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Long-term decline of *Acropora palmata* (Scleractinia: Acroporidae) in San Andrés Island: 25 years of monitoring inside a Marine Protected Area

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ABSTRACT

Introduction: The condition of coral reefs in the Caribbean has deteriorated sharply over the past few decades, with *Acropora palmata* — historically a dominant reef-building coral — experiencing a regional decline of over 90 % due to the cumulative impacts of white band disease, hurricanes, and recurrent thermal stress. In response, Marine Protected Areas (MPAs) have been widely implemented across the region, yet their effectiveness in conserving vulnerable coral species remains uncertain.

Objective: To document long-term trends in *A. palmata* cover at Little Reef, a secondary barrier reef located within the Seaflower MPAs surrounding San Andres Island, Colombia.

Methods: Using standardized ecological monitoring protocols (CARICOMP, SIMAC, and years in which RRA was conducted), we analyzed coral cover based on five monitoring events (1995, 2002, 2006, 2021, 2024) spanning 29 years at a representative reef site in the Seaflower Biosphere Reserve.

Results: Our results reveal a dramatic and statistically significant decline in *A. palmata* cover, from ~45 % total coral cover (dominated by *A. palmata*) in 1995 to just 1.13 % in 2024. The 2023 mass bleaching event led to near-complete mortality, with no visible signs of recovery observed during 2024 surveys. Statistical analyses confirmed a strong negative trend (Kendall's Tau = -1.0, p = 0.017; R² = 0.865, p = 0.022), indicating sustained decline despite long-term protection.

Conclusions: These findings reinforce growing evidence that MPAs alone may be insufficient to prevent coral loss under accelerating climate pressures. We highlight the need for conservation frameworks that combine passive protection with active restoration, climate-adaptive management, and genetic rescue approaches to safeguard *A. palmata* and other threatened reef-building species across the Caribbean.

Key words: Caribbean coral reefs; climate change; coral bleaching; coral reef decline; Marine Protected Areas; Seaflower Biosphere Reserve.



RESUMEN

Declive a largo plazo de *Acropora palmata* (Scleractinia: Acroporidae) en la isla de San Andrés: 25 años de monitoreo dentro de un Área Marina Protegida

Introducción: La condición de los arrecifes coralinos en el Caribe se ha deteriorado drásticamente durante las últimas décadas, con *Acropora palmata* — históricamente un coral formador de arrecifes dominante — experimentando un declive regional de más del 90 % debido a los impactos acumulativos de la enfermedad de la banda blanca, huracanes y estrés térmico recurrente. En respuesta, las Áreas Marinas Protegidas (AMPs) se han implementado ampliamente en la región, pero su efectividad en la conservación de especies de coral vulnerables sigue siendo incierta.

Objetivo: Documentar las tendencias a largo plazo en la cobertura de *A. palmata* en Little Reef, un arrecife de barrera secundaria ubicado dentro de las AMPs Seaflower que rodean la isla de San Andrés, Colombia.

Métodos: Utilizando protocolos estandarizados de monitoreo ecológico (CARICOMP, SIMAC y los años en que se realizó RRA), analizamos la cobertura coralina basada en cinco eventos de monitoreo (1995, 2002, 2006, 2021, 2024) que abarcan 29 años en un sitio arrecifal representativo de la Reserva de Biosfera Seaflower.

Resultados: Nuestros resultados revelan un descenso dramático y estadísticamente significativo en la cobertura de *A. palmata*, de ~45 % de cobertura coralina total (dominada por *A. palmata*) en 1995 a solo 1.13 % en 2024. El evento de blanqueamiento masivo de 2023 provocó una mortalidad casi total, sin signos visibles de recuperación observados durante los monitoreos de 2024. Los análisis estadísticos confirmaron una fuerte tendencia negativa (Tau de Kendall = -1,0, $p = 0,017$; $R^2 = 0,865$, $p = 0,022$), indicando un declive sostenido a pesar de la protección a largo plazo.

Conclusiones: Estos hallazgos refuerzan la creciente evidencia de que las AMPs por sí solas pueden ser insuficientes para evitar la pérdida de corales bajo presiones climáticas aceleradas. Destacamos la necesidad de marcos de conservación que combinen la protección pasiva con restauración activa, manejo adaptativo al clima y enfoques de rescate genético para salvaguardar *A. palmata* y otras especies de corales formadores de arrecifes amenazadas en todo el Caribe.

