Coral Bleaching in the Bonaire National Marine Park from 2016-2023

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Executive Summary

Mass coral bleaching is becoming more frequent and widespread, posing a major threat to coral reefs worldwide. Mass coral bleaching is often a response to prolonged thermal stress triggered by elevated water temperatures and/or ultraviolet radiation attributed to global climate change. Since 2016, STINAPA Bonaire has surveyed the severity of coral bleaching in the Bonaire National Marine Park (BNMP) at 10 sites on the leeward coast in Bonaire, Caribbean Netherlands. Each year, aside from 2021, > 5% of corals exhibited signs of thermal stress including paling, partial bleaching, and full colony bleaching, while in 2021 we did not conduct bleaching surveys as < 5% of corals exhibited signs of bleaching. No bleaching induced mortality was observed until 2020, where some coral mortality was seen beyond the maximum survey depth of 25 m. Because of this, STINAPA expanded monitoring in 2023 to include surveys of 35 m depth.

In 2023, Bonaire experienced the highest level of thermal stress observed since we began monitoring in 2016, where 84% of coral colonies were visibly affected by thermal stress to some degree. Because corals did not recover quickly and bleaching-induced mortality was observed, STINAPA conducted follow-up surveys in February 2024. At that time, 19% of coral colonies exhibited partial or complete mortality attributed to bleaching. Across survey years, there was significantly more coral bleaching over time, as well as greater bleaching at 25m depth compared to 5m. In 2023, several coral species, including Yellow pencil coral (*Madracis auretenra*), Ten-ray star coral (*Madracis decactis*), Great star coral (*Montastraea cavernosa*) and Mustard hill coral (*Porites astreoides*) did not appear as affected by thermal stress as other coral species.

While addressing the global-scale causes of coral bleaching is daunting, Bonaire's slogan is 'Nos ta biba di naturalesa' (nature is our livelihood) and STINAPA Bonaire, together with government and non-government partners, strives to promote conservation through local actions. Knowledge of the severity of coral bleaching is necessary to develop local management strategies that may improve the resistance and resilience of coral reefs in the Bonaire National Marine Park to climate change. STINAPA is currently undertaking a project together with Florida State University with funding from Lenfest Ocean Program to identify 'at-risk' areas for climate change, impacts and potential refuge areas, predict reef vulnerability and improve detection of and response to climate change events.

Introduction

Coral reefs are not only one of the most biodiverse ecosystems on the planet, (Connell 1978; Reaka-Kudla 1997), but also provide critical cultural value and socio-economic benefits for communities including supporting tourism, vital fisheries, and protecting coastlines from storm surge and erosion. For instance, on Bonaire, it is estimated that tourism generates $125 million annually (with ~40% of that revenue driven by nature-based tourism in the Bonaire National Marine Park), commercial and recreation fisheries generate $110 million annually, and coral reefs provide an estimated $70,000 in long-term coastal protection (TEEB NL 2012). However, stressors such as global climate change, overfishing, and terrestrial runoff of sewage and fertilizers are threatening both reef biodiversity and the critical ecosystem services reefs provide to our coastal communities (Costanza et al. 2014; Hoegh-Guldberg et al. 2017; Richards and Day 2018; Eddy et al. 2021).

Wide-scale coral bleaching is a stress response commonly triggered by high sea surface temperatures and irradiance (Brown 1997; Lesser 1997; Douglas 2003; Downs et al. 2009). It was first documented in the 1980's (Glynn 1984), though global bleaching events have become more common and more intense in the past decade (Hughes et al. 2017; Sully et al. 2019). In the tropics, sea surface temperatures are increasing at a rate of 1-2°C per century (Hoegh-Guldberg 1999), and since even 1°C of temperature increase beyond the historical maximum can trigger coral bleaching, it has become one of the principal management concerns of the 21st century (Baker et al. 2008). Starting in 2016 during a global coral bleaching event, STINAPA Bonaire began annual surveys of coral bleaching in all years where an estimated >5% of coral colonies exhibit visible bleaching signs (Eckrich et al. 2016). Through these monitoring efforts, STINAPA aims to track bleaching severity over time and across coral species, sites and depth ranges to inform site and species-specific management strategies to safeguard the resilience of Bonaire's reefs.

