REGIONAL REPORT V.0

Red List of Ecosystems assessment of Eastern Tropical Pacific coral reefs

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ABSTRACT

Coral reefs in the Eastern Tropical Pacific (ETP), covering 140 km^2 (0.04% of the total global coral reef extent), are under increasing climate and anthropogenic threats. Coral reef development and species distribution in the ETP are conditioned by the characteristic isolation of the region and its strong environmental variability, including El Niño-Southern Oscillation (ENSO) events and upwelling. Focusing on coral reefs, marginal reefs, and their degraded/collapsed counterparts, located in Mexico, El Salvador, Nicaragua, Costa Rica, Panama, Colombia, and Ecuador, and encompassing five coastal and five oceanic ecoregions, we applied a standardized method to assess the risk of ecosystem collapse based on four criteria (i.e., decline in distribution, restricted geographic distribution, environmental degradation, and disruption of biotic processes and interactions). The ETP is characterized by a high overall risk of coral reef ecosystem collapse, with nine of the ten ecoregions classified as Critically

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KEYWORDS

Red List of Ecosystems; coral reefs; ecosystem collapse; risk assessment; Eastern Tropical Pacific

Endangered and one ecoregion Collapsed. Across ecoregions, collapse risk was primarily associated with severe environmental degradation, particularly increasing thermal stress, although the relative contribution of other factors varied geographically. In three Critically Endangered ecoregions, severe environmental degradation was compounded by additional vulnerabilities, including reduced geographic distribution and disruption of biotic processes and interactions in Nicoya, reduced geographic distribution in the Eastern Galápagos Islands, and inherently restricted geographic distribution in Clipperton Atoll. The widespread high-risk status across both continental and oceanic ecoregions indicates that reef decline is not driven by a single pressure, but rather by the convergence of naturally marginal environmental conditions with accelerating climate and local anthropogenic stressors. These include thermal stress and coral bleaching, as well as land-based pollution, sediment and nutrient inputs, wastewater discharge, coastal development, and unsustainable fishing. The reef extent assessment conducted here represents the best available regional estimate and a standardized baseline for evaluating reef collapse risk. These results highlight the urgent need to safeguard the remaining coral-dominated reefs, persistent coral refugia, and herbivore and piscivore assemblages through coordinated regional management. Priority actions include reducing land-based pressures along continental margins, strengthening fisheries management and enforcement, maintaining ecological connectivity among reefs, as well as strengthening reef monitoring programmes regionally. Integrating these measures with transboundary governance, effective management of Marine Protected Areas, restoration actions, ecosystem-based management, direct conservation of resilient reefs, and climate-adaptation strategies will be essential to prevent further ecosystem collapse.

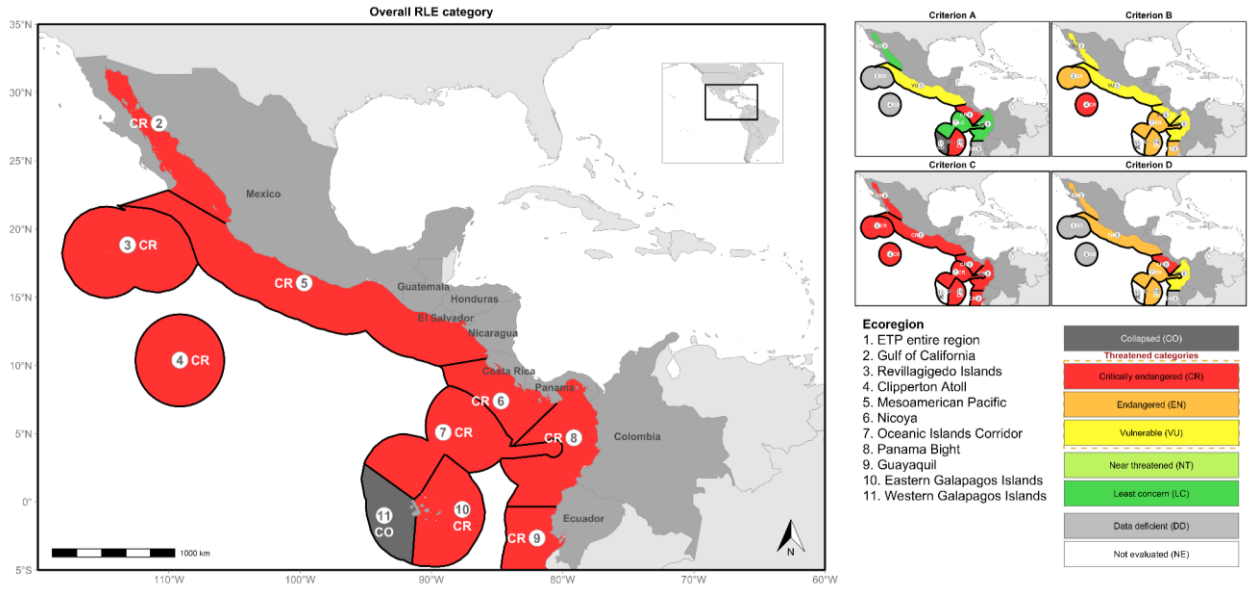


Figure 1. Distribution of the 10 coral reef ecoregions in the ETP. Panel A: Overall Red List of Ecosystems risk status. Panels B–E: Risk status results for criteria A–D.

1. Study Area

The Eastern Tropical Pacific (ETP) extends across the Pacific Ocean from southern Baja California (~25°N) to northern Peru (~3°S), encompassing both continental coastlines and remote oceanic islands and atolls, including the Revillagigedos, Clipperton, Isla del Coco, Malpelo, and the Galapagos. Collectively, these areas host 140 km^2 of coral reefs (corresponding to 0.04 % of the global coral reef extent) distributed across 10 coral reef ecoregions adapted from the Marine Ecoregions of the World (Spalding et al. 2007). These ecoregions are equivalent to Level 4 of the IUCN Global Ecosystem Typology (i.e., regional sub-groups) (Keith et al. 2022). Across the ETP, coral reefs differ in biodiversity and are exposed to broad ranges of temperature, upwelling intensity, and productivity, as well as to different levels of natural and anthropogenic threats (e.g., thermal stress, coastal development, and fishing pressure) (Halpern et al. 2008; Hughes et al. 2017). For the IUCN Red List of Ecosystems, coral reefs in each ecoregion were independently assessed using four criteria, namely Criterion A: Decline in distribution, Criterion B: Restricted Geographic Distribution, Criterion C: Environmental Degradation, and Criterion D: Disruption of Biotic Processes and Interactions (Annex 1).

Coral reefs in the ETP are shaped by the distinctive geographic isolation and environmental variability of the region. Coral reef development and species distribution, for instance, are conditioned by the influence of El Niño-Southern Oscillation (ENSO), strong upwelling, and highly dynamic current systems (Fiedler & Lavín 2017). Biological communities on ETP coral reefs are structured mainly by strong environmental filtering and are characterized by low species richness and high endemism compared to other coral reef regions (Cortés et al. 2017; Dubuc et al. 2023). Although compared with rocky reefs, coral reefs extend over a much smaller geographic extent in the ETP (Ramírez-Ortiz et al. 2017), both are confronted with the combined effects of intensifying ENSO events, accelerated ocean warming and deoxygenation, declining pH, overfishing and the illegal extraction of marine organisms, coastal development, deforestation, and tourism-related stressors (Cortés & Reyes-Bonilla 2017; Romero-Torres et al. 2020; Olán-González et al. 2023).

The present assessment focused exclusively on *coral reefs* and *marginal reefs* (including their *degraded* or *collapsed* counterparts), whilst excluding naturally occurring *rocky reefs,* the dominant reef type in the region. *Coral reefs* (Type A) are defined as structural frameworks built by the active carbonate accretion provided by scleractinian coral growth and calcareous algal cementation over centuries to millennia (Done 2011). *Marginal reefs* (Type B) are defined as reefs where corals persist

and form coral communities on a rocky substratum with limited to no carbonate accretion. *Degraded* or *collapsed reefs* represent transitional states of previously healthy Type A or Type B, and were distinguished from naturally-occurring rocky reefs by assembling published ETP reef distribution maps (e.g., Glynn et al. 2017) and by corroborating the reef location and reef type through the systematic and structured consultation of experts within the Eastern Tropical Pacific Node of the Global Coral Reef Monitoring Network (ETP Node of the GCRMN). This assessment, therefore, includes reefs located in the seven countries bordering the ETP (Mexico, El Salvador, Nicaragua, Costa Rica, Panama, Colombia, and Ecuador) encompassing both coastal territories and oceanic areas, as well as the French territory of Clipperton Atoll. The location and extent of these reefs comprised the basis for Criteria A-C of this assessment. For Criterion D, the assessment considered time series compiled by the ETP Node of the GCRMN for benthic and fish communities, spanning 1994–2024 and 2004–2024, respectively.

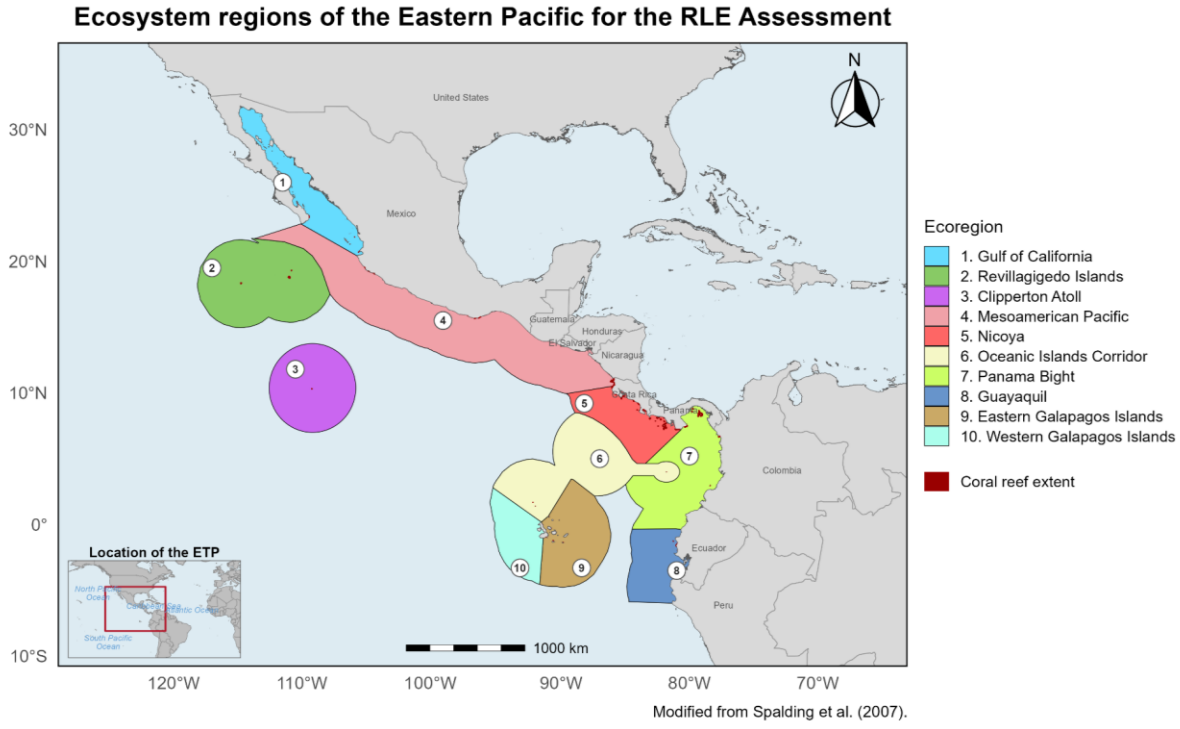


Figure 2. Coral reefs of the Eastern Tropical Pacific are grouped within 10 coral reef ecoregions (Units of Assessment) to be evaluated under the IUCN Red List of Ecosystems criteria and corresponding to Level 4 of the IUCN Global Ecosystem Typology.

2. Ecosystem Description

Coral reefs of the ETP are geographically fragmented and structurally heterogeneous, extending across continental margins and remote oceanic islands. True accreting coral reefs (Type A), with sustained biogenic carbonate accumulation and persistent reef frameworks developed over centennial to millennial timescales. They occur principally as fringing reefs, patch reefs, and other localized framework-building forms associated with shallow coastal margins, embayments and oceanic islands. Substantial Holocene *Pocillopora*-dominated frameworks have developed particularly along the coasts of Mexico, Costa Rica, Panama, and Colombia, while reefs dominated by massive *Porites*, *Pavona*, and *Gardineroseris* occur more broadly across the region (Glynn & Macintyre 1977; Glynn et al. 2017; Toth et al. 2017). Coral reefs on Clipperton Atoll represent an exceptional geomorphological expression within the ETP, with an annular structure developed around an isolated volcanic edifice, whereas most other reefs in the region occur as smaller fringing or coral patch formations rather than extensive barrier-reef systems (Glynn & Ault 2000).

Naturally marginal coral reefs (Type B) in the ETP occur where persistent coral assemblages retain the biodiversity and ecological processes characteristic of photic coral reefs, but natural environmental constraints prevent substantial net carbonate accumulation. Rather than forming thick biogenic frameworks, Type B reefs form coral patches, veneers, or low-relief assemblages over volcanic, rocky or other hard substrata, rather than thick biogenic frameworks. This type of reef is particularly important in areas where strong upwelling, high temperature variability, or low carbonate saturation constrain reef accretion. Marginal Type B reefs are common throughout the ETP, particularly in parts of the Galapagos, where true coral reefs have historically been limited and have undergone substantial regional losses (Glynn et al. 2018), as well as in the Gulf of California and the Gulf of Panama, where coral reef development is limited by cold sea surface temperatures in winter. Coral reefs and marginal reefs in the ETP therefore differ primarily in the magnitude and persistence of net biogenic accretion, yet both support relatively similar fish and invertebrate assemblages. Naturally-occurring rocky reefs, which comprise a relatively large proportion of the ETP coastlines but contain only isolated coral colonies, were excluded from the present assessment.

The spatial configuration of coral reefs and marginal reefs in the ETP reflects the distinctive geological and evolutionary history of the region. The ETP coral fauna was progressively isolated from the western Atlantic as the Central American Isthmus formed, with final closure of the marine connection approximately 2.8 million years ago, altering ocean circulation and placing Atlantic and eastern Pacific marine biotas on independent evolutionary trajectories (Lessios 2008). Exchange with the central Indo-Pacific has also remained restricted by the broad expanse of deep ocean separating the two regions, contributing to the comparatively depauperate but compositionally distinctive modern coral fauna of the ETP. Modern reef construction expanded during the Holocene, and geological records show that reefs have persisted in the ETP for roughly the last 7,000 years despite major temporal interruptions in framework growth (Toth et al. 2017). The contemporary ETP should therefore not be viewed as a uniformly marginal reef province, but as a regional continuum ranging from substantial, long-lived carbonate frameworks to naturally low-accreting coral communities, with reef morphology and framework development varying markedly among ecoregions. This structural continuum provides the ecosystem template used here to assess collapse risk across the ETP (Lopez-Perez 2005; Lopez-Perez 2017).

2.1. Key Biotic Components

The ETP supports species-poor coral assemblages compared to other tropical regions worldwide. Forty-seven zooxanthellate scleractinian species were reported regionally in the past, including eight considered endemic, with single localities generally supporting fewer than 20–25 species (Glynn et al. 2017). These estimates have been recently updated through whole-genome sequencing, revealing that no more than four to five *Pocillopora* species exist in the equatorial ETP (Connelly et al. 2026). Reef-building assemblages are dominated by *Pocillopora*, *Porites*, *Pavona*, and *Gardineroseris*, which exhibit marked differences in colony form and habitat association. Branching *Pocillopora* species commonly dominate shallow reef frameworks, contributing to three-dimensional habitat complexity, whereas massive *Porites* and *Pavona* are more prominent in deeper or locally sheltered habitats (Cortés et al. 2017; Cabral-Tena et al. 2018; Medellin-Maldonado et al., 2026). Benthic algal assemblages include crustose coralline algae, fleshy macroalgae, turf algae, and cyanobacteria, whose relative dominance varies markedly among ecoregions. Crustose coralline algae contribute to substrate consolidation and provide settlement surfaces for corals, whereas rapidly growing turf assemblages support benthic primary production and provide important resources for grazing fishes and invertebrates. These contrasts are evident in oceanic systems, ranging from habitats rich in crustose coralline algae in Malpelo to extensive turf-dominated assemblages in the Galapagos (Fong et al 2017; Glynn et al 2018) (Fig. 3).

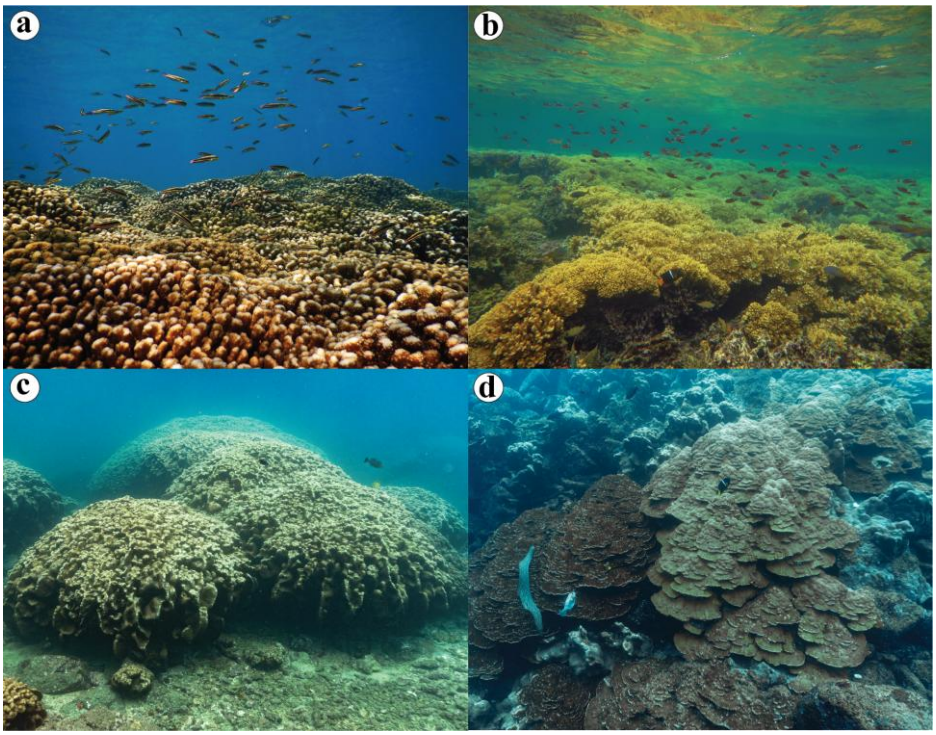


Figure 3. Common coral reef species observed in the Eastern Tropical Pacific. (a) *Pocillopora* spp. in the Gulf of California, (b) *Pocillopora* spp. in Gorgona Island, (c) *Pavona clavus* in Ecuador, (d) *Porites* spp. in the Galapagos Islands. Photos (a) Manuel Olan González, (b) Fernando A. Zapata, (c) and (d) Fernando Rivera.

Reef-associated invertebrates and fishes contribute substantially to the taxonomic and functional biodiversity in the ETP. Invertebrate inventories report >2,400 mollusks, ~850 crustaceans, and 722 echinoderms (265 of which are reportedly endemic), although only a few decapod crustaceans can be considered exclusively coral-reef dwellers (Cortés et al. 2017). These groups, together with sponges, polychaetes and a diverse cryptofauna, contribute to suspension feeding, grazing, predation, bioerosion, nutrient recycling, and habitat modification. Earlier coral reef fish inventories in the ETP reported a total of 1304 species (1193 bony fish and 111 elasmobranchs) (Cortés et al 2017; Robertson and Allen 2008). A more recent inventory reports 1470 shorefish species in the ETP, 684 of which are reef-associated, but only 676 of these are confirmed as distinct species (Robertson & Allen 2024). These inventories highlight the substantially lower number of coral reef fish species in the ETP compared to the Indo-Pacific (~4,810 species) (Parravicini et al. 2013; Mouillot et al. 2014; Kulbicki et al. 2013). Despite this lower richness, ETP reef fishes exhibit high regional endemism and

encompass diverse trophic strategies (Robertson & Cramer 2009; Mouillot et al. 2014; Dubuc et al. 2023). Further, their functional diversity rivals that of Caribbean reefs (Olán-González et al 2020) and it has been maintained over time in highly protected areas (Ramirez-Ortiz et al. 2022, 2025). Small-bodied blennies, gobies, and clingfishes contribute substantially to this diversity, particularly in rocky and mixed coral–rock habitats (Valencia-Méndez et al. 2020; Galland et al 2017). Together, corals, algae, invertebrates, and fishes sustain the habitat-forming, trophic, and biogeochemical processes characteristic of ETP coral reefs.

2.2. Key Abiotic Components

The abiotic environment of ETP reefs is defined by strong spatial and temporal variability in temperature, nutrient supply, carbonate chemistry, and water-column structure. ENSO is the dominant climatic forcing that periodically exposes reefs to shifts between anomalously warm temperatures (associated with bleaching and mortality) and cooler, nutrient-rich upwelling regimes that enhance productivity but can constrain calcification (Glynn et al. 2017; Stewart et. al. 2026). These dynamics interact with a shallow and variable thermocline, low aragonite saturation states, seasonal runoff, and sediment delivery, producing strong vertical gradients in light and oxygen availability across the region (Manzello 2010; Fiedler & Talley 2006). These conditions largely restrict coral reef development to shallow, hard-substrate habitats and contribute to pronounced variation in reef accretion and persistence among ecoregions (López-Pérez et al. 2026).

Sea surface temperature variability in the ETP is wide (Fiedler & Lavín 2017) and largely influenced by the El Niño–Southern Oscillation (ENSO), which drives strong interannual fluctuations in thermal and productivity regimes (Baker et al. 2017; Glynn et al. 2017). Reef development in the ETP is tightly constrained by the interaction of physical structure, water-column conditions, and carbonate chemistry. Reefs are typically restricted to shallow (<10 m), well-lit environments with suitable hard substrates, often volcanic rock or consolidated rubble, most common in sheltered settings such as bays and leeward margins. Consequently, ETP reefs are spatially discontinuous and structurally simple, lacking the extensive frameworks characteristic of other tropical regions. High light attenuation, low dissolved oxygen, and episodic sedimentation, frequently intensified by seasonal dynamics of the Intertropical Convergence Zone, further limit habitable depth and reduce water quality, constraining both photosynthesis and respiration (Velasco-Lozano et al. 2024). At the same time, low aragonite saturation states, exacerbated by CO_2-rich upwelled waters, reduce calcification and enhance carbonate dissolution (Glynn et al. 2017). Consequently, carbonate production is often

offset by erosion, and reef matrices remain weakly consolidated and highly susceptible to physical disturbance and bioerosion (Tortolero-Langarica et al. 2022).

The composition of the ETP coral-reef fauna reflects the combined effects of historical isolation, colonization from different regions and pronounced environmental heterogeneity (Glynn & Ault 2000; Robertson & Cramer 2009). The approximately 5,000-km Eastern Pacific Barrier greatly reduces—but does not impede —exchange with central Pacific populations: genetic evidence from transpacific reef fishes indicates repeated historical crossings, while biophysical models for reef-building corals predict weak connectivity and only rare bidirectional dispersal across the barrier (Lessios and Robertson 2006; Romero-Torres et al. 2018). Both tools have shown that the effect of ENSO is determinant for transport and eventual colonization from the central Pacific (Wood et al. 2016). Within the ETP, however, connectivity varies among taxa and locations, and many putative regional barriers appear to be permeable, particularly for species with dispersive pelagic larvae (Robertson and Cramer 2009; Romero-Torres et al 2018). Ocean circulation can therefore either facilitate or restrict larval transport, depending on current direction and strength, reproductive timing, larval duration and the distribution of suitable habitat (Lessios and Baums 2016; Romero-Torres et al 2018). Seasonal upwelling and associated variation in temperature, nutrient concentrations and carbonate chemistry can also constrain coral growth and reef development and, together with other forms of environmental heterogeneity, probably filter which taxa can establish and persist locally and regionally (Glynn 1976; Rodriguez-Ruano et al. 2023). The final formation of the Isthmus of Panama, approximately 2.8-3 million years ago, largely severed marine exchange between the Atlantic and Pacific, altered oceanographic conditions on both sides and set the resulting isolated populations on increasingly independent evolutionary trajectories (Lessios 2008; López-Pérez 2017; O'Dea et al. 2016). Present-day coral reef assemblages should therefore be understood as products of historical contingency, rare long-distance colonization, low habitat availability (for corals), high regional dispersal, and local biological interactions, rather than as the outcome of environmental filtering alone (Glynn & Ault 2000; Robertson and Cramer 2009).