Palabras clave: arrecifes coralinos del Caribe; cambio climático; blanqueamiento de corales; declive de arrecifes; Áreas Marinas Protegidas; Reserva de Biosfera Seaflower.

INTRODUCTION

Coral reefs are among the most productive and diverse marine ecosystems, providing vital ecological services such as coastal protection, fisheries, and habitat for thousands of marine species (Hoegh-Guldberg et al., 2007; Moberg & Folke, 1999). However, in recent decades these ecosystems have experienced severe and accelerating degradation, largely due to climate change, widespread bleaching, disease outbreaks, overfishing, and pollution (Bindoff et al., 2019; Gardner et al., 2003; Hughes et al., 2017; Pandolfi et al., 2003; Souter et al., 2021). These factors have led to a dramatic decline in coral cover and structural complexity, compromising the ecological functions and services of reef systems (Alvarez-Filip et al., 2009; Graham & Nash, 2013).

In the Caribbean, coral cover has declined significantly, with the loss of reef-building species fundamentally altering reef structure and function (Alvarez-Filip et al., 2009; Jackson et al., 2014). Among the most affected species is *Acropora palmata* (Lamarck, 1816), commonly known as elkhorn coral, which was historically the dominant shallow-water reef-builder across the region (Cramer et al., 2020). Since the 1980s, *A. palmata* populations have declined by over 90 %, largely due to white band disease, white pox disease, hurricanes, and thermal stress, leading to its classification as Critically Endangered by the IUCN (Aronson & Precht, 2001; International Union for Conservation of Nature and Natural Resources [IUCN], 2024; Miller et al., 2022; Neely et al., 2022). This decline has reduced reef complexity, biodiversity, and ecosystem services essential for coastal

communities especially those associated with wave energy reduction and coastal protection (Alvarez-Filip et al., 2009).

Marine Protected Areas (MPAs) have been established throughout the Caribbean to safeguard coral reefs. Yet, the continued decline of coral populations within MPAs highlights the limitations of passive protection under accelerating climate pressures (Selig & Bruno, 2010). MPAs are often designed with the expectation that reducing local stressors—such as overfishing or physical damage—will allow ecosystems to recover naturally (Allison et al., 1998). This rationale is based on the ecological mechanisms by which MPAs may enhance reef resilience, such as maintaining higher herbivorous fish biomass to reduce macroalgal competition, lowering direct anthropogenic damage, and preserving water quality. However, when chronic global stressors like marine heatwaves dominate, even well-enforced MPAs may fail to prevent coral mortality or facilitate recovery (Bruno et al., 2018; Mumby & Harborne, 2010). The Seaflower MPAs, surrounding San Andres Island, is one of the largest in the Caribbean (Guarderas et al., 2008) and includes zones under complete protection from extractive activities. Despite this, the island's reefs remain vulnerable to global stressors such as mass bleaching and disease outbreaks linked to climate change. In San Andres, long-term monitoring has documented progressive declines in coral cover, including the loss of *A. palmata* in several sites (Abril-Howard & Bolaños-Cubillos, 2007; Acosta-Chaparro, 2021; Pizarro, 2002).

Given that Marine Protected Areas may enhance coral persistence by reducing local stressors—such as herbivore depletion, sedimentation, and coastal pollution—the Seaflower MPAs provides an opportunity to evaluate whether long-term protection can mitigate the decline of a historically dominant reef-builder. However, monitoring at Little Reef has not been conducted annually, but rather through standardized assessments implemented in selected years between 1995 and 2024; thus, the resulting dataset represents a composite temporal

record rather than a continuous time series. Within this context, we hypothesized that if local management benefits were sufficient to buffer environmental stress, *A. palmata* within the MPAs would show signs of resistance or persistence relative to regional declines. Conversely, if thermal stress is the overriding driver, population trajectories inside the MPAs should mirror the broader Caribbean collapse. By analyzing approximately three decades of monitoring data, we aim to determine whether observed patterns reflect localized resilience supported by MPA-associated mechanisms or align with climate-driven regional degradation, thereby assessing the extent to which MPA status confers ecological persistence under intensifying thermal stress.

