STATUS AND TRENDS OF HARD CORAL COVER DERIVED FROM LONG-TERM MONITORING SITES IN THE MALDIVES: 1998 – 2021

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FOREWORD

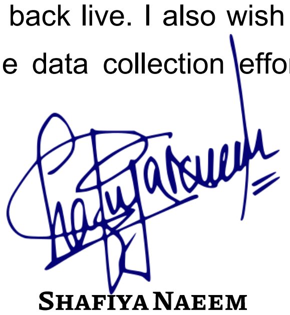
A National Coral Reef Monitoring Program was established in the Maldives after the first reported mass coral bleaching event of 1998, with the aim of collecting long term nationwide data on the status of the Maldivian coral reefs. Live coral cover after the bleaching impact dropped to as low as 1%, a stark contrast from the previous records of close to 50% mean live coral cover. Global warming has resulted in increased frequency and intensity of bleaching events impacting the potential for reefs to recover between these disturbances. Understanding the impacts of these natural events on our reefs is vital in the face of climate change affecting coral reefs globally, especially for small island nations like Maldives that depend entirely on the functions of healthy reef systems for their sustenance and economy.

Given the wide geographical spread of the country, data collection on coral reefs that is representative of the nation is challenging without contributions from partners across the country. The National Coral Reef Monitoring Program originally covered 16 sites across 6 atolls. With the need to expand the coverage of monitoring sites, a total of 31 long-term monitoring sites have been established to date in 10 atolls as seen from this report. In order to coordinate the coral reef monitoring efforts across the country by various parties, both government and private, a Coral Database was launched in 2016 and is now being upgraded with user feedback to make this a more useful platform for contributors.

A major caveat in this current report is that the status of the monitoring sites records only an estimate of hard coral cover, with no real means to account for the community variations within the reefs. The composition of hard coral cover, along with other environmental variables are important factors to consider when an interpretation of the overall reef health is made. We are now working toward a more holistic set of protocols, with the reef composition already integrated within our long-term monitoring program.

I would like to commend the staff of the Institute who have contributed to collecting the largest national set of coral reef data over the past 23 years, and the work carried out by the Author that resulted in this detailed trend analysis. The results presented here show an optimistic outlook with regards to the recovery trends seen in the overall coral cover, however more insight into community shifts and establishing connections with other environmental parameters is needed to make any inference on the health of the Maldivian coral reefs.

I wish to express my desire for coordination between environmental NGOs, Government organizations, private interest groups and individuals engaging in coral reef monitoring, toward compiling a national repository of reef health information through the Coral Database when it comes back live. I also wish to express my gratitude to the parties who have already been contributing to the data collection efforts initiated by the Maldives Marine Research Institute.



Shafiya Naeem

Director General

EXECUTIVE SUMMARY

Much like other reefs in the world, the 1998 mass bleaching event devastated the reefs of the Maldives with coral cover declining to an average of 2% across the country. In response to this event, the National Coral Reef Monitoring program, a program that carries out systematic long-term monitoring of designated reefs in the Maldives, was established. Repetitive monitoring of these site by the program has resulted in one of the longest coral datasets in the region which provides an insight into reef recovery after stressors like mass bleaching events.

This report compiles the data collected by the National Coral Reef Monitoring program at long-term monitoring sites between 1998 and 2021 to investigate the coral cover trends. The report aims to assess the overall trends in national hard coral cover, investigate effect of management regimes and depths, ascertain differences in regional trends, and explore the state of the long-term monitoring sites to better understand the impact of various stressors on Maldivian reefs.

Since the end of 2021, a total of 31 long-term monitoring sites have been established in 10 regions across the Maldives. Of these sites, 16 sites were established in 1998, 12 were established in 2011, and an additional 3 sites were established in 2021. Sites are attributed to clusters located within administrative atolls called “regions” and to one of three management regimes: community, resort and uninhabited. Data was collected from two depth categories, shallow (1-6 m) and deep (6-12 m), during surveys. Due to technical limitations during the late 1990s and early 2000s, the deep reef data is limited compared to the shallow reef data.

Coral cover data were investigated using Bayesian hierarchical generalized mixed models to derive temporal trends using three different analyses. The first was a broad scale model assessing the overall coral cover trend of the country. The second assessed the effect of management and depth on coral cover trajectories, and the third assessed the effect of regions on trends of coral trajectories. The three models were similarly structured; however, the third model did not include management regime. Of the three models, the regional model was the model most effective at explaining the variation in the trends of coral cover. This was followed by the management and depth model and finally by the broadscale model.

Trends derived from the broadscale overall model showed signals which closely matched stress events including minor and major bleaching. While national coral cover declined after each of these events, the scale of decline differed. In general, reefs showed a capacity for recovery on a national scale.

Comparison of regional trends revealed notable similarities and differences across regions. Haa Dhaal, Kaafu, Ari and Vaavu showed similar trends of coral cover over the 23-year period with similar overall positive recovery and a peak just before the 2016 bleaching event. On the other hand, Addu had a distinctly different trend with a peak shortly after the 1998 event followed by an overall decline before fluctuating around 20% coral cover.

Addu was also less affected by the 2016 bleaching event with coral cover declining less than all other regions with the exception of Vaavu. Vaavu suffered a similar restricted decline after the 2016 mass bleaching event and coral cover has remained high overall. Both of these regions are already showing signs of recovery with coral cover beginning to increase since 2016.

Site level analysis showed that there was intra-regional variability with some sites showing notable differences from their counterparts. The recovery trend in Vaavu after the 2016 event appeared to be strongly driven by a single site, Fohtheyo. This site suffered minimal coral cover loss and also appeared to be one of the most resilient reefs of all the long-term monitoring sites. Similarly, addition of new long-term monitoring sites to the Haa Dhaal region strengthened the recovery signal driven by Hondaafushi, a 1998 long-term monitoring site, after the 2016 bleaching event as coral cover of all these new sites were higher than the coral cover of the old long-term monitoring sites.

Trends driven by management regime and depth categories were also derived from the models. While these trends did differ between management regimes, they were relatively similar between depth categories. Resort and community reefs showed more similar trends than uninhabited reefs. Whilst there was fluctuation in the recovery of community and resort reefs, the recovery was mostly positive in uninhabited reefs. This was marked by a notably higher maximum coral reef cover post recovery in both deep and shallow reefs as compared to the other two regimes.

The results of this assessment highlight the usefulness of repetitive sampling of long-term monitoring sites when tracking the impact and recovery of stress events. It provides an increased confidence that coral reefs of the Maldives are able to resist and recover from smaller, localized stressors while being impacted by major, global stressors. However, the report only focused on total hard coral cover – a single facet of the coral reef system, its health, recovery, and resilience.

Whilst the results are optimistic, the effects of inter and intra-regional variability along with potential effects of management regimes and depth, highlight the need to expand data collection efforts to capture the variability more rigorously. With the cultural and socio-economic dependency of Maldivians on the coral reefs, capturing and accounting for such variability may mean the difference between sustainable and unsustainable utilization of reef resources.

With limited resources and capacity, capturing such variability may be difficult, but it is possible to identify priority areas. This includes the strengthening of citizen science for data collection, improving intersectoral and sub sectoral cooperation, collection of environmental parameters, and increasing the number of long-term monitoring sites both across and within regions.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS……..…………..…………..…………..…………..……....5

FOREWORD………….…………………..…………..…………..………..……...6

EXECUTIVE SUMMARY………………...…………...…………...……….....……...7

TABLE OF CONTENTS……………….…………..…………...…………....……..9

LIST OF FIGURES…..………..…………...…………...…………....………….…...11

LIST OF TABLES…………………………..…………..…………...………......…..12

INTRODUCTION……….…………………..…………..…………...…………..…...13

MATERIALS AND METHODS…………….…………..…………...…………......16

Definitions………………………………………………………………….…………..…....**17**

Sites……………………........……………………………………………………...................**17**

NCRM and MEMP overview………………………………………………………......**17**

Management regimes………………………………………………………….........**19**

Survey continuity………..........................……………………………………………......**20**

Survey methods……………………………….....................…………………………....**20**

Analysis……………………………………………………………………………....................**20**

Data cleaning and structure………...……………………………………………….......**20**

Trend analysis………..................………………………….……………………….........**21**

Site level analysis…………………….………………………………………………..………**21**

RESULTS……..................………………..…………..………………….....................22
Data exploration…………………………………………………………………………......23
Model results……………........…………………………………………………...............24
Overall national coral cover trend………………………………………………….........25
Regional trends and site specifics…………………………………………………………26
Regional comparison……………....………………………………………………….......26
Haa Dhaal………………………..…………………………………………………..........30
Noonu…………………………..………..……………………………………………......31
Raa……………………………………..………………………………...……………..32
Baa………………………………………………………………………………..…..33
Lhaviyani………………………………..…………………………..…………………......34
Kaafu…………………………………..…………………………………………..…..35
Ari………………………………..……………………………...………………………....36
Vaavu…………………………..…………………………………………………..........37
Gaaf Alif…………………………..……………………………………...………………..38
Addu……………………………..………………………………………..……………….39
National coral cover trend by management regime and depth category……..............................40

DISCUSSION………………...………….....………………...…………...……………..…43

CONCLUSION………………...…………….....……………………………......................49

RECOMMENDATIONS……………...………………...………………………………........51

REFERENCES ………………...………………...…………………………………………..54

APPENDIX…………………………....……………………....……………………………......58

LIST OF FIGURES

Figure 1. Long-term monitoring sites throughout the Maldives. The location of each site in each administrative atoll and the year of establishment are shown in each inset. Blue represents sites established in 1998, purple represent sites established in 2011, and red represent sites established in 2021………18

Figure 2. Histogram of proportion of coral cover at shallow (purple) and deep (yellow) reefs from Long-term Monitoring sites. The dotted line represents the median of the shallow and deep reef coral cover data…..……………………………………………………………………………………………..23

Figure 3. National coral cover trend derived from Long-term monitoring sites from 1998 to 2021. Solid lined arrows indicated years with major or minor bleaching events. The broken lined arrows indicate the year during which the tsunami occurred…………………………………………………………………25

Figure 4. Regional trends in hard coral cover of (A) Haa Dhaal, (B) Ari, (C) Kaafu, (D) Vaavu and (E) Addu from 1998 to 2021 derived from LTM sites within the regions. All five regions had LTM sites established in 1998……………………………………………………………………………………………28

Figure 5. Regional trends in hard coral cover of (A) Raa, (B) Noonu, (C) Baa and (D) Lhaviyani from 2011 to 2016 derived from LTM sites within these regions. The LTM sites for these regions were established in 2011……………………………………………………………………………………………29

Figure 6. Mean hard coral cover ± S.E of the long-term monitoring sites in Haa Dhaal. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented…………………..…….30

Figure 7. Mean hard coral cover ± S.E of the long-term monitoring sites in Noonu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.…………….…………31

Figure 8. Mean hard coral cover ± S.E of the long-term monitoring sites in Raa. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.……………………………...32

Figure 9. Mean hard coral cover ± S.E of the long-term monitoring sites in Baa. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.……………………………...33

Figure 10. Mean hard coral cover ± S.E of the long-term monitoring sites in Lhaviyani. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.……………………..34

Figure 11. Mean hard coral cover ± S.E of the long-term monitoring sites in Kaafu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.…………………..…...35

Figure 12. Mean hard coral cover ± S.E of the long-term monitoring sites in Ari. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.……………………………...36

Figure 13. Mean hard coral cover ± S.E of the long-term monitoring sites in Vaavu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented……………………...37

Figure 14. (A) Mean hard coral cover ± S.E of the long-term monitoring site in Gaaf Alif. The overall long-term mean (%) is also presented. (B) Hard coral cover trend of the site derived from the Bayesian Hierarchical Model ……………………………………………………………………..……………………38

Figure 15. Mean hard coral cover ± S.E of the long-term monitoring sites in Addu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented..……………………...39

Figure 16. National coral cover trend at community (pink), resort (purple), and uninhabited (blue) shallow (1-6m) and deep (6-12m) reefs in the Maldives from 1998 to 2021. Note the differing x axis scales for deep and shallow reefs as model range has been restricted to years with available data….41

LIST OF TABLES

Table 1. Model codes and comparison variables for coral cover trend models…………………………..24

Table 2. Specific details of the long-term monitoring sites established in the Maldives as part of the NCRM program. List of sites are accurate up to end of 2021. Management regimes are accurate up to the last sampling date used for analysis……………………………………………………………………58

INTRODUCTION

Climate change driven increases in sea surface temperatures and intensifying El Niño–Southern Oscillation episodes are leading to an increase in the frequency and severity of bleaching events across the world whereby reefs are likely degrade rapidly over the coming decades (Hoegh-Guldberg et al., 2017; Hughes, Anderson, et al., 2018). As the recovery interval of coral reefs continues to decrease with a simultaneous increase in the frequency of these events it is unlikely that reefs are able to return to their "original" state (Hughes et al., 2017). Transformations into different states in terms of coral cover, coral reef assemblages or a combination of both are likely (Hughes, Kerry, et al., 2018). Such transformations are complex, particularly on a regional or a local scale, because impacts of global stressors on coral reefs can be exacerbated or mitigated by local stressors and management approaches (Kennedy et al., 2013).

With an estimated 4495 km^2 of reef area, the 25 geographic atolls of the Maldives is comprised of 16 complex atolls, 5 oceanic faros, and 4 oceanic platform reefs (Naseer & Hatcher, 2004). Host to over 248 coral species from 57 genera (Pichon & Benzoni, 2007) and a multitude of reef fish species, the reefs of the Maldives are the most diverse in the region (Rajasuriya et al., 2002). These reefs provide an array of social, economic and ecosystem services to locals dependent upon them including tourism, fisheries, shore protection, coastal mitigation and cultural benefits (Agardy et al., 2017). Moreover, like reefs across the world, the reefs of the Maldives have been affected by and continue to be affected by the impacts of climate change and escalating anthropogenic pressure.

The 1998 bleaching event was not the first recorded bleaching event in the Maldives (Wood, 1987 cited in Zahir et al., 2010), but it was the first that was recorded to have devastating effects nationwide. Similar to other coral reefs in the Indian Ocean (Wilkinson et al., 1999), coral cover in the Maldives declined to 2% mean coral cover (Edwards et al., 2001) with coral-algal phase shifts being reported (McClanahan, 2000) as a result of this event.

By 2015, reefs had eventually reached a state where they were considered to have recovered (Morri et al., 2015; Pisapia et al., 2016), even though recovery was hindered by minor bleaching events and the 2004 tsunami event (Goffredo et al., 2007), and further aggravated by anthropogenic stressors related to various coastal development efforts. Any further recovery from the 1998 mass bleaching event was halted by the 2016 mass bleaching event.

Over 70% of the corals across various reefs in the Maldives bleached with a variety of coral genera affected, albeit to varying severity (Ibrahim et al., 2017).

Unexpectedly, reefs surveyed at depths of 10 m fared worse than reefs surveyed at 5 m during the 2016 event (Ibrahim et al., 2017). However, there can be other stressors that can complicate these trends including the use of reefs nearby. Differing management of reefs, closely associated with the use of the island and/or the reef, has meant that its capacity of resilience and recovery is variable (Jaleel, 2013). Numerous studies in the Maldives have investigated the impact of human pressure on various aspects of reef resilience and recovery with conflicting results: e.g., resorts offering a haven to facilitate reef recovery (Moritz et al., 2017) vs resorts having a negative impact on coral reef health (Cowburn et al., 2018). With such disparate results, perhaps dependent on the sampling of reefs that are simultaneously clustered and dispersed, there is a need to understand the drivers of such distinct differences to better conserve coral reef health, recovery, and resilience in the country.

In response to the mass bleaching event in 1998, systematic long-term monitoring of Maldivian reefs was initiated through the National Coral Reef Monitoring [NCRM] program. Now over 20 years old, the NCRM program has sites throughout the Maldives which have been repeatedly frequented resulting in one of the oldest and longest datasets in the region. Repetitive sampling of the same sites over time enables the assessment of potential impacts or variation in trends as a result of different types of drivers, stressors, or events. Hence, the overarching aim of this report is to investigate hard coral cover trends that can be derived from the long-term monitoring sites that have been established as part of the Maldives' NCRM program. This includes:

I. Generating and interpreting an overall hard coral cover trend for the country.
II. Investigating the effect of management regimes and depth on coral cover trends for the country
III. Constructing regional trends for hard coral cover
IV. Exploring regional and site level means over time
V. Discussing the implications of the results in the context of climate change, management regime, and its impact on the Maldives
VI. Proposing recommendations for reef monitoring based on the generated trends.

MATERIALS AND METHODS

Definitions

The following descriptor terms have been standardized for the data set and analysis.

