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Multi-temporal coral reef structure and health of Tayrona National Natural Park, Colombian Caribbean

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ABSTRACT

Introduction: Coral reefs are biodiversity-rich ecosystems increasingly threatened by disease and, in particular, mass bleaching events driven by elevated sea-surface temperatures.

Objectives: To assess spatio-temporal variation in reef structure and coral health across three reef zones within Tayrona National Natural Park (TNNP) from 1998 to 2023.

Methods: Coral cover (CC), algal cover (AC), and coral health (CH: bleaching and diseases) were quantified following the protocols of the Colombian Coral Reef Monitoring System.

Results: In Gayraca, mean CC was 37.05 %, dominated by massive corals with a declining trend. Mean AC was 43 %, and turf algae increased significantly through time. Black band disease and white plague were recorded with < 2 % incidence. In Chengue, mean CC was 30 % (massive corals), with disease incidence around 2 %, and the mean AC was 44 %. In Granate, mean CC was 28.2 %, largely massive corals with a downward trend, while mean AC was 47 %, dominated by turf algae with an increasing trend. Stony Coral Tissue Loss Disease (SCTLD) was not detected.

Conclusions: Bleaching increased sharply in 2023, reaching unprecedented levels. Across bays, we observed a tendency toward lower CC and higher AC in areas closer to human populations. Although disease prevalence across years was high, annual disease incidence remained low and did not track thermal stress, suggesting comparatively high biological robustness of local coral populations.

Key words: coral cover; coral health; Santa Marta; Colombian Caribbean.

RESUMEN

Análisis multitemporal de la estructura y salud coralina del Parque Nacional Tayrona, Caribe colombiano

Introducción: Los arrecifes de coral son ecosistemas de alta biodiversidad amenazados por enfermedades y especialmente blanqueamientos asociados con altas temperaturas.

Objetivos: Analizar la variación en la estructura y salud de tres zonas arrecifales dentro del Parque Nacional Natural Tayrona (PNNT) entre 1998 y 2023.

Métodos: Se evaluaron la cobertura coralina (CC), cobertura de algas (CA) y salud coralina (SC) como blanqueamiento y enfermedades, usando protocolos del sistema de monitoreo de arrecifes coralinos de Colombia.



Resultados: En Gayraca, la CC promedio fue 37.05 %, dominada por corales masivos con tendencia a la disminución. Las algas tuvieron una cobertura promedio de 43 %, destacando los tapetes con tendencia significativa al aumento. Se registró banda negra y plaga blanca con incidencia menor a 2 %. Chengue presentó una CC promedio de 30 %, dominada por corales masivos, y con una incidencia de enfermedades de un 2 %. Las algas alcanzaron un promedio de 44 %. En Granate, la CC promedio fue 28.2 % principalmente por corales masivos con tendencia a la disminución y las algas con un 47 %, dominadas por tapetes con tendencia al aumento. No se evidenció presencia de enfermedad de pérdida de tejido (SCTLD).

Conclusiones: Se evidenció aumento en el blanqueamiento para 2023 con valores nunca antes registrados, una tendencia a presentar menor CC y mayor CA en zonas más cercanas a poblaciones, una alta tasa de prevalencia de enfermedades, y una incidencia que se mantiene baja independientemente del estrés térmico, sugiriendo una alta robustez biológica de los corales en el área.

Palabras clave: cobertura coralina; salud coralina; Santa Marta; Caribe colombiano.

INTRODUCTION

Coral reefs are vital components of the global biosphere, functioning as major reservoirs of marine biodiversity and providing substantial nature's contributions to people (Buddemeier et al., 2004; Secaria-Fajardo et al., 2017; Wells & Hanna, 1992). Through coastal protection, fisheries production, and tourism, reefs sustain livelihoods and shape seascapes that underpin complex food webs (Birkeland, 1997; Buddemeier et al., 2004). Nevertheless, reefs have experienced widespread degradation due to natural disturbances (e.g., climatic anomalies, diseases, and bleaching) compounded by anthropogenic pressures (e.g., tourism, runoff, and overfishing), which can promote eutrophication and reduce water quality (Buddemeier et al., 2004; Burke et al., 2023; Díaz et al., 2000; García et al., 2003; Reyna-Fabián et al., 2018; Selman et al., 2008; Zapata & Vargas-Ángel, 2003). These stressors threaten biodiversity and the millions of people who depend on reef resources (González-Barrios et al., 2023; Sutherland et al., 2004; Wilkinson, 2008).