MATERIALS AND METHODS

Study site: All surveys were conducted at the same shallow fore-reef site at Little Reef, ensuring consistent spatial coverage across years. Little Reef is a small secondary barrier reef located within the lagoon on the northern leeward side of San Andres Island, Colombia (Fig. 1), (12°35'00" N, 81°41'08" W), inside the Seaflower MPAs, part of the Seaflower Biosphere Reserve (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2000). The reef lies approximately 120 m from the shoreline in the preservation (no-entry) zone of Spratt Bight and directly adjacent to the island's most densely populated urban area, making it both ecologically important and highly exposed to local stressors. Historically dominated by *Acropora palmata*, Little Reef has been the focus of ecological assessments since the 1990s due to its accessibility and its importance as one of the emblematic shallow habitats in the archipelago.

Data sources and monitoring protocols: Historical and recent data on *A. palmata* cover were compiled from monitoring efforts conducted between 1995 and 2024, derived from three standardized protocols widely applied in Colombia and the wider Caribbean: Caribbean

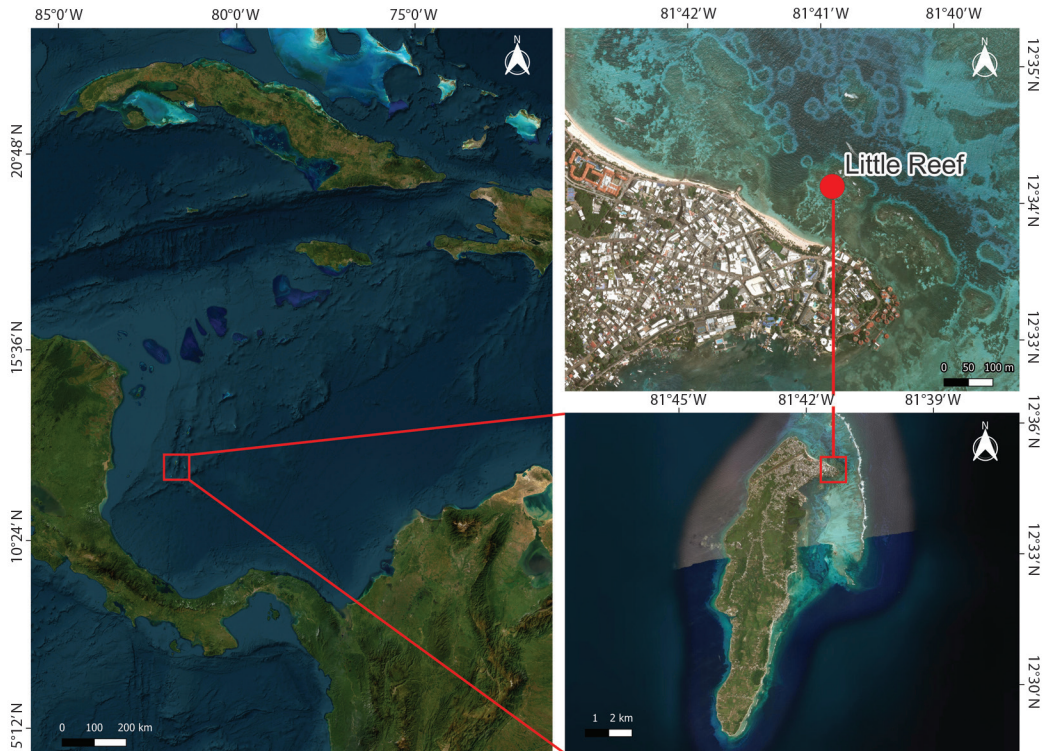


Fig. 1. Map of San Andres Island, Colombian Caribbean, showing the location of Little Reef, a secondary barrier reef system historically dominated by *Acropora palmata*.

Coastal Marine Productivity Program [CARICOMP] (CARICOMP, 2001) (1995–2003), the National Coral Reef Monitoring System of Colombia – SIMAC (Garzón-Ferrera & Rodríguez-Ramírez, 2010) (2004–2014), and Rapid Reef Assessments (RRA) surveys conducted in specific years (Acosta-Chaparro, 2021; Díaz et al. 1995; Pizarro, 2002; and the authors in 2024 for this study). Although sampling designs differed among programs, all surveys estimated benthic cover in situ through direct visual assessment, using line-intercept transects (CARICOMP, SIMAC) or consensus-based visual estimations around fixed georeferenced points (RRA). CARICOMP and SIMAC generally employed multiple 10-m line-intercept transects per station (typically 3–5, when reported in technical documents), whereas RRA surveys consisted of one or two consensus-based visual assessments around fixed georeferenced points per sampling event. To ensure methodological

consistency across time, we selected only the metric that was consistently recorded across all monitoring protocols: live coral cover percent (LCC) (*A. palmata*). Although sampling frequency varied, the dataset provides one representative estimate per monitoring year, allowing detection of long-term trends. Regardless of method, all data were standardized to express *A. palmata* cover as a percentage of the total benthic area surveyed in each sampling event. This allowed for direct temporal comparison, despite the methodological transitions.

