



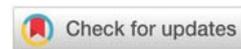
**Received:** 26 July, 2021  
**Accepted:** 14 August, 2021  
**Published:** 17 August, 2021

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**Keywords:** Scleractinian; Coral bleaching; Stress response; Global warming; Coral reef degradation; Consecutive bleaching; Persian Gulf

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## Research Article

# Four consecutive coral bleaching events in the Northern Persian Gulf: 2014–2017

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## Abstract

Climate change-induced bleaching is a serious threat to coral reefs worldwide. In recent years, the number of repeated extensive bleaching events has increased globally. Here, we present four consecutive bleaching events and post-bleaching mortalities from four sites on Hormuz and Larak Islands, Iran, in the Persian Gulf from 2014 to 2017. The high thermotolerance of the corals and their endosymbiotic algae and the strong water currents and sites' turbidity could not protect the majority of the corals against bleaching. Back-to-back bleaching events left almost no unbleached coral colony at any site by 2017. Despite that, coral mortality did not increase at the sites of Hormuz Island that may be a sign of the fast recovery of the Persian Gulf corals after each bleaching event. However, the abundance of coral colonies with 81%–100% mortality at the sites of Larak Island that was constantly minimal in the first three years significantly increased in 2017. Considering bleaching and mortality responses, and abundance dynamics of the coral genera at the study sites, it seems that *Dipsastraea* at the southwest of Larak Island was a short-term winner; despite facing widespread moderate bleaching (i.e., < 50 of a colony was bleached) in 2014–2016, it managed to significantly increase its population in 2015 and 2016. However, in 2017, when almost all colonies were severely bleached (i.e., > 50 of a colony was bleached), there was a non-significant 27% reduction in its abundance. *Dipsastraea* at the north of Larak Island also survived in the first three years, but > 66% of its colonies showed 81%–100% mortality in 2017. Such findings warn that the aforementioned successes by corals are unlikely to persist under annual severe bleaching as is predicted for coming decades.

## Introduction

In the past few decades, global coral reefs have been threatened by a wide range of human activities such as accelerated industrialization, urbanization, agriculture, and natural phenomena including storms and biological stressors [1–4]. However, global warming-induced coral bleaching and mortalities due to fast increases in temperatures that pass coral species' thermal tolerance have become the most prominent concern [5–7]. Such temperature anomalies have destroyed coral reefs worldwide, particularly during the four-year period from 2014 to 2017 [6–12]. For example, mass bleaching happened in the Great Barrier Reef, Australia, in 2016 and 2017

[7,8] and in the central Indian Ocean in 2015 and 2016 [13] including the Persian Gulf [14–18].

As the warmest coral sea [19], the Persian Gulf has been known for its thermotolerant corals, which exhibit the highest thermal tolerance limits known globally [20] and has been frequently considered one of the coral reef refugia against global warming by the end of the century [21,22]. Despite that, coral reefs in the Persian Gulf have frequently encountered massive bleaching and mortality events, especially in the southern part [15,23,24], where temperatures exceeding 35°C for a few weeks initiate bleaching [25,26]. These high temperatures occur due to the shallow depth (mean < 30 m) of the Persian Gulf, restricted exchange with the Indian Ocean, and the hyper-arid

nature of its surrounding environment. Some coral reefs of the southern Persian Gulf have experienced three consecutive coral bleaching and mortality events during 2010–2012 [27]. Severe bleaching has led to mass mortality of the reef-building corals of the Persian Gulf [14,28,29]. In particular, reports from the southern Persian Gulf show post-bleaching mortality events with different intensities in the late 1970s, 1996, 1998, 2002, 2010, 2011, 2012, and 2017 [15,24,27,30,31].