Mechanisms and consequences of coral bleaching

Corals have a symbiotic relationship with photosynthetic algae often called zooxanthellae (*Symbiodinium* spp.). While corals feed on plankton to meet some of their energy needs, zooxanthellae photosynthesize sugars for the coral host that can meet >85% of their energy needs (Muscatine and Porter 1977; Falkowski et al. 1984; Edmunds and Davies 1986), while corals provide zooxanthellae with shelter and nutrients (Roth 2014). When sea surface temperatures are ~1-2°C higher than historical seasonal averages, this impairs photosynthesis by zooxanthellae, causing them to release toxic reactive oxygen species (Warner et al. 1999; Baird et al. 2009). To protect themselves, coral hosts then expel these zooxanthellae (Fujise et al. 2014), though they cannot survive for long durations without the energy provided by zooxanthellae. The photosynthetic pigments in zooxanthellae is what gives transparent coral tissue it's characteristic color (Brown 1997; Douglas 2003), so when corals expel zooxanthellae their skeleton becomes visible, giving them a "bleached" appearance (Fig. 1).

During prologued bleaching events, corals cannot meet their energetic demands via eating plankton alone and will eventually starve, leading to bleaching related colony mortality (Cunning et al. 2017). However, if temperatures return to normal levels within a few weeks, corals can take up new zooxanthellae from the water column and recover (Fautin and Buddemeier 2004). In fact, they can sometimes take up more thermally-tolerant lineages of zooxanthellae which can increase their resilience to future thermal stress (Grottoli et al. 2014; Silverstein et al. 2015), provided temperatures are not too extreme (Ainsworth et al. 2016). However, even sublethal bleaching stress can still have long-term consequences for corals, including reduced growth and reproductive capacity, as well as impaired resilience to other stressors like disease (Meesters and Bak 1993; Johnston et al. 2020; Leinbach et al. 2021). Therefore, reducing other stressors to corals, such as competition with algae and cyanobacteria, or sewage runoff that be a disease vector, can be critical to promoting the resilience and recovery of corals during and after coral bleaching events.

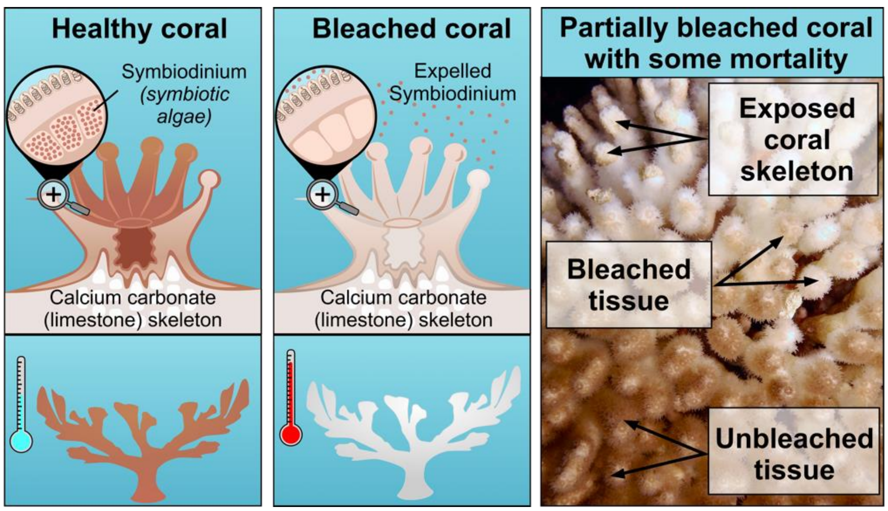

Fig. 1. Diagram showing from left to right: (1) a healthy coral with zooxanthellae (*Symbiodinium* spp.)., (2) a bleached coral with expelled zooxanthellae, and (3) a partially bleached *Madracis auretenra* coral colony with limited mortality in more light-exposed areas of the coral colony.

Managing coral bleaching

Researchers and management agencies use remote sensing of the intensity sea surface temperature anomalies and accumulated heat stress over time to calculate a combined metric of thermal anomaly intensity and duration known as degree heating weeks (McClanahan et al. 2007; Pernice and Hughes 2019). NOAA's Coral Reef Watch maintains a global monitoring platform of sea surface temperature hotspots and degree heating weeks to predict the likelihood of coral bleaching (Liu et al. 2014). Remote sensing can be used to inform local management agencies (like STINAPA) of thermal anomalies so that quick action and monitoring can take place. Traditional coral bleaching management strategies have focused on mitigating local stressors such as nutrient enrichment and overfishing to improve reef resilience to global scale climate change (Carilli et al. 2009), or closing sites with highest bleaching levels to mitigate tourism-related stress. Additionally, groups focused on coral restoration (like Reef Renewal Bonaire) may also outplant coral lineages that are known to be more tolerant to thermal stress, though there can be tradeoffs between coral thermal tolerance and growth capacity (Ladd et al. 2017).

