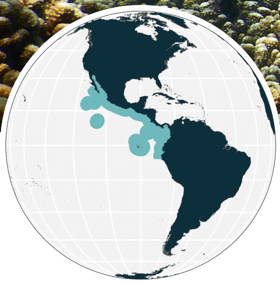
Cortez rainbow wrasses (*Thalassoma lucasanum*) over a Pocilloporid reef, La Paz, Gulf of California
Credit: Manuel Olán-González



EASTERN TROPICAL PACIFIC

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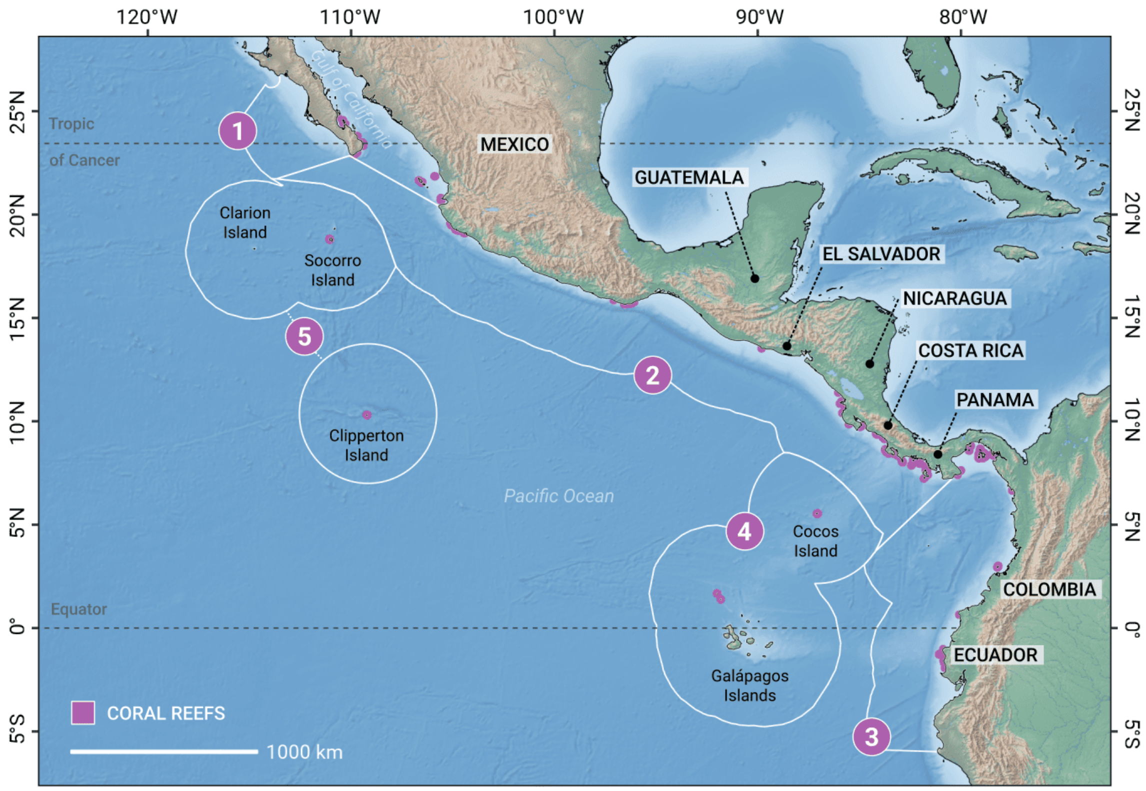
INTRODUCTION

The Eastern Tropical Pacific GCRMN region extends over a maritime area of approximately 4.8 million km^2, ranging across 30° of latitude and 41° of longitude. The region hosts 593 km^2 of coral reefs, which represent 0.2% of the world's coral reef extent, and is the smallest GCRMN region by coral reef extent. In addition to Clipperton Island, a French overseas territory, coral reefs occur within the exclusive economic zones of six other countries within the region, ranging from Mexico in the north to mainland Ecuador in the south and from Colombia in the east to Mexico (Clarion Island) in the west (Figure 2.5.1). The Chilean oceanic islands of Rapa Nui (Easter Island) and Salas y Gómez have recently been considered as part of the Eastern Tropical Pacific, extending its boundary to ~27° S [281], however, these two locations are not included within this chapter.



▲ **Figure 2.5.1.** The distribution of coral reefs within the Eastern Tropical Pacific region and respective subregions. White polygons and numbers represent subregions. Subregion 1 = Southern Baja California, Subregion 2 = Mesoamerican Pacific, Subregion 3 = Panama Bight/Guayaquil, Subregion 4 = Galápagos and Cocos, Subregion 5 = Revillagigedo and Clipperton. Coral reefs are delineated with a 20 km buffer to enhance interpretation, and only coral reefs within the region are represented. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the region.