Although some data sources did not explicitly distinguish coral species, *A. palmata* was historically the dominant—and often exclusive—species in the shallow reef zone at Little Reef. Consequently, LCC was interpreted as representative of *A. palmata* when historical monitoring reports described monospecific or strongly *A. palmata*-dominated stands at the site. This approach was applied consistently

across years based on visual assessments, photographic archives, and historical descriptions of the site.

Historical data were digitized from Abril-Howard & Bolaños-Cubillos (2007), Díaz et al. (1995), and Pizarro (2002). More recent monitoring includes the 2021 INVEMAR survey (Acosta-Chaparro, 2021), which employed five 10-m line-intercept transects per station, and our 2024 field assessment, which consisted of three 10-m transects placed across the shallow *A. palmata* zone of Little Reef. Photographs included in these surveys were used to confirm the continued presence—and subsequent loss—of *A. palmata* at the site.

Data analysis: To quantify long-term trends in *A. palmata* cover, we applied non-parametric statistics appropriate for non-normal ecological time series. Kendall's Tau-b (Kendal, 1955) and Spearman's rank correlation were used to assess monotonic trends over time, and simple linear regression was used to estimate the rate of change. Prior to analysis, data were transformed using arcsine square root for proportions and $\log(x+1)$ for counts to reduce skewness and heteroscedasticity. All analyses were conducted in R version 4.3.1 (R Core Team, 2023), using the packages stats for non-parametric tests, trend for Kendall's tau implementation, ggplot2 (Wickham, 2016) for data visualization, and dplyr (Wickham et al., 2025a) and tidyr (Wickham et al., 2025b) for data wrangling.

In addition to *A. palmata*, all monitoring protocols used in this study (CARICOMP, SIMAC, RRA) also included assessments of

other benthic components such as total live coral cover, macroalgae, turf algae, cyanobacteria, and abiotic substrates (e.g., sand, rubble). These data were recorded following national and regional monitoring guidelines and used to characterize overall reef condition. However, the present analysis focuses specifically on *A. palmata*, which historically dominated the shallow reef zone of Little Reef. Trends in other benthic groups, including increases in algal cover following coral mortality events, were noted but not analyzed in detail.

RESULTS

Live coral cover of *Acropora palmata* at Little Reef exhibited a continuous and severe decline over the 29-year monitoring period (1995–2024) (Table 1). Because *A. palmata* historically dominated the shallow zone of Little Reef, LCC values reported in earlier studies correspond predominantly to this species unless otherwise noted. Initial estimates indicated ~45 % live cover at Station 13 (Díaz, et al., 1995), with *A. palmata* described as the dominant species at that location; thus, we interpret the majority of this cover as *A. palmata* for long-term comparison. The time series integrates historical RRA assessments (1995, 2002), SIMAC transect data (2006), recent transect-based surveys (2021), and our 2024 monitoring.

The most pronounced losses occurred in three intervals: from 1995 to 2002, when cover declined from ~45 % to 30 %; from 2002 to 2006, when it decreased to 15 %; and from 2021 to 2024, when it dropped to 1.13 % (Fig. 2).

Table 1
Long-term records of live coral cover (LCC) at Little Reef, San Andres Island.

| Year | LCC (%) | Coral Group | Source |
|------|---------|--|--|
| 1995 | 45 % | Total Cover (<i>A. palmata</i> dominated) | Díaz et al. (1995) |
| 2002 | 30 % | Total Cover (<i>A. palmata</i> dominated) | Pizarro (2002) |
| 2006 | 16 % | Total Cover (<i>A. palmata</i> dominated) | Abril-Howard & Bolaños-Cubillos (2007) |
| 2021 | 12 % | Total Cover (<i>A. palmata</i> dominated) | Acosta-Chaparro (2021) |
| 2024 | 1.13 % | <i>A. palmata</i> | This study |