2.2. Key processes and interactions

Nutrient dynamics, driven by upwelling and a shallow thermocline, are central to ecosystem functioning in the ETP. Episodic and seasonal inputs of nutrient-rich waters enhance primary productivity across pelagic and benthic systems, supporting plankton, benthic algae, and coral symbionts (Fiedler & Talley 2006; Enochs & Glynn 2017). These inputs arise from multiple processes, including equatorial and coastal upwelling, wind-driven transport, and internal wave activity,

generating pronounced spatial and temporal variability in primary productivity (Fiedler & Lavín 2017). While nutrient enrichment increases energy availability, it can also shift competitive dynamics by promoting algal growth, particularly when herbivory is reduced or disturbance is frequent. Consequently, primary productivity varies strongly across space and time, tracking changes in nutrient availability and environmental conditions.

On the benthos, coral–algal interactions govern community structure through competition for space, light, and resources, mediated by processes such as overgrowth, shading, and sediment trapping (Chadwick & Morrow 2011). Herbivory by parrotfishes, surgeonfishes, damselfishes, and sea urchins plays a key regulatory role by limiting algal proliferation and facilitating coral settlement, growth, and persistence (Fong et al. 2017). Importantly, these herbivore groups have prevented phase shifts even under elevated nutrients and recurrent disturbances (Reyes-Bonilla 2003). These dynamics are embedded within broader trophic interactions, where herbivores, detritivores, and predators regulate energy flow, nutrient cycling, and substrate turnover (Enochs & Glynn 2017).

2.3. Main Threats

Coral reefs in the ETP face interacting global and local stressors that compound the region's naturally variable environmental regime. Climate-driven ocean warming and acidification increase thermal stress and reduce carbonate saturation, weakening coral calcification and reef-building capacity (Manzello et al. 2017). Strong El Niño events can raise temperatures by 2–5 °C above seasonal averages causing widespread bleaching and mortality, notably during the 1982–83, 1997–98 and 2023-2024 events (Glynn et al. 2017; Manzello et al. 2017; Lopez-Perez et al 2024). Conversely, La Niña can intensify upwelling and expose reefs to unusually cool, nutrient-rich, and CO_2-rich waters, reducing carbonate saturation and calcification and, under extreme conditions, causing cold-water coral bleaching (Hernandez et al 2010; Zapata et al. 2011; Paz-Garcia et al 2012; Olivier et al. 2023). Furthermore, La Niña frequently drives low sea-level stands, increasing the probability of subaerial exposure during extreme low tides which have resulted in massive coral mortality on shallow reef flats (Zapata 2017; Glynn 2025). Recurrent exposure to these contrasting thermal and chemical stress events can shorten the time available for recovery, enhance bioerosion, and promote persistent changes in benthic structure (Alvarado et al. 2017; Riegl et al. 2019). At the regional scale, overfishing and illegal extraction of coral colonies and reef associated biota further alter trophic structure and herbivory, potentially favoring algal proliferation and constraining coral recruitment following disturbance (Alvarado et al. 2011a, 2011b; Edgar et al. 2011; Mendoza et al. 2021).

Coastal development, tourism, and land-based pollution exert additional pressure, particularly on populated continental coasts and inhabited islands. Wastewater and runoff from urban and agricultural areas increase nutrient and contaminant loads, while deforestation and land-use change increase sediment delivery, reduce water clarity, and can alter coral–algal competition (García et al. 2006; Guzmán et al. 2008; Alvarado et al. 2012; Arias-Godínez et al. 2021; González et al. 2024). Vessel and port activity add localized impacts, including the risk of pollution and introduction of invasive species, anchoring, and accidental groundings (Lougheed et al. 2002). In 2001, for instance, the *Jessica* oil spill affected San Cristóbal and Santa Fe Islands in the Galápagos (Wikelski et al., 2002).

The intensity and combination of these threats vary among ETP ecoregions, but their convergence with recurrent ENSO-driven disturbances can reduce reef recovery capacity and drive persistent losses of coral cover, structural complexity, and carbonate production. Uneven management effectiveness across the region further contributes to spatial variation in ecosystem collapse risk (Barragán & Andrés 2016).

Table 1. Occurrence of major threats impacting coral reefs in each ecoregion, categorized based on the IUCN Threat Classification Scheme. Ecoregions are numbered as follows: (1) Gulf of California; (2) Revillagigedo Islands; (3) Clipperton Atoll; (4) Mesoamerican Pacific; (5) Nicoya; (6) Oceanic Islands Corridor; (7) Panama Bight; (8) Guayaquil; (9) Eastern Galapagos Islands; (10) Western Galapagos Islands. For each threat, information is provided regarding whether it is currently affecting the ecoregion ✓ (tick), whether it affected the ecoregion in the past – (dash), or a + (plus) if the threat is emerging and likely to become an issue in the near future. Cells are left blank when the threat does not impact the ecoregion.

Threat type	Subcategory	Ecoregion									
		1	2	3	4	5	6	7	8	9	10
1. Residential & commercial development	1.3 Tourism & recreation areas	✓	-	-	✓	✓	✓	✓	+	✓	✓
2. Agriculture & aquaculture	2.4 Marine & freshwater aquaculture	✓	-	-	✓	✓	-	✓	✓		
3. Energy production & mining	3.1 Oil & gas drilling	+	-	-	+	-	-	-	+		
4. Transportation & service corridors	4.3 Shipping lanes	✓	✓	✓	✓	✓	+	✓	✓	✓	
5. Biological resource use	5.4 Fishing & harvesting aquatic resources	✓	-	✓	✓	✓	✓	✓	✓	✓	✓
6. Human intrusions & disturbance	6.1 Recreational activities	✓	✓	-	✓	✓	✓	✓	+	✓	✓
7. Natural system modifications	7.3 Other ecosystem modifications	✓	-	-	✓	✓	-	✓	✓	+	-
8. Invasive & problematic species	8.1 Invasive non-native species	+	✓	✓	+	+	+	+	+	✓	+
9. Pollution	9.1 Domestic & urban waste water	✓	✓	-	✓	✓	+	✓	✓	✓	
	9.2 Industrial & military effluents (Oil spills)	✓	+	+	+	+	+	✓	✓	✓	+
	9.3 Agricultural & forestry effluents	✓	-	-	✓	✓	-	✓	✓	+	-
11. Climate change & severe weather	11.3 Temperature extremes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	11.4 Storms & flooding	✓	✓	✓	✓	✓	✓	✓	✓	+	+

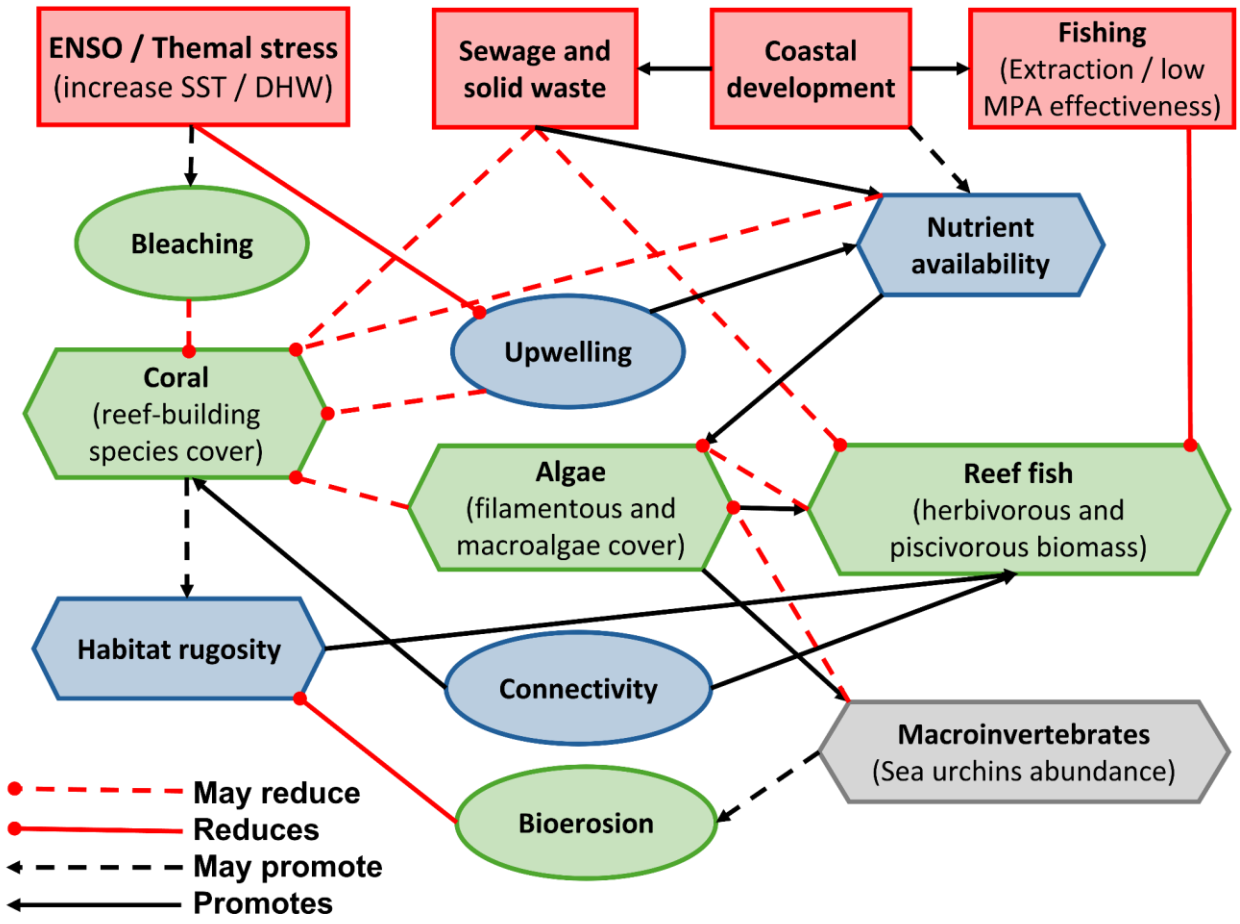


Figure 4. Conceptual model of the Eastern Tropical Pacific (ETP) coral reef ecosystems. The model illustrates key biotic and abiotic components, as well as external drivers, threats, and the processes and interactions between them.

2.4. Definition of the collapsed state of the ecosystem

Ecosystem collapse represents the final stage of degradation. It occurs when the biodiversity and defining features of an ecosystem decline to levels where the ecosystem transforms into a different state or is completely lost. This state can result from different pathways that reduce the capacity of ecosystems to sustain their characteristic biota. These pathways include disease, overharvesting, or a persistent change in environmental conditions. An ecosystem is classified as "Collapsed", if it has declined or degraded across its entire distribution, although recovery might still be possible.

Collapsed coral reefs have often simplified to rubble fields or transitioned from being coral-dominated to being dominated by other taxa, including algal turfs, fleshy algae, sponges, and other filter-feeding invertebrates.

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

For this assessment, coral reef ecosystem collapse is defined by any of the following:

1. Complete loss of coral reef area,
2. Hard coral cover falling below 5%,
3. Sea surface temperatures exceeding critical thresholds, resulting in frequent severe heatwaves and coral bleaching at an average return time between events of five 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:

- An algal-to-coral cover ratio exceeding 5:1,
- All 'functionally important' coral species being Critically Endangered under the Red List of Threatened Species,
- Severe depletion of key fish groups (herbivores and piscivores) to levels well below historical baselines.

Table 2. Key abiotic and biotic features and characteristics of the coral reef ecoregions in the Eastern Tropical Pacific, highlighting unique aspects of each ecosystem.

Ecoregion	Key Biotic	Key Abiotic	Key Threats
Gulf of California	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. achilles, A. nigricans, A. triostegus, A. xanthopterus)*, *Girella simplicidens, Kyphosus* spp. *(K. elegans,, K. sectatrix, K. vaigiensis)* , *Microspathodon* spp. *(M. bairdii, M. dorsalis), Nicholsina denticulata, Prionurus* spp. *(P. laticlavius, P. punctatus)* and *Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus).* • Piscivorous fishes: *Cephalopholis panamensis, Dermatolepis dermatolepis, Epinephelus labriformis, Lutjanus* spp. *(L. argentiventris, L. viridis)* and *Mycteroperca* spp. *(M. jordani, M. prionura, M. rosacea, M. xenarcha).*	Thermal Stress - Degree heating weeks	Extractive activities, maritime traffic, tourism, ecosystem modifications, water pollution, and extreme temperature events
Revillagigedo Islands	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. nigricans, A. triostegus, A. xanthopterus), Kyphosus* spp. *(K. elegans, K. sectatrix, K. vaigiensis), Microspathodon* spp. *(M. bairdii, M. dorsalis), Nicholsina denticulata, Prionurus* spp. *(P. laticlavius, P.*	Thermal Stress - Degree heating weeks	Fishing pressure, tourism, invasive species, and climate related disturbances

Ecoregion	Key Biotic	Key Abiotic	Key Threats
	punctatus), and *Scarus* spp. *(S. compressus, S. ghobban, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Dermatolepis dermatolepis, Epinephelus* spp. *(E. clippertonensis, E. labriformis)* and *Lutjanus viridis*		
Mesoamerican Pacific	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. nigricans, A. triostegus, A. xanthopterus), Kyphosus* spp. *(K. elegans, K. vaigiensis), Microspathodon (M. bairdii, M. dorsalis), Nicholsina denticulata, Prionurus* spp. *(P. laticlavius, P. punctatus),* and *Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Cirrhitus rivulatus, Epinephelus labriformis* and *Lutjanus (L. argentiventris, L. viridis)*	Thermal Stress - Degree heating weeks	Fishing, aquaculture, maritime traffic, tourism, ecosystem modifications, multiple sources of water pollution, and climate related disturbances
Nicoya	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. nigricans, A. triostegus, A. xanthopterus), Kyphosus* spp. *(K. elegans, K. ocyurus, K. sectatrix, K. vaigiensis), Microspathodon* spp. *(M. bairdii, M. dorsalis), Nicholsina denticulata, Prionurus* spp. *(P. laticlavius, P. punctatus),* and *Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Cirrhitus rivulatus, Dermatolepis dermatolepis, Epinephelus labriformis*, *Lutjanus* spp. *(L. argentiventris, L. viridis)* and *Mycteroperca xenarcha.*	Thermal Stress - Degree heating weeks	Fishing, aquaculture, maritime traffic, tourism, ecosystem modifications, multiple sources of water pollution, and climate related disturbances
Oceanic Islands Corridor	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. nigricans, A. triostegus, A. xanthopterus), Girella freminvillii, Kyphosus* spp. *(K. elegans, K. ocyurus, K. vaigiensis), Microspathodon* spp. (*M. bairdii* and *M. dorsalis*), *Prionurus* spp. *(P. laticlavius, P. punctatus)* and *Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Cirrhitus rivulatus, Dermatolepis dermatolepis, Epinephelus labriformis, Lutjanus* spp. *(L. argentiventris, L. jordani, L. viridis)* and *Mycteroperca* spp. *(M. olfax, M. xenarcha).*	Thermal Stress - Degree heating weeks	Fishing, tourism, and climate related disturbances

Ecoregion	Key Biotic	Key Abiotic	Key Threats
Panama Bight	• Macroalgae (although algal turfs are present in this ecoregion, and are generally more prominent than macroalgae, algal turf cover was directly and inversely collinear with coral cover. Therefore, algal turfs were not included in the analysis for Panama Bight). • Hard coral cover • Herbivorous fishes: *Acanthurus* spp. *(A. nigricans, A. triostegus, A. xanthopterus), Kyphosus* spp. *(K. elegans, K. ocyurus, K. vaigiensis), Microspathodon dorsalis, Prionurus punctatus, Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Epinephelus labriformis, Lutjanus* spp. *(L. argentiventris, L. viridis)* and *Mycteroperca xenarcha*	Thermal Stress - Degree heating weeks	Fishing, aquaculture, maritime traffic, tourism, ecosystem modifications, multiple sources of water pollution, and climate related disturbances
Guayaquil	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus spp. (A. nigricans, A. xanthopterus), Kyphosus* spp. *(K. elegans, K. ocyurus, K. vaigiensis), Microspathodon* spp. *(M. bairdii, M. dorsalis), Nicholsina denticulata, Prionurus laticlavius,* and *Scarus* spp. *(S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Dermatolepis dermatolepis, Epinephelus labriformis, Lutjanus argentiventris* and *Mycteroperca* spp. *(M. olfax, M. xenarcha)*	Thermal Stress - Degree heating weeks	Fishing, aquaculture, maritime traffic, multiple sources of water pollution, ecosystem modifications, and climate related disturbances
Eastern Galapagos Islands	• Macroalgae and algal turfs • Hard coral cover • Herbivorous fishes: *Acanthurus xanthopterus, Girella freminvillii, Kyphosus elegans,, Microspathodon* spp. (*M. bairdii* and *M. dorsalis*), *Nicholsina denticulata, Prionurus laticlavius, and Scarus* spp. *(S. compressus, S. ghobban, S. perrico, S. rubroviolaceus)* • Piscivorous fishes: *Cephalopholis panamensis, Cirrhitus rivulatus, Dermatolepis dermatolepis, Epinephelus labriformis, Lutjanus* spp. (*L. argentiventris, L. jordani,* and *L. viridis*) *and Mycteroperca olfax*	Thermal Stress - Degree heating weeks	Fishing, maritime traffic, tourism, invasive species, water pollution and extreme temperature events

3. Criterion Assessment

Coral reefs in 10 ecoregions within the ETP were assessed using IUCN Red List of Ecosystems (RLE) Criteria A–D. The following section briefly describes the approach used for each criterion with the detailed methods presented in Annex 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 5% 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 if they experienced a 30–50% decline, Endangered if the decline was 50–80%, and Critically Endangered if the decline exceeded 80%. Reefs with declines of 27–30% were classified as Near Threatened, and all others were considered Least Concern.

Criterion B — Restricted Geographic Distribution

Criterion B assesses the extent of occurrence (EOO) and area of occupancy (AOO) for the current distribution of coral reefs. EOO is the total area within the outer limits of reef distribution, while AOO is the area occupied by the ecosystem, measured as the number of 10 by 10 km grid cells. Both metrics were derived from a unified layer of four different sources: the Millennium Coral Atlas, the Allen Coral Atlas (retaining the areas where experts confirmed that the representation was most accurate), lists of monitoring sites and local polygons generated by site-level research. Thresholds from the RLE guidelines were applied to assess risk according to both metrics.

Criterion C — Environmental Degradation

Criterion C evaluates the degradation of the abiotic environment and its impact on ecosystem persistence. Globally, the most pertinent threat to coral reefs is the increasing occurrence of extreme marine heatwave events that cause coral bleaching and mortality. Under Criterion C, we evaluated historical changes in the frequency of marine heat waves over the past 50 years (sub-criterion C1, 1975–2025) and projected changes for the next 50 years (sub-criterion C2, 2026–2075). For both periods, annual maximum Degree Heating Weeks (DHW), a satellite-derived measure of accumulated heat stress, was used to identify years in which widespread bleaching or severe mortality events occurred. Two complementary pathways to ecosystem collapse were assessed: a chronic pathway, capturing the progressive degradation driven by the long-term effects of frequently recurring bleaching events. This was assessed using the average return interval between severe bleaching events over a 30-year period. The second approach corresponds to a pulse pathway, capturing acute

collapse driven by the clustering of extreme high-mortality events within any 5-year window. For both C1 and C2, the relative severity of decline was calculated by comparing the magnitude of past and projected changes against initial conditions and thresholds for coral reef collapse. Collapse thresholds were set at one severe bleaching event every three years for the chronic pathway, and three severe mortality events within five years for the pulse pathway. Analyses for C2 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. Risk categories were assigned using the severity–extent matrix, based on the proportion of reef area within each ecoregion experiencing different levels of relative decline. The most severe risk status across both C1 and C2 and chronic and pulse approaches was taken as the final risk status under Criterion C.

Criterion D — Disruption of Biotic Processes and Interactions

Criterion D assesses the disruption to four key biotic components over the past 50 years. These components include coral cover, algae-to-coral ratio, herbivore biomass, and piscivore biomass derived from in-situ monitoring data (Table 2). For each reef site, the decline of each indicator was measured relative to both the state of the reef 50 years ago and a hypothetical collapse threshold, representing the point at which the biotic component was no longer functional. The proportion of sites experiencing varying degrees of decline was then evaluated, and a risk matrix was used to determine the risk status for each indicator. Lastly, a heuristic step-wise approach across all indicators was 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 Eastern Tropical Pacific (ETP) under the Red List of Ecosystem criteria.

Criterion	Sub-criterion	Indicator(s)	Data Sources	Collapse or Risk Threshold(s)	Criterion Assessed? (Yes/No)	Comments
A Reduction in geographic distribution	A1 – (Past 50 years)	Percentage of monitoring sites below the (5%) collapse threshold	Benthic cover from UVC surveys	80% loss of sites over 50 years - CR	Yes	Based on change in benthic cover detected through UVC surveys
B Restricted geographic distribution	B1 –Extent of Occurrence (EOO)	Extent of Occurrence (EOO) + ongoing decline or number of threat defined locations	Regional reef maps, expert knowledge	EOO < 50,000 km^2 + ongoing decline or threats - Threatened	Yes	Calculated per ecoregion using minimum convex polygons
	B2 –- Area of Occupancy (AOO)	Area of Occupancy (AOO) + ongoing decline or number of threat defined locations	Grid-based reef presence (10×10 km), monitoring data	AOO < 50 + ongoing decline or threats - Threatened	Yes	Fluctuation data limited; AOO estimates incomplete

Criterion	Sub-criterion	Indicator(s)	Data Sources	Collapse or Risk Threshold(s)	Criterion Assessed? (Yes/No)	Comments
C	C1 – Environmental degradation	Degree Heating Weeks (DHW))	NOAA Coral Reef Watch	Return interval of ≤ 3 years between bleaching events or 3 severe marine heatwave events occurring within 5 years - Collapsed	Yes	Reference period: 1850–present; long-term warming trend assessed
C	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 - Collapsed	Yes	Ecoregion average
D	D1 – Disruption of biotic processes	Hard coral cover, Algae-coral ratio, Herbivorous fish and Piscivorous fish	Benthic cover from UVC surveys	Hard coral cover <= 5%, ACR 0.833, herbivorous fish 10% of baseline biomass and piscivorous fish 20% of baseline biomass - Collapsed	Yes	Data sparse or inconsistent across ecoregions

4. Risk Status

Coral reefs within nine ecoregions of the ETP (i.e., Gulf of California, Revillagigedo islands, Clipperton Atoll, Mesoamerican Pacific, Nicoya, Oceanic Islands Corridor, Panama Bight, Guayaquil, and Eastern Galapagos Islands) were assessed as Critically Endangered (CR), whereas reefs in the Western Galapagos Islands were categorized as Collapsed (CO) (Table 4). Critical risk levels in all the CR ecoregions were driven by severe environmental degradation (Criterion C), even in ecoregions considered of Least Concern (LC), Vulnerable (VU), or Endangered (EN) under Criteria A, B, and D. Only three ecoregions were considered of Least Concern (LC) under a single criterion (Criteria A), namely the Gulf of California, the Oceanic Islands Corridor, and Panama Bight. No ecoregions in the ETP were assessed as LC across all criteria, highlighting the widespread and escalating pressures facing reefs in the region.

Table 4. Summary of RLE assessment results for the Eastern Tropical Pacific (ETP) coral reef ecoregions. The overall Red List of Ecosystems status is the highest risk level identified across all assessed criteria. NT: Near threatened, LC: Least concern, VU: Vulnerable, EN: Endangered, CR: Critically endangered, DD: Data deficient, NE: Not evaluated, CO: Collapsed. Criterion A: Reduction in geographic distribution over the past 50 years (A1); Criterion B: Restricted geographic distribution in terms of Extent of Occurrence (B1) and Area of Occupancy (B2); Criterion C: Environmental degradation in terms of thermal stress over the past 50 years (C1) and in the next 50 years (C2); Criterion D: Disruption of Biotic Processes and Interactions including D(coral): hard coral cover coral, D(a-c ratio): Algae-to -coral ratio, D(herb): Herbivorous fish biomass and D(pisc): Piscivorous fish biomass.