THREATS AND DISTURBANCES

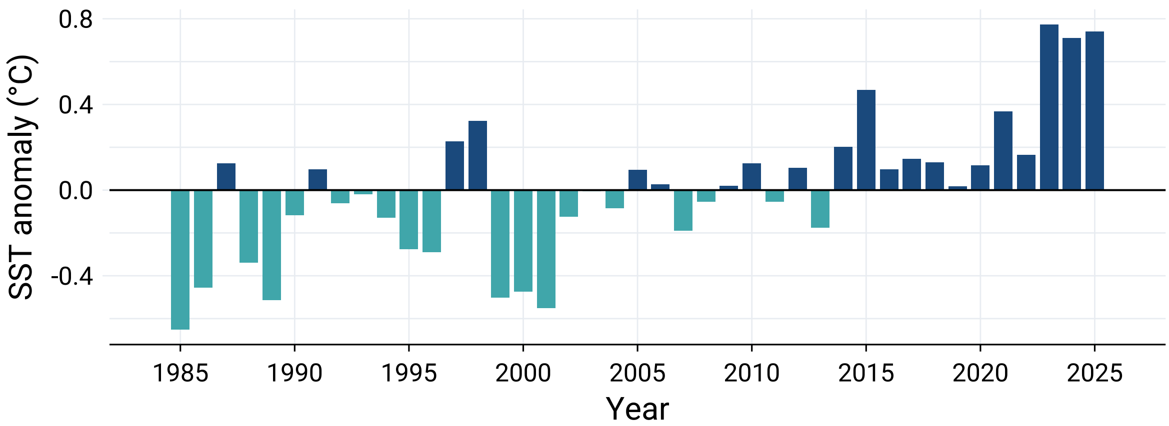
Heat stress

From 1985 to 2025, the long-term average sea surface temperature (SST) over Eastern Tropical Pacific coral reefs was 27.85 °C. During this period, regional SST increased by 0.79 °C, an average warming rate of 0.20 °C per decade (Table A.3). A significant warming trend since 2000 features increasingly frequent and larger positive anomalies, alongside diminishing negative anomalies (Figure 2.5.2). Notably, the period 2023–2025 exhibits the highest positive anomalies recorded.

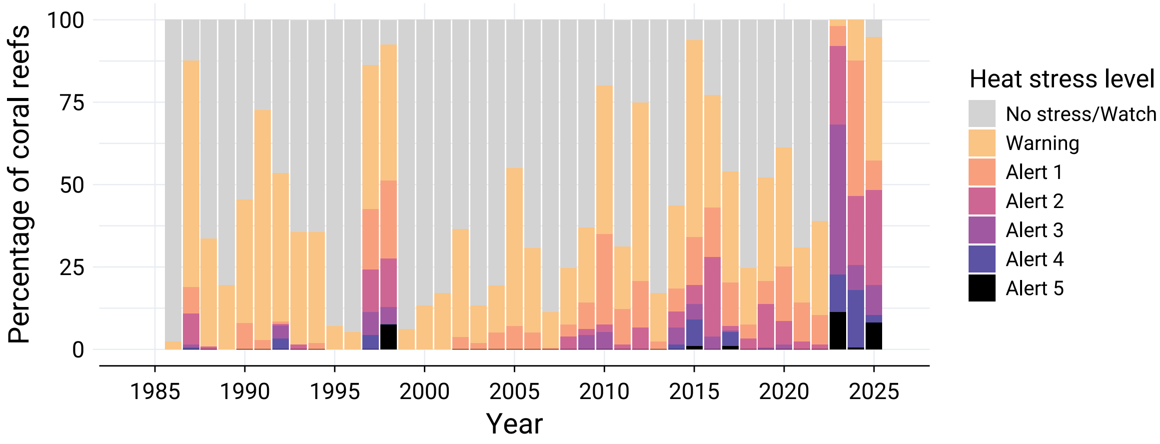
Inter-annual SST variations linked to the ENSO cycle remain the primary drivers of hard coral cover decline and recovery in the Eastern Tropical Pacific. Generally, larger positive SST anomalies (Figure 2.5.2) increase the percentage of reefs affected by heat stress, which can lead to extensive coral bleaching and mortality (Figure 2.5.3).

While thermal impacts are spatially variable, the most severe, widespread El Niño events occurred in 1982–1983, 1997–1998, 2015–2016 and 2023–2024. Across all these events, reefs near the Eastern Tropical Pacific latitudinal limits (Galápagos Islands, Southern Baja California, and continental Mexico) suffered the greatest and most widespread coral mortality and long-term consequences, including increased bioerosion, particularly after the 1982–1983 event [282]. However, impacts can also be highly localized. During the 2015–2016 event, high coral mortality was observed in the Gulf of Chiriquí (Panama), Islas Marías (Mexico), Clipperton Atoll, and Costa Rica, but was considerably less severe elsewhere. Additionally, anthropogenic climate change exacerbates El Niño impacts by raising baseline ocean temperatures, thereby increasing bleaching frequency and severity [282–284].

Conversely, La Niña introduces unique but similarly impactful stressors. Plunging temperatures can trigger cold-water bleaching, which caused significant coral mortality during the 2007–2008 event in the Galápagos and in 2008 and 2011 in the Gulf of California [285]. Furthermore, La Niña frequently drives low sea-level stands, increasing the probability of subaerial exposure during extreme low tides and resulting in massive coral mortality on shallow reef flats [284].



▲ **Figure 2.5.2.** Annual mean sea surface temperature (SST) anomalies (°C) over the coral reefs of the Eastern Tropical Pacific region from 1985 to 2025. SST anomalies were calculated based on the long-term average over the period 1985–2025. Positive values (red bars) indicate SST warmer than the long-term average, whereas negative values (blue bars) indicate SST cooler than the long-term average. Derived from NOAA Coral Reef Watch data (Skirving *et al.* [107]; see Materials and Methods).



▲ **Figure 2.5.3.** Percentage of the coral reefs within the Eastern Tropical Pacific region experiencing heat stress levels per year, from 1986 to 2025. No stress/Watch (DHW = 0); Warning (possible bleaching, $0 < DHW < 4$); Alert 1 (reef-wide bleaching, $4 \leq DHW < 8$); Alert 2 (reef-wide bleaching and mortality of heat-sensitive corals, $8 \leq DHW < 12$); Alert 3 (multi-species mortality, $12 \leq DHW < 16$); Alert 4 (severe multi-species mortality, $16 \leq DHW < 20$); and Alert 5 (near-complete mortality, $DHW \geq 20$). Derived from NOAA Coral Reef Watch data (Skirving *et al.* [107]; see Materials and Methods).