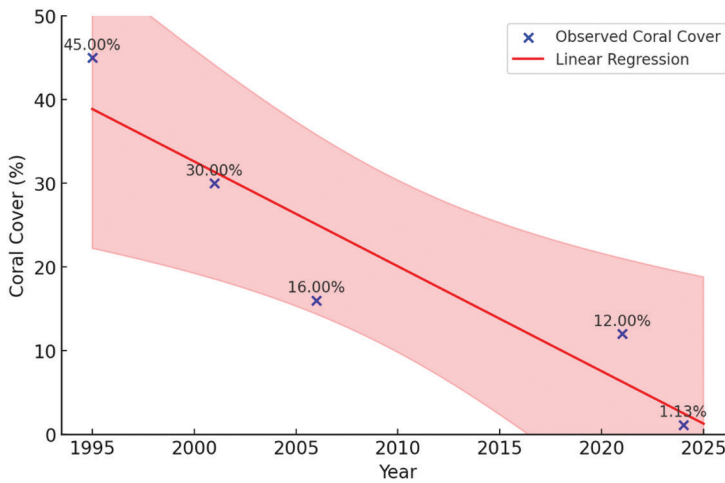


Fig. 2. Long-term decline of *Acropora palmata* live coral cover at Little Reef (1995–2024). A fitted regression line ($R^2 = 0.91$) indicates a consistent downward trend culminating in near-total loss following the 2023 mass bleaching event.

These values correspond to estimates reported in previous studies that were incorporated into our time series: Pizarro (2002) documented 30 % cover in 2001 and Abril-Howard and Bolaños-Cubillos (2007) 16 % in 2006, and Acosta-Chaparro et al. (2021) reported 12 % in 2021. Following the 2023 region-wide bleaching event, our 2024 field survey recorded only 1.13 % live cover, with many transects containing isolated skeletal remnants or no surviving tissue. Overall, this represents a loss of approximately 98 % of *A. palmata* cover since 1995.

Statistical analyses confirmed a strong and significant negative trend in coral cover over time. Kendall's Tau indicated a perfectly monotonic decline ($\tau = -1.0$, $p = 0.017$), while Spearman's rank correlation also showed a perfect negative association ($\rho = -1.0$, $p < 0.001$). A simple linear regression explained 86.5 % of the variation in coral cover across the time series ($R^2 = 0.865$, $p = 0.022$).

Field observations in 2024 revealed that most remaining colonies consisted of dead skeletal framework with patchy algal overgrowth. Juvenile colonies were rare or absent, and no signs of recent recruitment or natural recovery were detected. The current low coral cover contrasts sharply with the structurally complex

and shallow reefscape documented in early surveys. These reductions occurred in a context of increasing coastal development and declining water quality documented for San Andres during that period.

Although this study focused on *A. palmata*, monitoring protocols (CARICOMP, SIMAC, RRA) also recorded broader benthic components, including total live coral cover, macroalgae, turf algae, and abiotic substrates (sand, rubble). These data contextualize overall reef condition, and increases in algal cover were commonly observed following mortality events; however, such patterns were not analyzed in detail for the present study.

DISCUSSION

Long-term monitoring at Little Reef reveals a severe and sustained decline of *A. palmata* over nearly three decades, culminating in near-total loss by 2024. Historically a dominant reef-builder in shallow Caribbean environments, *A. palmata* played a critical role in generating structural complexity, providing shoreline protection, and supporting diverse reef-associated communities (Aronson & Precht, 2001; Precht

& Aronson, 2004). Its collapse therefore represents not only the loss of a species but also the erosion of essential ecosystem functions. The first major decline, between 1995 and 2006, coincided with the emergence of white band disease and the widespread regional collapse of *A. palmata* across the Caribbean (Aronson & Precht, 2001). Limited recovery in subsequent years suggests extremely low recruitment, persistent sublethal stress, and increasing structural fragility of remnant colonies (Miller et al., 2009).