Survey: represents a collection of transect replicates collected at a specified depth at a specified point in time

Station: represents a location on a reef or reef structure where surveys are carried out; the station and the site can be same where there is a single station on the reef structure.

Site: represents a reef or a pre-determined area of a reef structure where surveys are conducted; sites can have a singular station or multiple stations.

Region: represents a cluster of sites located within administrative atolls.

Depth category: refers to the depth bands at which a survey of a reef is considered to have been carried out at a "shallow" or "deep" reef.

Shallow reef: refers to reef between 1 m and 6 m depths.

Deep reef: refers to reef between 6 m and 12 m depths.

Management regime: refers to the island or reef use status of reefs where long term sites have been established that provide and function as a pseudo management plan for the reef or island. Regimes are either "community", "resort" or "uninhabited", and can change over time.

Community reef: Reefs with islands that are inhabited by local communities. Reefs are managed by the local inhabitants of the island.

Uninhabited reef: Isolated reefs or reefs associated with uninhabited islands or islands with restricted use by a highly limited group.

Resort reef: Reefs within the designated boundary of reefs and islands that are leased for resort use. These reefs are managed by the resort management.

Long-term monitoring site: sites at which data has been collected during multiple years by the National Coral Reef Monitoring Program.

Sites

Long-term monitoring [LTM] sites are located across 10 administrative atolls (Figure 1). These sites were established with the aim of collecting data representative of the Maldivian reef system by accounting for geographic spread of atolls, usage, and management, as well as current development and future development plans for an atoll.

NCRM and MEMP overview

Sixteen LTM sites were established by the NCRM program in 1998. These sites are located on the administrative atolls of Addu (Seenu), Gaaf Alif, Vaavu, Alif Alif, Kaafu, and Haa Dhaal. An additional 3 sites have been established in Haa Dhaal to improve intra atoll and management regime representation. This process of incorporating additional sites is underway across all survey atolls with established LTM sites.

Twelve additional sites were established in Noonu, Raa, Baa and Lhaviyani atoll by the Maldives Environmental Management Project [MEMP] in collaboration with the NCRM program in 2011. These sites have since been absorbed into the NCRM program and are part of the resurvey efforts.

As of December 2021, a total of 31 LTM sites in the NCRM program. Additional site details are provided in the appendix.

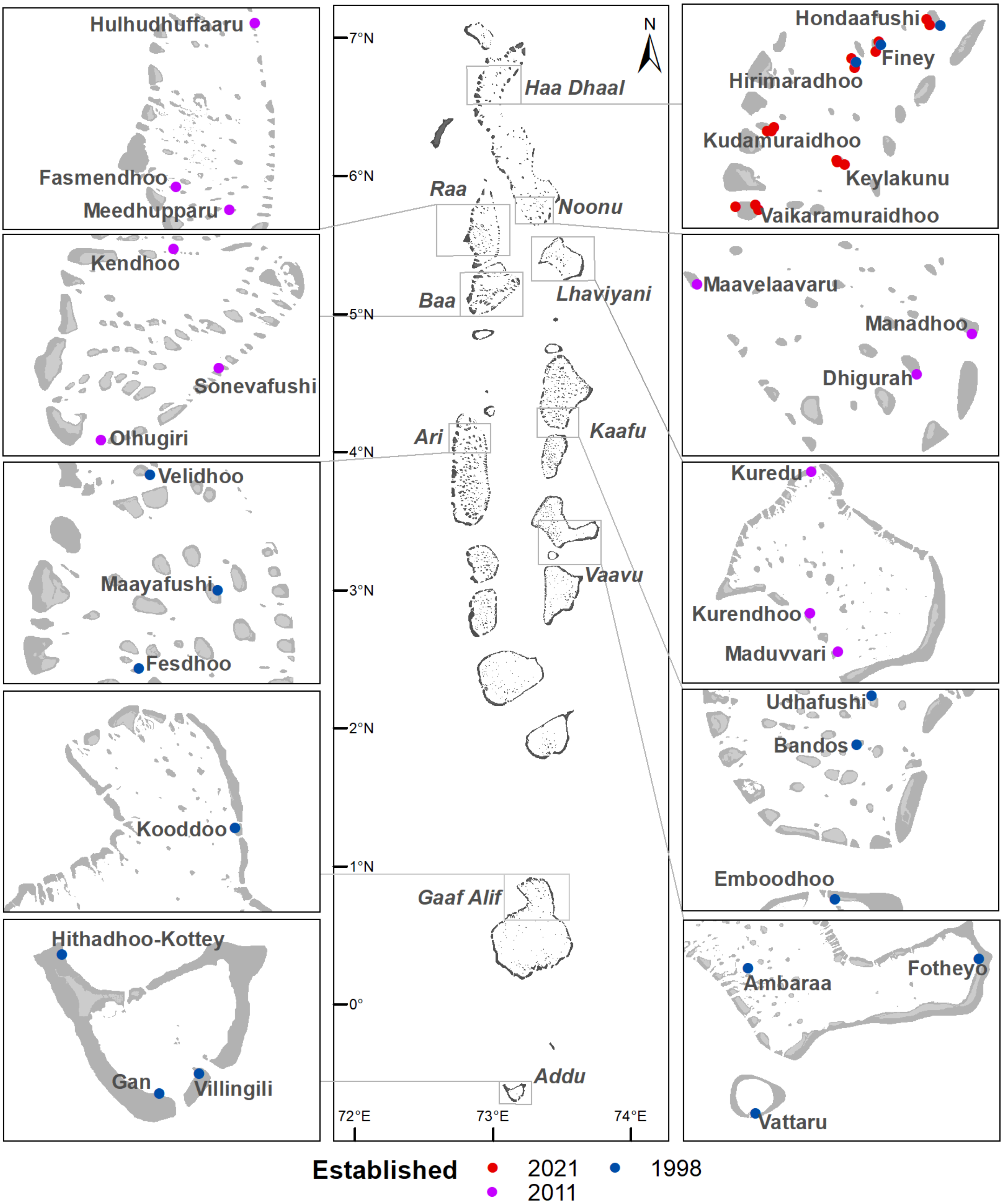


Figure 1. *Long-term monitoring sites throughout the Maldives. The location of each site in each administrative atoll and the year of establishment are shown in each inset. Blue represents sites established in 1998, purple represent sites established in 2011, and red represent sites established in 2021*

Haa Dhaal

The Haa Dhaal region is part of the Boduthiladhumathi geographic atoll and has 6 LTM sites with three stations per site (Figure 1). Finey, Hondaafushi, and Hirimaradhoo were established in 1998 with a single station per site. An additional two stations per site were established for these three sites in 2021. Keylakunu, Vaikaramuraidhoo and Kudamuraidhoo were established in 2021 with three stations per site.

Noonu

The Noonu region is part of the Boduthiladhumathi geographic atoll and includes three LTM sites with one station per site. Manadhoo, Maavelaavaru and Dhigurah were established in 2011 (Figure 1).

Raa

All three LTM sites in the Raa region are part of the geographic atoll of Raa (Figure 1). Fasmendhoo, Hulhudhufaaru and Meedhuhparu were all established in 2011.

Baa

The three LTM sites in Baa region are all located within one of the three geographic atolls that make up the Baa administrative atoll. Kendhoo, Sonevafushi (Kunfunadhoo) and Olhugiri were all established in 2011(Figure 1).

Lhaviyani

The three LTM sites, Kuredhoo, Kurendhoo and Maduvvari, are all located within the geographic atoll of Lhaviyani. All three sites were established in 2011.

Kaafu

The three LTM sites of the Kaafu region includes two sites (Bandos and Udhafushi) from the North Male' geographic atoll and one site (Emboodhoo) from the South Male' geographic atoll. All three sites have a single station and were established in 1998.

Ari

The Ari region contains three LTM sites from the Alif Alif administrative atoll but are all part of the geographic Ari atoll (Figure 1). Fesdu, Maayafushi and Velidu all have a single station and were all established in 1998.

Vaavu

The LTM sites of the Vaavu region comprises of two sites (Fohtheyo and Ambaraa) in the Vaavu geographic atoll and one site (Vattaru) on the Vattaru oceanic faro (Figure 1). All three sites have a single station and were established in 1998.

Gaaf Alif

The Gaaf Alif region consists of a single site with a single station established in 1998 (Figure 1) at Koodoo.

Addu

There are three LTM sites in the Addu region: Gan, Hithadhoo-Kottey and Villingili (Figure 1). Each site has a single station and were all established in 1998.

Management regimes

From 1998 to 2020, three main types of "management" regimes are associated with sites. The three traditional regimes are "community", "resort" and "uninhabited" regimes.

Since 2021 the NCRM program has begun efforts to incorporate additional regimes (e.g., Marine Protected Areas, agriculture) with the diversification of island and/or reef use.

For analyses conducted here, sites are associated with the traditional regimes for the consistency required for a trend analysis.

Survey continuity

Limited resources and human capacity as well as logistical restrictions has meant that LTM sites could not be consistently monitored annually. Consequently, there are varying degrees of data collection gaps across the program.

Survey methods

Primarily, three types of methods have been utilized to collect benthic data during monitoring surveys at the LTM sites in the 23 years between 1998 and 2021.

Triplicate 50m Line Intercept Transects [LIT] (English et al., 1997) were used to collect benthic data from 1998 to 2005. Quadruplicate 20m Point Intercept Transect [PIT] based on Reef Check (Hodgson et al., 2006) were used from 2009 to 2015, while quadruplicate 20m PIT based on the National Coral Reef Monitoring Framework [NCRMF] protocols were used in 2016. From 2017 onwards, Photo Quadrats [PQ] were predominantly used for benthic assessment. PQ images were annotated using CoralNet with twenty-five random points on each image.

Surveys were carried at two depth categories: “shallow” and “deep”. Reefs between 1-6 m were categorized as shallow, and reefs between 6-12 m were categorized as deep. Due to technical and logistical constraints most surveys prior to 2009 were only shallow surveys (Zahir et al., 2010). Hence, deep reef data preceding 2009 is limited compared to shallow reef data.

Despite the differences, all methods were transect based and collected the same or analogous variables. Consequently, coral cover, the most consistently collected variable, was relatively comparable across methods (Contreras-Silva et al., 2020; Leujak & Ormond, 2007) and could be collated for comparison and analysis.

Analysis

All analyses were carried out using R (v4.0.5 2021) and R Studio (v 2022.02.1-461). Figures were plotted using the R package “ggplot2” (Wickham, 2016).

The compiled data set was initially explored with histograms to explore any patterns that may exist within the data set.

Data cleaning and structure

Benthic survey data from 1998 to 2021 were compiled and checked for duplicity and consistency in naming.

“NA” values were checked for whether they were included due to a lack of survey or because coral cover was zero. Where the former occurred, survey records were removed from the analysis; where the latter occurred, “NA” values were converted to zero.

The management regime of each site was checked through time as it is common for sites to shift from uninhabited to resorts status.

Sites were nested into a factor called “region” based a combination of their positions within administrative and geographic atolls. This was to compensate for the differences in a site’s attributed “atoll” during analyses that arise due to conflicts in administrative atolls, geographic atolls, and oceanic faros.

The last sample date for Noonu, Raa, Baa and Lhaviyani atoll was 2022. This data is excluded from the report as data analysis was ongoing at the time of data collection at these sites in 2022.

Trend analysis

Coral cover data were converted to proportions for utilization of the beta family distribution in analyses. Bayesian hierarchical generalized additive mixed models [HGAMM] (Bürkner, 2017) were then used to identify trends in coral cover over time following procedures used by Kimura et al (2022).

Three separate HGAMMs were created. The first model aimed at identifying national level trends of fixed factors (regions, management, depth), with sites as a random term. The second model tested the effect of management * depths, with sites as a random term. The third model was used to identify regional trends and incorporated a region effect with fixed factors, with sites included as a random term.

For all three models, factors including time, management, depth category and other relevant additional factors like exposure, method, etc., were included or excluded using a stepwise approach to assess whether the model improved. The number of divergences for models that converged were noted. They were then visually inspected and any models with R-hat values below 1.01 were rejected. The models were then compared, and the most effective model selected, using the Leave-One-Out cross validation, Leave-One-Out Information Criterion (LOOIC), Widely Applicable Information Criterion (WAIC) and the model R2.

Model predictions are constrained to the range of data available for regions and depth categories.

Models were run using the R package "brms" (Bürkner, 2017) and compared using the package "performance"(Lüdecke et al., 2021).

Site level analysis

Mean and standard errors were calculated to visualize distribution of data and variation of coral cover at site level.

A long-term mean, defined as the mean of data from the date of data collection to the last surveyed date, was calculated at three levels for each site: overall, shallow, and deep.

RESULTS

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DATA EXPLORATION

Although there was more shallow reef data than deep reef survey data, the difference was not as vast as expected. Of all the surveys carried out at the LTMS sites over the 23 years between 1998 and 2021, 58% were shallow and 42% were deep reef surveys. The distribution of coral cover at shallow and deep reefs were both positively skewed (Figure 2).

The median proportion of coral cover for shallow reefs was 0.069. This was lower than median proportion of deep reefs at 0.089. Most of the data of both shallow and deep reef fall the to the left of the median (Figure 2). This effect was more strongly observed in shallow reefs as compared to deep reefs.

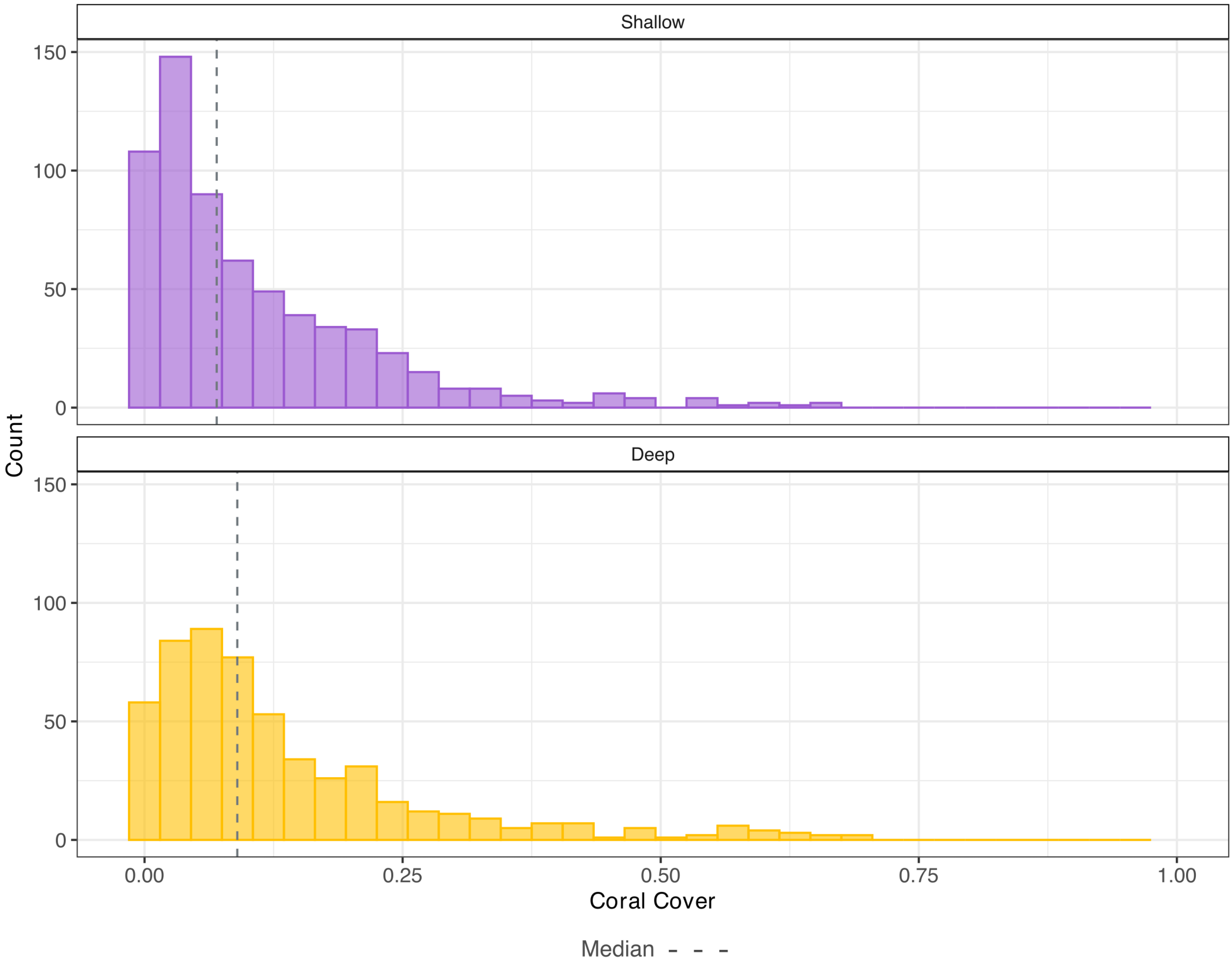

Figure 2. *Histogram of proportion of coral cover at shallow (purple) and deep (yellow) reefs from Long-term Monitoring sites. The dotted line represents the median of the shallow and deep reef coral cover data.*

Model results

After assessing the performance of models with various factors and combinations, three separate models were generated to analyze the overall trends, the effect of depth and management on the overall trend and the effect of region on coral cover trends.