Ecoregions		A1	B1	B2	C1	C2	D1	Overall
1	Gulf of California	LC	LC	VU	VU	CR	EN	CR
2	Revillagigedo Islands	DD	EN	EN	DD	CR	DD	CR
3	Clipperton Atoll	DD	CR	EN	VU	CR	DD	CR
4	Mesoamerican Pacific	VU	LC	VU	EN	CR	EN	CR
5	Nicoya	CR	VU	NT	EN	CR	CR	CR
6	Oceanic Islands Corridor	LC	LC	EN	VU	CR	EN	CR
7	Panama Bight	LC	LC	VU	VU	CR	VU	CR
8	Guayaquil	DD	EN	EN	EN	CR	DD	CR
9	Eastern Galapagos Islands	CR	VU	EN	CR	CR	EN	CR
10	Western Galapagos Islands	CO	NE	NE	NE	NE	NE	CO

Criterion A: Reduction in Geographic Distribution

Of the ten ETP ecoregions, three were classified within threatened categories (VU, EN, or CR), namely the Mesoamerican Pacific, Nicoya, and Eastern Galapagos Islands (Tables 4 and 5) under Criterion A, whereas West Galapagos was assessed as Collapsed (CO). This reflects that reefs in West Galapagos, which are situated in a region of marginal coral reef development (Glynn et al. 2018), and suffered geological uplift in 1954 and emmersion events (Glynn and Wellington, 1983), experienced almost complete coral mortality (95%) during the 1982-83 El Niño event, were further degraded by decades of intense bioerosion (Glynn 1988, Reaka-Kudla et al 1996; Glynn et al 2009), and have since failed to recover (Glynn et al 2015; 2018). Collectively, these findings highlight the significant coral reef area losses that have occurred in four out of the seven evaluated ecoregions over the past 50 years. Arguably this finding is at odds with the recent report on the status of coral reefs of the world which highlights the ETP as a region where no general change occurred from the 2000s (González-Rivero et al 2026). This difference is explained by the different methods used to determine change across reports. Here, we quantified reef loss by computing the percentage of sites that crossed the 5% cover threshold when comparing the earliest period for each ecoregion with the most recent data (post-2020). Gonzalez-Rivero et al (2026) computed absolute and relative change in coral cover between years and decades based on benthic transect datasets. The ETP has historically remained low in coral cover compared to other coral reef ecoregions globally. Therefore, even small inter-decadal changes in coral cover may equate to large proportions of sites falling below the collapse threshold used here. Three ecoregions - the Gulf of California, the Oceanic Islands Corridor, and Panama Bight - were assessed as Least Concern, whereas three ecoregions - Revillagigedo Islands, Clipperton Atoll, and Guayaquil- were considered Data Deficient (DD).

Table 5. Risk status of the Eastern Tropical Pacific (ETP) coral reef ecoregions under Criterion A, determined from estimated declines in coral reef area over the last 50 years. NT: Near threatened, LC: Least concern, VU: Vulnerable, EN: Endangered, CR: Critically endangered, DD: Data deficient, NE: Not evaluated, CO: Collapsed.

Coral Reef Ecoregion	Proportion of reef sites below critical hard coral cover threshold	Risk status
Gulf of California	0.05	LC
Revillagigedo Islands	DD	DD
Clipperton Atoll	DD	DD
Mesoamerican Pacific	0.33	VU
Nicoya	0.80	CR
Oceanic Islands Corridor	0	LC
Panama Bight	0	LC
Guayaquil	DD	DD
Eastern Galapagos Islands	0.92	CR
Western Galapagos Islands	0	CO

Criterion B: Restricted Geographic Distribution

Under Criterion B, four ecoregions were assessed as Vulnerable (i.e., Gulf of California, Mesoamerican Pacific, Nicoya, and Panama Bight), four more as Endangered (Revillagigedo Islands, Oceanic Islands Corridor, Guayaquil and Eastern Galapagos Islands), and one as Critically Endangered (CR) (Clipperton Atoll). Criterion B could not be evaluated for the Western Galapagos Islands because all its reefs are currently considered collapsed.

Table 6. Risk status of the Eastern Tropical Pacific (ETP) coral reef ecoregions under Criterion B, determined from the distribution of coral reefs measured as the Extent of Occurrence (EOO) and Area of Occupancy (AOO). NT: Near threatened, LC: Least concern, VU: Vulnerable, EN: Endangered, CR: Critically endangered, DD: Data deficient, NE: Not evaluated, CO: Collapsed.

Coral Reef Ecoregion	Extent of Occurrence EOO (km^2)	Area of Occupancy (AOO)	Risk Status
Gulf of California	74535	27	VU
Revillagigedo Islands	17815	7	EN
Clipperton Atoll	12.2	2	CR
Mesoamerican Pacific	241301	35	VU
Nicoya	41818	52	VU
Oceanic Islands Corridor	200880	4	EN
Panama Bight	205272	27	VU
Guayaquil	3297	8	EN
Eastern Galapagos Islands	20050	7	EN
Western Galapagos Islands	NE	NE	NE

Criterion C: Environmental Degradation

Nine out of ten ecoregions were classified as Critically Endangered (CR) under Criterion C based on historical and projected sea-surface temperature (SST). Criterion C was not evaluated for the Western Galapagos Islands because all of its reefs are currently considered Collapsed. The Revillagigedo Islands ecoregion was classified as data deficient (DD). Based on very limited literature, we proposed preliminary DHW thresholds for the ecoregion and generated provisional results. According to experts, however, the response of these reefs to thermal stress has not been systematically studied, largely because the hurricane season coincides with the months of peak sea surface temperatures, which has prevented regular monitoring campaigns. The California Current and hurricanes are thought to buffer the region against heatwaves, but how these factors interact to shape the response of coral reefs to thermal stress remains unknown.

Table 7. Risk status of the Eastern Tropical Pacific (ETP) coral reef ecoregions under Criterion C, determined from estimated declines in abiotic conditions, specifically changes in extreme heat events. NT: Near threatened, LC: Least concern, VU: Vulnerable, EN: Endangered, CR: Critically endangered, DD: Data deficient, NE: Not evaluated, CO: Collapsed. The range of variation representing uncertainty around the best estimate (minimum decline to maximum decline) is shown in parentheses.

Coral Reef Ecoregion	Risk Status Criterion C1	Risk Status Criterion C2
Gulf of California	VU (VU-CO)	CR
Revillagigedo Islands	DD	CR
Clipperton Atoll	VU (LC-EN)	CR
Mesoamerican Pacific	EN (LC-CR)	CR
Nicoya	EN (LC-CR)	CR
Oceanic Islands Corridor	VU (NT-EN)	CR
Panama Bight	VU (LC-EN)	CR
Guayaquil	EN (EN-EN)	CR
Eastern Galapagos Islands	CR (EN-CO)	CR
Western Galapagos Islands	NE	NE

Criterion D: Disruption of biotic processes or interactions

Criterion D could only be assessed completely (including all ecological indicators) for six of the ten ecoregions. All of these ecoregions -Gulf of California, Mesoamerican Pacific, Nicoya, Oceanic Islands Corridor, Panama Bight, and Eastern Galapagos Islands- met the thresholds to be considered Vulnerable, Endangered, or Critically Endangered (Tables 4 and 8). Three ecoregions, (i.e., Revillagigedo Islands, Clipperton Atoll, and Guayaquil) were considered Data Deficient under Criteria D because they lacked either benthic time series (e.g., Revillagigedo Islands and Guayaquil) or both benthic and fish time series (e.g., Clipperton Atoll). Although time series were available for the Western Galapagos Islands, reef status according to Criteria D could not be assessed in this ecoregion

for the present report. Available data on herbivore and predator biomass suggest moderate to severe disruption of trophic interactions in several ecoregions.

Table 8. Risk status of the Eastern Tropical Pacific (ETP) 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. The overall risk status is determined through a step-wise approach considering the risk of each indicator in order from left to right. Risk ranges (e.g., EN-CR) represent uncertainty in the outcomes. Where relevant, the most likely category is presented (outside of the parentheses) in addition to the range. Overall risk is considered DD if the risk category according to hard coral cover is DD. NT: Near threatened, LC: Least concern, VU: Vulnerable, EN: Endangered, CR: Critically endangered, DD: Data deficient, NE: Not evaluated, CO: Collapsed.

Coral Reef Ecoregion	Hard coral	Algae-coral ratio	Herbivorous fish	Piscivorous fish	Overall
Gulf of California	VU	VU	NT-VU	EN	EN
Revillagigedo Islands	DD	DD	NT	VU	DD
Clipperton Atoll	DD	DD	DD	DD	DD
Mesoamerican Pacific	EN	EN-CR	NT-VU	EN	EN
Nicoya	CR	VU	EN	VU	CR
Oceanic Islands Corridor	EN	NT	NT (LC-NT)	NT	EN
Panama Bight	LC-NT	LC	VU	EN	VU
Guayaquil	DD	DD	VU (VU-EN)	LC-NT	DD
Eastern Galapagos Islands	EN	VU	NT	LC (LC-NT)	EN
Western Galapagos Islands	NE	NE	NE	NE	NE

5. Conclusion and recommendations

Coral reefs within the ETP are biogeographically isolated, small (140 km^2, 0.04 % of global extent) and fragmented. These reefs sustain distinct coral, algae, invertebrate, and fish assemblages shaped by strong environmental filtering and recurrent ENSO events. The present assessment categorized most ETP coral reefs as being at high risk of collapse (Critically Endangered) with reefs in one ecoregion (Western Galapagos Islands) already Collapsed. This categorisation reflects mainly a severe level of environmental degradation, particularly due to increasing thermal stress and direct anthropogenic threats. In three of the Critically Endangered ecoregions, this status resulted from the effects of severe environmental degradation (Criterion C) compounded with a) the reduction in geographic distribution (Criterion A) and severe disruption of biotic processes and interactions (Criterion D) (i.e., Nicoya), b) the reduction in geographic distribution (Criterion A) (i.e., Eastern Galapagos Islands), and c) an inherent restricted geographic distribution (Criterion B) (i.e., Cliperton Atoll). Because certain coral reefs in the ETP are not mapped (i.e., lack local reef extent polygons), we

relied on satellite images to estimate reef area. This approach generated a reef area layer, which, taken as a basis for the calculation of all criteria, may capture patterns that apply to other coastal ecosystem types. Despite these limitations, this assessment generated the most accurate reef extent layer from the available information. Overall, the assessment shows that, at least in some parts of the ETP (irrespective of whether they are continental or oceanic), the risk of collapse is not driven by one single pressure, but by the convergence of naturally marginal environmental conditions with accelerating local and global stressors.

Conservation and management strategies should prioritize the protection of remaining coral-dominated reefs, persistent coral refugia and sites with functionally diverse species assemblages. Along continental margins, management efforts should focus on reducing land-based pollution, sediment delivery, nutrient enrichment, wastewater discharge, overfishing, and poorly planned coastal development, particularly in watersheds connected to reef-bearing bays, islands, and embayments. These actions align directly with the Antigua Convention and its North-East Pacific Action Plan, and with the Lima Convention/South-East Pacific Action Plan for Colombia, Ecuador, Panama and Peru. In oceanic systems, especially the Oceanic Islands Corridor, the Marine Corridor of the Eastern Tropical Pacific (CMAR; by its Spanish Acronym) should serve as the main platform for coordinated protection of ecological connectivity among Isla de Coco, Coiba, Malpelo, Gorgona and Galápagos, including joint monitoring, enforcement, vessel regulation, biosecurity and climate-adaptation planning. Fisheries measures should reduce illegal and unregulated extraction, protect herbivorous and piscivorous fishes, and strengthen coordination with the Inter-American Tropical Tuna Commission (IATTC) and the Organización del Sector Pesquero y Acuícola del Istmo Centroamericano (OSPESCA) where relevant. Measures for highly mobile species such as sharks, rays, turtles, and other migratory species should also be linked to CITES, CMS and the Inter-American Convention for Sea Turtles, while mangroves and coastal wetlands that buffer reefs from sediment and nutrient inputs should be incorporated through Ramsar implementation.

A major priority is consolidating a permanent GCRMN-ETP monitoring framework across all ecoregions. This standardized monitoring should include hard coral cover, relative algal cover, coral recruitment, coral health (including bleaching, diseases, and mortality), herbivorous and piscivorous fish biomass, abundance of mobile invertebrates (particularly sea urchins), temperature, oxygen, carbonate chemistry and DHW-based thermal stress. In line with the World Ocean Assessment and the Kunming–Montreal Global Biodiversity Framework, future regional action should integrate science-based monitoring, transboundary governance, protected-area effectiveness, fishing enforcement, restoration planning and local threat reduction. These steps are essential for refining

collapse thresholds, evaluating management effectiveness, and directing conservation investment towards reefs with the highest ecological value and recovery potential. The overall Critically Endangered classification of the ETP indicates that the region is at an extremely high risk of collapse. However, evidence of historical post-ENSO recovery and the high thermal tolerance of some coral populations (e.g., in Ecuador) highlight important opportunities for conservation (Romero-Torres et al., 2020). In some *Pocillopora* populations, for instance, association with thermotolerant symbionts, including *Durusdinium glynnii*, has contributed to particularly high resistance to bleaching and mortality (Palacio-Castro et al., 2023). These biological capacities, together with ongoing restoration initiatives and collaboration through the ETP Coral Restoration Network, offer opportunities to support recovery and strengthen ecological resilience (Tortolero-Langarica et al., 2025; Coral Restoration Consortium, 2025). Protecting surviving coral populations, reducing local pressures and implementing scientifically guided restoration can help buffer ecological degradation and sustain recovery potential. These efforts should build on locally demonstrated resilience, preserve genetic and functional diversity, and evaluate outcomes under recurrent climatic disturbances.

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

The designation of geographical entities in this publication, and the presentation of the material, do not imply the expression of any opinion whatsoever on the part of IUCN concerning the legal status of any country, territory, or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

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10. Contributors

In the modified version of the CRediT (https://credit.niso.org/) table below, all contributors are listed marking their specific contribution(s) to the RLE assessment and publication with an x.

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11. Annex

11.1. Boundary definitions

Ecoregional boundaries were based on the Marine Ecoregions of the World (MEOW) framework and refined using regional biogeographic evidence and expert knowledge.

Table 9. Boundary definitions per ecoregion, including countries and coral reef area (km^2) within each ecoregion, the description of the boundaries, and a brief explanation of how coral reefs in each ecoregion are different from other ecoregions.

Ecoregion	Country/ Territory	Coral Reef Area (km^2)	Boundary Description	Justification (Description as to why coral reefs in each ecoregion are different from one another)
Gulf of California	Mexico	5.33	Based on the MEOW boundary, with the northern limit extended to encompass areas characterized by high coral diversity and distinctive oceanographic conditions. oceanographic uniqueness	The Gulf of California is a semi-enclosed subtropical sea characterized by strong seasonal temperature variability, localized upwelling, high productivity, and a pronounced north–south environmental gradient. Its coral communities occur near the northern distributional limit of reef-building corals in the ETP and develop primarily on rocky substrates. These conditions, together with the region's distinctive species composition and relative geographic isolation, differentiate it from the tropical reef systems farther south.
Revillagigedo Islands	Mexico	3.30	Encompasses the remote oceanic islands of Socorro, Clarión, San Benedicto, and Roca Partida, located several hundred kilometers from mainland Mexico.	Revillagigedo is distinguished by its extreme isolation, volcanic substrates, relatively high coral richness within western Mexico influence of, oceanic currents, exposure to ENSO events and, tropical storms, and ecological

Ecoregion	Country/ Territory	Coral Reef Area (km^2)	Boundary Description	Justification (Description as to why coral reefs in each ecoregion are different from one another)
				ecological connections between shallow reefs and pelagic predator assemblages.
Clipperton Atoll	France	0.45	Encompasses Clipperton Atoll (Île de la Passion), near 10°18′N, 109°13′W, including the annular reef system surrounding the isolated atoll and its enclosed lagoon.	Clipperton is the only true atoll in the ETP and the most isolated reef system included in the assessment. Its distinctive geomorphology, small reef area, simplified coral assemblage, extreme isolation, and dependence on oceanic connectivity make it ecologically unique.
Mesoamerican Pacific	Mexico and Costa Rica	31.4	Extends along the mainland Pacific coast from western and southern Mexico through Guatemala, El Salvador and Nicaragua to northern Costa Rica. It combines the Tropical Mexican Pacific and the Chiapas–Nicaragua biogeographic sectors.	This ecoregion comprises an extending mainland reef system characterized by strong latitudinal gradients, and heterogeneous coastal habitats, estuaries, mangroves, rocky shores, sediment-rich coasts, and contrasting current influences. It is also highly exposed to land-based pressures, tourism, overfishing, wastewater, sedimentation, and habitat fragmentation.
Nicoya	Costa Rica	55.0	Encompasses most of Costa Rica's Pacific coast south of the northern transition and extends into western Panama including sheltered gulfs, rocky headlands, and continental islands.	Nicoya is a highly productive mainland ecoregion shaped by the Papagayo wind jet, seasonal coastal upwelling, pronounced rainfall gradients, river discharge, sediment inputs, and high coastal habitat diversity.
Oceanic Islands Corridor	Ecuador, Costa Rica, Colombia	1.74	Defined as a discontinuous oceanic corridor connecting Isla del Coco, Malpelo, and the northern Galápagos islands of Darwin and Wolf. These isolated volcanic islands and pinnacles provide stepping-stone habitats across the open ETP.	This ecoregion is characterized by extreme isolation, steep volcanic bathymetry and limited reef area. It is of major importance for regional connectivity through larval exchange and it hosts large predator aggregations. Consequently, its ecological importance is disproportionate to its small reef area.
Panama Bight	Panama, Colombia	40.10	Extends from eastern Panama along the Pacific coast of Colombia to northern Ecuador (excluding Malpelo which belongs to the Oceanic Islands Corridor). Coral reefs occur around islands, rocky shores, and sheltered embayments along coastlines strongly influenced by mangroves and riverine discharge.	Panama Bight is a humid equatorial mainland ecoregion shaped by high rainfall, strong river discharge, tidal forcing, localized seasonal upwelling, the Panama wind jet, turbidity gradients, and strong land–sea interactions. These conditions distinguish it from the drier coast of Central America and the transitionalGuayaquil region.
Guayaquil	Ecuador	1.25	Encompasses southern Ecuador and northern Peru, particularly the outer Gulf of Guayaquil and adjacent ocean-influenced coasts. Coral communities are highly localized and occur near the southern continental limit of coral reef development in the ETP.	Guayaquil represents the edge of the distribution range of coral reef fauna. All coral reefs along the coast of Ecuador are located far from estuaries and from the Gulf of Guayaquil, and they experience relatively stable seasonality, with limited temperature variation. In addition, all of them are located within Marine Protected Areas (MPAs). As a result, these areas are free from industrial pollution, where trawling is prohibited. Despite these

Ecoregion	Country/ Territory	Coral Reef Area (km^2)	Boundary Description	Justification (Description as to why coral reefs in each ecoregion are different from one another)
				favorable conditions, coral reefs in Ecuador are affected by overfishing, inadequate tourism practices, and sedimentation caused by runoff during periods of extreme rainfall. The El Niño events that have occurred since 1997/98 have had no long term impact on the reefs, given that they have recovered the associated coral cover losses.
Eastern Galapagos Islands	Ecuador	0.70	Includes San Cristóbal, Española, Floreana, and adjacent islands and islets, approximately between 0°30′N–2°S and 89°–91°W, within the Galápagos Marine Reserve. Coral communities occur as discontinuous patches in sheltered bays and along leeward coasts.	Eastern Galápagos experience a stronger tropical and Panamic influence than western Galápagos, although it is also affected by the Humboldt, Panama, and equatorial current systems. Its reefs are patchy, have experienced severe ENSO-related mortality, and are exposed to tourism, fishing, wastewater, plastics, vessel traffic, and invasive species.
Western Galapagos Islands	Ecuador	0.00	Includes Fernandina and the western and southwestern coasts of Isabela, approximately between 0°30′S–1°30′S and 91°–92°W. This ecoregion used to have coral reef systems in the past. However all its mapped coral reef area is considered as collapsed in the 2026 reef layer.	Western Galápagos is the coolest and most strongly upwelled ecoregion of the archipelago, and is directly influenced by the Equatorial Undercurrent. Persistent cold upwelling, low carbonate saturation, macroalgal dominance, strong thermal variability, ENSO disturbance, and bioerosion have constrained modern reef-building development and have contributed to the collapse of its coral reefs.

11.2. Methods description (detailed)

Data

The spatial extent of coral reefs in the ETP was defined by combining the Millennium Coral Reef Mapping Project layer curated by UNEP-WCMC, the Allen Coral Atlas benthic habitat layer (using only coral/algae polygons), and a layer of coordinates of reef-monitoring sites contributed by researchers of the ETP Node of the GCRMN. Researchers within the ETP Node of the GCRMN and other regional experts reviewed the combined layers to identify missing reefs, remove areas incorrectly classified as reefs, relocate records where necessary, and distinguished *true coral reefs* (Type A) from *marginal coral reefs* (Type B), as well as from rocky reefs and other formations. Where validated reef locations were represented only by points, 300-m-diameter circular buffers were applied to approximate reef extent. These buffers were restricted to the marine environment and were merged with the validated reef polygons to produce the regional coral reef extent layer.

Benthic and fish monitoring data were contributed by researchers from the ETP node of the GCRMN. The benthic data comprised 87 datasets containing estimates of percent cover of corals, algae, and other benthic categories collected using a variety of methods including point-intercept transects, quadrats, photo-transects, and video transects. Benthic surveys spanned 1994–2024 (i.e., 2 to 25-years long time series) across all the ecoregions. The regional fish dataset combined 114 local datasets derived from underwater visual censuses conducted along belt transects of different areas (i.e., between 30 m^2 and 600 m^2). Fish biomass was standardized by surveyed area and expressed as g m^{-2}. Fish surveys spanned 2004–2024 (i.e., from 6 to 21-years long time series) across ecoregions. Local-scale datasets were incorporated through a standardized data ingestion and quality-control protocol. Original data were preserved, linked to source and authorship metadata, and processed using reproducible workflows in R. Site names, coordinates, sampling information, and identifiers were standardized, and only sites validated as *true coral reefs* or *marginal coral reefs* were retained.

Reef typology

Coral reefs included in this assessment were defined and classified in different types defined by the IUCN Global Ecosystem Typology (Keith et al 2022). Within this typology, we considered *true coral reefs* (Type A)*, which* are described under the ecosystem functional group 'M1.3 Photic Coral Reefs' (https://global-ecosystems.org/explore/groups/M1.3). Type A reefs are characterized by net biogenic accretion and the development of persistent carbonate frameworks built primarily by scleractinian corals. These also include reefs Type A (alternative), which refer to Type A accreting reefs with other geomorphology (e.g., fringing reefs, spur-and-grove systems, bommies) as opposed to classic barrier reefs or atolls. We also included Type B naturally occurring *marginal coral reefs* (Type B) characterized by coral communities occurring in places that restrict significant calcium carbonate accretion and the development of biogenic reef structures.

In the ETP, naturally occurring *rocky reefs* (Type C), which belong to the IUCN ecosystem function group *M.1.6. Subtidal rocky reefs* were excluded from the present analysis. Although *rocky reefs* may host hard corals, their habitat structure is underpinned mostly by rocks (rather than by biogenic features) and are therefore classified as a different ecosystem type. We also included and distinguished *collapsed* reefs, which historically met the definition of Type A, Type A (alternative), or Type B, even when their current condition resembled *rocky reefs*, because their transformation represents ecosystem degradation relevant to the assessment of collapse risk.

The classification of all ETP reef sites in Type A, Type A (alternative), Type B, Type C, and *collapsed* reefs was consolidated by reviewing global and regional reef maps, as well as the layers of coordinates containing reef monitoring sites and known reefs not monitored, in close cooperation with the researchers of the ETP Node of the GCRMN. These researchers proposed modifications on initial global coral layers, including additions, removals, and relocations. Only sites confirmed as Type A, Type A (alternative), Type B, and sites known to formerly belong to any of these categories but now considered *collapsed* were included in this analysis. Naturally occurring *rocky reefs* were excluded.

Criterion A: Reduction in geographic distribution

Criterion A considered the reduction in ETP coral reef extent over a 50-year period. As part of this criterion, we assessed sub-criterion A1, which measures the percentage of reduction in coral reef extent per ecoregion over the past 50 years (1975–2025). The sub-criteria A2a and A2b, which assess future reductions, as well as A3, which assesses historical reductions since 1750, could not be evaluated in the ETP because the spatial data required over the relevant assessment periods are currently unavailable. Coral reefs can undergo ecological and structural degradation without a detectable change in the coral reef extent mapped through remote sensing. Direct estimation of the reduction in ecosystem extent from historical and contemporary spatial layers was therefore not feasible. We inferred reduction in ecosystem extent under subcriterion A1 using recent hard-coral cover estimates from monitoring conducted between 2020 and 2024 as a proxy for the proportion of the historical reef distribution that remained in a non-degraded condition (Obura et al. 2021).