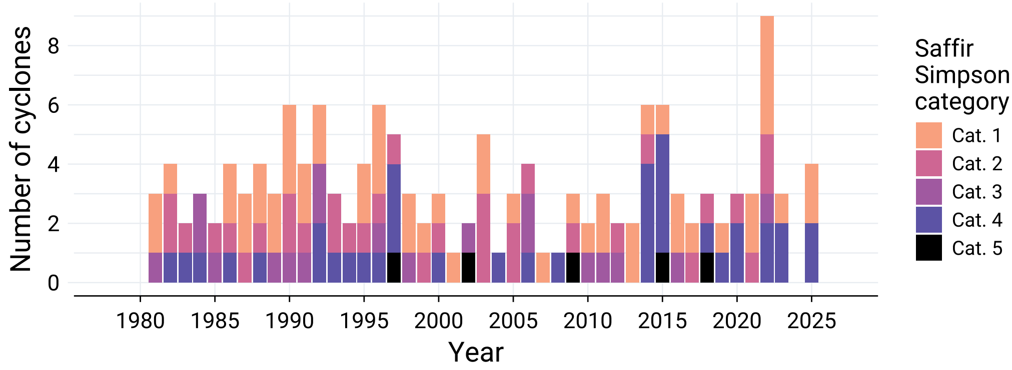
Cyclones

Cyclones in the Eastern Tropical Pacific originate north of 10° N and west of 90° W, and move towards the north-west, affecting mostly the oceanic islands of Revillagigedo and Clipperton, and the continental coasts of Nicaragua, El Salvador, Guatemala, and Mexico. The southern half of the region, including Costa Rica, Panama, Colombia, Ecuador, and their oceanic islands, is not affected by cyclones [286]. From 1980 to 2025, a total of 146 cyclones passed within 100 km of Eastern Tropical Pacific coral reefs, averaging 3.2 $\pm$ 1.8 SD cyclones per year (Figure 2.5.4). The cyclone with the highest sustained wind speed during this period was the cyclone Linda (September 1997) which passed 24 km from a reef with a wind speed of 274 km.h^{-1} (Figure 2.5.5). Although the 100 km threshold was selected, cyclones passing at a greater distance, not shown in Figure 2.5.5, may also impact coral reefs [108].

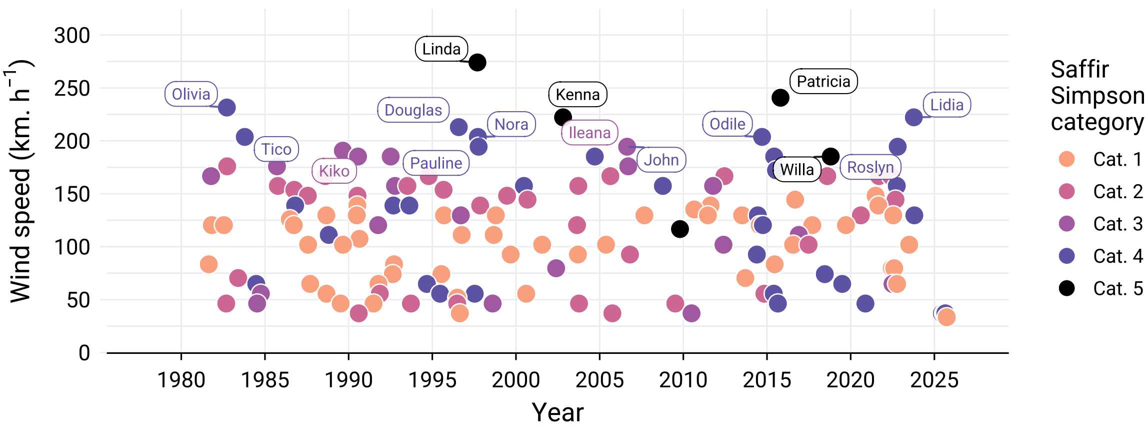
Other regional pressures

Shallow coral reef flats are subaerially exposed during extreme low tides across much of the equatorial Eastern Tropical Pacific, including in Ecuador, Colombia, Panama, and Costa Rica. With tidal amplitudes reaching up to 6 m, reefs in Panama and Colombia are particularly susceptible. At Saboga Island (Panama), for instance, at least 10 significant emersion events have occurred over a 24-year period [287]. These events, often intensified by La Niña's lower sea level stands [284], cause noticeable coral bleaching and mortality through desiccation, extreme heating, intense solar radiation, and osmotic stress from torrential rain during exposure [288, 289].

Upwelling significantly shapes Eastern Tropical Pacific coral reefs, acting as both a critical stressor and a potential refuge [290, 291]. Driven by seasonal trade winds that displace surface waters and force the shoaling of a shallow thermocline, upwelling introduces cool, low-oxygen deep waters into shallow habitats. The associated influx of nutrients and CO_2 lowers local pH, driving ocean acidification. Such conditions pose a severe threat to Eastern Tropical Pacific coral reefs [292] by lowering aragonite saturation states and inhibiting calcification. Reduced calcification not only stunts coral growth,



▲ **Figure 2.5.4.** Number of cyclones that passed within 100 km of the coral reefs of the Eastern Tropical Pacific region from 1980 to 2025. Colors correspond to the Saffir–Simpson category of the cyclone along its entire track. Derived from IBTrACS data (Knapp *et al.* [118]; see Materials and Methods).