The first, broad scale temporal model assessed the "Overall" trend of coral cover in the Maldives over time by smoothing time with depth and management acting as fixed factors.

The second "Management and Depth" model utilized the same structure and also incorporated a smoother for management and depth to account for its effect.

The third and final "Regional" model does not use management as one of its fixed factors. Instead, depth category and region act as its fixed factors with a smoother for region incorporated to account for its effect.

Models incorporating exposure and method either did not converge or had higher LOOIC and WAIC than the above-described models. Hence, the three models used for the analysis were the best models for its purpose based on the fact that it had the lowest LOOIC and WAIC values.

The LOOIC, WAIC, R2 and marginal R2 differ between the three models (Table 1). The "Regional" model was the best model as it has the lowest WAIC and highest R2 of the three models. This was followed by the "Management*Depth" model and the "Overall" model respectively.

Comparing the R2 and marginal R2 of the "Regional" and "Management*Depth" model suggests that the derived trends were more strongly driven by a region effect as compared to a management and depth effect.

Table 1. *Model codes and comparison variables for coral cover trend models.*

Model	Code	LOOIC ± SE	WAIC	R^2/Marginal R^2
Overall	Coral cover ~ s(year) + management + depth category + region + (1|site)	-3693.512 ± 108.867	-3694.067	0.420/0.093
*Management*depth*	Coral cover ~ s(year, by = management*depth) + management + depth category + region + (1|site)	-3873.531 ± 110.373	-3875.952	0.542/0.343
Regional	Coral cover ~ s(year, by = region) + region + depth category + (1|site)	-4135.283 ± 103.473	-4138.798	0.682/0.454

Overall national coral cover trend

Following the 1998 bleaching event, coral cover in the Maldives was at 3.0 ± 2.0%: the lowest coral cover over the 23-year period between 1998 and 2021 (Figure 3). Cover steadily increased, reaching a minor peak in 2004 followed by a minor decline before increasing once more until 2010 when a minor bleaching event was recorded in the country. Coral cover declined before increasing steeply between 2013 and 2016. After the major bleaching event in 2016, national coral cover declined rapidly, reaching the second lowest percentage at 5.0 ± 3.0% cover during the 2019-2020 period. Coral cover appears to be increasing since then.

The confidence intervals of the national trend, represented by the models Highest Posterior Density (HPD), was relatively similar from 1998 to 2021, though there was some variation. The confidence interval was greatest between 2005 and 2009 (Figure 3) where there was break in the dataset. In contrast, the confidence intervals were lowest at the start and end of the time period. It is notable that even with uncertainties in coral cover associated with the trend derived from the "overall" model, the general pattern remains.

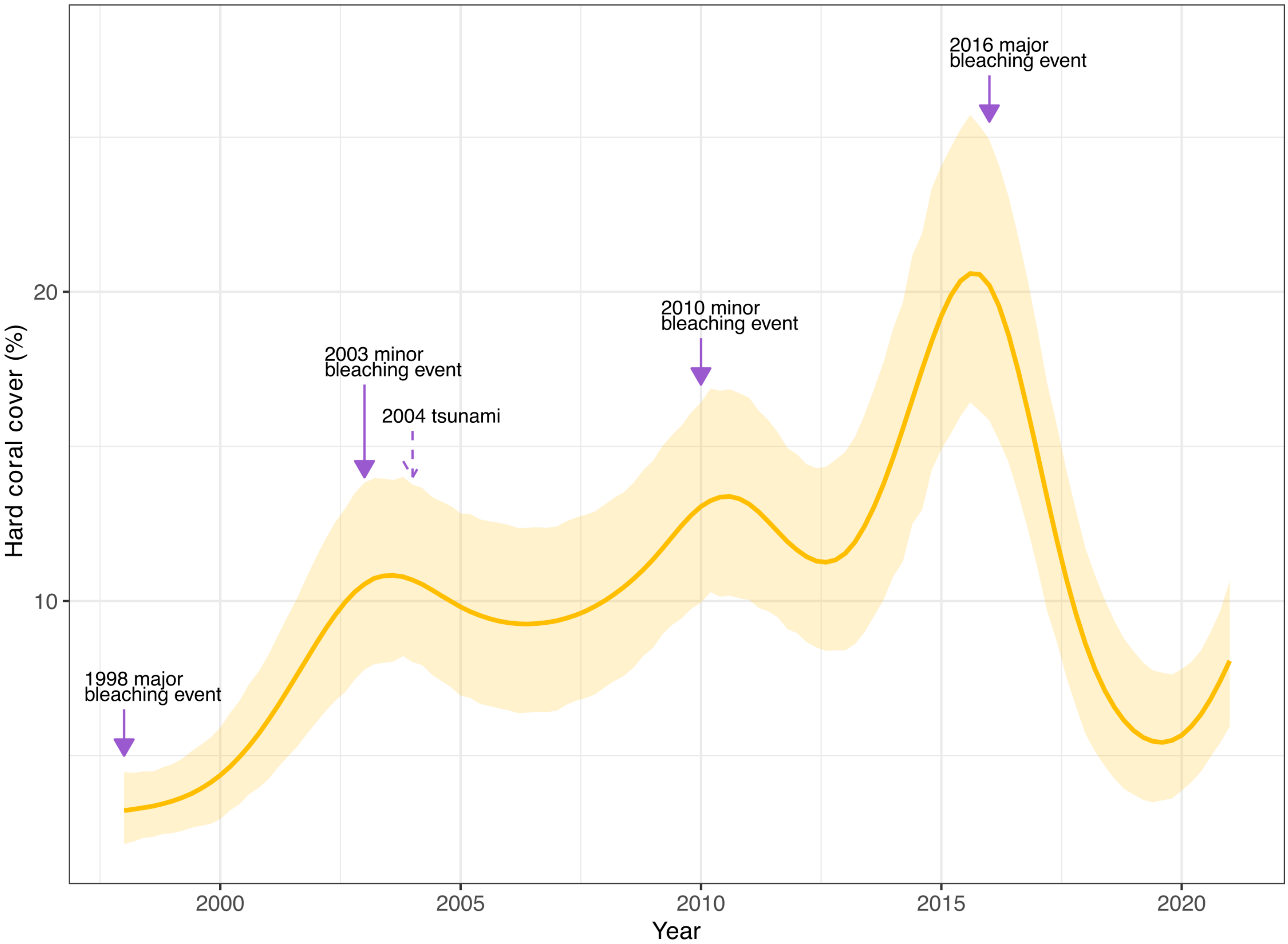

Figure 3. *National coral cover trend derived from Long-term monitoring sites from 1998 to 2021. Solid lined arrows indicated years with major or minor bleaching events. The broken lined arrows indicate the year during which the tsunami occurred.*

Regional trends and site specifics

While trends were successfully derived for the regions, there were differences in the confidence intervals and the trends' level of uncertainty. This was not entirely unexpected due to the differences in survey effort that was possible at different regions over 23-year time period. Therefore, regions with similar data availability are presented together to both avoid misconstruing trends and the comparison of trends with high uncertainty intervals.

Annual means and standard errors were derived for all NCRM LTM sites. These site level specifics are presented from the northern to the southern regions.

Regional comparison

Despite similarities, there were distinct variations in the trends between the regions supporting the notion that differences in coral cover can be strongly driven by the regions. Whilst some regions showed positive recovery and a strong indication of potential resilience, other regions had a weaker recovery.

Overall coral cover trends between 1998 and 2021 were most similar between Haa Dhaal (Figure 4A), Ari (Figure 4B), Kaafu (Figure 4C) and Vaavu (Figure 4D). Despite a minor decline in coral cover that coincides with the 2010 minor bleaching event in three of the four regions (Haa Dhaal, Ari and Vaavu), overall recovery was positive with coral cover reaching a maximum just before the 2016 mass bleaching event. Recovery in Kaafu appeared to steady throughout the period and no signals that coincide with any minor bleaching events, nor the tsunami were detected between 1998 and 2015.

In contrast, coral cover in Addu (Figure 4E) had a rapid recovery in the first few years after 1998 reaching a maximum coral cover just before 2005. This was the fastest recovery post the 1998 bleaching event between Haa Dhaal, Ari, Kaafu and Vaavu (Figure 4). However, coral cover has since declined in Addu and appears to fluctuate around 20% cover after 2010. Similar to Haa Dhaal, Ari and Vaavu, Addu also appeared to have been affected by the 2010 minor bleaching event. Just before 2010, coral cover appears to have begun to increase after the decline that began just before 2005. However, this recovery was lost and decline continued. An increase coral cover and recovery only started after 2012.

After the 2016 mass bleaching event, coral cover of these five regions declined. Haa Dhaal, Ari and Kaafu regions were the most affected, with coral cover reaching close to 0% cover (Figure 4A, 4B, 4C). Moreover, signs of recovery in Ari and Kaafu have yet to be detected. The slight increase recovery in Haa Dhaal (Figure 4A) may not be a true sign of recovery as it may be driven by a single LTM site and the new LTM sites were established in 2021. This is further described in the site specifics.

Vaavu and Addu, on the other hand, were not as affected by the 2016 bleaching event. While coral cover did decline after the event, in both these regions the coral cover only declined by ~50% (Figure 4D,4E). These regions also show signs of being more resilient as coral cover is already increasing with the cover in 2021 close to what it was before the 2016 mass bleaching event.

Coral cover in Raa, Noonu, Baa and Lhaviyani (Figure 5) were similar (~10%) at the start of 2011. Reef recovery in these four regions appeared to be slow but steady in the years between 2011 and 2016. Overall, the trends of these four regions were similar to the other regions found in central and north Maldives (Haa Dhaal to Vaavu) and dissimilar to the region found in south Maldives (Figure 4, Figure 5).

Comparing the regional trends to the overall trend of the Maldives, Addu was the most dissimilar in the period between 1998 and 2015 (Figure 3, Figure 4, Figure 5). However, after 2016, the overall trend was most similar to Addu and Vaavu (Figure 3, Figure 4D, 4E) suggesting these regions may be strong contributors to the observed overall trend and further supporting the notion of region being a strong driver in coral cover trends.

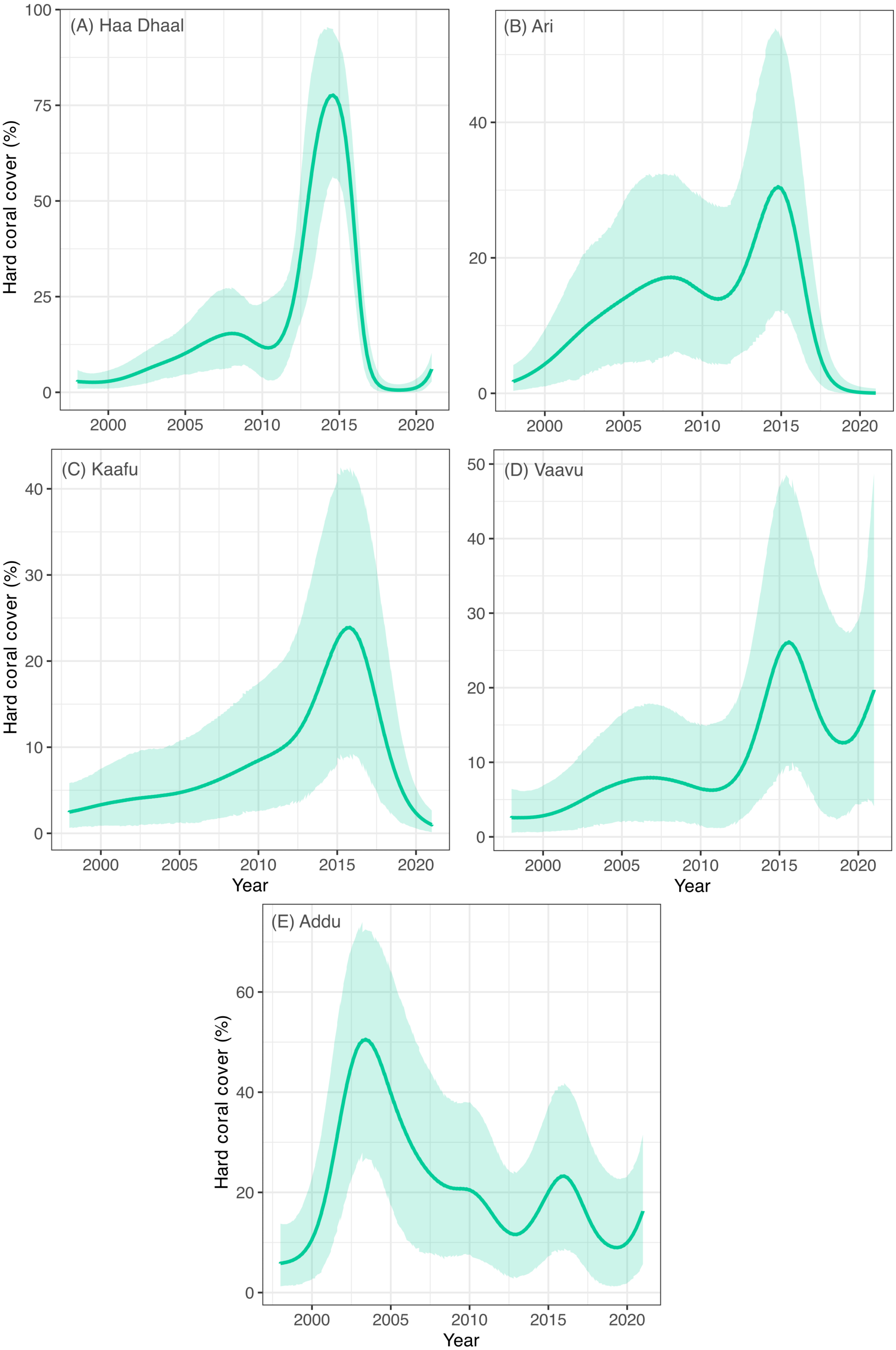

Figure 4. *Regional trends in hard coral cover of (A) Haa Dhaal, (B) Ari, (C) Kaafu, (D) Vaavu and (E) Addu from 1998 to 2021 derived from LTM sites within the regions. All five regions had LTM sites established in 1998.*

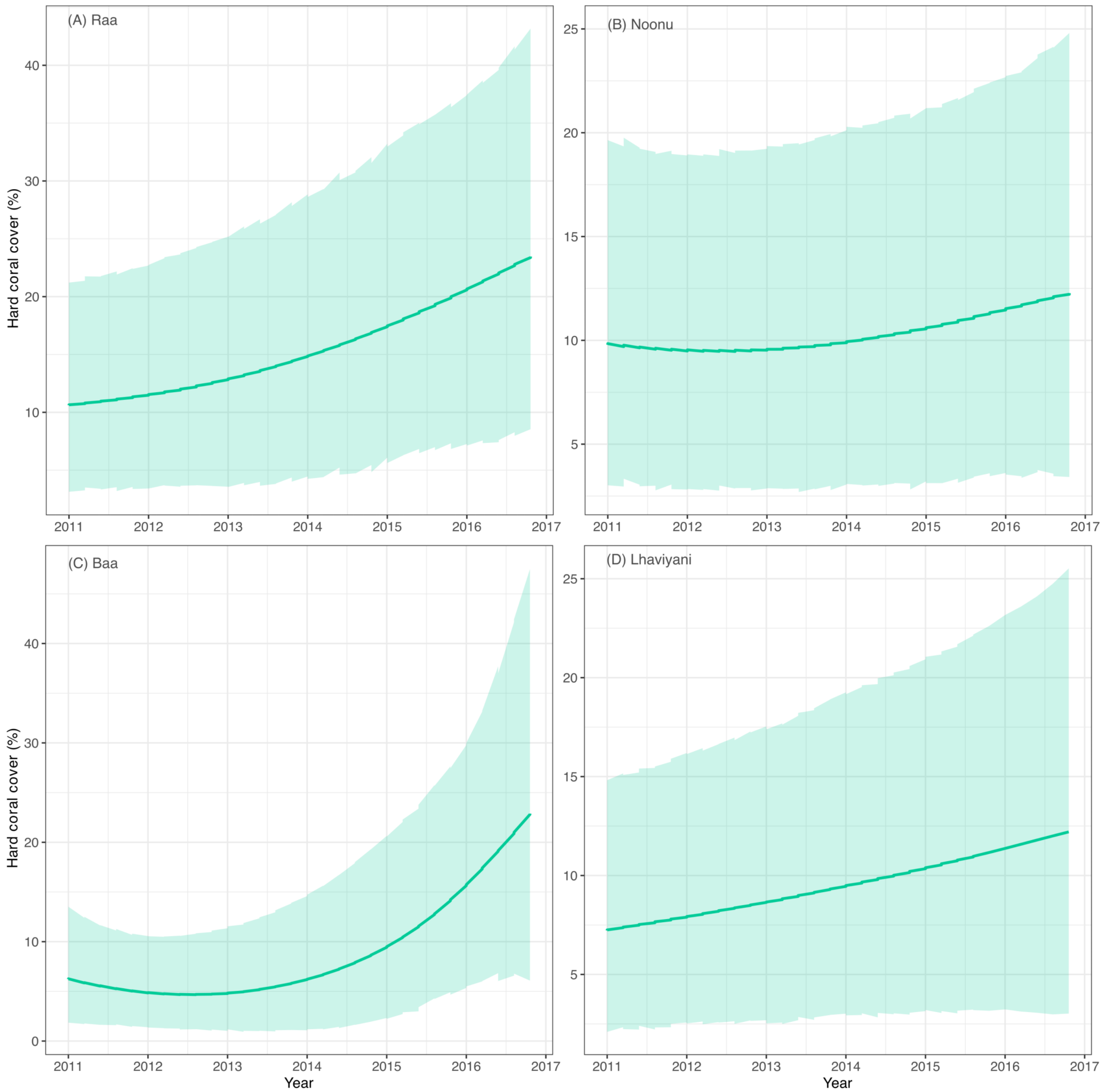

Figure 5. *Regional trends in hard coral cover of (A) Raa, (B) Noonu, (C) Baa and (D) Lhaviyani from 2011 to 2016 derived from LTM sites within these regions. The LTM sites for these regions were established in 2011.*

Haa Dhaal

From 1998 to 2002, there was little variability in mean hard coral cover between the three original LTM sites (Figure 6). The difference in mean cover began in 2003 with Hondaafushi consistently having the highest cover and Hirimaradhoo the lowest of the three during the surveyed years till 2016. Post the 2016 bleaching event, coral cover dropped close to 0% cover for all three sites which was similar to the post 1998 mean cover state. Unlike after 1998 however, Hondaafushi appeared to have recovered faster than its counterparts reaching close to 10% mean coral cover by 2016 while the other two remained close 0-1% coral cover.