Each reef site was classified as non-degraded or severely degraded using an operational threshold of approximately 5% hard coral cover. This threshold represents a level below which coral abundance was considered insufficient to maintain positive carbonate accretion (Perry et al. 2013) . A sensitivity analysis was conducted using thresholds ranging from 1% to 10% to evaluate the robustness of estimated reductions to the choice of coral-cover threshold (Fig. 5). In the absence of spatially explicit estimates of reef condition, monitoring sites were weighted equally, and reduction in extent was estimated as the proportion of sites falling below the selected coral-cover threshold. All monitored sites were assumed to have been in a non-degraded reef state in 1975, as there were no records or reports from this period. Conversely, 12 sites (distributed through Eastern and Western Galapagos Islands) known to have collapsed or been permanently lost between 1975 and 2019 due to anthropogenic or environmental pressures, including cyclones, tectonic uplift, dredging, sedimentation, coastal development, or severe bleaching, were included even when they were no

longer surveyed in ongoing monitoring programs. This allowed documented historical losses to be incorporated into the estimated reduction in ecosystem extent. Records and expert knowledge were available to identify collapsed sites in the Eastern and Western Galapagos Islands. However, there is a potential underrepresentation of collapsed sites in the remaining ecoregions due to the lack of comprehensive historical data.

Where data were adequate, risk categories were assigned by comparing the percentage of sites with current coral cover below the collapse threshold (5%) (as an estimate for decline in extent) with the Red List of Ecosystems thresholds for Criterion A1, i.e., declines of >80%: Critically Endangered, 50–80%: Endangered, 30–50%: Vulnerable, 27–30%: Near Threatened, and <27%: Least Concern (see Table 5).

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%

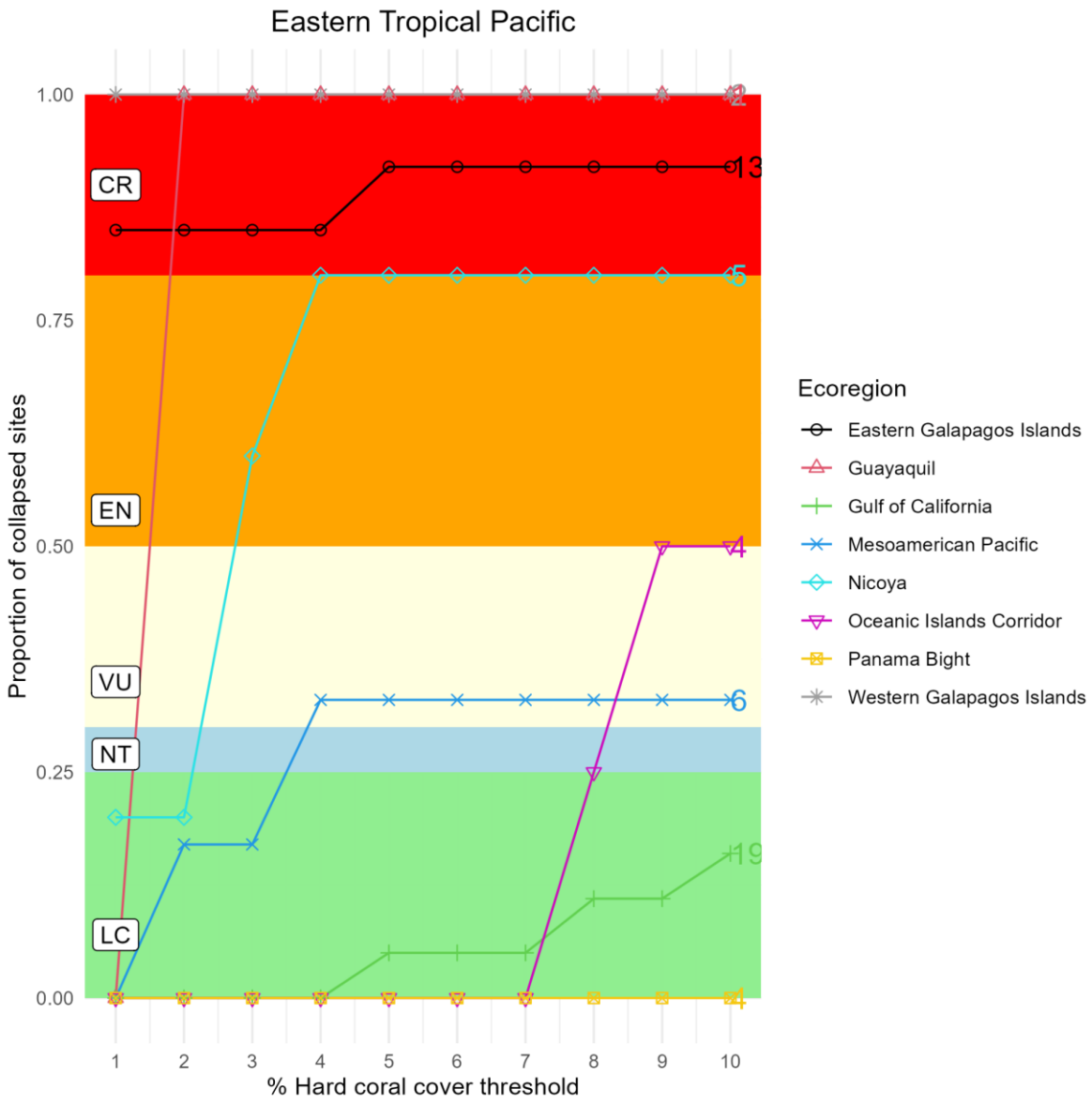


Figure 5. Sensitivity analysis. Proportion of collapsed sites resulting from each coral cover collapse threshold. Each line with its corresponding symbol represents an ecoregion, and the colored bands indicate the resulting risk category. At the end of each curve we present the number of sites included in the assessment of criterion A: Gulf of California = 19 sites, Mesoamerican Pacific = 6 sites, Nicoya = 5 sites, Panama Bight = 4 sites, Oceanic Islands Corridor = 4 sites, Guayaquil = 1 site, Eastern Galapagos Islands = 13 sites, Western Galapagos Islands = 2 sites.

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 standardized spatial metrics:

(i) Sub-criterion B1: Extent of Occurrence (EOO) – the area within the outer boundary of the ecosystem's known distribution; and

(ii) Sub-criterion B2: Area of Occupancy (AOO) – the area occupied by the ecosystem, measured using 10 × 10 km grid cells.

Selection and validation of coral reef extent layer:

This analysis requires a spatial layer representing the current distribution of reefs (including *true coral reefs* and *marginal reefs*). For the ETP, a unified regional coral reef extent layer was produced by integrating global, regional, and geographic information data layers. These included coral reef occurrence points from the Millennium Coral Reef Mapping Project layer curated by the UNEP World Conservation Monitoring Centre (UNEP-WCMC) (WCMC008 CoralReef2021, version 4.1); reef polygons from the Allen Coral Atlas benthic habitat layer; a layer including coordinates of monitoring sites (classified as Type A, Type A (Alternative), and Type B), as well as expert-determined coordinates of sites also corresponding to these three types but not represented in the monitoring efforts or datasets. Higher-resolution local reef polygons were incorporated for Gorgona Island, Colombia (Mejía et al. 2024), the continental coast of Ecuador (Rivera & Martínez, in press 2026), and Darwin and Wolf Islands in the Galápagos Archipelago (Moity 2026). The source of each polygon was retained in the layer attribute to ensure spatial-data provenance and traceability in the unified regional layer.

These spatial layers had been reviewed by researchers of the ETP Node of the GCRMN to identify missing reefs, remove areas incorrectly classified as reefs, and confirm the coordinates as well as the type assigned to each site. Further, where validated reef occurrence was represented only by a point and no accurate reef polygon was available, a 300 m diameter (150 m radius) circular buffer was used to approximate reef extent. These buffers were clipped to the marine environment to prevent overland with land and combined with the validated global and higher-resolution local polygons to produce the unified regional coral reef extent layer.

For Criterion B1, the validated reef extent layer was projected to the WGS 84 (EPSG:4326) coordinate reference system, and the *makeEOO* function in the *redlistr* package in R [version 2.1.0] was used to generate a minimum convex polygon enclosing the mapped reef distribution within each ecoregion. The *getAreaEOO* function was then used to calculate Extent of Occurrence (EOO) in km^2. For Criterion

B2, the reef extent layer was intersected with a 10 × 10 km grid generated using the *makeAOOGrid* function, and the number of grid cells containing reefs (of Type A, A(Alternative), B) was counted to estimate the Area of Occupancy (AOO). Following the assessment protocol, cells in which the cumulative mapped area of the reef ecosystem represented <1% of the grid-cell area were excluded from the AOO estimate. To determine risk classifications for Criterion B, EOO and AOO values were compared with the thresholds defined in the Red List of Ecosystems guidelines (Fig. 4). Ecoregions with EOO or AOO values within 10% of the Vulnerable (VU) threshold were classified as Near Threatened (NT). Meeting the EOO or AOO thresholds alone was not sufficient to assign a threatened category under B1 or B2. For each ecoregion meeting a spatial threshold, regional experts evaluated the additional Criterion B requirements by documenting observed or inferred continuing declines or ongoing threats likely to cause continuing declines, including ocean warming, pollution, coastal development, and overfishing. The final Criterion B status therefore integrated restricted geographic distribution with evidence of processes that can contribute to ecosystem collapse.

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 environmental degradation through changes in the abiotic conditions that support ecosystem functioning and persistence, including alterations in disturbance regimes such as floods, fires, storms, and marine heatwaves. Under this criterion, the magnitude, spatial extent, and temporal scale of abiotic degradation are evaluated in relation to their potential to drive ecosystem collapse. For coral reefs, ocean warming and increasingly frequent marine heatwaves represent a major threat because prolonged thermal stress can cause widespread bleaching and mass mortality (Hughes et al., 2017). Increasing thermal stress alters the disturbance regime under which reef-building corals establish, survive, and recover, increasing the probability of large-scale mortality (Elma et al., 2023; Mudge & Bruno, 2023). Repeated mortality can reduce coral abundance, structural complexity, and carbonate accretion (Williams et al., 2019; Williams & Graham, 2019), while recurrent bleaching can reduce reproductive output and increase susceptibility to disease (Briggs et al., 2024; Croquer & Weil, 2009; Levitan et al., 2014). As intervals between severe heatwaves shorten,

opportunities for recovery decline, increasing the risk of progressive degradation and ecosystem collapse (Emslie et al., 2024; Hughes et al., 2018). We therefore assessed changes in thermal-stress regimes associated with severe marine heatwaves to quantify current and projected degradation of the thermal environment supporting coral reef ecosystems in the ETP.

Indicator selection

To assess the likelihood of recurrent marine heatwaves contributing to ecosystem collapse at regional scales, we evaluated two 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 progressively impair coral condition, growth, and reproduction. As bleaching events become more frequent, recovery intervals shorten, limiting recovery between successive disturbances and driving cumulative ecosystem degradation. The second is an acute (pulse) pathway, characterized by abrupt ecosystem degradation caused by a small number of extreme heat-stress events over a short period. Such events may cause widespread mortality across coral taxa, including relatively stress-tolerant taxa, potentially resulting in rapid loss of coral dominance and progression towards ecosystem collapse. We assessed relative changes in thermal-disturbance regimes for two assessment periods: the past 50 years (1975–2025) under sub-criterion C1 and the next 50 years (2026–2075) under sub-criterion C2. For the chronic pathway, we quantified the recurrence of severe bleaching events over 30-year periods using their average return interval, defined as the mean number of years between successive events. For the pulse pathway, we quantified the frequency of severe coral-mortality events occurring within a 5-year window.

Using DHW as a proxy for bleaching events

For both pathways, Degree Heating Weeks (DHW), which quantify accumulated heat stress over a rolling 12-week period, were used to approximate the occurrence of severe bleaching and mortality events (Liu et al., 2014). Although historical observations of coral bleaching are available (Donner et al., 2017; Eakin et al., 2026; van Woesik & Kratochwill, 2022), their spatial and temporal coverage is insufficiently consistent for a standardized regional assessment. DHW data have global coverage from 1985 onwards and are also available from future climate projections (Mellin et al., 2024; Skirving et al., 2019). DHW is also strongly associated with bleaching responses across coral reef regions (Heron et al., 2016; Liu et al., 2006; Sully et al., 2019).

DHW values of approximately 4°C-weeks or higher are generally associated with the onset of widespread bleaching, whereas values of approximately 8°C-weeks or higher have historically been

associated with severe bleaching and increased risk of coral mortality (Kayanne, 2017; Liu et al., 2006; Skirving et al., 2019). These thresholds underpin NOAA Coral Reef Watch alert levels and DHW-based assessments of bleaching risk under climate change (Beyer et al., 2018; Mason et al., 2025; Mellin et al., 2024; Obura et al., 2022). Although DHW does not fully capture variation in bleaching severity at fine spatial or temporal scales, it provides a robust, scalable, and comparable indicator of regional changes in thermal disturbance regimes

Data

Sub-criterion C1 was assessed using satellite-derived DHW data from NOAA Coral Reef Watch at a spatial resolution of 5 km (Liu et al., 2014). The standard RLE assessment period for C1 is 50 years, corresponding to 1975–2025. However, satellite DHW data were available only from 1985. To extend the analysis to the full C1 assessment period, thermal-stress conditions during 1975–1984 were approximated using the earliest available decade of the satellite record (1985–1995). This extrapolation assumes that thermal-stress regimes during these periods were broadly comparable and was necessary because no equivalent spatially continuous DHW product exists before 1985. The assumption is consistent with the subsequent emergence of widespread mass-bleaching events and the marked intensification of ocean warming from the mid-1990s onwards (Hoegh-Guldberg, 1999; Cheng et al., 2017, 2023; Heron et al., 2016; Merchant et al., 2025). Thus, 1985–1995 was used as the closest available baseline for approximating thermal-stress conditions during 1975–1984 in the ETP.

DHW values were spatially attributed to the mapped reef distribution. Only DHW pixels located within 50 km of the mapped coral reef extent were retained, and DHW values were spatially interpolated to reef pixels. Sub-criterion C2 was assessed using modeled projections of daily DHW for 1985–2100 from Mellin et al. (2024). Projections were available for three Shared Socioeconomic Pathway (SSP) scenarios: SSP2-4.5, SSP3-7.0, and SSP5-8.5. Projections corresponding to SSP1-1.9 were not available in the dataset. All three available pathways were assessed to evaluate the sensitivity of future ecosystem risk to alternative emissions trajectories, although SSP2-4.5 and SSP3-7.0 were treated as the primary scenarios. SSP5-8.5 was retained as a high-emissions scenario.

For both sub criteria, daily DHW values were summarized for each reef pixel by first calculating monthly maxima and then extracting the maximum value within each local thermal-stress season. Monthly maxima were calculated first, after which the highest value recorded during each local summer season was extracted. This produced a time series of seasonal maximum DHW values for every reef pixel across the historical and projected assessment periods.

Thresholds

To convert seasonal maximum DHW values into disturbance-event time series, ecoregion-specific DHW thresholds were applied to classify each year as an event (1) or not (0). Separate thresholds were defined for the chronic and pulse pathways to reflect differences in the severity of the associated ecological responses. For the chronic pathway, a severe bleaching event was defined as widespread bleaching affecting more than 50% of coral colonies, potentially accompanied by substantial mortality of thermally sensitive taxa but not widespread mortality across the coral assemblage. For the pulse pathway, a severe mortality event was defined as an extreme thermal-stress event that causes more than 50% mortality across the coral assemblages, including relatively stress-tolerant species. Applying these thresholds produced two binary event time series for each reef pixel, used in the chronic and pulse analyses.

Ecoregion-specific thresholds were calibrated by matching documented observations of widespread bleaching and mortality with the corresponding DHW values. Earlier events were used to characterize thermal sensitivity near the beginning of the historical period, whereas observations from recent events, particularly 2015–2025, informed current thresholds. Thresholds were allowed to vary through time because comparable ecological responses may occur at different DHW levels as coral assemblages change through species turnover, selective loss of thermally sensitive taxa, acclimatization, or adaptation (Hoegh-Guldberg, 1999; Heron et al., 2016; Pratchett et al., 2013; Sully et al., 2019). Where recent observations indicated comparable responses only at higher thermal stress, thresholds were increased accordingly. For C2, plausible threshold ranges were used to represent uncertainty in future thermal sensitivity, including potential community filtering, acclimatization, and adaptation. All thresholds were reviewed using regional expert knowledge, and two plausible DHW values were evaluated for each pathway where uncertainty could not be resolved.

In the Gulf of California, widespread bleaching and mortality associated with the 1998 event supported initial thresholds of 4 DHW for both pathways. Observations from 2006 supported thresholds of 6 DHW for widespread bleaching and 8 DHW for severe mortality. More recent responses supported current thresholds of 8 DHW for widespread bleaching and 12 DHW for severe mortality. For C2, ranges of 8–12 DHW were evaluated for widespread bleaching and 12–14 DHW for severe mortality, representing lower and higher levels of future thermal adaptation or acclimation. In Revillagigedo Island (for bleaching) an 8 DHW threshold was used for the period between 1985 and 2016, a threshold of 8-12 DHW was used for the period between 2017 and 2025, and a threshold of 12-14 DHW was used for the future calculations. In Revillagigedo Island (for mortality) an 8-10

DHW threshold was used for the period between 1985 and 2016, a threshold of 8-12 DHW was used for the period between 2017 and 2025, and a threshold of 12-14 DHW was used for the future calculations. In the Mesoamerican Pacific, the 1998 event supported initial thresholds of 4 DHW for both pathways. More recent observations retained 4 DHW as the widespread-bleaching threshold but a higher severe-mortality threshold of 8 DHW by 2025. For C2, ranges of 4–8 DHW were evaluated for widespread bleaching and 8–12 DHW for severe mortality. In Nicoya, the 1998 event supported initial thresholds of 4 DHW for both pathways. Observations from 2016 supported thresholds of 6 DHW for widespread bleaching and 8 DHW for severe mortality. Recent observations supporting a current bleaching threshold of approximately 6 DHW, with severe mortality occurring within a plausible range of 8–12 DHW. For C2, ranges of 6–8 DHW were evaluated for widespread bleaching and 10–12 DHW for severe mortality. In Panama Bight, observations from 1998 supported thresholds of 4 DHW for widespread bleaching and 8 DHW for severe mortality. Recent observations retained a bleaching threshold of approximately 4 DHW, while the severe-mortality threshold was represented by a range of 8–12 DHW. For C2, ranges of 4–8 DHW were evaluated for widespread bleaching and 8–12 DHW for severe mortality. In the Oceanic Islands Corridor, the 1998 event supported initial thresholds of 4 DHW for both pathways. More recent observations supported current thresholds of 8 DHW for widespread bleaching and 12 DHW for severe mortality. For C2, ranges of 8–12 DHW were evaluated for widespread bleaching and 12–14 DHW for severe mortality. In Guayaquil (for bleaching) an 4-8 DHW threshold was used for the period between 1985 and 1998, a threshold of 8-12 DHW was used for the period between 1999 and 2016, a threshold of 12-16 DHW was used for the period between 2017 and 2025, and a threshold of 16-18 DHW was used for the future calculations. In Guayaquil (for mortality) an 4-8 DHW threshold was used for the period between 1985 and 1998, a threshold of 8-12 DHW was used for the period between 1999 and 2016, a threshold of 16 DHW was used for the period between 2017 and 2025, and a threshold of 16-18 DHW was used for the future calculations.

Table 10. Ecoregional DHW thresholds representing thermal stress levels resulting in widespread bleaching for the chronic pathway. Thresholds can be time-varying to represent changing coral responses and increased warming.

Ecoregion	C1 – observed: Timeframe	C1 – Widespread bleaching (DHW range)	C2 – predicted: Timeframe	C2 – Widespread bleaching (DHW range)
Gulf of California	1985-1998	4	2026-2100	8–12
	1999-2006	6		
	2007-2025	8		
Revillagigedo Islands	1985-2016	8	2026-2100	12-14
	2017-2025	8-12		
Clipperton Atoll	1985-2025	4-5	2026-2100	6-8

Ecoregion	C1 – observed: Timeframe	C1 – Widespread bleaching (DHW range)	C2 – predicted: Timeframe	C2 – Widespread bleaching (DHW range)
Mesoamerican Pacific	1985-1998	4	2026–2100	4–8
	1999-2025	4-5		
Nicoya	1985-1998	4	2026–2100	6–8
	1999-2016	6		
	2017-2025	6		
Oceanic Islands Corridor	1985-1998	4	2026–2100	8–12
	1999-2025	8		
Panama Bight	1985-1998	4	2026–2100	4–8
	1999-2025	4		
Guayaquil	1985-1998	4-8	2026–2100	16-18
	1999-2016	8-12		
	2017-2025	12-16		
Eastern Galapagos Islands	1985-1998	4	2026-2100	8-12
	1999-2025	8		
Western Galapagos Islands	Not estimated	—	Not estimated	—

Table 11. Ecoregional DHW thresholds representing thermal stress levels that result in severe mortality for the pulse pathway. Thresholds can be time-varying to represent changing coral responses and increased warming.

Ecoregion	C1 – observed: Timeframe	C1 – Severe mortality (DHW range)	C2 – predicted: Timeframe	C2 – Severe mortality (DHW range)
Gulf of California	1985-1998	4	2026–2100	12–14
	1999-2006	8		
	2007-2025	12		
Revillagigedo Islands	1985-2016	8-10	2026-2100	12-14
	2017-2025	8-12		
Clipperton Atoll	1985-2025	4	2026-2100	6-8
Mesoamerican Pacific	1985-1998	4	2026–2100	8–12
	1999-2025	6-8		
Nicoya	1985-1998	4	2026–2100	10–12
	1999-2016	8		
	2017-2025	8–12		
Oceanic Islands Corridor	1985-1998	4	2026–2100	12–14
	1999-2025	12		
Panama Bight	1985-1998	8	2026–2100	8–12
	1999-2025	8–12		
Guayaquil	1985-1998	8	2026–2100	16-18
	1999-2016	12		
	2017-2025	16		
Eastern Galapagos Islands	1985-1998	4	2026-2100	8-12
	1999-2016	8		
	2017-2025	8		
Western Galapagos Islands	Not estimated	—	Not estimated	—

Sufficient paired bleaching or mortality observations and corresponding DHW data were not available to establish defensible ecoregion-specific thresholds for Clipperton and Revillagigedo Islands. Criterion C was therefore not assessed for these ecoregions using the regional-threshold approach. The absence of a Criterion C assessment did not determine their overall RLE status, which was evaluated across all applicable criteria.

Calculation of decline and risk

Current values

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

Relative severity of decline (%) = (current conditions – initial conditions) / (collapse threshold – initial conditions) × 100

The **chronic pathway** was assessed using the average return interval of severe bleaching events over a 30-year period (DeCarlo & Whitaker, 2025; Hughes et al., 2018). The return interval is an ecologically meaningful indicator because recovery from severe disturbance can require 10–15 years for fast-growing coral species and considerably longer to restore the full complement of coral life histories and morphologies (Gilmour et al., 2013; Robinson et al., 2019). As bleaching events become more frequent, shorter intervals between disturbances can constrain recovery, promote cumulative coral loss, and increase the likelihood of ecosystem-level collapse (Eakin et al., 2026, p. 201; Hughes et al., 2018; Pratchett et al., 2021). In the ETP, return intervals were estimated by fitting a binomial logistic regression to the binary bleaching-event time series for each reef pixel. The probability of a severe bleaching event each year was modeled as a function of time (DeCarlo & Whitaker, 2025). This approach generated a continuous estimate of annual event probability, while reducing sensitivity to interannual variability and characterizing the underlying trajectory of the disturbance regime. Modeled annual probabilities were summed across all possible 30-year windows within the assessment periods for C1 (1985/1986–2025) and C2 (2026–2075) to estimate the expected number of severe bleaching events in each window. For each window, the return interval was calculated as 30 years divided by the expected number of events. The maximum level of degradation was represented by the shortest return interval among all 30-year windows, indicating the greatest recurrence of severe bleaching. For C1, the model was fitted using observed DHW data from 1985 to

2025, whereas for C2, it was fitted using projected DHW data from 1985 to 2100 and evaluated over 2026–2075.

For the **pulse pathway**, the maximum level of degradation was assessed using a 5-year moving window across the C1 and C2 assessment periods for each reef pixel. The number of severe mortality events within each window was counted, and the maximum event count across all windows was retained. This value represented the greatest observed or projected clustering of extreme events. Unlike the smoothed chronic metric, this approach preserved short-term temporal variability and captured clusters of extreme events characteristic of the acute collapse pathway.