▲ **Figure 2.5.5.** Maximum sustained wind speed of cyclones that passed within 100 km of a coral reef in the Eastern Tropical Pacific region between 1980 and 2025. Colors correspond to the Saffir–Simpson category of the cyclone along its entire track. However, the values of sustained wind speed are extracted from the nearest cyclone position from a coral reef. For this reason, some sustained wind speed values are below the lower threshold of category 1 Saffir–Simpson scale (*i.e.* 119 km.h^{-1}). Derived from IBTrACS data (Knapp *et al.* [118]; see Materials and Methods).

but also weakens the submarine cementation necessary to maintain reef frameworks [293, 294].

Finally, as coastal human populations expand, reefs face escalating localized threats, including overfishing, pollution, eutrophication, and increased sedimentation driven by coastal development [295].

STATUS OF CORAL REEFS IN THE REGION

The Eastern Tropical Pacific presents one of the most marginal environments for coral reef development in the world, yet coral reefs in the region exhibit remarkable resilience, consistently achieving rapid recovery in the wake of recurrent disturbances [284, 296]. Coral reefs in the Eastern Tropical Pacific are characterized by their low coral species diversity, yet they have a high potential for growth, often attaining high coral cover before being impacted by recurrent, large-scale natural disturbances like El Niño events and tidal emersion events. Consequently, live hard coral and algal cover are often highly dynamic. In addition, coral reefs are scarce, small, and patchy, making hard coral cover data highly spatially variable.

Hard coral cover

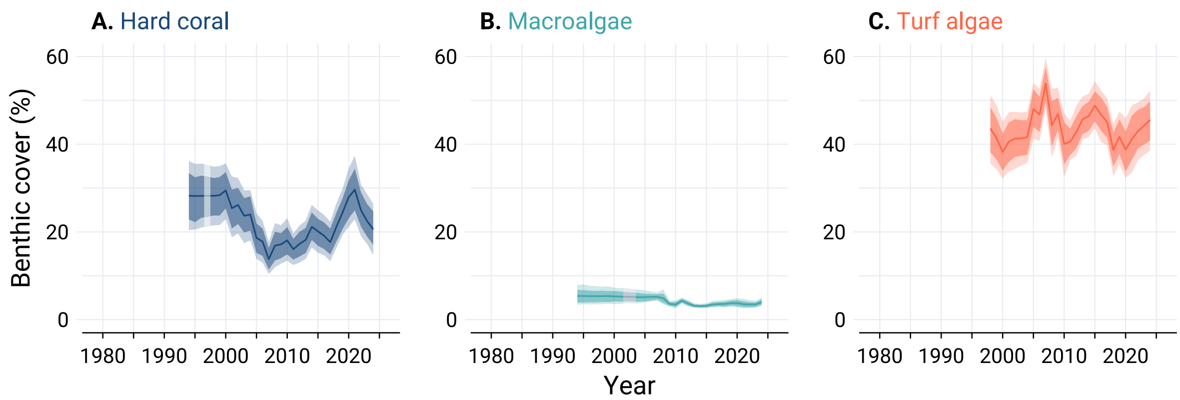
The data show no evidence of a change in hard coral cover between 1994–2009 and 2020–2024. However, this comparison masks periods of decline and increase, as hard coral cover throughout the Eastern Tropical Pacific has been highly dynamic over the last three decades (Figure 2.5.6A).

Hard coral cover declined from 28.1% in 1994 to 13.8% in 2007, corresponding to a loss of 14.3 percentage points, representing a 50.8% relative decline. This decline was followed by a fluctuating recovery, with strong evidence of hard coral cover increase from 2007 to 2021, rising from 15.9 percentage points over the period. Subsequently, however, hard coral cover was reduced to 20.6% by 2024 (Figure 2.5.6A).

Historically, periods of hard coral cover decline in this time series have been driven by recurrent natural disturbances, notably heat stress from the 1997–1998 El Niño (which most severely impacted reefs at the region's latitudinal edges) and significant tidal emersion events in the Panama Bight [289]. Mirroring these historical patterns, the most recent downturn (2021 to 2024) was driven by an extremely strong marine heatwave during the 2023–2024 El Niño, exacerbated by severe tidal emersion events at the beginning of both years.

Macroalgal cover

In contrast to hard coral cover, macroalgal cover has remained consistently low in the region, with a median of around 4.4% from 1994 to 2024 (Figure 2.5.6B). This low macroalgal cover is likely due both to the dominance of turf algae (Figure 2.5.6C) and to intense herbivory. Macroalgal cover remained around 5.2% between 1994 and 2008, declined to 3.4% in 2010, and has since ranged between 3.1% and 4.3% (Figure 2.5.6B).



▲ **Figure 2.5.6.** Modeled temporal trends of benthic cover in the Eastern Tropical Pacific region from 1980 to 2024 for hard coral (A), macroalgae (B), and turf algae (C). The solid line represents the estimated median benthic cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.