In the northern Persian Gulf, where bleaching threshold temperatures are at least 1.5°C to 2.5°C lower than the southern part, bleaching and mortality events were reported in 2012 [29], 2007, and 2017, with severe long-term consequence [14,16,18]. Here, we report four back-to-back bleaching and mortality events at four sites on two Iranian islands, Hormuz and Larak Islands, during the period 2014–2017. This is to our knowledge the first time in the history of modern coral reefs that some reefs have experienced four consecutive bleaching events.

## Materials & methods

### Study sites

Two major reef sites of Hormuz Island, located in the south (known as the Red Soil, *H-RS*; 27°01'N, 56°27'E) and in the east (*H-E*; 27°03'N, 56°30'E) and two sites on Larak Island, at the north of the island (*L-N*; 26°88'N, 56°35'E) and at the southwest (*L-SW*; 26°49'N, 56°18'E) were chosen. The 2012 mass bleaching was previously studied and recorded at both the Hormuz Island and *L-SW* site of Larak Island [29]. The composition of coral taxa was different among sites and faced various stressors in the past [28,29,32,33]. Turbidity is a natural characteristic of all sites, particularly at the sites of Hormuz Island. The most turbid site is *H-RS*, where horizontal visibility declines to < 2 meters. In addition, water currents at the *H-E* site are very strong so that it even made it difficult for us to conduct this research. The depth of corals at all sites was less than 10 m.

### Survey method

At each site in each year, eight belt transects of 20m\*1 m were randomly selected and photographed/recorded. The coral colonies inside each transect were identified to the genus level. Each colony was categorized based on its bleaching status as unbleached or Healthy (H) if there was no sign of bleaching, moderately bleached (M) if it was bleached < 50%, or severely bleached (S) if it was bleached for > 50%. Each coral colony was identified based on its mortality status as one of the following categories: 1) 0%–20%; 2) 21%–40%; 3) 41%–60%; 4) 61%–80%, and 5) 81%–100%. Mean abundance of coral colonies at each site was calculated based on the average number of coral colonies per transect ( $n = 8$ ).

### Statistical analysis

All statistical analysis were performed in RStudio software (RStudio, Boston, United States). Bleaching rate, mortality rate, and abundance of corals at the study sites in 2014–2017 were assessed using a three-way ANOVA. For all the aforementioned parameters, data were averaged per site ( $n = 8$  transects). The normality of the residuals was verified with a Shapiro–

Wilk's test and the homogeneity of variances was tested using Levene's test. A Tukey-adjusted pairwise comparison between years or between bleaching/mortality categories at each year at each site was applied as a post hoc test when the ANOVA analysis showed a significant effect.

