# MSc Thesis

## Marine Sciences MSc, Utrecht University

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February 2024

*Brain coral field devastated by Stoney coral tissue loss disease*

# Assessing the impact of stony coral tissue loss disease on coral cover in Bonaire's reef ecosystems

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## Abstract

This MSc thesis presents a comprehensive investigation into the effects of Stony Coral Tissue Loss Disease (SCTLD) on Bonaire's coral reefs following its first sighting in March 2023. Through a series of surveys over the last 9 years and a rigorous statistical analysis, this study not only quantifies the overall decline in coral cover but also investigates the spatial variability of SCTLD's impact across different subregions of the reef. In the year 2023, a crucial period in the initial phase of the progression of SCTLD, a significant reduction in coral coverage was observed, with six key reef-building coral species showing a notable vulnerability.

Importantly, the research identifies specific subregions that have been disproportionately affected, which may help in targeted conservation actions. The insights gained from this study are important for the development of specific conservation strategies for Bonaire, underscoring the importance of precision in disease management and the necessity for ongoing ecosystem monitoring to safeguard the future of coral reefs in a changing ocean. By advancing our understanding of SCTLD dynamics, this research contributes to the global effort to preserve coral reef ecosystems in the face of emerging coral diseases.

## Introduction

Coral reefs, often compared to the rainforests of the sea, are among the most biologically diverse and productive ecosystems on our planet (Moberg & Rönnbäck, 2003). The significance of these ecosystems spans biodiversity, fisheries, coastal protection, tourism, and medicine (Bertness et al., 2001; Newman et al., 2015; Brathwaite et al., 2022; Uyarra et al., 2008; Abdelhafez et al., 2019), rendering their conservation an important concern for marine scientists and environmentalists globally. However, coral reef systems have been suffering and declining globally in the last decades (Høegh-Guldberg et al., 2007). Indeed, climate change-induced bleaching, ocean acidification, hurricanes, diseases, and diverse anthropogenic stressors have posed significant challenges and contributed to this recent decline (Precht et al., 2016; Graham et al., 2014; Kjerfve et al., 2021; Mallela & Crabbe, 2009; Aronson & Precht, 2001).

Bonaire's reefs are widely recognized as some of the most robust and vibrant in the Caribbean, the shore diving capital maintained the reputation over the years (Parsons & Thur, 2008; Perry et al., 2013; Uyarra et al., 2008). This status has established the island as a first choice destination for diving enthusiasts, who are drawn to the high coral cover and the thriving marine life it supports (Parsons & Thur, 2008). Despite their resilience, Bonaire's reefs are not immune to the environmental stressors that challenge coral ecosystems globally. A range of stressors, from various diseases to climate-induced bleaching have contributed to a discernible decline in reef health and cover (Lessios, 2016; De Bakker et al., 2017; De Bakker et al., 2019; Aronson & Precht, 2001).

This MSc research encompasses the monitoring and analytical assessment of coral reef health, with a specific focus on the influence of Stony Coral Tissue Loss Disease (SCTLD) on key coral species.

It forms part of a larger initiative by Wageningen Marine Research, under the supervision of Dr. Erik Meesters, which is dedicated to conducting a long-term analysis of the leeward side coral reefs of the Bonairian island. This initiative aims to monitor the evolving dynamics of these ecosystems in light of climatic (Meesters & Bak, 1993) and anthropogenic stressors (Meesters et al., 2022).

This monitoring program has conducted surveys from 2014, with the most recent dataset collected in 2023, marking the fourth round of sampling (2014; 2017; 2020; 2023). These surveys yield a comprehensive dataset on fish populations and benthic organisms, which facilitates tracking long-term ecological transformations: a key aspect of the ongoing research by Wageningen Marine Research (WMR) (De Bakker et al., 2017).

Stony Coral Tissue Loss Disease (SCTLD) has emerged as a significant threat to coral reefs, afflicting at least one-third of the approximately 60 species of scleractinian corals in the Caribbean, with some species more severely impacted than others (SCTLD Case Definition, 2018; Costa et al., 2021). Initially identified in Florida in 2014 as a “white plague” disease (Precht et al., 2016), SCTLD has proliferated across numerous countries (Hernández-Delgado & Weil, 2019; Álvarez-Filip et al., 2019; Brandt et al., 2021), eventually reaching the reefs of Bonaire in 2023. The research urgency is accentuated by SCTLD's rapid and catastrophic impact on coral colonies, with instances of complete colony death occurring within weeks following the onset of symptoms, arguably one of the most lethal coral diseases ever observed in our time (Precht et al., 2016).

Although the presence of SCTLD in Bonaire was only recently confirmed in March 2023 (STINAPA), time is ticking as the coral disease spreads fast. This Master Thesis research helps quantify SCTLD's repercussions on Bonaire's coral cover and helps develop informed strategies for its mitigation.

## Research Question

**Main Research Question:**

- What is the impact of Stony Coral Tissue Loss Disease (SCTLD) on the population dynamics, spatial distribution, and overall reef ecosystem health of sensitive coral species in Bonaire's reefs?

**Sub-questions:**

1. How do the population dynamics and spatial distribution of the SCTLD-sensitive coral species vary in response to SCTLD across different subregions of Bonaire since its outbreak?
2. How do the rates of decline change for sensitive species since the SCTLD outbreak in 2023?

## Background

The Caribbean Sea is often considered a coral disease "hotspot" and has very well-documented outbreaks (Van Woesik & Randall, 2017). Coral diseases often emerge as a result of biological stresses from pathogens like bacteria, fungi, and viruses, as well as from non-biological stresses including elevated sea surface temperatures, ultraviolet radiation, and pollutants (Rosenberg & Ben-Haim, 2002; Jones et al., 2021). As frequently observed in complex ecosystems, one form of stress can intensify the effects of another, compounding the impact on coral health.

Over the past decade, the incidence of coral diseases has escalated quickly, leading to significant mortality rates among reef-building corals (Precht et al., 2016; Costa et al., 2021). Many researchers attribute this phenomenon to declining water quality from anthropogenic pollutants and rising sea surface temperatures, which may facilitate the growth and spread of pathogenic particles (Merselis et al., 2018; Rosenberg & Ben-Haim, 2002). Yet, determining definitive causes for coral diseases is challenging; they are often the combination of multiple environmental stressors (Jones et al., 2021).

Although the specific pathologies of many coral diseases are not fully understood, their destructive impact on coral structures is well-recorded (Precht et al., 2016; Costa et al., 2021; Bak & Criens, 1981). Diseases such as black-band, red-band, and yellow-blotch/band manifest as distinct discolored bands, spots, or lesions on corals and (usually) slowly degrade the living tissue, revealing the white skeleton underneath (Rosenberg & Ben-Haim, 2002). Other diseases, including white band, white plague, white pox, and SCTLD, can cause large patches of coral tissue to deteriorate, exposing the underlying skeleton (Aronson & Precht, 2001; Cróquer et al., 2021). This exposure can lead to the skeleton becoming colonized with algae and invertebrates, further compromising the coral's health and often leading to an irreversible decline of the entire colony.

Initially characterized as a form of white-plague disease (WPD) causing rapid tissue loss (Precht et al., 2016), SCTLD is now identified for its distinctive and simultaneous lesions, which often manifest centrally within a colony (Cróquer et al., 2021; SCTLD Case Definition, 2018;). The cause of the SCTLD symptoms is still an ongoing topic of research, but they have been associated with Filamentous virus-like particles (Howe-Kerr et al., 2023) and 2 classes of bacteria (Rosales et al., 2020).

Other coral diseases typically impact a limited range of two to five species (Aronson & Precht, 2001; Kline & Vollmer, 2011; Gochfeld et al., 2006; SCTLD Case Definition, 2018), whereas SCTLD has a far-reaching effect, afflicting at least 20 species of Caribbean corals (Costa et al., 2021). Furthermore, SCTLD targets key species that are essential for constructing the calcareous framework characteristic of coral reef ecosystems, such as *Orbicella Annularis*, a key reef-building coral of the reefs of Bonaire.

SCTLD has proven to be a significant threat to coral reefs, sometimes infecting up to 81% of the hard corals present on the reef (Precht et al., 2016) with its impact varying among species. Highly susceptible species, such as *Meandrina meandrites* and *Colpophyllia natans*, often exhibit early signs of the disease, which can lead to rapid and extensive mortality In contrast, intermediately susceptible species may show symptoms later, with smaller colonies potentially succumbing within months (SCTLD Case Definition, 2018). Notably, slow-growing, thermally resistant brain corals, despite their resilience, are frequently among the first to be afflicted, with some large colonies succumbing to turf algae overgrowth in just a few weeks (Álvarez-Filip et al., 2022; SCTLD Case Definition, 2018).

Patterns of susceptibility and prevalence can differ regionally, with some species previously thought to be less affected in one area confirmed to be impacted in another, suggesting environmental, physical, and ecological factors may influence SCTLD's impact (Muller et al., 2020).

Since its initial detection in Florida's hard coral populations in 2014, SCTLD has been documented to rapidly proliferate, spreading to more than 25 countries and territories within approximately eight and a half years, leaving a trail of significant ecological disruption across thousands of kilometers of affected reefs (Figure 18). Indeed, SCTLD is known for its swift transmission via water currents (Dobbelaere et al., 2020; Muller et al., 2020), and research suggests its dissemination is linked to the movement of vessels (Studivan et al., 2022)

## Situation on Bonaire

Coral reefs in Bonaire have long been subjected to various stressors, including diseases that have historically impacted their health and vitality. Notably, coral diseases such as white band disease have had catastrophic effects on local coral reefs, decimating acroporid corals across the region (Bak & Criens, 1981; Gladfelter, 1982). Additionally, some diseases indirectly affect coral ecosystems by disrupting natural grazing patterns; for instance, a significant disease outbreak led to a drastic decline in the population of the sea urchin *Diadema antillarum*, which in turn allowed algal overgrowth due to reduced grazing (Lessios, 2016). These incidents highlight the fragility of coral ecosystems and underscore the importance of ongoing monitoring and disease mitigation efforts, if any of those are feasible. However, no coral disease had until now a range of infection as broad as the SCTLD (Costa et al., 2021; SCTLD Case Definition, 2018). According to STINAPA spread map based on local sightings, SCTLD arrived in Bonaire's water only in March 2023. However, as you can see on Figure 1 the situation barely 9 months later is already critical, with the disease reported to having spread from its initial point (Kralendijk) up to all the way in the north of the island even where the no-diving zone was declared. The actual impact of the disease on Bonaire's coral species hasn't been documented up until now.

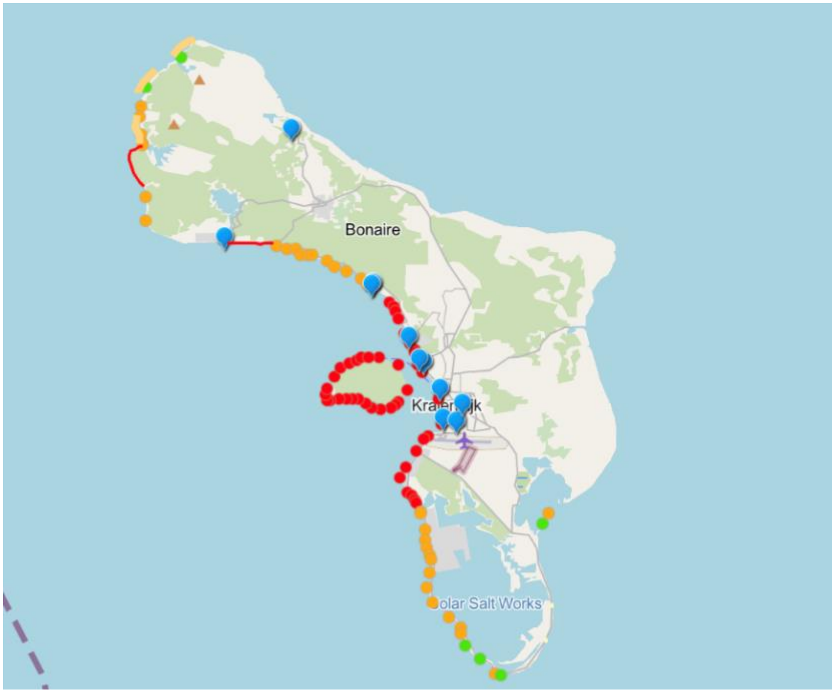


*Figure 1: STINAPA SCTLD spread map as of 14th of December 2023. Red: high disease levels; Orange: intermediate levels; Green: No disease.*

The majority (>99%) of reports of SCTLD displayed pictures of maze (*Meandrina meandrites*), flower (*Eusmilia Fastigiata*), great star (*Montastraea cavernosa*) and the brain corals

(*Pseudodiploria strigosa, Diploria labyrinthiformis and Colpophyllia natans*). these species are frequently observed, however other highly sensitive corals like *Dendrogyra cylindrus* and *Dichocoenia stokesi* were not prevalent in the analysis due to their sparse or virtually absent populations, which limits their representation in the data set and potentially overlooks their risk of disease sensitivity on Bonaire.

On Bonaire, these 6 sensitive species constitute the bulk of SCTLD infections and SCTLD-like symptoms, presenting a unique case compared to other islands.

Such specificity in disease impact has not yet been documented on Bonaire, given that SCTLD has only recently been observed in the region. This emergence presents a new frontier in the ongoing study of coral diseases and their localized effects on coral populations. Certain coral species, previously deemed as "winners" in the face of recent stressors, have shown remarkable resilience and even expansion over the last five decades, as documented in the literature (De Bakker et al., 2016). *Pseudodiploria strigosa*, commonly known as the smooth brain coral, is one such example, having increased its coverage significantly, often filling ecological niches left by more sensitive species. Nonetheless, the onslaught of SCTLD presents a new and significant challenge, potentially altering the trajectory of this species from a resilient "winner" to one that is notably vulnerable to emerging epidemics (Figure 3). Indeed, these thermo-resilient brain corals are often among the first to get infected by SCTLD (Álvarez-Filip et al., 2022; SCTLD Case Definition, 2018).


