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Evaluating coral ecosystem health in Aruba – the development and future of Aruba's coral reefs

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Abstract

Hard coral cover throughout the Caribbean has been in decline for at least fifty years due to large-scale disturbances such as White-Band-Disease, die-off of sea urchin populations, and coral bleaching. Local stressors, like coastal water pollution and eutrophication, have amplified this decline. The ecosystem services of coral reefs offer opportunities for tourism, recreation, employment and biodiversity. In Aruba, coral cover is naturally low due to a high abundance of sand, leaving less benthic area available for coral growth. The outbreak of stony coral tissue loss disease in Aruba in December 2022 presented a new threat for local coral reef communities. Assessment of coral cover is necessary to devise methods to mitigate the stressors that corals in Aruba face. In this study, 12 sites were identified that reflect the heterogeneous status of Aruba's coral reefs for investigation to examine coral health and the development of the ecosystem since 2019. While on average, coral cover remained constant, almost half of the surveyed sites showed an increase in (macro)algae cover coupled with a decrease in coral cover, indicating stress on coral reefs. Five out of 12 sites showed a degrading ecosystem trend within the last four years. By assessing the spread of stony coral tissue loss from the surveyed data, a metric for the development of Aruba's coral reefs was determined. We found that nine coral species, including important reef-building coral species such as *Montastraea cavernosa*, *Orbicella annularis* and *Orbicella faveolata* have been infected by the disease. About six months after the outbreak of the disease, ~ 13 % of all coral showed signs of the disease. This number is expected to increase, indicating strong changes for Aruba's coral reefs in the near future.

KEY WORDS: coral reefs – ecosystem trend – reef health – Aruba – SCTLD

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1 Introduction

Living coral coverage has declined by approximately 50 % globally since the 1950s (Eddy et al., 2021; Almond et al., 2022). Globally, human activities and warming sea temperatures caused by climate change are main drivers of coral reef ecosystem degradation (Souter et al., 2021). Since 1970, coral cover in the Caribbean has decreased by more than 80 %, showing a greater decline than any other region in the world (Jackson et al., 2014; Almond et al., 2022). Eutrophication, sedimentation, coral bleaching, ocean acidification, hurricanes, tropical storms, the presence of diseases and declining physiological processes are human induced and natural disturbances that are considered to contribute profoundly to the decline of coral reefs worldwide (Hafizt et al., 2023; Ampou et al., 2018; Traganos et al., 2018; Devlin et al., 2015). Three specific types of disturbances have been attributed to strong declines in live hard coral cover in the Caribbean: (1) White-Band-Disease in the 1970s and 1980s resulted in degradation of *Acroporid* populations, (2) pathogen induced die-off from 1983 to 1984 of *Diadema antillarum* (an efficient invertebrate herbivore in the Caribbean), and (3) a coral bleaching in 2005 (Souter et al., 2021). Besides the three large-scale ecological disturbances, local stressors as coastal water pollution and eutrophication contribute to the reduction of coral health in the Caribbean region (Kaufman et al., 2011; Souter et al., 2021). The invasive lionfish, the influx of the *Sargassum* macroalgae and the spread of stony coral tissue loss disease (SCTLD) were identified as new threats for Caribbean coral reefs (Souter et al., 2021). Coral reefs and associated ecosystems are playing an important role in Caribbean economies as they support recreation and tourism, livelihoods, food, and other social, cultural and economic benefits (Souter et al., 2021). The economic value of Aruba’s natural ecosystem is relatively high, as Aruba is the second most dependent country on tourism worldwide (Palacios et al., 2021). A 50 % decrease in visitor numbers is estimated in case of nature loss in Aruba (Polaszek et al., 2018). Hence, the tourism industry recognizes Aruba’s natural scenery as a prime asset (Murphy, 2011).

Aruba is part of the Leeward Group of the Dutch Caribbean, together with Bonaire and Curaçao (Bak, 1975). Sandy bottoms dominate Aruba’s reefs due to its location on the Venezuelan continental flat. Therefore, less benthic area is available for corals to grow on and coral abundance in Aruba is naturally low compared to its neighboring islands Curaçao and Bonaire. The community composition of hard corals in Aruba is mostly similar to the coral species composition throughout the Southern Caribbean, being dominated by *Orbicella* spp., *Madracis mirabilis* and *Agaricia agaricites*. In the south of Aruba, where stronger water movement occurs, the coral community composition differs from the remaining part of the island. *Montastraea cavernosa*, *Diploria strigosa* and *Millepora* spp., being common coral species for sites with increased turbulence, dominate the southern tip of Aruba (Vermeij et al., 2019). While Bonaire's and Curaçao's coral reef communities are being studied frequently (e.g., Bak et al., 2005; Steneck et al., 2019), there is a lack of research being done on Aruba's nearshore communities. Only three studies dating back to 1986 (Bak, 1987), 1988 (Eakin et al., 1993) and 2019 (Vermeij et al., 2019) have reliably surveyed Aruba's coral reefs in the past. These studies show that coral cover in Aruba has decreased from 22.2 % in 1986 and 1988 to 8 % on average in 2019 (Bak, 1987; Eakin et al., 1993; Vermeij et al., 2019). The Coral Reef Baseline study for Aruba identified the status of Aruba's coral reefs along the leeward side of the island in 2019. This investigation found that even though average coral cover is declining in Aruba, locally, Aruba harbors small but very healthy reef communities. Furthermore, this study suggests that the overall degradation of the marine environment in Aruba extends to native seagrass communities which are being overgrown by the invasive seagrass *Halophila stipulacea* (Vermeij et al., 2019).

The overall degradation of the marine environment has been recognized in Aruban policy stated by the Nature and Environment policy note (2018-2021). To mitigate the observed trend of degradation of Aruba's nearshore marine environment, several marine protected areas (MPA) have been established to help protect from further degradation. These MPAs constitute the Parke Marino Aruba (Aruba Marine Park), which was established in 2018, and is managed by the Fundacion Parke Nacional Aruba (FPNA; Aruba National Park Foundation; Figure 1) since 2019. The restoration initiatives by the FPNA include deployment of multiple artificial reefs, which were deployed in 2023 at four locations within the Parke Marino Aruba.

Figure 1: Map of Aruba. Protected areas under the management of the FPNA are colored.

Assessing ecosystem health can be a metric for determining the capacity of resistance to disturbances, such as the spread of SCTLD for Aruba's coral reefs. There are multiple analysis techniques used to quantify the health of coral reefs, including single indicators, the application of scoring and weighting techniques on indices, and statistical analysis to relate coral reef health indicators to environmental parameters (Hafizt et al., 2023). Oftentimes, a high percentage of live hard coral cover is used as a single indicator to identify coral reefs as healthy (Vermeij et al., 2019; Souter et al., 2021). Indices used to quantify coral ecosystem health are based on averaged indicative parameters. Benthic cover (like live coral cover, fleshy macroalgae cover and encrusting coralline algae cover), reef fish (like biomass of herbivorous fish and biomass of commercially significant fish), and microbes (concentration of *Vibrio* spp.) are indicative parameters used to provide indices like the Coral Health Index (CHI), or the Reef Health Index (RHI). The differences between these indices are based on the available data used to quantify an index (Hafizt et al., 2023). To improve the evaluation of reef health, Díaz-Pérez et al. (2016) suggest complementing health indices as the RHI with classic community indices, or to include diversity indices of fish and corals for higher accuracy. The Shannon Diversity Index (*also:* Shannon Wiener Index; Shannon, 1948) is a popular index used in ecology to indicate the diversity of species in a community.

In the near future, an emerging problem for Aruba's coral reefs will likely be the outbreak of SCTLD (Figure 2). SCTLD can cause lower calcification rates and reduced architectural complexity and functionality (Estrada-Saldívar et al., 2020; Alvarez-Filip et al., 2013). The disease was first reported off Florida's coast in 2014. The Atlantic and Gulf Rapid Reef Assessment (AGRRA) program is an international cooperation of scientists, managers, and local supporters who collect, review, and verify data that tracks the spread of SCTLD in the Caribbean region. According to AGRRA, the disease affects more than 30 different species of stony coral throughout the Caribbean. In 2023, the disease has been reported in 28 countries/territories. SCTLD is highly infectious and has spread quickly along the Florida coastline at a rate of 7 - 10 km per month (agrra.org; Weil and Hernández-Delgado, 2021). The first reports of SCTLD presence in Aruba were documented in December 2022. Since then, the disease has spread around most parts of the island (agrra.org). Within a few months, the disease can lead to coral community changes as many reef-building coral species infected by the disease die off. Monitoring in the northern part of the Mexican Caribbean showed that important reef-builders like *Diploria strigosa* and *Siderastrea siderea* decline while less-susceptible species as *Agaricia agaricites* and *Porites astreoides* show a slight increase in relative abundance (Estrada-Saldívar et al., 2020). Reef building corals provide a three-dimensional structure having an important impact on the biota depending on those structures, e.g., for shelter, but also for shoreline protection due to reduction of wave attenuation functions (Graham and Nash, 2013; Steele, 1999). Coral species like *Agaricia agaricites* and *Porites astreoides* do not contribute essentially to this framework because of their small-sized colonies. Therefore, they are characterized as non-framework building corals (Green et al., 2008; Buglass et al., 2016; Perry et al., 2014).

The change from reef building to non-framework building corals has been identified as one of the most pressing issues for Caribbean coral reefs (Perry and Alvarez-Filip, 2019; Estrada-Saldívar et al., 2019). This coral community change is catalyzed further by SCTLD due to the mass die-off of reef-building coral species being susceptible to the disease. Highly affected species include *Dendrogyra cylindrus*, *Dichocoenia stokesii*, *Eusmilia fastigiata* and *Meandrina* spp. Other susceptible species include starlet corals, brain and boulder corals as well as star corals as *Orbicella* spp. and *Montastraea cavernosa* (agrra.org).

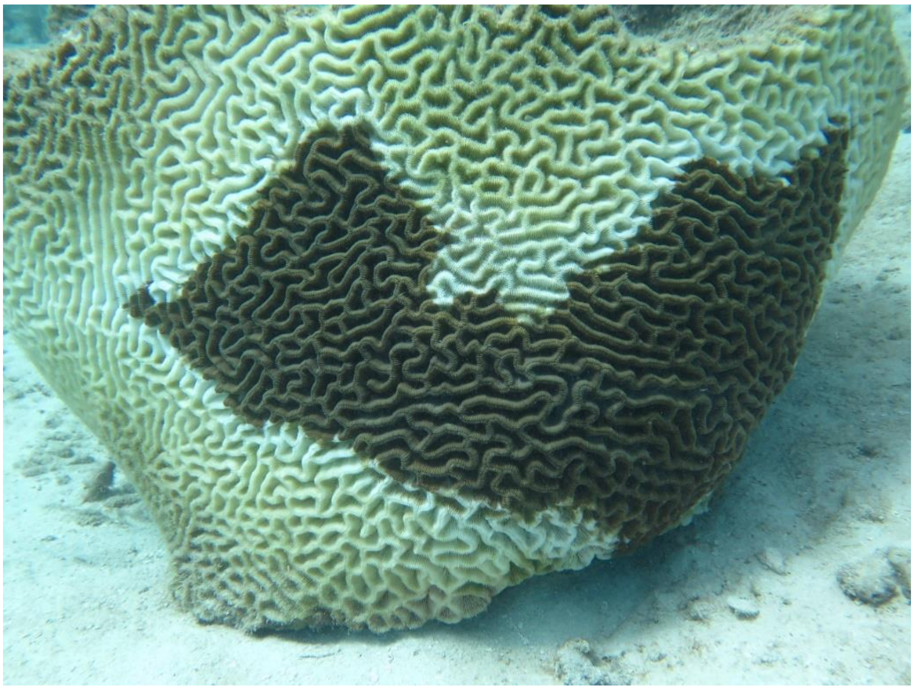

Figure 2: Diploria strigosa in Aruba affected by SCTLD. The dark part of the coral is healthy tissue. The white surrounding is the spread of SCTLD.

To elucidate the drivers of reef health in Aruba and, thus, their ability to resist SCTLD, this thesis evaluated the development, condition and future of Aruba's coral reefs in three steps. First, reef health indicators were monitored and documented for 2019, 2021 and 2023 following the guidelines of the Global Coral Reef Monitoring Network (GCRMN). Secondly, the ecosystem health was quantified based on the Reef Health Index complemented by the development of the system between 2019 and 2023 as well as the Shannon Diversity Index. The development of the reefs, hereafter called ecosystem trend, was quantified by comparing the monitoring data of the last four years of live coral cover and macroalgae cover. This data as well as the Shannon Diversity Index complement the Reef Health Index and better reflect the state of the ecosystem. Therefore, if the RHI indicates a healthy ecosystem but the trend indicates stress within the past four years, this suggests that the system is not as healthy as reflected by the index. Lastly, assessments about documented SCTLD cases were used to predict the development of Aruba's coral reefs in the future.

2 Methods

The GCRMN-Caribbean guidelines for coral reef biophysical monitoring were used to measure the ecosystem health of Aruba's coral reefs. Following those guidelines, different elements of the coral reef ecosystem were monitored at each site along five, 30 m transect lines. Monitoring the reefs following the GCRMN-Caribbean guidelines makes comparison between reefs in different locations possible, as other (Caribbean) islands (e.g., Curaçao, St Maarten and Saba) quantify the health and condition of their reef communities also using this method. Additionally, the GCRMN-Caribbean guidelines include a social economic level of monitoring. However, this component was not adopted for this study.

The biophysical monitoring of the GCRMN-Caribbean guidelines includes six elements of a coral reef ecosystem: abundance and biomass of key reef fish taxa (1), relative cover of reef-building organisms (corals, coralline algae) and their dominant competitors (2), assessment of coral health (3), recruitment of reef-building corals and recruit habitat (4), abundance of key macro-invertebrate species (5), and water quality (6). Within the guidelines, different levels of detail for measuring these elements are presented, with Level 1 being the minimum standard for gathering reliable data and Level 3 being the most complex and thorough method (United Nations Environment Programme, 2016; Table 1). The highest measuring level has been used whenever possible.

Table 1: Monitoring levels 1-3 for each of the measured ecosystem elements according to the GCRMN-Caribbean guidelines.

	Level 1 (minimum standard)	Level 2 (recommended)	Level 3 (highly recommended protocol)
Abundance and biomass of key reef fish taxa	Use of a comparable field method like stationary point count or transects of different dimensions	Count and size only core species along the transect	Count and size all fish present along the transect
Relative cover of reef-building organisms and their dominant competitors	Line-point intercept approach, e.g., from ReefCheck[1]	Core benthic composition using a standardized, accepted and reliable method with adequate replication	Photoquadrat method (Image-based benthic data collection)

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[1] www.ReefCheck.org

Assessment of coral health	-	Assessment by a surveyor whether quadrat is „with disease“ or not; alternative: prevalence rate of diseased coral colonies along 10 m belt transect	Photoquadrat method for estimating relative coral disease prevalence
Recruitment of reef-building corals and recruit habitat	Count number and diameter of coral recruits without further specification	Coral recruits are recorded to the finest taxonomic level possible (family, genus or species)	
Abundance of key macro-invertebrate species	Count all long-spined sea urchins, other sea urchins, sea cucumbers, lobsters, and conchs		
Water quality	Measure annually	Measure monthly	Measure weekly

Each site received an ID, which is designated as an abbreviation of the site's name (Table 2). All sites were specifically selected to represent the heterogeneity of Aruba's coral reef ecosystem. TIRE has been replaced by TOPA in 2023, as TIRE was not accessible in 2023. TOPA is located very close to TIRE (Figure 3).

Table 2: Site ID for each site in 2019, 2021 and 2023.

Site ID (2021 and 2023)	**Site**	**Site ID in Vermeij et al., 2019**
AIRP	Airplanes	ARU_24
ARRE	Arashi Reef	ARU_03
BARE	Barcadera Reef	ARU_30
HARE	Harbor Reef	ARU_20
INHE	Indian Head	ARU_48
ISOR	Isla di Oro	ARU_37
JADS	JADS Shop	ARU_51
MHIN	Mangel Halto Inside	ARU_35
MHOU	Mangel Halto Outside	ARU_34
SACA	Santana di Cacho	ARU_53
SEBE	Sea Berth	ARU_42
TIRE/TOPA	Tire Reef/Topaz Reef	ARU_28

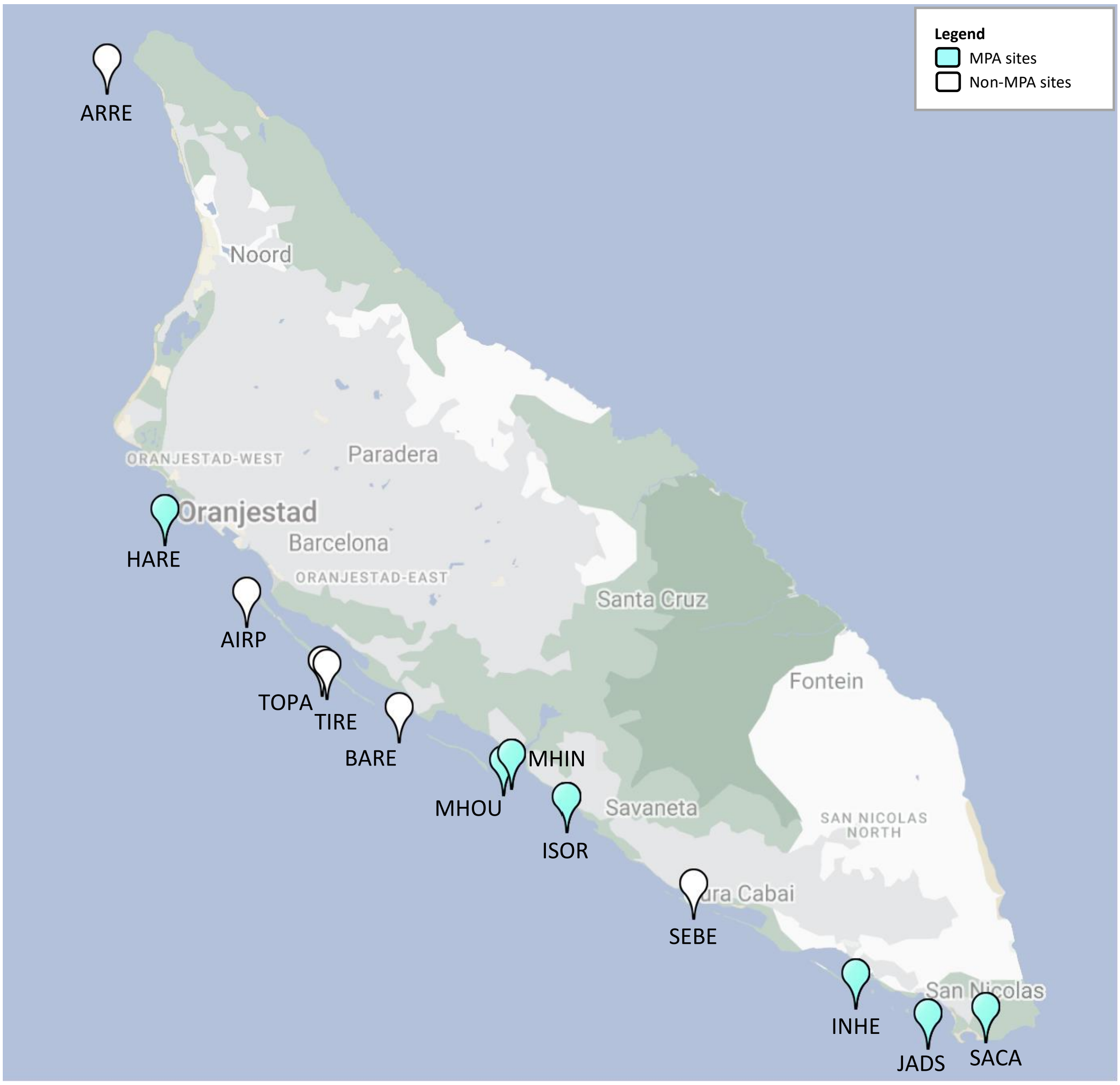

Figure 3: Map of Aruba showing the surveyed sites.

At each site, each of the six elements as described by the GCRMN-Caribbean guidelines was assessed in 2019, 2021 and 2023. In 2019, these measurements were done by CARMABI as part of the Coral Reefs Baseline Study for Aruba. In 2021 and 2023, the Aruba National Park Foundation (FPNA) oversaw the monitoring. Each categorical topic listed below describes the approach of each survey assessment performed to determine each of the six elements.

2.1 Abundance and biomass of reef fish taxa

Fish identification was conducted along each transect line of 30 m for 8-12 minutes, observing the water column up to 2 m above and 1 m to each side of the transect line. The fish were sorted into nine size categories: <5 cm, 5-10 cm, 11-15 cm, 16-20 cm, 21-25 cm, 26-30 cm, 31-35 cm, 36-40 cm and >40 cm, referring to the fork length of the fish within each bin size. For abundant and ecologically important species, fish counts were conducted at species level. Other abundant fish groups were identified at family level (Level 2-3). Large and rare species such as barracuda, sharks, rays, turtles, and mammals were included as a separate category. If data for calculating the biomass was available, these species were included in the biomass for that site. The invasive lionfish (*Pterois volitans* and *Pterois miles*) was included as well (Appendix 1).

The weight-length formula was used to estimate individual fish biomass (W):

$$W = a * L^b \qquad \text{(Eq. 1)}$$

where L represents the fork length in cm and a and b are species-specific parameters (Froese, 2006). The fork length describes the length from the most anterior point of the fish, being the snout or mouth, to the end of the central caudal fin ray. In this study, the mid-point of the size bin was used as fork length of an individual sorted in one of the size categories described above. Parameters a and b have been derived from FishBase (Froese and Pauly, 2023; Appendix 1). If those parameters were not available for a species, values of closely related species with similar morphological traits were chosen. Individual fish biomass was standardized into g m^{-2} by deriving the biomass in gram for all fish observed over the five transects measuring 2 by 30 m. Fish biomass is given as an average to make comparisons between different sites possible.

To keep observer bias as small as possible, fish identification was done by the same person at every site who had the most extensive knowledge of local fish species within one year of surveying. In 2019, more detail was provided for the fish identification due to greater knowledge of the surveyor. Fish have been grouped by category for less abundant or unidentified species to avoid false indication and inflating biodiversity estimates.

2.2 Relative cover of reef-building organisms and their dominant competitors

Following Level 3 of the GCRMN-Caribbean guidelines, pictures have been taken at every uneven meter along the 150 m transect line, alternating between sides and starting on the right. In total, 75 pictures have been shot per site, starting at 1 m, and covering an area of 1 m^2 per photoquadrat.