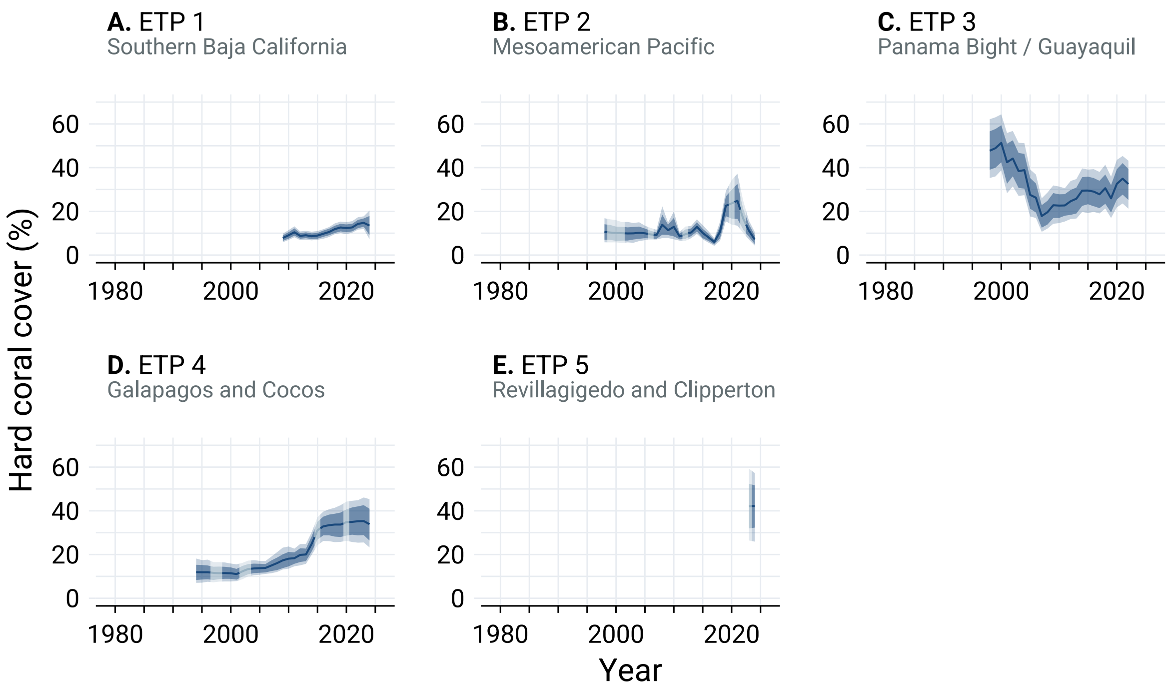
Turf algal cover

In the Eastern Tropical Pacific, turf algal cover has been several orders of magnitude higher and much more dynamic compared to macroalgal cover (Figure 2.5.6C). From 1994 to 2024, turf algal cover ranged between 38.2% and 53.8%, and showed no evidence of a change between the 1994–2009 and 2020–2024 periods (Figure 2.5.6C). There was strong evidence that turf algal cover increased between 1994 and 2007, rising by 10.2 percentage points over the period. This was followed by a period of decline between 2007 and 2014, with an absolute decline of 7.3 percentage points. Turf algal cover then remained relatively stable between 2014 and 2017, at around 46.7%. There was strong evidence of an increase in turf algal cover between 2018 and 2024, rising from 38.7% in 2018 to 45.5% in 2024, corresponding to an absolute gain of 6.6 percentage points (a 17.4% relative change).

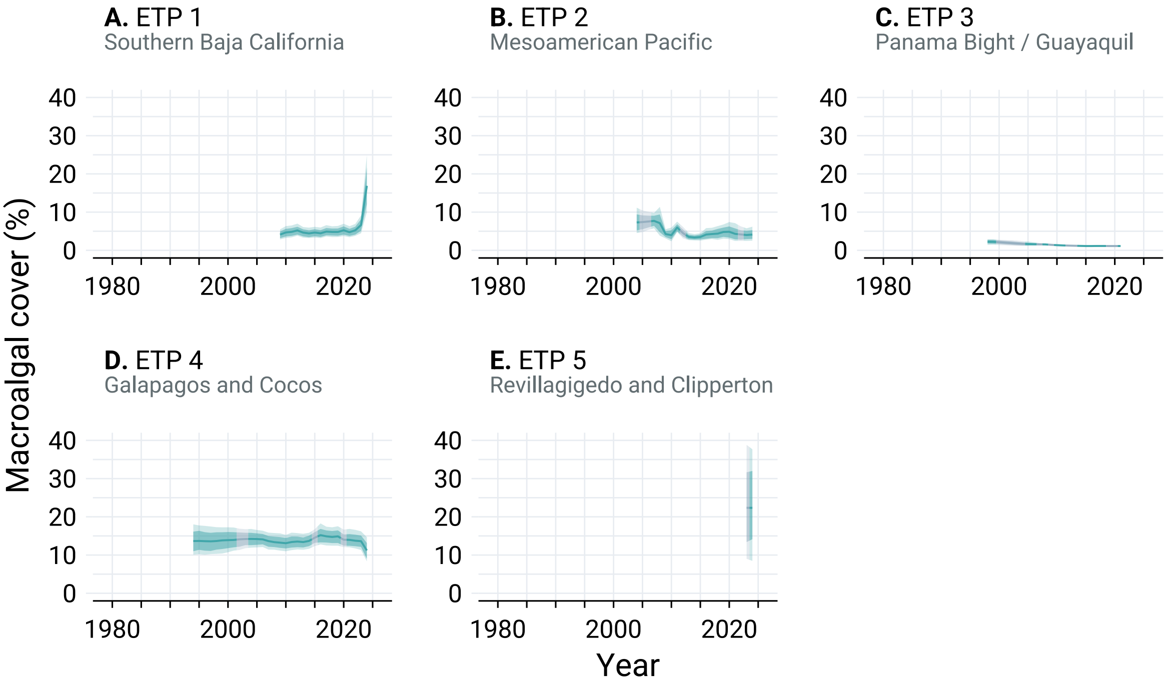
STATUS OF CORAL REEFS IN THE SUBREGIONS

ETP 1 - Southern Baja California

Hard coral cover within the Southern Baja California subregion demonstrates an atypical but general upward trend over the last 15 years. There was strong evidence that hard coral cover increased from 2009 to 2020–2024, rising from 7.8% in 2009 to a peak of 14.7% in 2023 (Figure 2.5.7A). This represents an absolute gain of 5.6 percentage points, corresponding to a 73.4% relative increase. Although largely consistent, this recovery experienced several minor interruptions, including a decline associated with cold-water bleaching in 2011–2012, a growth plateau around 2021, and a recent drop to 13.5% in 2024 following the severe 2023–2024 El Niño event.