Initial values

To calculate relative severity of decline, initial values representing the baseline disturbance regime were established separately for C1 and C2.

For the **chronic pathway under C1**, the initial condition represented a historical disturbance regime in which severe bleaching occurred no more than once every 10–15 years, equivalent to approximately two to three events per 30 years. Such recurrence intervals were considered sufficient to allow substantial coral recovery between successive disturbances (Baker et al., 2008; Gilmour et al., 2013; Graham et al., 2011; Hughes et al., 2018; Robinson et al., 2019). For the **chronic pathway under C2**, the initial condition was estimated over the 30-year period immediately preceding the projected assessment period (1996-2025), using the same probabilistic framework as for the projected DHW time series. For the **pulse pathway under C1**, the initial condition was defined as the maximum number of severe mortality events occurring within any 5-year window at the beginning of the satellite time series (approximately 1985/1986–1990/1991). For the **pulse pathway under C2**, the initial condition was the maximum number of severe mortality events occurring within any 5-year window during the decade immediately preceding 2026 (2016–2025).

Collapse thresholds

To calculate relative severity of abiotic degradation, we defined the collapse threshold as the thermal-disturbance regime expected to result in a high likelihood of transition to the collapsed ecosystem state. The collapsed state was operationally defined as the near-complete loss of hard corals, corresponding to **<5%** hard coral cover. The same disturbance thresholds were applied to C1 and C2 to maintain a consistent endpoint against which historical and projected abiotic degradation could be compared.

For the **chronic pathway**, the collapse threshold was defined as severe bleaching events occurring, on average, once every three years over a 30-year period, equivalent to approximately 10 events per 30-year window (DeCarlo & Whitaker, 2025). At this frequency, intervals between disturbances are expected to be too short for substantial coral recovery, allowing recurrent bleaching and associated mortality to accumulate and drive progressive ecosystem degradation (Emslie et al., 2024; Hughes et al., 2018). To evaluate uncertainty in this collapse threshold, a less frequent disturbance regime of one event every five years, equivalent to approximately six events per 30-year window, was also evaluated because 5-year recovery intervals may still be insufficient for complete reef recovery and can generate cumulative degradation over successive disturbances (Hughes et al., 2018). Annual severe bleaching has also been used as an endpoint in projections of future reef exposure (De Clippele et al., 2023; van Hooidonk et al., 2016; Zeng et al., 2025). However, we did not use annual bleaching as the primary collapse threshold because it represents a more extreme disturbance regime than may be necessary to drive ecosystem collapse (Bland et al., 2017; Obura et al., 2022).

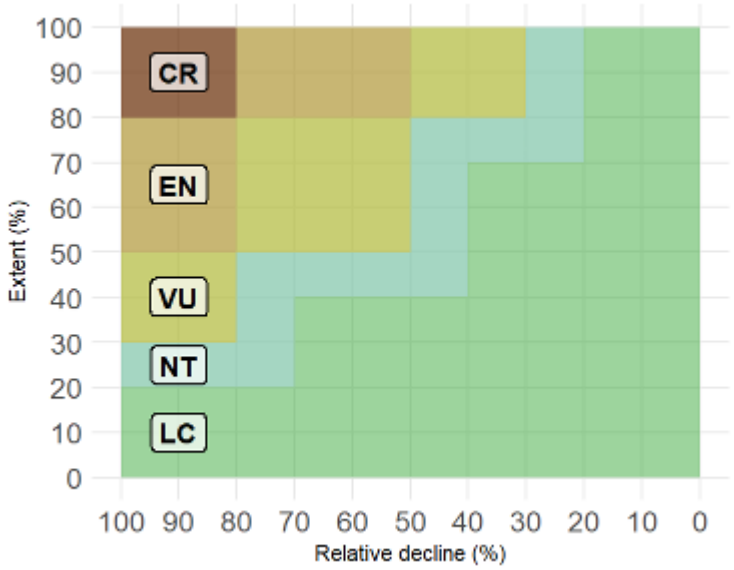
For the **pulse pathway**, the collapse threshold was defined as two to three severe mortality events occurring within any 5-year window. This threshold represents a substantially greater concentration of acute disturbance than the two severe bleaching events per decade previously used in RLE assessments of the Western Indian Ocean and Mesoamerican Reef (Bland et al., 2017; Obura et al., 2022). Several reefs, including those of the Great Barrier Reef and Little Cayman, experienced two or more severe bleaching events within a decade between 2015/2016 and 2025 without transitioning to a collapsed state (Emslie et al., 2024; Henley et al., 2024; Pratchett et al., 2021). These observations indicate that repeated bleaching alone does not necessarily result in rapid ecosystem collapse and support the use of a more severe endpoint for the pulse pathway. This threshold was therefore used as an operational representation of an acute disturbance regime with a high likelihood of driving reefs towards a collapsed state.

Risk status assignment

To assign risk status under sub-criteria C1 and C2 for each ecoregion, the relative severity of abiotic degradation was interpreted together with the proportion of reef extent affected, using the RLE severity–extent matrix. The relative extent of degradation was estimated as the cumulative proportion of mapped reef area within each ecoregion experiencing relative severity values of ≥20%, ≥30%, ≥50%, ≥70%, ≥80%, and 100%.

The chronic and pulse pathways were evaluated independently. Where the two pathways produced different risk categories, results were compared according to the strength of evidence supporting each pathway; where neither pathway was clearly better supported, the range of plausible risk categories across both pathways was retained. Uncertainty associated with DHW thresholds, collapse thresholds, and initial conditions was propagated through the assessment by repeating the analysis across all plausible combinations of these parameters, producing a distribution of relative-severity estimates and corresponding risk categories for each ecoregion.

For C1, the final reported risk status was derived from the mean relative severity across the evaluated parameter combinations and its corresponding extent of degradation. For C2, the primary reported status was based on SSP2-4.5 and the higher plausible future DHW thresholds, representing a comparatively optimistic scenario in which coral assemblages exhibit increased thermal tolerance through processes such as community filtering, acclimatization, or adaptation. Results from the remaining parameter combinations and emissions scenarios were retained to characterize the range of plausible future outcomes.



Criterion D: Disruption of Biotic Processes and Interactions

Criterion D was evaluated to identify degradation of biotic components, processes, and interactions that underpin ecosystem identity and function. This includes declines in characteristic species, shifts in community structure, and loss of ecological functions necessary to maintain ecosystem identity. We evaluated multiple complementary components of reef structure and trophic functioning to

capture different pathways through which biotic degradation may increase the risk of ecosystem collapse. This assessment evaluated degradation over the past 50 years (sub-criterion D1) by estimating the relative severity and spatial extent of change in each biotic indicator relative to its reference and collapse states.

Indicator selection

In the ETP, four key biotic components were assessed using data from reef monitoring datasets shared by researchers of the ETP Node of the GCRMN. These datasets included point-intercept transects and photoquadrats for benthic cover and visual censuses within belt-transects for reef fishes. These components represented complementary dimensions of reef structure and trophic functioning:

- **Hard corals**, as foundation taxa and ecosystem engineers that generate three-dimensional habitat and contribute to reef-framework development and carbonate accretion;
- **Macroalgae and turf algae**, as major benthic competitors of corals for space and other limiting resources;
- **Herbivory**, representing top-down control of algal biomass and an important process influencing coral–algal interactions; and
- **Piscivory**, representing the upper level of the trophic structure of reef-fish assemblages and predator-mediated trophic interactions.

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

Hard coral cover was selected as the indicator of coral dominance because it provides a direct measure of the abundance of the principal habitat-forming organisms and is widely available across long-term reef-monitoring programs. Relative algal cover (or Algae-coral cover ratio) was used to represent the balance between algal and coral dominance, rather than algal cover alone, thereby accounting for simultaneous changes in both benthic components. Algae included turf and fleshy macroalgae to account for inconsistencies in taxonomic resolution among monitoring programmes. Relative algal cover was calculated as:

Relative algal cover = algal cover / (algal cover + hard coral cover)

To estimate fish biomass associated with key trophic functions, we selected species from genera recognized as important herbivores or piscivores in the ETP. Herbivorous fishes included species belonging to the genera *Acanthurus, Prionurus, Scarus, Nicholsina, Kyphosus, Girella,* and *Microspathodon*, whereas piscivorous fishes included species of *Epinephelus, Mycteroperca, Cephalopholis, Dermatolepis, Lutjanus,* and *Cirrhitus*. Species composition varied among ecoregions according to regional occurrence and their documented trophic roles. These taxa represented important components of the herbivorous and piscivorous fish assemblages captured by the available monitoring datasets, with several of the selected species also being particularly susceptible to fishing pressure.

Additional indicators could not be included because of insufficient spatial or temporal coverage. Large predators, such as sharks, were excluded because many are highly mobile, and underwater visual censuses can underrepresent. Moreover, when transect areas are small relative to the movements and home ranges of these species, occasional encounters can disproportionately influence biomass estimates, potentially resulting in substantial overestimation at the site level. Mobile invertebrates (e.g., sea urchins and sea stars; Ramírez-Ortiz et al. 2017), which are monitored in some ETP sites, were also excluded because available data were insufficient to establish consistent regional baselines. These components should be incorporated into future assessments as spatial and temporal coverage improves.

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 with a historical baseline, representing its approximate condition 50 years ago, and a hypothetical collapse threshold.

Current values

Current values for each indicator were calculated at the site level using monitoring data available from 2020–2025. For Criterion D, a *site* was defined as a place where transects, quadrats, photoquadrats, or other sampling units were aggregated. Coordinates located within 500 m of one another were considered part of the same monitoring site. Where multiple observations were available for a site during 2020–2025, values were averaged across all surveys to obtain a single current value for each indicator.

Table 12. Mean current value and measures of variation for each indicator in each ecoregion (n = number of monitoring sites). Hard coral cover is expressed as percentage cover, the algae-to-coral ratio is dimensionless, and fish biomass is expressed in g/m^2.

Ecoregion	Indicator	n	Mean	Std. dev	Min value	Max value
Gulf of California	Hard coral cover	22	25.59	22.96	0.17	97.0
	Algae-to -coral ratio	22	0.57	0.32	0.38	0.81
	herbivorous fish biomass	14	15.13	20.19	0.00	171.46
	piscivorous fish biomass	14	5.37	7.58	0.00	72.56
Revillagigedos	Hard coral cover	DD	DD	DD	DD	DD
	Algae-to -coral ratio	DD	DD	DD	DD	DD
	herbivorous fish biomass	2	4.29	0.76	1.83	401.26
	piscivorous fish biomass	2	0.36	0.40	0.00	153.90
Clipperton Atoll	Hard coral cover	DD	DD	DD	DD	DD
	Algae-to -coral ratio	DD	DD	DD	DD	DD
	herbivorous fish biomass	DD	DD	DD	DD	DD
	piscivorous fish biomass	DD	DD	DD	DD	DD
Mesoamerican Pacific	Hard coral cover	6	21.54	18.22	0.08	94.60
	Algae-to -coral ratio	19	0.93	0.13	0.15	1.00
	herbivorous fish biomass	9	70.42	151.74	0.00	224.73
	piscivorous fish biomass	9	7.38	6	0.00	23.21
Nicoya	Hard coral cover	1	34.09	0	0.20	91.04
	Algae-to -coral ratio	1	0.72	0	0.49	0.88
	herbivorous fish biomass	1	6.19	0	0.00	302.48
	piscivorous fish biomass	1	0.60	0	0.00	13.90
Oceanic Islands Corridor	Hard coral cover	5	18.87	6.04	0.19	100
	Algae-to -coral ratio	5	0.49	0.22	0.23	0.811
	herbivorous fish biomass	7	8.89	7.47	0.09	239.13
	piscivorous fish biomass	7	4.13	5.27	0.00	155.38
Panama Bight	Hard coral cover	4	66.54	16.80	2.60	96.94
	Algae-to -coral ratio	4	0.09	0.18	0.002	0.06
	herbivorous fish biomass	2	4.32	2.68	1.53	42.70
	piscivorous fish biomass	2	4.63	6.55	0.00	12.19
Western Galapagos Islands	Hard coral cover	NE	NE	NE	NE	NE
	Algae-to -coral ratio	NE	NE	NE	NE	NE
	herbivorous fish biomass	NE	NE	NE	NE	NE
	piscivorous fish biomass	NE	NE	NE	NE	NE
Eastern Galapagos Islands	Hard coral cover	3	5.43	5.27	0.12	32.95
	Algae-to -coral ratio	3	0.58	0.27	0.40	0.95
	herbivorous fish biomass	4	20.14	20.55	0.00	307.43
	piscivorous fish biomass	4	5.21	2.27	0.00	93.11
Guayaquil	Hard coral cover	DD	DD	DD	1.89	92.59
	Algae-to -coral ratio	DD	DD	DD	0.28	0.60
	herbivorous fish biomass	1	3.56	0	0.00	185.72
	piscivorous fish biomass	1	0.30	0	0.00	46.94

Initial values

A reference state representing the condition of each indicator approximately 50 years ago, circa 1975, should be established to quantify long-term change according to the IUCN guidelines. However, monitoring data from this period were unavailable, as consistent and standardized reef monitoring within the regional dataset began in 1994. Initial conditions were therefore reconstructed primarily from long-term regional monitoring data. Rather than assigning a single baseline value per ecoregion, initial conditions were represented as distributions characterized by the mean, standard deviation, minimum, and maximum, allowing spatial variability and uncertainty in historical ecosystem condition to be incorporated into the assessment. The first step was to determine, for each ecoregion, whether reefs were likely to have been in relatively good condition around the mid-1970s or had already experienced substantial local degradation. This assessment, made separately for each indicator, then informed the most appropriate approach for reconstructing initial conditions.

Method 1 – Literature-derived benthic baselines

Benthic baselines should be derived from early reef surveys conducted during the 1980s and 1990s. However, this was not possible for the ETP because benthic monitoring data prior to 1994 were unavailable. Although a few published studies conducted between 1975 and 1990 were available (Dana, 1975; Glynn et al 1972), they did not evaluate the entire time window of interest (1970). These studies allowed us to use the earliest coral cover registered to inform the baseline selection for Panama Bight. However, as these studies were too small-scale we could not rely on them to inform baseline calculations for other ecoregions.

Method 2 – Maximum-value approach

Long-term monitoring datasets were used to reconstruct baseline benthic conditions. To this aim, only sites where at least one sampling event was spaced from the first by a span of at least 6 years and reached their maximum value (e.g., coral cover) no later than 2019 were considered because the current period starts in 2020. This allowed us to identify sites with time series long enough to capture relatively favorable conditions throughout the monitoring period, which could provide a proxy for the best plausible historical condition within each ecoregion. Specifically, for hard corals, the maximum cover recorded throughout the monitoring time series of each qualifying site was extracted. The distribution of these site-level coral cover maxima per ecoregion was then aggregated to estimate the baseline mean, standard deviation, minimum, and maximum. A similar approach was applied to set baselines for relative algal cover. In this case, we identified sites (spanning at least six

years of monitoring data) that reached their minimum relative algal cover value no later than 2019. Where no data existed, we assigned DD/NE to that ecoregion as no baseline could be determined. Pre-1994 baselines were instead defined through consultation with experts from the respective ecoregions within the ETP Node of the GCRMN. These experts were asked to evaluate the ecological plausibility of the baseline estimates generated using the maximum-value approach (see **Method 2**). The value resulting from this second method was retained for all ecoregions except Panama Bight, because the resulting values were higher and did not match those reported in Glynn (1982). In this case, coral cover from Guayaquil was used, with a standard deviation of 20, so that it would match the initial reported values in Glynn (1982).

Table 13. Mean initial values and measures of variation for hard coral cover in each ecoregion (n = 46 of sites).

Ecoregion	Mean	Std. dev	Min value	Max value	n
Gulf of California	45.72	27.11	14	97	10
Revillagigedo Islands	DD	DD	DD	DD	DD
Clipperton Atoll	DD	DD	DD	DD	DD
Mesoamerican Pacific	52.76	31.21	10.49	94.6	10
Nicoya	28.39	16.28	11.27	47.41	7
Oceanic Islands Corridor	44.22	28.84	20.39	100	10
Panama Bight	55.56	20	35.56	75.56	3
Western Galapagos Islands	NE	NE	NE	NE	NE
Eastern Galapagos Islands	10.64	3.71	7.41	14.80	4
Guayaquil	55.56	52.37	18.51	92.59	2

Table 14. Mean initial values and measures of variation for the algae-to-coral cover ratio in each ecoregion (n = 57 sites).

Ecoregion	Mean	Std. dev	Min value	Max value	n
Gulf of California	0.57	0.22	0.12	0.82	10
Revillagigedo Islands	DD	DD	DD	DD	DD
Clipperton Atoll	DD	DD	DD	DD	DD
Mesoamerican Pacific	0.61	0.34	0.02	1	19
Nicoya	0.66	0.15	0.44	0.83	7
Oceanic Islands Corridor	0.45	0.23	0.03	0.76	12
Panama Bight	0	0	0	0	3
Western Galapagos Islands	NE	NE	NE	NE	NE
Eastern Galapagos Islands	0.58	0.17	0.32	0.69	4
Guayaquil	0.24	0.34	0	0.49	2

Fish baseline estimation

Baseline values for fish indicators were estimated using a space-for-time substitution approach. Fishing pressure was considered to have been lower in the 1970s, particularly for exploited fish groups, and their biomass was therefore expected to have been higher than under current conditions. Because comparable fish surveys from the 1970s were unavailable for the ETP, contemporary sites experiencing relatively low fishing pressure were used to approximate historical conditions. Contemporary fish assemblages at relatively well-protected and ecologically comparable reference sites were consequently used as proxies for pre-1970 conditions. Potential reference sites and sampling years were ranked according to hard coral cover, duration of protection, and IUCN protected-area category. These criteria were used to identify sites and sampling years most likely to represent relatively favorable fish-community conditions (i.e. typical biomass of unexploited reefs) while maintaining ecological comparability with the assessed reefs. Data from the selected reference sites and years were aggregated within each ecoregion to reconstruct baseline distributions for herbivorous and piscivorous fish biomass, including the mean, standard deviation, minimum, and maximum.

After calculating initial fish biomass per ecoregion, the results did not adequately represent potential initial values for three ecoregions (i.e., Eastern Galapagos Islands, Revillagigedo Islands and the Gulf of California). To address this, we opted for assigning baseline values from other ecoregions with comparable conditions. For Eastern Galapagos Islands, the herbivore biomass value was too high, so it was replaced with the Oceanic Islands value. Similarly, piscivore biomass in Revillagigedo was too low and was replaced with the Oceanic Islands Corridor value. In the case of the Gulf of California, piscivore biomass was also too low, so it was replaced with the Mesoamerican Pacific value.

The earliest studies of fish communities in the ETP did not measure fish biomass. Consequently, we relied on expert knowledge to validate that the biomass levels at our reference sites were plausible for ~1975.

Table 15. Mean initial values and measures of variation calculated from reference MPA sites for herbivorous and piscivorous fish biomass in each ecoregion (n = number of sites; biomass in g m^{-2}).

Ecoregion	Indicator	Mean	Std. dev	Min value	Max value	n
Gulf of California	Herbivorous fish biomass	3	16.66	0	19.66	2
	Piscivorous fish biomass	11.23	11.36	0	22.62	1
Revillagigedo Islands	Herbivorous fish biomass	4.29	14.3	0	18.6	2
	Piscivorous fish biomass	0.62	1.01	0	1.66	1

Ecoregion	Indicator	Mean	Std. dev	Min value	Max value	n
Clipperton Atoll	Herbivorous fish biomass	DD	DD	DD	DD	DD
	Piscivorous fish biomass	DD	DD	DD	DD	DD
Mesoamerican Pacific	Herbivorous fish biomass	3.76	6.88	06	10.65	1
	Piscivorous fish biomass	11.26	11.36	0	22.62	1
Nicoya	Herbivorous fish biomass	4.67	16.5	0	21.23	3
	Piscivorous fish biomass	0.87	2.59	0.00	3.47	4
Oceanic Islands Corridor	Herbivorous fish biomass	8.97	26.13	0	35.11	1
	Piscivorous fish biomass	0.65	1.01	0	1.66	1
Panama Bight	Herbivorous fish biomass	4.95	13.22	0	18.17	1
	Piscivorous fish biomass	3.09	11.37	0.00	14.46	1
Western Galapagos Islands	Herbivorous fish biomass	NE	NE	NE	NE	NE
	Piscivorous fish biomass	NE	NE	NE	NE	NE
Eastern Galapagos Islands	Herbivorous fish biomass	8.97	26.13	0	35.10	1
	Piscivorous fish biomass	2.7	6	0	8.8	3
Guayaquil	Herbivorous fish biomass	1.44	6.18	0	7.62	2
	Piscivorous fish biomass	0.85	1.87	0	2.72	2

Collapse thresholds

Collapse thresholds were defined per indicator to represent the levels beyond which the characteristic structure or ecological function is lost, leading to fundamental ecosystem transformations. For benthic indicators, thresholds represented a transformation away from coral-dominance towards persistent algae-dominance. For hard coral cover, a threshold of 5% was applied, representing near-complete loss of coral dominance and approaching coral functional collapse. A threshold of 0.833% was used for relative algal cover. This corresponds to algal cover being five times higher than hard coral cover and represents the establishment of algal dominance:

Relative algal cover = 5 / (5 + 1) = 0.833

For fish biomass, the thresholds represented severe depletion of herbivorous or piscivorous fish biomass and the associated erosion of their trophic function. Thresholds were based on published

evidence and expert judgment and were applied consistently across all ecoregions. Collapse thresholds for herbivorous fish were set at 10% of their baseline biomass and for piscivorous fish at 20% of their baseline biomass, following the thresholds previously applied by Obura et al. (2022) in the assessment of collapse risk for Western Indian Ocean reefs.

Calculating relative severity of decline

Relative severity of decline was calculated per indicator and site based on current values using the formula:

Relative severity of decline (%) = [(current value − initial value)/(collapse threshold − initial value)] × 100

Under this formulation, a value of 0% represents no decline relative to the estimated initial condition, while a value of 100% indicates that the collapse threshold has been reached. Uncertainty regarding initial conditions was incorporated using a resampling approach. For each ecoregion and indicator, initial conditions were represented by a distribution defined by the estimated mean, standard deviation, and observed range. Initial values were randomly sampled from the corresponding ecoregional distribution and assigned to monitoring sites.

The highest risk category was determined using the decline–extent matrix (Fig. SX), with ecosystem extent estimated as the proportion of monitoring sites exceeding relative-severity thresholds of ≥20%, ≥30%, ≥50%, ≥70%, ≥80%, and 100%. This procedure was repeated across 750 iterations, and the highest risk category obtained in each iteration was recorded. The final risk category per indicator was determined from the distribution of outcomes across all iterations. Where at least 80% of iterations produced the same category, that category was assigned as the final status. Where no category reached this level of agreement, an intermediate category or range of plausible categories was assigned to reflect uncertainty in the assessment. For example, if 50% of iterations led to the Least Concern category and 50% to the Vulnerable category, the indicator was classified as Near Threatened, representing an intermediate level of risk between these outcomes.

The analysis assumed that monitoring sites broadly represented ecosystem conditions across the corresponding ecoregion. Where spatial coverage was uneven or limited, expert judgment was used to assess whether observed patterns were representative of unsampled areas, considering the spatial distribution of relevant pressures and environmental conditions. Where the available data were

insufficient to reliably characterize ecosystem-wide patterns, the corresponding indicator or ecoregion was classified as Data Deficient.

Determining final risk class for Criterion D

The overall risk category for Criterion D per ecoregion was determined by integrating results across all available indicators using a stepwise approach, following previous coral reef RLE assessments. Indicators were evaluated sequentially according to their ecological roles and interactions:

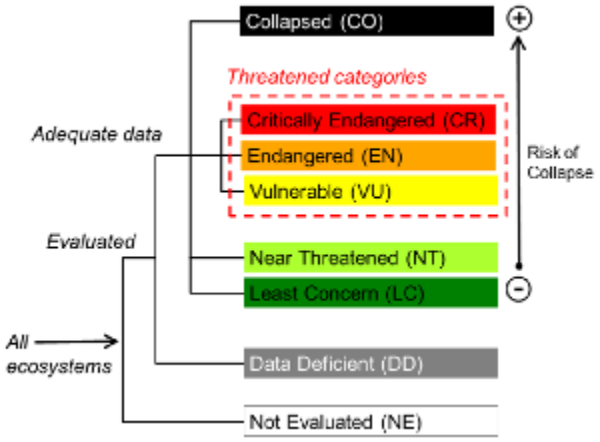
1. **Hard coral cover** — reef-building and habitat-forming component;
2. **Relative algal cover** — coral–algal dominance and benthic competitive dynamics;
3. **Herbivorous fish biomass** — top-down control of algae; and
4. **Piscivorous fish biomass** — upper trophic structure and predator-mediated interactions.