*Figure 2. The 6 (infected) sensitive coral species. A: PSTR; B:DLAB; C:CNAT; D:EFAS; E:MMEA; F:MCAV*

The coral reefs of Bonaire are not just natural wonders but also pillars of the island's economy. These vibrant reefs support a diverse array of marine life, functioning as critical habitats for species at various stages of their life cycles. They also constitute the backbone of Bonaire's tourism sector, attracting divers from around the world eager to explore the island's renowned shore-diving (Uyarra et al., 2008). This influx of tourism significantly contributes to the local economy, creating jobs and supporting businesses. The health of Bonaire's reefs is linked to the well-being of its economy, making the study and preservation of these ecosystems a matter of both environmental and economic necessity.

# Material and methods

## Study site and experimental design

Bonaire is a tropical island of the Dutch Caribbean of 288 km$^2$. The calmer leeward side attracts divers from all around the world for its shore diving (Uyarra et al., 2008). The survey spans 115 sites (Figure 4) located every 500m along the west coast of Bonaire (Table I Appendix). These sites are divided into different subregions based on Carbonate accretion and proximity to anthropogenic stressors, very homogenously distributed (De Bakker et al., 2019).

To conduct comprehensive surveys on the benthos and fish communities as part of this research, a four-member team followed a systematic protocol.

Surveys were done from the shore, or from boat when inaccessible from shore. Boat days were based on weather forecasts and boat/captain availability. On average 3 to 4 sites were surveyed each day between 9:00 and 17:00 in the months of September to November 2023. Given the exceptional circumstances with the arrival of SCTLD in March, dive sites 71 to 104 were strictly forbidden to SCUBA diving activities to slow down the spread of SCTLD. Furthermore, our diving gear and material had to be disinfected after each "red zone" (Figure 4) survey.

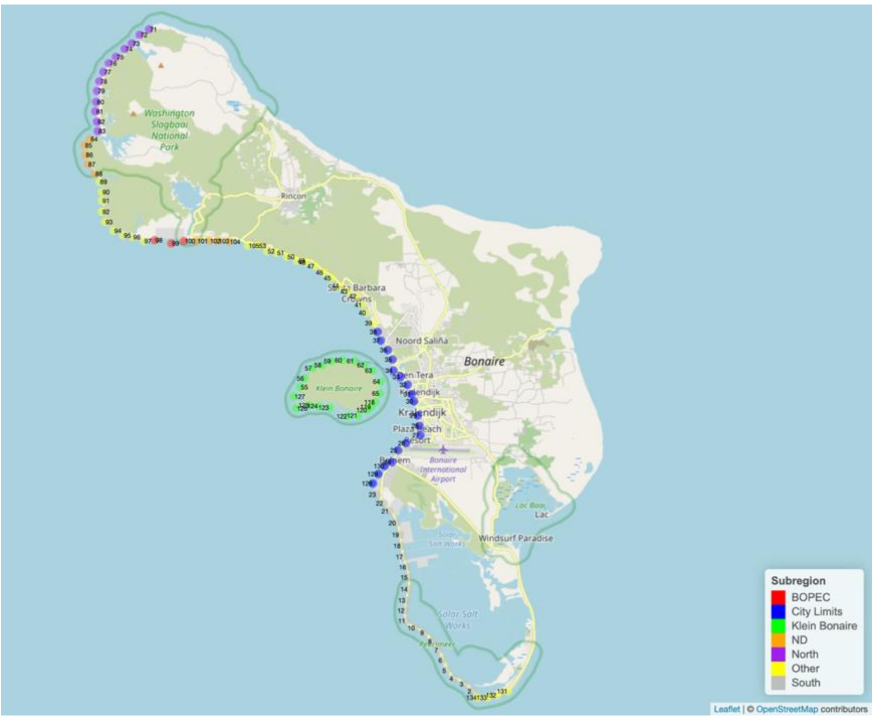


*Figure 3. The 7 sub-regions defined in De Bakker et al., 2019 on the leeward side of Bonaire.*

In the water protocol

For each of those sites, data was collected rolling out two transect lines, each by one pair of divers, parallel to the reef front following the isobath (Hill & Wilkinson, 2004) at the Drop-off zone (10-15m depth) and at the Lower Terrace zone (5m depth).

After descending to 10m, a small weight (Figure 16) marks the starting point. The pairs split, starting the fish count after 5 meters, maintaining a few meters gap between them.

The fish surveyor follows the 10-meter isobath, covering a 25-meter transect with a 4-meter wide belt, totalling 100m². Pelagic fish species are counted, identified, and size estimated. The benthos surveyor, following the fish surveyor, rolls out the transect line, signalling the end of the transect at 25 meters. As the benthos surveyor begins the benthic inventory along the last 10 meters, photographs are taken to document coral species. To ensure diversity, images alternate between the left and right sides of the transect line.

The fish surveyor returns along the entire 25m transect, counting, identifying, and measuring demersal and reef fish species. Parrotfish are distinguished by their phase (juvenile, initial, or terminal).

After completing the fish inventory, the fish surveyor returns to the end of the transect line for urchin identification. The urchin inventory covers the same 10 meters as the benthic inventory, within a 2-meter-wide belt, covering 20m².

The benthic surveyor completes the coral inventory along the last 10 meters of the transect line. Additionally, rugosity was estimated using the height of the nearest coral colony (living or dead), while quadrats of 0.25 x 0.25 meters were placed for additional analysis (Figure 4), including the percentage of crustose coralline algae, cyanobacteria, macroalgae, and turf.

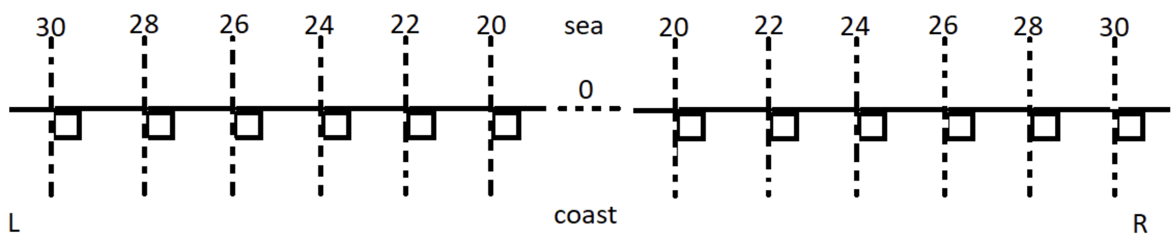


*Figure 4. Transect lines left and right containing quadrats. L is left and R is right. Dotted line in the middle contains every metre in between the two transects from 20 to 0 metres. Squares are quadrats of 0.25 x 0.25 m.*

Pictures of the benthos were taken with an Olympus Tough tg-6 camera, equipped with a Weefine WFL-02 wide-angle lens (52 mm). Camera settings were configured as detailed in Figure 28.

### Data processing

We carefully improved the benthic images, each 50cm by 50cm, by using editing software to make them clearer and sharper. This included changing the colors, brightness, and sharpness to make sure the pictures looked as close to real life as possible. The CoralNet AI was chosen as it is an advanced image analysis resource, for the classification of benthic organisms (Beijbom et al., 2015). Each edited image was uploaded to the platform, ensuring careful adherence to the specified categorization and organization as per our Table ii: LabelSet CoralNet AI. Upon upload, CoralNet AI's deep neural networks facilitated the annotation process, identifying and categorizing benthic features within the images. Each automated annotation was rigorously reviewed. This step ensured that the annotations were a precise representation of the corals depicted in the imagery, thus allowing for accurate analysis of benthic organism distribution and abundance. The use of CoralNet AI greatly accelerated and simplified the processing phase, which was essential for the assessment of coral cover across Bonaire's reef systems.

## Data Analysis

The first step in the research involved an in-depth descriptive analysis of coral cover for the sensitive coral species *Meandrina meandrites, Colpophyllia natans, Pseudodiploria strigosa, Diploria labyrinthiformis, Eusmilia fastigiata*, and *Montastraea cavernosa* across Bonaire's leeward reefs (Figure 3). These species were chosen based on literature (Precht et al., 2016; Costa et al., 2021) and personal experience, due to their vulnerability to SCTLD and their significant contribution to the total coral cover in Bonaire, representing roughly 15% of the average total coral cover on the hard corals there. Furthermore, preliminary observations indicated that the total coral cover values excluding these sensitive species didn't significantly change between 2020 and 2023, as illustrated by Figure 5. This approach allowed us to concentrate on the changes most indicative of SCTLD's effects on the reef ecosystem.

Descriptive statistics and 95% confidence intervals were used to evaluate the spatial distribution of these sensitive species across 7 sub-regions (De Bakker et al., 2019), while linear model trends were presented as a visual aid rather than as the main analytical tool. These 95% confidence intervals were computed in R by first transforming the mean cover values using a fourth root. Then, the standard error (SE) of the transformed values was calculated, accounting for sample size. Subsequently, the lower and upper bounds of the confidence interval were determined based on the t-distribution with a 95% confidence level and degrees of freedom equal to the sample size minus one. After obtaining the bounds for the transformed values, they were back-transformed to their original scale by raising them to the power of 4 to fit back the confidence intervals in the plot.

Our assessment considered varying depths of 10 and 5 meters and transects across four datasets spanning the years 2014, 2017, 2020, and 2023. The mapping of subregions, defined by sites (Figure 4; Table i: Coordinates of each site), was crucial for understanding the spatial dynamics of coral health. We used R programming tools to calculate and aggregate the coral cover data, adjusting for factors such as transect orientation (left/right) and depth categorization.

The skewed and zero-inflated distribution of our data presented analytical challenges, to partly address this issue, we applied a 4th squared root transformation to the coral cover values, which aimed to stabilize the variance and improve the symmetry of the distribution (Figure 19; Figure 20).

This methodology was replicated at the species level, which provided insight into individual species trends, despite the interpretive challenges posed by the prevalence of zero cover at numerous sites when sensitive coral species are not aggregated.

The linear trend lines derived from these models, while indicative of general patterns and changes in coral cover, were interpreted with caution. The primary evidence for significant differences in coral cover came from the analysis of the 95% confidence intervals. Where these intervals did not overlap between time points or subregions, it suggested notable changes in coral cover. We placed greater reliance on these 95% intervals rather than on the trend lines for making inferences about the health of the coral populations.

Ultimately, our approach gave us critical insights into the impacts of SCTLD on coral health across different regions in 2023, when comparing it with the other years. The analysis allowed us to assess the cumulative effects of SCTLD on the entire coral community while considering the potential for zero values and proportion variations in the dataset.

In this study, we took a straightforward approach to analyzing coral cover data. Using basic stats and 95% confidence intervals, we've been able to spot important patterns and differences in the coral reef's condition. This simple method has given us some good initial insights. This sets room for more specialized models that are designed for the kind of data we have and can reduce the p-values. For now, this approach allows for future, more in-depth research.

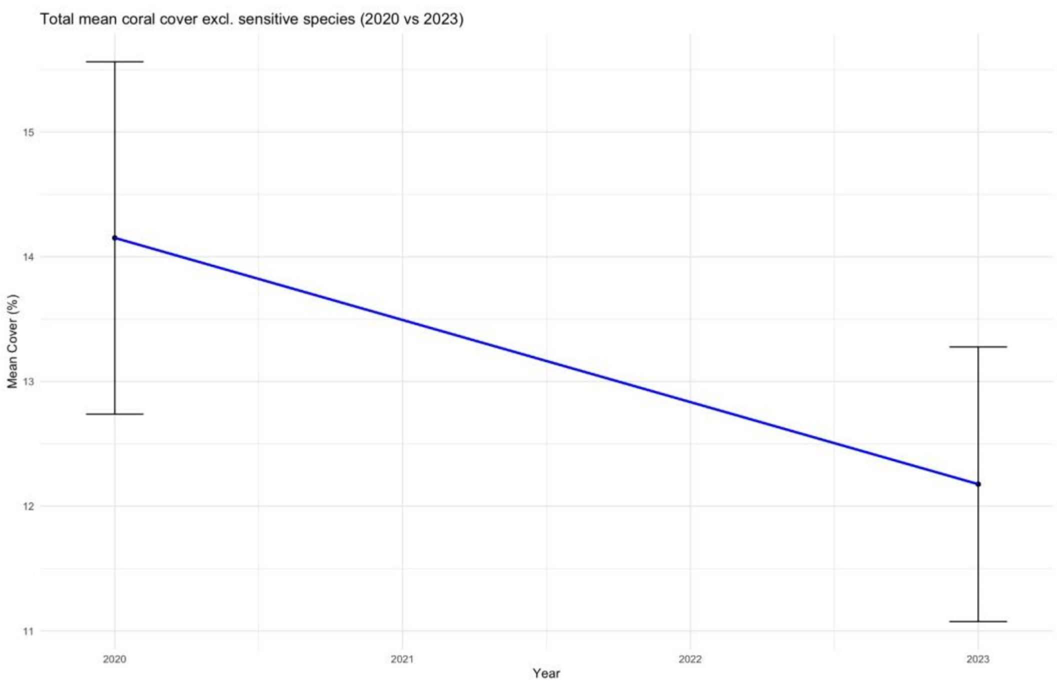


*Figure 5. total mean coral cover excluding sensitive species from 2020 to 2023, illustrating a downward trend with 95% confidence intervals representing variability, but no significant difference as the 95% CI don't overlap.*

# Results

## Overall trends

In this section, we will first focus on the overall trends and patterns and then focus on regional and species-specific changes in the year 2023 in comparison with the other data sets.

The analysis of coral cover trends on the island of Bonaire's reefs reveals a concerning pattern of decline among the sensitive coral species on Bonaire.

The data from 2018 and 2023 both show a significant decrease in corals sensitive to SCTLD (Figure 7). As hypothesized, total coral coverage excluding these sensitive species didn't display such a decline between 2020 and 2023 (Figure 5).