Methods

Starting in 2016, STINAPA began surveys of coral bleaching events across 10 sites in the Bonaire National Marine Park on the leeward coast of Bonaire and Klein Bonaire (Fig. 2). These surveys include annual monitoring except for 2021, where <5% of corals exhibited signs of bleaching, so no data were collected for this year. Note that in 2018, only the portion of the colony that was affected was quantified instead of the entire colony, therefore the numbers from 2018 represent the total percent of coral affected rather than the percentage of colonies affected by thermal stress and should not be compared directly. For a detailed description of coral bleaching and the methodologies and results from the 2016-2020 surveys, see Eckrich et al., (2021) Coral Bleaching in the Bonaire National Marine Park 2016-2020.

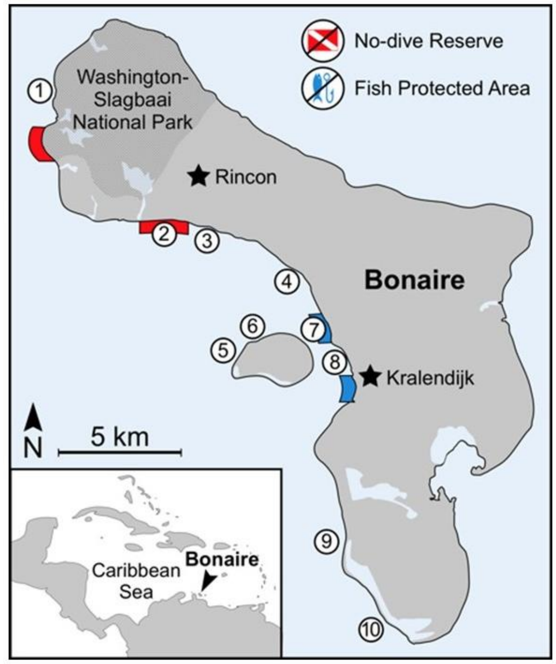

Figure 2. Map of the 10 coral bleaching survey sites on the leeward coast of Bonaire and Klein Bonaire, Caribbean Netherlands, including 1) Playa Funchi, 2) Rei Willem Alexander Reserve, 3) Karpata, 4) Oil Slick Leap, 5) Mi Dushi – Klein Bonaire, 6) Ebo's Special – Klein Bonaire, 7) Reef Scientifico, 8) Playa Lechi, 9) Invisibles, and 10) Vista Blue.

2023 Surveys

To capture the most severe coral bleaching, SINAPA began monitoring the week after the peak recorded sea surface temperature began to decrease (Appendix 1) from November 7-24, 2023. We conducted line intercept surveys of coral bleaching intensity along two 30 m transects at 5, 10 and 25 m depth (notably, only four sites had corals at 5 m). Additionally, as surveyors observed notable bleaching beyond 25 m, two video surveys were recorded along 10 m transects at 35 m. If any portion of a colony appeared affected by thermal stress, the severity of coral bleaching was categorized using the recommendation of *A Global Protocol for Assessment and Monitoring of Coral Bleaching* (Oliver et al., 2004) as follows: Unbleached, Pale Tissue Present, Partially Bleached, Fully Bleached, Recent Mortality attributed to bleaching. In addition, we recorded colony size and disease prevalence. After bleaching monitoring was completed, we observed that corals did not regain their coloration as quickly as in the previous years and some colonies exhibited partial or complete mortality. Therefore, we decided to conduct follow-up monitoring from January 25 – February 16 to determine the percentage of corals that exhibited partial or complete mortality due to coral bleaching.

Statistical analyses

We conducted an Analysis of Variance (ANOVA) using type II sum of squares to compare the percentage of corals that exhibited any visible signs of bleaching in response to site, year, survey depth (treated as an ordinal variable). We used a post-hoc Tukey test to evaluate differences between depths. We assessed model fit via visual inspection of residuals. For 2023 surveys, we conducted a Kruskal-Wallis test of the percent of colonies with thermal stress by coral species, as visual inspection of residuals and a Shapiro test indicated non-normality of residuals. We used a post-hoc Dunn's test to assess pair-wise differences in bleaching between coral species. Additionally, to compare patterns in coral bleaching severity (unbleached, paling, partially bleached, fully bleached, and recent mortality) among sites, we conducted a Chi-squared test. We conducted all analyses using R statistical software version 4.4.1.