In terms of the regional trend, coral cover remained relatively low from 1998 through to 2010 (Figure 4A). Post 2010, coral cover appeared to recover rapidly and decline just as quickly following the bleaching event with coral reaching levels of those following the 1998 event. There were signs of early recovery from 2020-21(Figure 4A) – however, the signal may be stronger than what it actually may be. While the recovery signal appears partially related to the recovery of Hondaafushi, it also strongly correlated to the higher coral cover of the new LTM sites (Figure 6).

These differences between the old LTM sites and the new LTM sites to the region showed evidence of intra-regional variability in terms of recovery of

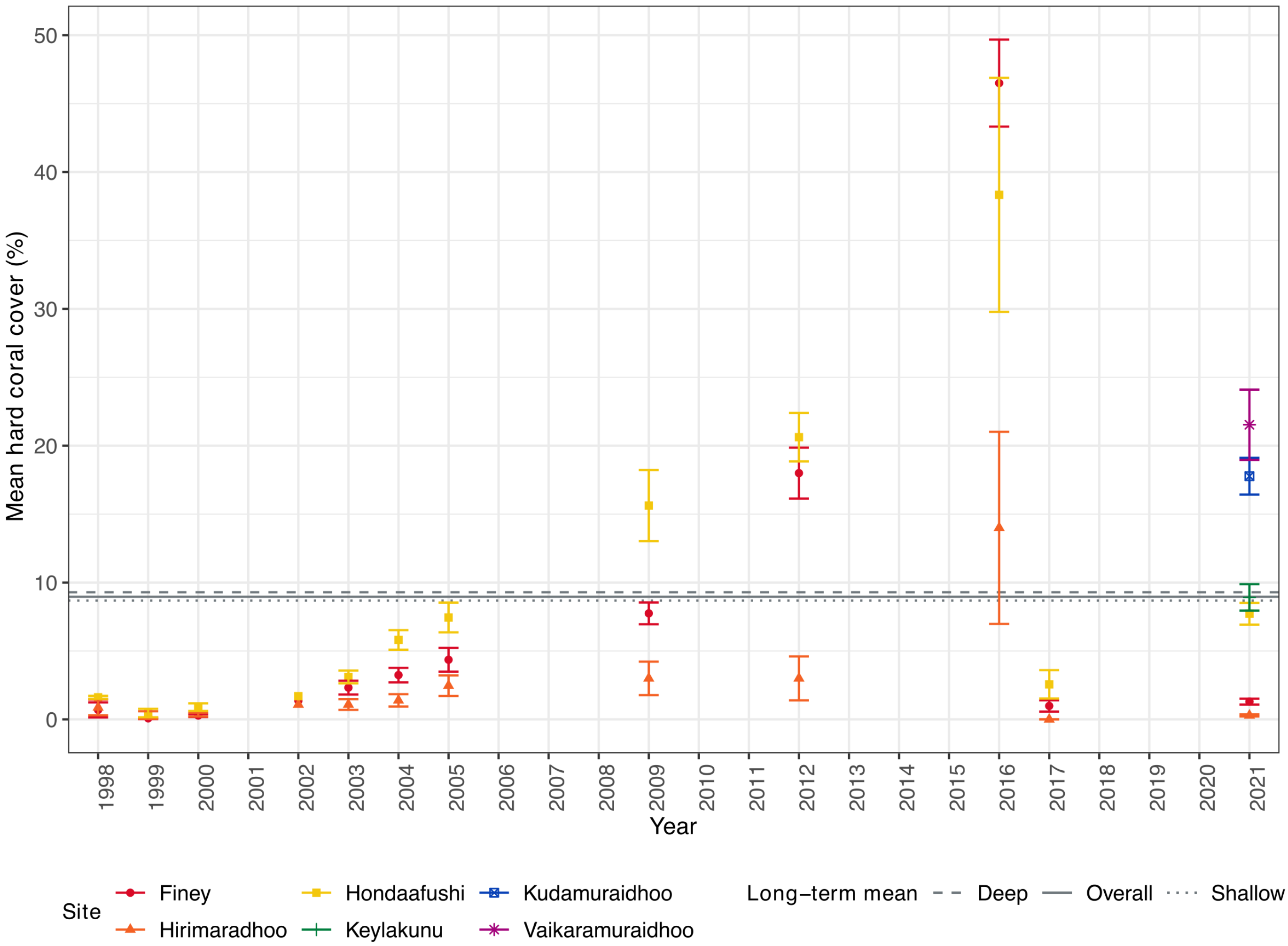

Figure 6. *Mean hard coral cover ± S.E of the long-term monitoring sites in Haa Dhaal. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

reefs. The mean coral cover of the new LTM sites were all higher than the mean coral cover of the old LTM sites (Figure 6). Of the three new sites, Vaikaramuraidhoo had the highest, reaching above 20% coral cover, and Keylakunu had the lowest at around 10% coral cover.

The long-term deep reef mean (9.29 ± 0.99%) was slightly higher than both the overall long-term mean (8.96 ± 0.89%) and the long-term shallow reef mean (8.69 ± 0.88%) but all three were clustered close together (Figure 6). For most of the 23-year period, the site level means were below the long-term means for the region.

Noonu

There was slight decline in mean coral cover at all three sites from 2011 to 2012 (Figure 7) However, with the exception of Dhigurah, mean coral cover had increased by 2016. The mean cover of Dhigurah decline from 8.0% down to less than 5% cover in 2016. The cover of Dhigurah was very similar to that of Maavelaavaru in 2012 (mean and standard errors nearly fully overlap in Figure 7). On the other hand, in 2016, Manadhoo coral cover was close to 9.0% and Maavelaavaru was close to 20% cover. Between 2011 and 2017, the increase in coral cover in the region was minute only increasing by 1-2 % (Figure 5B).

The overall long-term mean of the atoll was 9.27 ± 0.83%. The deep reef long-term mean was slightly lower than the overall at 8.45 ± 0.75% while the shallow reef long-term was slightly higher than the overall at 10.09 ± 1.49%.

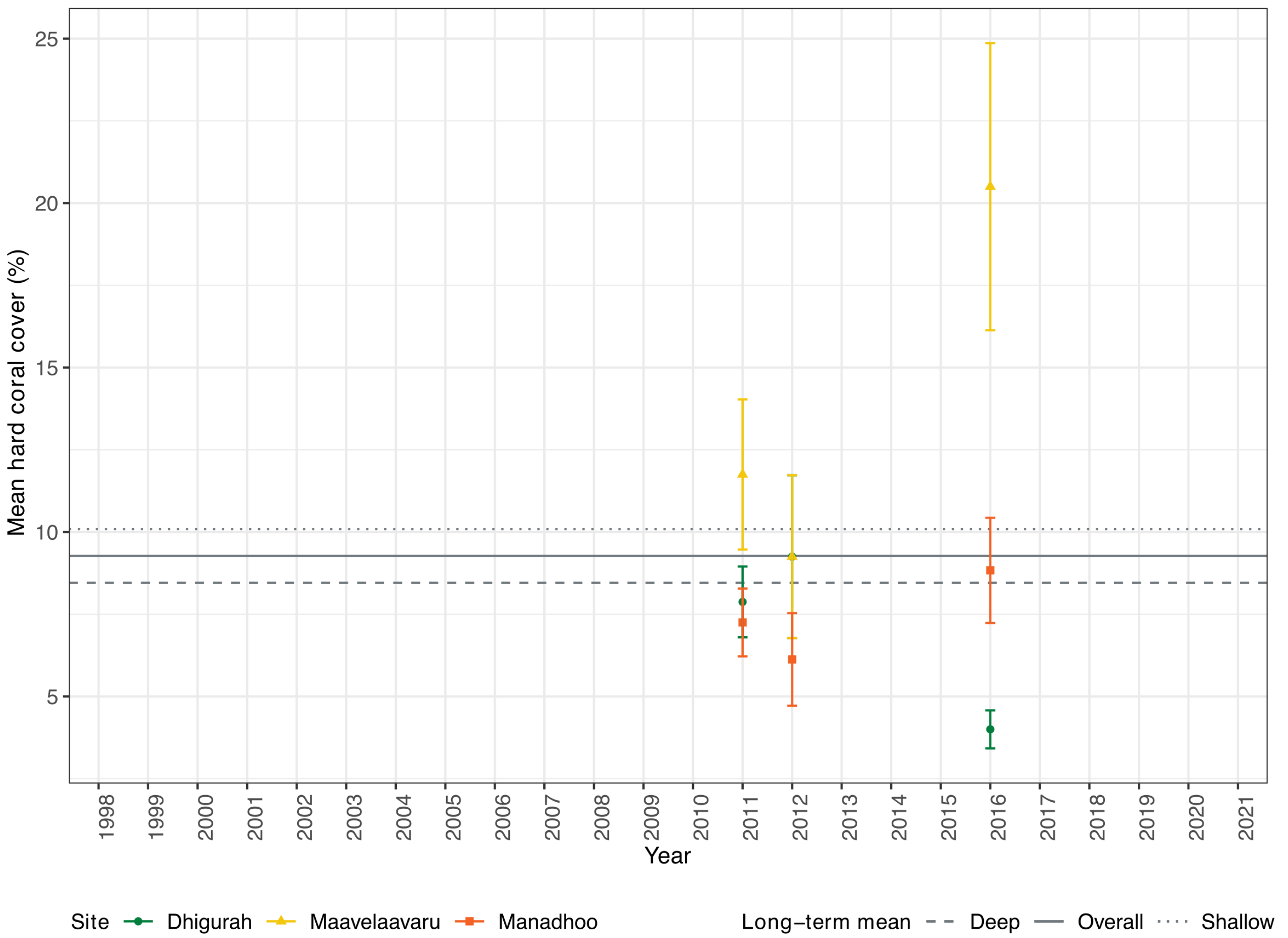

Figure 7. *Mean hard coral cover ± S.E of the long-term monitoring sites in Noonu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

Raa

The regional trend trended upwards with a steeper slope than the slope of the Noonu region (Figure 5A, 5B).

This was reflected in the site level data with coral cover for all three sites higher in 2016 as compared to 2011 (Figure 8). Hulhudhufaaru consistently had the highest mean coral cover of the three sites. Fasmendhoo had higher mean coral cover than Meedhuparu in 2011 and 2012 but this flipped in 2016 although the difference was small. The overall long-term mean of the region was 11.94 ± 0.94%. The long-term mean of deep reefs was lower than the overall at 11.00 ± 1.26%. The long-term mean of shallow reefs was higher than the overall at 12.88 ± 1.39%.

The mean of Fasmendhoo was always below the overall long-term mean of the region. On the other hand, means of Hulhudhufaaru was above all the long-term means for two of the sampling periods.

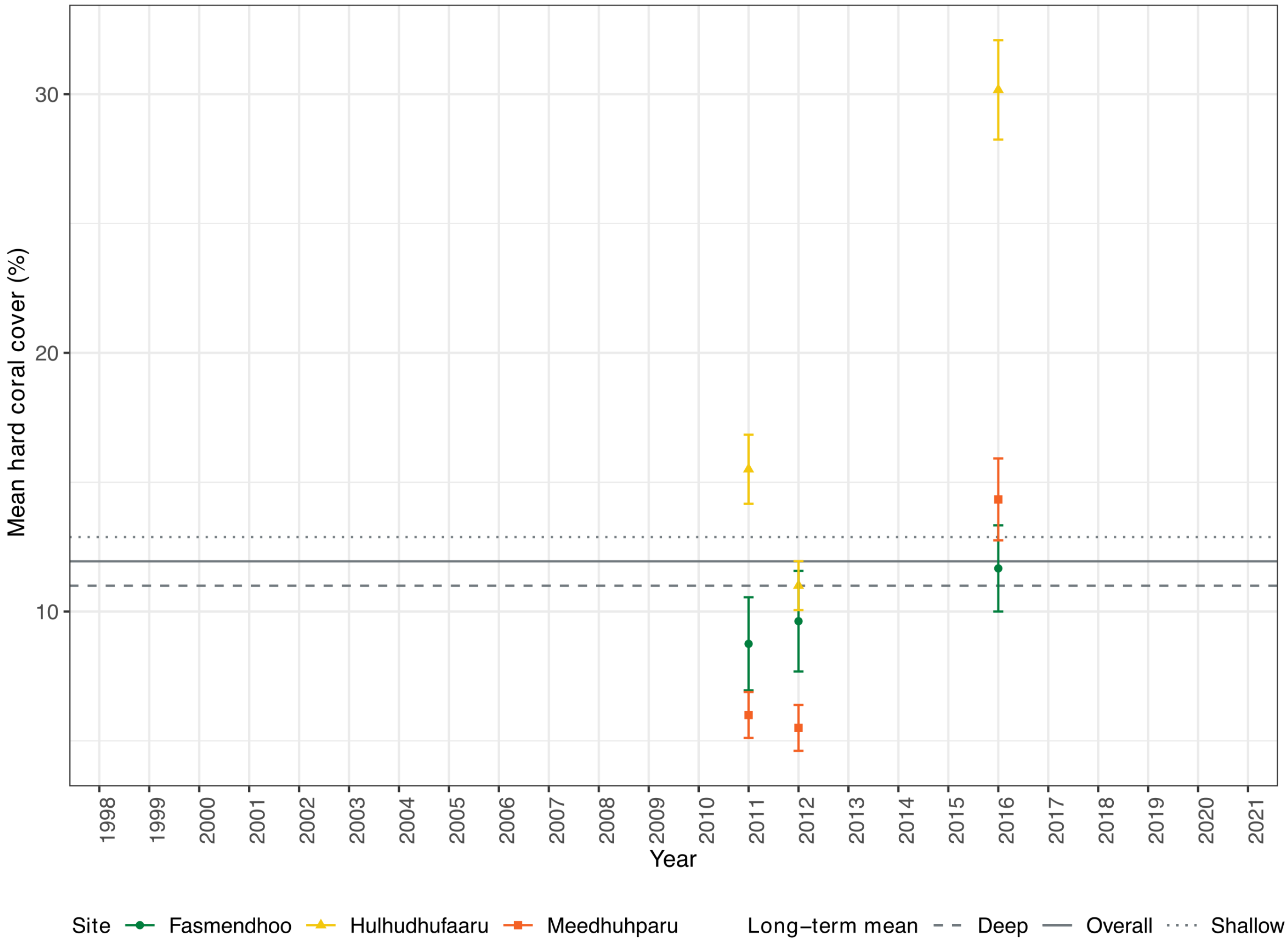

Figure 8. *Mean hard coral cover ± S.E of the long-term monitoring sites in Raa. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

Baa

Sonevaushi consistently had the lowest mean hard coral cover of the three sites (Figure 9). In contrast, Kendhoo and Olhugiri both alternated which site had the higher cover during 2012 and 2016 after having similar a mean coral cover in 2011. Olhugiri had the higher cover in 2012 while Kendhoo had the higher cover in 2016.This meant that while mean cover decline and then increased for Kendhoo, coral cover continued to increase over the three years for Olhugiri.