## Results

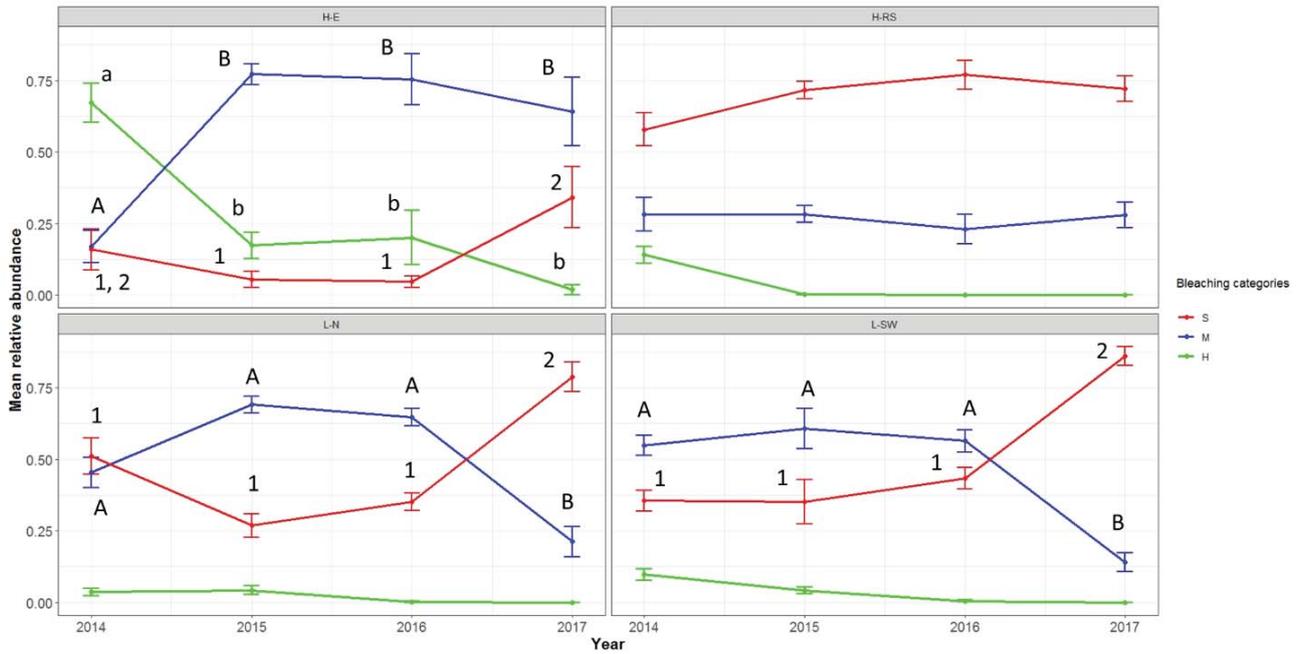
There were significant differences among the three bleaching categories in each year and for each bleaching category among years for each site (Table 1). There were four distinguishable bleaching patterns observed at the sites (Figure 1, Table 2). At site *H-E*, about 69% of the coral colonies were unbleached in 2014 while in 2017 the percent of unbleached coral colonies dropped to < 20%. In 2015, the percent of moderately bleached corals rose from < 20% in 2014 to about 78% and remained almost constant in 2016 and 2017. However, the percent of severely bleached colonies, which was < 15% in the first three years, significantly increased in 2017. At site *H-RS*, in all four years, the percent of severely bleached colonies was significantly higher than the other two categories and the percent of moderately bleached coral colonies was significantly higher than that of healthy (unbleached) corals in 2015 and 2017, and numerically higher in 2014 and 2016. None of the bleaching categories showed a difference between years. At site *L-N*, the percent of unbleached coral colonies was about 5% in 2014 and reached 0 in the following years. In 2014, there was no significant difference between the percent of moderately and severely bleached corals (Table 1). However, in the following two years, moderately bleached corals reached a significantly higher proportion and in 2017 the percent of severely bleached corals increased to about 78%, which was significantly higher than the percent of moderately bleached corals. The bleaching pattern at *L-SW* was similar to that of *L-N* with one major difference: the differences between the proportion of moderately and severely bleached corals in 2014, 2015, and 2016 were non-significant.

Bleaching intensity for the majority of coral genera under consecutive bleaching events significantly increased in 2017 compared to previous years so that coral genera that were mainly moderately bleached in the first three years were severely bleached in 2017 (Figure S1). *Dipsastraea* at the site *H-RS*, whose whole population was severely bleached in the previous three years, showed a significant reduction in the percent of severely bleached corals without any increase in the percent unbleached corals (Figure S1).

There were significant differences among the mortality categories in each year and for each bleaching category among years for each site (Table 3). Mortality remained low at *H-E*

**Table 1:** Three-way ANOVA analysis of coral bleaching at the study sites from 2014 to 2017.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Bleaching categories	2	11.445	5.723	296.39	0.000	***
Site : year	9	0	0	0	1.000	
Site : bleaching categories	6	7.965	1.328	68.76	0.000	***
Year : bleaching categories	6	4.861	0.81	41.96	0.000	***
Year : bleaching categories: site	18	4.748	0.264	13.66	0.000	***



**Figure 1:** Bleaching patterns of corals at the study sites shown based on percent mean relative abundance. H = healthy (unbleached), M = moderately bleached, and S = severely bleached. Significant differences in percent healthy, moderately, and severely bleached corals between years are shown with small letters, capital letters, and numbers, respectively. Similar letters/numbers mean no significant difference. Wherever there are no letters/numbers, it means there was no significant difference for that category between years (e.g., all bleaching categories at *H-E*). Bar values represent means and error bars represent the standard error of the mean. The significant differences between bleaching categories are presented in Table 2.