In response, Marine Protected Areas (MPAs) have been established to mitigate local impacts and preserve biodiversity. Tayrona National Natural Park (TNNP) was created in 1964 in the department of Magdalena (Colombian Caribbean) and includes extensive marine ecosystems, notably coral reefs. However, conservation remains challenged by proximity to

urban centers and accelerating coastal development, which intensify pressures on ecosystem services. Numerous studies have described the composition, structure, and dynamics of TNNP reefs (Bayraktarov et al., 2014a; Bayraktarov et al., 2014b; Díaz et al., 2000; Garzón-Ferreira & Cano, 1991; Garzón-Ferreira et al., 2002; Gómez-Cubillos et al., 2019; Gómez-Cubillos et al., 2020; Invemar-MinAmbiente, 2020; Martínez & Acosta, 2005; Navas-Camacho et al., 2010; Rodríguez-Ramírez et al., 2010; Vega-Sequeda et al., 2008). Collectively, this work indicates that reef structure and dynamics are shaped by multi-scale environmental drivers, including upwelling and salinity, and provides a baseline for conservation assessments and restoration planning.

Here, we compile and analyze historical monitoring records (1998-2023) of reef benthic structure and coral health in three major TNNP bays. Specifically, we evaluate temporal variation in coral and algal cover by growth form and identify the growth categories and taxa most affected by bleaching and disease, providing information to prioritize management and conservation actions in the park.

MATERIALS AND METHODS

TNNP is located on the Northeastern coast of Colombia and includes fringing reefs and coral patches covering approximately 750 ha (Díaz et al., 2000; Invemar-MinAmbiente,

2020). The park's Southwestern boundary lies adjacent to Taganga Bay (< 1 km) and ~5 km from the urban perimeter of Santa Marta. To the East, the park borders the municipality of Dibulla (~40 km from the main administrative area) and is influenced by runoff from the Piedras and MendiHuaca rivers (5-10 km from the Eastern sector) (Restrepo & Kjerfve, 2004). These proximities introduce localized terrestrial inputs and anthropogenic stressors that are relevant when assessing reef condition. The park is a biodiversity hotspot in the Colombian Caribbean, adjacent to the Sierra Nevada de Santa Marta, and hosts diverse coastal ecosystems including coral reefs, seagrass beds, algal mats, and mangroves (Garzón-Ferreira & Cano, 1991; Garzón-Ferreira & Díaz, 2003; Garzón-Ferreira, 1999).

Sampling sites were located in Chengue (4-12 m), Gayraca (8-12 m), and Granate (8-12 m) bays (Fig. 1). Each bay has a wind- and wave-exposed Western sector and a more sheltered Eastern sector. Seasonal winds drive coastal upwelling between December and April, generating physicochemical variability that can influence coral communities (Bayraktarov et al., 2013; Franco-Herrera, 2005). Together, these bays include some of the most extensive fringing and patch reefs in the Colombian continental Caribbean, with ~6.7 km² occupied by coral formations (Díaz et al., 2000; Invemar-MinAmbiente, 2020).

Data were collected in Chengue during 1998-2013, 2017, and 2023, and in Granate and Gayraca during 2003, 2004, 2008, 2010, 2013, 2017, and 2023.