Standard error of the mean was compact in 2011. It was larger for all three sites in 2012 and 2016. Sonevafushi was particularly notable as it had a very high standard error associated with its mean though it did not overlap with the other three sites.

Similar to the Haa Dhaal region, the long-term deep reef mean (9.88 ± 1.06%) was higher than the overall long-term mean (9.03 ± 0.79%) and the long-term shallow reef mean (8.18 ± 1.16).

The coral cover trend of Baa is the most different from of the four regions with data ranges between 2011 and 2017 (Figure 5). The trend was U shaped, coral cover declining to a minimum in 2012 and then increasing thereafter. This trend is closely reflected in the pattern of the site level means over the time period of this region as well.

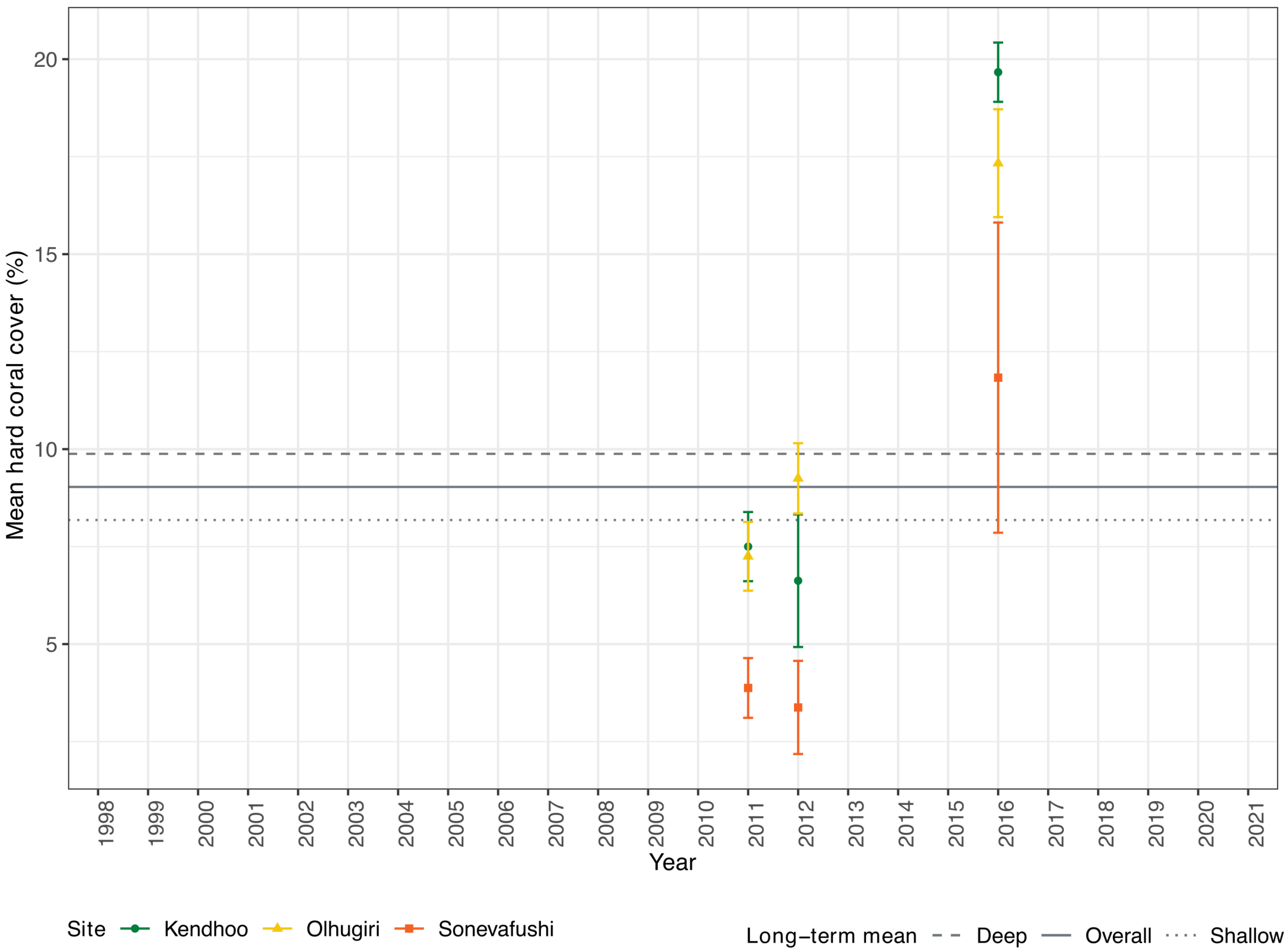

Figure 9. *Mean hard coral cover ± S.E of the long-term monitoring sites in Baa. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

LHAVIYANI

The status of Maduvvari in 2016 was unknown due to missing data.

The mean coral cover of Kuredhoo and Kurendhoo increased over the three sampled years (Figure 10). Though data for Maduvvari was missing in 2016, they showed a similar pattern to the other two sites. Maduvvari also had the highest coral cover, with difference of at least 3% to the other two sites, in 2011 and 2012. Kuredhoo and Kurendhoo had similar mean hard coral cover with overlapping standard errors over the three sampled years.

The overall long-term mean of the region was 7.23 ± 0.56%. This was similar to both the long-term deep reef mean (7.40 ± 0.78%) and the long-term shallow reef mean (7.04 ± 0.81).

The regional trend and confidence intervals of Lhaviyani (Figure 5D) was similar to both Noonu (Figure 5B) and Raa (Figure 5A). However, unlike these three regions, the trend line was most linear of the three regions with coral cover steadily increasing.

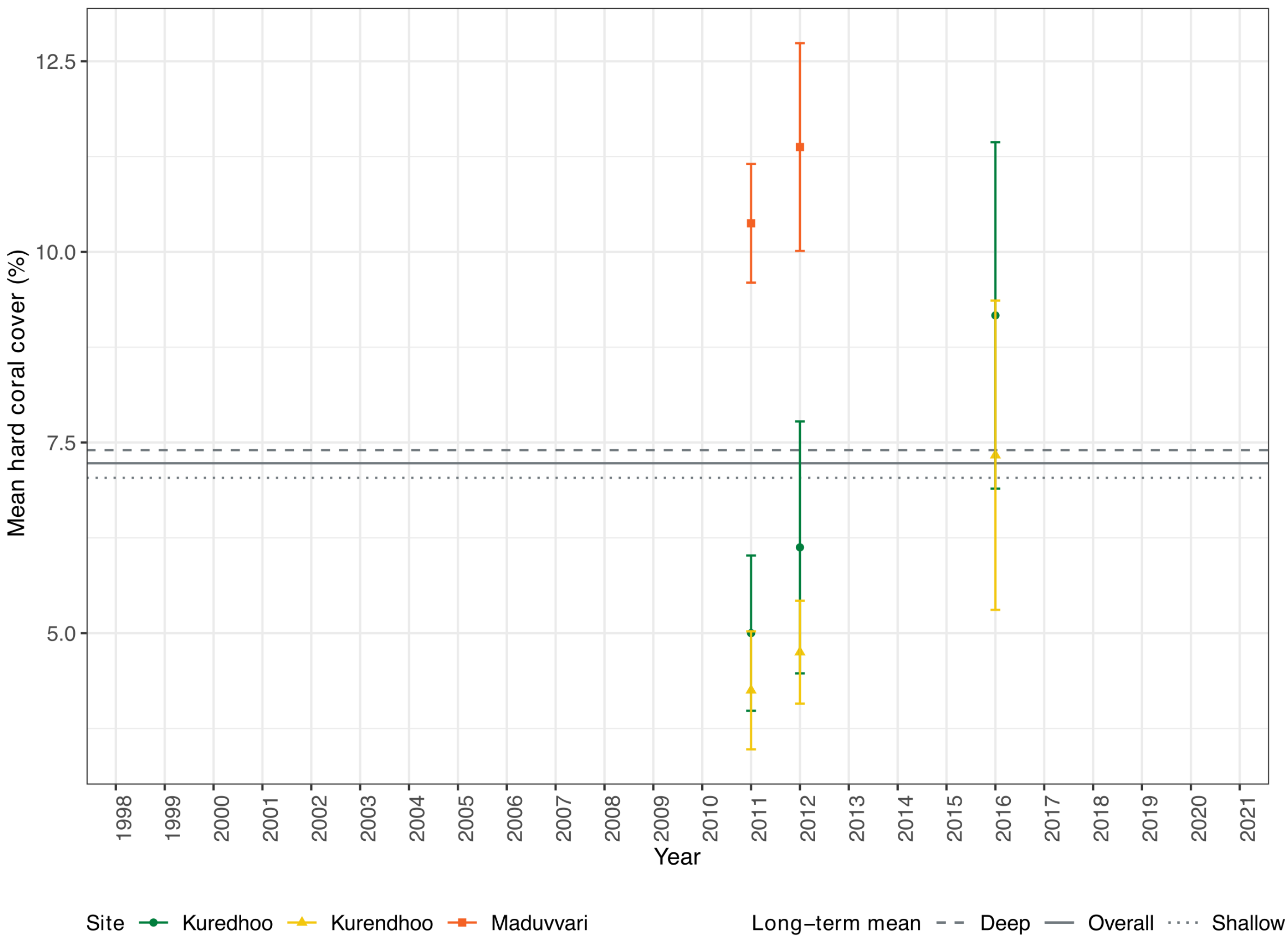

Figure 10. *Mean hard coral cover ± S.E of the long-term monitoring sites in Lhaviyani. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

Kaafu

There were years with missing data for some sites (2004, 2005, 2012) and years where low replicability meant that a standard error could not be calculated (2002).

The mean hard coral cover was a little above 0% for all three LTM sites post the 1998 bleaching event (Figure 11) and did not exceed beyond 10% for close to 10 years post the bleaching event. This is notable as the overall long-term mean coral cover was 10.88 ± 0.89%. This is similar to the other regions as well. The long-term deep reef (13.08 ± 1.49%) mean was higher than both the overall and the long-term shallow reef mean (9.19 ± 1.05%) for the region.

Mean cover increased beyond 10% for Bandos in 2009, Emboodhoo in 2011 and Udhafushi in 2016 (Figure 11). Coral cover was highest for all three sites in 2016: Emboodhoo had the highest reaching to above 40% cover, followed by Bandos at ~30% and Udhafushi at ~20% mean coral cover. Post the 2016 mass bleaching event, coral of all three sites dropped to below 5% mean coral cover with both Emboodhoo and Bandos reaching close to 0% cover.

Hard coral cover steadily increased from 1998 to 2016 reaching a peak of close to 30% cover. From there, post the 2016 bleaching event, coral cover steeply declined reaching close to 0% cover once more. This low cover around 2020 in the trend (Figure 4C) is reflected in the site level means which are clustered close together at less than 5% mean coral cover (Figure 11).

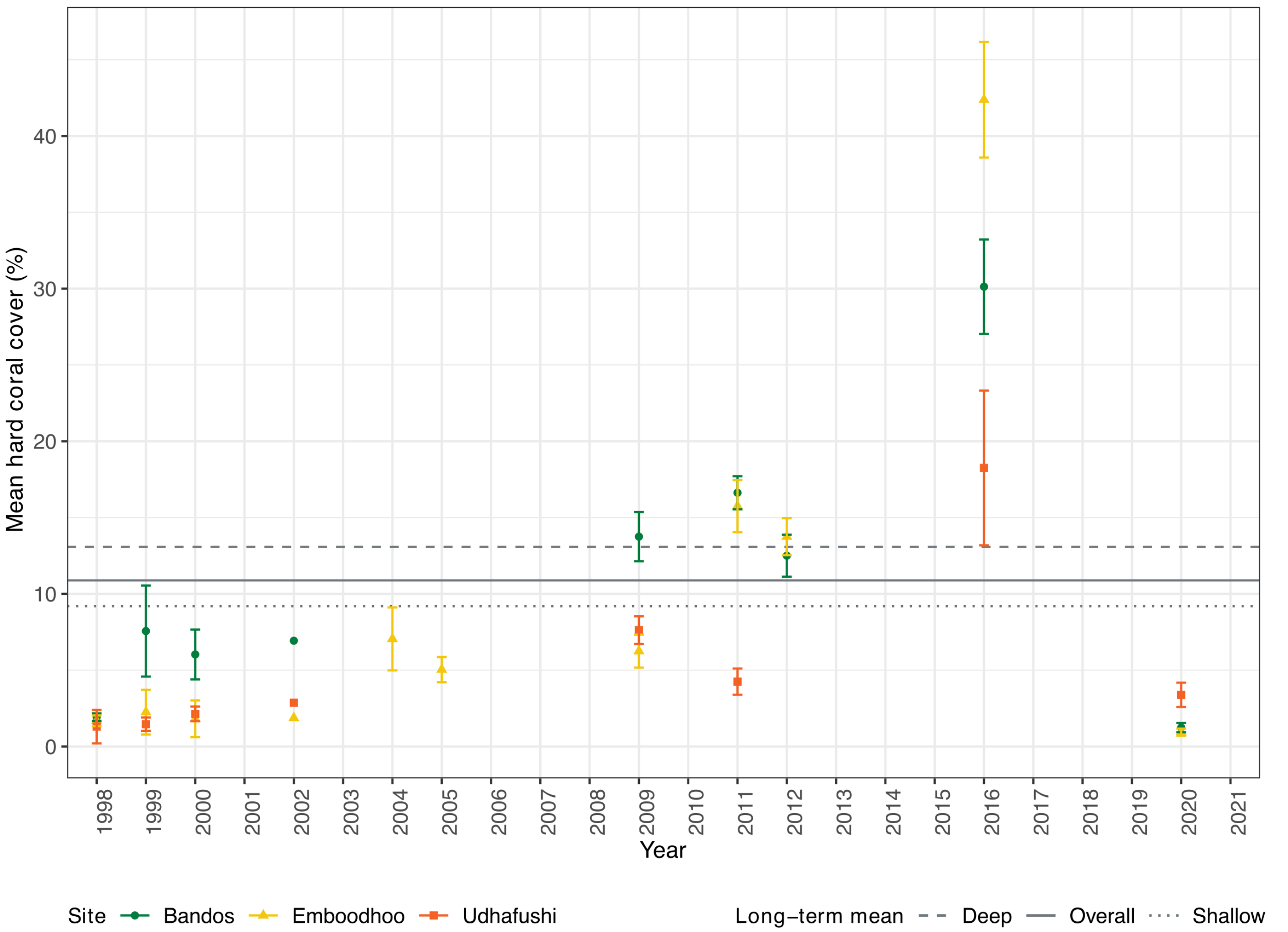

Figure 11. *Mean hard coral ± S.E of the long-term monitoring sites in Kaafu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

Ari

Similar to Kaafu, there were years where low replicability has meant no standard error could be calculated (2002) and there is one year with data missing for one site (2016).

In general, the mean hard coral cover was considerably more dispersed, especially after the year 2000, over the 23-year time period as compared to previous regions (Figure 12). While Maayafushi and Velidu had very similar coral cover from 1998 to 2002, they also began to separate and differ after 2004. However, the mean cover of all three sites clustered back up at close to 2% cover again in 2018 after the 2016 bleaching event.

Mean coral cover of Maayafushi never reached above 10% cover, reaching a peak in 2009 (Figure 12). This declined in the 2012 sampling, increased in the 2016 sampling, and then greatly declined in 2018. Velidu also followed a similar patter although the mean coral cover was much higher than that of Maayafushi. Mean coral cover of Fesdu was consistently higher than that of other three sites till 2012. With no data from 2016, it is not possible to tell whether this persisted. However, unlike in 1998, coral cover of Fesdu also dropped to similar level as that of the two sites.

The overall long-term mean was 11.39 ± 0.96%, long-term deep reef mean was 13.45 ± 1.48% and the long-term shallow reef mean was 9.62 ± 1.23%.