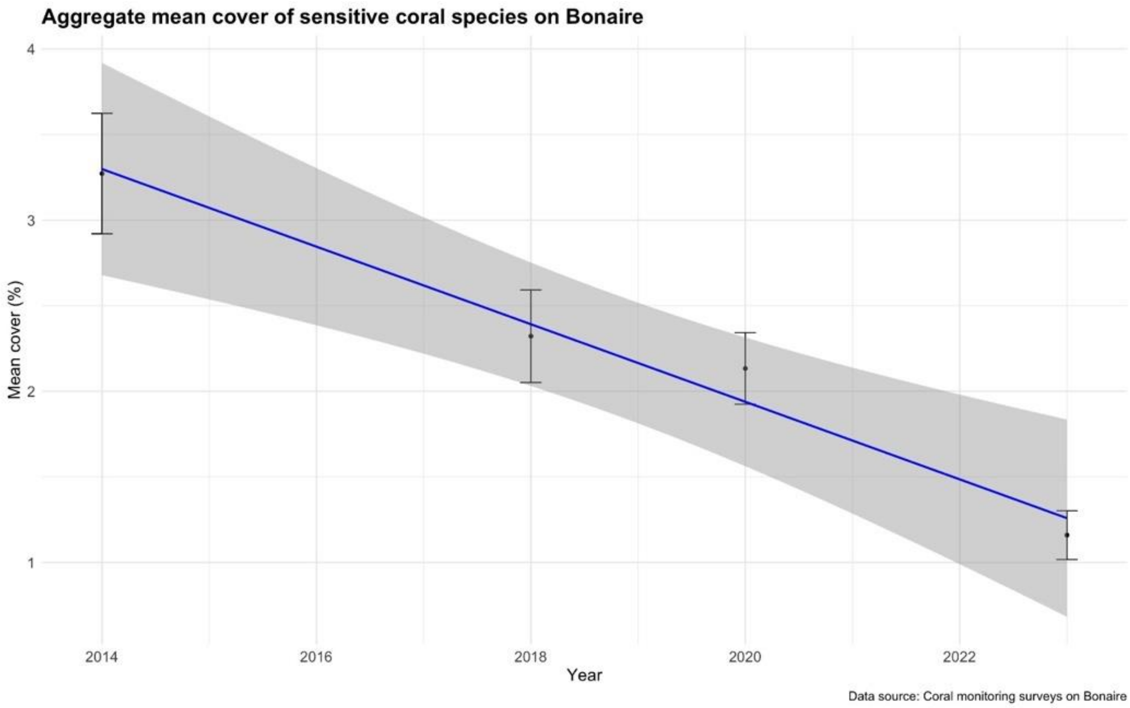


*Figure 6: Aggregate mean cover of sensitive coral species on Bonaire from 2014 to 2023 displaying a continuous decline throughout the period. The 95% confidence intervals illustrate variability in the data.*

Individual species trends

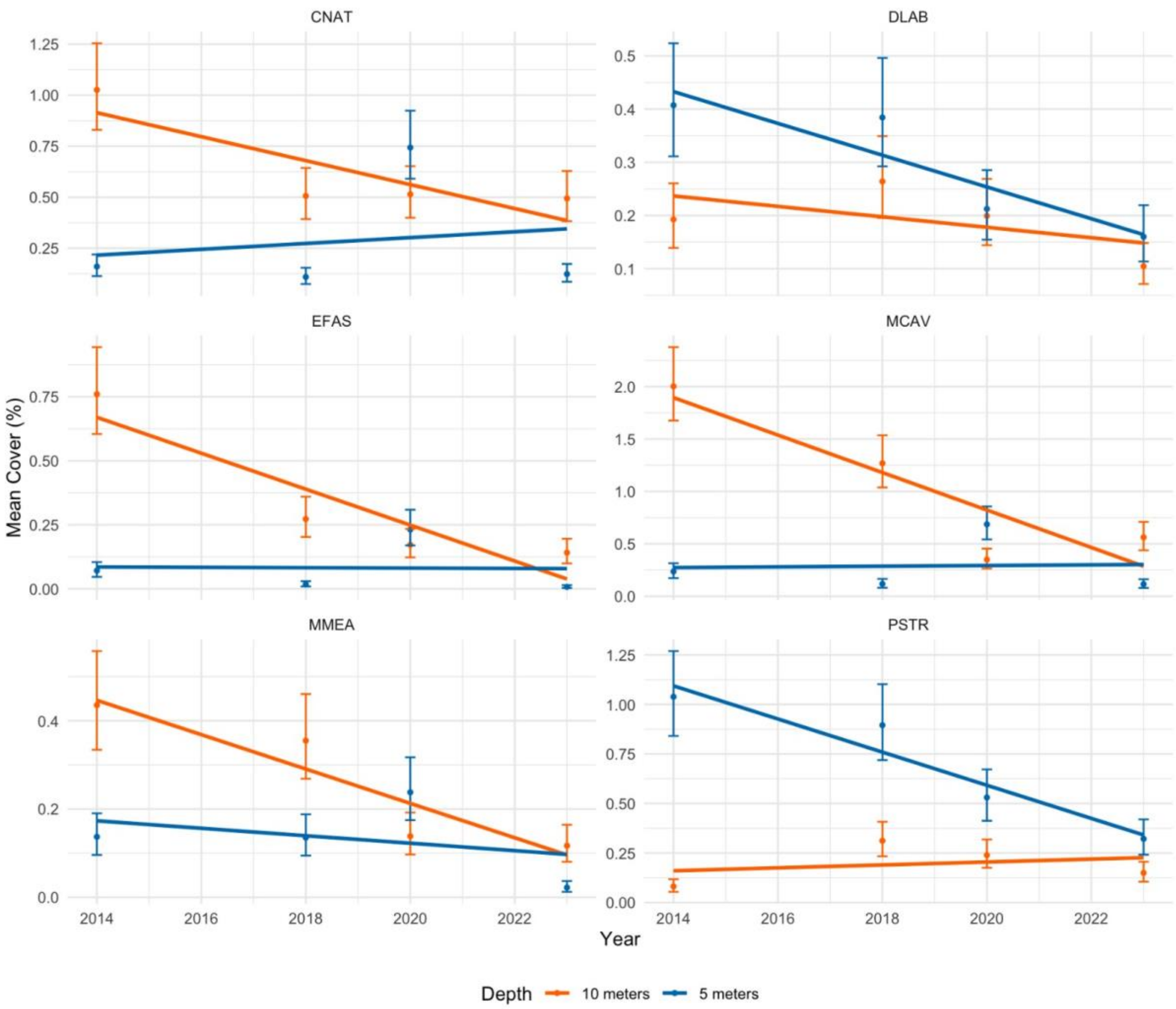


*Figure 7. Comparative decline in mean coral cover for the six sensitive coral species at Depths of 5 Meters (Orange) and 10 Meters (Blue) from 2014 to 2023. Significant differences are shown when the 95% CI don't overlap.*

Our analysis of sensitive coral species from 2014 to 2023 indicates a discernible decline, with 2023 often marking the lowest mean covers (Figure 7).

*Colpophyllia Natans* (CNAT) is typically more prevalent at a 10-meter depth, which is consistent with the trends observed. At 10 meters, there's a noticeable decrease in mean cover by 2018, illustrating the species' decline in its preferred habitat.

For *Diploria Labyrinthiformis* (DLAB), the reduction in mean cover continues through 2023, with a significant decrease at 5 meters depth in 2020. This species, which is found across various depths, shows a consistent downward trend, but with a more notable impact in shallower regions.

*Eusmilia Fastigiata* (EFAS) has suffered a strong decline in cover at 10 meters, especially in 2018, aligning with its ecological preference for deeper reefs. By 2023, the mean cover at this depth reached its lowest point, highlighting the species' susceptibility.

*Montastraea Cavernosa* (MCAV), commonly found at greater depths, reveals a concerning decline at both 5 meters and 10 meters.

*Meandrina Meandrites* (MMEA) presence is generally lower at shallower depths, and the mean cover has shown a steep decline at 10 meters by 2023, with a significant decrease in 2020.

*Pseudodiploria Strigosa* (PSTR), exhibits a steady decline in mean cover at both depths examined. The year 2023 marks the lowest recorded cover for PSTR, with an especially sharp decrease at 5 meters.

The 2023 analysis suggests that although all species are impacted, the decline likely initiated before SCTLD arrived in 2023, for certain species, as indicated by significant decreases in CNAT, MCAV, and EFAS in previous datasets. However, it's important to interpret these results cautiously, as many of the species examined are relatively rare (0,1-1% coverage) and observed trends could potentially be influenced by random chance. Therefore, aggregating these species and examining regional trends will yield more accurate insights into the possible impact of SCTLD.

## Regional trends

### Sensitive coral cover

The regional analysis of sensitive coral cover in 2023 reveals a heterogenous pattern of decline. A significant reduction in sensitive coral cover is observed in the City Limits and Klein Bonaire subregions, with the majority of transects indicating a decline to nearly 0% cover (Figure 9.; Figure 10.).

Other subregions (see Sensitive species) also suggest declines in sensitive coral cover in 2023, although these decreases were mostly not significant.

In contrast, where most regions indicated a downward trend for both depths, the North subregion displayed stable sensitive coral cover levels between 2014 and 2023.

Looking at the sensitive coral cover in other subregions, while there are declines noted in 2023, they do not exhibit the severity seen in City Limits and Klein Bonaire (see Sensitive species).

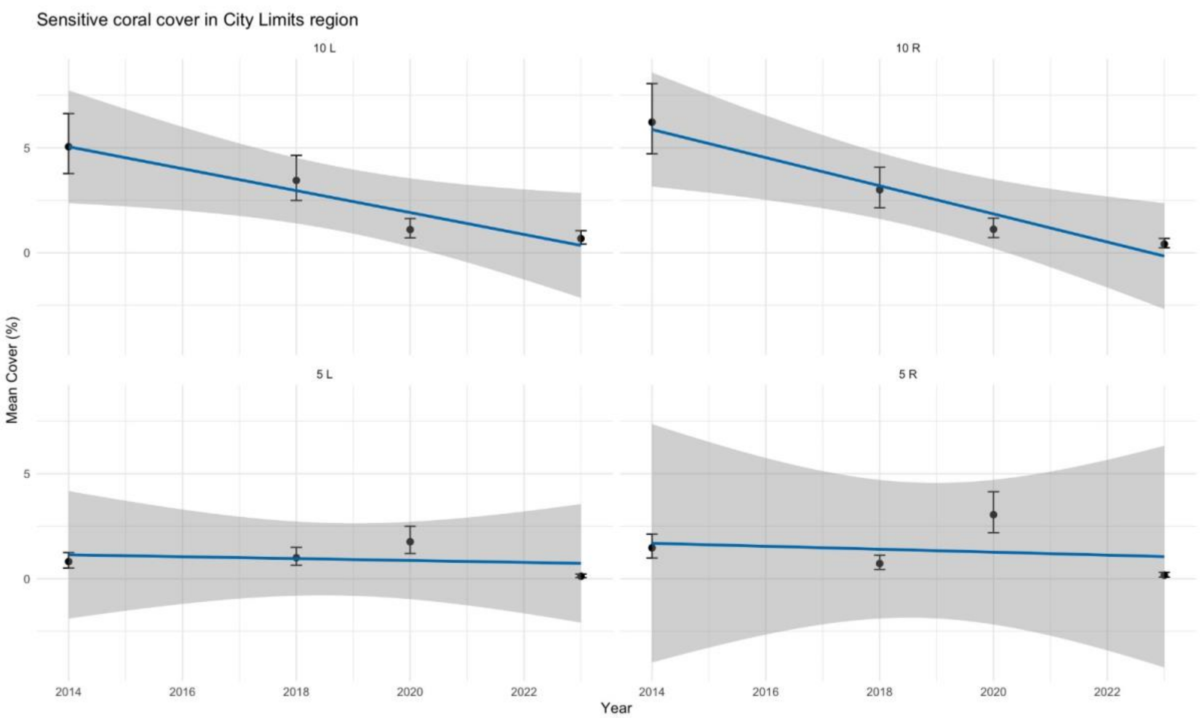


*Figure 8. Trend analysis of sensitive coral species cover in the City limits region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

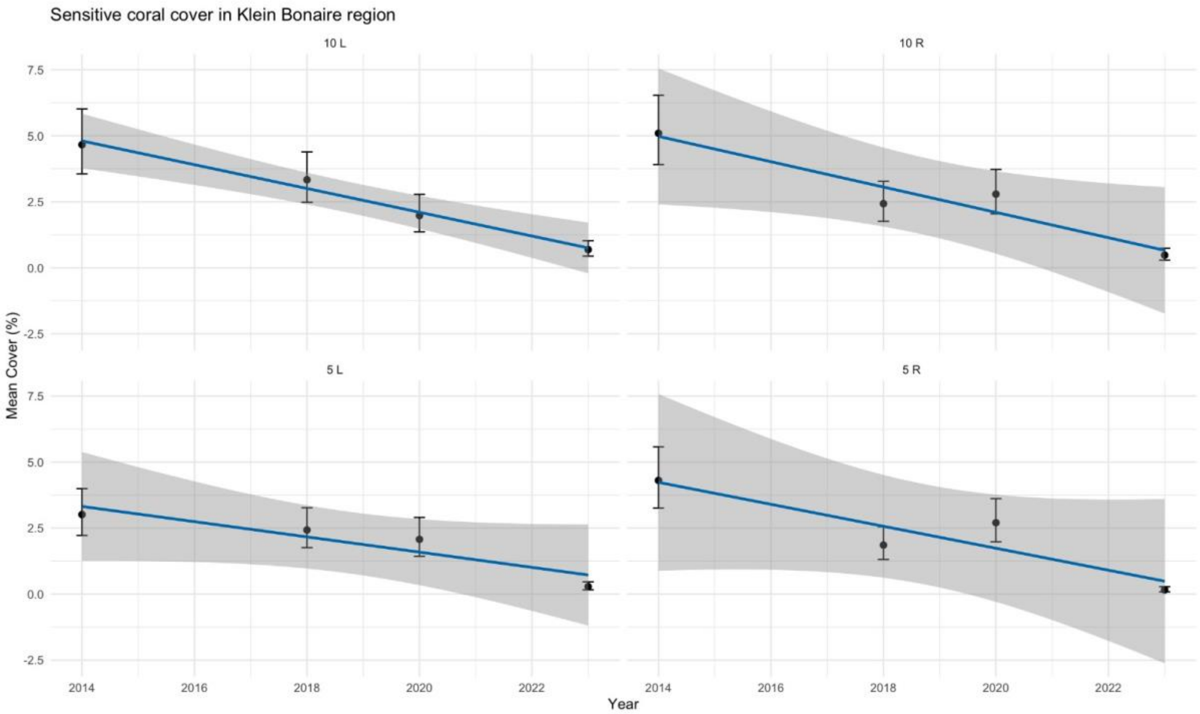


*Figure 9. Trend analysis of sensitive coral species cover in the Klein Bonaire region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