Hard coral cover provided the initial Criterion D classification because reef-building corals represent the foundational biotic component defining coral reef ecosystem identity. The remaining indicators were then incorporated sequentially. When the ecoregion was data deficient for coral cover, the ecoregion was marked as data deficient for criterion D. At each step, if the risk category of the additional indicator was more severe (closer to *collapsed*) than the cumulative category obtained from the preceding indicators, the cumulative classification was increased by one risk level. If the additional indicator was equal to or less severe (closer to Least Concern) than the cumulative category, the classification remained unchanged. This stepwise approach gave highest weight to hard corals as the primary habitat-forming component while allowing for degradation of coral–algal dynamics, herbivory, and piscivory to progressively modify the overall Criterion D risk. This approach also prevented the final classification from being disproportionately determined by any single secondary indicator while capturing the cumulative disruption of multiple biotic components and ecological processes.

Overall risk status

Once all applicable RLE criteria and sub-criteria had been assessed, the overall risk status of coral reefs within each ecoregion was determined from the most severe category assigned across the evaluated criteria. Following the precautionary principle of the RLE framework, the highest risk category was retained as the final ecosystem status. This approach recognizes that ecosystem

collapse can result from different degradation pathways and ensures that a high risk detected under any individual criterion is retained in the overall assessment.



11.3. Discussion

Regional collapse risk and ecological context

The ETP is characterized by a high overall risk of coral reef ecosystem collapse, with nine of the ten ecoregions classified as Critically Endangered and one ecoregion (Western Galapagos Islands) already collapsed since the 1980s. Across ecoregions, collapse risk was primarily associated with severe environmental degradation, particularly increasing thermal stress, although the relative contribution of other factors varied geographically. In three Critically Endangered ecoregions, severe environmental degradation was compounded by additional vulnerabilities, including reduced geographic distribution and disruption of biotic processes and interactions in Nicoya, reduced geographic distribution in the Eastern Galápagos Islands, and inherently restricted geographic distribution in Clipperton Atoll.

Risk patterns reflect the small geographic extent of coral reefs in the region, their fragmented distribution across continental margins and oceanic islands, and the interaction between naturally variable environmental conditions and increasing anthropogenic pressures. Although ETP reefs represent only a small fraction of global coral reef area, approximately 140 km^2 or 0.04% of global coral reef extent, they support distinctive coral, algal, invertebrate, and fish assemblages. These are shaped by strong environmental filtering and recurrent ENSO-driven disturbance and characterized by high endemism and restricted connectivity (Glynn & Ault 2000; Robertson & Cramer 2009; Cortés

et al. 2017; Glynn et al. 2017). This first RLE assessment therefore identifies the ETP as a region where even limited additional losses of coral cover, reef area or ecological function can have disproportionate consequences for ecosystem persistence.

Spatial, environmental and biotic dimensions of collapse risk

Our results indicate that reductions in coral reef distribution and condition over the past 50 years (Criteria A) have been an important component of collapse risk, yet unevenly distributed among ecoregions. The strongest signals of decline occur where coral-dominated states have been lost or severely reduced, particularly in Eastern and Western Galápagos Islands and the Central American ecoregions of Nicoya and Mesoamerican Pacific affected by coastal development, sedimentation, pollution, and recurrent thermal disturbance (Glynn et al. 2001; Alvarado et al. 2012, Glynn et al. 2018; Arias-Godínez et al. 2021). Coral reef loss in the ETP cannot be interpreted only as a reduction in mapped reef area. In many places, reefs may persist spatially but no longer retain the carbonate accretion or habitat-forming structure needed to function as coral reef ecosystems. This is particularly important for naturally marginal reefs, where small declines in coral abundance may rapidly shift the system towards rocky, rubble or algal-dominated states (Toth et al. 2012; Toth et al. 2017; Glynn et al. 2018). In this context, the importance of having georeferenced data on the historical distribution of coral reefs stands out, the absence of which is a major challenge for the region. Quantifying their deterioration requires knowledge of the baseline state, yet comprehensive historical records of previously degraded sites are lacking.

The restricted geographic distribution of ETP reefs (Criterion B) is a central feature of their vulnerability. In many ecoregions, reefs occupy very small reef areas. Even large ecoregions contain discontinuous coral reefs that concentrate in relatively few bays, islands or shallow environments. This increases the probability that localized disturbances, such as bleaching events, storms, sediment pulses, oil spills, vessel impacts or disease outbreaks, affect a large proportion of the ecosystem within an ecoregion. The high risk detected under Criterion B reflects a biological reality of the ETP, whereby coral reefs are naturally patchy, isolated and often located near environmental thresholds for coral growth and carbonate accretion (Glynn & Ault 2000; Toth et al. 2017; Manzello et al. 2017). This underscores the importance of mapping and protecting connectivity pathways across these discontinuous systems, as well as the need for regional or multi-country strategies for long-term monitoring and conservation.

Criterion C provides the clearest indication that future collapse risk is likely to intensify as thermal disturbance regimes change. ENSO has long structured coral reef dynamics in the ETP, with El Niño periodically exposing reefs to warm-water bleaching and mortality, and La Niña causing upwelling-associated cool, nutrient-rich, CO_2-rich and sometimes low-oxygen conditions that can constrain calcification and recovery (Glynn 1990; Glynn et al. 2001; Fiedler & Talley 2006; Manzello et al. 2017). Climate change is altering the frequency and severity of these disturbances. Recurrent marine heatwaves reduce the time available for coral recovery between events, while increasing thermal stress can push already marginal reefs closer to collapse thresholds (Hughes et al. 2017, 2018; Eakin et al. 2026). The implication is that ETP reefs are not responding to climate change from a stable baseline. Instead, warming is superimposed on a naturally dynamic oceanographic regime, where coral communities are already constrained by shallow thermoclines, variable carbonate chemistry, intermittent recruitment and strong environmental filtering (Fiedler & Lavín 2017; Glynn et al. 2017; Manzello et al. 2017). However, the potential adaptation of reef-building species was not evaluated. Incorporating community-level collapse threshold, instead of the threshold per ecoregion currently used, would allow for more detailed predictions helping to identify communities capable of persisting over time. In addition, we must improve our capabilities to continuously monitor the role of coral refugia in the persistence of coral communities in the ETP. For example, Revillagigedo Islands has the conditions to be considered a coral refuge, but monitoring of coral responses to thermal stress is limited because the warm months coincide with the hurricane season, which restricts monitoring using SCUBA diving.

Collapse risk in certain ecoregions is also defined by the disruption of biotic processes and interactions (Criterion D). Declines in hard coral cover indicate erosion of the foundation component of the ecosystem, while high relative algal cover reflects shifts in benthic dominance that can limit coral recruitment and recovery (Chadwick & Morrow 2011; Fong et al. 2017). Changes in herbivorous fish biomass suggest a weakening of top-down control on algal proliferation, whereas depletion of piscivorous fishes indicates a broader alteration of trophic structure and fishing-sensitive components of reef assemblages (Alvarado et al. 2011a, Edgar et al. 2011). These results show that reef degradation in the ETP is multidimensional. A reef may retain some coral cover but still lose herbivorous and piscivorous fish (which erodes both herbivory and piscivory), as well as suffer reductions in coral recruitment or alterations in the coral–algal dynamics. Conversely, reefs with apparently stable benthic cover may remain vulnerable if fish assemblages have been simplified by fishing pressure or if recovery processes are compromised.

Together, all four criteria indicate that collapse risk in the ETP is produced by interacting pathways rather than by a single driver. The restricted spatial distribution of coral reefs increases their exposure to localized shocks. Environmental degradation increases the probability of recurrent bleaching and mortality. Biotic disruption reduces recovery capacity. Further, local pressures, such as overfishing, illegal extraction, wastewater discharge, sedimentation, coastal development, tourism, shipping and invasive species can amplify the effects of climate extremes (Halpern et al. 2008; Alvarado et al. 2012; Barragán & Andrés 2016). Oceanic ecoregions are especially vulnerable because of their small reef area, isolation, limited recolonization potential and dependence on regional connectivity (Lessios 2008; Robertson & Cramer 2009; Dubuc et al. 2023). Continental ecoregions, by contrast, are additionally exposed to land–sea pressures, including watershed degradation, urban runoff, port development, aquaculture and fishing. These contrasts indicate that conservation strategies must be regionally coordinated but locally differentiated.

Interacting pressures and geographic differences

Our findings are consistent with previous regional syntheses highlighting that ETP reefs are naturally constrained by low coral diversity, strong environmental filtering, shallow thermoclines, low or variable aragonite saturation and recurrent ENSO disturbance (Glynn & Ault 2000; Glynn et al. 2001; Cortés et al. 2017; Glynn et al. 2017; Toth et al. 2017; Manzello et al. 2017). They also align with global evidence that coral reefs with short recovery windows, limited habitat redundancy, and high local pressure are especially vulnerable to climate-driven degradation (Hughes et al. 2017, 2018; Bland et al. 2017; Obura et al. 2022). The ETP differs from many high-diversity reef provinces because environmental marginality is central to its reef identity. Despite their high risk of collapse, ETP coral reefs have shown a remarkable capacity to persist over time. Many ETP reefs naturally occur as small, shallow, patchy or weakly accreting systems. For this reason, high risk status should not be interpreted as evidence that all reefs are uniformly degraded, but rather as evidence that, at the regional scale, coral reefs have limited capacity to absorb and cope with further disturbances.

Uncertainties and limitations of the assessment

Several uncertainties should temper the interpretation of the results presented here. First, reef mapping remains incomplete in parts of the ETP, particularly where coral communities occur within complex rocky habitats. As a result, local coral reef polygons are unavailable in several ecoregions. This meant that we relied on satellite-derived layers for some areas, which are known to potentially

over- or underestimate reef extent in this region. Improving the resolution of the regional reef extent layer is a priority for future assessments.

Second, Criteria A and D rely heavily on hard coral cover as a proxy for ecosystem condition. Although coral cover is widely used and ecologically meaningful, it does not fully capture colony size structure, recruitment, species composition, carbonate production rates or differences among major reef-building genera such as *Pocillopora*, *Porites*, *Pavona* and *Gardineroseris* (Glynn et al., 2017; Toth et al., 2017). For an improved assessment of risk according to Criteria A and D, collapse thresholds could, in future, be further refined by genus or species groups according to their thermal tolerance limits.

Third, Criterion C depends on DHW thresholds that may vary among ecoregions, coral assemblages and time periods, and bleaching records are not yet sufficiently standardized to fully resolve local thermal sensitivity or acclimatization (Heron et al., 2016; Sully et al. 2019; Mellin et al. 2024). Further, there is a significant knowledge gap regarding the amount of thermal stress in DHW that has triggered widespread coral bleaching events in the different ETP ecoregions over time. This gap limited our capacity to determine whether coral reefs have progressively become more resistant to thermal stress (i.e., requiring a higher amount of thermal stress to trigger widespread bleaching and/or mortality) over time, following repeated thermal stress events. Sparse bleaching records associated with the DHW that have caused them, leave a knowledge gap regarding the initial DHW that triggered the bleaching and mortality and how it changed in the bleaching events over time. In addition, the lack of consistency in the metrics used makes spatial and temporal comparison difficult. This leaves us with a wide range of interpretations regarding the DHW thresholds used to define the onset of bleaching and mortality events, interpretations that could be improved with a stronger theoretical basis specifically evaluating DHW thresholds for ETP regions. Lastly, Criterion D was constrained by the uneven taxonomic resolution of the benthic surveys and limited long-term data for mobile invertebrates such as sea urchins and sea stars, despite their importance for grazing, bioerosion and post-disturbance dynamics (Alvarado et al. 2017; Enochs & Glynn 2017). An improved assessment of risk under Criterion D could have been achieved if the benthic monitoring datasets distinguished algae at a higher taxonomic or functional-group resolution. Differentiating among algal groups that compete most directly with corals for space is key to identifying patterns of change over time. However, current algal monitoring in some regions is limited to broad functional groups (e.g., fleshy algae, turf algae, calcareous algae). Improving the distinction of key genera that compete for space with corals could in future allow for improvements in this context enabling the evaluation of spatial competition over time. Although key macroinvertebrates are surveyed within

many of the ETP monitoring programs, the local-scale datasets have yet to be harmonized and curated at the regional level. This lack of regional harmonization and curation limited the assessment of risk across all ecoregions according to one of the key aspects of Criterion D. Completing this work is a current priority of the ETP Node of the GCRMN.

Conservation implications and priorities for future assessment

Overall, this first RLE assessment in the ETP shows that coral reefs face a high risk of collapse across the region through the combined effects of restricted distribution, climate exposure, local anthropogenic pressures and disruption of key biotic processes. This should be read as a warning sign regarding the specific vulnerabilities of each ecoregion, not as a sentence of impending future collapse. The prominent contribution of thermal stress to collapse risk under Criterion C underscores the urgent need for rapid, deep and sustained reductions in global greenhouse gas emissions.

The key to continuing to improve our ability to predict collapse lies in our capacity to predict the trajectory of the biotic and abiotic processes that mediate it. The most urgent regional priorities are to 1) improve existing maps of the different reef types that are characteristic of the ETP, 2) track consistently the factors that may shift the outcome of spatial competition between corals and other non reef builders, 3) monitor the abundance, feeding rates, and dietary preferences of herbivorous and piscivorous fish across local- and region-scale environmental gradients, 4) further investigate the evolution of corals and their microbiome, which mediate thermal stress resistance over time. This information can refine future RLE assessments, help identify persistent coral refugia, evaluate protected-area effectiveness, and guide conservation investment. In a region where reefs are naturally small, isolated, and environmentally marginal, preventing further collapse will depend on global reductions of greenhouse gases alongside efforts to reduce local pressures while strengthening coordinated monitoring, enforcement and climate-adaptation planning across the full ETP reef network. Local conservation measures remain essential to support reef persistence and recovery, but cannot substitute for global action to limit warming.

Criterion C – Environmental Degradation: supplementary figures

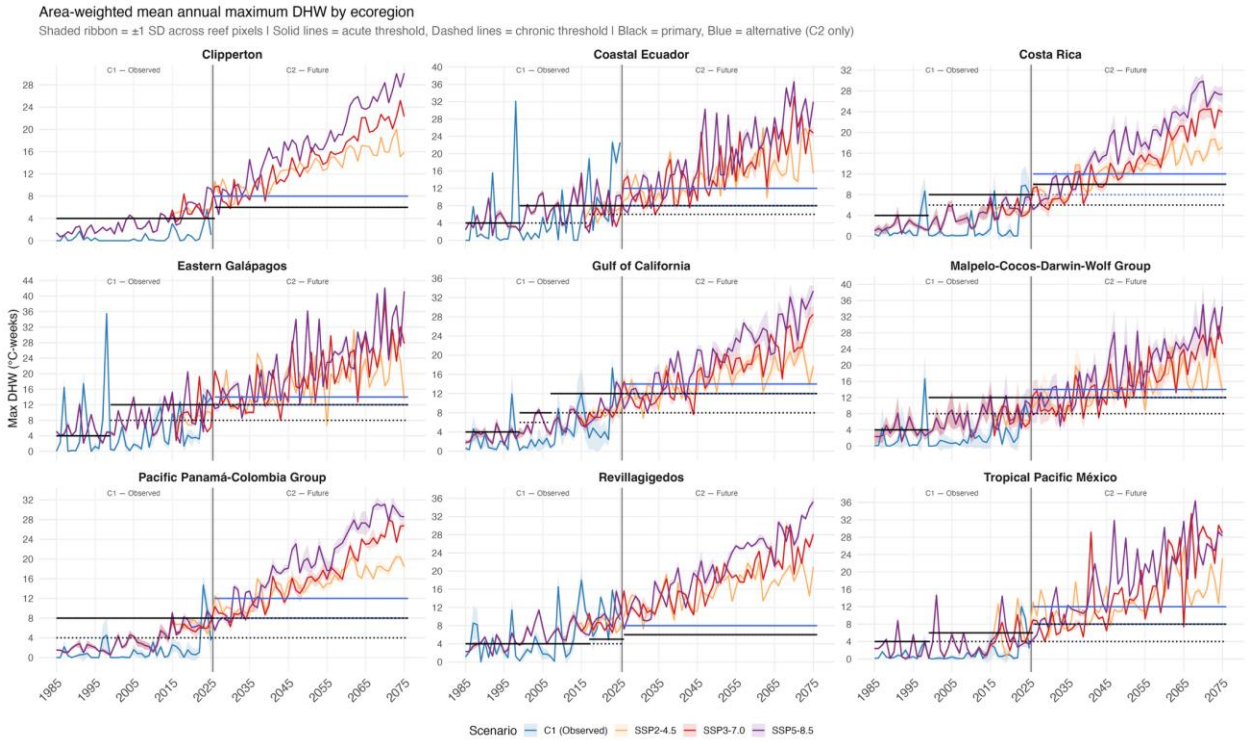


Figure S1. Annual maximum Degree Heating Weeks (DHW) averaged across coral reefs within each ecoregion from 1985-2075 for four trajectories: observed data used to assess sub-criterion C1 from 1985-2025 (blue line), and projections under three Shared Socioeconomic Pathways — SSP2-4.5 (orange), SSP3-7.0 (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.

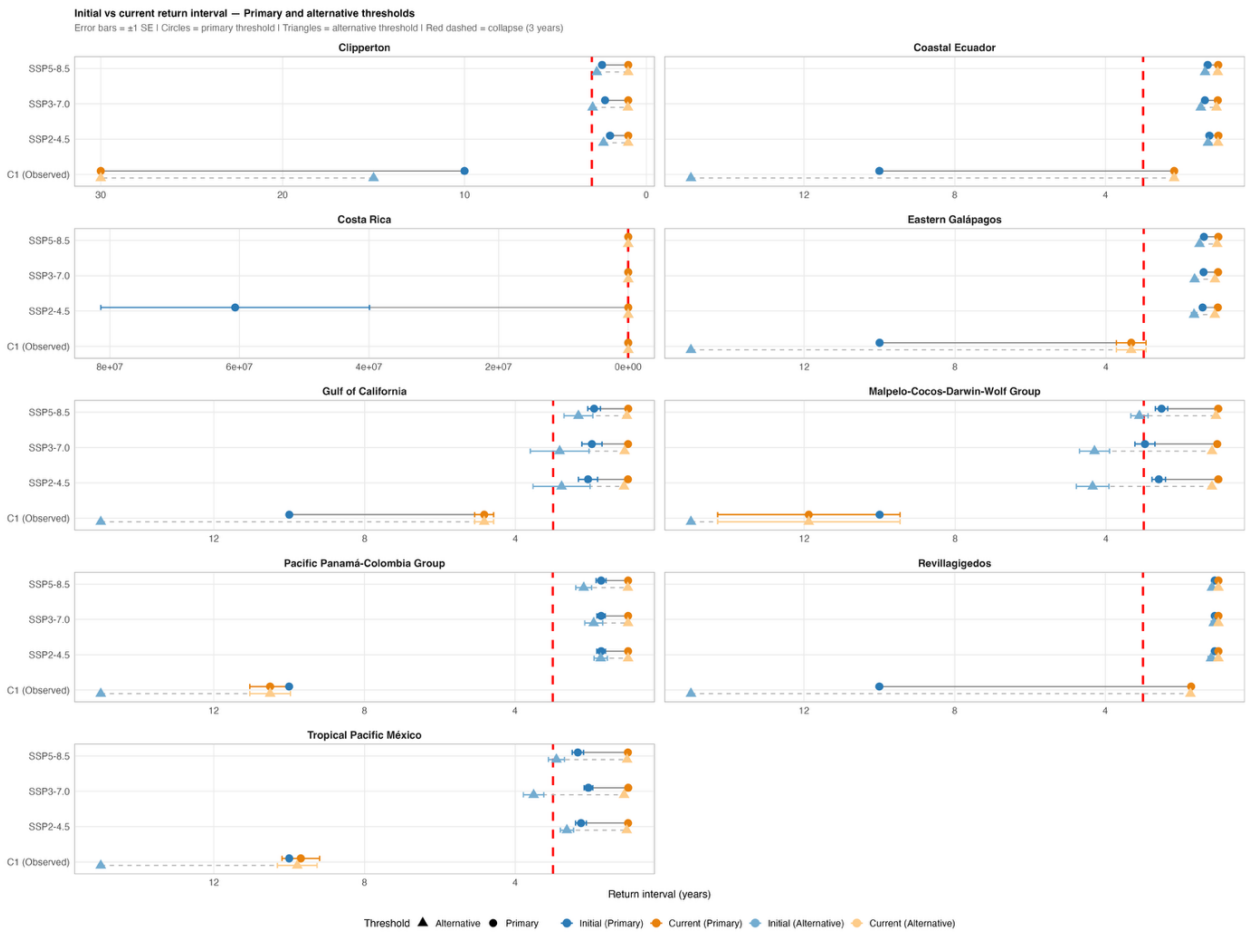


Figure S2. Change in the average return interval between severe bleaching events (years) for each ecoregion (x-axis), comparing initial conditions (blue) to current or projected future conditions (orange) across four trajectories (y-axis): observed data (C1) and projections under SSP2-4.5, SSP3-7.0, 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.

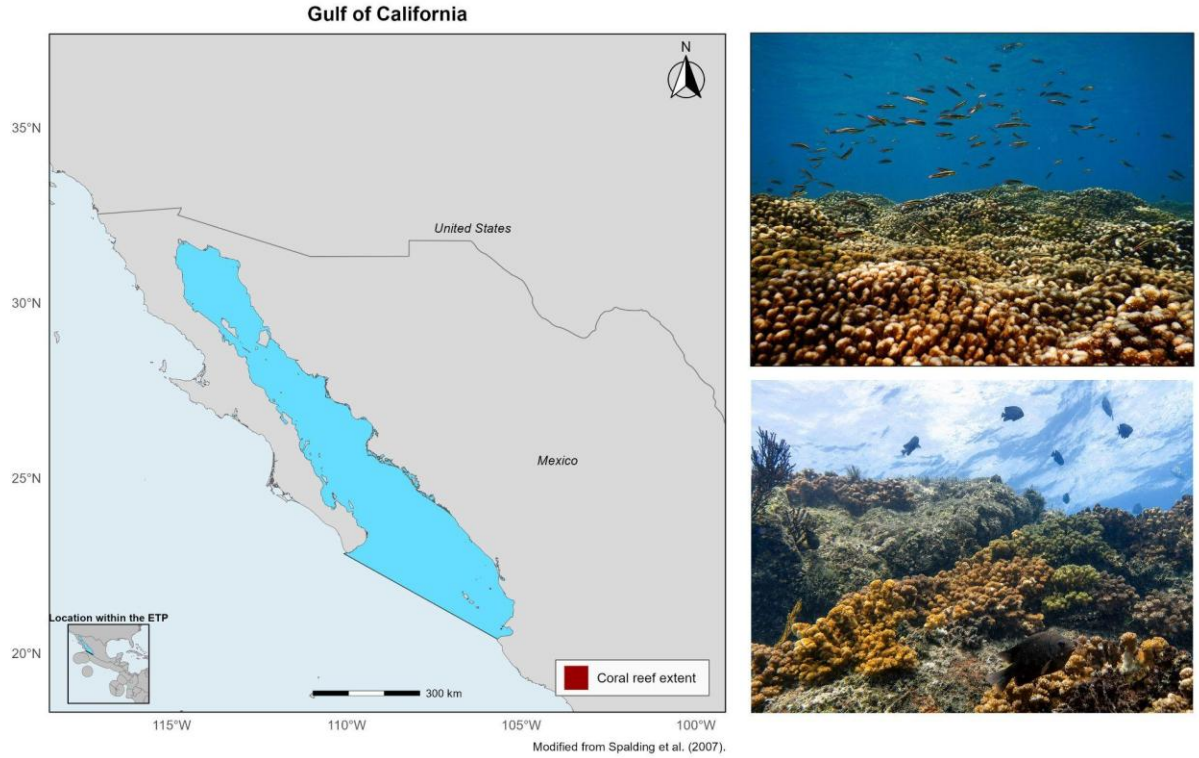
Appendices:

Factsheets – 2 pages per ecoregion

Gulf of California (IUCN status: Critically Endangered)

Spatial distribution

The ecoregion Gulf of California occupies the marine and coastal waters between the Baja California Peninsula and mainland Mexico, extending approximately from 23°42′N to 31°48′N. Coral communities are concentrated mainly in the central and southern Gulf and occur as discontinuous patches associated with islands, rocky shores, and protected embayments. The mapped coral-reef extent used in this assessment totals 5.33 km².