All pictures were processed using the website CoralNet[2], which randomly generated 25 points within the picture to classify the benthic category. This included reef-building organisms such as coral and crustose coralline algae and their dominant competitors, fleshy macroalgae, and turf algae. Coral rubble, sand, sponges, and gorgonians have been included as well. Reef-building corals were identified to the species level. There were no pictures taken from SACA in 2021. Therefore, the relative cover of reef-building organisms and their dominant competitors were only analyzed for 2019 and 2023 for this site.

2.3 Assessment of coral health

Coral health has been analyzed using the pictures taken for benthic cover (Level 3). Corals have been categorized as healthy, bleached, showing stony coral tissue loss disease, other diseases, or recently dead. Pictures showing at least one of the above-mentioned categories or presence of cyanobacteria were marked, whereas diseased corals were identified to the species level.

2.4 Recruitment of reef-building corals

Coral recruits were counted using a quadrat of 625 cm^2, which was put next to the transect line every 2 m for the first 10 m, alternating between sides, for the first three transects. In total, 15 quadrats were placed per site. According to the GCRMN-Caribbean guidelines, all coral recruits smaller than 4 cm in diameter (boulders, plates) or height (branching) and bigger than 0.5 cm were counted (Level 1). This gave an estimate of juvenile corals which are likely to contribute to the next generation of adult corals (Vermeij et al., 2019). Categorization of coral recruits to a taxonomic level is prone to false identification at such an early life stage. Therefore, counting coral recruits without identifying a taxonomic level was found sufficient, as the surveys included non-specialist volunteers.

2.5 Macroalgae and turf algae height

Macroalgae and turf algae height were measured using a 625 cm^2 quadrat (Level 2-3). Turf algae height gives an indication of herbivory presence, with lower turf algae height indicating a higher abundance of herbivores. Macroalgae compete with reef-building corals for space and therefore limit their growth (Tanner, 1995). Macroalgae height, an indicator for growth,

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[2] https://coralnet.ucsd.edu

was measured to the nearest cm in each of the four corners of the quadrat while turf algae height was measured to the nearest mm. The quadrat was placed following the same methodology as for coral recruits.

2.6 Abundance of key macro-invertebrate species

Key macro-invertebrate species are described as important herbivores that influence the cover of fleshy macroalgae. Fleshy macroalgae compete with corals for space (Vermeij et al., 2019). Mobile invertebrates were counted along the first 10 m of the first three transects, covering 1 m on each side of the transect line as recommended by the GCRMN-Caribbean guidelines. There is no differentiation into levels for this monitoring according to the GCRMN-Caribbean guidelines.

2.7 Water quality

In 2021 and 2023, water quality was measured, following the GCRMN-Caribbean guidelines, by using a Secchi disc. The Secchi disc is black and white and 20 cm wide in diameter. The measurement was taken by one diver holding the Secchi disc vertically at the beginning of the first transect line, while a second diver was responsible for noting the distance between the beginning of the transect and the point at which the disc could just be seen coming towards the disc along the transect line. This has been done at each site in the same way. The distance gives an indication of the concentration of particulates in the water column (turbidity). This measurement has been taken once per site (Level 1). In 2019, measurements of different aspects reflecting or influencing the water quality (e.g., assessment of the chemical composition of the seawater at certain sites or counting and categorizing all pieces of trash) were included in the survey (Vermeij et al., 2019).

2.8 Data Analysis

ANOVA and post-hoc comparisons (Tukey-Kramer test) were performed to evaluate whether the perceived changes between 2019, 2021 and 2023 for the different elements of the ecosystem were significant.

2.8.1 Reef Health Index

The health of the ecosystem was calculated using the Reef Health Index (RHI) developed by the Healthy Reefs Initiative (Mcfield et al., 2007; Appendix 4). Live coral cover, fleshy macroalgae cover, herbivorous fish biomass and commercially important fish biomass were used to calculate the RHI. Each of the four indicators obtained a value between 1 and 5. These values were averaged to indicate reef health, with value 1 being critical, value 2 being poor, value 3 being fair, value 4 being good and value 5 being very good. The fish families *Scaridae* and *Acanthuridae* were used to calculate the herbivorous fish biomass. Species in these families reduce the overgrowth of fleshy macroalgae and are among the most important grazers. *Lutjanidae* and *Serranidae* biomass was used for commercially important fish biomass due to their commercial value and their important predatory influence in the coral reef ecosystem (Díaz-Pérez et al., 2016; Hafizt et al., 2023).

2.8.2 Shannon Diversity Index and Evenness

The Shannon Diversity index (*also*: Shannon-Wiener index) reflects on the number of different types (such as species) in a habitat and how evenly individuals are distributed among these types (Okpiliya, 2012).

The Shannon Diversity index was used to estimate fish and coral diversity (H):

$$H = - \Sigma\, pi * ln(pi) \qquad \text{(Eq. 2)}$$

where pi is the proportion of the entire community made up of species i. A higher index value indicates a higher number of types as well as increasing evenness and therefore higher diversity. This number is maximized if all individuals are divided equally amongst the different types (Rosenzweig, 1995; Okpiliya, 2012).

Evenness (E_H) describes how evenly individuals are distributed among the species. It was calculated by:

$$E_H = H/ln(S) \qquad \text{(Eq. 3)}$$

where S is the total number of unique species. This formula gives values between 0 and 1. The closer the value is to 1, the more evenly distributed the individual abundance among the families or species. The diversity and therefore the health of the community increases with evenness closer to 1 (Okpiliya, 2012).

2.8.3 Ecosystem trend

The trend of the ecosystem reflects the development of elements being indicative for reef health. Ecological change on coral reefs can be indicated by changes in algae cover relative to coral cover, with increased algae cover and decreased live coral cover indicating stress on coral reefs (Souter et al., 2021). A decrease in live coral cover together with an increase in macroalgae cover from 2019 to 2023 was identified as a negative trend at a given site. A steady increase in coral cover from 2021 to 2023 was identified as a positive trend, as coral cover is oftentimes used as a single indicator for reef health (Hafizt et al., 2023; Díaz-Pérez et al., 2016).

3 Results

3.1 Relative cover of reef-building organisms and their dominant competitors

Average coral cover for the observed 12 sites did not differ significantly between 2019 and 2023 (ANOVA *p*=0.985) with 9.26 % in 2019, 8.85 % in 2021 and 9.35 % in 2023 (Figure 4). The Coral Reef Baseline study for Aruba estimated an average coral cover of 8.8 % in Aruba, indicating that the average cover around the island is lower than estimated based on the measurements of the observed 12 sites. Turf algae is included in *macroalgae* in benthic cover in 2021 and 2023 while cyanobacteria are included in *sand/rubble* since it was difficult to distinguish between those categories based on the pictures. Benthic cover of sand/rubble, gorgonian coral and sponge increased steadily within the four surveyed years. Crustose coralline algae (CCA) showed a steady decrease within that time (Figure 5).

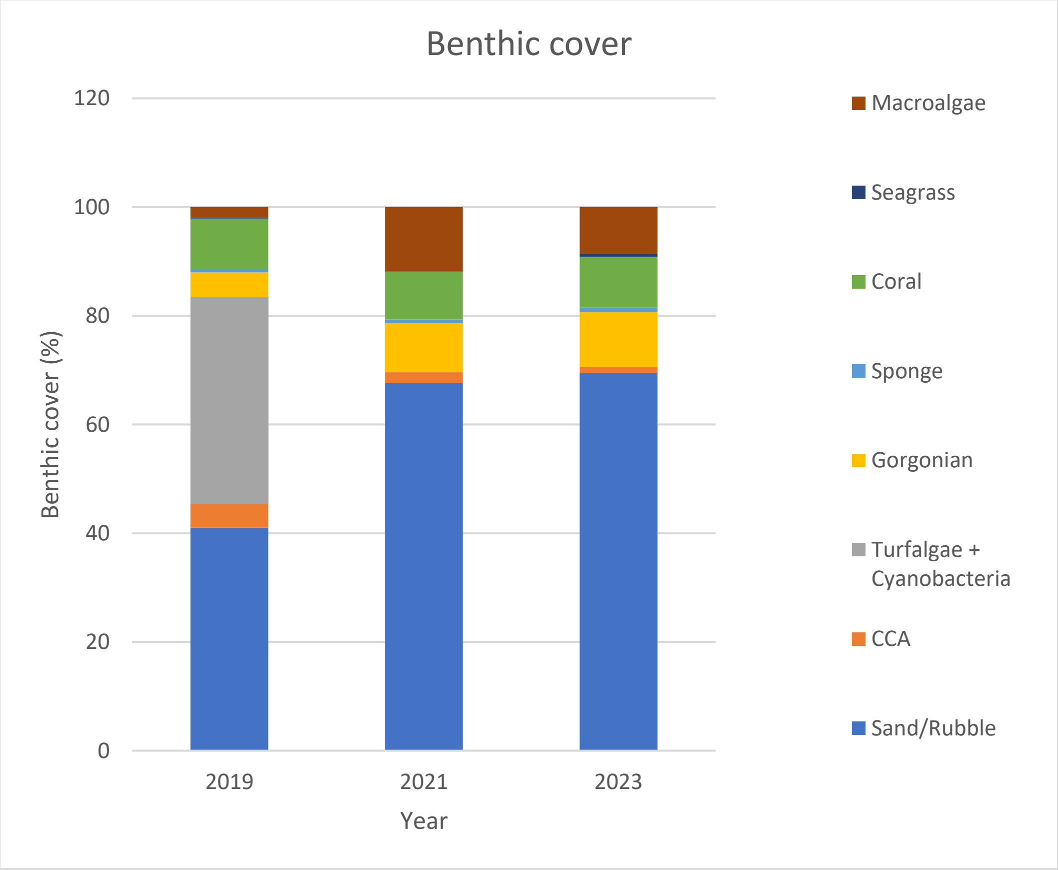

Figure 4: Average benthic cover as % of total in 2019, 2021 and 2023.

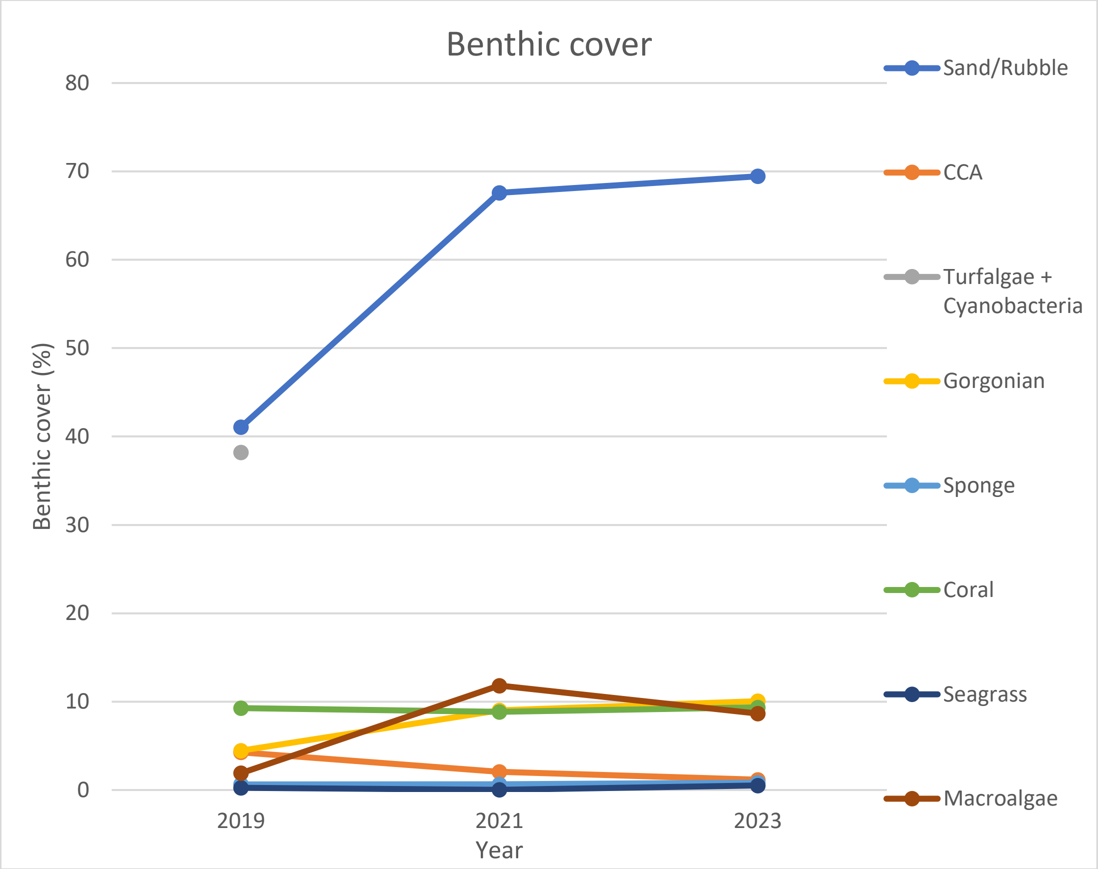

Figure 5: Average benthic cover per category in % in 2019, 2021 and 2023.

Six sites (AIRP, BARE, INHE, ISOR, JADS and SACA) showed a steady increase, while four sites (ARRE, HARE, MHIN and SEBE) displayed a steady decrease in coral cover over the last four years (Figure 6). In ARRE, most of the ground was covered by a coral rubble and algae mix, being difficult to distinguish. Macroalgae cover differed significantly between 2019 and 2023 (ANOVA *p*=0.002). It was relatively low in 2019 and increased significantly until 2021. After 2021, it decreased non-significantly at all sites except SEBE, JADS, and SACA, where data for 2021 was missing (Figure 7).

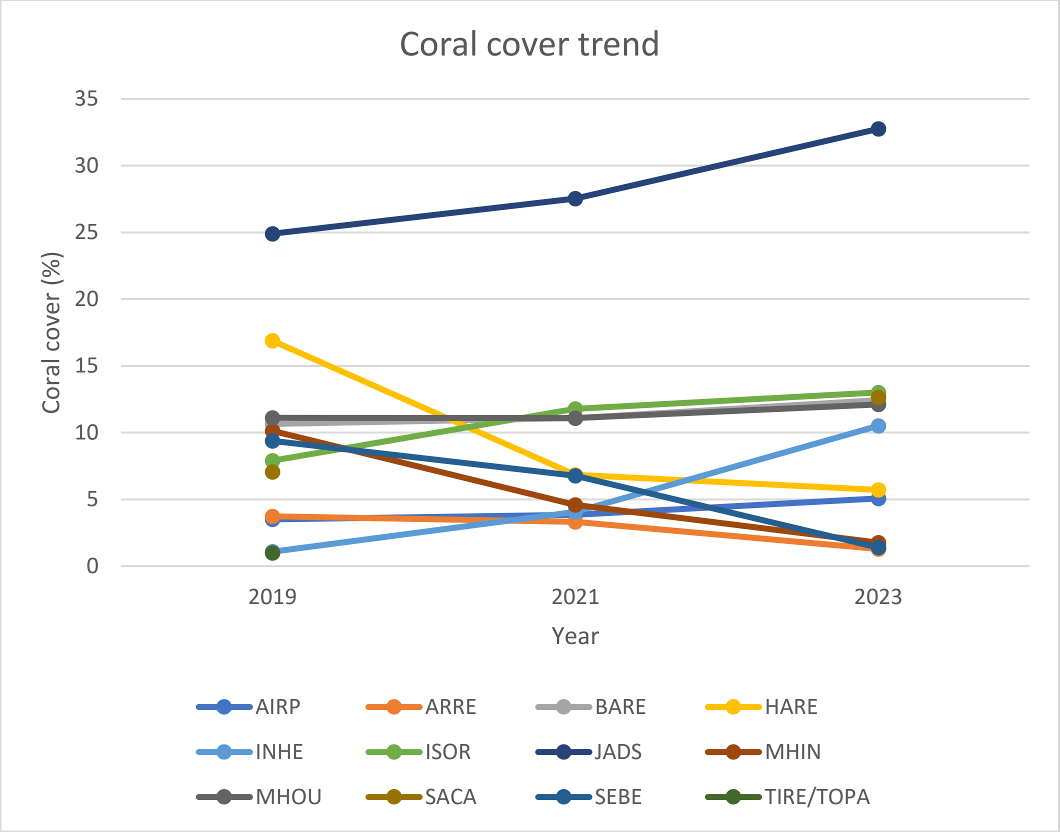

Figure 6: Average coral cover in % per site in 2019, 2021 and 2023.

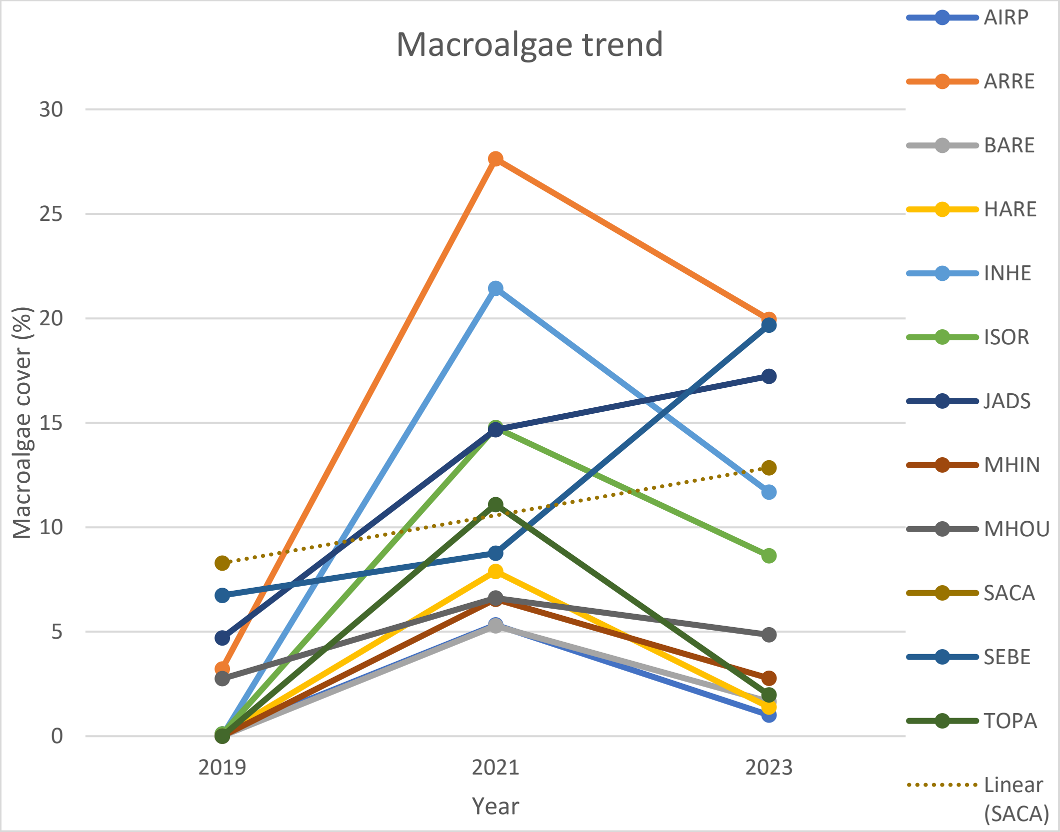

Figure 7: Average macroalgae cover in % per site in 2019, 2021 and 2023.

16 coral species were observed in the 2023 survey. In total, the most abundant coral species in 2023 was *Orbicella annularis*, followed by *Orbicella faveolata* (Figure 8).

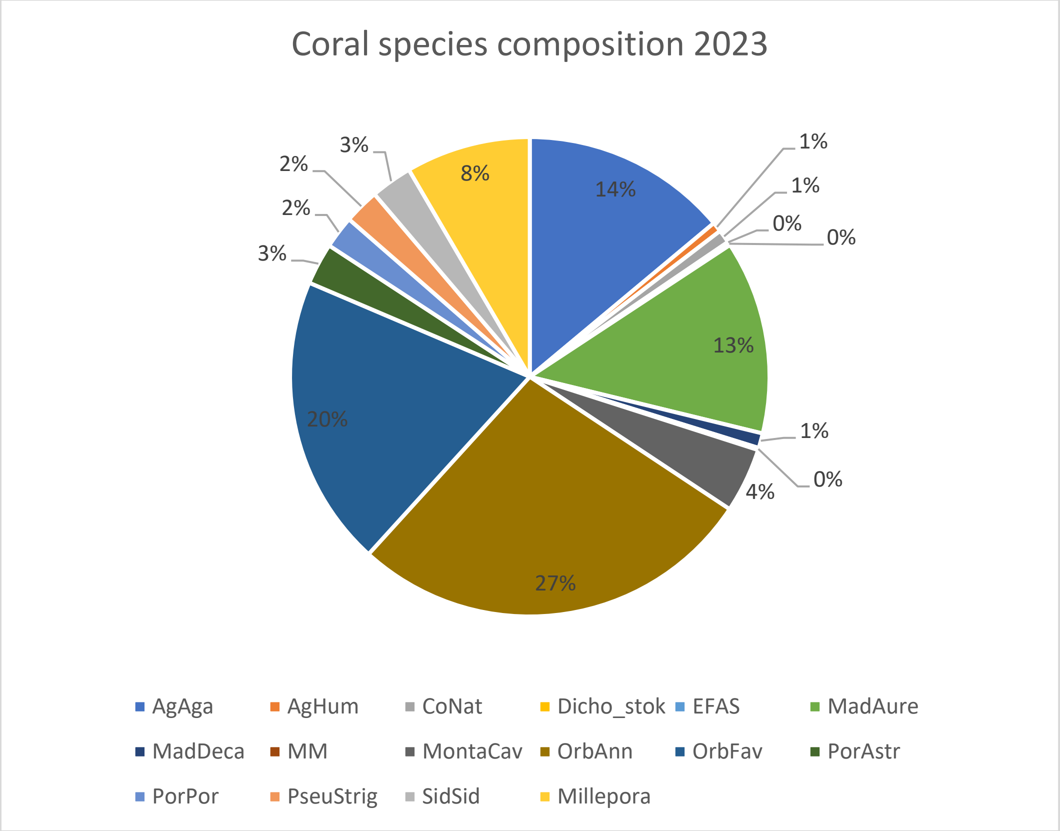

Figure 8: Coral species composition in % in 2023. For the full species name of each abbreviation see Appendix 2.