A second phase of decline (2006–2021) unfolded under chronic thermal anomalies, habitat degradation, and repeated hurricane impacts, including storms Eta and Iota (2020) and Julia (2022). These disturbances likely exacerbated existing vulnerabilities by fragmenting colonies, intensifying bioerosion, and diminishing reproductive capacity. Local stressors may also have amplified coral susceptibility during earlier stages of decline (Gavio et al., 2010). Little Reef lies adjacent to the most urbanized area of San Andres Island, where rapid coastal development and population growth since the 1990s have increased eutrophication, sedimentation, and pollution in nearshore waters. Although high-resolution environmental data for that period are lacking, multiple assessments documented increases in sedimentation, nutrient inputs, and eutrophication in the island's coastal zone (Gavio et al., 2010; Instituto de Investigaciones Marinas y Costeras “José Benito Vives De Andrés” [INVEMAR], 2000), conditions known to compromise coral health and reduce resilience. Their combined influence may have further limited the capacity of *A. palmata* to recover from disease outbreaks and thermal stress. Future work should investigate how local and global drivers interact to shape reef degradation in this region.

The most dramatic collapse occurred between 2021 and 2024, coinciding with the 2023 Caribbean-wide marine heatwave, one of the most extreme thermal stress events on record (NOAA Coral Reef Watch, 2024). Regional assessments document unprecedented

bleaching and mortality, including *A. palmata* die-offs across multiple Caribbean locations (Birkart & Alvarez-Filip, 2025; Doherty et al., 2025). These findings echo broader regional trends in which coral mortality is increasingly linked to global warming rather than localized disturbances (Eakin et al., 2010; Hughes et al., 2018). Surveys at Little Reef in 2024 showed widespread tissue loss and an absence of recovery, aligning with this basin-wide pattern and underscoring the dominant role of ocean warming and marine heatwaves in shaping the fate of thermally sensitive species such as *A. palmata*.

Persistent declines despite long-term protection highlight the limitations of passive conservation tools. Little Reef lies within a no-entry zone of the Seaflower MPAs, yet *A. palmata* populations continued to deteriorate. This pattern of “protection without persistence,” as exemplified by Bruno and Valdivia (2016), has been reported throughout the Greater Caribbean region. In the Florida Keys, for example, the 2023 heatwave resulted in the loss of over 75 % of remaining native genotypes within protected sites—only 37 of the original 160 founder genotypes persisted (Williams, 2024). In the same region, MPAs were similarly unable to prevent the functional extinction of *A. palmata* and *A. cervicornis* following the same event (Manzello et al., 2025). Comparable outcomes have been observed elsewhere, including the Mesoamerican Reef (Rodríguez-Martínez et al., 2014), Belize (Mumby et al., 2007), and Los Roques (Croquer et al., 2016), where warming has outpaced the capacity of local management to support coral persistence. Collectively, these cases reinforce a growing consensus: while MPAs reduce local stressors, they are not sufficient to safeguard corals under accelerating climate change (Doherty et al., 2025).

The collapse of *A. palmata* at Little Reef therefore signals a critical need to transition from passive protection to proactive, intervention-based conservation. As Rinkevich (2008) argued, species that have undergone population collapse require more than spatial protection—they require targeted restoration,



genetic rescue, and adaptive management. Interventionist strategies such as coral nurseries, assisted sexual reproduction, selective propagation of thermally tolerant genotypes, and cryopreservation are increasingly necessary to prevent further loss (Hagedorn et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2018; Suggett & van Oppen, 2022; van Oppen et al., 2015). To ensure long-term persistence of Caribbean reef ecosystems, conservation efforts must integrate active restoration techniques—including coral gardening, larval propagation, and the cultivation of heat-resilient genotypes—with resilience-based indicators such as genetic diversity, recruitment, and survivorship (Banaszak et al., 2023; Chamberland et al., 2015; McClanahan et al., 2020; Morikawa & Palumbi, 2019). Within the Seaflower MPAs, these approaches could form the foundation of a resilience-oriented management framework supported by sustained monitoring and local stakeholder engagement.

The absence of natural recovery and recruitment observed in 2024 suggests the population is approaching functional collapse—a state in which a species no longer fulfills its ecological role despite the presence of surviving colonies (Kennedy et al., 2013). Remnant colonies appear too sparse and genetically eroded to support natural recovery (Baums et al., 2019; Toth et al., 2019), further reducing the likelihood that natural processes alone can reverse the decline. Preventing irreversible biodiversity and ecosystem function loss will therefore require management strategies centered on genetic conservation, active restoration, and climate-adaptive planning.

Ultimately, effective coral conservation in the Anthropocene will require reimagining MPAs not as static refuges but as dynamic platforms for intervention, innovation, and resilience building. This paradigm shift—from protection alone to proactive, science-driven restoration—will be essential to safeguard *A. palmata* and other reef-building species across a rapidly warming Caribbean.

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