Results

Across surveyed years, there was significantly more bleaching over time after accounting for site and survey depth (Fig. 3; $F_{(1, 158)} = 79.3681$, $p < 0.001$), with an estimated 7.1% more colonies with thermal stress by year after accounting for site and survey depth effects. Notably, the highest percent coral bleaching was observed in 2023, where 83.6% of coral colonies surveyed affected by thermal stress to some degree. Additionally, across years and sites (Fig. 4, Appendix 2), there were significant differences in percent coral bleaching by depth ($F_{(3, 158)} = 4.2653$, $p = 0.006$) with an estimated 17.8% more colonies bleached at 25 m depth on average compared to 5 m (95% CI = [2.8%, 32.8%]; Tukey HSD, $p = 0.012$), but no other significant differences between depths.

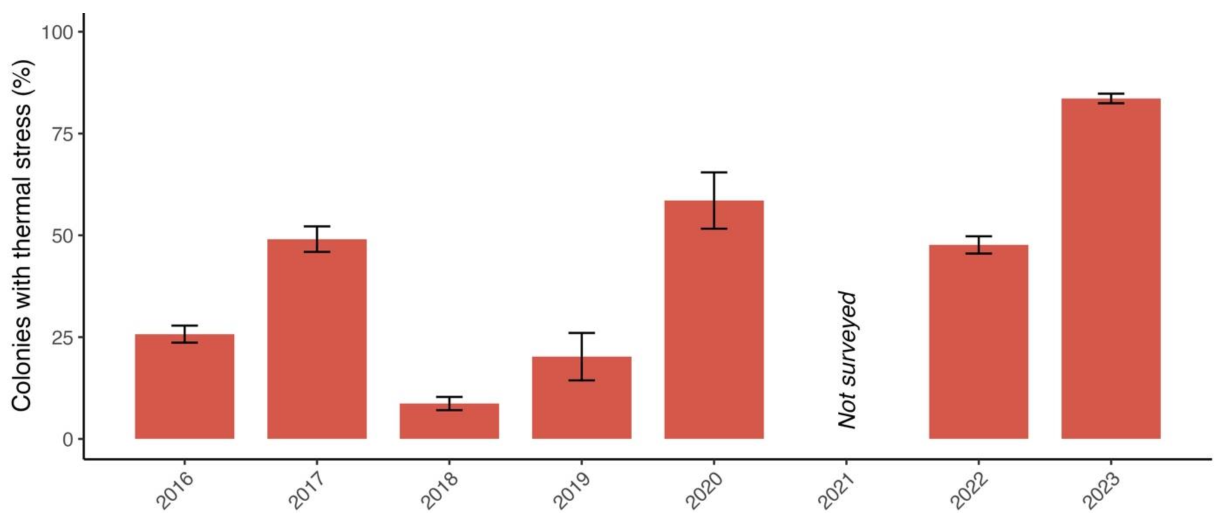

Figure 3. Mean percentage (±SE) of coral colonies visibly affected by thermal stress from 2016 – 2023 in Bonaire, Caribbean Netherlands. Thermal stress categories ranged from colony paling to full bleaching. Data from all depths and sites surveyed are pooled (n = 10 sites). In 2021, bleaching surveys were not conducted as <5% of corals appeared to exhibit any signs of bleaching.