3.2 Biomass of reef fish taxa and abundance of key macro-invertebrate species

Average fish biomass for the 12 sites differed significantly from 2019 to 2023 (ANOVA p=0.008). In total, the most abundant fish species were *Stegastes partitus* (Bicolor damselfish), *Chromis multilineata* (Brown chromis) and *Chromis cyanea* (Blue chromis). Spots with relatively high fish biomass in 2019 like JADS, ISOR, MHIN and TOPA showed the strongest decline within the four years (Figure 9). In the 2023 survey, the only large species (one ray and one turtle) were observed in ARRE. Biomass of herbivory fish families *Scaridae* and *Acanthuridae* decreased on average from 67.12 g m^{-2} in 2021 to 30.99 g m^{-2} in 2023.

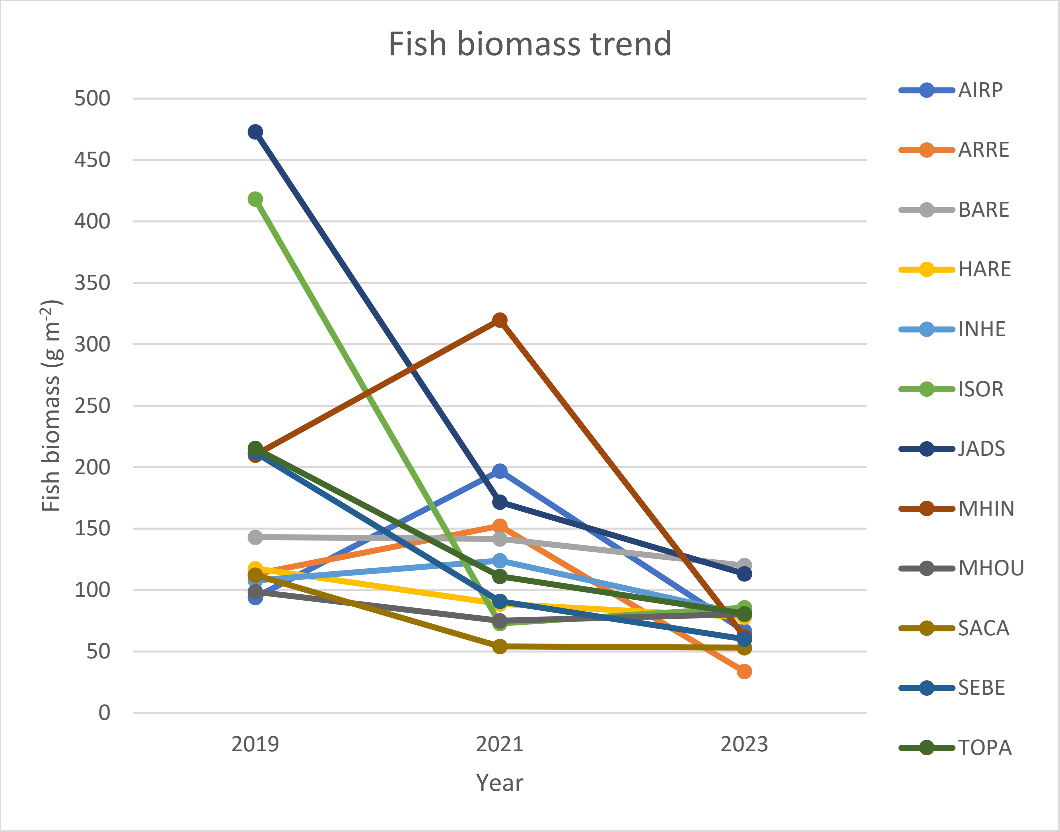

Figure 9: Average fish biomass in g m^{-2} per site in 2019, 2021 and 2023.

Abundance of key macro-invertebrate species was low at each site (≤7 individuals per site) except for ARRE in 2023 due to a high abundance of hermit crabs (Appendix 3).

3.3 Assessment of coral health

In 2023, 199 out of 1725 pictures showed in total 163 corals infected by SCTLD, giving a disease prevalence of 12.91 %. SCTLD was present at every observed site with the highest prevalence at INHE. Nine out of the 16 coral species were identified as diseased in the 2023 survey. *Montastraea cavernosa* was the most susceptible species in Aruba in 2023, followed by *Orbicella faveolata*, *Orbicella annularis* and *Diploria strigosa* (Figure 10).

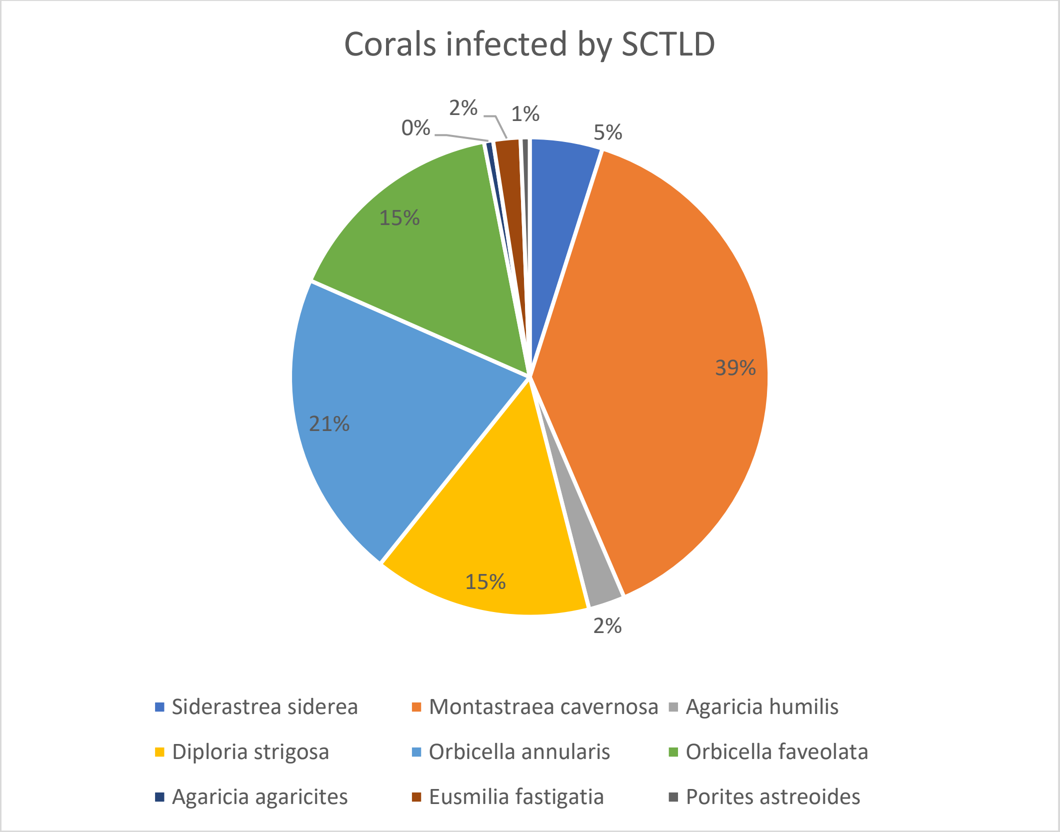

Figure 10: Percentage of corals infected by SCTLD in 2023 per species.

Cyanobacteria were present in 659 out of 1725 pictures. 538 of these pictures were from 2023, indicating an increase in presence of cyanobacteria from 14.67 % in 2021 to 59.78 % in 2023 (Figure 11).

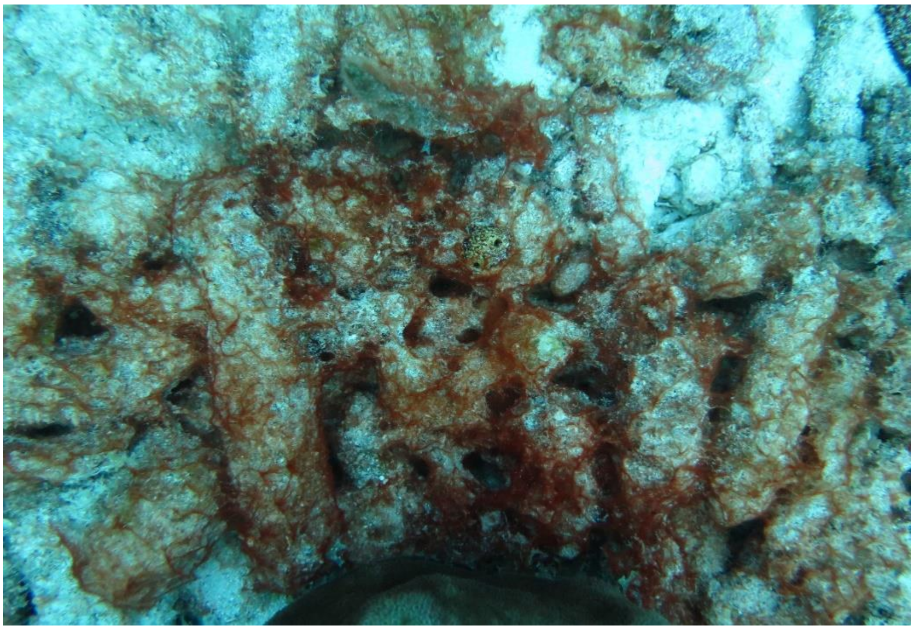

Figure 11: Cyanobacterial mat on coral rubble in ARRE.

3.4 Recruitment of reef-building corals

The density of coral recruits for the 12 observed sites differed significantly between 2019 and 2023 (ANOVA *p*=0.001). In the first instance, coral recruitment density decreased significantly from 2019 to 2021, however then increased non-significantly from 2021 to 2023 (Figure 12). The strongest increase over the four years was observed in INHE, while ARRE and ISOR showed the strongest decrease (Appendix 3).

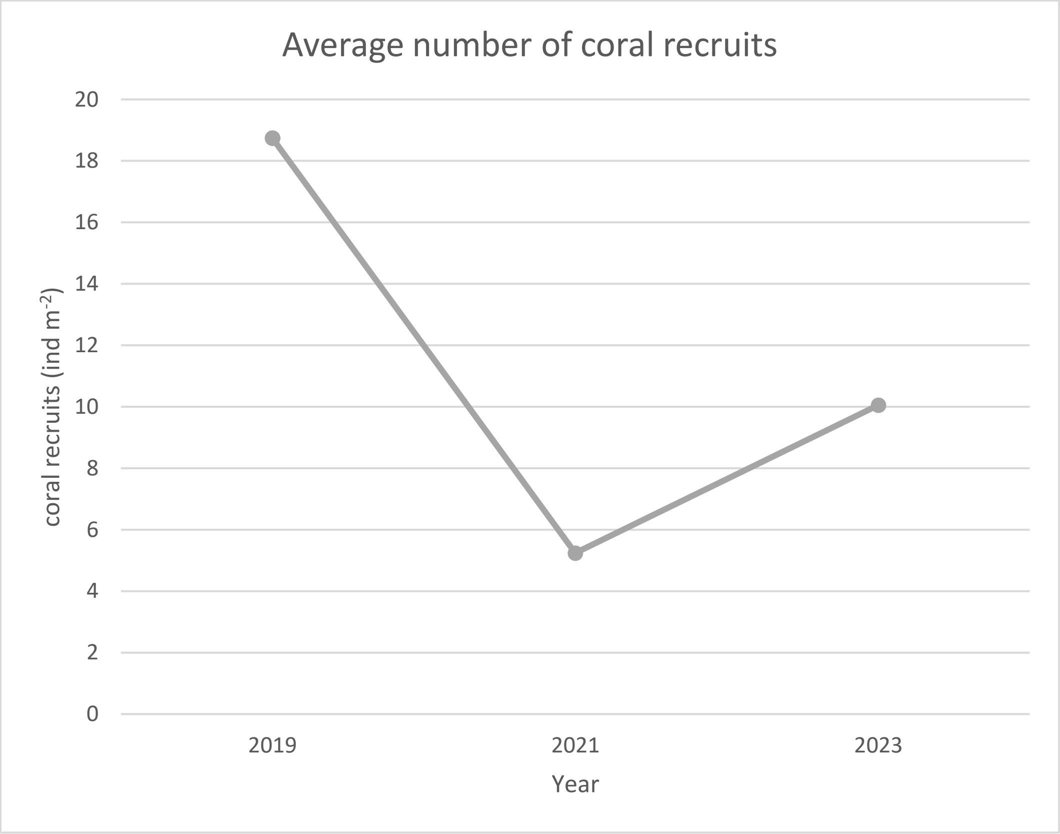

Figure 12: Average number of coral recruits in individuals m^{-2} in 2019, 2021 and 2023.

3.5 Macroalgae and turf algae height

Average turf height did not vary significantly between 2019 and 2023 (ANOVA *p*=0.907). Average macroalgae height increased strongly from 2021 to 2023. There was no data on macroalgae height in 2019 (Figure 13). The average macroalgae height increased at each site except at INHE from 2021 to 2023. Turf algae height remained constant at almost all sites. Exceptions were the site TIRE/TOPA, where turf algae height increased strongly, and ARRE, where it decreased strongly. There was no data for macroalgae height for 2019 and no data for macroalgae and turf algae height at SACA for 2021. In 2023, the average macroalgae height in SACA was 1.83 cm and 0.1 mm for the average turf algae height (Appendix 3).

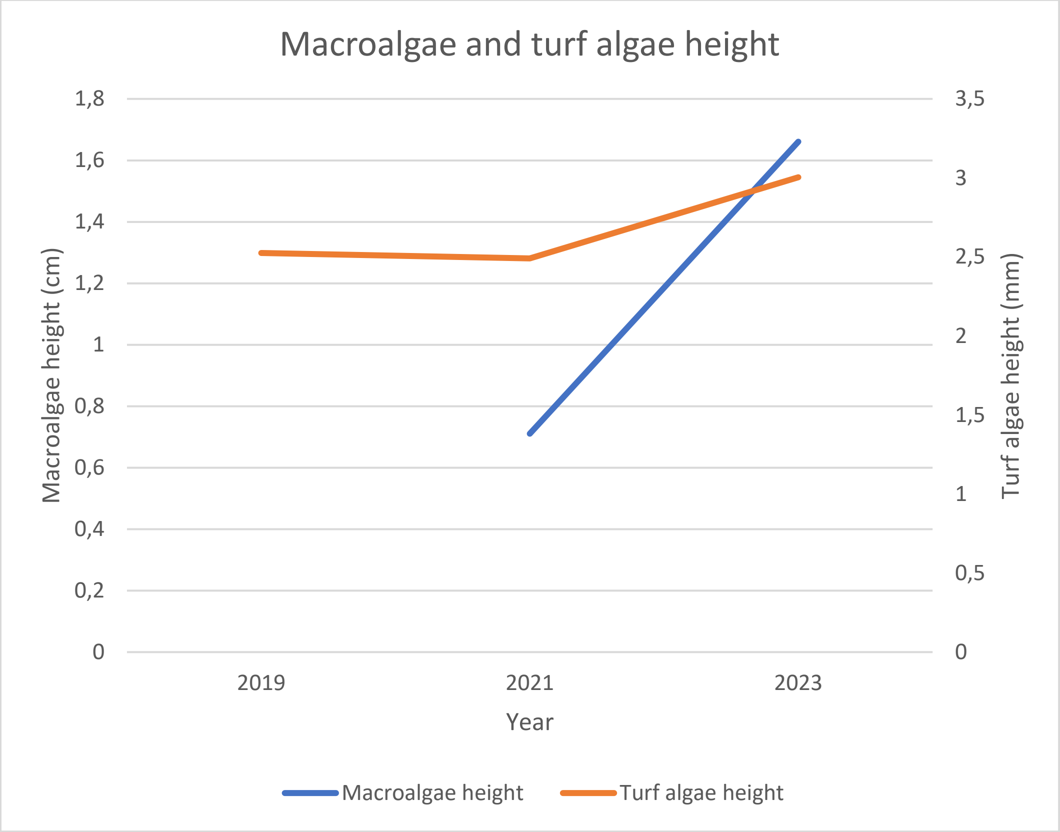

Figure 13: Average macroalgae and turf algae height in 2019, 2021 and 2023. Macroalgae height is given in cm and turf algae height in mm.

3.6 Coral Reef Health Indicators

The RHI indicates that not one site was in good or very good condition in 2023 (Appendix 5). Five sites (BARE, INHE, ISOR, JADS, MHOU) were in fair or fair to good condition. The remaining sites were in poor to fair condition (AIRP, HARE, MHIN, SACA, TIRE/TOPA), and ARRE and SEBE were even in critical to poor condition. Five sites (ARRE, HARE, MHIN, SEBE, TIRE/TOPA) showed a negative trend between 2019 and 2023. On the contrary, six sites (AIRP, BARE, INHE, ISOR, JADS and SACA) showed a positive trend within that time. Only MHOU showed a neutral trend between 2019 and 2023. The Shannon Diversity index for fish species differed between 1.46 (AIRP) and 2.22 (MHIN). For coral species, the index was between 1.29 (AIRP) and 2.05 (BARE; Figure 14).

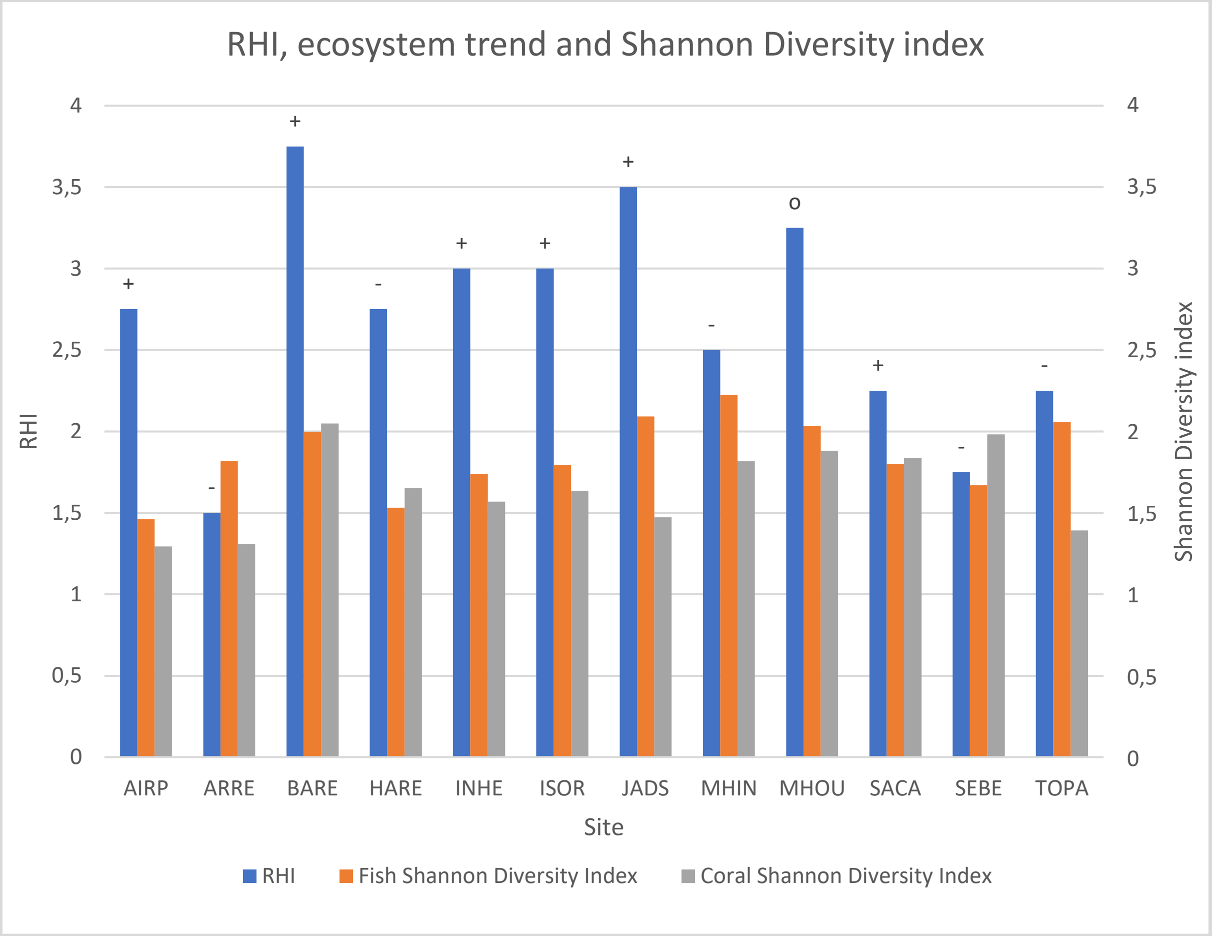

Figure 14: RHI, trend of the ecosystem and Shannon Diversity index for fish and corals per site in 2023. A RHI value of (1) indicates a critical, of (2) a poor, of (3) a fair and of (4) a good condition of the ecosystem. A (+) indicates a positive trend, a (o) a neutral trend and a (-) a negative trend.

Evenness for fish species was between 0.46 and 0.7. Coral species evenness was between 0.61 and 0.95, indicating a rather even distribution (Appendix 6).

4 Discussion

The status of Aruba's coral reefs strongly differs along the islands leeward shore. On average, coral cover was stable for the last four years whereas crustose coralline algae and fish biomass decreased strongly. Almost half of the observed sites showed a negative trend of the ecosystem, indicating stress on those coral reefs. While turf algae height increased slightly within the last four years, macroalgae height increased strongly. Herbivory fish biomass was reduced by more than half in that time-period. This together with the overall trend of increasing macroalgae cover indicates a negative development of Aruba's coral reefs.

Conducting long-term monitoring of coral reefs helps managing authorities and residents acquire knowledge regarding health and status of their coastal ecosystem which enables them to take informed action. Therefore, these surveys taken every second year are an important part of understanding which processes take place and how management interventions can change the marine ecosystem of Aruba. Gathering this data is not only important for decision-making on a regional level, but also on a global level, e.g., for international agreements as the Agenda 2030 of the United Nations General Assembly (e.g., Sustainable Development Goals; Obura et al., 2019). More data on the short- and long-term effects of SCTLD might help to understand the development of coral reef communities when undergoing coral community changes, that have been identified as one of the biggest threats for Caribbean coral reefs.

