmour, J. P., Smith, L. D., Heyward, A. J., Baird, A. H., & Pratchett, M. S. (2013). Recovery of an isolated coral reef system following severe disturbance. *Science*, 340(6128), 69–71. <https://doi.org/10.1126/science.1232310>
- Graham, N. A. J., Nash, K. L., & Kool, J. T. (2011). Coral reef recovery dynamics in a changing world. *Coral Reefs*, 30(2), 283–294. <https://doi.org/10.1007/s00338-010-0717-z>
- Gudka, M., Aboud, S., & Obura, D. (2023). Establishing historical benthic cover levels for coral reefs of the Western Indian Ocean. *Western Indian Ocean Journal of Marine Science*, 22(1). <https://doi.org/10.4314/wiojms.v22i1.11>
- Gudka, M., Obura, D., Trembl, E., Samoilys, M., Aboud, S. A., Osuka, K. E., Mbugua, J., Mwaura, J., Karisa, J., Knoester, E. G., Musila, P., Omar, M., & Nicholson, E. (2024). Leveraging the Red List of Ecosystems for action on coral reefs through the Kunming-Montreal Global Biodiversity Framework. *Conservation Science and Practice*, 6(12), e13255. <https://doi.org/10.1111/csp2.13255>
- Henley, B. J., McGregor, H. V., King, A. D., Hoegh-Guldberg, O., Arzey, A. K., Karoly, D. J., Lough, J. M., DeCarlo, T. M., & Linsley, B. K. (2024). Highest ocean heat in four centuries places Great Barrier Reef in danger. *Nature*, 632(8024), 320–326. <https://doi.org/10.1038/s41586-024-07672-x>
- Heron, S. F., Johnston, L., Liu, G., Geiger, E. F., Maynard, J. A., De La Cour, J. L., Johnson, S., Okano, R., Benavente, D., Burgess, T. F. R., Iguel, J., Perez, D. I., Skirving, W. J., Strong, A. E., Tirak, K.,

- & Eakin, C. M. (2016a). Validation of reef-scale thermal stress satellite products for coral bleaching monitoring. *Remote Sensing*, 8(1), 59. <https://doi.org/10.3390/rs8010059>
- Heron, S. F., Maynard, J. A., van Hooidonk, R., & Eakin, C. M. (2016b). Warming trends and bleaching stress of the world's coral reefs 1985–2012. *Scientific Reports*, 6(1), 38402. <https://doi.org/10.1038/srep38402>
- Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50(8), 839–866. <https://doi.org/10.1071/mf99078>
- Hughes, T. P., Anderson, K. D., Connolly, S. R., Heron, S. F., Kerry, J. T., Lough, J. M., Baird, A. H., Baum, J. K., Berumen, M. L., Bridge, T. C., Claar, D. C., Eakin, C. M., Gilmour, J. P., Graham, N. A. J., Harrison, H., Hobbs, J.-P. A., Hoey, A. S., Hoogenboom, M., Lowe, R. J., ... Wilson, S. K. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371), 80–83. <https://doi.org/10.1126/science.aan8048>
- Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., ... Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, 543(7645), 373–377. <https://doi.org/10.1038/nature21707>
- IUCN (2024). *Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria, Version 2.0*. Keith, D. A., Ferrer-Paris, J. R., Ghoraba, S. M. M., Henriksen, S., Monyeke, M., Murray, N. J., Nicholson, E., Rowland, J., Skowno, A., Slingsby, J. A., Storeng, A. B., Valderrábano, M., & Zager, I. (Eds.). Gland, Switzerland: IUCN. <https://portals.iucn.org/library/sites/library/files/documents/2024-021-En.pdf>
- Kayanne, H. (2017). Validation of degree heating weeks as a coral bleaching index in the northwestern Pacific. *Coral Reefs*, 36(1), 63–70. <https://doi.org/10.1007/s00338-016-1524-y>
- Liu, G., Eakin, C. M., Rauenzahn, J. L., Christensen, T. R. L., Li, J., Skirving, W., Strong, A. E., & Burgess, T. (2012). *NOAA Coral Reef Watch's Decision Support System for Coral Reef Management*.
- Liu, G., Strong, A., Skirving, W., & Arzayus, F. (2005). Overview of NOAA Coral Reef Watch program's near-real time satellite global coral bleaching monitoring activities. *Proceedings of the 10th International Coral Reef Symposium*, 1, 1783–1793.