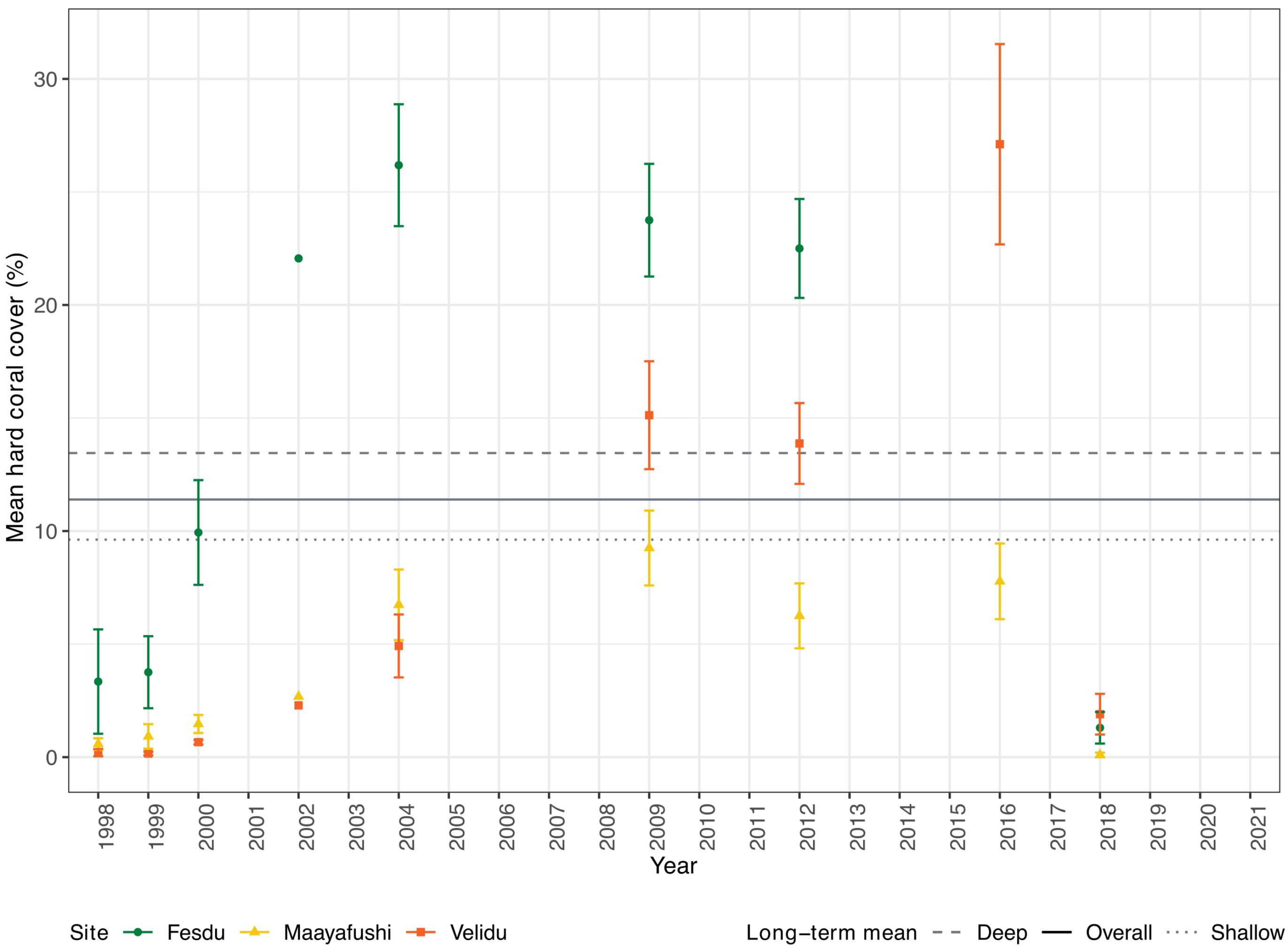

Figure 12. *Mean hard coral cover ± S.E of the long-term monitoring sites in Ari. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

This dispersion of mean coral cover of each of the LTM sites is likely one of the reasons why the confidence intervals of the trend was larger where there was more scatter and small where it was more clustered (Figure 4B). Nevertheless, there were two distinct peaks to coral cover in the region: first a minor peak in 2008 and then again a maximum peak in 2015 reaching close to 30% cover. There was a gradual decline in the regions coral cover from 2015 after the 2016 bleaching event before tapering off close to 1% coral cover.

Vaavu

Data is mostly consistent throughout the 23-year time period with the exception of 2005 where data from one site is not available.

Mean hard coral cover of the three LTM sites remained clustered and low at around 5% from 1998 through to 2002 (Figure 13). The mean coral cover began to differ from 2003 - there was no consistent pattern to the dispersion. Similar to Ari, this dispersion was also present with the long-term means: the overall long-term mean was 15.36 ± 1.24%, the long-term deep reef mean was 20.43 ± 2.07 and the long-term shallow reef mean was 12.01 ± 1.45%.

After means start to disperse from 2003, Fohtheyo consistently had the highest mean hard coral cover of the region reaching close to 60% at its peak in 2016. Unlike most other LTM sites (not just within this region), the mean hard coral cover of Fohtheyo

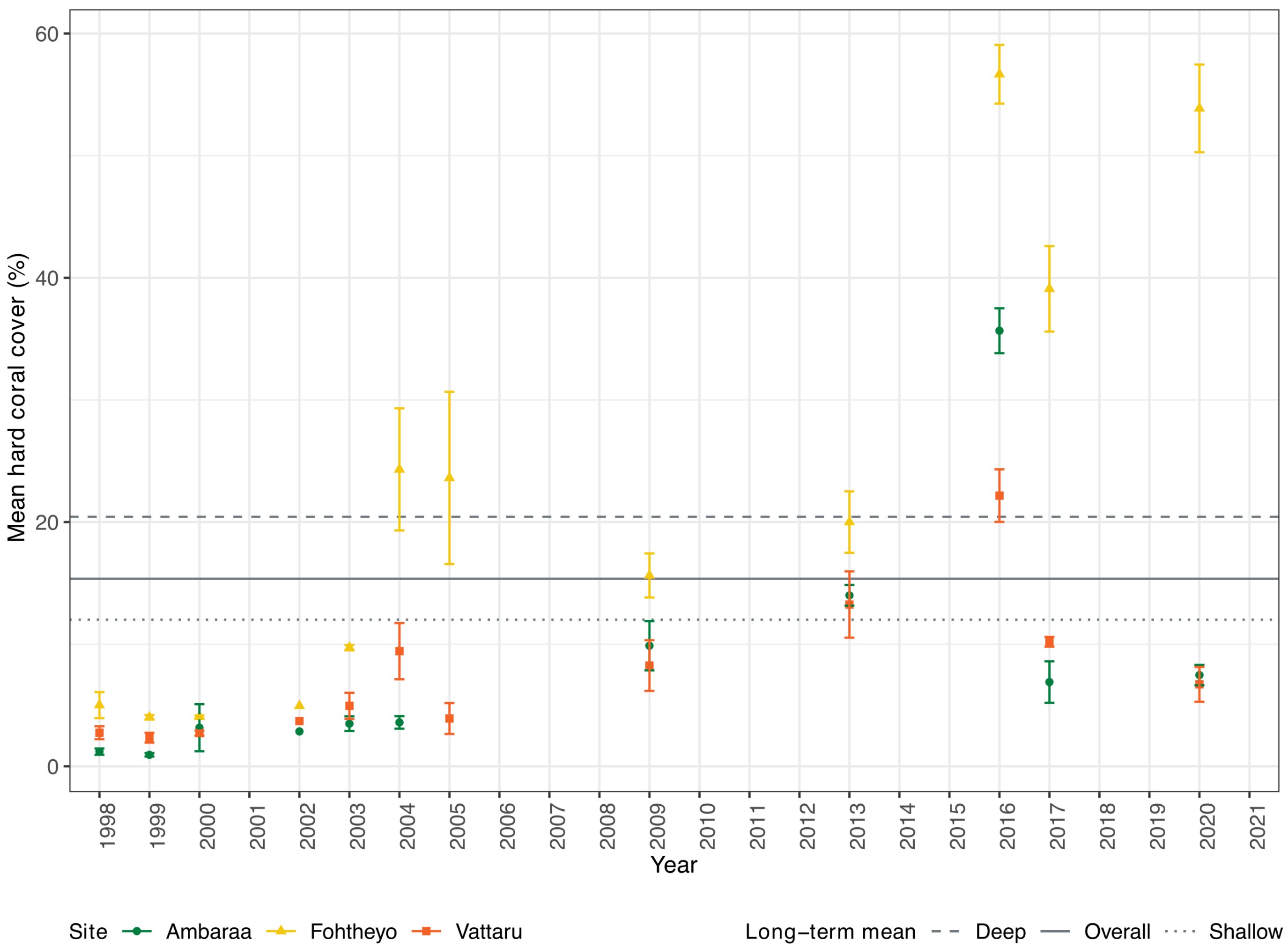

Figure 13. *Mean hard coral cover ± S.E of the long-term monitoring sites in Vaavu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

remained high after 2016 albeit a slight decline in 2017 (Figure 13). Comparing to other LTM sites, Fohtheyo also appears to be one of the more resilient and healthiest sites.

Mean hard coral cover of both Ambaraa and Vattaru remained relatively similar except for during 2004 and 2016. The site with the higher coral cover also changed on different years. For the most part, the mean cover of these two sites remained below the overall long-term mean of the region although this was still higher than the mean coral covers of most LTM sites.

This region also had large confidence intervals though the trend through time remained consistent despite this (Figure 4D). Hard coral cover gradually increased from 1998 reaching a minor peak in 2007. After a slight decline in 2010, hard coral cover increased once more reaching a peak in 2015-2016. Post the 2016 bleaching event, coral cover declined slightly before beginning to recover to levels similar to before the bleaching event.

Gaaf Alif

Gaaf Alif only has a single LTM site. Therefore, the "regional" trend of Gaaf Alif is actually the site trend, and the trend should not be treated and misconstrued as a reflection of the trend of the region.

Furthermore, of all the LTM sites, this was the most poorly sampled with only three samples before 2003. Due to the combination of the poor sampling and there only being a single LTM site, the derived trend is not presented with the trend of any of the other regions. Although coral was close to 1% after the 1998 bleaching event, it had started to increase in the years that followed (Figure 14A). This is reflected in the trend that was derived (Figure 14B). However, the uncertainty of the trend is very high and nothing substantial can be reported nor interpreted.

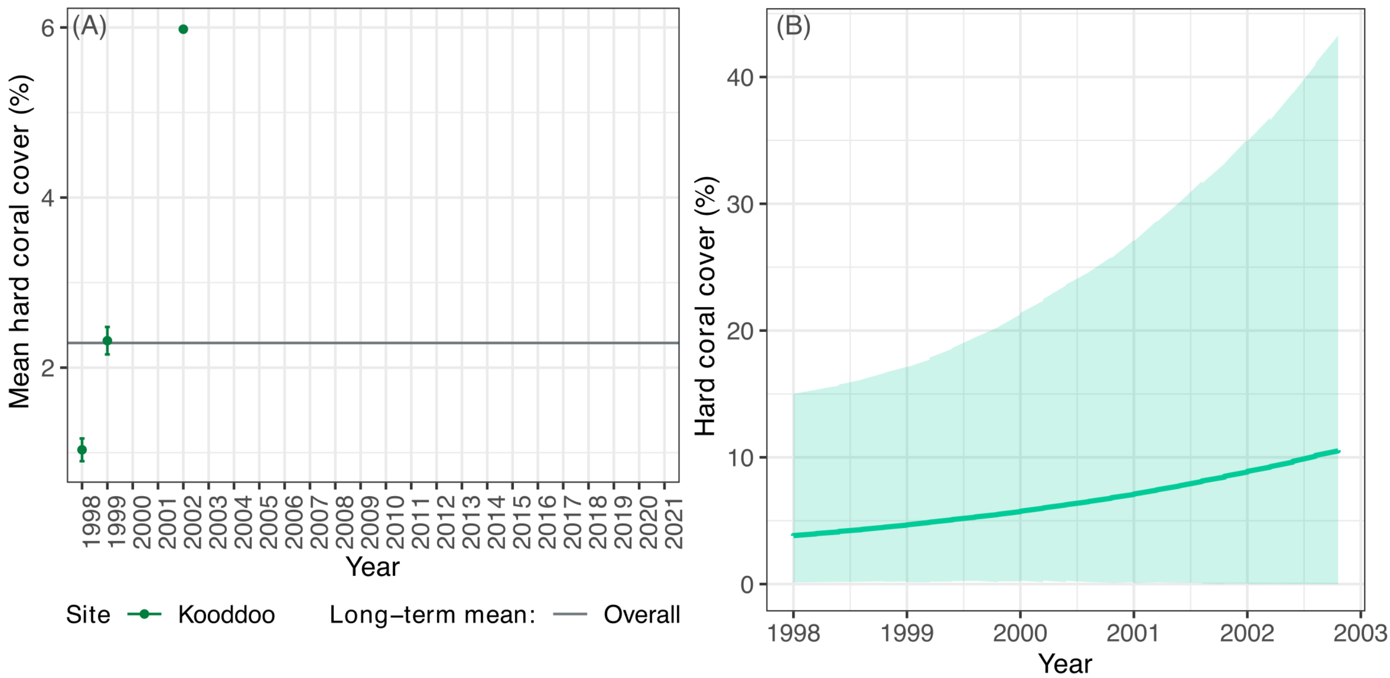

Figure 14. *(A) Mean hard coral cover ± S.E of the long-term monitoring site in Gaaf Alif. The overall long-term mean (%) is also presented. (B) Hard coral cover trend of the site derived from the Bayesian Hierarchical Model.*

Addu

While there was some missing data from the early years of monitoring, data for later years a relatively consistent throughout the 23-year time period.

Mean coral cover was close to 5% for all sites in 1998 and increased in the following years (Figure 15). Mean coral cover peaked in 2004 for Villingili reaching close to 60% cover. Similarly, the Hithadhoo-Kottey region reached a peak in 2003, reaching close to 60%. Mean coral cover of both these sites had declined when 2009. From then on, mean cover fluctuated, increasing and decreasing every other year. As some data is missing for Gan, it is difficult to say whether it would have peaked in the same time period as Villingili and Hithadhoo-Kottey. Mean coral cover of Gan remains below 10% which was relatively low compared to the other two LTM sites.

The data for Villingili during 2016 is not available so the state of the reef during that year was unknown. However, the mean coral cover remains relatively the same in 2015 and 2017 before and after the 2016 bleaching event (Figure 14A). Mean coral cover in 2016 was higher than 2015 and dropped in 2017 compared to 2016 for both Gan and Hithadhoo-Kottey.

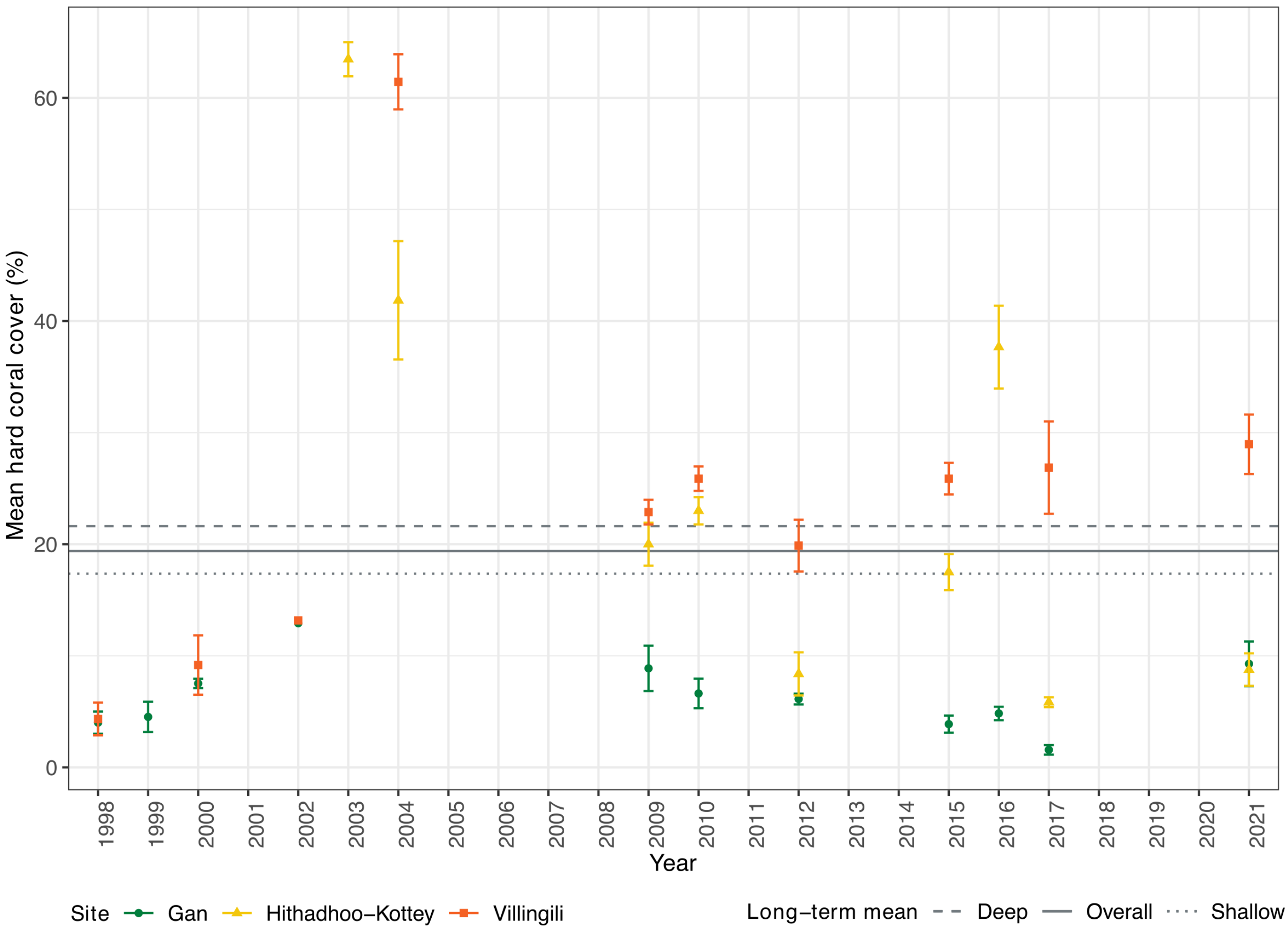

Figure 15. *Mean hard coral cover ± S.E of the long-term monitoring sites in Addu. The long-term overall, deep, and shallow coral cover mean (%) of the region are also presented.*

The long-term means of the region were the highest of all the regions. The overall long-tern mean was 19.38 ± 1.23%, the long-term deep reef mean was 21.62 ± 2.02%, and the long-term shallow reef mean was 17.37 ± 1.44%.