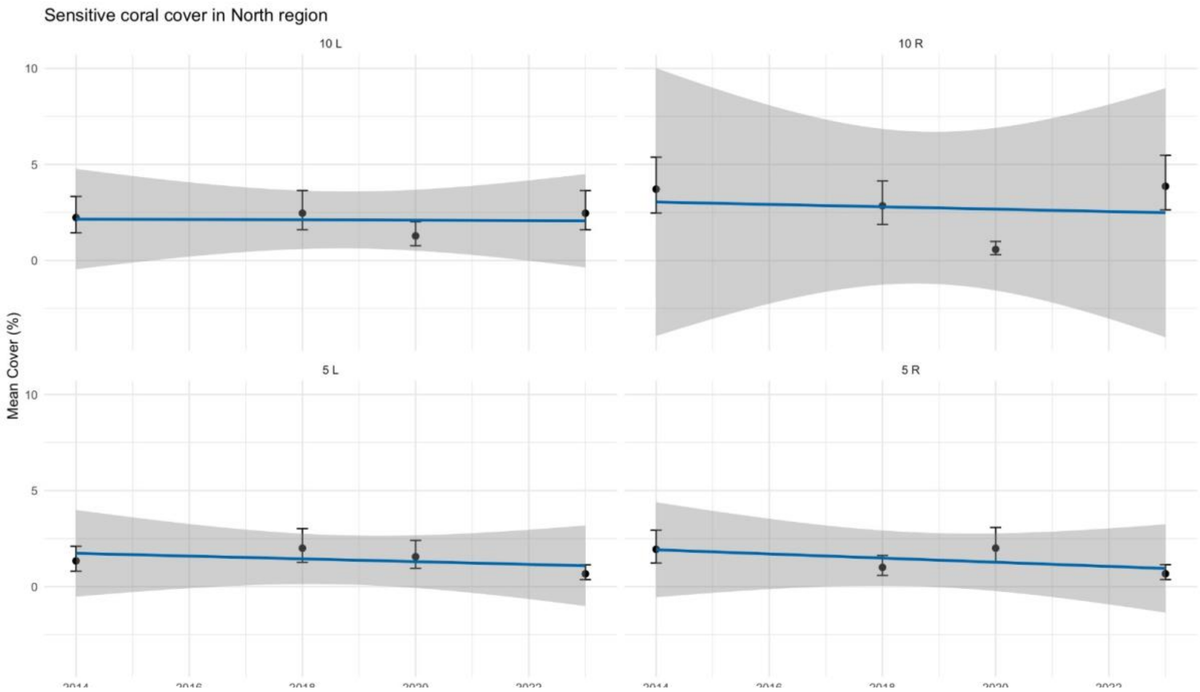


*Figure 10. Trend analysis of sensitive coral species cover in the North region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

## Total coral cover

The findings on individual species trends reveal a variable but generally declining pattern in coral cover between 2020 and 2023. However, these differences are not significantly more pronounced since the arrival of SCTLD in Bonaire.

Nonetheless, sensitive coral cover values showed spatial heterogeneity, with city limits and Klein Bonaire the most impacted subregions (Figure 9; Figure 10). In contrast, regions like the north seem to do fine for now (Figure 11; see Sensitive species) .

Interestingly, the significant differences observed on Klein Bonaire and City Limits on the sensitive species are even observed on the total coral cover (Figure 12.; Figure 13.). While six out of seven subregions of Bonaire showed no significant decrease in total coral cover in the last year, Klein Bonaire's coral community experienced a significant decrease in mean coral cover in 2023, indicating an immediate and substantial impact on the reef system (Figure 13). In the City Limits subregion, a long-term significant decrease from 2014 to 2023 was observed, with the most significant reduction occurring in the final year (Figure 12).

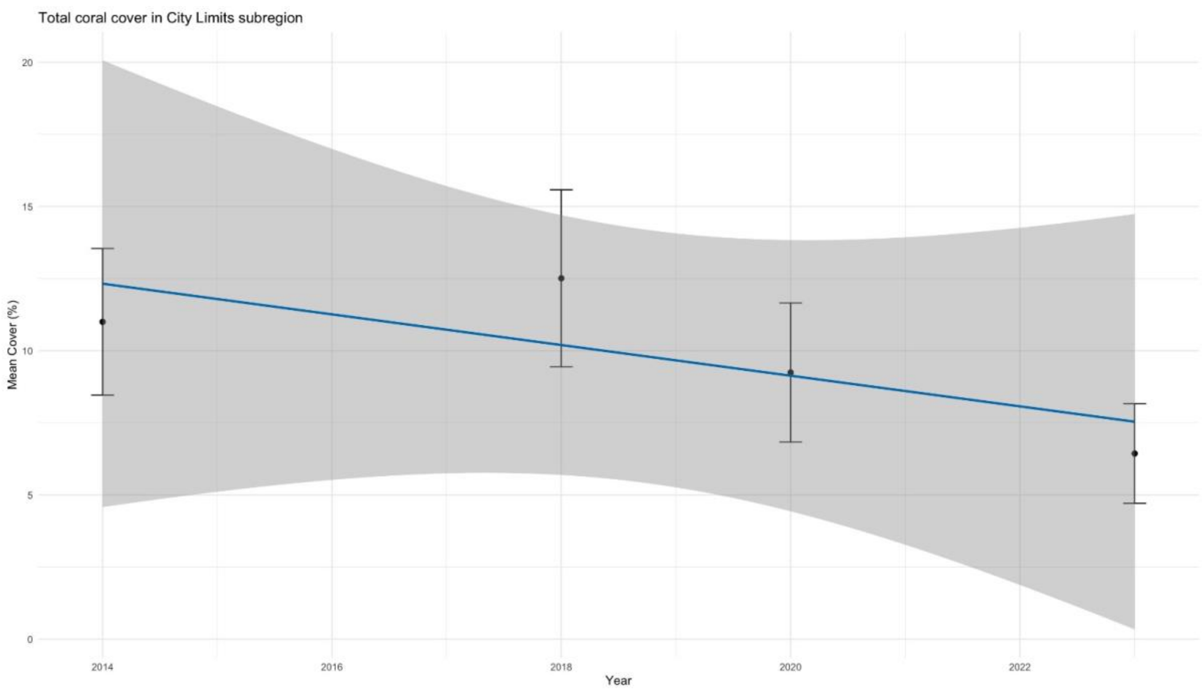


*Figure 11. Total coral cover in City Limits subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

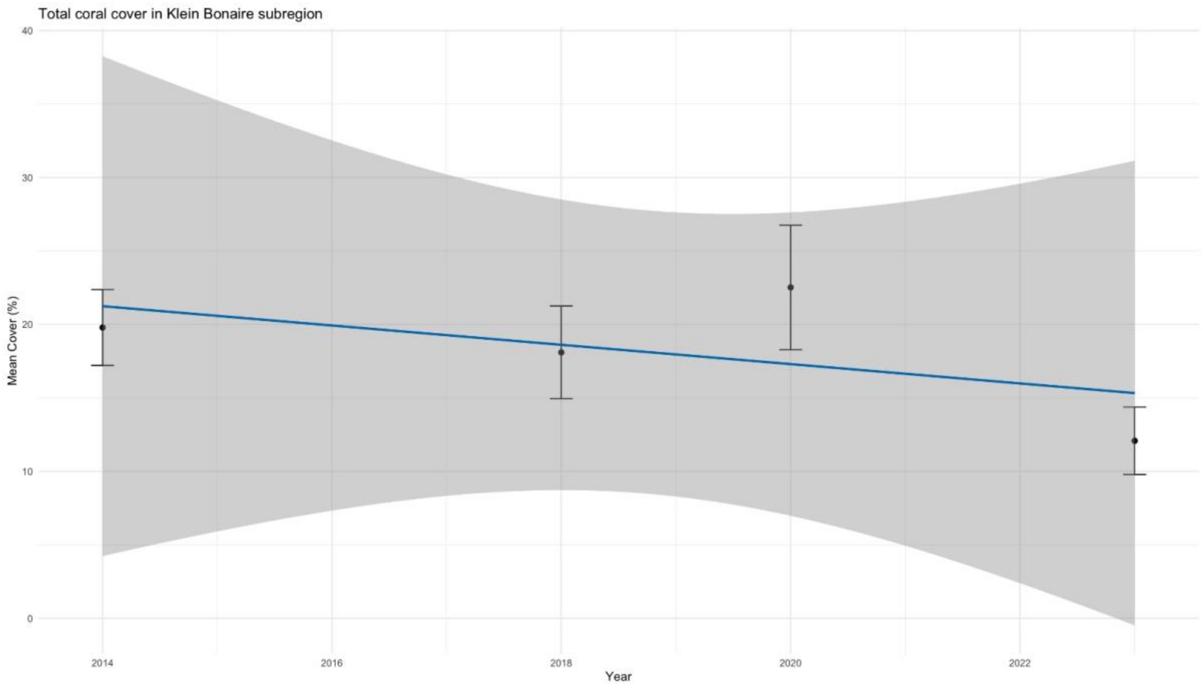


*Figure 12. Total coral cover in Klein Bonaire subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

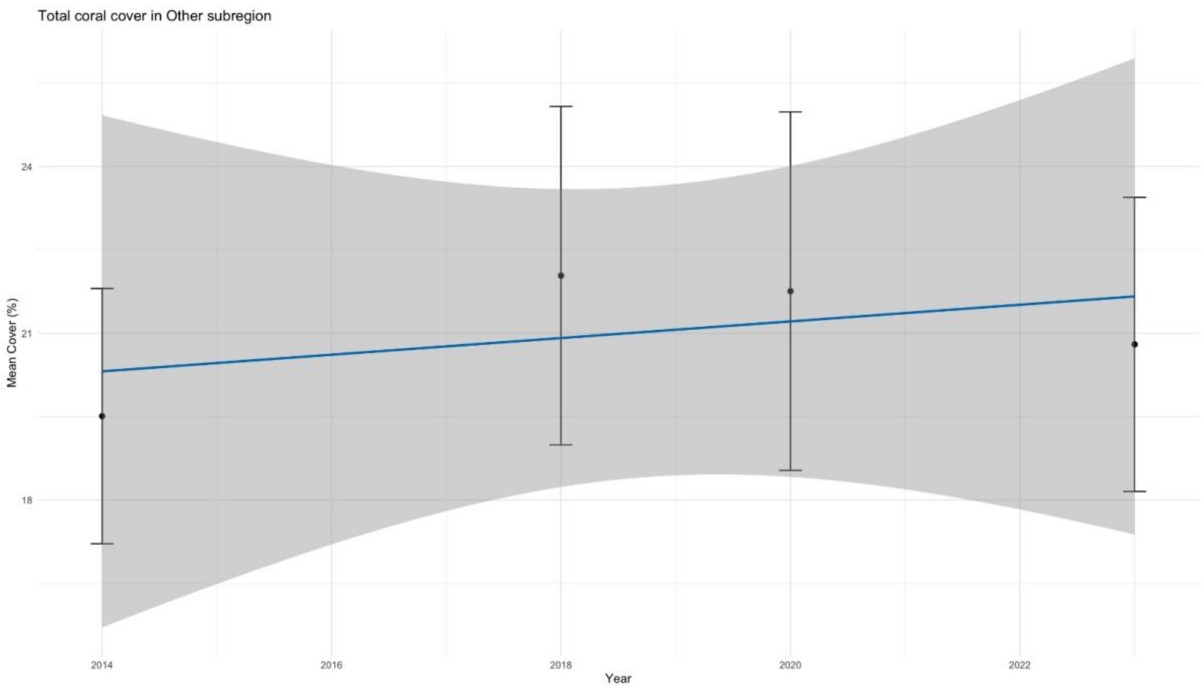


*Figure 13. Total coral cover in Other subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

These results underscore the urgency of addressing the declines in coral cover by identifying contributing factors. As we move into discussing the implications of these results, the focus will shift to understanding SCTLD's impact, especially in the North region where its presence has been minimal during the survey timeframe (Figure 1).

# Discussion

## Interpretation

The spatial analysis conducted reveals a complex landscape of SCTLD's impact across Bonaire's coral reefs. Notably, the decline in coral cover is not uniformly distributed among the subregions as delineated by De Bakker et al., 2019. Our results indicate a degree of resistance in the North subregion, suggesting a potential lower prevalence of SCTLD or the influence of different environmental factors that may be offering a refuge or resilience against the disease. Conversely, the South region, the City Limits, and Klein Bonaire exhibit significant declines. These areas, particularly City Limits and Klein Bonaire, show acute declines, closely mirroring the SCTLD spread patterns mapped by STINAPA (Figure 1).

This spatially variable impact of SCTLD is further nuanced by our findings on individual coral species trends. In 2023, the six sensitive coral species all indicated a downward trend. The marked susceptibility of species such as EFAS at 10 meters, the steep decline of MMEA at 10 meters, and the steady decline of PSTR at 5m highlight that 2023 frequently recorded the lowest mean cover values for these species. Such uniformly low levels across different species underscore the widespread impact of SCTLD on the coral populations in just 6 to 9 months after its arrival in Bonaire's waters.

Interestingly, our color maps (Figure 14; Figure 15) indicate a gradient of declining coral cover emanating from the port of Kralendijk towards the outer regions. This pattern could be interpreted as a dual signature of heightened human activity near the port and the progressive spread of SCTLD from its point of initial detection. This observation aligns with other studies suggesting that coral reef health is influenced by both anthropogenic stressors and disease dynamics (Brandt et al., 2021; Costa et al., 2021; De Bakker et al., 2016; Van Der Geest et al., 2020).