Ecosystem description

Coral reefs of the Gulf of California form a compositionally distinct ecoregion at the transition between tropical and subtropical eastern Pacific biotas. Twenty zooxanthellate coral species are reported, principally species of *Porites*, *Pavona* and *Pocillopora* (Glynn et al. 2017). Reef development is spatially restricted and commonly takes the form of patch reefs and coral veneers on rocky or volcanic substrates rather than extensive barrier systems. Deep basins, volcanic islands, coastal lagoons and strong tidal mixing create pronounced environmental heterogeneity. Seasonal upwelling and localized cyclonic circulation, including Ekman pumping in the Bay of La Paz, deliver nutrients to surface waters and sustain high planktonic productivity (Arreguín-Sánchez et al. 2017; Coria-Monter et al. 2024). Sea-surface temperature varies strongly seasonally and interannually under ENSO and Pacific Decadal Oscillation influences. This variability shapes coral growth, bleaching exposure and reef-associated fish communities. The region also supports exceptional marine endemism associated with its geological history, habitat diversity and partial isolation (Robertson & Cramer 2009). Major pressures include marine heatwaves, overfishing, coastal development, sediment and nutrient inputs, pollution and intensive tourism. The interaction of restricted coral habitat, high natural variability, endemic biota and increasing human pressure produces ecological dynamics that distinguish these reefs from both the tropical Mexican Pacific and oceanic ETP islands.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
5.33 km²	15	20	4

Key Biotic	Key Abiotic	Key Threats
20 coral species; 4 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	Marine heatwaves and ENSO; overfishing; coastal development; pollution and sedimentation; intensive tourism.

Key values

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km²)	AOO			Baseline	Current
0.05	74535	27		hard coral cover	45.72%	25.59%
				algae-coral ratio	0.57	0.57
				herbivore abundance	3 g m²	15.3 g m²
				piscivore abundance	11.23 g m²	5.37 g m²

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	LC	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	LC	VU	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	VU (VU/CO)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	VU	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

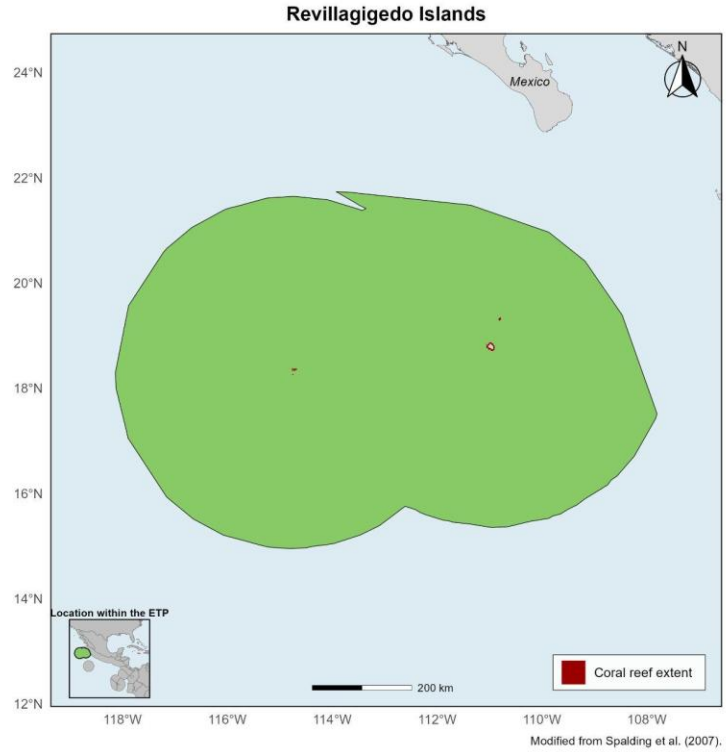
Key findings and recommendations

- **Maintain long-term benthic and fish monitoring across the region environmental gradients.**

Revillagigedo Islands (IUCN status: Critically Endangered)

Spatial distribution

This remote Mexican archipelago lies about 458 km from the mainland and comprises Socorro, Clarión, San Benedicto and Roca Partida. Its volcanic islands form an oceanic stepping-stone between the central and eastern Pacific. Coral habitats occur mainly around Clarión and Socorro, with a mapped reef extent of 3.30 km².





Ecosystem description

Coral reefs of the Revillagigedo Islands constitute an isolated oceanic ecoregion with the highest documented coral richness in western Mexico. Twenty-five coral species are recognized in the regional synthesis, with *Pocillopora* dominating many shallow habitats and massive *Porites* and *Pavona* becoming more prominent at depth (Glynn et al. 2017). Reef development is primarily fringing or patch-like around volcanic islands; localized frameworks may reach several meters in thickness. The archipelago lies where the California Current system interacts with the North Equatorial Current, while episodic eastward or westerly flows can influence trans-Pacific dispersal. Local upwelling, high irradiance, low freshwater input and strong depth-related thermal gradients further structure coral assemblages (Glynn 1996). ENSO periodically produces warming, altered fish assemblages and suppressed coral growth. Tropical storms cause acute physical disturbances. At the same time thermal stress is mitigated by the hurricane season, which coincides with the months of peak sea surface temperatures. After the temperature peak, the influence of the California Current strengthens, rapidly lowering water temperatures and allowing corals to recover quickly from bleaching. Historical soil erosion and grazing by introduced sheep increased nearshore turbidity around Socorro, while illegal fishing and bycatch remain concerns despite national-park protection. The archipelago is also important for large pelagic predators, linking shallow reefs to offshore food webs. Geographic isolation, relatively high coral richness, volcanic substrates, oceanic connectivity, and episodic disturbance combine to produce ecological conditions distinct from both mainland Mexico and Clipperton Atoll.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
3.30 km^2	1	25	3

Key Biotic	Key Abiotic	Key Threats
25 coral species; 3 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	ENSO-related bleaching; tropical storms; illegal fishing and bycatch; historical erosion and sedimentation; invasive terrestrial species.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km^2)	AOO			Baseline	Current
DD	17815	7		hard coral cover	DD	DD
				algae-coral ratio	DD	DD
				herbivore abundance	4.29 g m^2	4.29 g m^2
				piscivore abundance	0.62 g m^2	0.36 g m^2

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR)]. Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	DD	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	EN	EN	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	EN	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	DD	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

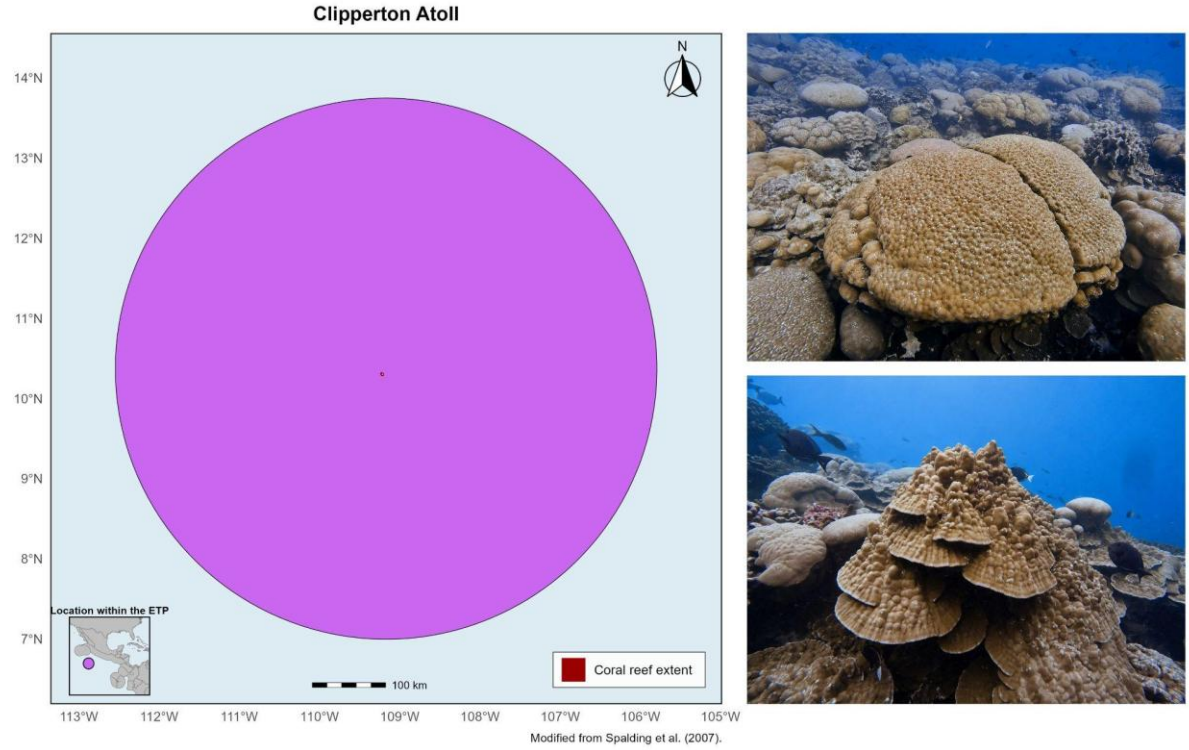
Key findings and recommendations

- Protect representative shallow and mesophotic coral habitats within the national park.

Clipperton Atoll (IUCN status: Critically Endangered)

Spatial distribution

Clipperton Atoll (Île de la Passion) lies near 10°18'N, 109°13'W, approximately 1,300 km southwest of Mexico. It is the most isolated and westernmost coral-reef system included in the ETP assessment. The mapped reef habitat totals 0.45 km² and surrounds a small, nearly circular atoll and enclosed brackish lagoon.



Ecosystem description

Clipperton is the ETP's only true atoll and therefore its most distinctive geomorphological reef system. Twenty-one coral species are recorded, including *Pocillopora*, *Porites*, *Pavona* and *Leptoseris* (Glynn et al. 2017). A low annular reef encircles a shallow brackish lagoon above an isolated volcanic edifice. Reef habitat extends from shallow flats to deep terraces near 50–58 m. Clear zonation includes crustose coralline algae in breaker zones, *Pocillopora*- and *Porites*-built spur-and-groove formations at intermediate depths, and *Pavona*-dominated lower slopes (Glynn et al. 1996; Charpy et al. 2010). Live coral cover can be locally very high despite low regional species richness. The North Equatorial Countercurrent is the principal oceanographic influence, with occasional contributions from other equatorial flows. Sea-surface temperatures are generally warm and comparatively stable, although ENSO can generate acute thermal anomalies, bleaching and mortality. Cyclones and wave exposure cause physical disturbance. The small reef supports disproportionately high fish diversity and endemism relative to its area. Illegal fishing in surrounding waters can alter trophic structure and affect predators and seabirds, while introduced terrestrial species have disrupted seabird populations and nutrient transfer to the reef. Extreme isolation, atoll morphology, simplified coral assemblages and strong dependence on oceanic connectivity make Clipperton ecologically unique within the ETP.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
0.45 km²	1	21	2

Key Biotic	Key Abiotic	Key Threats
21 coral species; 2 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	ENSO and bleaching; tropical cyclones; illegal fishing; invasive terrestrial species; extreme isolation and limited recolonization potential.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km²)	AOO			Baseline	Current
DD	12.2	2		hard coral cover	DD	DD
				algae-coral ratio	DD	DD
				herbivore abundance	DD	DD
				piscivore abundance	DD	DD

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	DD	DD	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	CR	EN	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	VU (LC/EN)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	DD	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

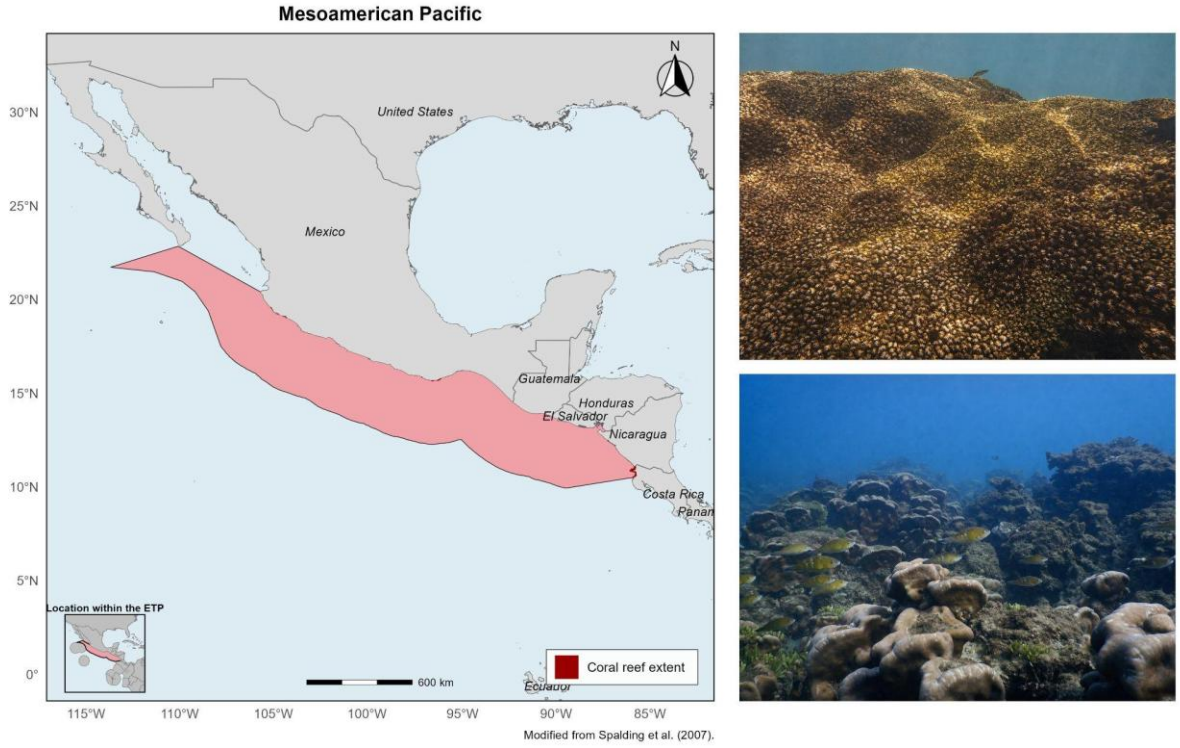
Key findings and recommendations

- Establish standardized coral-cover, recruitment and bleaching monitoring across depth zones.

Mesoamerican Pacific (IUCN status: Critically Endangered)

Spatial distribution

The ecoregion follows the Pacific coast from Jalisco to Chiapas in Mexico and continues through Guatemala, El Salvador, Nicaragua and northern Costa Rica. It combines the Tropical Mexican Pacific and Chiapas–Nicaragua biogeographic sectors. Coral habitats occur discontinuously in protected bays, coastal lagoons and around offshore rocks, totaling 31.4 km² of mapped reef extent (2026).



Ecosystem description

Coral reefs of the Mesoamerican Pacific form a broad mainland ecoregion linking the tropical Mexican coast to Central America. Approximately 30 coral species are represented when locality inventories are combined without duplication (derived from Glynn et al. 2017). *Pocillopora*, *Porites* and *Pavona* form patch reefs, coral-algal assemblages and localized frameworks in sheltered embayments; extensive reefs are uncommon along sediment-rich or high-energy coasts. Sandy beaches, mangroves, estuaries and rocky shores create a heterogeneous coastal mosaic that supports reef fish, mollusks and other macroinvertebrates. Northern areas are affected by the equatorward California Current and the poleward Mexican Coastal Current, whereas southern areas receive the North Equatorial Countercurrent and strong seasonal forcing from the Intertropical Convergence Zone. Temperature, salinity and productivity consequently vary substantially along the ecoregion. ENSO has repeatedly caused bleaching and coral mortality. Biological pressures include corallivory, bioerosion and sea-urchin grazing, while eutrophication may encourage opportunistic macroalgae and hypoxia. Overfishing, tourism development, land-use change, sedimentation, wastewater, coral disease and habitat fragmentation compound climate stress. The combination of latitudinal extent, continental runoff, oceanographic transition zones and discontinuous coral habitats produces greater internal heterogeneity than in the remote oceanic ecoregions, making coordinated multinational management essential.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
31.4 km^2	31	≈30	≈5

Key Biotic	Key Abiotic	Key Threats
≈30 coral species; ≈5 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	ENSO and marine heatwaves; overfishing; eutrophication and wastewater; sedimentation; tourism and coastal development; habitat fragmentation.

Key values

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km^2)	AOO			Baseline	Current
0.33	241301	35		hard coral cover	52.76%	21.54%
				algae-coral ratio	0.61	0.93
				herbivore abundance	3.76 g m^2	70.42 g m^2
				piscivore abundance	11.26 g m^2	7.38 g m^2

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as **Critically Endangered (CR)**. Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	VU	LC	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	LC	VU	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	EN (LC/CR)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	EN	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

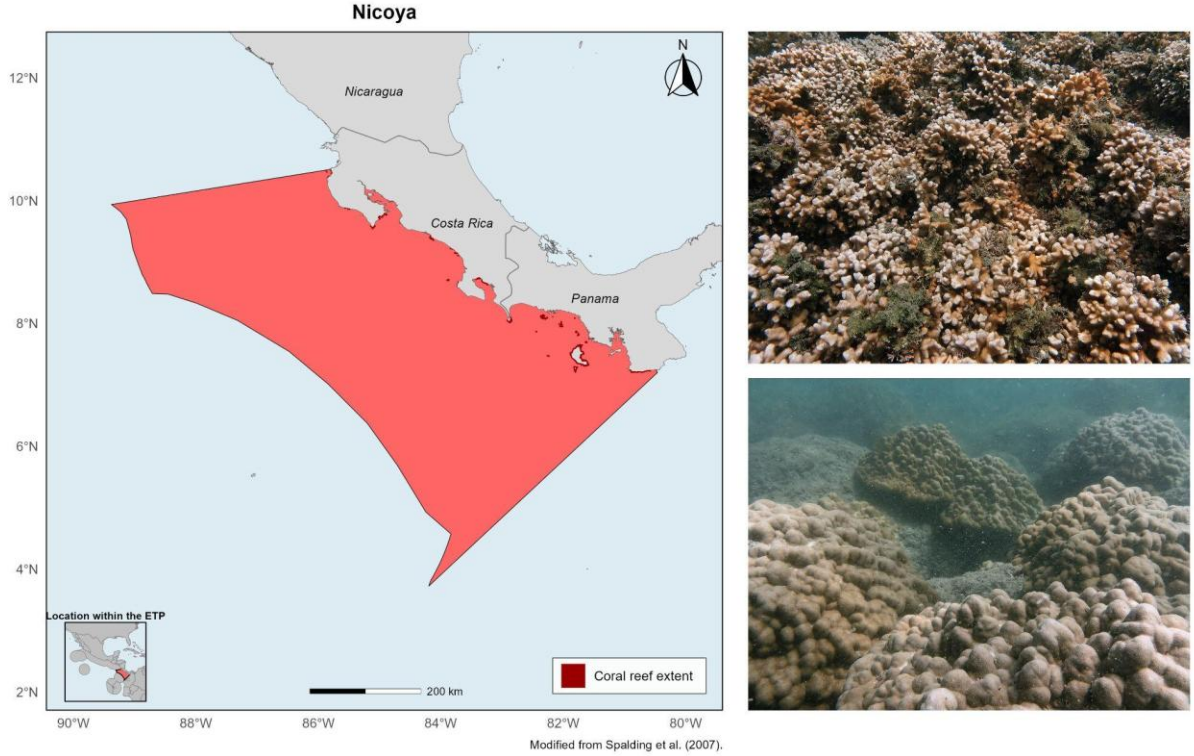
Key findings and recommendations

- Prioritize recovery and compliance actions at persistent coral refuges and recruitment sources.

Nicoya (IUCN status: Critically Endangered)

Spatial distribution

Nicoya encompasses most of Costa Rica's Pacific coast south of the northern transition and continues into western Panama. Sheltered gulfs, rocky headlands, islands, submerged platforms and mangrove-lined estuaries provide habitat for fringing and patch reefs. The ecoregion contains the largest mapped reef extent in this assessment, 55 km².



Coral reefs of Nicoya form a productive mainland ecoregion shaped by seasonal upwelling, high coastal habitat diversity and strong rainfall gradients. Approximately 29 coral species occur across the combined Costa Rican and western Panamanian inventories (derived from Glynn et al. 2017). *Pocillopora*, *Porites*, *Pavona* and *Psammocora* dominate patch reefs, fringing formations and coral veneers on rocky substrates. The Papagayo wind jet drives seasonal coastal upwelling, lowering sea-surface temperature locally to about 22–24°C while increasing nutrients and primary productivity. During the rainy season, river discharge produces sharp changes in salinity, turbidity and sediment supply. The Intertropical Convergence Zone controls much of this seasonal contrast. These naturally variable conditions favor stress-tolerant coral assemblages but can also constrain carbonate accretion. ENSO-driven warming causes bleaching, whereas anomalously intense upwelling may create cold-water and hypoxic stress. Rapid tourism and urban growth have increased habitat conversion, sedimentation, wastewater and nutrient inputs. Fishing, harmful algal blooms, ocean acidification and changing sea level add cumulative pressure. The spatial juxtaposition of upwelling centres, sheltered gulfs, wet tropical watersheds and offshore islands generates distinct reef communities over short distances. This environmental mosaic and its position between northern Central America and Panama distinguish Nicoya as a separate coral-reef ecoregion.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
55 km²	26	≈29	≈5

Ecosystem description

Key Biotic	Key Abiotic	Key Threats
≈29 coral species; ≈5 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity, and marked thermal or productivity variability.	Thermal and hypoxic stress; coastal tourism and urbanization; sediment and nutrient inputs; overfishing; harmful algal blooms.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km^2)	AOO			Baseline	Current
0.80	41818	52		hard coral cover	28.39%	34.09%
				algae-coral ratio	0.66	0.72
				herbivore abundance	4.67 g m^2	6.19 g m^2
				piscivore abundance	0.87 g m^2	0.60 g m^2

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as **Critically Endangered (CR)**. Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	CR	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	VU	NT	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	EN (VU/CR)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	CR	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

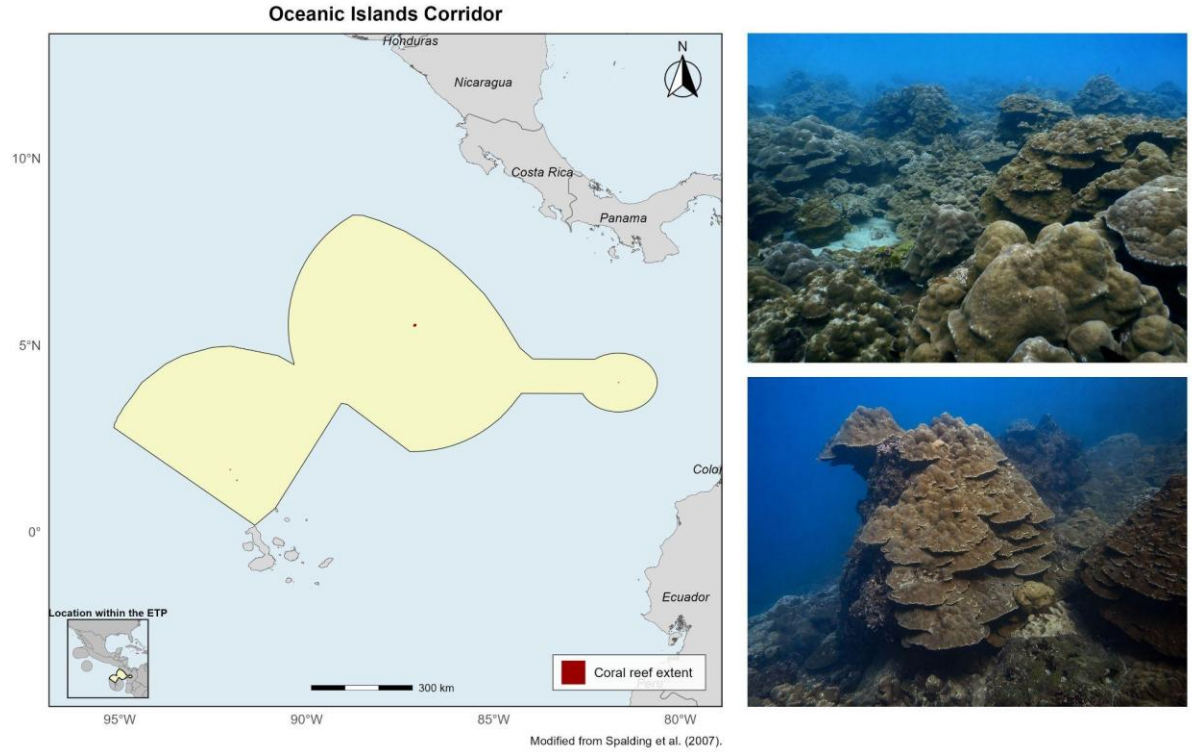
Key findings and recommendations

Monitor temperature, oxygen and coral condition across upwelling and non-upwelling sites.