With respect to reef resilience and health, herbivorous fish play an important role as they keep establishment and growth of algae limited that hinder coral recruitment (Hughes et al, 2007; Green and Bellwood, 2009). Turf- and macroalgae height as well as cover increased while herbivory fish biomass decreased by more than 50 %. Hence, Aruba's coral reefs are already in a critical state. Moreover, this degrading trend is supported by the increase in cyanobacterial mats from 2021 to 2023. A high abundance of cyanobacteria can lead to an anoxic environment as microbes mineralize organic material produced by cyanobacteria and various algal groups in reef sediments. Consequently, corals and fish cannot survive in those anoxic environments. The high abundance of benthic cyanobacterial mats underlines the severe degradation of Aruba's coral reefs that has been taking place (Vermeij et al., 2019). The northwestern part shows high abundance of "microbialized" landscapes dominated by cyanobacteria, that were predicted to worsen due to land-based pollution in 2019, which leads to enhanced growth of cyanobacterial mats (Vermeij et al., 2019; Brocke et al., 2015). This becomes evident when looking at ARRE, where the ground was covered in a coral rubble and macroalgae mix with cyanobacterial mats, that likewise received the lowest RHI. The low biomass of commercially important fish and low abundance of key macro-invertebrate species underline the findings of Vermeij et al. (2019) of strong (historic) overfishing. The observed reef health and trends cannot be directly connected to tourism, since many different factors like land-based pollution, sewage influxes and overfishing contribute to the state of the ecosystem as well. However, sites in the northwestern part of Aruba, where the tourism industry dominates, show lower reef health than sites like JADS and MHOU that are not easily accessible for tourists (Vermeij et al., 2019).

Furthermore, the results imply a positive correlation between the RHI, trend of the ecosystem and Shannon Diversity index. The diversity indices did not differ greatly between the sites as did evenness. However, fish evenness was relatively low, indicating that some individuals are far more abundant than others. This effect is due to a high abundance of bicolor damselfishes, brown chromis and blue chromis across all sites. Coral evenness was relatively high, indicating a rather even distribution of individuals among different species. However, only 16 coral species were observed in 2023, explaining the rather low coral diversity index. BARE was the only site in good condition in 2023 as supported by the RHI, trend of the ecosystem and Shannon Diversity index. SACA was the only site in bad condition showing a positive trend and moderate fish and coral Shannon Diversity index, indicating that reef health is higher than estimated by the RHI. These findings suggest that it is important to differentiate between sites when evaluating Aruba's coral reefs and highlight the importance of including long-term monitoring when quantifying the health of the coral reef ecosystem. Only a few sites showed a high fish diversity index but low coral diversity index or vice versa. ARRE and TOPA, for instance, showed a comparably high fish diversity index, contradicting the rather low RHI, but low coral diversity. JADS showed a relatively low coral diversity index, contradicting the rather high RHI, but high fish diversity. Compared to other indices quantifying reef health, the RHI estimates reef health rather high (Díaz-Pérez et al., 2016). This is supported by the overall low fish and coral diversity indices. The importance of including diversity indices is also highlighted when looking at AIRP. According to the RHI and trend of the ecosystem, this site seems to be in a poor to fair condition with a positive trend. Both diversity indices, however, indicate low diversity and therefore lower reef health and resilience. All in all, the RHI seems to be a good indicator for reef health as it is mostly supported by the trend of the ecosystem and the Shannon Diversity indices.

SCTLD was present at every observed site in the 2023 monitoring. As the outbreak of the disease happened only six months prior to the 2023 survey, it is very likely that it will spread further at each site. 12,91 % of corals already showed signs of SCTLD six months after the first reports of the disease. Within the next years, this percentage is expected to increase, as a prevalence rate of 66 – 100 % has been documented for highly susceptible species (Souter et al., 2021). In the near future, this will likely lead to a higher percentage of recently dead coral. A shift in the coral community composition and smaller colonies were observed in Southeast Florida (Hayes et al., 2022), which may occur in Aruba as well. One can assume that SCTLD will have the strongest effect at spots with high live coral cover like JADS, BARE, ISOR, MHOU and SACA. However, less healthy systems are less resilient. Therefore, based on the RHI and the development of the system within the last four years, ARRE, SEBE, MHIN and TIRE/TOPA can be expected to show strong decreases in coral cover and ecosystem health due to SCTLD in the future. *Montastraea* spp. is one of the most dominant reef-building corals in the Caribbean. Hence, coral diseases affecting these coral species are especially threatening for Caribbean coral reefs (Knowlton, 2001). In Aruba, *Orbicella* spp. is the most frequent reef-building coral. As *Montastraea cavernosa*, *Orbicella annularis* and *Orbicella faveolata* are corals seeming to be highly susceptible to SCTLD in Aruba, the disease will most likely lead to a strong decrease in reef-building coral cover within the next years. In Florida, coral tissue loss due to SCTLD of more than 60 % has been documented (Walton et al., 2018) and can be expected for Aruba as well. The artificial reef deployment by FPNA, however, might mitigate some of the consequences of SCTLD as the species that are being deployed are only slightly susceptible to SCTLD.

The future of Aruba's coral reefs looks bleak. As live coral cover is the most frequently gathered data, it is often used to quantify reef resilience, although many factors influence resilience. Analysis of disturbed and recovered sites in the Caribbean, based on percent coral cover, show a loss of about 57 % of their hard coral cover. As the frequency and intensity of disturbances increase, coral reefs have no time to recover. Together with local stressors increasing, chances of recovery are low after disturbing events (Souter et al., 2021). This suggests that Aruba's coral reefs will most likely experience strong declines in coral cover due to SCTLD, and natural recovery is unlikely due to strong local stressors. Therefore, local pressures need to be reduced to maintain resilience of coral reefs while global threats increase (Souter et al., 2021). That said, local management interventions are needed to protect Aruba's nearshore marine communities. Coral Reefs Baseline Study for Aruba found that land-based pollutants are present along Aruba's entire leeward shore and their abundance reflects activities on shore (Vermeij et al., 2019). Measuring the water quality in different spots on a regular basis would show the effect of local interventions. Long-term effects of the establishment of the Parke Marino Aruba will be of interest as well.

5 Conclusion

Aruba's coral reefs differ in their health status and trend along the leeward shore. According to the Reef Health Index, 25 % of the observed sites are in a fair to good condition. The remaining sites are in a fair, poor or critical condition. Five out of 12 sites show a degrading ecosystem trend within the last four years, indicating stress on coral reefs. Despite the fact that coral cover on average remained constant since 2019, several factors indicate an overall degrading trend for Aruba's coral reefs. The outbreak of stony coral tissue loss disease will most likely have strong effects on the development of Aruba's coral reefs within the next years. As coral cover is relatively low in Aruba, the severe effects observed in other countries/territories might be less extreme for Aruba. Nine coral species, including important reef-building coral species in Aruba such as *Montastraea cavernosa*, *Orbicella annularis* and *Orbicella faveolata* have been identified as infected by the disease. This can lead to a shift in coral community composition, as those species are abundant in Aruba's coral reefs.

6 Further Research

On a final note, future monitoring should include measuring the water quality around Aruba on a regular basis. The GCRMN-Caribbean guidelines recommend taking measurements of water quality weekly (Level 3), monthly (Level 2) or at least annually (Level 1). Local stressors as sewage water influx need to be reduced to interfere with the degradation of Aruba's marine communities. Even though Secchi disc measurements are a rather simple approach to assess basic elements of water quality and shall be repeated further, more detailed measurements as done by Vermeij et al. (2019) should be conducted in the future to increase knowledge about Aruba's local stressors. Social welfare, economic responsibility and ecological resilience are interconnected fields. Therefore, socio-economic monitoring as done by the TEEB study in 2018 should play a role in future research projects for decision-making regarding Aruba's ecosystem (Souter et al., 2021; Polaszek et al., 2018). This research was conducted at the beginning of the outbreak of SCTLD. The spread and impact of SCTLD should be researched more detailed than included in the GCRMN-Caribbean guidelines in the future to assess the likely changes Aruba's coral reefs face within the next years. Monitoring the effect of SCTLD might also help decision-making about investing in future projects as e.g., the artificial reef deployment that took place in 2023.

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Appendices

Appendix 1: Fish species list including biomass parameters a and b

Common name	**Scientific name**	**Parameter a**	**Parameter b**
Ocean Surgeonfish (Surgeonfish)	*Acanthurus tractus*	0.0257	2.9
Doctorfish	*Acanthurus chirurgus*	0.0209	2.93
Blue Tang	*Acanthurus coeruleus*	0.0324	2.95
Yellow Goatfish	*Mulloidichthy martinicus*	0.0120	3.10
Spotted Goatfish	*Pseudupeneus maculatus*	0.0158	3.05
Goatfish	*Mullidae*	0.0139	3.75
French Grunt	*Haemulon flavolineatum*	0.0186	2.99
Bluestriped grunt	*Haemulon sciurus*	0.0245	2.92
Grunts	*Haemulidae*	0.0186	2.99
Squirrelfishes	*Holocentridae*	0.0229	2.86
Bicolor Damselfish	*Stegastes partitus*	0.0182	3.152
Brown Chromis	*Chromis multilineata*	0.0240	2.86
Blue Chromis	*Chromis cyanea*	0.0240	2.86
Damselfishes	*Pomacentridae*	0.0240	2.86
Schoolmaster	*Lutjanus apodus*	0.0174	3.01
Yellowtail Snapper	*Ocyurus chrysurus*	0.0295	2.79
Gray Snapper	*Lutjanus griseus*	Not observed	
Mahogany Snapper	*Lutjanus mahogoni*	0,0617	2,65
Snappers	*Lutjanidae*	0.0269	2.85
Rainbow parrotfish	*Scarus guacamaia*	Not observed	
Blue/Midnight Parrotfish	*Scarus coeruleus/coelestinus*	Not observed	
Queen parrotfish	*Scarus vetula*	0,0135	3
Princess parrotfish	*Scarus taeniopterus*	0,0135	3
Stoplight parrotfish	*Sparisoma viride*	0.0257	2.93
Striped parrotfish	*Scarus iseri*	0.0158	3.02
Redband parrotfish	*Sparisoma aurofrenatum*	0.0117	3.15
Yellowtail parrotfish (*also*: redfin parrotfish)	*Sparisoma rubripinne*	0.0178	3.02
Parrotfishes	*Scaridae*	0.0204	3.1
Goliath Grouper	*Epinephelus itajara*	Not observed	
Nassau Grouper	*Epinephelus striatus*	Not observed	
Yellowfin Grouper	*Mycteroperca venenosa*	0.015	3.03
Graysby, Red-/Rock Hind	*Cephalopholis cruentata, Epinephelus gutattus/adscensionis*	0.0116	3.12
Coney	*Cephalopholis fulva*	0.0148	3.04
Groupers	*Epinephelidae*	0.0132	3.08
Green moray	*Gymnothorax funebris*	0.0008	3.19
Morays	*Muraenidae*	0.0008	3.19
Angelfishes	*Pomacanthidae*	0.049	2.96
Butterflyfishes	*Chaetodontidae*	0.0234	3.19
Ray	*Batoidea*	0,0295	3
Lionfish	*Pterois*	0,0049	3,26
Turtle	*Testudines*	No parameters found	

Appendix 2: Coral species list

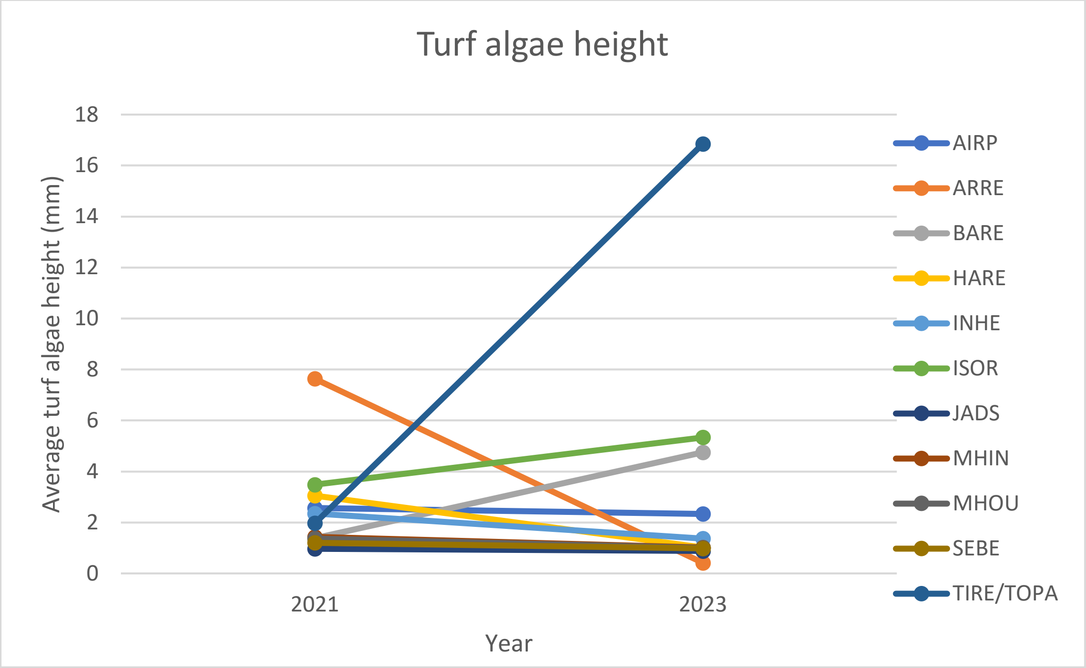
Name	**Abbreviation**
Agaricia agaricites	AgAga
Agaricia humilis	AgHum
Colpophyllia natans	CoNat
Dichocoenia stokesii	Dicho_stok
Eusmilia fastigiata	EFAS
Madracis auretenra	MadAure
Madracis decactis	MadDeca
Meandrina meandrites	MM
Montastraea cavernosa	MontaCav
Orbicella annularis	OrbAnn
Orbicella faveolata	OrbFav
Porites astreoides	PorAstr
Porites porites	PorPor
Pseudodiploria strigosa also: *Diploria strigosa*	PseuStrig
Siderastrea siderea	SidSid
Millepora spp.	Millepora

Appendix 3: Raw data

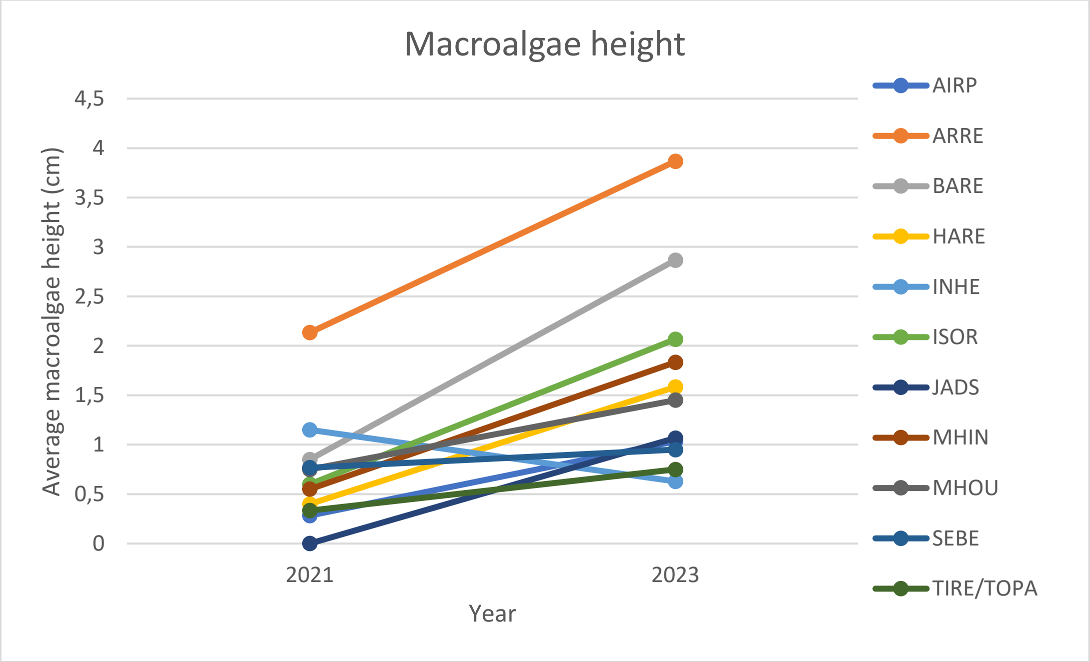
Water quality measurements per site per year:

	2021	2023
AIRP	35 m	21 m
ARRE	20 m	18 m
BARE	32 m	38 m
HARE	14 m	19 m
INHE	35 m	26 m
ISOR	28 m	32 m
JADS	45 m	29 m
MHIN	32 m	19 m
MHOU	35 m	28 m
SACA	44 m	37 m
SEBE	35 m	29 m
TIRE/TOPA	28 m	24 m

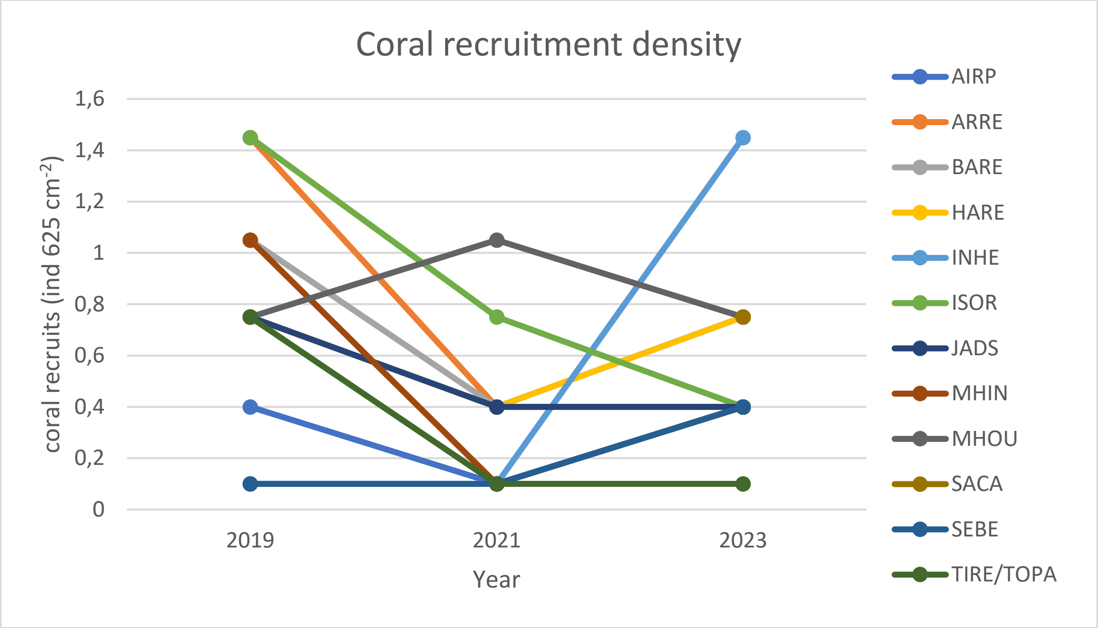
Turf algae height per site in 2021 and 2023:



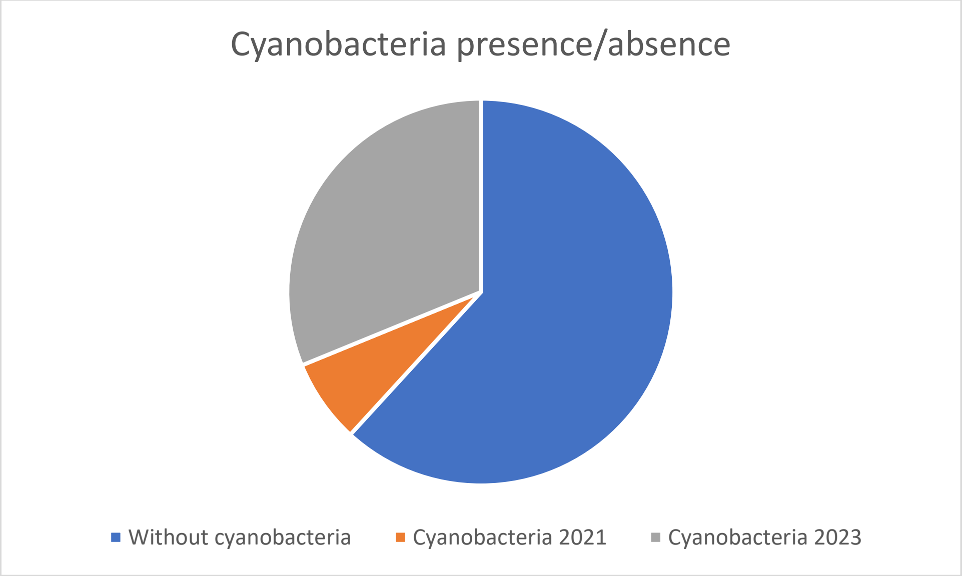
Macroalgae height per site in 2021 and 2023:



Coral recruitment density in individuals cm^{-2} per site in 2019, 2021 and 2023:



Total cyanobacteria presence and absence in 2021 and 2023.