Moreover, the specificity of the significant decline in the City Limits and Klein Bonaire underscores the need for targeted conservation measures in these regions. While SCTLD's presence has been minimal in the North during our survey period, the pronounced vulnerability of certain species since 2020 implies that an important part of the decline in coral cover may also be attributed to pre-existing stressors. The impact of SCTLD has been proven to be immediate on these 6 sensitive species, just leaving behind infected colonies that often die within weeks, even for the centuries old and meters-wide colonies of CNAT.


*Figure 14: Color map showing the relative decrease in sensitive species coral cover values by subregions between 2023 and 2020*

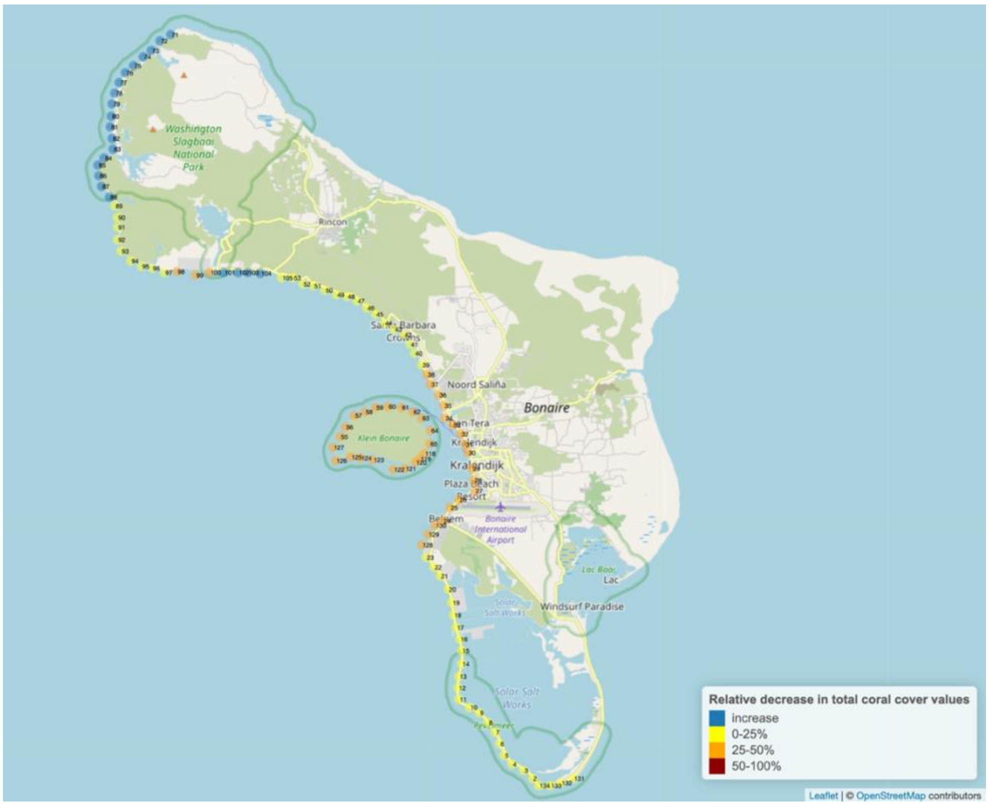


*Figure 15: Color map showing the relative changes in total coral cover values by subregions between 2023 and 2020*

## Limitations

Our study provides a detailed examination of the decline in coral species particularly susceptible to SCTLD across the subregions of Bonaire in the initial year of the disease's emergence. The limitations inherent in observational studies, as well as the specific methodologies employed for data collection, must be acknowledged. The use of photographic records to estimate coral cover introduces potential bias, where the density of corals and the presence of outliers could influence the results. Furthermore, the high variability in species density across different regions and depths, and the skewed nature of the data, which is heavily inflated with zeros and lower proportions (between 0 and 0.2), present a significant challenge. These conditions make it difficult to use most standard statistical models accurately. This was a key limitation in my analysis, added with my own limited experience with advanced statistical methods. These issues are especially important to consider when comparing the differences by individual species (see Figure 7) which have often relatively low densities, meaning we need to be particularly careful when we interpret these results.

Prior to 2023, the decline in sensitive species might have been influenced by factors such as the mass bleaching events from 2014-2017 and human-induced stressors, which could have heightened their vulnerability to diseases (Eakin et al., 2019; Merselis et al., 2018). This pre-existing decline complicates the task of isolating the specific impacts of SCTLD on coral cover, especially in areas near anthropogenic activities where environmental disturbances could be very difficult to interpret.

Moreover, the virulent nature of SCTLD and its selective impact on only a subset of species adds to the complexity of correlating disease prevalence with changes in coral cover. This necessitates a cautious interpretation of the results and underlines the importance of continued, rigorous research to unravel the intricate interactions between SCTLD and other stressors affecting coral ecosystems.

In our analysis, we leveraged linear trend models to give visual cues about the evolution of the means over the time. Additionally, 95% confidence intervals were calculated for each mean. In many cases, these confidence intervals helped show a statistical difference between means when they didn’t overlap. While this approach has yielded and proven significant declines in many cases (Figure 13; Figure 9; Figure 10; Sensitive species), it is a precursor to more sophisticated analyses that could explain the declines hinted by the trend lines (See

PSTR in Figure 7; More examples in Sensitive species), by reducing p-values and offering a more complete interpretation of the data.

## Future research

The full impact of SCTLD has yet to be assessed, as it only reached the northern part of the island 7-8 months after its arrival through the water. Furthermore, for now it affects a fraction of the species it usually does. Indeed, several coral species affected by SCTLD in regions like Florida appear to exhibit resilience in Bonaire's waters for now (Precht et al., 2016). This opens avenues for future monitoring to determine if this trend persists or if these species might eventually exhibit symptoms. Furthermore, it's crucial to consider other stressors that may impact these species, such as thermal stress, pollution, and runoffs (Eakin et al., 2019; H. Meesters et al., 2022Van Der Geest et al., 2020). Although slow-growing brain corals are typically known for their thermal resistance, they are not impervious to the ravages of Stony Coral Tissue Loss Disease (Álvarez-Filip et al., 2022), which has diminished their populations and eroded their resilience to climate change. Notably, species such as *Pseudodiploria strigosa* (PSTR), once increasing in cover (De Bakker et al., 2016), have suffered declines in this year's data likely due to SCTLD, indicating a concerning shift in reef composition.

Our findings, highlighting the immediate and mid-term effects of SCTLD on key coral species, add to the extensive list of stressors affecting Bonaire's reefs and inform targeted restoration efforts (Bak & Criens, 1981; Gladfelter, 1982). To date, reef renewal efforts in Bonaire have predominantly focused on acroporids, devastated by White Band Disease (WBD). The gradient of coral health decline suggests two scenarios: either proximity to human activity is exacerbating the disease's impact, or SCTLD has not yet reached its full effect in the more remote areas (North). Future research could expand on our findings by correlating the presence of recently dead corals with water quality parameters, offering a more nuanced understanding of SCTLD's spread and the influence of anthropogenic factors.

# Conclusion

This Master's thesis has provided an in-depth analysis of the impact of SCTLD on sensitive coral species in Bonaire's reefs. The comprehensive surveys conducted from 2014 to 2023 have revealed a marked decline in 6 coral species coverage, particularly in 2023, indicating SCTLD's significant detrimental effect on coral health. This decline is not uniformly distributed across the reef's subregions, suggesting that local environmental factors and the spread of the disease vary across different areas.

The study's findings contribute vital insights into the complex dynamics of coral reef ecosystems under the stress of disease outbreaks. Our results have shown that valuable species known for their thermal resilience, such as certain brain corals, are extremely susceptible to SCTLD also in Bonaire. The spatial variability in coral decline points towards the intricate interplay of SCTLD with regional environmental conditions and anthropogenic factors.

These observations underscore the urgent need for targeted conservation and disease mitigation strategies. Future research should focus on long-term monitoring to track the progression of SCTLD and investigate the potential resilience mechanisms in certain coral species. Additionally, exploring the role of environmental and anthropogenic factors in influencing disease spread could provide critical insights for managing coral reef health more effectively.

The health of Bonaire's coral reefs is not only an ecological concern but also a matter of economic and community well-being. Therefore, this research not only contributes to the scientific understanding of coral diseases but also has significant implications for the conservation and sustainable management of these vital marine ecosystems.

## Acknowledgments

I would like to express my deepest gratitude to Dr. Erik Meesters of Wageningen University & Research for his invaluable guidance, patience, and expert advice throughout this project. His expertise and knowledge have been a great source of inspiration and learning.

Special thanks to Professor Appy Sluijs of Utrecht University for his insightful feedback and support as my second supervisor.

I am immensely grateful to my family for their endless love, understanding, and support from Switzerland to the Netherlands. They have been my foundation and a constant source of motivation during this academic adventure.

I also wish to thank my colleagues and fellow MSc students in Marine Sciences, Viggo Van der Roest, Olivier Vlam, and Sam Nouse, for their camaraderie and collaborative spirit during our fieldwork in Bonaire. Their contributions and companionship have been invaluable.

This journey would not have been possible without the collective effort and encouragement of everyone mentioned above and many others who have contributed in various capacities. Thank you.

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# Appendices

## site coordinates

*Table i: Coordinates of each site*

| Site | Zone | Latitude | Longitude | Area |
|---|---|---|---|---|
| | | | | |
| **2** | DO | 12.02840 | -68.25250 | South |
| **3** | DO | 12.03133 | -68.25605 | South |
| **4** | DO | 12.03378 | -68.26042 | South |
| **5** | DO | 12.03702 | -68.26340 | South |
| **6** | DO | 12.04129 | -68.26528 | South |
| **7** | DO | 12.04576 | -68.26711 | South |
| **8** | DO | 12.04942 | -68.26974 | South |
| **9** | DO | 12.05306 | -68.27320 | South |
| **10** | DO | 12.05525 | -68.27697 | South |
| **11** | DO | 12.05801 | -68.28089 | South |
| **12** | DO | 12.06243 | -68.28152 | South |
| **13** | DO | 12.06696 | -68.28116 | South |
| **14** | DO | 12.07170 | -68.28006 | South |
| **15** | DO | 12.07647 | -68.27990 | South |
| **16** | DO | 12.08090 | -68.28086 | South |
| **17** | DO | 12.08536 | -68.28221 | South |
| **18** | DO | 12.08995 | -68.28306 | South |
| **19** | DO | 12.09459 | -68.28370 | South |
| **20** | DO | 12.09985 | -68.28528 | South |
| **21** | DO | 12.10480 | -68.28820 | South |
| **22** | DO | 12.10815 | -68.29071 | South |
| **23** | DO | 12.11175 | -68.29387 | South |
| **24** | DO | 12.12566 | -68.28722 | City Limits |
| **25** | DO | 12.13053 | -68.28440 | City Limits |
| **26** | DO | 12.13355 | -68.28092 | City Limits |
| **27** | DO | 12.13686 | -68.27478 | City Limits |
| **28** | DO | 12.14094 | -68.27529 | City Limits |
| **29** | DO | 12.14547 | -68.27608 | City Limits |
| **30** | DO | 12.15139 | -68.27755 | City Limits |
| **31** | DO | 12.15454 | -68.27860 | City Limits |
| **32** | DO | 12.15845 | -68.28046 | City Limits |
| **33** | DO | 12.16195 | -68.28330 | City Limits |
| **34** | DO | 12.16468 | -68.28672 | City Limits |
| **35** | DO | 12.16924 | -68.28681 | City Limits |
| **36** | DO | 12.17318 | -68.28890 | City Limits |
| **37** | DO | 12.17725 | -68.29205 | City Limits |
| **38** | DO | 12.18108 | -68.29340 | City Limits |
| **39** | DO | 12.18467 | -68.29546 | Other |
| **40** | DO | 12.18893 | -68.29823 | Other |
| **41** | DO | 12.19229 | -68.30008 | Other |
| **42** | DO | 12.19598 | -68.30241 | Other |
| **43** | DO | 12.19824 | -68.30627 | Other |
| **44** | DO | 12.20042 | -68.30999 | Other |
| **45** | DO | 12.20380 | -68.31346 | Other |
| **46** | DO | 12.20630 | -68.31691 | Other |
| **47** | DO | 12.20886 | -68.32068 | Other |
| **48** | DO | 12.21061 | -68.32420 | Other |
| **49** | DO | 12.21133 | -68.32845 | Other |
| **50** | DO | 12.21290 | -68.33277 | Other |
| **51** | DO | 12.21449 | -68.33735 | Other |