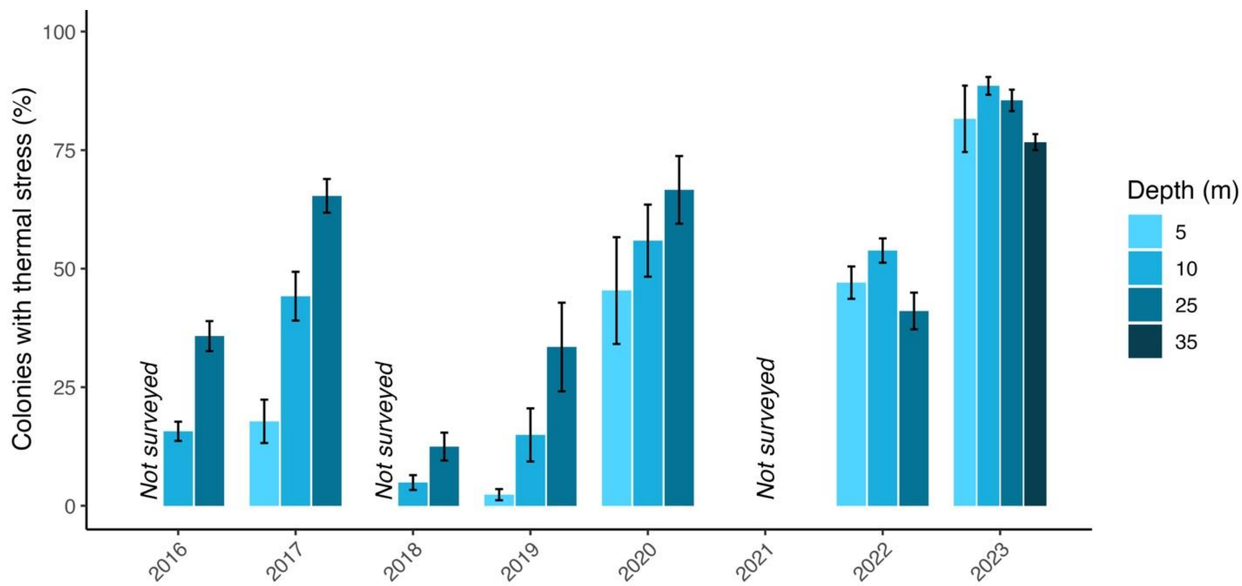

Figure 4. Mean percentage (±SE) of coral colonies affected by thermal stress from 2016-2023 by depth (n = 2 transects per site and depth range, with 10 survey sites). Notably corals are only found at 5 m depth at four of the ten study sites, and no surveys were conducted at 5 m depth in 2016 or 2018. In 2023, survey efforts were expanded to include 35 m depth. In 2021, bleaching surveys were not conducted as <5% of corals appeared to exhibit any signs of bleaching.

In 2023, there were significant differences in the percentage of colonies that exhibited signs of bleaching ranging from tissue paling to recent mortality among species ($\chi^2_{(17)} = 70.075$, $p < 0.001$), where *Madracis auretenra*, *M. decactus*, *Montastraea cavernosa* and *Porites astreoides* had significantly less bleaching compared to most other species (Fig. 5, Table 1). Additionally, there were differences in the proportions of coral colonies that exhibited tissue paling, partial bleaching, full bleaching and recent mortality across sites ($\chi^2_{(36)} = 121.59$, $p < 0.001$). Notably, there appeared to be more fully bleached coral colonies at sites on Klein Bonaire such as Ebo's Special and Mi Dushi, and more recent mortality at sites such as Reef Scientifico and Vista Blue (Fig. 6).

In November 2023 surveys 4.3% of coral colonies exhibited partial or complete mortality attributed to bleaching. However, recovery was slow and during the surveys in February 2024, 19% of coral colonies exhibited partial or complete mortality attributed to bleaching.