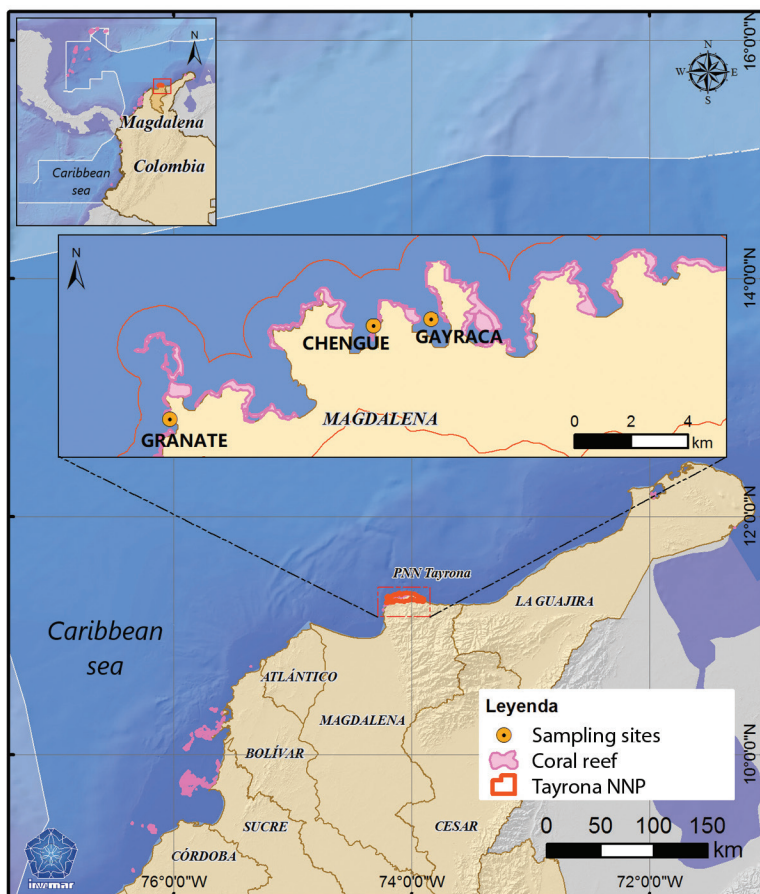


Fig. 1. Coral reef sampling sites in the TNNP at Granate, Chengue and Gayraca bays.

Field methods and growth-form classification followed CARICOMP Level 1 protocols (CARICOMP, 1994), modified for the Colombian Coral Reef Monitoring System. Corals were classified as branching, foliose, massive, or encrusting. Algae were classified as turf (filamentous, < 1 cm height), leafy (> 1 cm, soft), calcareous (hard, slightly elevated), or encrusting (hard layer with smooth texture) (Garzón-Ferreira et al., 2002).

Coral cover (CC) and algal cover (AC) were quantified using five 10 m transects per site, spaced linearly within areas with representative coral development. A guideline was laid along each transect, and a chain with 14.2 mm links was draped over the substrate. Substrate components and their proportional cover were estimated by counting links intercepting each component (Garzón-Ferreira et al., 2002). Coral health (CH) was assessed within 10 × 2 m belt transects aligned with the cover transects. All colonies > 5 cm diameter were recorded and classified as healthy or affected by bleaching and/or disease (black band, white band, yellow band, white plague, dark spots, white pox, tumors, or Stony Coral Tissue Loss Disease-SCTLD). Results are reported as the percentage of healthy, bleached, and/or diseased colonies by growth form for each bay.

CC and AC were averaged to obtain one value per sampling year and bay, both overall and by growth form. Temporal trends were evaluated using the Mann–Kendall test (Mann, 1945) implemented in PAST 4.03 (Hammer et

al., 2001). CH data were summarized as annual incidence (percentage of colonies affected each year) and overall prevalence (percentage of years with presence/absence across the time series), calculated following Weil et al. (2012).

RESULTS

Gayraca (Fig. 2) showed a mean CC of 37.05 ± 3.8 % SD and was dominated by massive corals (~33 % cover). *Montastraea cavernosa* was the most abundant species, followed by *Pseudodiploria strigosa*, *Orbicella franksi*, and *Porites astreoides*. Other taxa (e.g., *Agaricia agaricites*, *Siderastrea siderea*, *Colpophyllia natans*, and *Meandrina meandrites*) each contributed < 4 % cover. Mean AC was 43.02 ± 4.4 % SD; turf and encrusting algae dominated (28.9 % and 11 %, respectively), whereas calcareous and leafy algae remained low (< 4 %). Coral cover was relatively stable after 2008, but trend tests indicated a decline in massive corals (Mann–Kendall $S = -17$, $p = 0.01$) and an increase in turf algae ($S = 13$, $p = 0.03$) (Table 1). Disease prevalence included black band (14 %), dark spots (71 %), white plague (71 %), and yellow band (14 %), with incidence generally near 2 %; SCTLD was not observed. Bleaching peaked in 2010 and 2023, primarily affecting *M. cavernosa* and *Diploria labyrinthiformis* (incidence 10.2 % and 10.6 %, respectively).