**Table 2:** Pairwise comparisons between percent mean abundance three bleaching categories in each year at each studied site. H = healthy, M = moderately bleached, and S = severely bleached. Significant differences are shown with asterisks.

H-E				
2014		H	M	S
	H		*	*
	M			
2015		H	M	S
	H		*	
	M			*
2016		H	M	S
	H		*	
	M			*
2017		H	M	S
	H		*	*
	M			*
H-RS				
2014		H	M	S
	H			*
	M			*
2015		H	M	S
	H		*	*
	M			*
2016		H	M	S
	H			*
	M			*
2017		H	M	S
	H		*	*

L-N				
				*
2014		H	M	S
	H		*	*
	M			
2015		H	M	S
	H		*	
	M			*
2016		H	M	S
	H		*	*
	M			*
2017		H	M	S
	H			*
	M			*
L-SW				
2014		H	M	S
	H		*	
	M			
2015		H	M	S
	H		*	*
	M			
2016		H	M	S
	H		*	*
	M			
2017		H	M	S
	H			*
	M			*



and H-RS with no significant difference between mortality categories in each year or for each mortality category between years (Figure 2, Table 4). Similarly, mortality rates at L-N and L-SW were low with no significant difference except in 2017, when abundance of colonies with 81–100% mortality was significantly higher than the other categories (Table 4).

The coral genera mainly showed limited mortality and many of them showed signs of mortality in just one year (Figure S2). For example, almost all *Acropora* colonies at the site L-N that were recorded with minimal mortality in the first three years showed 81%–100% mortality in 2017. *Acropora* at the site L-SW and *Porites* at the site L-N showed significant increases in percent coral colonies that were severely bleached from 2014 toward 2017 (Figure S2).

The abundance of coral colonies at none of the sites showed any significant difference between years, except for L-N, where the abundance of corals significantly declined in 2017 compared to 2015 (Figure 3). The majority of coral genera did not show significant changes. Those genera were mainly limited to < 5 colonies per transect per year at all sites (Figure