The trend pattern of Addu region is notably different from all other regions whose LTM sites were established in 1998. Whilst the other regions had major peaks in 2015/2016 before the 2016 mass bleaching event, Addu had its peak in 2003 soon after the 1998 mass bleaching event (Figure 4). Coral cover in the region declined again after 2003 and then fluctuated at about 20% over the next 20 years. While the confidence intervals are relatively large, the trend pattern is retained.

National coral cover trends by management regime and depth category

Uninhabited reefs demonstrated a clear positive recovery after the 1998 bleaching event, reaching greater maxima in comparison to the other management regimes, whereas the recovery of community and resort reefs appeared to fluctuate.

Although trends related to management regimes and depths can be inferred from the model, the trend must be interpreted with the understanding that the model performance results (Table 1) suggest that differences in trends may be better explained by the effect of regions as opposed to the effect of management regimes.

While trends differ between management regimes, with the exception of community reefs, trends were relatively similar between depth categories within the same regime, albeit at different percent cover scales (Figure 16). Distinctly, uninhabited reefs appeared to fluctuate minimally and had a near continuous recovery from 1998 until the 2016 bleaching event. This was more pronounced in shallow uninhabited reefs as compared to deep reefs where there appeared to be only a brief decline. In contrast, community and resort reefs were more dynamic at both depths. Moreover, the pattern of the fluctuation was noticeably similar for both these management regimes and they both reach a lower maximum coral cover during this recovery period before the 2016 mass bleaching event as compared to uninhabited reefs.

As no data from deep reefs was collected before 2003, trends were not predicted for the years between 1998 and 2003 (Figure 16). Hence, it was not possible to directly compare differences of the immediate impact of the 1998 bleaching event between the two depth categories.

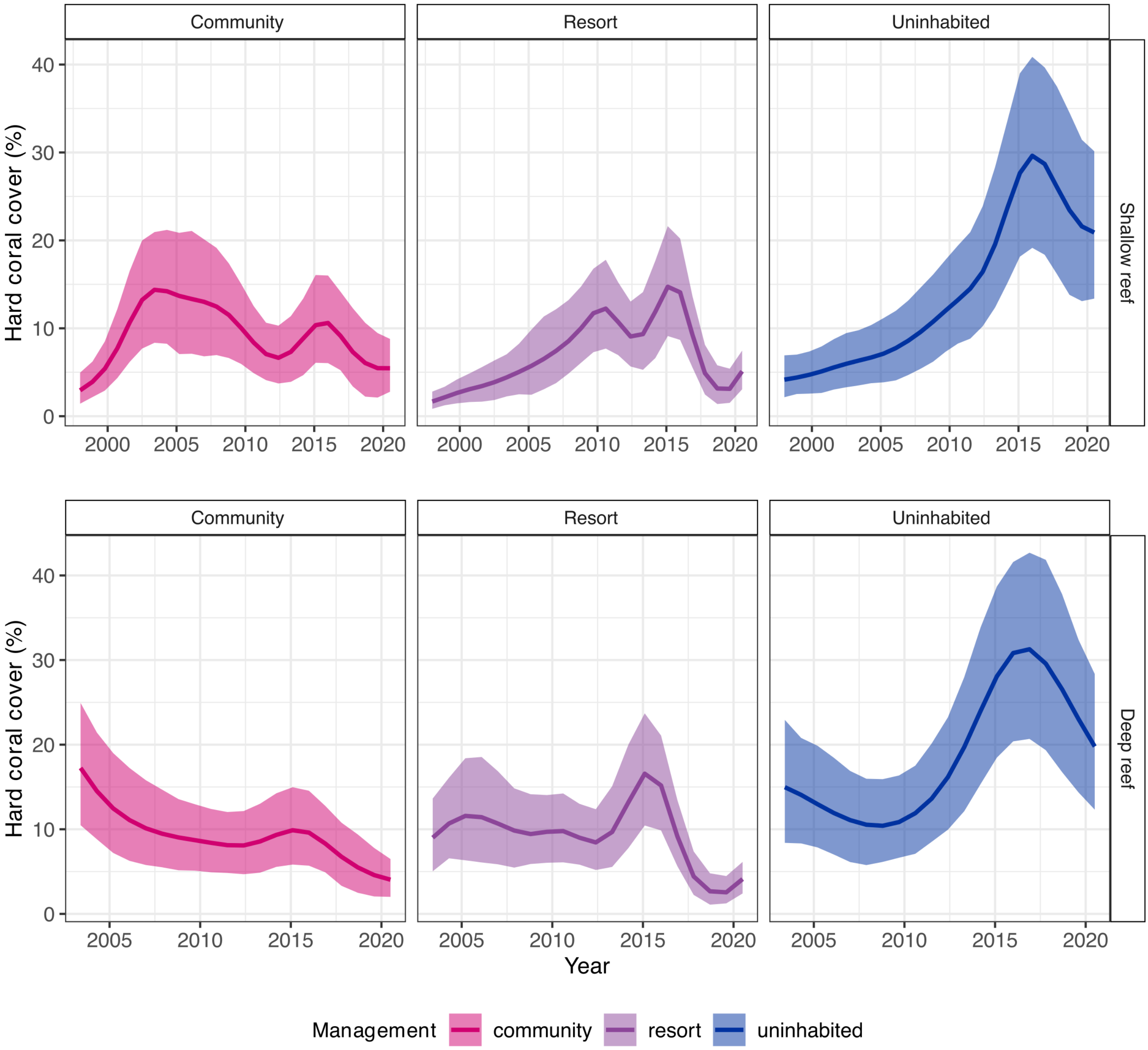

Figure 16. *National coral cover trend at community (pink), resort (purple), and uninhabited (blue) shallow (1-6m) and deep (6-12m) reefs in the Maldives from 1998 to 2021. Note the differing x axis scales for deep and shallow reefs as model range has been restricted to years with available data.*

Confidence intervals of deep reefs, and consequently uncertainty, of the trend remained relatively consistent across the time period for all three regimes. In contrast, with the exception of uninhabited reefs, the confidence interval greatly varied over the full time period across the shallow reefs of the other management regimes. The confidence interval was highest in the 2005-2009 period for community reefs across the management regimes in shallow reefs. Nevertheless, similar to the overall national trend (Figure 3), the trends across management regimes and depth categories (Figure 16) retained their pattern even with uncertainties.

Coral cover at deep community reefs steadily declined from ~12% cover in 2005 to approximately 9%, and then peaked between 2015-2016 before declining again, down to approximately 4% after the 2016 bleaching event, with no signs of recovery apparent during the survey years (Figure 16).

In contrast, coral cover in the shallow community reefs fluctuated over the survey period, with two peaks during the 2003-2004 and 2015-2016 survey periods at approximately 15% and 11% respectively (Figure 16). Coral cover declined after the 2016 bleaching event and is seen to be stabilizing at about 5% over the most recent survey years covered in this report.

While both deep and shallow resort reefs had two peaks in their coral cover trends, the timing and the lag between these two peaks differed (Figure 16). Deep resort reefs were similar to shallow community reefs in that they experienced these peaks 2005 and 2015. However, shallow resort reefs experienced their first peak in 2010 and a second, higher peak in 2015.

The coral cover trends in uninhabited reefs at both depths showed a completely different pattern to the other two management regimes (Figure 16). The shallower reefs continued a recovery pattern from 1998 to 2016 with coral cover increasing from <5% to 30% respectively. The deep uninhabited reefs gradually declined in coral cover between 1998 (15%) and 2009 (10%) and continued on a steady increase, peaking in 2016 (>30%). Both depths showed a sharp decline post 2016 bleaching event, with coral cover at both depths dropping to approximately 20% by 2020, with no apparent signs of recovery during the survey years.

It was also notable that nearly all the depth associated management trends differed from the overall national trend (Figure 3; Figure 16). The one exception to this were the shallow resort reefs between 2009 and 2021 where the trend very closely followed the trend of the overall national trend. In terms of general coral cover, resort and community reefs had similar coverage over the 23-year period. Uninhabited reefs had similar coverage but had considerably higher peak than the other two regimes.

DISCUSSION

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This report synthesizes and analyses data collected over a 23-year period between 1998 and 2021. Representing one of the lengthiest repetitive sampling efforts in the country, data were collected from 10 regions and includes 31 LTM sites, all established between 1998 and 2011, allowing for a wide spatial representation of reefs from across the country. The design of these surveys has meant that varying degrees of human influence has been captured through management regimes; and although efforts were limited in the early days of the program, the influence of depth has been captured through surveys at two depth categories: "shallow" and "deep" reef. Such repetitive sampling of the same sites over a long period of time enables derivation of trends and connections to stressors, both global and local, that may drive them.

While information regarding the exact structure and extent of coral cover of Maldivian reefs prior to the 1998 coral bleaching event are relatively sparse, there is enough available to approximate what reefs would have been like.

Reefs were reported to be widely dominated by branching corals as opposed to other morphologies (Bianchi et al., 2006; Ciarapica & Passeri, 1993). Coral cover estimates vary between 50-80% in the 1970s (Scheer, 1972, 1974) to between 30-47% (Zahir, 1998, 2002) and 70-80% (Montefalcone et al., 2020) before the 1998 bleaching event.

The 1998 bleaching decimated reefs in the Maldives. Live cover ranged between 1-3% after the 1998 event (McClanahan, 2000; Zahir, 1998, 2002). Branching corals were differentially affected during this event and shifts in coral morphological composition towards massives were reported in both natural (Loch et al., 2002, 2004; McClanahan, 2000) and artificially propagated reefs (Edwards et al., 2001). While the data used for this report is not able to discern any differences to the composition of hard coral morphology, the post 1998 coral cover is similar to what has been reported. This is true across the national, regional, site and depth associated management analyses with the exception of deep sites where there is a lack of data for the model prior to 2003. However, surveys carried out at 10m during the same event at other reef systems in the Indian Ocean (Sheppard et al., 2008; Stobart et al., 2005) suggest that Maldivian 10m reefs may have also faced decline either similar to or greater than what has been observed for shallow 5m reefs. Hence, it's likely that actual trend line for the deep sites would be within the lower spectrum of the uncertainty range.

Results of post-bleaching reef recovery studies that tracked coral recruitment were promising, although they suggested that there may be a shift of hard coral composition towards massive and encrusting morphologies (McClanahan, 2000). Reefs with high recruitment rates have a higher chance of recovery marked with increases in coral cover following bleaching events (Ritson-Williams et al., 2009). Between 1999 and 2005, recruitment rates were higher than (Kumara & Cumaranathunga, 2007) and/or comparable (Sheppard et al., 2008) to the rest of the Indo-pacific, although variable across the Maldives. In Male' atoll, juvenile coral densities ranged between ~40 individuals/m^2 and ~50 individuals/m^2, with similar densities reported in other central and central-south atolls (McClanahan, 2000; Zahir et al., 2002). The steady increase in coral cover nationally between 1998 and 2005 (Figure 3) could be partially attributed to the high rates of coral recruitment that were recorded during this period. Although there appears to be differences in recruitment based on depth between different genera of corals (Bianchi et al., 2006), it is likely that coral recruitment is a factor driving the recovery of shallow communities, uninhabited and resort reefs, as inferred by the increase in coral cover post the bleaching events (Figure 16).

Despite the high juvenile coral densities and an increase in coral after the 1998 bleaching event, the post 1998 recovery of Maldivian reefs was reported to be slower than other reef systems in the Indian Ocean. For example, shallow reefs in Chagos were reported to have recovered to pre-1998 bleaching coral cover by 2006 (Sheppard et al., 2008). The slow recovery could be partially attributed to the sheer devastation of the 1998 event where there was a massive loss of mature colonies. This would have simultaneously reduced and capped the reproductive capacity of the reef systems and created a situation where the system would have had to wait for juveniles to mature for any additional reproductive capacity to come into effect.

At the same time slow recovery could also be associated with three notable events that affected reefs on a national scale between 1998 and 2016: the 2004 tsunami and the 2003 and 2010 minor bleaching events. It has been suggested that these minor events, whilst not causing major damage to reef in a scale akin to mass bleaching events by itself, can hinder the recovery process of reefs. Reports indicate that whilst the direct effects of the tsunami were minimal, it differentially affected areas that were already suffering from the 1998 bleaching event (Zahir et al., 2005). Additionally, minor bleaching may not cause mortality in corals, but the stress has impacts to growth (patchy mortality within colony, stasis) and reproduction (depressed) as energy reserves are directed to resistance and recovery of the stress. The minor declines in national coral cover immediately following these relatively minor events corroborate Zahir et al.(2005)'s findings and substantiate the notion that minor stress events hinder reef recovery.

Juvenile coral densities remained high from 2005 to 2015 (Cardini et al., 2012; McClanahan & Muthiga, 2014), enabling many reefs to recover from 1998 bleaching event despite the setbacks posed by the relatively minor events. Hence, coral cover kept increasing at a rate of 1-3% per year, to about 20% cover in 2015/2016. Whilst this cover is not by any means close to the pre-1998 estimates by Montefalcone et al. (2020), it is similar to estimates by Zahir (1998, 2002). While both these studies have sites within the same regions, the difference between the two estimates could be attributed to differences in the reefs within each region where data was collected from. It should be noted that the estimates by Zahir include data collected from some of the LTM sites, making the estimate more directly comparable to the estimates of this study.

Regardless of differences that are driven by regional or site variation, the results of this study suggests that reefs had recovered to a state similar to what the LTM reefs may have been like pre-1998 by the year 2015/2016—a near 17-year recovery period.

This is slower in comparison to reef recovery of systems with limited local stressors where typically a 9-12 year recovery period may be observed (Gouezo et al., 2020). Nevertheless, results presented here are consistent with other studies from the Maldives which have reported reef recovery taking over a decade and coral cover peaking in 2015/2016 (Morri et al., 2015; Pisapia et al., 2016).

The 2016 mass bleaching event negated much of the recovery from the 1998 bleaching event. With sea surface temperatures breaking a record 32°C during this event, 73% of live coral cover bleached across reefs in the country (Ibrahim et al., 2017). Similar to 1998 there were differences in the magnitude of the impact associated with depth. However, unlike the 1998 bleaching event, the national scale assessments suggests that the difference appeared to be reversed with shallow reefs (0-7m) faring better than deep reefs (7-13m) (Ibrahim et al., 2017). Yet at the same time, region focused assessments during this same period reported similar discrepancies but with deeper reefs faring better where this resilience has been linked to deep reef communities having more thermally resistant massive and encrusting corals (Cowburn et al., 2019). This is consistent with the regional effect detected within the analysis of this report. In contrast, the results of this report could not detect a depth associated trend in terms of rate of decline in any of the management regimes following the 2016 event. Live coral cover appears to decline at similar rates at both shallow and deep reef sites within each management regime.

The decline in national coral cover after the 2016 bleaching event appears to be more gradual as opposed to the 1998 event. Whereas a major decline in national live coral cover was detected immediately after the 1998 event (Montefalcone et al., 2020; Morri et al., 2015; Zahir, 2002), it took a few years to reach a minimum of close to 3-5% national live coral cover post-2016. Though the minimum coral cover reached following the 2016 bleaching event is different between community, resort, uninhabited and national coral cover, the pattern of deterioration of coral cover is the same with it taking a few years to reach a slump.