Chengue (Fig. 3) had a mean CC of 30.02 ± 2.16 % SD and was dominated by massive corals (~27 % cover), mainly *P. strigosa*, *S. siderea*,

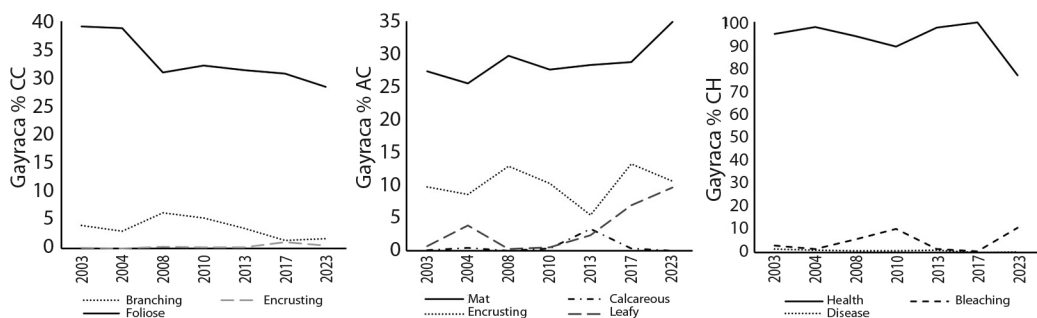


Fig. 2. Coral cover (CC), Algal Cover (AC) and Coral Health (CH) in Gayraca bay.

Table 1
Mann–Kendall trend tests for each growth category and bay.

Bay	Coral	Mann-Kendall test	Trend	Algae	Mann-Kendall test	Trend
Gayraca	Branching	Not reported		Turf 0.03	S 13	Increase
		p 0.03				
	Encrusting	S -9	No	Calcareous	S 0	No
		p 0.119			p 0.5	
	Foliose	S 11	No	Encrusting	S 5	No
		p 0.1			p 0.28	
	Massive	S -17	Decrease	Leafy	S 11	No
		p 0.01			p 0.6	
Chengue	Branching	S -63	Decrease	Turf	S 3	No
		p 0.01			p 0.93	
	Encrusting	S -96	Decrease	Calcareous	S 21	No
		p < 0.05			p 0.4	
	Foliose	S 7	No	Encrusting	S -2	No
		p 0.8			p 0.96	
	Massive	S -10	No	Leafy	S 42	No
		p 0.71			p 0.09	
Granate	Branching	S -6	No	Turf	S 15	Increase
		p 0.14			p 0.001	
	Encrusting	S 3	No	Calcareous	S 2	No
		p 0.36			p 0.36	
	Foliose	S 8	No	Encrusting	S 5	No
		p 0.07			p 0.23	
	Massive	S 11	Decrease	Leafy	S 0	No
		p 0.03			p 0.5	

S is the Mann–Kendall statistic and p is the significance value (significant at $p < 0.05$).