Abundance of key macro-invertebrates in 2021 and 2023:

	AIRP		ARRE		BARE		HARE		INHE		ISOR	
	2021	2023	2021	2023	2021	2023	2021	2023	2021	2023	2021	2023
Diadema			1									
Other urchins				2	2		1					
Sea cucumbers						1						
Conch						4	3				1	
Lobster		2				1						

Hermit crabs	1			19	5	1	1					
Octopus												

	JADS		MHIN		MHOU		SACA		SEBE		TOPA/TIRE	
	2021	2023	2021	2023	2021	2023	2021	2023	2021	2023	2021	2023
Diadema												
Other urchins					3						1	
Sea cucumbers												
Conch												
Lobster												
Hermit crabs					3							
Octopus												

Appendix 4: RHI health grades for each indicator (HRI, 2012)

RHI Category (Indicators)	Very Good (5)	Good (4)	Fair (3)	Poor (2)	Critical (1)
Coral cover %	≥40	20 – 39.9	10 – 19.9	5 – 9.9	<5
Fleshy algae cover %	0 – 0.9	1 - 5	5.1 - 12	12.1 - 25	>25
Herbivorous fish biomass (g 100 m^{-2})	≥3,480	2880 – 3,479	1920 - 2879	961 - 1919	<960
Commercial fish biomass (g 100 m^{-2})	≥1,680	1260 – 1,679	840 - 1259	421 - 839	<420

Appendix 5: RHI values and trends per site in 2023

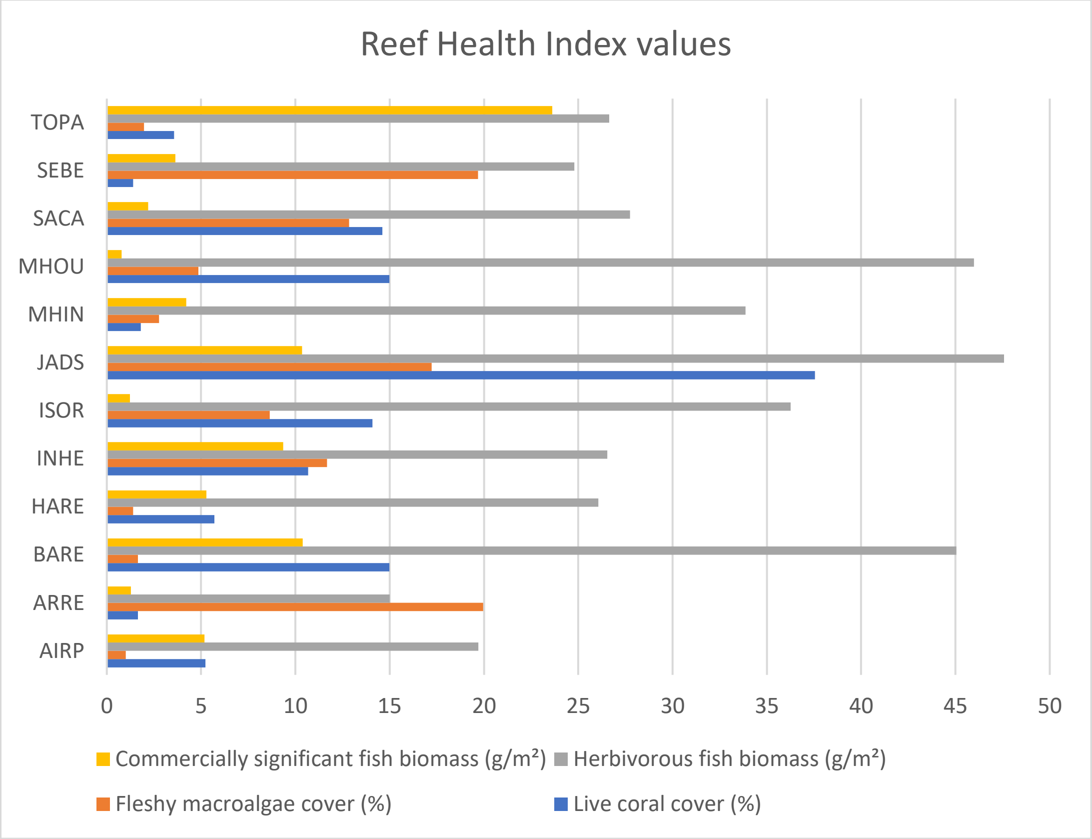
Indicators for calculating the RHI per site in 2023:

	AIRP	ARRE	BARE	HARE	INHE	ISOR
Live coral cover (%)	5,23	1,65	14,99	5,71	10,67	14,08
Fleshy macroalgae cover (%)	1,01	19,95	1,65	1,39	11,68	8,64

Herbivorous fish biomass (g 100m-2)	1970,0	1499,8	4504,5	2606,9	2653,8	3625,1
Commercially significant fish biomass (g 100m-2)	517,8	127,3	1039,1	528,6	935,6	121,8

	JADS	MHIN	MHOU	SACA	SEBE	TOPA
Live coral cover (%)	37,55	1,81	14,99	14,61	1,39	3,57
Fleshy macroalgae cover (%)	17,23	2,77	4,85	12,85	19,68	1,97
Herbivorous fish biomass (g 100m^{-2})	4757,1	3386,0	4597,6	2773,5	2479,8	2664,0
Commercially significant fish biomass (g 100m^{-2})	1036,1	420,6	78,8	219,0	364,1	2361,2

Reef Health index values per site. Fish biomass is given in g m^{-2}, coral and macroalgae cover are given in % (of total benthic cover):



Trend of indicative elements for the development of the ecosystem per site. A + in macroalgae cover indicates a decrease in macroalgae cover:

	Live coral cover trend	Macroalgae cover trend
AIRP	+	-
ARRE	-	-
BARE	+	-
HARE	-	-
INHE	+	-
ISOR	+	-
JADS	+	-
MHIN	-	-
MHOU	+	-
SACA	+	-
SEBE	-	-
TIRE/TOPA	-	-

RHI and trend of the ecosystem per site:

	RHI	Trend
AIRP	Poor - fair (2,75)	+
ARRE	Critical - poor (1,5)	-
BARE	Fair - good (3,75)	+
HARE	Poor - fair (2,75)	-
INHE	Fair (3)	+
ISOR	Fair (3)	+
JADS	Fair - good (3,5)	+
MHIN	Poor - fair (2,5)	-
MHOU	Fair - good (3,25)	o
SACA	Poor - fair (2,25)	+
SEBE	Critical - poor (1,75)	-
TIRE/TOPA	Poor - fair (2,25)	-

Appendix 6: Shannon Diversity Index values

Fish Shannon Diversity index:

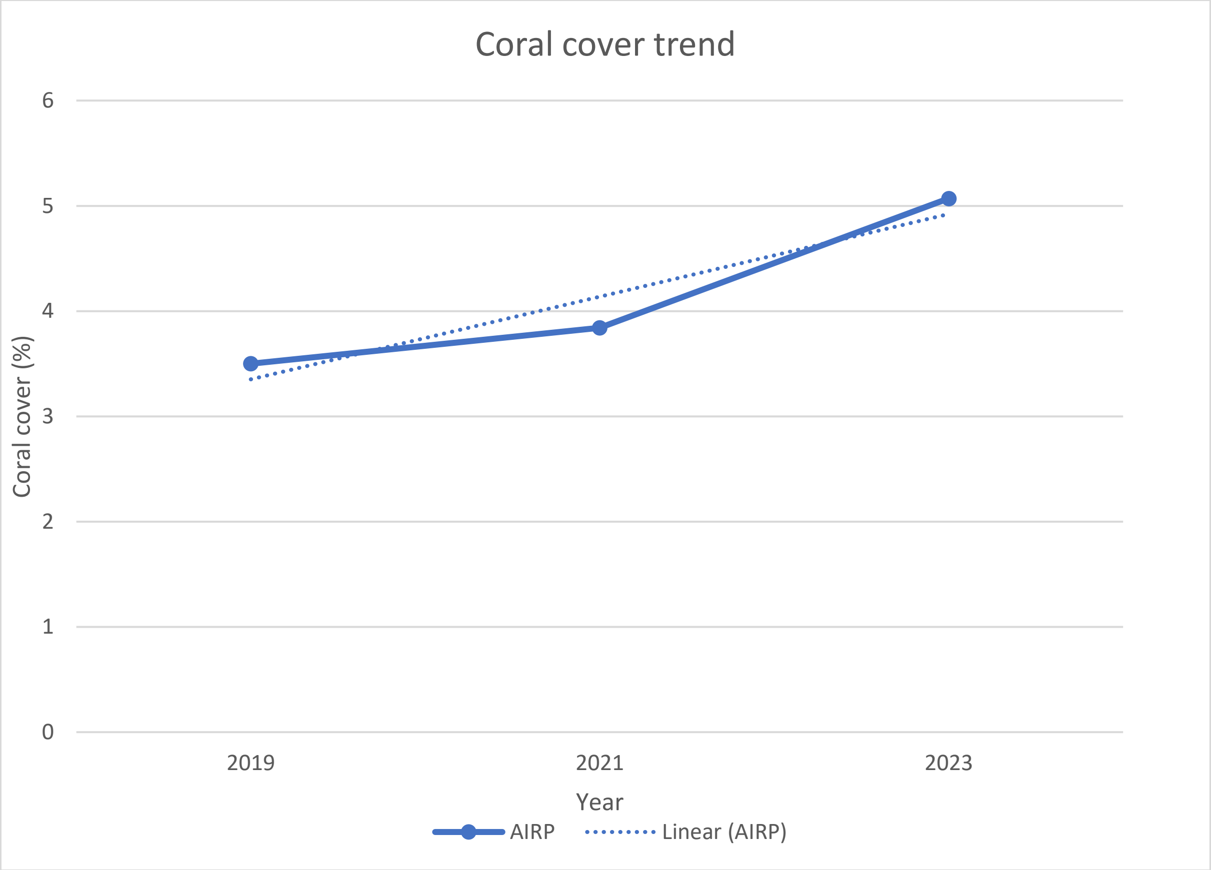
	Shannon Diversity Index	Evenness
AIRP	1,460251963	0,465716682
ARRE	1,819421496	0,629476638
BARE	1,998338608	0,620818794
HARE	1,532267628	0,503286693
INHE	1,738945583	0,554600157
ISOR	1,792230391	0,563939595
JADS	2,091340211	0,658056887
MHIN	2,224131155	0,7093399
MHOU	2,032404206	0,690251766
SACA	1,801771138	0,611923409
SEBE	1,66883424	0,539893665
TOPA	2,058084457	0,675995825

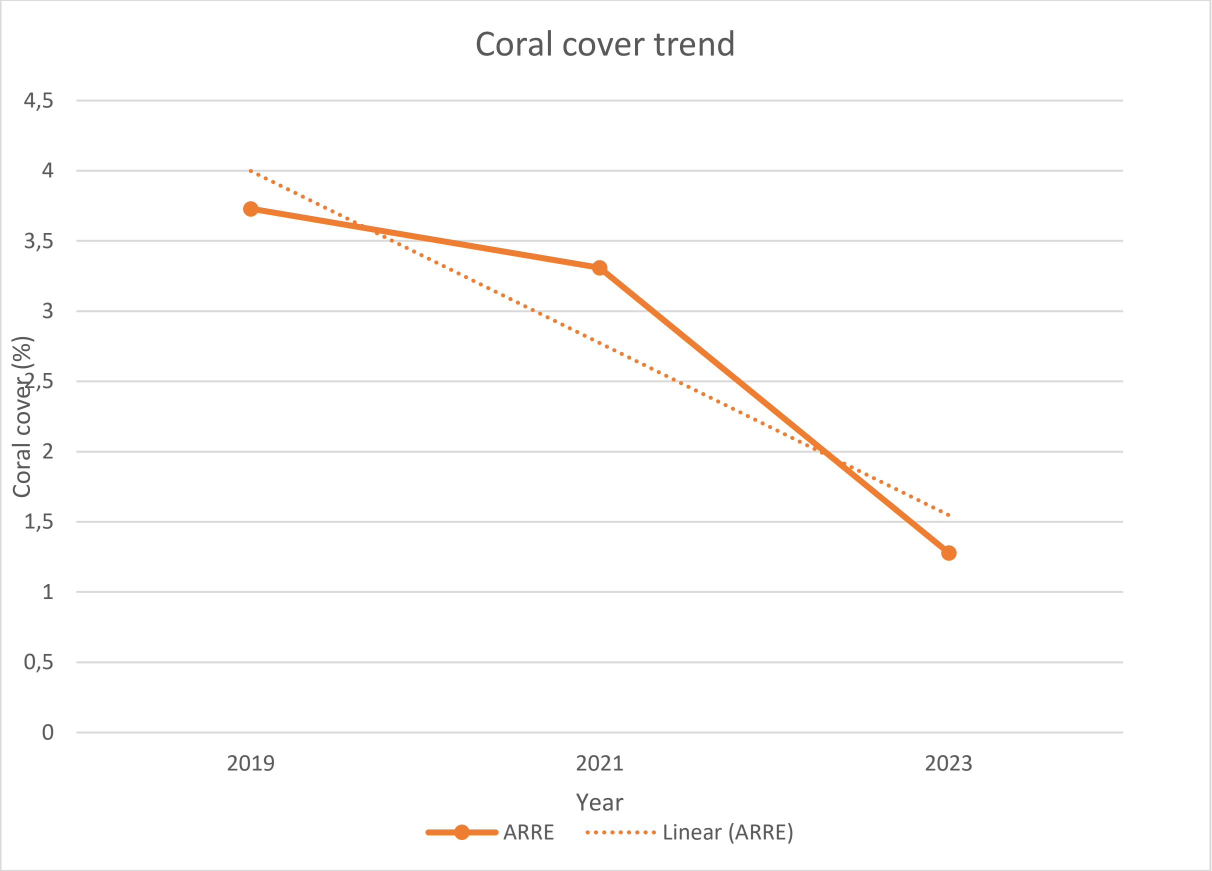
Coral Shannon Diversity index:

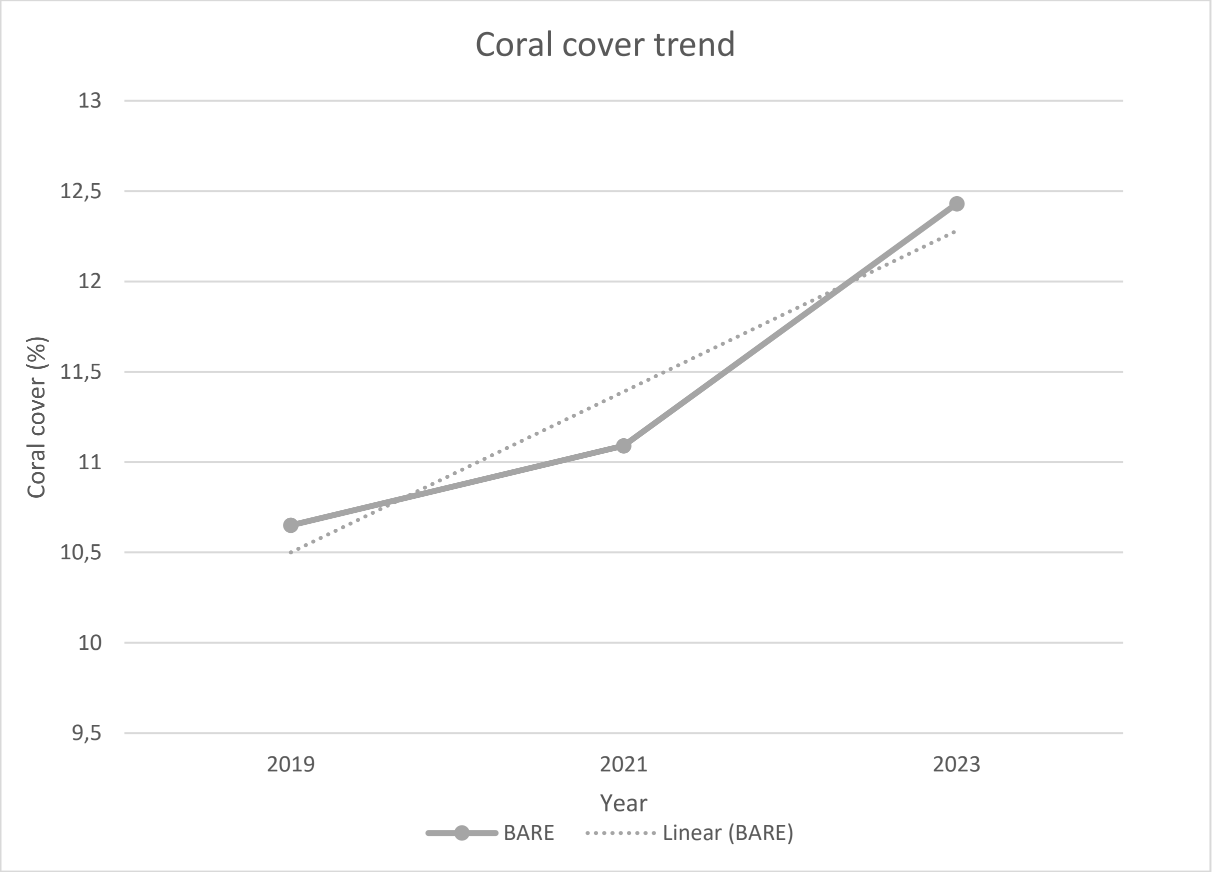
	Shannon Diversity Index	Evenness
AIRP	1,29276925	0,72150826
ARRE	1,31028111	0,73128181
BARE	2,04941785	0,79900909
HARE	1,65144719	0,75160601
INHE	1,56919744	0,75462446
ISOR	1,6354763	0,65816408
JADS	1,47343953	0,61447201
MHIN	1,81587206	0,93317364
MHOU	1,88249666	0,78506208
SACA	1,83813021	0,76655984

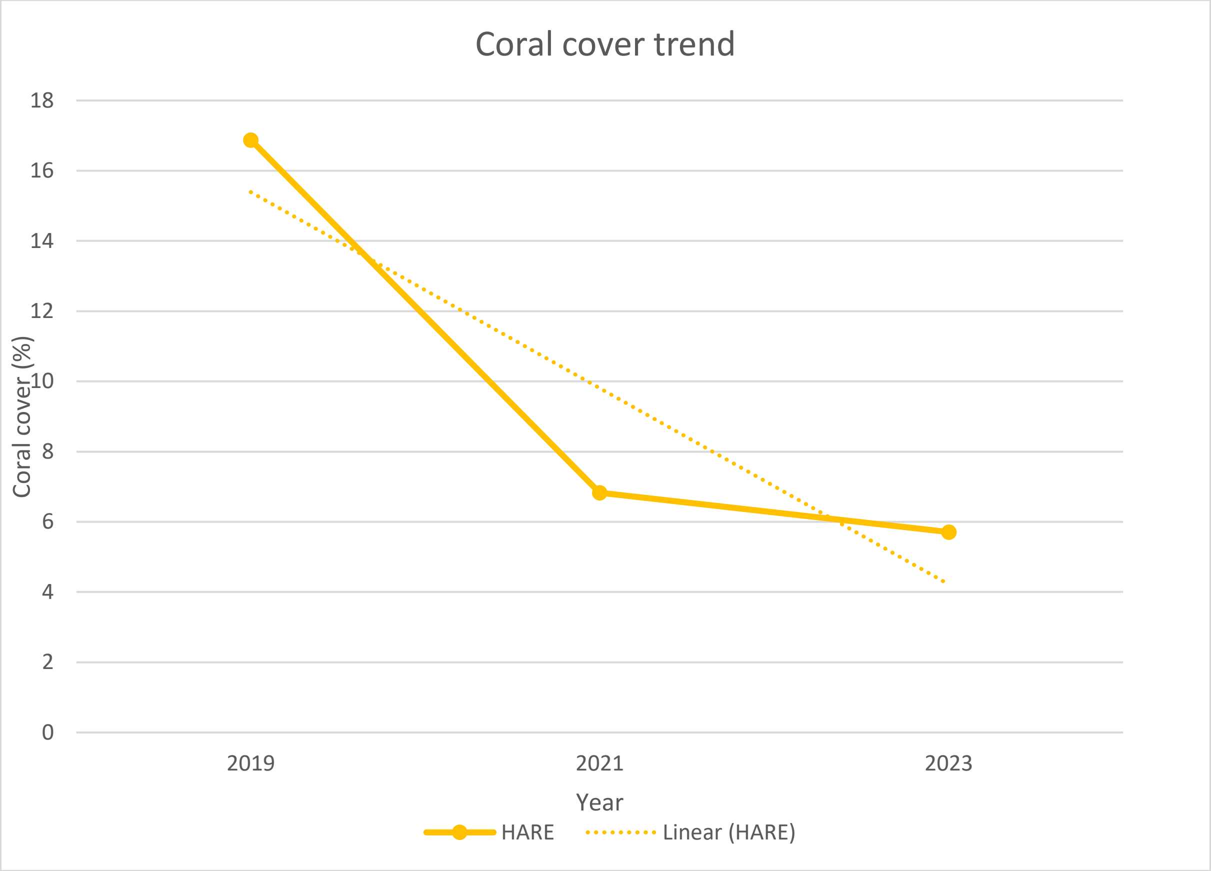
SEBE	1,98179123	0,95304012
TOPA	1,39128321	0,77648994

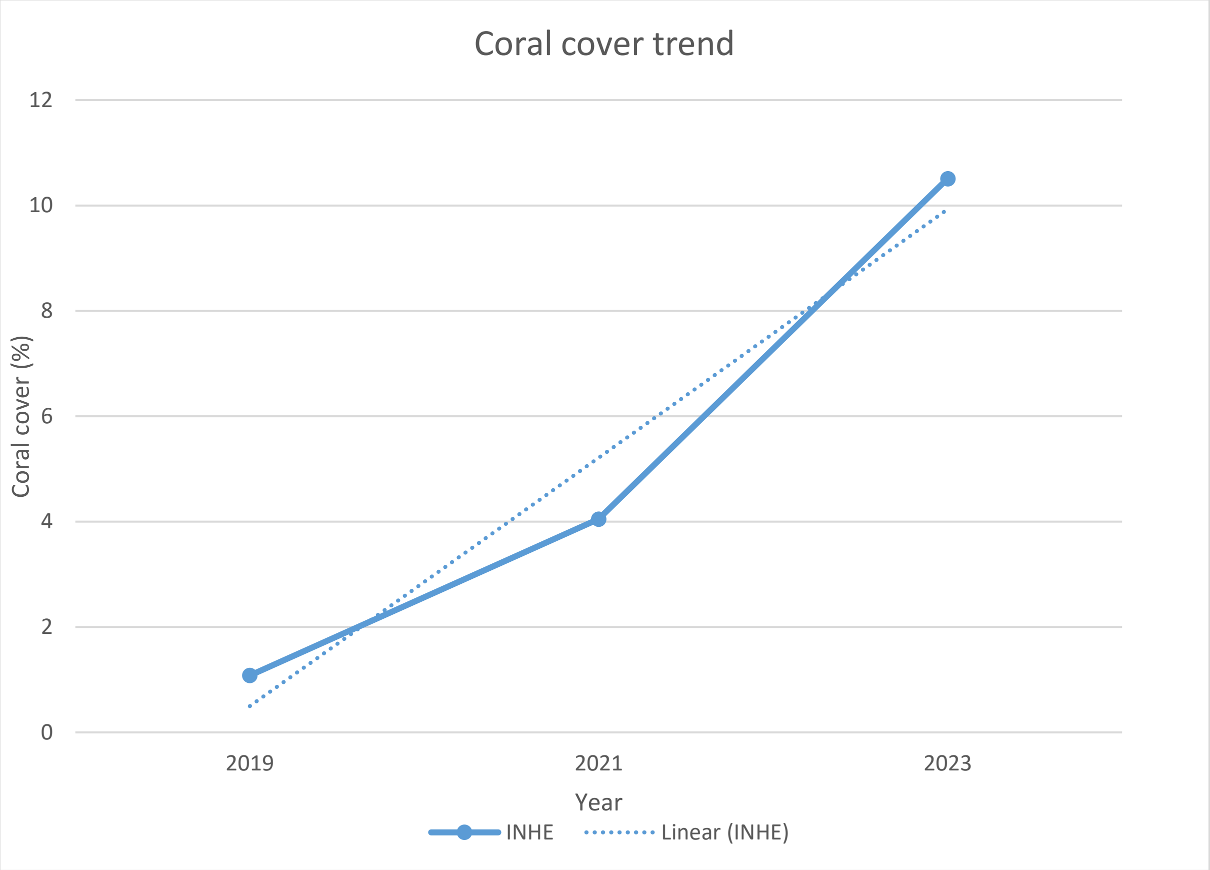
Appendix 7: Coral and macroalgae cover trend per site with trendline:

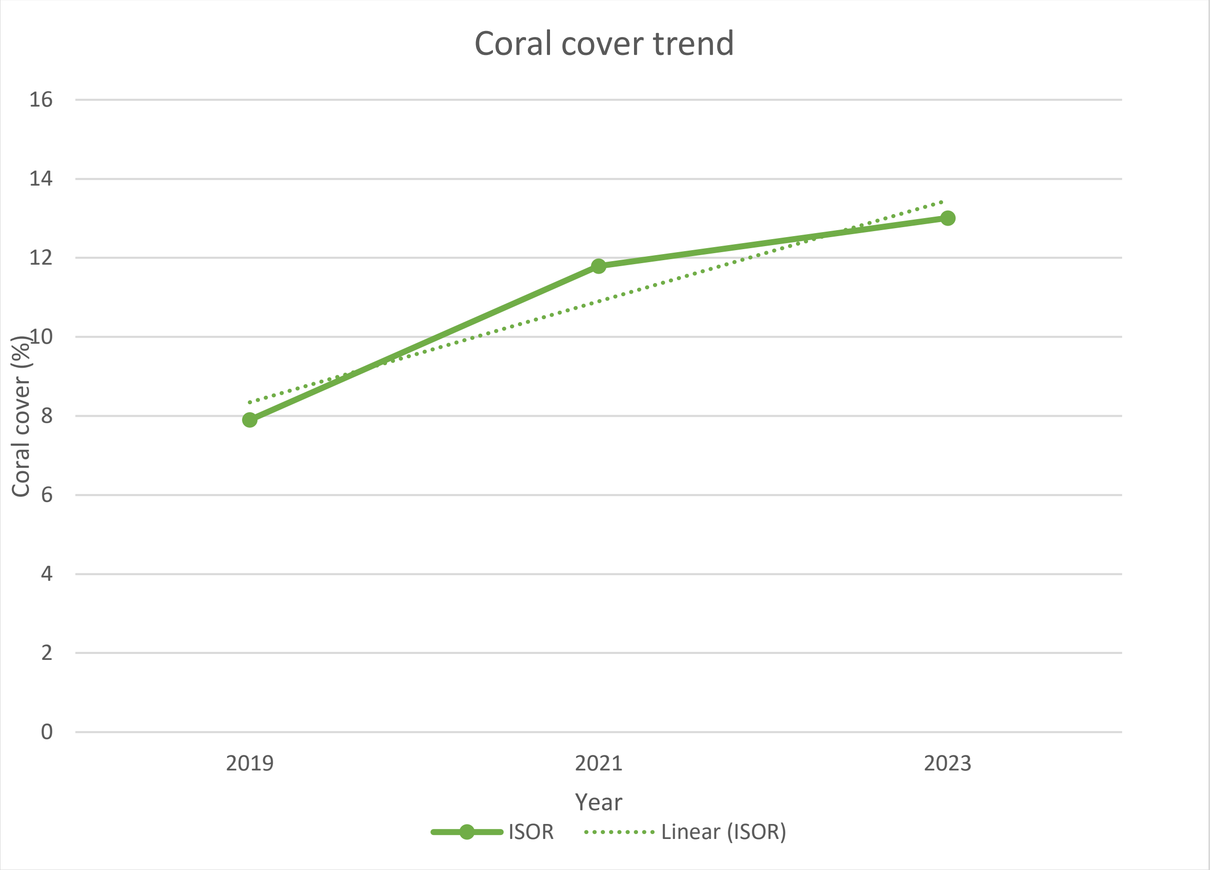


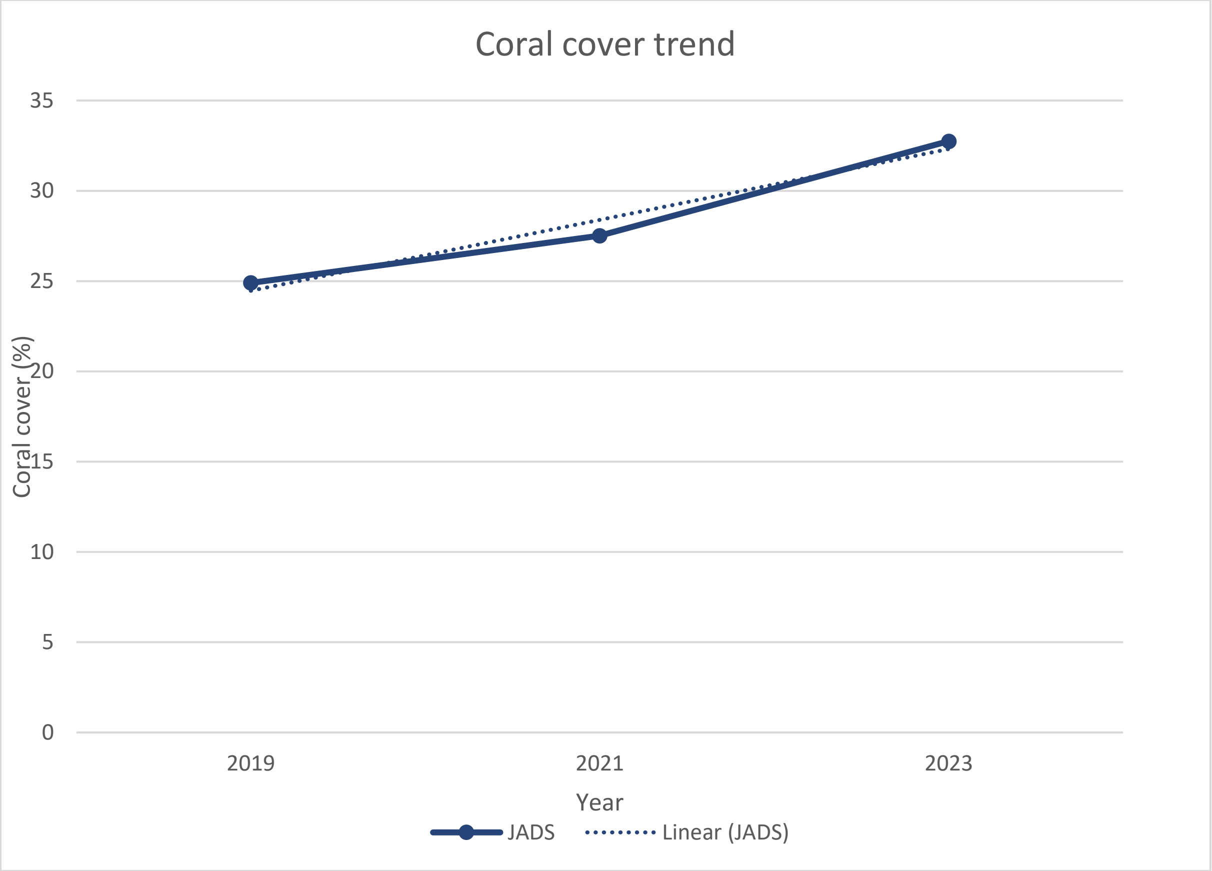

Coral cover trend
4,5
4
3,5
3
2,5
2
1,5
1
0,5
0
Coral cover (%)
2019
2021
2023
Year
ARRE
Linear (ARRE)

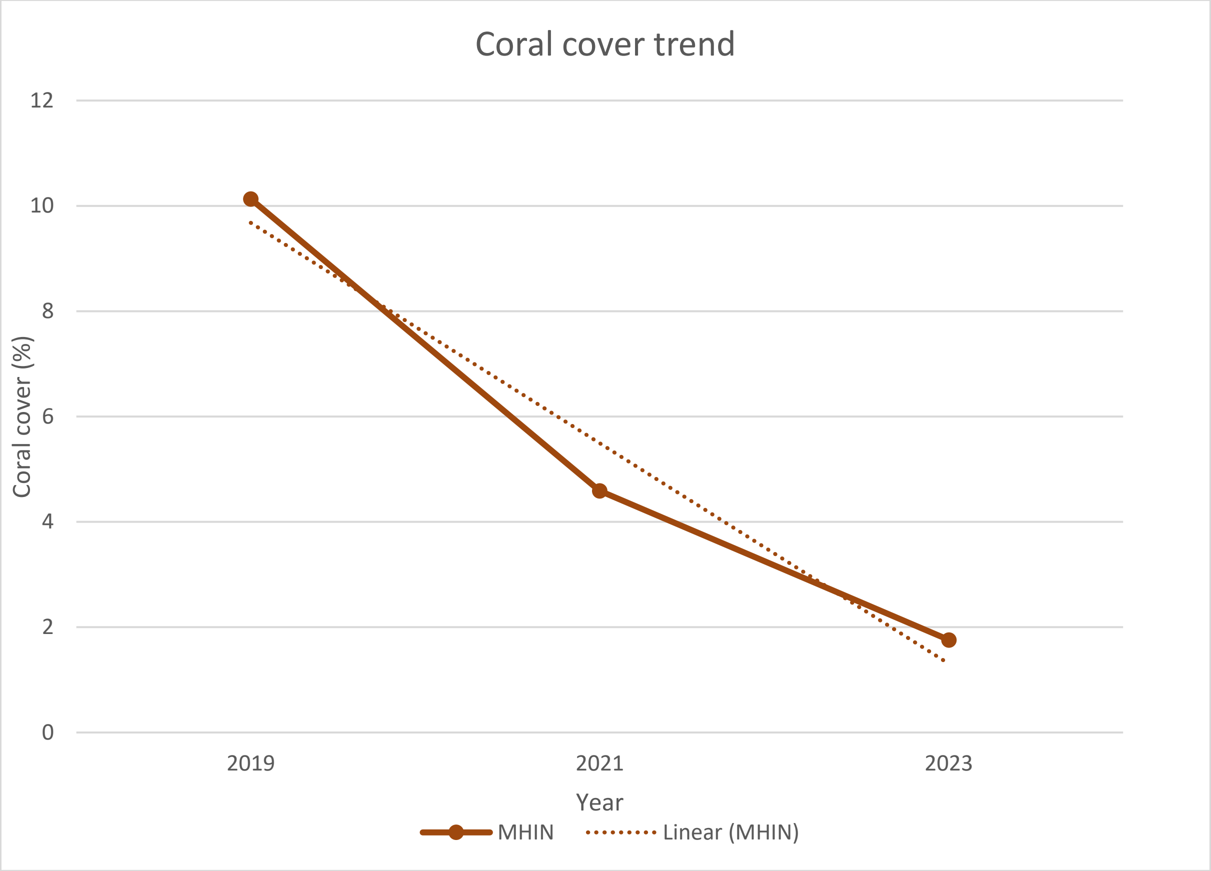

Coral cover trend
13
12,5
12
11,5
11
10,5
10
9,5
Coral cover (%)
2019
2021
2023
Year
BARE
Linear (BARE)

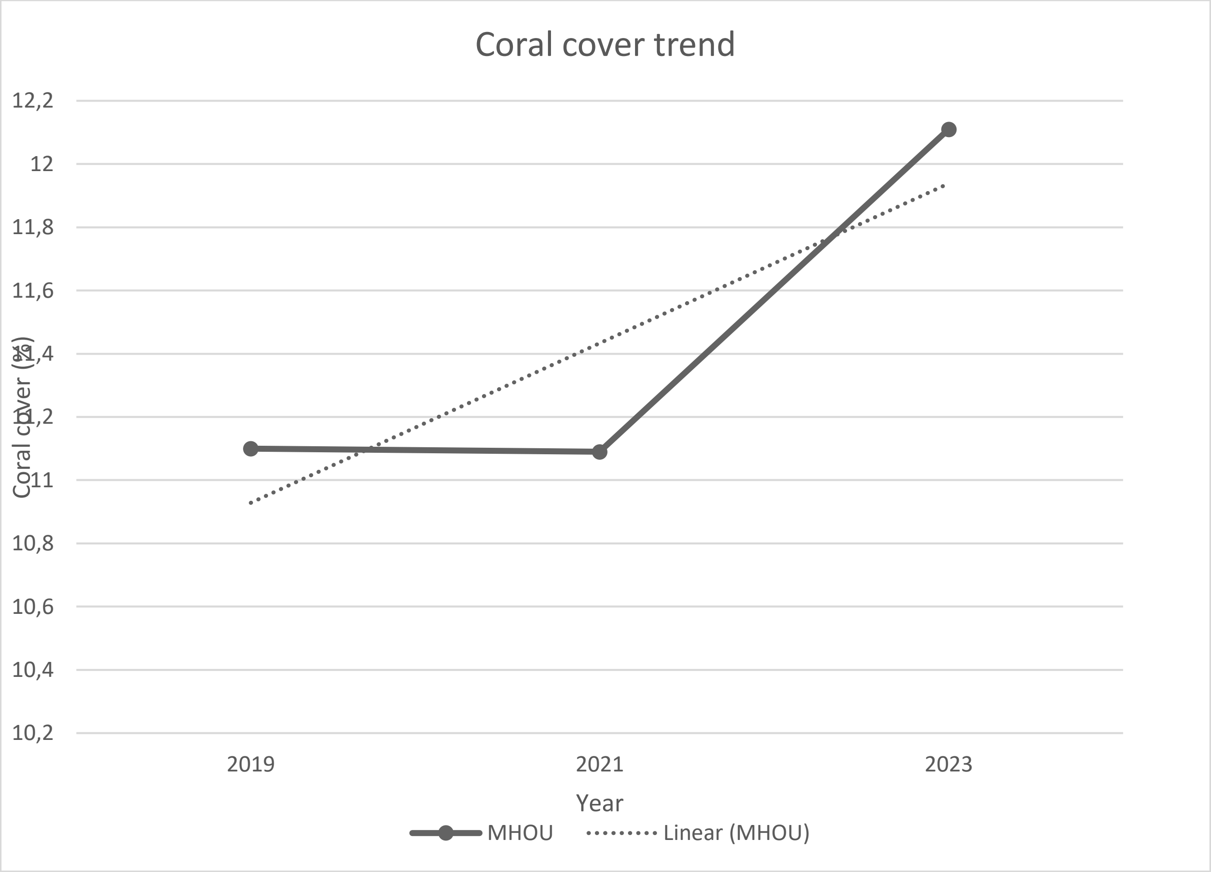

Coral cover trend
18
16
14
12
10
8
6
4
2
0
Coral cover (%)
2019
2021
2023
Year
HARE
Linear (HARE)

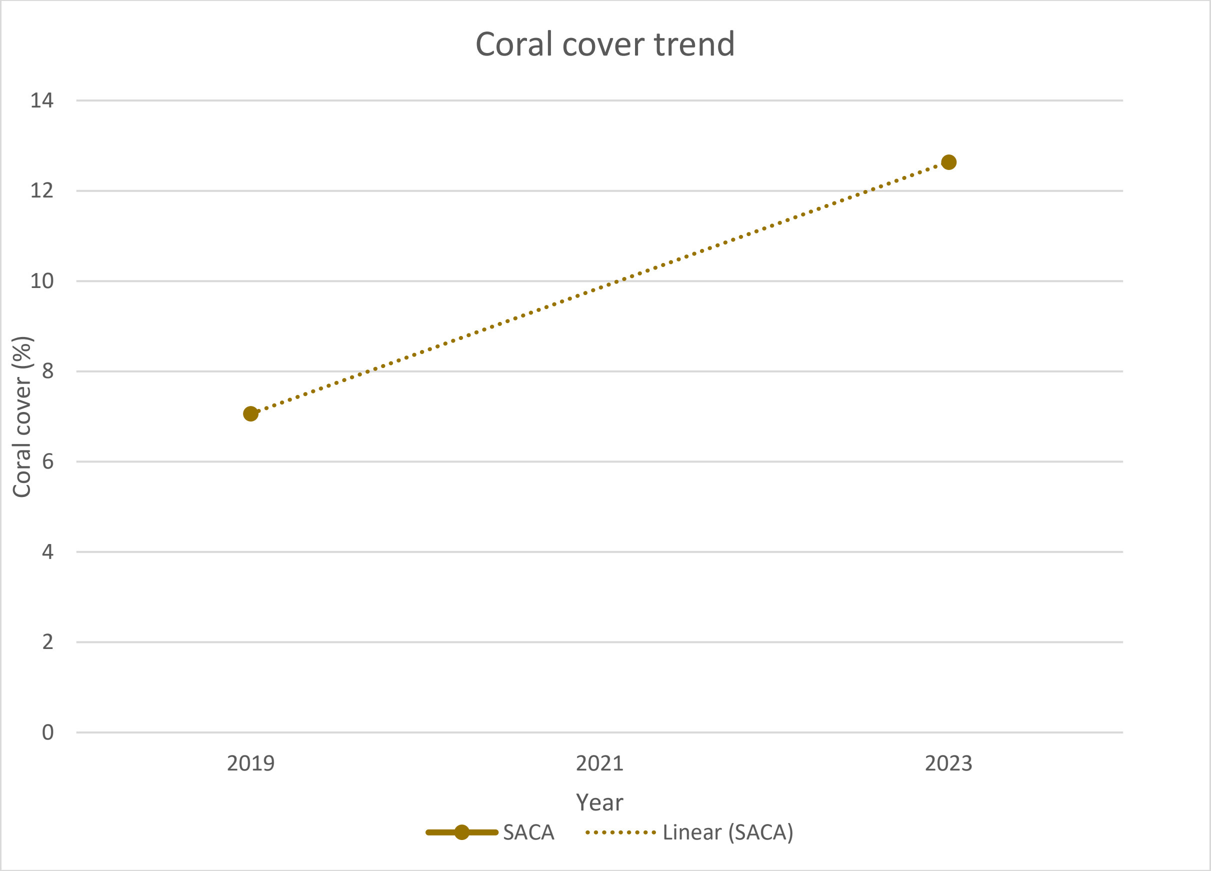

Coral cover trend
Coral cover (%)
12
10
8
6
4
2
0
2019
2021
2023
Year
INHE
Linear (INHE)

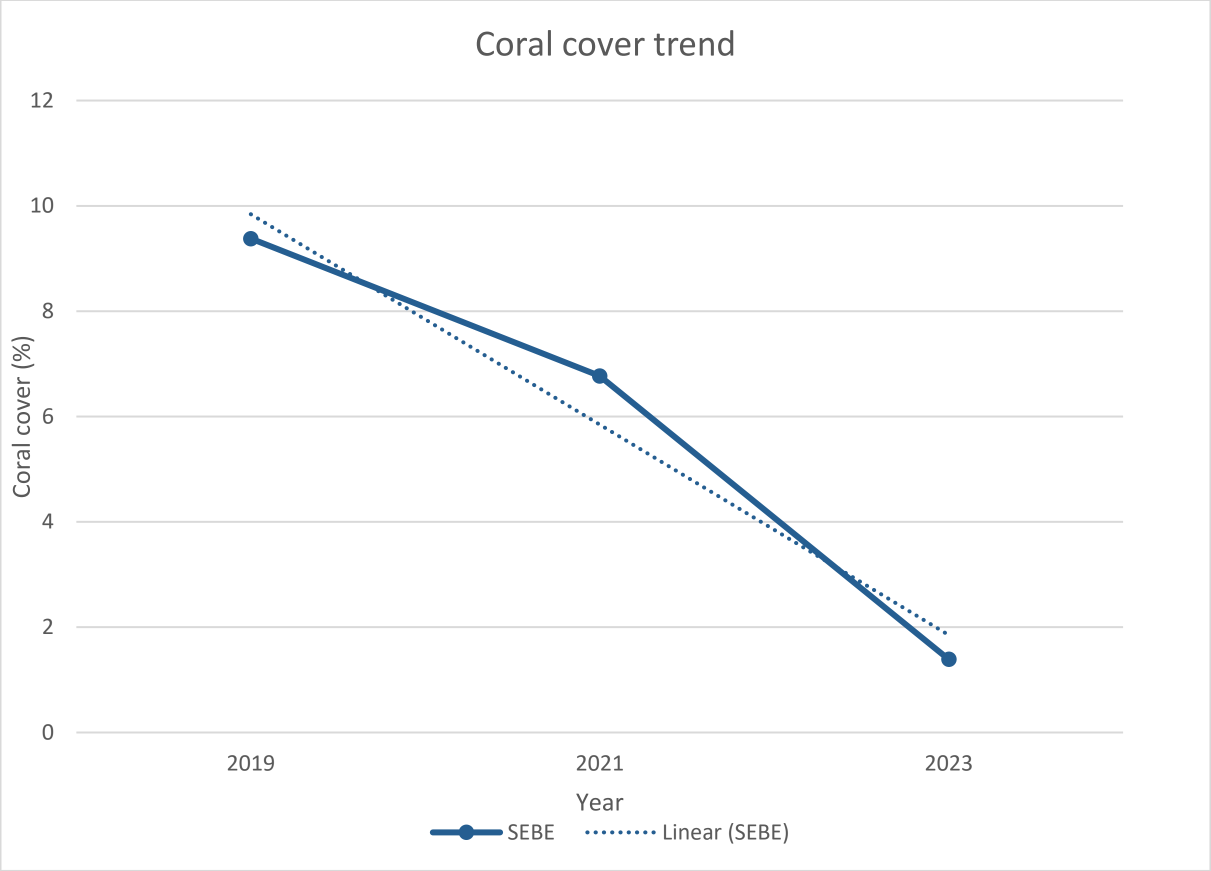

Coral cover trend
Coral cover (%)
16
14
12
10
8
6
4
2
0
2019
2021
2023
Year
ISOR
Linear (ISOR)