Studies investigating the effect of management regimes and their capacity to effect reef recovery differ. Whilst some studies have shown that resorts have a protective effect where reefs may be more resilient (Moritz et al., 2017; Pisapia et al., 2017), others argue that the picture is much more complicated where resorts may be just as likely to affect detrimental effects (Cowburn et al., 2018). Moreover, whilst studies in the Maldives have demonstrated that community reefs near highly localized stressors are more vulnerable to cover loss (Pancrazi et al., 2020), resulting in slower recovery processes (Montefalcone et al., 2020), others argue that following the 2016 bleaching event, any management linked coral cover effect may be weak and therefore not an effective predictor of how reefs may recover or fair in a future bleaching event on its own (Dryden, Basheer, Moritz, et al., 2020). The depth associated management trend findings of this study demonstrate the range of outcomes that can be obtained in a study that evaluates managements and emphasizes the necessity of accounting for other factors that influence and affect reef health, resilience and recovery.

There is a greater decline in resort reefs as compared to uninhabited and community reefs in the same time period following the 2016 bleaching event. The result is unexpected in the context of a highly accepted local postulation that community reefs would have the highest and most chronic localized stressors of the three regimes and the understanding that localized stressors can exacerbate the detrimental effects of thermal events (Donovan et al., 2021). The postulation arises from the idea that uninhabited reefs have limited direct human impact and reefs within resort boundaries are informally protected thereby facilitating lower local stressors by restricting access and use. However, it is crucial that the results of this study cannot directly link trends solely to the effect of management regimes. As the model results suggest, inter and intra-regional differences of reef could be a stronger driver of the variation instead.

A possibility is that corals at community reefs have adapted to a constant stream of localized stressors unlike resorts, and that this adaptation enabled them to withstand the impact of an additional stressor in the form of thermal stress from the bleaching event in 2016. Yet at the same time, the minute uptick in coral cover of community reefs in 2019 compared to resort reefs suggests that these same community reefs may be considerably slower to recover due these same localized stressors. It is known that chronic stressors can disrupt the capacity of reefs to recover from major stressors even if the stressors cause a minimal or reduced disturbance to adult coral communities (Hughes & Connell, 1999).

National cover begins to increase again only after 2019 - 3 years after the 2016 bleaching event. The 3-year steady decline in coral cover is in stark contrast to post-1998 where there was no similar lag to increases in coral cover. While the exact reasons for this are not yet discernable, lower recruitments rates as compared to 1998 (Perry & Morgan, 2017), which while variable was still high compared recruitment rates of other reefs in the Indo-Pacific (Manikandan et al., 2017), could play a role in this delayed recovery. A nationwide study by Noo Raajje (2021) reported mean density of juvenile corals as 14.3 individuals/m^2 whist another nationwide study by Dryden et al. (2020) reported a lower mean density of 7.4 individuals/m^2, although they had sites reporting as high as 15.7 individuals/m^2. Due to the stress of bleaching and the untimely death of mature colonies, a decline in recruitment rates of reefs affected by bleaching is expected (Hughes et al., 2019; Loch et al., 2004). However, the difference in recruitment rates post 1998 and 2016 and along with the difference in recruitment rates reported by two nationwide studies in 2020 further suggests that there are other mechanisms to consider, including inter and intra-regional variability, changes to coral communities, benthic habitat differences and reproductive potential, which may be driving reef recovery in the Maldives.

The fact that the rate of increase in coral cover looks to be much faster after 2019 than it was after the 1998 bleaching event is another indication of the intricacy of the situation. Despite the initial urge to attribute this to the effect of intra and inter regional variation related to the sites surveyed post-2016, the overall effect may balance out as the LTM sites visited were sites located within regions with lowest long term coral cover (Haa Dhaal) and sites with the highest long term coral cover (Vaavu). Since these effects would also be present in patterns that began immediately after 1998, region might not be the primary driver of the difference between the two periods. A potential explanation lies within the post-bleaching coral communities - studies have shown that trends in coral cover may be explained by a co-examination of the generic and morphological trends of coral communities (Thomson et al., 2020). The data analyzed in this report only captures percent cover, not genus or morphology, and therefore, it is not possible to confidently say whether shifts in communities could be a driver in the difference in patterns post 1998 and 2016.

Furthermore, although the increase in coral cover from 2019 suggests that national coral cover is recovering, the national mean coral derived from these LTM in 2021 sites is currently less than 10%. This results contradicts the finding of other recent studies - nearly half of what was reported by Noo Raajje (2021) and Dryden et al. (2020) in 2020, and nearly a quarter of what was reported by Montefalcone et al. (2020) for 2019. This conflicting result could be attributed to site level variations in coral cover between the LTM sites and sites surveyed in other studies. Site location and the structure of those sites along with the pressures they face (e.g., exposure and human factors) could explain some of the differences, although not for all of them. The NCRM LTM sites are scattered throughout the country both inter and intra-regionally, similar to the sites surveyed

Dryden et al. (2020). The Noo Raajje (2021) study however, surveyed sites that were on outer the western face of each atoll, with no eastern or inter atoll sites considered. Additionally, human pressure over time could play a strong role in driving this difference. Although the NCRM LTM sites from each region originally comprised of a mix of community, resort, and uninhabited reefs, much of the uninhabited reefs are now developed into resorts with considerable coastal development works possibly impacting the monitoring sites.

The results of this report also strongly indicate there is high inter and intra-regional variation within the Maldives. Some of the regions had limited intra-regional variation. Haa Dhaal was particularly notable as site means remained fairly clustered together. Coral cover was markedly low with long-term averages below 10% cover. This is perhaps unsurprising when considering the effect of recruitment, as the region has historically reported low recruitment rates (Tkachenko, 2012, 2014a, 2014b). However, the recruitment rate in Haa Dhaal atoll was 10.1 individuals/m^2 in 2020 (Noo Raajje, 2021), which is higher than previously reported rates (Tkachenko, 2012, 2014a, 2014b). However, the results are unusual in terms of expected management effects as Haa Dhaal has low population densities which would translate into low anthropogenic pressure.

Results of the LTM sites within Vaavu were less clustered than those of Haa Dhaal. Although mean coral cover was twice that of Haa Dhaal in Vaavu, the trends were relatively similar. The high coral cover results from this region are consistent with other studies (e.g., Dryden et al., 2021c, 2021a, 2021b). The higher coral cover could be driven by a combination of low human pressure relative to the other central Maldivian atolls and the higher recruitment rates in the region compared to regions like Haa Dhaal. The coral recruitment rate in Vaavu atoll was 23.3 individuals/m^2, the highest of all atolls investigated in 2020 by Noo Raajje (2021).

Moving south to the southernmost region, inter regional variability is at its most prominent. The results of the LTM sites are scattered similar to those of Vaavu. High variability in coral cover is indicative of differential recovery rates that have been detected within the Addu atoll since the 1998 bleaching event (Wallace & Zahir, 2007), and this pattern seems to be repeating post 2016. In contrast to both Haa Dhaal and Vaavu, however, the regional trend is entirely dissimilar and further supports the notion that regional variation as a driver of differential reef recovery. Compared to both Haa Dhaal and Vaavu, Addu is latitudinally the furthest south, isolated, and a small geographic atoll, all of which likely affect the structure of corals and formation of reefs, driving differences in trends more so than differences in anthropogenic pressure or recruitment.

CONCLUSION

Trends derived from the LTM sites of the National Coral Reef Monitoring program show clear evidence of impacts both global and local stressors. While it was expected that the results would detect the impact of the mass bleaching events of 1998 and 2016, it was not expected that it would detect the impact of minor events, like the tsunami and minor bleaching events, at a national scale.

THE RESULTS OF THIS ASSESSMENT PROVIDE AN INCREASED CONFIDENCE THAT REEFS ARE ABLE WITHSTAND THE DETRIMENTAL EFFECTS OF RELATIVELY SMALLER, LOCALIZED STRESSORS, WHILST AFFECTED BY MAJOR EVENTS.

It suggests that while recovery may be slow, there is a possibility for impacted reefs to recover despite the increasing magnitude and frequency of climate change impacts and accelerating developmental pressure. However, due to limitations of the data available from 1998 to 2021 this report solely analyses hard coral cover which is only one aspect of reef health, recovery, and resilience. Within these limitations, the results of this study cannot disentangle what this recovery fully resembles or entails. In order to assess the health of reefs, reliable assessments of coral community structure, and effects of local temperature variability is necessary.

Indeed, there may be recovery in terms of overall hard coral cover which maintains an aspect of the habitat required for coral reef associate flora and fauna. However, it does not necessarily mean that the same coral communities, both in terms of composition and diversity, will also recover. Different communities with different compositions and diversities may replace those that once existed even if overall hard coral cover returns to what it was previously. Consequently, the result of this study leaves an ambiguity about the true extent recovery of coral communities, including the structural and functional recovery of coral reef systems, through these stressor events.

With the socio-economic and cultural dependency of Maldivians on the coral reefs these changes are a concern because of the implications on what the reefs can continue to provide and support. Transformations of coral communities can shift the characteristics of reef systems and this in turn alter the other flora and fauna that these coral reefs support. Consequently, there is a question of whether Maldivians would be able to depend on or extract that same resources and services these ecosystems provide in the post-disturbance and recovered reefs.

TO FULLY UNDERSTAND THE STATE OF THE REEFS OF THE COUNTRY, OTHER REEF ELEMENTS, INCLUDING STRUCTURAL AND FUNCTIONAL DIFFERENCES OF HARD CORAL COMMUNITIES, ALONG WITH ABIOTIC COMPONENTS WILL NEED TO BE INCORPORATED AND ASSESSED.

Moreover, given the interactions of different drivers, these aspects will need to be investigated whilst accounting for inter and intra-regional effects.

The effect of inter and intra-regional variation along with variability related to the influence of management regimes are also prominent, whereas it would not be possible to rely on a single explanatory factor to resolve the trends of patterns. With increasing urbanization and development across the country putting pressure on reefs and reef related resources, such complexities can pose difficulties in management, mitigation, and conservation efforts. Hence, there is a need to expand data collection that reflects such variability. It will only be through such reflection that data and the respective analyses fully inform conservation and planning strategies such that social, economic, cultural, and ecological will continue to be sustained.

RECOMMENDATIONS

The National Coral Reef Monitoring program bears the mandate of assessing the state and changes to reefs in the Maldives driven by both global and local natural and anthropogenic pressures. Based on the analysis of this report, the following are recommended to bolster the representation, reliability and the sustainability of a national program that collects long term data to provide meaningful inputs into reef management.

The suggested recommendations are listed in order of priority.

I. As a minimum, capture the morphology of hard corals to more reliably assess variation to coral reef functionality and capacity for resilience and recovery. As skill and capacity improves, this should be paired with capture of genus and then species of hard coral present within a reef system.

II. More diligently capture and report the type, abundance and state of other benthic organisms and substrates in assessments of coral reef health, resilience and recovery.

III. To further support robust and holistic assessments of coral reef ecosystem health, more rigorously incorporate the capture and reporting of marine fauna associated with coral reefs.

IV. Improve and strengthen the civil science component of the NCRM program by engaging with citizen scientists, atoll and island councils, NGOs, and other relevant and interested persons from various regions of the country. This would enable the program to have more spatial coverage from various atolls while simultaneously allowing the program to understand the status and trends from atolls with no LTM sites and improving the reliability and accuracy of any regional or national trends that are generated. This would also contribute to better representation of the atolls where long term monitoring takes place

V. Improve and strengthen intersectoral and sub sectoral collaboration and cooperation the implementation of monitoring programs and analysis of data sets. Improved collaboration will decrease the burden of implementation of programs when resources are limited and where there are various logistical constraints. This should entail coordination with the tourism sector as well as the local governments.

VI. Collect environmental and water quality parameters to complement and assess assumptions of localized stressors. A reliable assessment of the reef health requires site level parameters affecting the state of the reefs to compare with the changes in coral cover. This also better equips the monitoring programs to more directly relate the changes to anthropogenic or climate change effects, if any.

VII. More widely incorporate the assessment of coral recruitment to supplement and support information garnered from coral cover data as it relates to reef health, resilience and recovery.

VIII. More widely incorporate the assessment of reef complexity and change over time to determine the capacity of reefs to support and continue to support coral reef associate flora and fauna.

IX. Increase the number of LTM sites in regions with existing LTM sites. Any additional sites should aim to first account for reef exposure and spatial distribution within a region. Balancing the three traditional management regimes and incorporating additional regimes (e.g., MPAs, agriculture, industrial) as secondary regimes can proceed afterwards.

X. Establish new LTM sites and re-initiate NCRM program monitoring in the Gaaf Alif region. The data available for the region within the program is currently severely outdated and available data is from a single site. The region is part of the largest geographic atoll in the Maldives and there is a need to understand status and trends within this atoll. This would also enable better representative assessments of trends and patterns from the southern sector (Huvadhoo to Addu) of the Maldives. Currently, the only consistent contributor to these assessments is Addu.

XI. Establish LTM sites in the south-central sector of the country between Ari and Laamu atoll. Currently, there is a significant gap in the NCRM LTM network from this region and this in turn weakens the reliability of national trends derived from the sites, and this would only be possible with better representation of the reefs of the atoll.

XII. Once re-initiation of the Gaaf Alif region is completed LTM sites will be also established in the Gaaf Dhaal administrative atoll. This will enable status and trend analysis of the geographic Huvadhoo atoll as a whole and further improve reliability and accuracy of analyses of the south sector of the country.

XIII. Establish LTM sites in the Shaviyani administrative atoll. Once these sites are established within this atoll, there will LTM sites distributed throughout the geographic Boduthiladhumathi atoll such that status and trends analysis can be carried out with improved spatial representation, reliability, and accuracy specific to the geographic atoll as opposed to regions.

XIV. Establish LTM sites in the administrative Alif Dhaal atoll. Currently all Ari region sites are clustered in the northern sector of the geographic atoll within the administrative Alif Alif atoll. Similar to both Huvadhoo and Boduthiladhumathi geographic atolls, establishing LTM sites within this administrative atoll will improve the spatial representation, reliability, and accuracy specific to the geographic atoll.

XV. Increase and/establish additional stations on LTM sites to capture intra reef variation. This would be particularly important for long reefs facing pressures from multiple islands with different management regimes.

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APPENDIX

Table 2. *Specific details of the long-term monitoring sites established in the Maldives as part of the NCRM program. List of sites are accurate up to end of 2021. Management regimes are accurate up to the last sampling date used for analysis*

Region	Site	Year established	Latitude	Longitude	Management regime attribution at last sampling date
Haa Dhaal	Hondaafushi	1998	6.772167	73.1325	Resort
	Hirimaradhoo	1998	6.731	73.021833	Community
	Finey	1998	6.751	73.059333	Community
	Kudamuraidhoo	2021	6.63969	72.92262	Uninhabited
	Keylakunu	2021	6.60159	73.00484	Uninhabited
	Vaikaramu-raidhoo	2021	6.54528	72.87829	Uninhabited
Noonu	Maavelaavaru	2011	5.802009	73.175428	Resort
	Manadhoo	2011	5.758521	73.41436	Community
	Dhigurah	2011	5.723524	73.366286	Resort
Raa	Hulhudhufaaru	2011	5.770236	73.014285	Community
	Fasmendhoo	2011	5.492924	72.884717	Resort
	Meedhupparu	2011	5.45558	72.973825	Resort
Baa	Kendhoo	2011	5.277423	73.009608	Community
	Sonevafushi	2011	5.110336	73.076183	Resort
	Olhugiri	2011	5.004195	72.905392	Uninhabited
Lhaviyani	Kuredu	2011	5.546381	73.467689	Resort
	Kurendhoo	2011	5.335826	73.465061	Community
	Maduvvari	2011	5.286148	73.505478	Uninhabited
Kaafu	Bandos	1998	4.266667	73.485333	Resort
	Udhafushi	1998	4.314167	73.502	Resort
	Emboodhoo	1998	4.118667	73.467333	Resort
Ari	Fesdhoo	1998	4.007987	72.811966	Resort
	Maayafushi	1998	4.082333	72.8865	Resort
	Velidhoo	1998	4.082333	72.8865	Resort
Vaavu	Ambaraa	1998	3.435167	73.422167	Uninhabited
	Fohtheyo	1998	3.448333	73.7545	Uninhabited
	Vattaru	1998	3.224833	73.433333	Uninhabited
Gaaf Alif	Kooddoo	1998	0.7355	73.429333	Community
Addu	Hithadhoo-Kottey	1998	-0.584789	73.091206	Community
	Gan	1998	-0.688979	73.162753	Community
	Villingili	1998	-0.675069	73.190801	Resort

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