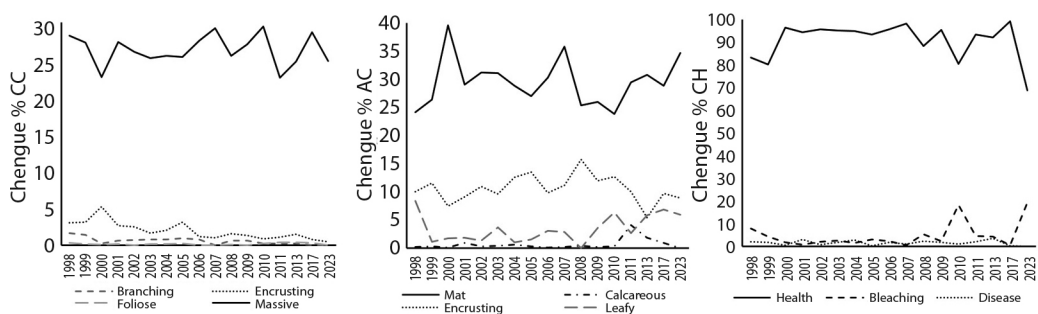


Fig. 3. Coral cover (CC), Algal Cover (AC) and Coral Health (CH) in Chengue bay.

and *Orbicella faveolata*. Encrusting, branching, and foliose corals each contributed $< 3\%$ cover. Mean AC was $44.12 \pm 2.88\%$ SD and was largely turf algae ($\sim 30\%$ cover); calcareous, encrusting, and leafy algae averaged 0.6, 10.6, and 3.4 %, respectively. Massive coral cover

fluctuated over the years, whereas other growth forms remained consistently low; algal cover varied more strongly, particularly turf. Trend tests indicated significant declines in branching (Mann-Kendall $S = -63$, $p = 0.01$) and encrusting corals ($S = -96$, $p < 0.05$), while algal trends

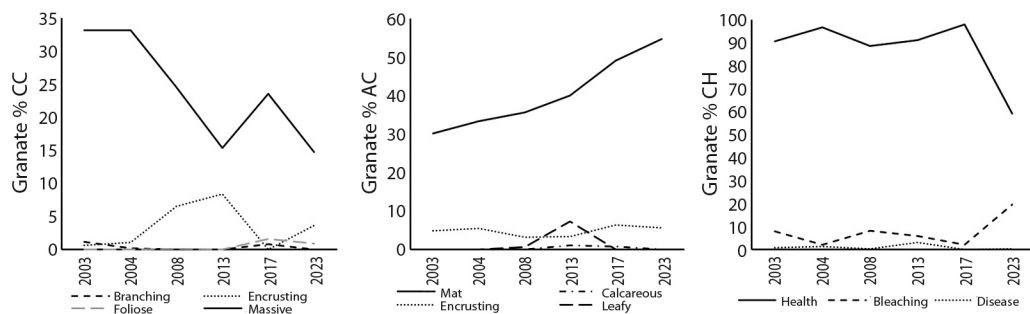


Fig. 4. Coral cover (CC), Algal Cover (AC) and Coral Health (CH) in Granate bay.

were not significant (Table 1). Documented diseases included black band (prevalence 37 %), white spots (18 %), dark spots (94 %), white band (41 %), white plague (100 %), white pox (24 %), and yellow band (41 %), all with incidence < 2 %. SCTLD was not recorded. Bleaching increased in 2010 (18.2 %) and was highest in 2023 (19.5 %), mainly affecting *O. faveolata* and *D. labyrinthiformis*.

Granate (Fig. 4) exhibited a mean CC of 28.2 ± 5 % SD and was dominated by massive corals, particularly *O. franksi*. Mean AC was 47 ± 9.1 % SD, with turf algae accounting for 40.5 % cover; encrusting algae averaged 4.6 %, and leafy and calcareous algae each remained < 2 %. Massive coral cover declined through time, whereas most algal categories were stable except for turf, which increased and showed greater interannual variability. Trend tests indicated a decline in massive corals (Mann-Kendall $S = -11$, $p = 0.03$) and an increase in turf algae ($S = 15$, $p = 0.001$) (Table 1). Dark spots (prevalence 20 %) and white pox (80 %) were observed, affecting < 3 % of colonies. Bleaching was recorded mainly in *O. franksi*, with peaks in 2008 (8.4 %) and 2023 (22 %). SCTLD was not reported.