| | | | | |
|---|---|---|---|---|
| **52** | DO | 12.21520 | -68.34142 | Other |
| **53** | DO | 12.21759 | -68.34509 | Other |
| **55** | DO | 12.15736 | -68.32709 | Klein Bonaire |
| **56** | DO | 12.16127 | -68.32492 | Klein Bonaire |
| **57** | DO | 12.16559 | -68.32171 | Klein Bonaire |
| **58** | DO | 12.16704 | -68.31741 | Klein Bonaire |
| **59** | DO | 12.16851 | -68.31344 | Klein Bonaire |
| **60** | DO | 12.16897 | -68.30858 | Klein Bonaire |
| **61** | DO | 12.16856 | -68.30333 | Klein Bonaire |
| **62** | DO | 12.16675 | -68.29902 | Klein Bonaire |
| **63** | DO | 12.16454 | -68.29542 | Klein Bonaire |
| **64** | DO | 12.15970 | -68.29221 | Klein Bonaire |
| **65** | DO | 12.15495 | -68.29229 | Klein Bonaire |
| **71** | DO | 12.30951 | -68.39281 | North |
| **72** | DO | 12.30724 | -68.39668 | North |
| **73** | DO | 12.30350 | -68.40019 | North |
| **74** | DO | 12.30095 | -68.40330 | North |
| **75** | DO | 12.29784 | -68.40717 | North |
| **76** | DO | 12.29507 | -68.41002 | North |
| **77** | DO | 12.29148 | -68.41253 | North |
| **78** | DO | 12.28748 | -68.41426 | North |
| **79** | DO | 12.28326 | -68.41527 | North |
| **80** | DO | 12.27858 | -68.41572 | North |
| **81** | DO | 12.27467 | -68.41607 | North |
| **82** | DO | 12.27020 | -68.41529 | North |
| **83** | DO | 12.26613 | -68.41506 | North |
| **84** | DO | 12.26299 | -68.41836 | ND |
| **85** | DO | 12.26012 | -68.42088 | ND |
| **86** | DO | 12.25626 | -68.42057 | ND |
| **87** | DO | 12.25197 | -68.41951 | ND |
| **88** | DO | 12.24817 | -68.41617 | ND |
| **89** | DO | 12.24479 | -68.41421 | Other |
| **90** | DO | 12.24045 | -68.41322 | Other |
| **91** | DO | 12.23673 | -68.41308 | Other |
| **92** | DO | 12.23206 | -68.41314 | Other |
| **93** | DO | 12.22753 | -68.41191 | Other |
| **94** | DO | 12.22386 | -68.40815 | Other |
| **95** | DO | 12.22197 | -68.40405 | Other |
| **96** | DO | 12.22125 | -68.40001 | Other |
| **97** | DO | 12.21968 | -68.39500 | Other |
| **98** | DO | 12.21984 | -68.39038 | BOPEC |
| **99** | DO | 12.21872 | -68.38299 | BOPEC |
| **100** | DO | 12.21960 | -68.37745 | BOPEC |
| **101** | DO | 12.21952 | -68.37207 | ND |
| **102** | DO | 12.21969 | -68.36666 | ND |
| **103** | DO | 12.21945 | -68.36283 | ND |
| **104** | DO | 12.21929 | -68.35798 | ND |
| **105** | DO | 12.21755 | -68.34968 | Other |
| **118** | DO | 12.15105 | -68.29460 | Klein Bonaire |
| **119** | DO | 12.14924 | -68.29614 | Klein Bonaire |
| **120** | DO | 12.14782 | -68.29778 | Klein Bonaire |
| **121** | DO | 12.14557 | -68.30189 | Klein Bonaire |
| **122** | DO | 12.14501 | -68.30643 | Klein Bonaire |
| **123** | DO | 12.14880 | -68.31443 | Klein Bonaire |
| **124** | DO | 12.14951 | -68.31926 | Klein Bonaire |
| **125** | DO | 12.14982 | -68.32302 | Klein Bonaire |
| **126** | DO | 12.14827 | -68.32878 | Klein Bonaire |
| **127** | DO | 12.15339 | -68.32993 | Klein Bonaire |
| **128** | DO | 12.11642 | -68.29540 | City Limits |

| | | | | |
|---|---|---|---|---|
| **129** | DO | 12.12071 | -68.29302 | City Limits |
| **130** | DO | 12.12382 | -68.29032 | City Limits |
| **131** | DO | 12.02832 | -68.23692 | Other |
| **132** | DO | 12.02647 | -68.24147 | Other |
| **133** | DO | 12.02556 | -68.24572 | Other |
| **134** | DO | 12.02550 | -68.25025 | Other |

## Label set

*Table ii: LabelSet CoralNet AI*

| Name | Short Code | Functional Group |
|---|---|---|
| **Agaricia agaricites** | AAGA | Hard coral |
| **Acropora cervicornis** | ACER | Hard coral |
| **Agaricia fragilis** | AFRA | Hard coral |
| **Agaricia humilis** | AHUM | Hard coral |
| **Agaricia lamarcki** | ALAM | Hard coral |
| **Acropora palmata** | APALM | Hard coral |
| **Agaricia tenuifolia** | ATEN | Hard coral |
| **Bleached Hard Coral** | BL_HC | Hard coral |
| **Colpophyllia natans** | CNAT | Hard coral |
| **Dendrogyra cylindrus** | DCYL | Hard coral |
| **Diploria labyrinthiformis** | DLAB | Hard coral |
| **Dichocoenia stokesi** | DSTO | Hard coral |
| **Eusmilia fastigiata** | EFAS | Hard coral |
| **Fully Bleached Agaricia agricites** | FBAA | Hard coral |
| **Fully Bleached Diploria labyrinthiformis** | FBDL | Hard coral |
| **Fully Bleached Orbicella Annularis** | FBOA | Hard coral |
| **Fully Bleached Orbicella faveolata** | FBOF | Hard coral |
| **Favia fragum** | FFRA | Hard coral |
| **Helioseris cucullata** | HCUC | Hard coral |
| **Madracis auretenra** | MAUR | Hard coral |
| **Montastraea cavernosa** | MCAV | Hard coral |
| **Madracis decactis** | MDEC | Hard coral |
| **Mycetophyllia ferox** | MFER | Hard coral |
| **Meandrina meandrites** | MMEA | Hard coral |
| **Orbicella annularis** | OANN | Hard coral |
| **Orbicella faveolata** | OFAV | Hard coral |
| **Orbicella franksi** | OFRA | Hard coral |
| **Porites astreoides** | PAST | Hard coral |
| **Partially Bleached Agaricia agricites** | PBAA | Hard coral |
| **Partially Bleached Diploria labyrinthiformis** | PBDL | Hard coral |
| **Partially Bleached Coral** | PB_HC | Hard coral |
| **Partially Bleached Orbicella Annularis** | PBOA | Hard coral |
| **Partially Bleached Orbicella faveolata** | PBOF | Hard coral |
| **Pseudodiploria clivosa** | PCLIV | Hard coral |
| **Porites porites** | PPOR | Hard coral |
| **Pseudodiploria strigosa** | PSTRI | Hard coral |
| **Recent Dead Coral** | RD_HC | Hard coral |
| **Solenastrea bournoni** | SBOU | Hard coral |
| **Scolymia** | SCOL | Hard coral |
| **Stephanocoenia intersepta** | SINT | Hard coral |
| **Siderastrea radians** | SRAD | Hard coral |
| **Siderastrea siderea** | SSID | Hard coral |
| **Condylactis gigantea** | CONGI | Other Invertebrates |
| **Encrusting gorgonian** | ENGR1 | Other Invertebrates |
| **Erythropodium caribaeorum** | ERYCAR | Other Invertebrates |
| **Gorgonia spp.** | GORG | Other Invertebrates |
| **Millepora alcicornis** | MILA | Other Invertebrates |
| **Millepora complanata** | MILC | Other Invertebrates |
| **Palythoa** | PALYTHO | Other Invertebrates |
| **Plexaurella spp.** | PLEX | Other Invertebrates |
| **Pseudoplexaura spp.** | PSPLEX | Other Invertebrates |
| **Pseudopterogorgia** | PSPTER | Other Invertebrates |
| **Pterogorgia** | PTER | Other Invertebrates |
| **Soft Coral plumes** | SCplu | Other Invertebrates |
| **Boring sponge** | SPBO | Other Invertebrates |

| | | |
|---|---|---|
| **Sponge** | SPON | Other Invertebrates |
| **Tridiemum solidum.** | TRID | Other Invertebrates |
| **Sand** | SAND | Soft Substrate |
| **Bare Substrate** | BARESUB | Hard Substrate |
| **Dead coral** | DC | Hard Substrate |
| **Cyanobacteria** | CYAN | Other |
| **Unclear** | DISCUSS | Other |
| **Fish** | FISH | Other |
| **Rubble** | RUBB | Other |
| **TAPE** | TAPE | Other |
| **Tape_TWS** | TAPE2 | Other |
| **Unknown** | UNK | Other |
| **CCA (crustose coralline algae)** | CCA | Algae |
| **Dictyota** | DIC | Algae |
| **Lobophora** | LOBO | Algae |
| **Macroalgae** | MA | Algae |
| **Benthic Microalgae on Sand** | MicroS | Algae |
| **Sargassum** | SARG | Algae |
| **Turbinaria (algae)** | Turbin | Algae |
| **Turf algae** | TURF | Algae |
| **Halophila stipulacea** | HalophStip | Seagrass |
| **Thalassia testudinum** | ThalTes | Seagrass |
| | | |

## Ratio coral cover

*Table iii: The ratios of coral covers for the years 2023 compared to 2020 used for the color map. A ratio greater than 1 indicates an increase in cover values, while a ratio less than 1 signifies a decrease.*

| Subregion | Ratio sensitive species | Ratio total coral cover |
|---|---|---|
| BOPEC | 0.8217103 | 0.5523313 |
| **City Limits** | 0.1955673 | 0.6961178 |
| **Klein Bonaire** | 0.1664776 | 0.5362756 |
| **ND** | 0.9136046 | 1.1989198 |
| **North** | 1.4281678 | 1.2468547 |
| **Other** | 0.6255843 | 0.9560449 |
| **South** | 0.5842209 | 0.7947095 |

## Protocol

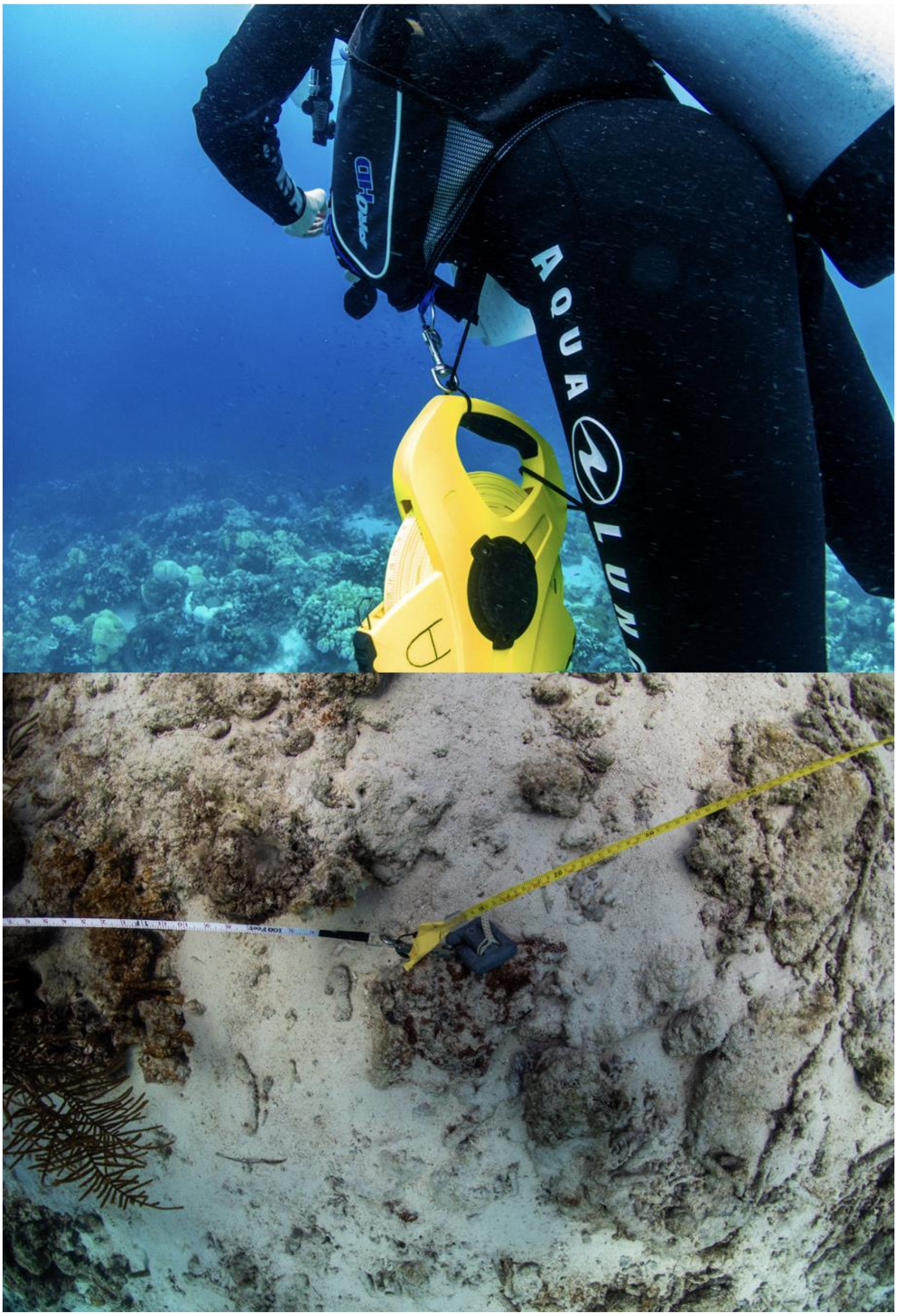


*Figure 16: securing the transect lines*

*Figure 17: fish surveyer rolling out transect line*

## Spread of SCTLD


| Year | Location | Map ID |
|---|---|---|
| 2014 | Florida | 1 |
| 2017 | Jamaica | 2 |
| 2018 | Mexico | 3 |
| | Sint Maarten | 4 |
| 2019 | U.S. Virgin Islands | 5 |
| | Dominican Republic | 6 |
| | Turks and Caicos Islands | 7 |
| | Saint-Martin | 8 |
| | Belize | 9 |
| | Sint Eustatius | 10 |
| | The Bahamas | 11 |
| | Puerto Rico | 12 |

| Year | Location | Map ID |
|---|---|---|
| 2020 | British Virgin Islands | 13 |
| | Guadeloupe | 14 |
| | St. Lucia | 16 |
| | Honduras | 17 |
| | Martinique | 18 |
| 2021 | St. Kitts & Nevis | 19 |
| | Saba | 20 |
| | Saint Barthélemy | 21 |
| | Dominica | 22 |
| 2022 | St Vincent & Grenadines | 23 |
| | Grenada | 24 |
| | Colombia | 25 |

*Figure 18 : (From Kramer et al 2022, [FIELD GUIDE for Monitoring Coral Disease Outbreaks in the Mesoamerican Region]). Location of countries/territories where SCTLD has been confirmed in Wider Caribbean Region as of July 2022. (Map designed by AGRRA). For recent updates, see the AGRRA SCTLD Tracking Map.*