▲ **Figure 2.5.7.** Modeled temporal trends of hard coral cover in Eastern Tropical Pacific (ETP) subregions from 1980 to 2024. The solid line represents the estimated median hard coral cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.



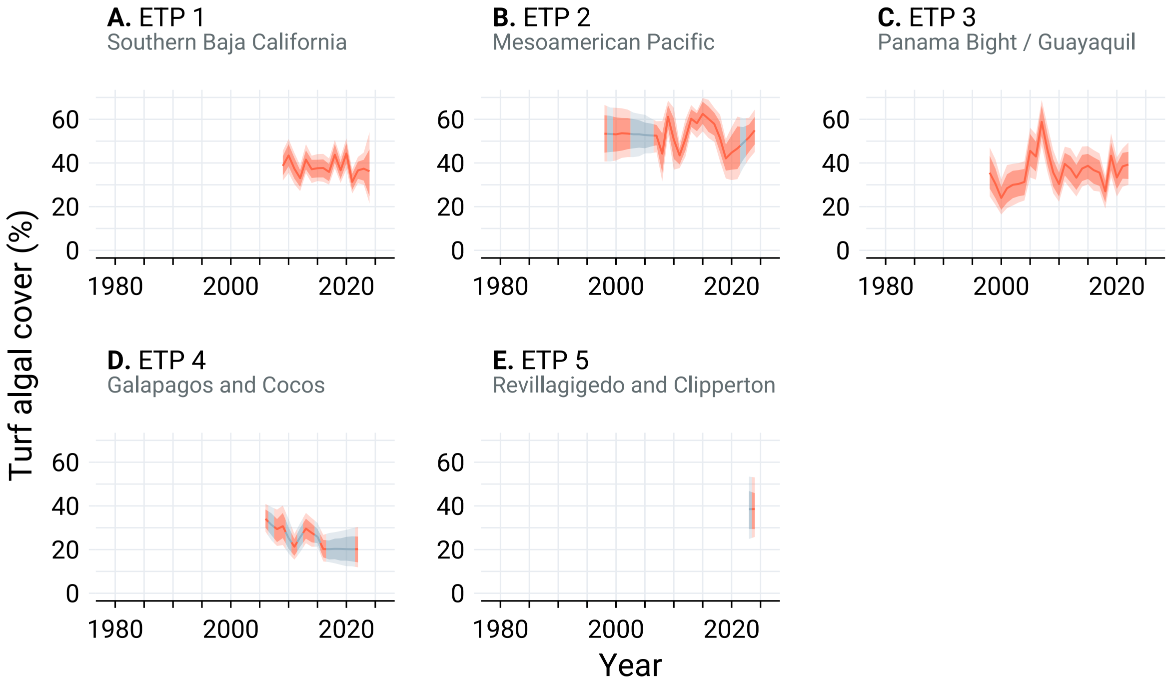
▲ **Figure 2.5.8.** Modeled temporal trends of macroalgal cover in Eastern Tropical Pacific (ETP) subregions from 1980 to 2024. The solid line represents the estimated median macroalgal cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.

Although mass coral mortality events since 2010 freed space for algal colonization, macroalgal cover has remained relatively low and stable at around 4.7% between 2009 and 2021 (Figure 2.5.8A). However, there was strong evidence that macroalgal cover increased between 2021 and 2024, rising from 4.7% to 16.9% over this period. The steepest part of this increase occurred between 2023 and 2024, concurrent with the recent El Niño and severe bleaching-driven hard coral decline (Figure 2.5.8A).

Turf algal cover remained relatively consistent, fluctuating interannually around 38.0%, without exhibiting a clear long-term trend or an apparent response to the 2015 and 2023–2024 bleaching events. Accordingly, there was no evidence of a change in turf algal cover between 2009 and 2020–2024 (Figure 2.5.9A). The relative stability of both macroalgal and turf algal cover likely reflects the consistently abundant herbivorous communities (fish and sea urchins) in the subregion [297, 298]. This supports the hypothesis that the macroalgal peak observed in 2024 may be transient.

ETP 2 - Mesoamerican Pacific

Hard coral cover in the Mesoamerican Pacific subregion generally remained stable with values fluctuating around 10.2% from 1998 to 2018, with no evidence of change over the period (Figure 2.5.7B), though this apparent stability at the subregional scale masks distinct local dynamics. Following a marked subregional low in median hard coral cover of 6.0% in 2017, there was strong evidence of an increase until 2021, when cover reached 24.9%, corresponding to an absolute gain of 18.9 percentage points. However, this transient peak is widely considered to be a sampling artifact resulting from heterogeneity in data collection. Beyond these artifacts, observed changes appear to be strongly driven by heat stress.



▲ **Figure 2.5.9.** Modeled temporal trends of turf algal cover in Eastern Tropical Pacific (ETP) subregions from 1980 to 2024. The solid line represents the estimated median turf algal cover while darker and lighter ribbons represent 80% and 95% credible intervals, respectively. Grey areas represent periods during which no field data were available.

There was strong evidence that macroalgal cover declined between 1998–2009 and 2020–2024, with a relative decrease of 39.4%. Macroalgal cover reached its highest values between 1998 and 2008, averaging around 7.4% (Figure 2.5.8B).

Turf algal cover in the subregion remained stable at around 53.1% from 1998 to 2007, but subsequently fluctuated, declining to 42.1% in 2019 before rising to a maximum of 55.0% in 2024 (Figure 2.5.9B). However, there was no evidence of a change in turf algal cover between 1998–2009 and 2020–2024.