DISCUSSION

The shift toward higher algal cover relative to coral cover has been previously documented in TNNP (Gómez-Cubillos, 2020; Márquez & Díaz, 2005; Vega-Sequeda et al., 2008) and is

often interpreted as a consequence of coral mortality rather than its primary cause (McCook et al., 2001; Mejía-Niño & Garzón-Ferreira, 2003). Multiple drivers may contribute, including reduced herbivory following the decline of key grazers such as *Diadema antillarum*, whose populations in TNNP have decreased by ~93 % despite their role in limiting algal proliferation (González-Gaviria & García-Ureña, 2011; Levitan et al., 2023). Additional pressures include invasive species that alter community interactions and may introduce pathogens (Acero et al., 2019; Gómez-Cubillos et al., 2019), as well as pollution, sedimentation, eutrophication, and warming (Díaz et al., 2000; Rogers & Miller, 2006), which can promote macroalgal phase shifts, intensify bleaching, and reduce biodiversity and structural complexity. In TNNP, these stressors are spatially structured: bays closer to population centers and to continental discharges (e.g., Granate) tend to be more impacted than more distant bays (e.g., Chengue and Gayraca) (Erhardt & Werding, 1975; Martínez & Acosta, 1993; Zea, 1993). Conversely, TNNP oceanography is strongly influenced by seasonal coastal upwelling driven by the Northeast Trade Winds (December–April), which introduces cooler, nutrient-rich waters and shapes local thermal regimes (Duarte et al., 2024).

Our results are consistent with this spatial gradient. Gayraca—farthest from major terrestrial and urban influences—showed the highest mean CC and lowest mean AC, followed by Chengue and then Granate. Similar patterns

have been reported elsewhere, where proximity to population centers and nutrient-enriched runoff (e.g., phosphorus and organic carbon) can favor algal dominance and compromise coral performance, particularly near sources of input (Barott et al., 2012; Gómez-Cubillos et al., 2015; Gómez-Cubillos et al., 2019; Gómez-Cubillos et al., 2020; Martínez & Acosta, 2004; McClanahan et al., 2002).

The significant declines in massive corals in Gayraca and Granate, coupled with increasing turf algae, have important implications for resilience. Both bays contained higher representation of *Orbicella* spp., which generally show low recruitment (Alvarado-Chacón et al., 2020; Miller et al., 2000) and can be disproportionately affected by bleaching and disease under stress (Navas-Camacho et al., 2010; Restrepo & Alvarado, 2011). Expanding turf assemblages can trap sediments and impede coral recovery, while occupying available substrate and creating physical and chemical barriers to larval settlement and early survival (Birrell et al., 2005; Gorgula & Connell, 2004; Harris, 2015; Gómez-Cubillos et al., 2019). In contrast, Chengue's dominance by disturbance-tolerant taxa such as *S. siderea* and *P. strigosa* (Acevedo et al., 1989; Caballero et al., 2004; Cubillos-Romero, 2024) may contribute to the comparatively stable massive coral cover and reduced opportunity for algal expansion. The observed declines in encrusting and branching corals in Chengue likely reflect susceptibility to breakage and fragmentation, which can cause partial mortality but may also generate asexual recruits depending on local conditions (García-Ureña et al., 2020; Hughes & Connell, 1999).

Overall, our findings reflect regional coral deterioration and the capacity of algae to out-compete corals when environmental conditions are favorable (Buddemeier et al., 2004; de Bakker et al., 2017; Harris, 2015; Hughes et al., 2017; Rogers & Miller, 2006; Sully et al., 2019). Similar trajectories have been reported across Colombian reefs and other tropical systems (Acosta-Chaparro et al., 2025; Garzón-Ferreira, 1998; Kramer, 2003; Rodríguez-Ramírez et al., 2006; Wicquart et al., 2025). Notably, mean

CC in TNNP remains comparatively high relative to other Colombian localities, including Corales del Rosario y San Bernardo (37.9 % in 2023; Invemar, 2025) and Old Providence McBean Lagoon (37.1 % in 2023; Invemar, 2024), and to parts of the Mesoamerican Reef where CC was < 25 % in 2023 (McField et al., 2024). This underscores the importance of sustaining protection and strengthening medium- and long-term strategies, including active restoration initiatives such as “One million corals for Colombia”, which combine nursery production and outplanting with monitoring of local stressors.