- Mellin, C., Brown, S., Cantin, N., Klein-Salas, E., Mouillot, D., Heron, S. F., & Fordham, D. A. (2024). Cumulative risk of future bleaching for the world's coral reefs. *Science Advances*, 10(26), eadn9660. <https://doi.org/10.1126/sciadv.adn9660>
- Merchant, C. J., Allan, R. P., & Embury, O. (2025). Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance. *Environmental Research Letters*, 20(2), 024037. <https://doi.org/10.1088/1748-9326/adaa8a>
- Obura, D. O., Gudka, M., Samoilys, M., Osuka, K., Mbugua, J., Keith, D. A., Porter, S., Roche, R., van Hooidonk, R., Ahamada, S., Araman, A., Karisa, J., Komakoma, J., Madi, M., Ravinia, I., Razafindrainibe, H., Yahya, S., & Zivane, F. (2022). Vulnerability to collapse of coral reef ecosystems in the Western Indian Ocean. *Nature Sustainability*, 5, 104–112. <https://doi.org/10.1038/s41893-021-00817-0>
- Perry, C. T., Murphy, G. N., Kench, P. S., Smithers, S. G., Edinger, E. N., Steneck, R. S., & Mumby, P. J. (2013). Caribbean-wide decline in carbonate production threatens coral reef growth. *Nature Communications*, 4, 1402. <https://doi.org/10.1038/ncomms2409>
- Pratchett, M. S., Heron, S. F., Mellin, C., & Cumming, G. S. (2021). Recurrent mass-bleaching and the potential for ecosystem collapse on Australia's Great Barrier Reef. In J. G. Canadell & R. B. Jackson (Eds.), *Ecosystem Collapse and Climate Change* (pp. 265–289). Springer. https://doi.org/10.1007/978-3-030-71330-0_10
- Pratchett, M. S., McCowan, D., Maynard, J. A., & Heron, S. F. (2013). Changes in bleaching susceptibility among corals subject to ocean warming and recurrent bleaching in Moorea, French Polynesia. *PLoS ONE*, 8(7). <https://doi.org/10.1371/journal.pone.0070443>

- Robinson, J. P. W., Wilson, S. K., & Graham, N. A. J. (2019). Abiotic and biotic controls on coral recovery 16 years after mass bleaching. *Coral Reefs*, 38(6), 1255–1265. <https://doi.org/10.1007/s00338-019-01831-7>
- Sarofim, M. C., Smith, C. J., Malek, P., McDuffie, E. E., Hartin, C. A., Lay, C. R., & McGrath, S. (2024). High radiative forcing climate scenario relevance analyzed with a ten-million-member ensemble. *Nature Communications*, 15(1), 8185. <https://doi.org/10.1038/s41467-024-52437-9>
- Skirving, W. J., Heron, S. F., Marsh, B. L., Liu, G., De La Cour, J. L., Geiger, E. F., & Eakin, C. M. (2019). The relentless march of mass coral bleaching: A global perspective of changing heat stress. *Coral Reefs*, 38(4), 547–557. <https://doi.org/10.1007/s00338-019-01799-4>
- Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G., & van Woesik, R. (2019). A global analysis of coral bleaching over the past two decades. *Nature Communications*, 10(1), 1264. <https://doi.org/10.1038/s41467-019-09238-2>
- UNEP-WCMC, WorldFish Centre, WRI, TNC (2021). Global distribution of coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Version 4.1, updated by UNEP-WCMC. Includes contributions from IMaRS-USF and IRD (2005), IMaRS-USF (2005) and Spalding et al. (2001). Cambridge (UK): UN Environment Programme World Conservation Monitoring Centre. Data DOI: <https://doi.org/10.34892/t2wk-5t34>
- van Hooidonk, R., Maynard, J., Tamelander, J., Gove, J., Ahmadi, G., Raymundo, L., Williams, G., Heron, S. F., & Planes, S. (2016). Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, 6(1), 39666. <https://doi.org/10.1038/srep39666>
- Zeng, K., He, S., & Zhan, P. (2025). Inevitable global coral reef decline under climate change-induced thermal stresses. *Communications Earth & Environment*, 6(1), 827. <https://doi.org/10.1038/s43247-025-02790-4>