ETP 3 - Panama Bight/Guayaquil

Hard coral cover in the Panama Bight/Guayaquil subregion experienced a pronounced decline from 47.7% in 1998 to a historical low of 17.9% in 2007 (Figure 2.5.7C). Accordingly, there was strong evidence of a decline in hard coral cover from the 2000s to the 2010s, corresponding to a decrease of 6.0 percentage points. Hard coral cover subsequently recovered until 2014, reaching 29.5%, a trajectory consistent with observations from Gorgona Island, Colombia [289]. More broadly, there was strong evidence of an increase in hard coral cover between the 2010s and the 2020s, with a gain of 6.1 percentage points.

Macroalgal cover in the Panama Bight/Guayaquil subregion showed strong evidence of a decline between 1998–2009 and 2020–2022, with an absolute decrease of 0.7 percentage points, corresponding to a relative decline of 37.9%. However, the decline from 1.8% to 1.1% also underscores the consistently low levels of macroalgal cover throughout the entire period (Figure 2.5.8C).

Conversely, turf algal cover increased almost continuously from 35.5% in 1998 to a peak of 58.8% in 2007 (Figure 2.5.9C). Between 2007 and 2013, there was strong evidence of a decline in turf algal cover, which fell to 33.2% before fluctuating around 36.7% until 2022.

ETP 4 - Galápagos and Cocos

The Galápagos and Cocos subregion exhibits a remarkable long-term recovery of hard coral cover, facilitated by its remote location shielding it from localized anthropogenic stressors. There was strong evidence of an increase in hard coral cover between 1994–2009 and 2020–2024, with a 21.7 percentage point absolute increase over the period (Figure 2.5.7D). Following an initial period of stability between 1994 and 2007, where hard coral cover averaged at 12.5%, there was strong evidence of an increase from 2007 to 2014. Indeed, hard coral cover rose from 15.0% to 24.9% between these two years, representing a 9.9 percentage point increase (a 66.3% relative change). This trend continued through 2017, when hard coral cover reached 33.4%. From 2018 to 2024, hard coral cover remained relatively stable, with no evidence of a change over the period. In the Galápagos Islands, hard coral cover recovery was exclusively confined to the northern Darwin and Wolf islands. Indeed, coral reefs were functionally lost across most of the archipelago after the catastrophic 1982–1983 El Niño, with their remaining frameworks reduced to rubble by the bioeroding sea urchin *Eucidaris galapagensis* [299].

Macroalgal cover in the Galápagos and Cocos subregion was the highest recorded across the entire Eastern Tropical Pacific region. However, there was no evidence of a long-term change in macroalgal cover between 1994–2009 and 2020–2024, with cover remaining around 13.8% throughout the period (Figure 2.5.8D). Nevertheless, there was strong evidence of a decline in macroalgal cover between 2018 and 2024, from 14.7% to 11.2%, respectively. The long-term stability in macroalgal cover was likely driven by conditions in the Northern Galápagos, where consistently high herbivorous fish biomass and strong hydrodynamic energy promote algal dislodgement [300].

There was no evidence of a change in turf algal cover between 1994 and 2007, during which it remained relatively stable at around 33.9%. Between 2007 and 2011, however, turf algal cover declined to 21.3%, mirroring the increase in hard coral cover observed over the same period. Following a transient increase to 29.6% in 2013, turf algal cover stabilized at around 20.3% from 2016 through 2024 (Figure 2.5.9D). Overall, there was strong evidence that turf algal cover declined between 1994–2009 and 2020–2024, corresponding to an absolute decrease of 12.9 percentage points.

ETP 5 - Revillagigedo and Clipperton

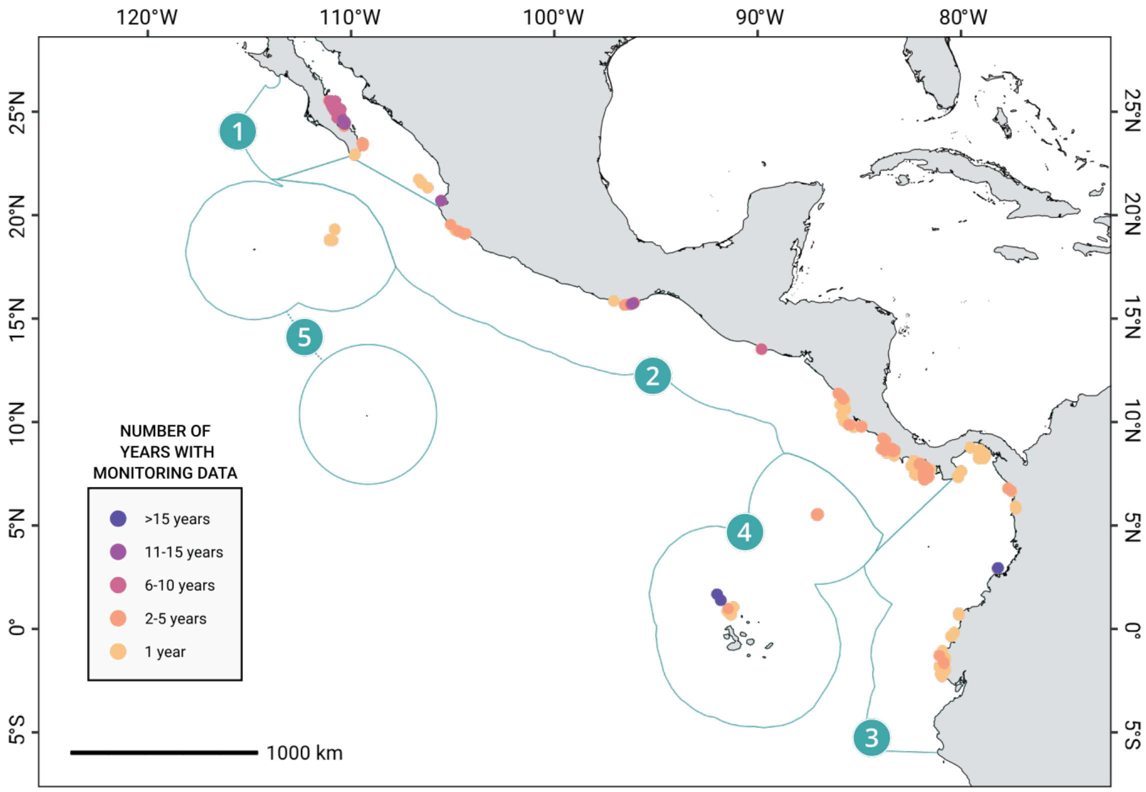
A single 2024 sampling in the Revillagigedo Islands provides the subregion's only data record, revealing median hard coral cover of 42.2% (Figure 2.5.7E), turf algal cover of 38.6% (Figure 2.5.9E), and an Eastern Tropical Pacific record macroalgal cover of 22.4% (Figure 2.5.8E). At Clipperton Atoll, hard coral cover approaches 100% in stable, deep-water refugia [301]. Despite periodic declines from recurrent ENSO anomalies and violent cyclones, overall hard coral cover steadily increased over the last two decades. Estimates of 42.3% at 5 m and 81.3% at 16 m in 1994 [301] rose to 48.7% in 2005 and 58.3% in 2019 [302]. However, severe global disturbances drove a major shift, transforming the coral reef from stress-susceptible branching *Pocillopora* to a highly resilient coral assemblage dominated by massive *Porites* [302].