Bleaching peaks were observed in 1997–1999 (Chengue), 2003 (Granate), and in 2010 and 2023 across all bays. The drivers of the 1997–1998 event are not fully resolved but may be linked to elevated sea-surface temperatures during El Niño (Rodríguez-Ramírez et al., 2010; Wiedenmann et al., 2013). Severe bleaching and coral mortality were reported throughout the wider Caribbean during this period, with 50–90 % of corals affected in Belize, Honduras, and Panama (Wilkinson, 2000). The 2003 Granate event has been associated with localized warming near populated areas during periods of increased rainfall (Leal-Cancelado, 2003; Romero-Rodríguez et al., 2014). In 2010, region-wide warming was linked to anomalously high rainfall across the Caribbean, coinciding with severe bleaching across many reefs (Navas-Camacho et al., 2010; Romero-Rodríguez et al., 2014). In our study region, freshwater inputs—particularly from the Magdalena River—can be influential during periods of weak winds and reduced upwelling, when cooling is diminished (Bayraktarov et al., 2013; Martínez & Acosta, 2005).

The most recent mass bleaching episode (February 2023–April 2024; NOAA, 2024) appears to be the most severe on record. Reports from Colombia indicate > 70 % of coral formations affected, and aerial surveys documented extensive bleaching on the Great Barrier Reef in 2024 (> 60 % of surveyed cover) (Cantin et al., 2024). NOAA (2024) recognized this as the fourth global bleaching event since 1982 and



the second within the last decade, reinforcing the need for combined global emissions mitigation, local stressor reduction, and targeted restoration (Reimer et al., 2024). Estimates of bleaching magnitude and severity depend on how closely assessments coincide with the disturbance, and the full consequences for TNNP are still being quantified. Future evaluations should integrate physicochemical and oceanographic variables to resolve spatial patterns (Gil-Agudelo et al., 2005; Romero-Rodríguez et al., 2014). In TNNP, seasonal upwelling in the dry season increases salinity and lowers temperatures (Bayraktarov et al., 2013), potentially providing a thermal refuge and facilitating recovery, however, increasingly intense and prolonged heat anomalies may exceed this buffering capacity.

The occurrence in TNNP of the full suite of diseases reported for the Colombian continental Caribbean (Gil-Agudelo et al., 2009; Navas-Camacho et al., 2010) suggests that potential exposure is high, consistent with the Caribbean being a global hotspot for coral diseases. However, annual incidence in our time series generally remained < 4 %, which may indicate limited transmission and/or acquired resistance. Even at low incidence, disease-related mortality can be substantial when entire colonies are affected, as documented for white plague (e.g., *C. natans*), black band (e.g., *O. faveolata*), and white pox (e.g., *Acropora palmata*). Continued monitoring is therefore essential, particularly given the cumulative nature of reef degradation (Hawkins & Roberts, 1997). Importantly, the absence of SCTLTD suggests that this highly virulent disease has not yet reached the Colombian continental Caribbean, a positive finding given its documented lethality in massive corals (Lucas et al., 2024).

Our results differ from the pattern described by Bruno et al. (2007), in which temperature spikes coincide with large disease outbreaks. Instead, the persistently low incidence we observed is consistent with Bayraktarov et al. (2013), who reported that ~90 % of colonies bleached in 2010 within TNNP recovered. This supports the interpretation that,

with respect to disease and bleaching, TNNP reefs can exhibit comparatively high resistance despite local stressors (West & Salm, 2003). Notably, disease incidence remained below 2 % in 2023 despite unprecedented bleaching, suggesting substantial physiological resistance or biological robustness in local coral populations. Recurrent exposure to thermal variability in upwelling systems may promote acclimation that reduces host susceptibility to opportunistic pathogens (Anthony et al., 2015). Consequently, TNNP may function as a regional refuge where disease impacts remain limited relative to broader Caribbean trends.

Ethical statement: The authors declare that they all agree with this publication and made significant contributions; that there is no conflict of interest of any kind; and that we followed all pertinent ethical and legal procedures and requirements. All financial sources are fully and clearly stated in the acknowledgments section. A signed document has been filed in the journal archives.

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