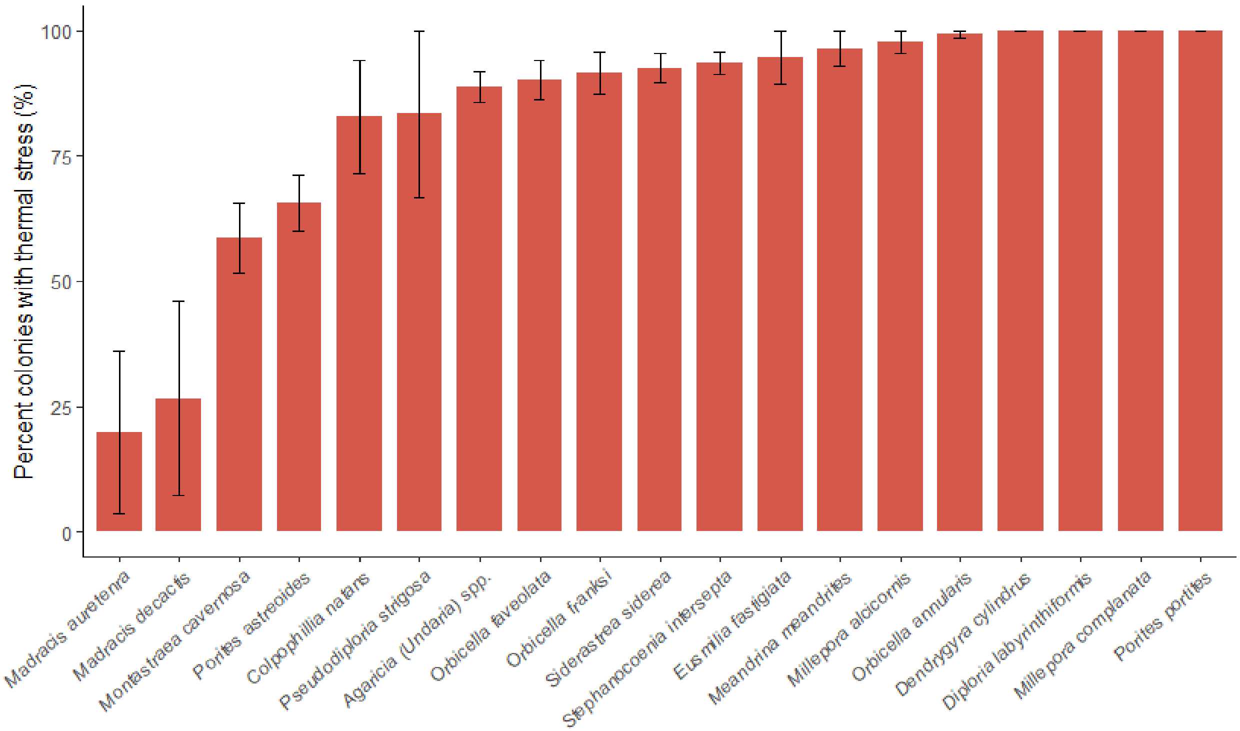

Figure 5. Mean percentage (±SE) of coral colonies visibly affected by thermal stress by species in 2023 in Bonaire. Species are arranged left to right from lowest to highest percent of colonies with visible signs of bleaching, ranging from tissue paling to recent mortality.

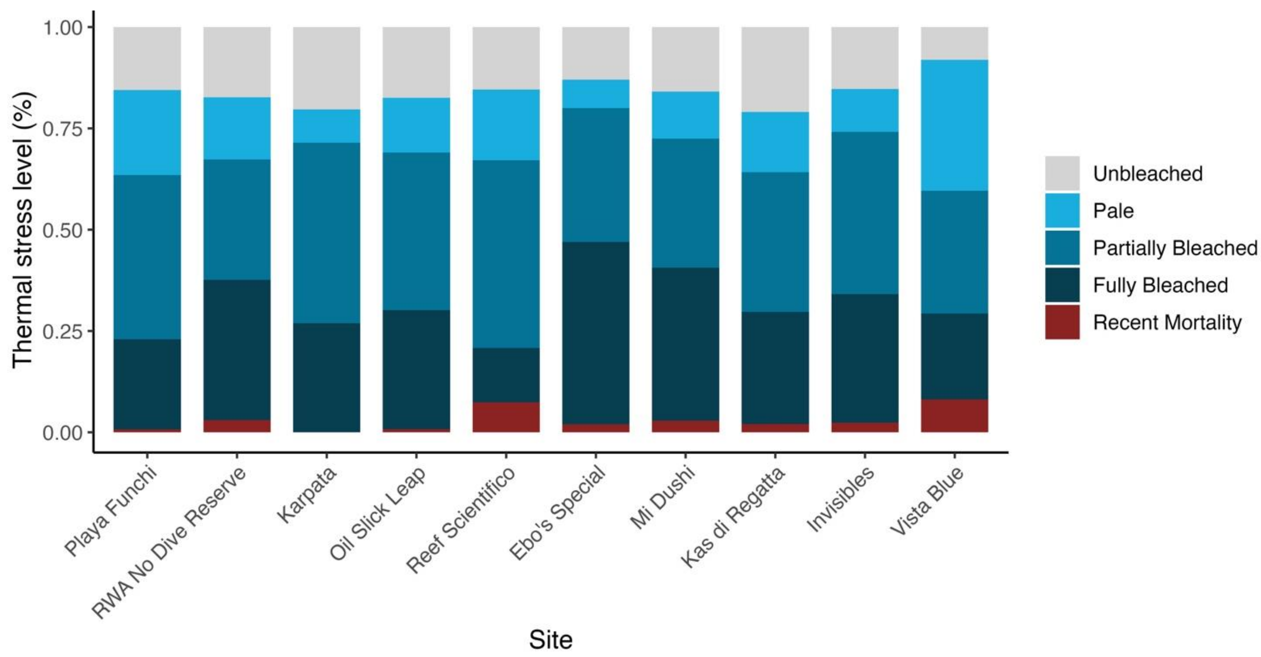

Figure 6. Mean percent coral colonies visibly affected by thermal stress by category and site in November 2023 (n = 6-8 transects per site across depths).