## Distributions of the data

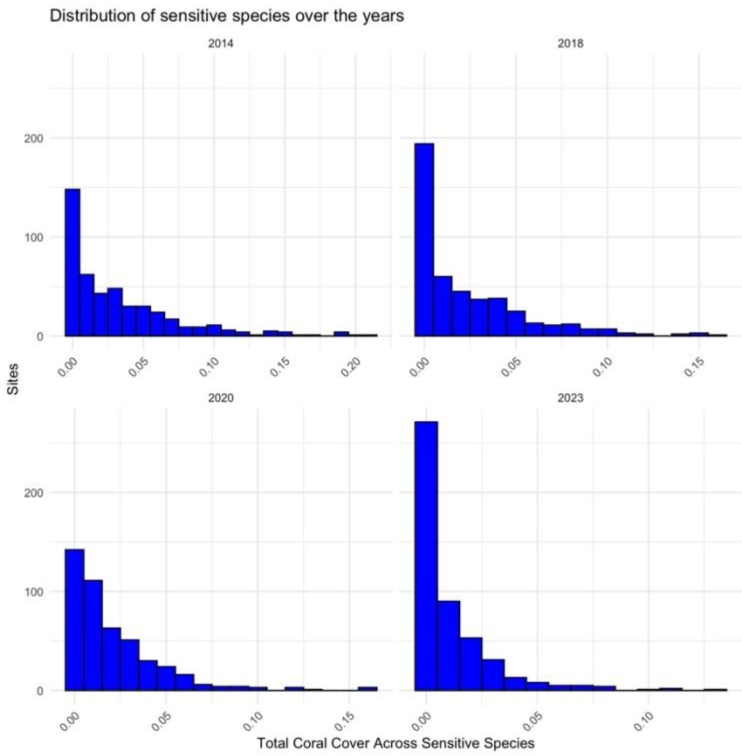


*Figure 19: Histogram for the aggregated sensitive species in each dataset (2014-2023)*

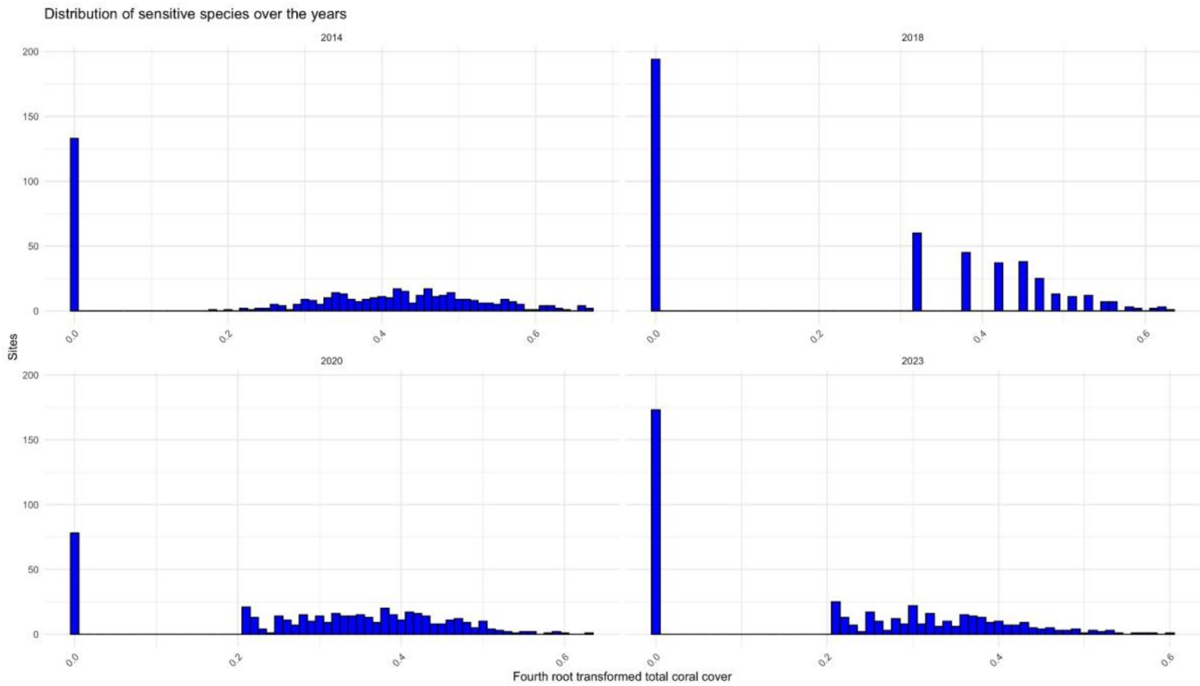


*Figure 20: Histogram for 4th root transformed data of aggregated sensitive species in each dataset (2014-2023)*

# Regional trends

## Total coral cover

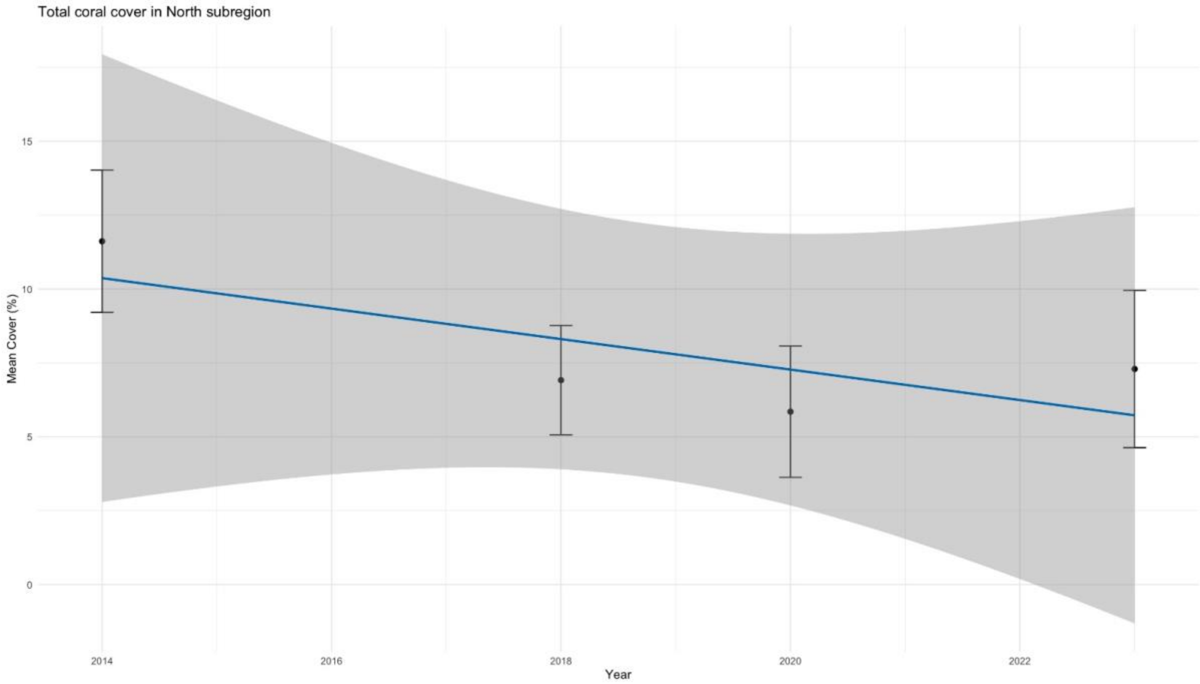


*Figure 21: Total coral cover in North subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

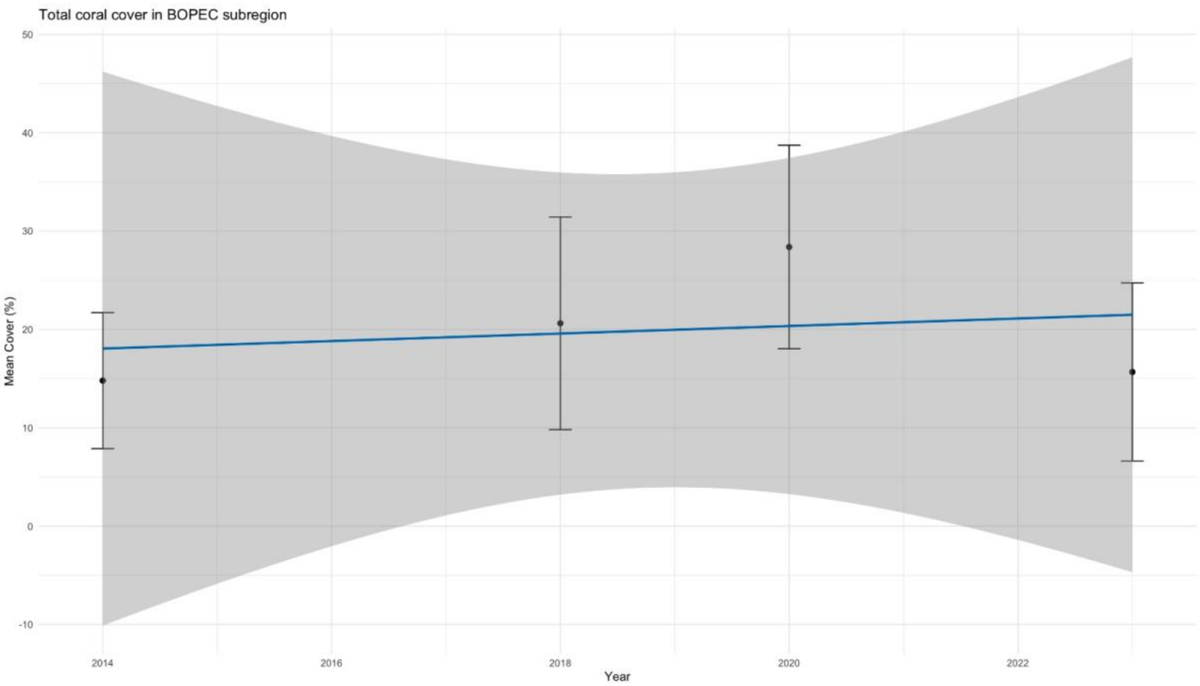


*Figure 22: Total coral cover in BOPEC subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

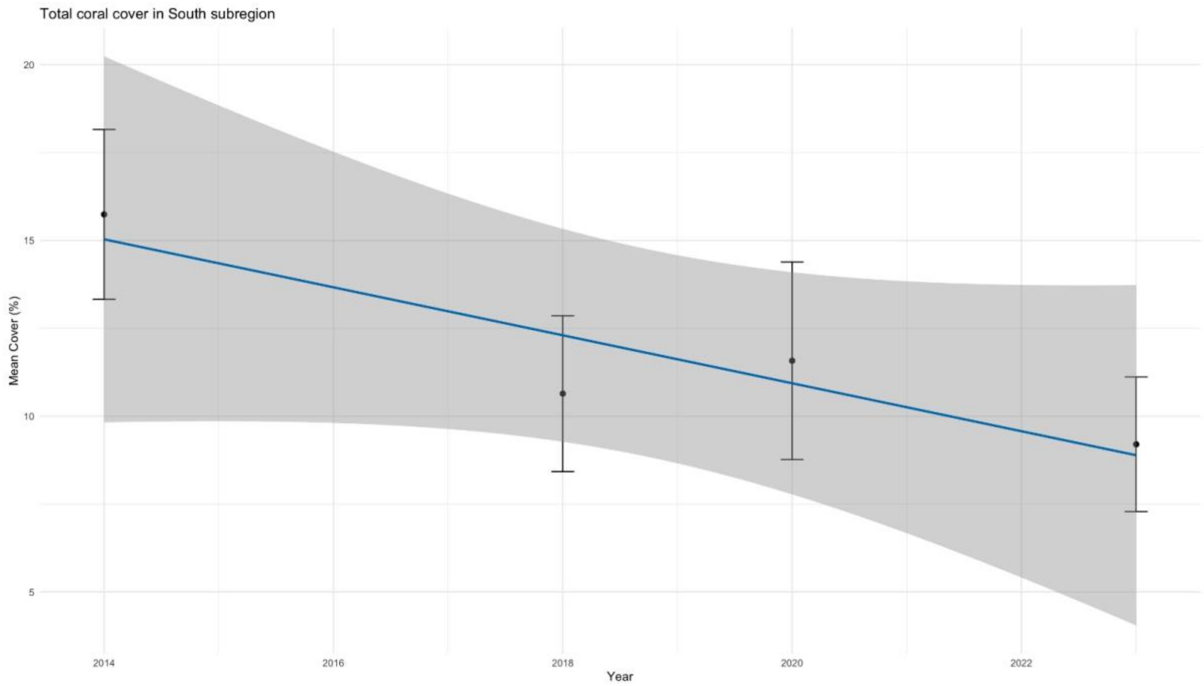


*Figure 26: Total coral cover in South subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

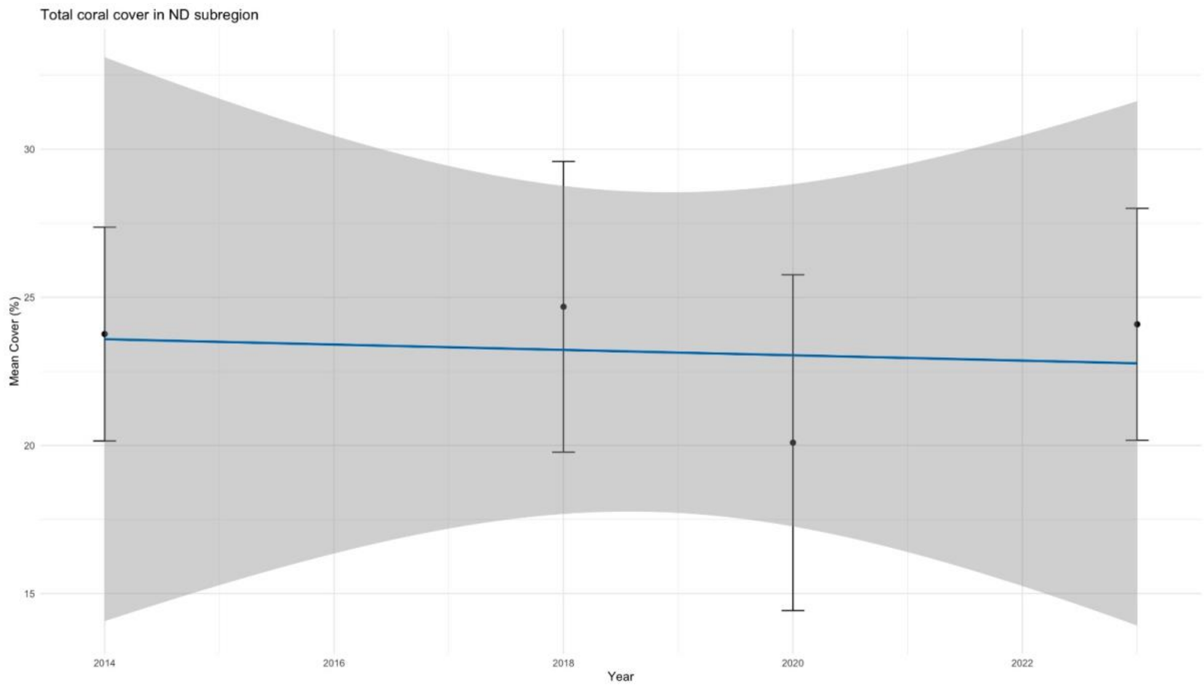


*Figure 27: Total coral cover in ND subregion from 2014 to 2023, illustrating a relatively stable trend over time at sampled depths, with 95% confidence intervals reflecting the variation within the data.*