DESCRIPTION OF MONITORING DATA

Temporal trends in the percentage cover of benthic categories were estimated using data from five datasets, encompassing 781 monitoring sites. These data were collected from 2,666 surveys conducted between 1994 and 2025, with 90% of surveys conducted after 2007 (Figure A.1). Of all surveys carried out in the region between 1994 and 2025, 36.8% (representing 49.4% of surveyed sites) were conducted in subregion 1, whereas only 0.4% (0.6% of sites) were conducted in subregion 5 (Table A.4).

CONCLUSIONS

The Eastern Tropical Pacific stands out as a comparatively resilient region amid the broader global coral reef crisis. Despite suboptimal environmental conditions and severe recurrent disturbances, including ENSO-driven marine heatwaves, cyclones, and extreme tidal emersion events, hard coral cover has shown an upward trajectory in three of the five subregions (Southern Baja California, Panama Bight/Guayaquil, and Galápagos and Cocos). However, this positive trend was likely disrupted by the severe 2023–2024 El Niño event.



▲ **Figure 2.5.10.** Spatio-temporal distribution of benthic cover monitoring sites across the Eastern Tropical Pacific region and respective subregions. Light blue polygons and numbers represent subregions. Subregion 1 = Southern Baja California, Subregion 2 = Mesoamerican Pacific, Subregion 3 = Panama Bight/Guayaquil, Subregion 4 = Galápagos and Cocos, Subregion 5 = Revillagigedo and Clipperton. The scale bar provides distance at the equator and may not accurately represent distance over the entire latitudinal range of the region.

Given the Eastern Tropical Pacific has experienced ocean warming rates comparable to those in other regions, the region's resilience can be attributed to its highly dynamic oceanography. The high natural environmental variability of the Eastern Tropical Pacific appears to mitigate the physiological impacts of extreme thermal fluctuations, effectively pre-conditioning corals to endure stress. Furthermore, local adaptation has played a critical role in driving this recovery. Evidence indicates that at some localities, *Pocillopora*, the dominant reef-building coral genus in the region, is shifting its symbiont algal composition toward species of the genus *Durusdinium*, conferring greater tolerance to high-temperature stress [303].

Ultimately, the Eastern Tropical Pacific demonstrates that coral reefs can adapt and persist despite severe environmental pressures. The long-term recovery observed across several subregions reinforces the region's status as a potential biological refuge, offering a uniquely positive perspective and valuable lessons for global reef conservation. However, whether reefs in the Eastern Tropical Pacific will continue to adapt and persist at a pace sufficient to keep up with ongoing global change remains uncertain.

DATA CONTRIBUTORS

Andrés Felipe Acosta-Chaparro, David Alejandro Alonso-Carvajal, Juan José Alvarado, Imelda G. Amador-Castro, Andrea Arriaga-Madrigal, Arturo Ayala-Bocos, William Bensted-Smith, Luis Calderon-Aguilera, Margarita Brandt, Jose Julio Casas-Maldonado, Luis Chasqui, Amilcar Leví Cupul-Magaña, Graham J. Edgar, Jan Freiwald, Diana Isabel Gómez-López, Ollin T. Gonzalez-Cuellar, Rebeca Granja-Fernández, Cristian Jitala, Inti Keith, Mathieu Leray, Andres Lopez-Perez, Priscilla Carlota Martínez-Panizo, Jenny Mihaly, Nicolas Moity, Raúl Navas-Camacho, Elizabeth Oh, Manuel Alejandro Olán-González, Damien Olivier, Sophie Osborn, Caroline Palmer, Georgina Ramírez-Ortiz, Héctor Reyes-Bonilla, Fernando E. Rivera, Favio J. Rivera-Martinez, Alma Paola Rodríguez-Troncoso, Jenny Carolina Rodríguez-Villalobos, Fabián A. Rodríguez-Zaragoza, Laura Sánchez-Valencia, Johanna Segovia-Prado, Rick D. Stuart-Smith, Omar Valencia-Mendez, Fernando A. Zapata.

Access to online supplementary materials

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

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