Oceanic Islands Corridor (IUCN status: Critically Endangered)

Spatial distribution

The corridor links Isla del Coco, Malpelo, and the northern Galápagos islands of Darwin and Wolf. These isolated volcanic islands and pinnacles form stepping-stones across the open ETP and connect reef populations with mainland systems. Coral patches and frameworks occupy only 1.74 km² of mapped habitat but occur across a geographically extensive oceanic network (2026).



Ecosystem description

Coral reefs of the Oceanic Islands Corridor are defined by extreme isolation, steep volcanic bathymetry and ecological connectivity among Isla del Coco, Malpelo, and the northern islands of the Galapagos Archipelago (Darwin and Wolf). Twenty-eight coral species occur across the combined island inventories (derived from Glynn et al. 2017). Reef expression ranges from coral communities on vertical rock and boulder habitats to Porites-dominated frameworks at the northern Galápagos. *Pocillopora* and *Pavona* contribute important shallow and deeper assemblages. Abrupt slopes, pinnacles and local eddies intensify mixing and concentrate nutrient plumes near coral habitats. Upwelling around Darwin and Wolf supports high primary productivity, while ENSO periodically suppresses nutrient delivery, raises temperature and causes bleaching. These islands support large aggregations of hammerhead sharks, jacks and other predators, demonstrating tight coupling between reefs and pelagic food webs. Larval studies indicate strong retention between the northern islands of the Galapagos Archipelago (Darwin and Wolf), with intermittent dispersal toward southern Galápagos and export toward Malpelo and Isla del Coco. Climate warming and acidification threaten coral persistence, while overfishing targets ecologically important fishes and invertebrates. Tourism and shipping increase the risk of introducing invasive species, while diving tourism can cause localized physical damage through diver contact, including colony breakage and abrasion (Giglio et al. 2025; Moity 2025). The corridor's small reef area has regional importance disproportionate to its extent because its islands function as biodiversity reservoirs, stepping-stones and potential sources of recruits across the ETP.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
1.74 km^2	5	28	4

Key Biotic	Key Abiotic	Key Threats
28 coral species; 4 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	Ocean warming and ENSO; overfishing; invasive species; tourism and vessel traffic; small and isolated coral populations.

Key values

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km^2)	AOO			Baseline	Current
0	200880	4		**hard coral cover**	44.22%	18.87%
				algae-coral ratio	0.45	0.49
				herbivore abundance	8.97 g m^2	8.89 g m^2
				piscivore abundance	0.65 g m^2	4.13 g m^2

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	LC	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	LC	EN	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	VU (NT/EN)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	EN	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

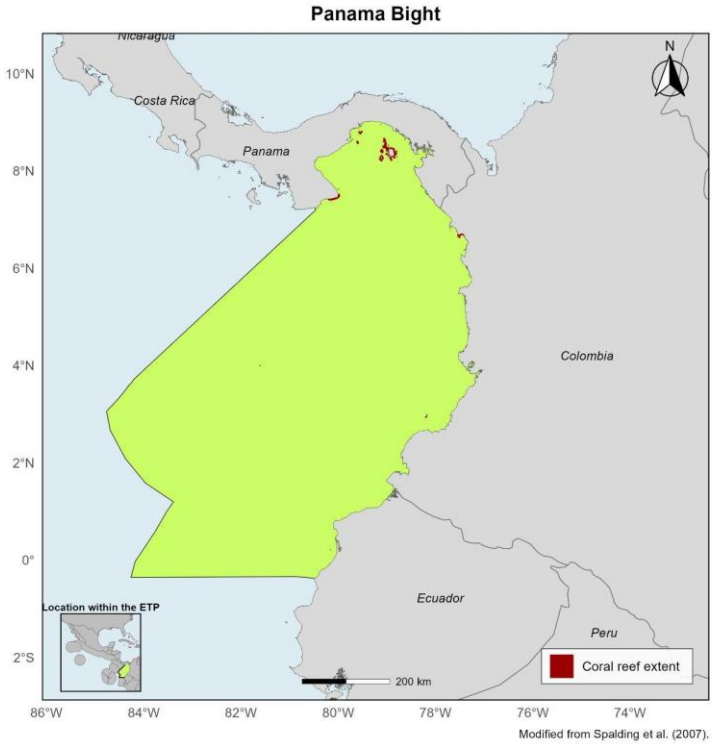
Key findings and recommendations

Coordinate transboundary monitoring and enforcement among Costa Rica, Colombia and Ecuador.

Panama Bight (IUCN status: Critically Endangered)

Spatial distribution

Panama Bight extends from eastern Panama along the Pacific coast of Colombia to northern Ecuador. Coral reefs and communities occur around islands, rocky shores and protected embayments embedded within mangrove- and river-dominated coastlines. The mapped coral-reef extent totals 40.1 km². Malpelo is treated separately within the Oceanic Islands Corridor ecoregion.





Ecosystem description

Coral reefs of Panama Bight form a humid equatorial mainland ecoregion characterized by high rainfall, extensive river discharge, strong tidal forcing, and localized seasonal upwelling. Approximately 32 coral species occur across inventories from Panama, Colombia, and northern Ecuador (derived from Glynn et al. 2017). *Pocillopora*, *Porites*, *Pavona* and *Gardineroseris* form patch and fringing reefs around islands such as Coiba and Gorgona, and in protected coastal settings. Seasonal migration of the Intertropical Convergence Zone drives pronounced hydrographic change. During the dry season, the Panama wind jet can cool surface waters by several degrees and enhance nitrate, phosphate, and primary productivity. During wetter periods, major rivers deliver freshwater, sediments and nutrients, producing strong salinity and turbidity gradients. ENSO weakens upwelling, elevates temperature, and has repeatedly caused mass bleaching. Extreme low tides can expose shallow corals, while herbivorous fishes and invertebrates influence post-disturbance algal succession. Local pressures include illegal and unregulated fishing, port and coastal development, poorly managed tourism, deforestation, sedimentation, sewage, agrochemicals, industrial discharge, and solid waste. The interaction between equatorial rainfall, seasonal upwelling, large river systems, islands and diverse coral assemblages creates reef dynamics distinct from drier Central America and the Guayaquil transition zone.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
40.1 km²	26	20	4

Key Biotic	Key Abiotic	Key Threats
≈32 coral species; ≈5 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	ENSO bleaching; low-tide exposure; illegal fishing; deforestation and sedimentation; sewage and industrial pollution; port development.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km²)	AOO			Baseline	Current
0	205272	27		hard coral cover	55.56%	66.54%
				algae-coral ratio	0	0.09
				herbivore abundance	4.95 g m²	4.32 g m²
				piscivore abundance	3.09 g m²	4.63 g m²

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	LC	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	LC	VU	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	VU (LC/EN)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	VU	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

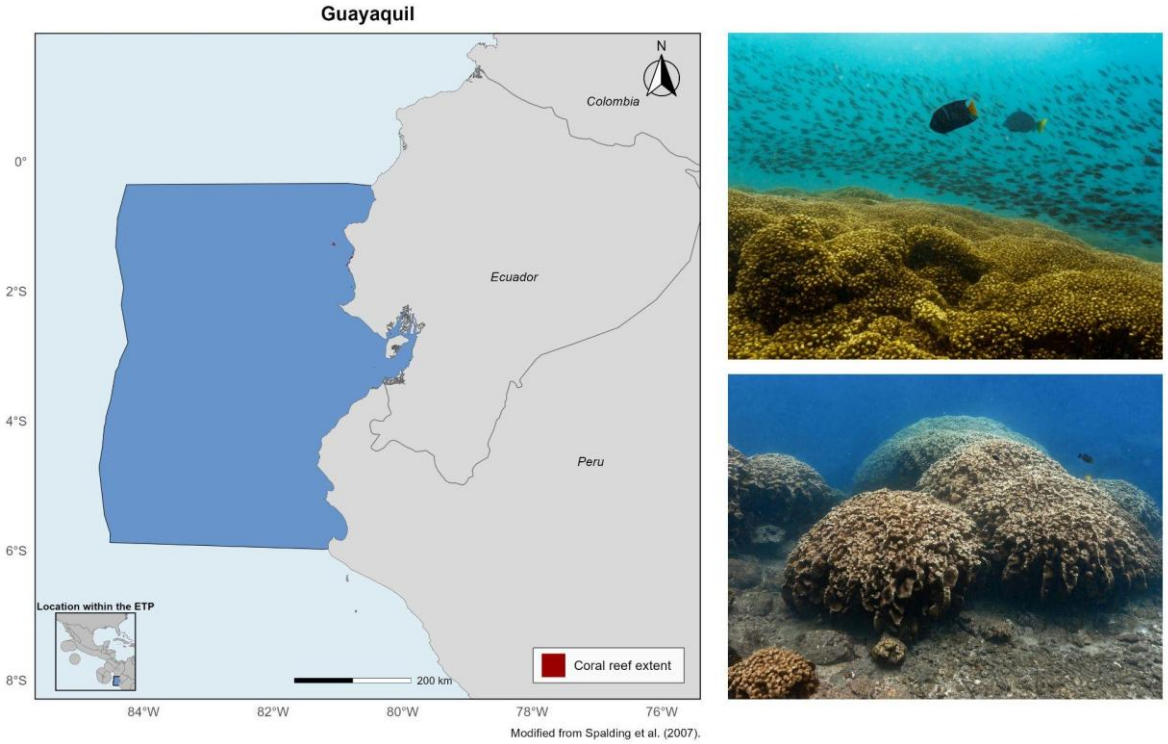
Key findings and recommendations

Reduce land-based pollution and sediment delivery in priority coastal watersheds.

Guayaquil (IUCN status: Critically Endangered)

Spatial distribution

The Guayaquil ecoregion includes southern Ecuador and northern Peru, including the outer Gulf of Guayaquil and adjacent ocean-influenced coasts. Coral occurrence approaches its southern continental limit in the ETP and is highly localized. The mapped coral habitat totals 1.25 km² (2026), with communities concentrated in comparatively stable marine settings rather than the inner estuary.



Ecosystem description

Following an extensive inventory along the coast of Ecuador, 20 species of zooxanthellate corals have been documented in the Guayaquil Ecoregion (Rivera & Martínez, in press). Coral formations are dominated by the genera *Pavona*, *Pocillopora*, *Porites*, *Psammocora* and *Gardineroseris*, which form fringing reefs around islands such as Isla de la Plata, Salango Island, and Sucre Islet, as well as reef patches and coral communities along the mainland coast. An intertidal reef patch of *Pocillopora* sp. at Puntilla de Santa Elena, the westernmost point of mainland Ecuador, may be the southernmost reef in the ETP. This reef persists under harsh conditions, remaining exposed to air for several hours during extreme low tides (Rivera & Martínez, in press). The ecoregion environment is shaped by the Guayas River estuary, seasonal rainfall, strong tides, and the cool Humboldt Current, which together produce marked spatial and temporal variation in temperature, salinity, turbidity, and nutrient availability (Borbor-Cordova et al., 2019; Twilley et al., 2001). El Niño events can temporarily warm the region and alter rainfall, freshwater input, nutrient dynamics, and the occurrence of harmful algal blooms (Borbor-Cordova et al., 2019). In addition, these coral habitats face local pressures such as sediment runoff, unsustainable tourism practices, and fishing.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
1.25 km²	14	≈20	≈4

Key Biotic	Key Abiotic	Key Threats
≈20 coral species; ≈4 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	Estuarine and thermal variability; harmful algal blooms; urban and industrial pollution; sedimentation; overfishing and trawling.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km²)	AOO			Baseline	Current
DD	3297	8		hard coral cover	55.56%	DD
				algae-coral ratio	0.24	DD
				herbivore abundance	1.44 g m²	3.56 g m²
				piscivore abundance	0.85 g m²	0.30 g m²

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	DD	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	EN	EN	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	EN	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	DD	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

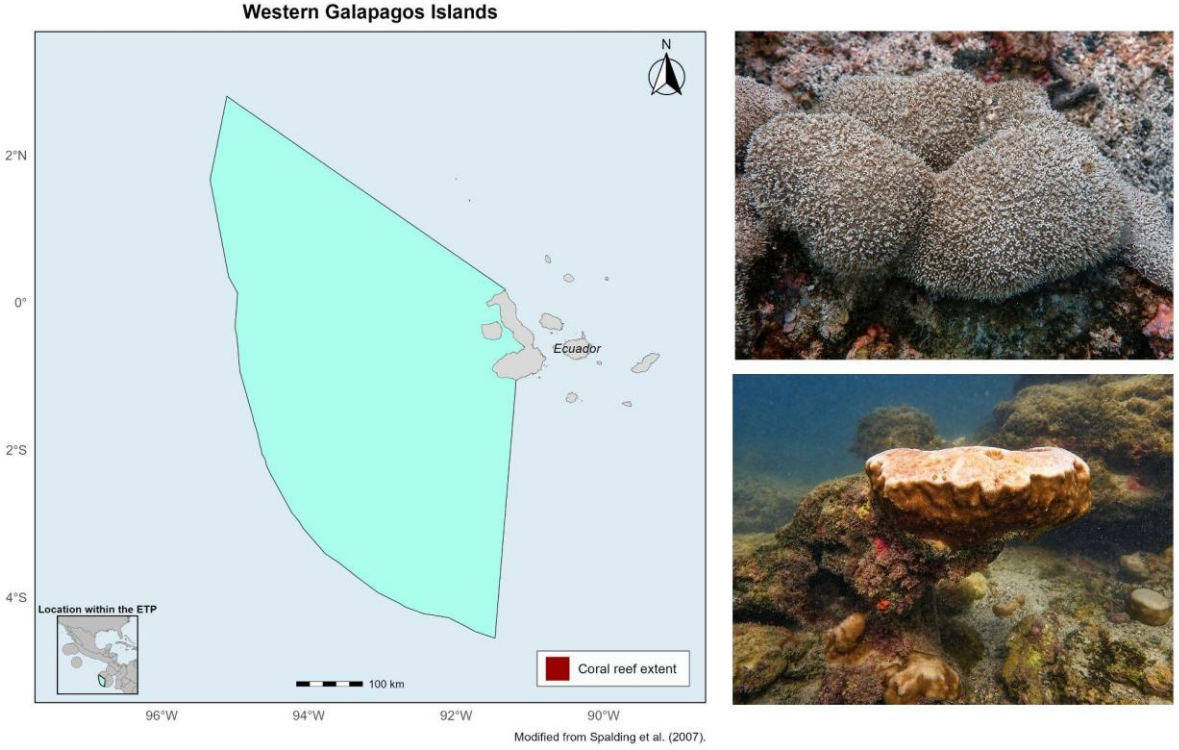
Key findings and recommendations

- Reduce watershed sediment, wastewater and industrial contaminant inputs.

Western Galapagos Islands (IUCN status: Collapsed)

Spatial distribution

Western Galápagos encompasses Fernandina and the western and southwestern coasts of Isabela, approximately between 0°30'S–1°30'S and 91°–92°W. It lies directly in the principal upwelling influence of the Equatorial Undercurrent. Coral habitat is scarce and fragmented, and the historically developed reef frameworks are now highly reduced, although persistent coral communities remain at some sites on rocky substrates. Given that the remaining communities do not match the reef types included in this study, the ecoregion was excluded from the 2026 reef layer.



Ecosystem description

Western Galápagos is the coolest and most strongly upwelled coral-reef ecoregion in the ETP. The regional factsheet uses approximately 20 coral species as an archipelago-level southern-island proxy because a reliable east–west species inventory is not available (Glynn et al. 2017). Modern reef-building coral development is very limited. Isolated *Pavona, Porites lobata* and *Pocillopora* colonies occur in sheltered bays and lagoons, often within macroalgae-dominated rocky habitats. The nutrient-rich Equatorial Undercurrent shoals around Fernandina and west Isabela, producing cold, productive water, strong thermal fluctuations and low carbonate saturation that constrain reef accretion. Interactions with the Humboldt and Panama currents generate sharp biological gradients and support unusually high endemism, cool-temperate species and productive fish and invertebrate assemblages. ENSO temporarily suppresses upwelling and elevates temperature, producing bleaching, coral mortality and shifts in community structure. Subsequent cold events may impose additional physiological stress. Bioeroding sea urchins can inhibit framework recovery. Tourism, vessel traffic, marine debris and non-native species create further risks even within the marine reserve. Geological disturbances, including tectonic uplift and volcanism, have also contributed to the degradation and loss of coral reefs that developed in the region in the past. Persistent cold upwelling, high productivity, macroalgal dominance, range-edge coral populations and extreme climatic variability make western Galápagos fundamentally different from the warmer eastern and northern island systems.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
0 km^2	1	≈20	≈4

Key Biotic	Key Abiotic	Key Threats
≈20 coral species; ≈4 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	Extreme thermal variability; ENSO; low carbonate saturation; bioerosion; tourism, vessel traffic, marine debris; geological disturbances.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km^2)	AOO			Baseline	Current
0	NE	NE		**hard coral cover**	NE	NE
				algae-coral ratio	NE	NE
				herbivore abundance	NE	NE
				piscivore abundance	NE	NE

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Collapsed [CO]. Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	CO	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	NE	NE	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	NE	NE	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	NE	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CO		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

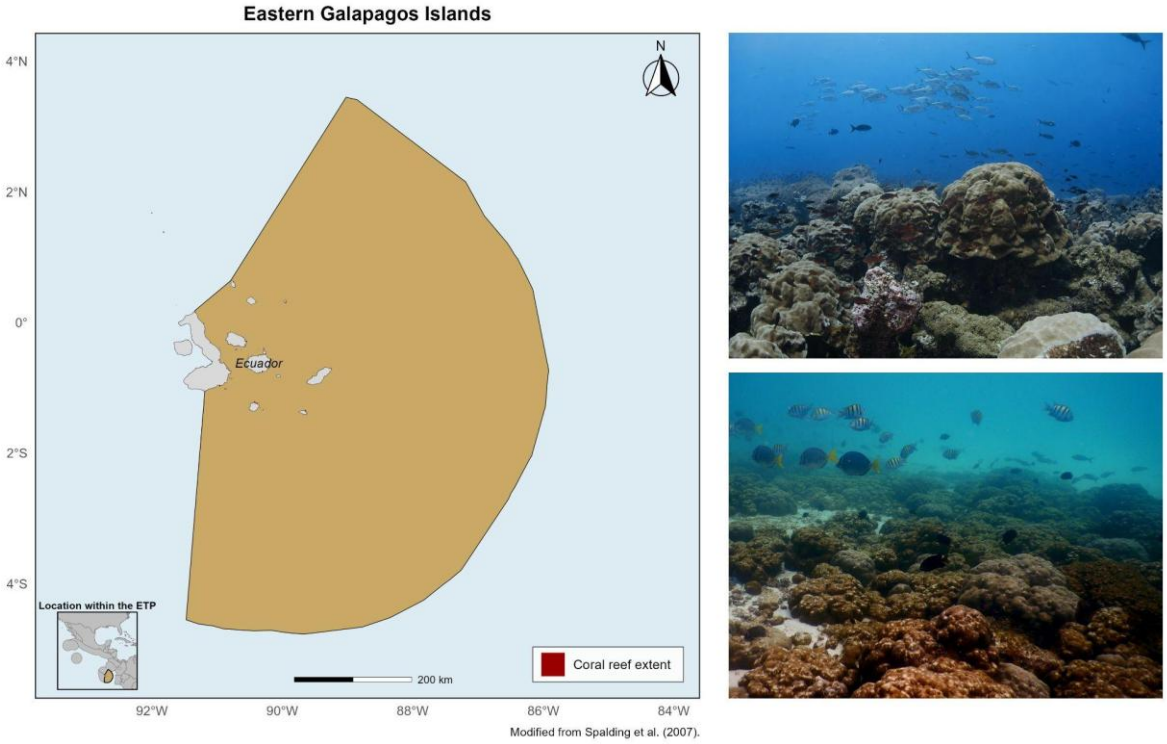
Key findings and recommendations

Minimize anchoring, visitation and pollution impacts at the few sheltered coral sites. Coral communities existed within the ecoregion in at least two areas: western Isabela and Fernandina (Glynn, 1983). However, by 1989, they were reported as degraded, that is, as lost reef areas (Glynn, 2018).. In the present, expert knowledge confirmed that all sites in this ecoregion have transformed from former reefs Type A or B into Type C (i.e., rocky reefs) or into completely degraded systems. Although experts have also observed limited recovery in certain places, no site has recovered enough to revert to Type A or B.

Eastern Galapagos Islands (IUCN status: Critically Endangered)

Spatial distribution

Eastern Galápagos includes San Cristóbal, Española, Floreana and adjacent islands and islets, approximately between 0°30'N–2°S and 89°–91°W. Coral communities occur as discontinuous patches in shallow, usually sheltered bays within the Galápagos Marine Reserve. The mapped reef extent totals 0.73 km². The northern islands of the archipelago (i.e. Darwin and Wolf) are included in the Oceanic Islands Corridor ecoregion.



Ecosystem description

Coral reefs of Eastern Galápagos form a patchy oceanic ecoregion where tropical Panamic species coexist with cool-water influences. Approximately 20 coral species are used as the best available proxy from the southern Galápagos inventory (Glynn et al. 2017). *Porites lobata*, *Pocillopora* and *Pavona* dominate many surviving communities, which occur mainly as coral patches and low-relief assemblages rather than extensive frameworks. The ecoregion lies at the convergence of the Humboldt, Panama and equatorial current systems. Seasonal upwelling supplies nutrients and supports productive food webs but also creates marked temperature variability. ENSO reverses many of these conditions, warming surface waters, reducing nutrient supply and causing bleaching. The 1982–83 event produced widespread mortality and long-term loss of several coral communities; recovery has been spatially uneven. Fishing pressure on predators and invertebrates can alter trophic interactions, including increases in bioeroding sea urchins. Rapid tourism growth, coastal infrastructure, vessel traffic, anchoring, wastewater, plastics and introduced marine species add cumulative stress. Eastern Galápagos differs from the western ecoregion through its stronger tropical influence, greater exposure to Panamic connectivity and more favorable conditions for reef-building corals. Nevertheless, its fragmented habitat and history of severe ENSO mortality indicate limited redundancy and high sensitivity to future warming.

Mapped coral-reef extent	Protected areas	Coral species	Threatened coral species
0.73 km²	1	≈20	≈4

Key Biotic	Key Abiotic	Key Threats
≈20 coral species; ≈4 threatened coral species; reef-associated fishes and invertebrates.	Strong ENSO influence, current-driven connectivity and marked thermal or productivity variability.	ENSO and marine heatwaves; bioerosion; fishing; tourism and infrastructure; wastewater, plastics and invasive species.

Key values

Directly produceable and exportable from analysis

Proportion of assessed coral reef sites below the 5% hard-coral-cover threshold over the last 50 years (Criterion A)	Distribution (Criterion B)		SST-anomaly past 50 years (Criterion C)	Biotic Indicator Values (Criterion D)		
	EOO (km²)	AOO			Baseline	Current
0.92	20050	7		hard coral cover	10.64%	5.43%
				algae-coral ratio	0.57	0.58
				herbivore abundance	8.97 g m²	20.14 g m²
				piscivore abundance	2.7 g m²	5.21 g m²

Criteria Assessment

Overall, the risk of collapse of the coral reefs in the Eastern Tropical Pacific was assessed as Critically Endangered (CR). Summary of the assessment:

CRITERION			
A. Reduction in Geographic Distribution	A1	A2	A3
	Past 50 years	Future or any 50y period	Historical (1750)
	CR	NE	NE
B. Restricted Geo. Distribution	B1	B2	B3
	Extent of Occurrence	Area of Occupancy	# Threat-defined Locations < 5?
	VU	EN	NE
C. Environmental Degradation	C1	C2	C3
	Past 50 years (1970)	Future or any 50y period	Historical (1750)
	CR (EN/CO)	CR	NE
D. Disruption of Biotic Processes	D1	D2	D3
	Past 50 years (1970)	Future or Any 50y period	Historical (1750)
	EN	NE	NE
E. Quantitative Risk Analysis	NE		
OVERALL RISK CATEGORY	CR		

DD = Data Deficient; LC = Least Concern; NE = Not Evaluated

Key findings and recommendations

- Strengthen marine tourism, fisheries, biosecurity and wastewater management across inhabited islands.

Birkeland, C., Meyer, D. L., Stames, J. P., & Buford, C. L. (1975). Subtidal communities of Malpelo island. *Smithson. Contrib. Zool*, *176*, 55-68.