## Sensitive species

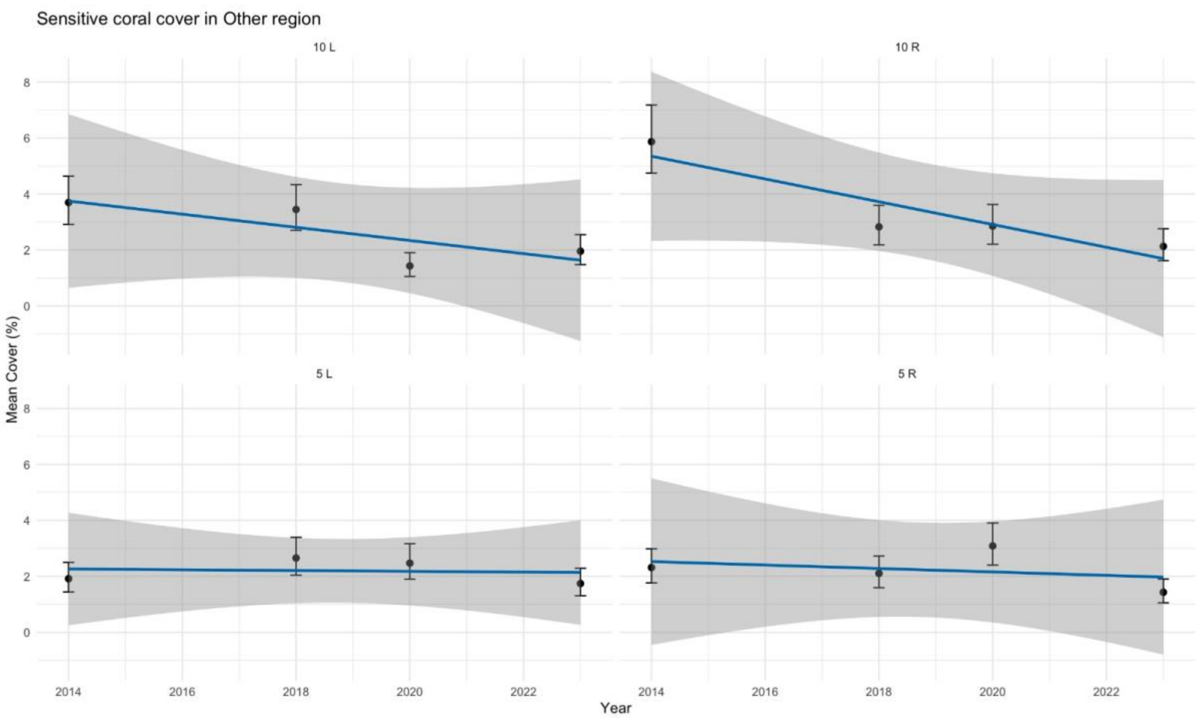


*Figure 23: Trend analysis of sensitive coral species cover in the Other region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

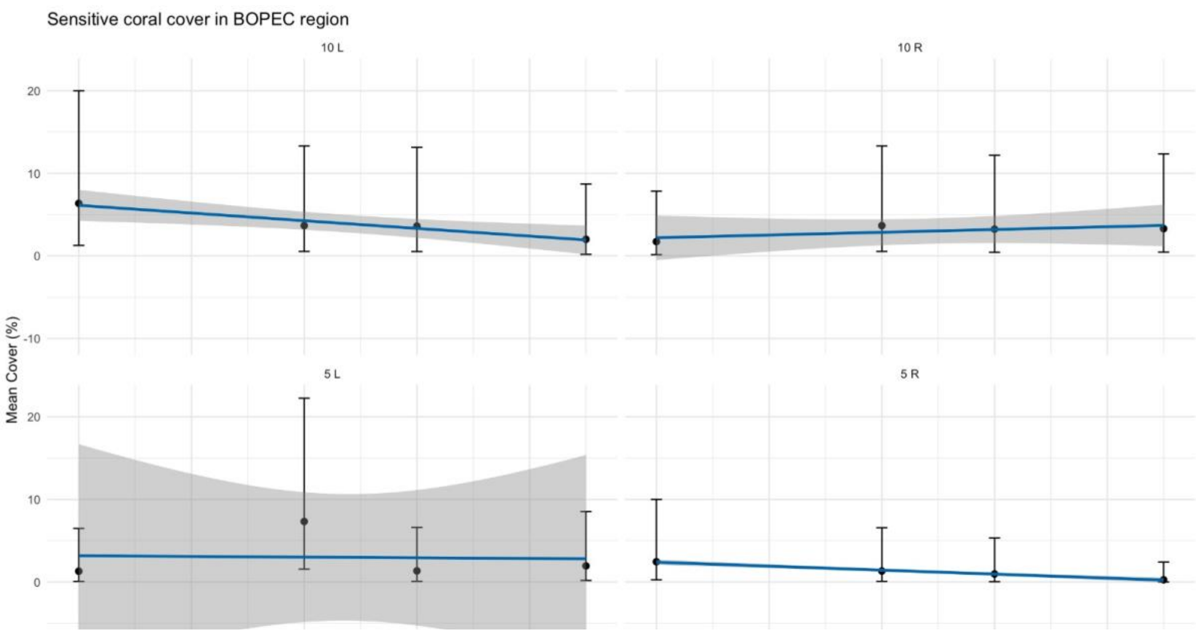


*Figure 24: Trend analysis of sensitive coral species cover in the BOPEC region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

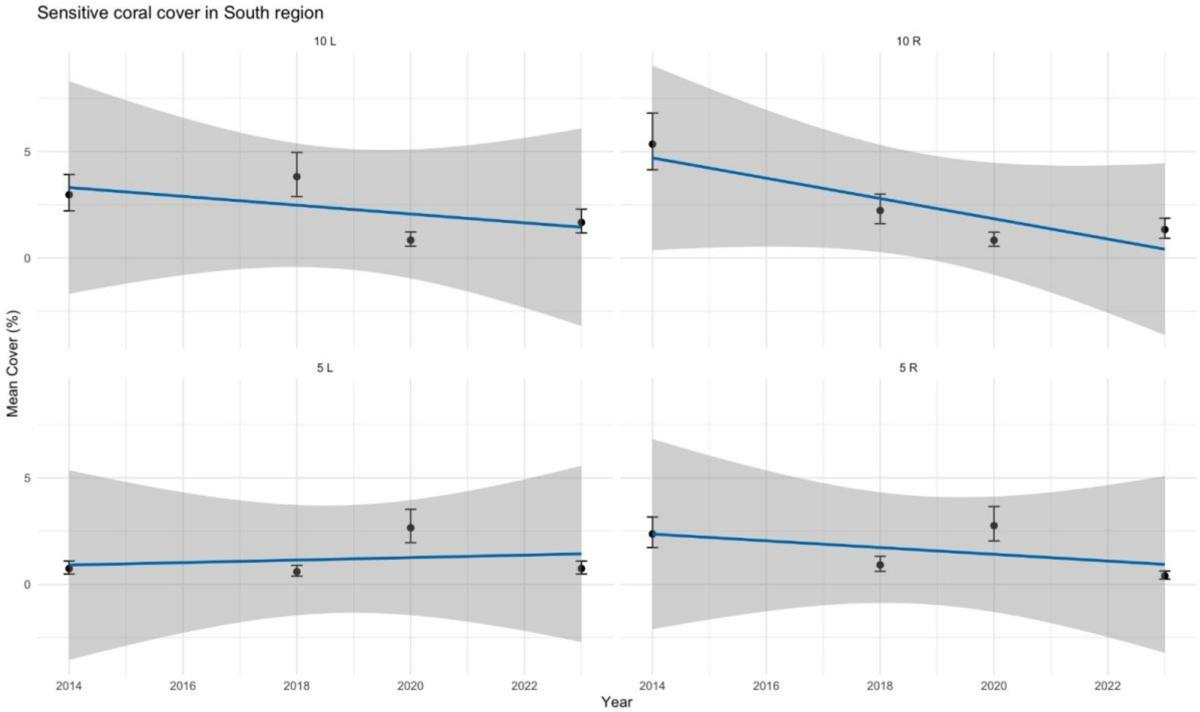


*Figure 26: Trend analysis of sensitive coral species cover in the South region from 2014 to 2023, with separate lines representing depths of 5 meters (5 L/R) and 10 meters (10 L/R). Each point is accompanied by 95% confidence intervals illustrating variability.*

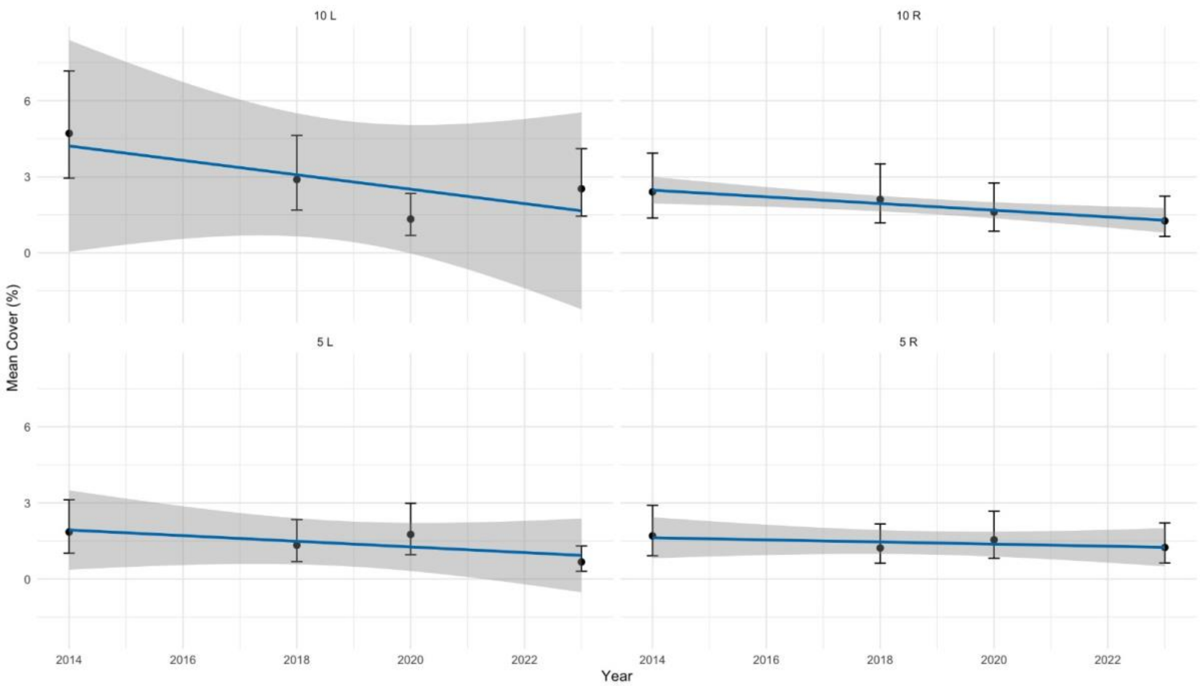


*Figure 25: Mean cover of sensitive coral species in the ND region from 2014 to 2023, showcasing a consistent decline over time at both 5 meters (5 L/R) and 10 meters (10 L/R) depths, with 95% confidence intervals indicating the range of variability in the data.*

Camera settings

**BACKSCATTER**
UNDERWATER VIDEO & PHOTO

## OLYMPUS TG-6 BEST SETTINGS
WIDE-ANGLE PHOTO WITH A STROBE

### Essential Gear
**Accessory Optic:** M52 Wide Angle Lens
**Lighting:** Dual Strobes

### On The Boat
- Set them and forget them
- May evolve with your skills

**Live View Boost:** ON
**Mode:** Aperture Priority (A)
**Aperture:** Middle Value (f2.8)
**ISO:** Auto (Limit 100-400)
**Minimum Shutter Speed:** 1/125
**Quality:** RAW or RAW & JPEG "LF"
**White Balance:** Auto
**Focus Mode:** AF
**Flash:** Fill-In or 1/64 Manual
**Image Stabilization:** On
**Frame Rate:** Single

### In The Water
- Based on scene & subject
- May change during the dive

*Relative to scene & subject*
*May need to be adjusted during dive*
**Exposure Comp:** -1.0 to -2.0 stops (Adjustable for blue background)
**Working Distance:** 10 cm to 1 meter
**Zoom:** With your fins, not the camera
**Focus Area:** Closest foreground element
**Strobe Position:** Above center line and behind dome edge, pointed forward or slightly out
**Strobe Power:** Start at 1/2, then adjust as needed
**Remember:** Shoot, Review, Adjust

### Wide Angle Notes
- Get close, then get closer.
- Focus on the closest foreground element.
- Only 2 things to adjust on dive: Exposure Compensation & Strobes
- Adjust exposure comp for more blue, less cyan.
- Use strobes to light & separate foreground from background.
- Keep strobes and subject equal distances apart from the camera to avoid lighting water in front of the lens.

### Super Simple Settings
- Underwater Wide preset mode
- Strobes set to TTL

*Figure 27: Olympus TG-6 Settings for wide-angle photo with a strobe from Backscatter website.*