Table 1. Summary of pairwise comparisons in percent coral bleaching between species based on 2023 surveys based on a post-hoc Dunn test, showing significant differences coral species with less bleaching (columns) are compared with corals with more bleaching (rows). Numbers show the adjusted p-values, where NS indicates non-significant differences between species.

		Coral species with less bleaching			
		Madracis auretenra	*Madracis decactis*	*Montastraea cavernosa*	*Porites astreoides*
Coral species with more bleaching	*Colpophillia natans*	0.04	NS	0.02	NS
	Dendrygyra cylindrus	0.05	NS	0.04	NS
	Diploria labyrinthiformis	0.01	0.01	0.00	0.01
	Eusmilia fastigiata	0.01	0.02	0.01	0.02
	Millepora alcicornis	0.01	0.01	0.00	0.01
	Meandrina meandrites	0.01	0.02	0.01	0.01
	Orbicella annularis	0.00	0.01	0.00	0.00
	Orbicella franksi	0.03	NS	0.01	0.04
	Millepora complanata	0.05	NS	0.04	NS
	Orbicella faveolata	NS	NS	0.04	NS
	Porites portites	0.02	0.03	0.01	0.03
	Stephanocoenia intersepta	NS	NS	0.03	NS
	Siderastrea siderea	0.04	NS	0.02	NS

Discussion

Through annual monitoring of coral bleaching in the Bonaire National Marine Park since 2016, STINAPA seeks to inform local management and coral reef conservation efforts, as well as contribute to our understanding of coral bleaching patterns across coral reefs worldwide. While coral bleaching events began infrequently in the 1990s, they have become more frequent and severe globally over the past decade, with similar trends in Bonaire. Steneck et al., 2011, recorded ~10% coral mortality in 2010 and since 2016, the reefs of Bonaire have suffered transient bleaching almost every year where corals pale or bleach but recover after the temperature drops to more normal levels (Eckrich et al., 2021). However, even transient bleaching events can affect the health and reproductive success of corals, as they can alter the dynamics and composition of symbiotic zooxanthellae communities living within the corals that provide corals with nutrients via photosynthesis (Johnston et al., 2020). In September and October 2024, STINAPA and Reef Renewal monitored for coral spawning during peak hours and no corals were observed spawning. The 2023 bleaching event at its peak affected 84% of the corals surveyed and, two months later, approximately 19% suffered partial or complete mortality. Some corals remained pale as late as March and April of 2024 (authors' observations). This marks the most severe bleaching event recorded for Bonaire's corals. At the time of this report (December 2024), Bonaire's reefs have been through yet another severe bleaching event (data is currently being analyzed). Although there is little Bonaire can do to stop immediate coral bleaching, STINAPA's management strategies focus on implementing local measures that improve the resistance and resilience of our coral reefs to global stressors including coral bleaching and related climate change.

Leading management recommendations to promote local reef resilience in the face of increasing climate change related disturbances like coral bleaching include protecting herbivorous fishes that graze algae and cyanobacteria (Jackson et al. 2014; Adam et al. 2015), which can overgrow corals and inhibit their recruitment if left unchecked (Kuffner et al. 2006). Since 2010, the Island Government of Bonaire has protected herbivorous fishes from harvest island-wide (Executive Council of the Bonaire Island Territory 2010), following a 2010 bleaching event. Since that time, herbivorous fish populations have increased, algae levels have declined, and levels of both juvenile and adult corals recovered to pre-bleaching levels (Steneck et al. 2019). Another key management recommendation is to decrease levels of sewage and other land-based nutrient input (Jackson et al. 2014). Sewage and related nutrient enrichment can increase the susceptibility of corals to bleaching, harm their growth, act as a vector for transmission of some coral diseases, and promote the overgrowth of algae and cyanobacteria (Wear and Thurber 2015). Starting in 2014, Bonaire implemented a centralized sewage treatment to help control levels of nutrient runoff into reefs (Slijkerman et al. 2014) and for the past few years, STINAPA has been collaborating with Wageningen Marine Research to monitor the concentrations of key nutrients impacting water quality and reef health in the Bonaire National Marine Park. Through these actions over the past two decades Bonaire's government, STINAPA, and the island community have been working to promote local reef resilience.