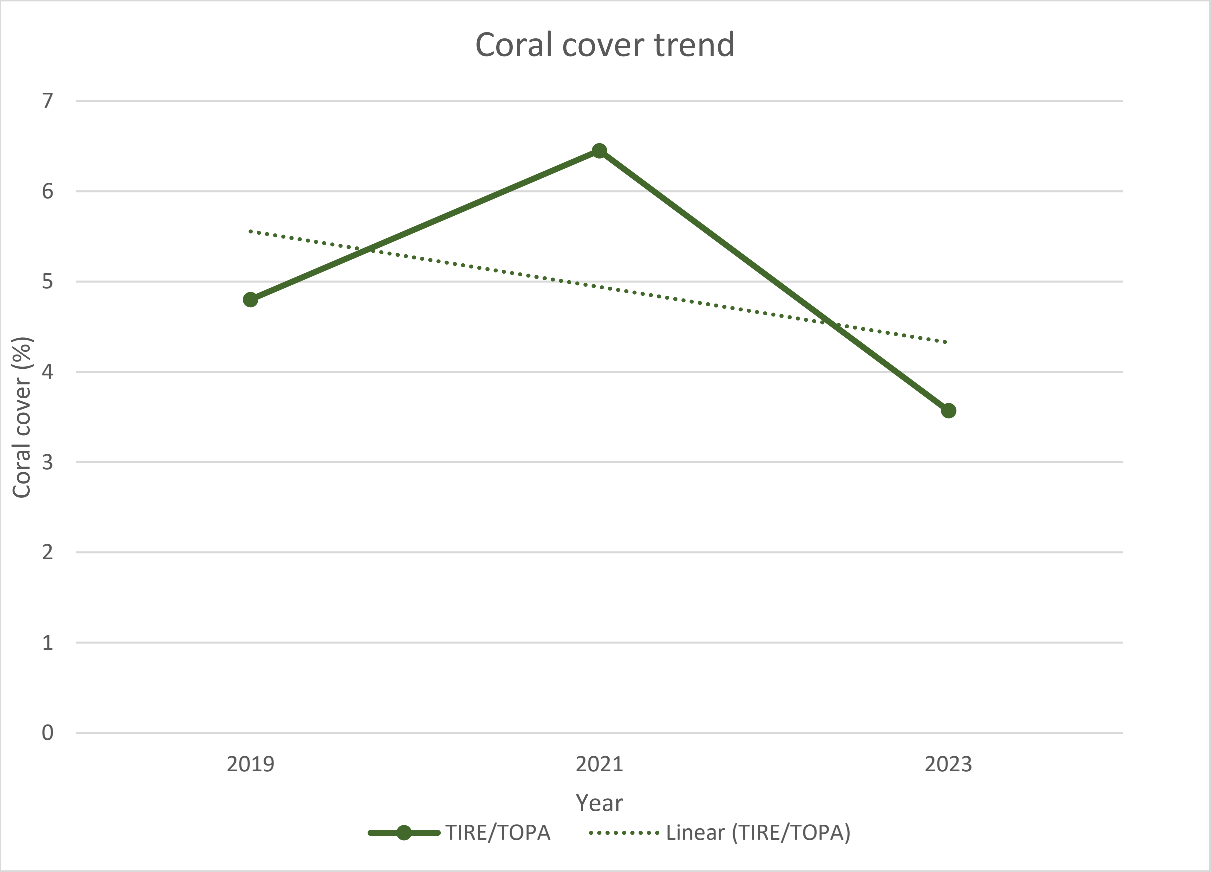

Coral cover trend
35
30
25
20
15
10
5
0
Coral cover (%)
2019
2021
2023
Year
JADS
Linear (JADS)

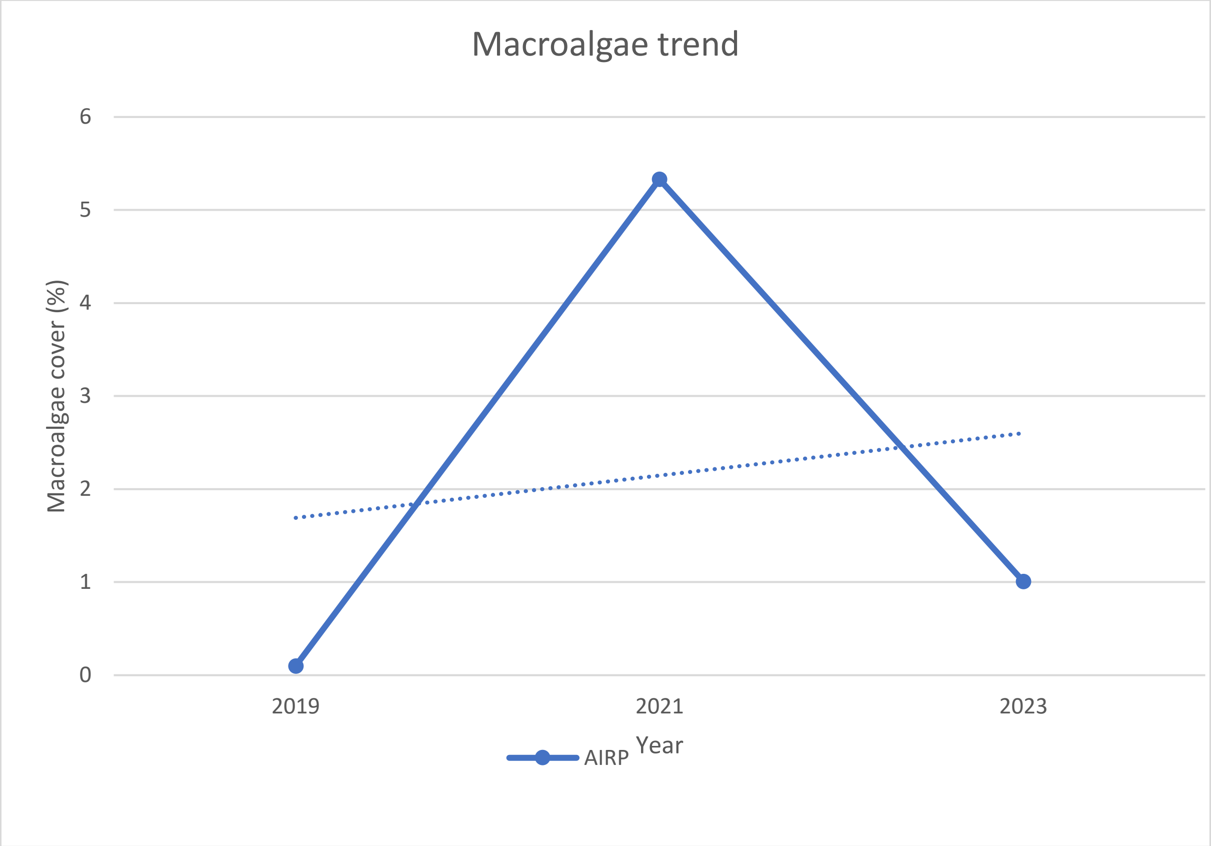

Coral cover trend
Coral cover (%)
12
10
8
6
4
2
0
2019
2021
2023
Year
MHIN
Linear (MHIN)

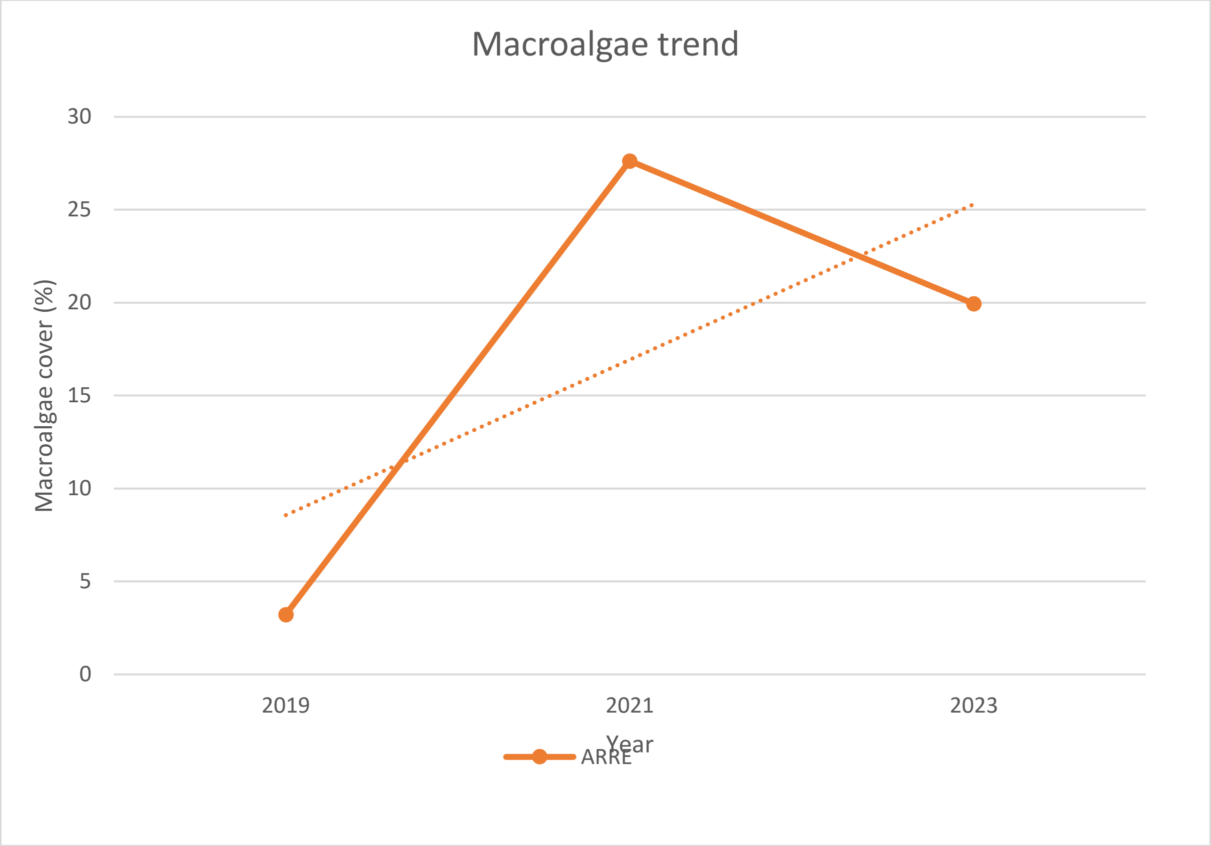

Coral cover trend
Coral cover (%)
12,2
12
11,8
11,6
11,4
11,2
11
10,8
10,6
10,4
10,2
2019
2021
2023
Year
MHOU
Linear (MHOU)

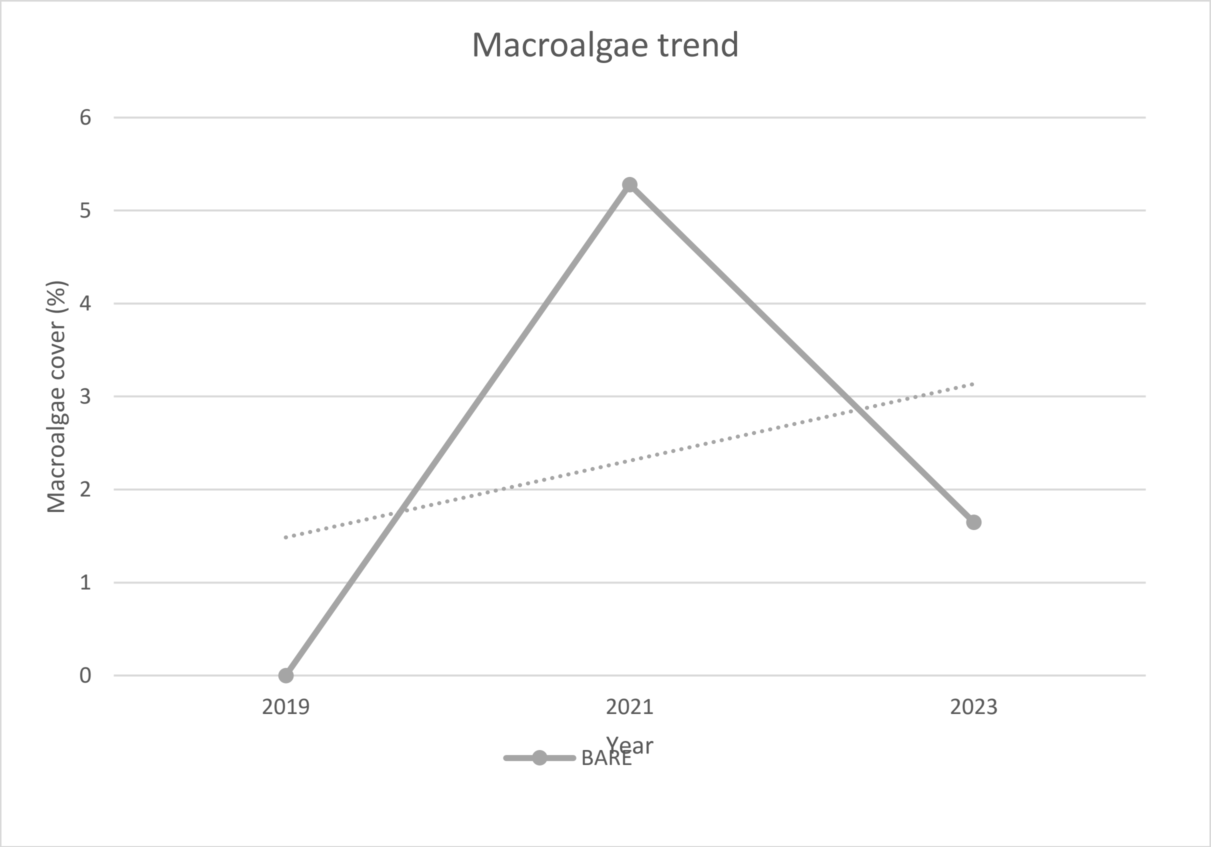

Coral cover trend
Coral cover (%)
14
12
10
8
6
4
2
0
2019
2021
2023
Year
SACA
Linear (SACA)

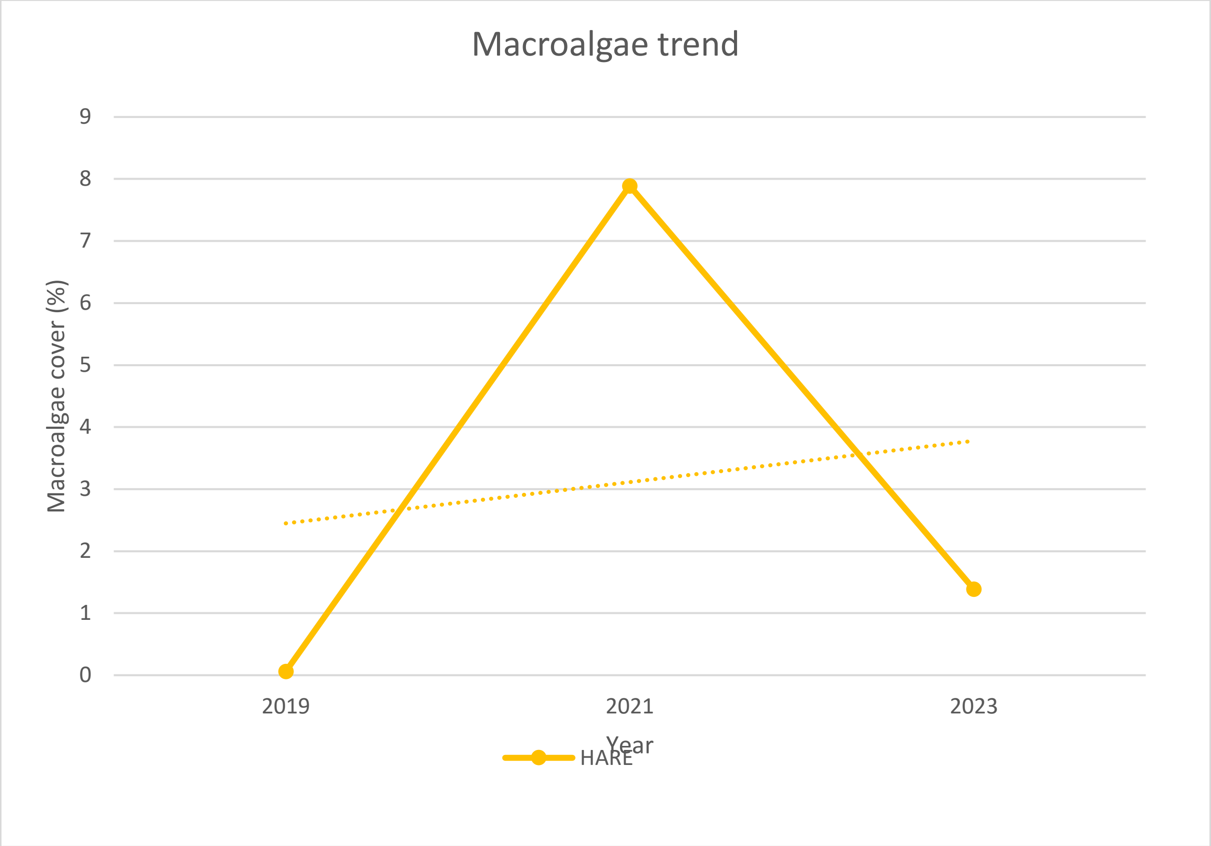

Coral cover trend
12
10
8
6
4
2
0
Coral cover (%)
2019
2021
2023
Year
SEBE
Linear (SEBE)

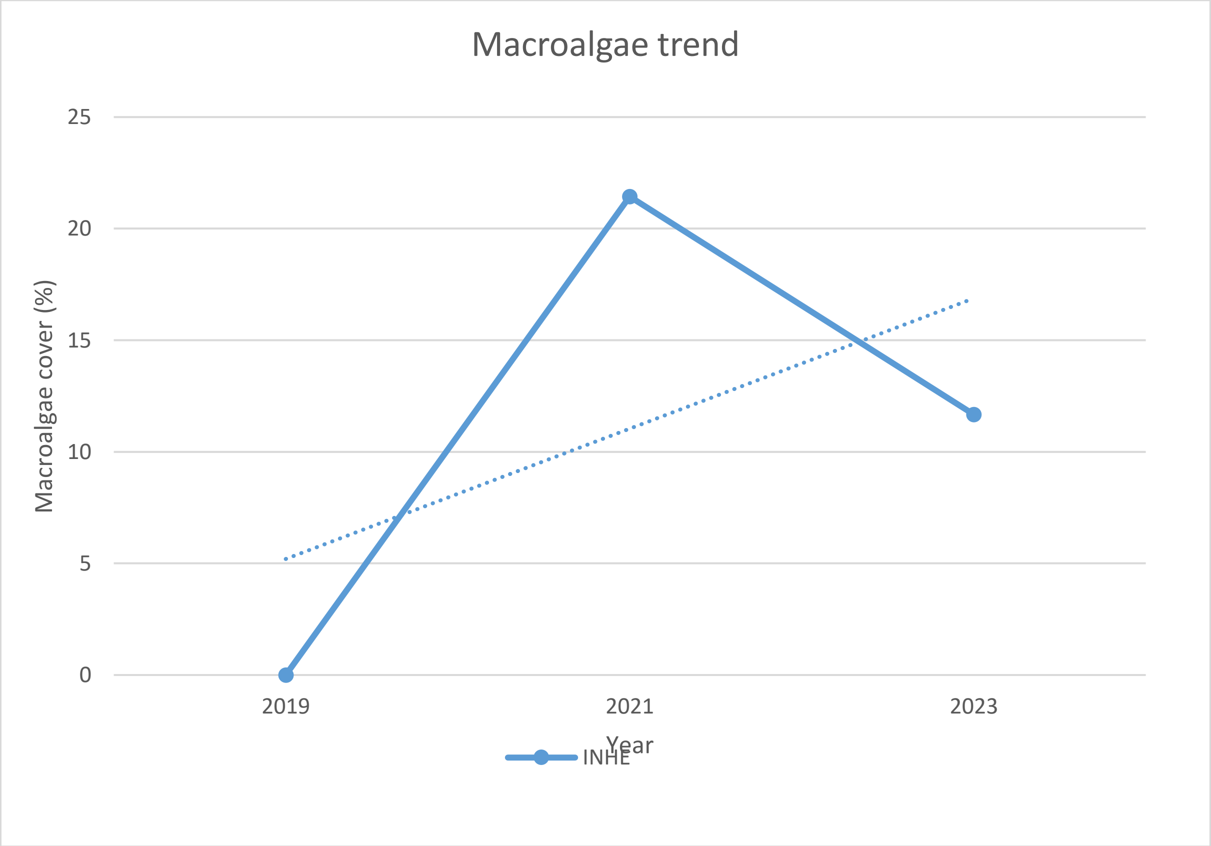

Coral cover trend
7
6
5
4
3
2
1
0
Coral cover (%)
2019
2021
2023
Year
TIRE/TOPA
Linear (TIRE/TOPA)