Furthermore, ongoing collaborative efforts, such as the Climate Resilience in the Bonaire National Marine Park project, will provide critical insight for STINAPA Bonaire assess broad-scale and apply science-based management techniques to further promote reef resilience. Working together with Florida State University, RASSTER Lab and the Lenfest Ocean's Program, we are researching the impacts of climate change by evaluating stressors (like high temperatures) that cause coral bleaching, coral diseases, and recreational impacts in the Bonaire National Marine Park. A unique aspect of this project is its broad engagement—research contributions span from international universities to local dive centers that help collect sensor data, allowing community members to play an active role. Through this project, we aim to identify 'at-risk' areas for climate change, impacts and potential refuge areas, predict reef vulnerability and improve detection of and response to climate change events.

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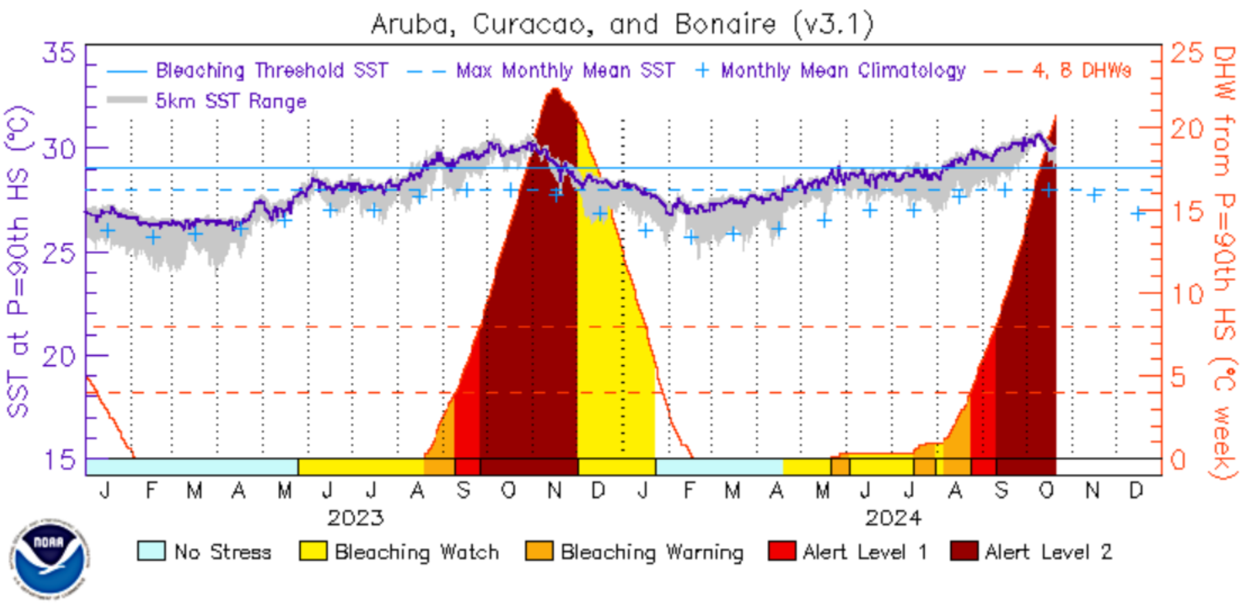
Appendices

Appendix 1. A graph showing cumulative thermal stress from January 2023 to October 2024 for Aruba, Curacao and Bonaire recorded by US National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch program. Sea surface temperatures (SST) are shown on the left, where a typical bleaching threshold of 29°C is shown in blue, the purple line shows observed SST, blue crosses show the historical average temperature (°C), and gray lines show the SST within a 5 km range. Degree heating weeks (DHW) are shown on the right, calculated based on how high SSTs are above historical mean monthly values and how long those temperatures have been sustained. Bleaching Watches (yellow) occur when SST approaches 29°C, Warnings (orange) occur when DHWs exceed 0, Alert Level 1 (bright red) occurs at 4 DHWS when bleaching is likely for some coral species, and Alert Level 2 (dark red) occurs at 8 DHWs when widespread bleaching and significant coral mortality are likely.



Appendix 2. Mean percentage of coral colonies affected by visible thermal stress ranging from paling to recent mortality from 2016 - 2023 by site and depth (n=2 surveys per depth).