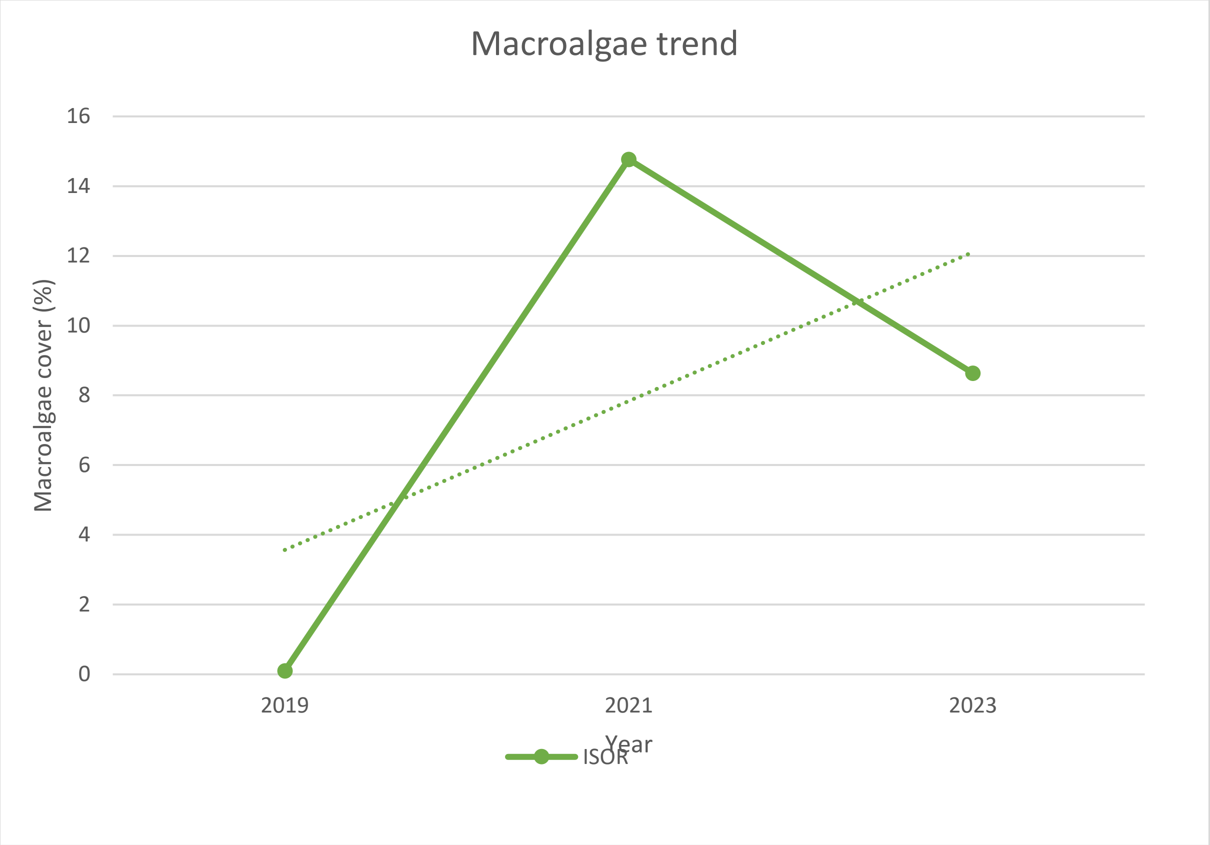

Macroalgae trend
Macroalgae cover (%)
6
5
4
3
2
1
0
2019
2021
2023
Year
AIRP

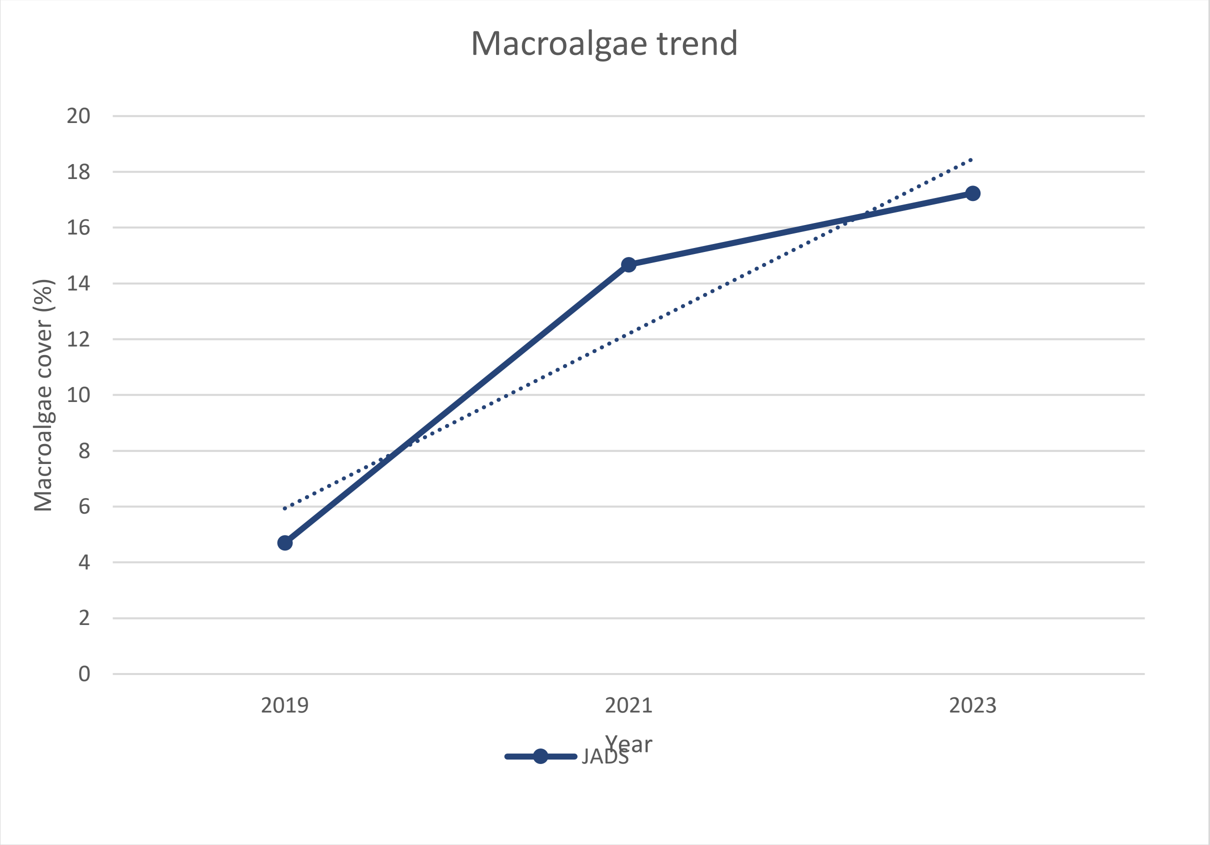

Macroalgae trend
Macroalgae cover (%)
30
25
20
15
10
5
0
2019
2021
2023
Year
ARRE

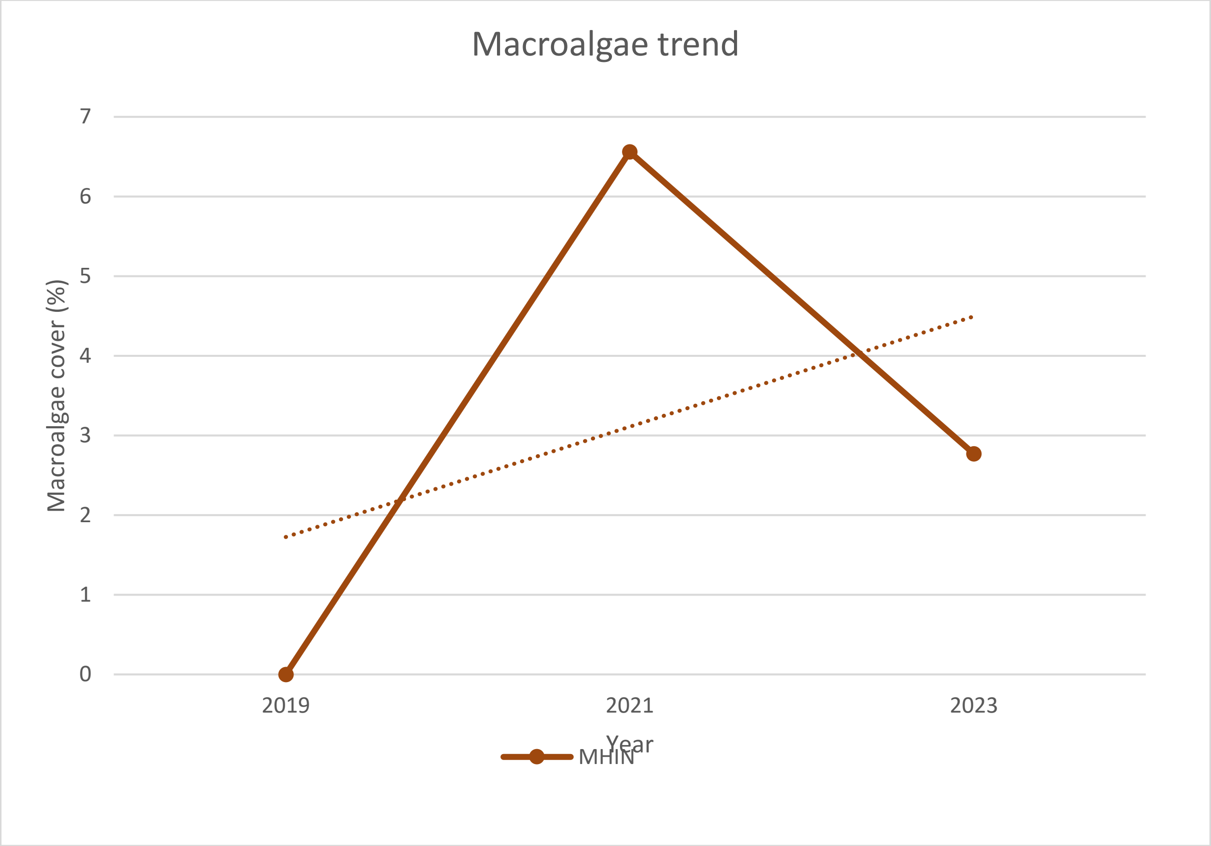

Macroalgae trend
Macroalgae cover (%)
6
5
4
3
2
1
0
2019
2021
2023
Year
BARE

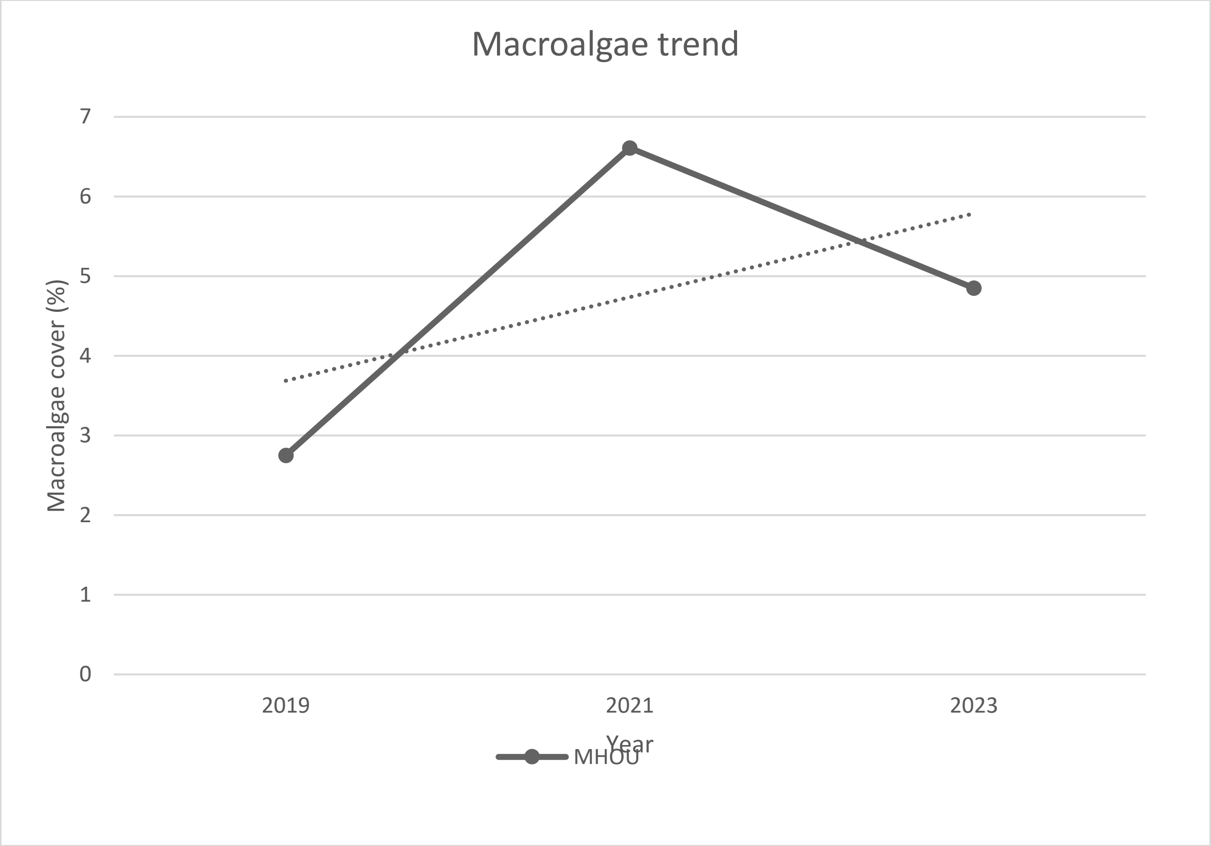

Macroalgae trend
Macroalgae cover (%)
9
8
7
6
5
4
3
2
1
0
2019
2021
2023
Year
HARE

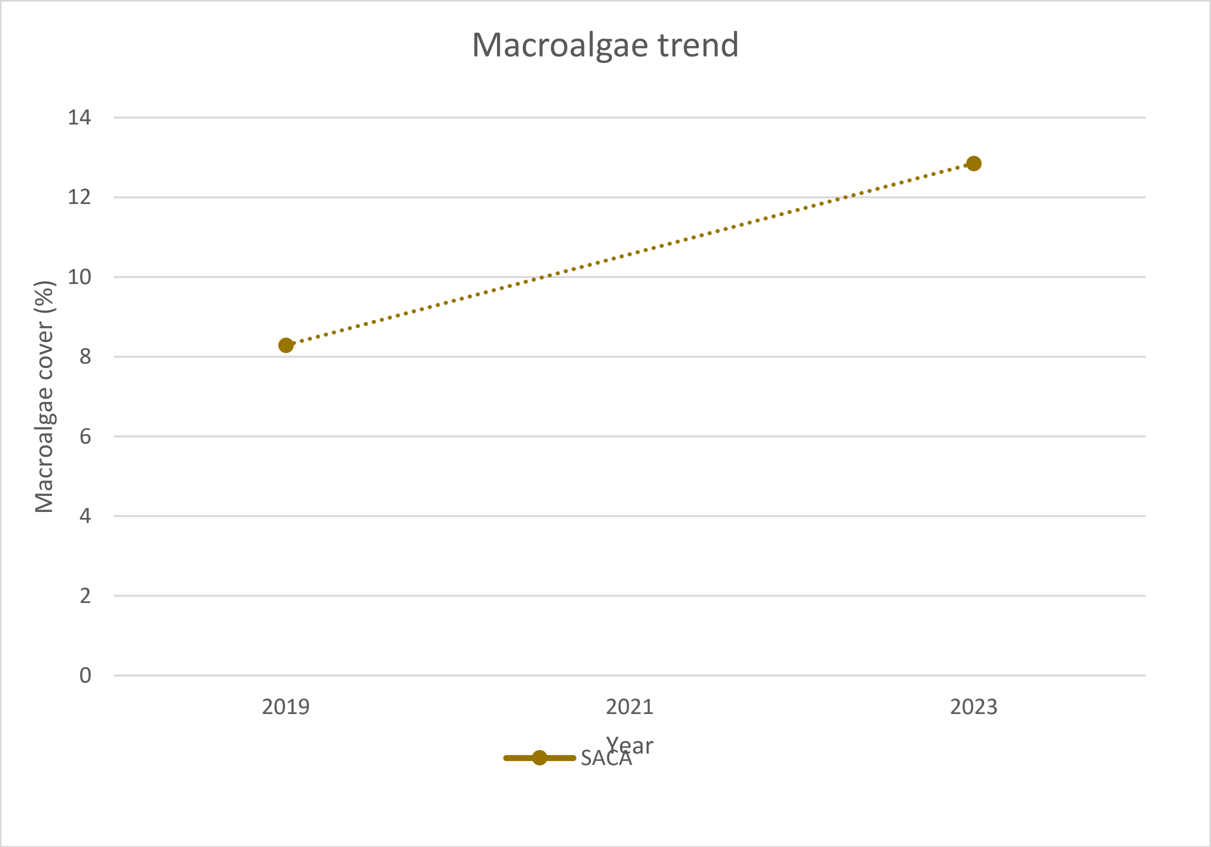

Macroalgae trend
Macroalgae cover (%)
25
20
15
10
5
0
2019
2021
2023
Year
INHE

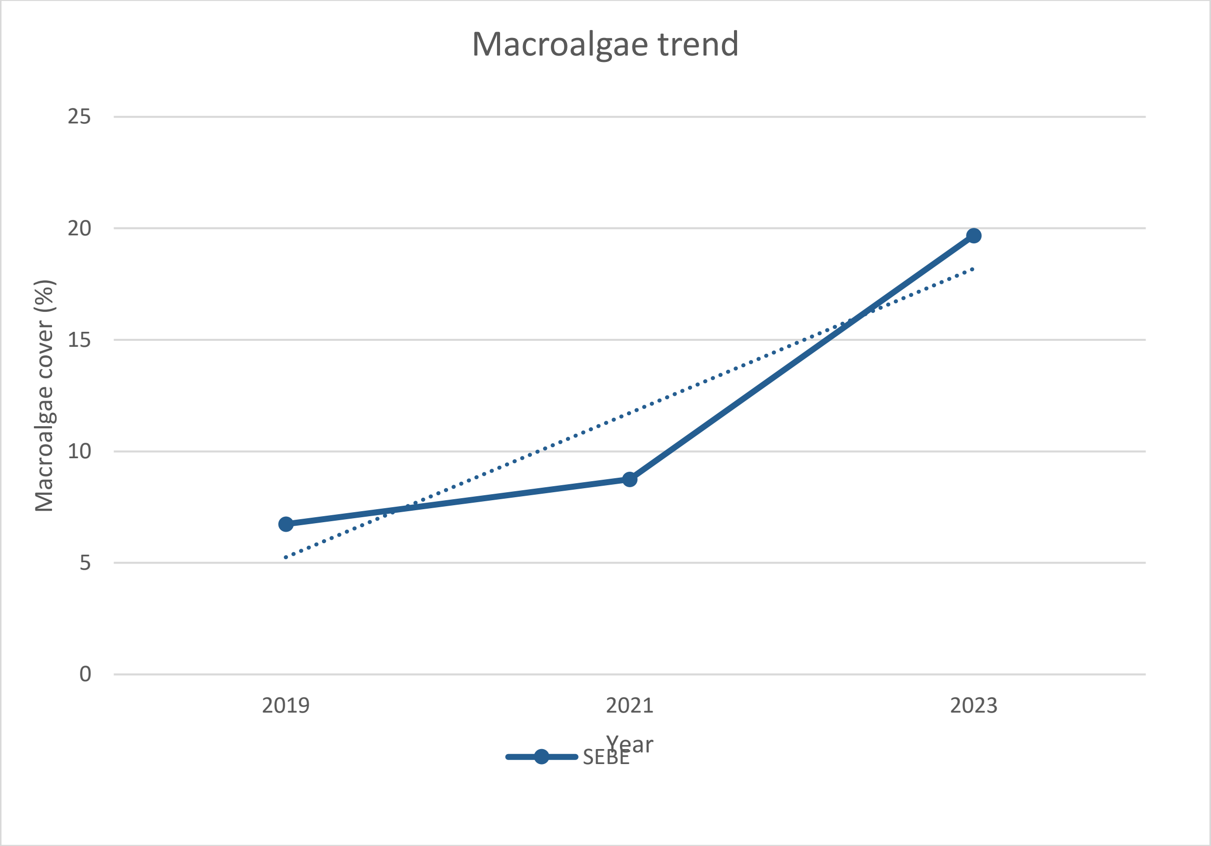

Macroalgae trend
Macroalgae cover (%)
16
14
12
10
8
6
4
2
0
2019
2021
2023
Year
ISOR


Macroalgae trend
Macroalgae cover (%)
20
18
16
14
12
10
8
6
4
2
0
2019
2021
2023
Year
JADS

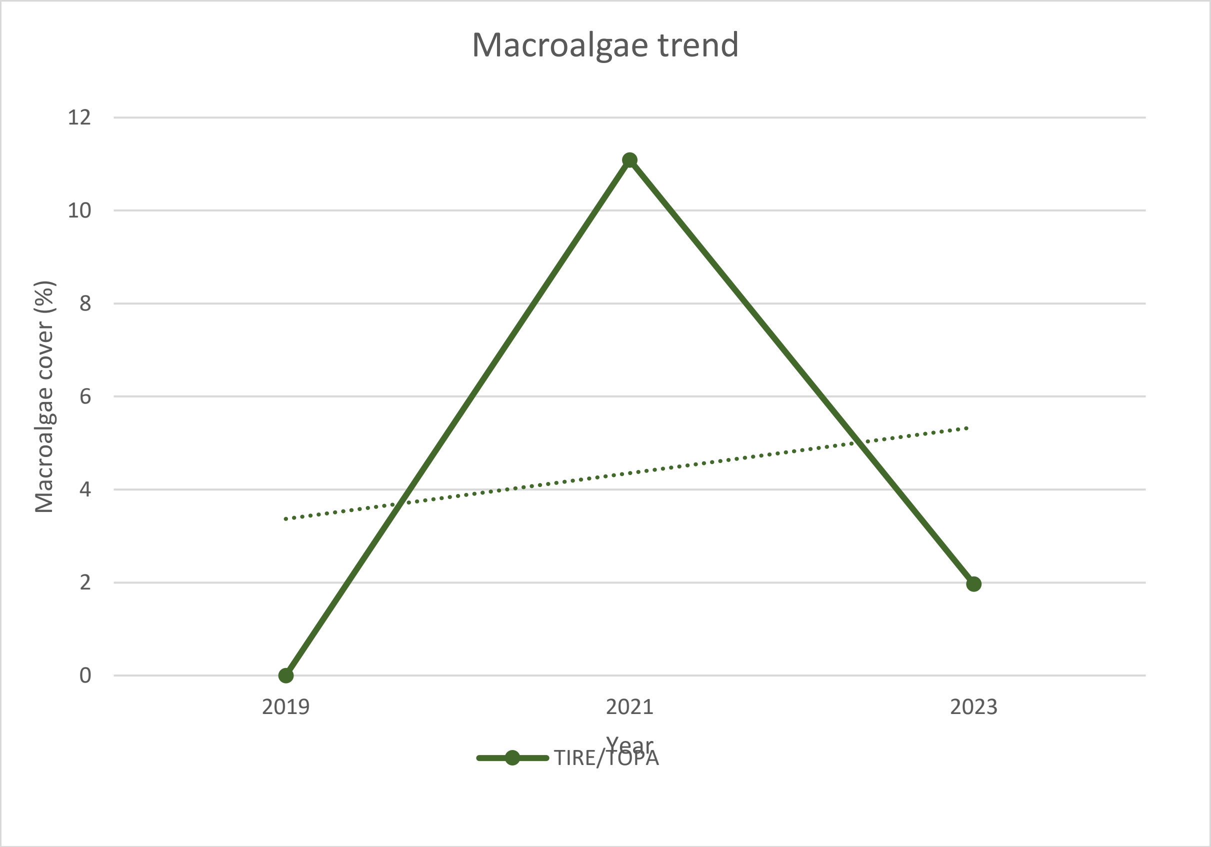

Macroalgae trend
Macroalgae cover (%)
7
6
5
4
3
2
1
0
2019
2021
2023
Year
MHIN


Macroalgae trend
Macroalgae cover (%)
7
6
5
4
3
2
1
0
2019
2021
2023
Year
MHOU


Macroalgae trend
Macroalgae cover (%)
14
12
10
8
6
4
2
0
2019
2021
2023
Year
SACA



Macroalgae trend
Macroalgae cover (%)
25
20
15
10
5
0
2019
2021
2023
Year
SEBE



Macroalgae trend
Macroalgae cover (%)
12
10
8
6
4
2
0
2019
2021
2023
Year
TIRE/TOPA