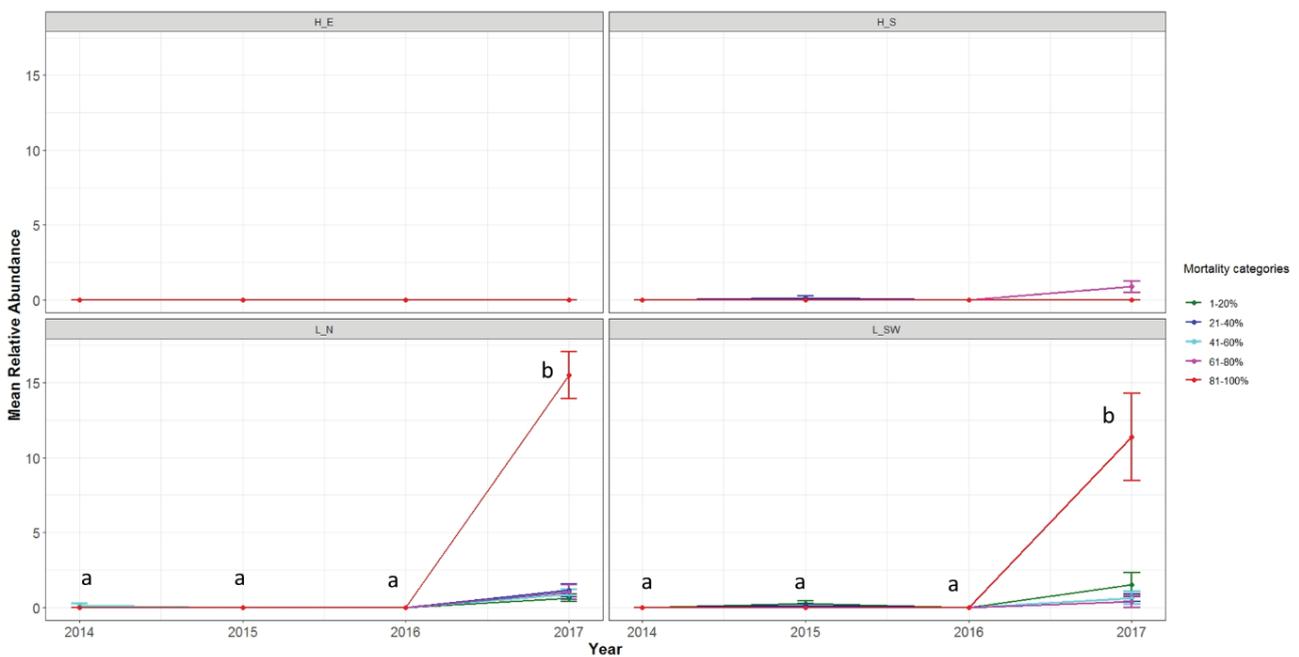
S3). *Favites* from the site H-RS that comprised 15 colonies per transect in 2014 declined to almost 0 in 2017 (only 3 colonies in 8 transects; Figure S3). *Porites* at the site L-N declined 66% in 2017 compared to 2014. *Acropora* at the site L-N and *Porites* at the site L-SW showed significant increases in 2015 and 2016 compared to the previous years, respectively; however, they both declined by approximately 50% in the following year (significantly for *Acropora* and non-significantly for *Porites*; Figure S3). The abundance of *Dipsastraea* at the site L-SW showed significant increases in 2015 and 2016 compared to previous years, but a non-significant decline in 2017 (Figure S3).

### Discussion

To the best of our knowledge, this is the first time in the history of modern coral reefs that four consecutive bleaching events have been reported. It must be taken as a serious warning message for all the world’s coral reefs because first, the Persian Gulf has been considered a coral reef refugium, where corals could survive climate change by 2100 [21,22]. Secondly, these corals are known to encompass some of the most thermotolerant reef-building corals [19,34] and associated endosymbiotic algae [35–38] and face the highest SST records in the world [14,39]. Third, seawater turbidity, which may reduce the severity of bleaching [40–45] is an intrinsic characteristic of the Persian Gulf including our study sites, particularly on Hormuz Island [28,29]. Fourth, strong water currents that were suggested to ameliorate the negative effects of thermal stress on corals [45–47], were present at the site H-E. Conversely, our data question such predictions and show that neither the thermotolerance of the corals and their symbionts nor the natural turbidity and strong water currents could protect coral reefs of the Persian Gulf. It was suggested

**Table 3:** Three-way ANOVA analysis of coral mortality at the study sites from 2014 to 2017.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Site	3	5.4	1.793	7.896	0.000	***
Year	3	16.8	5.587	24.601	0.000	***
Mortality categories	4	11.7	2.927	12.887	0.000	***
Site : Year	9	15.9	1.767	7.78	0.000	***
Site : mortality categories	12	13	1.085	4.777	0.000	***
Year : status	12	35.8	2.987	13.15	0.000	***
Site : year : mortality categories	36	39.1	1.087	4.787	0.000	***



**Figure 2:** Mortality patterns of corals at the study sites shown based on percent mean relative abundance (i.e., %). Bar values represent means and error bars represent the standard error of the mean. Significant differences in each mortality category between years are shown with small letters. Similar letters mean no significant difference. The significant differences between mortality categories in each year are presented in Table 4.



that the Persian Gulf will be the last place where coral reefs will face annual severe bleaching [21]. However, our study warns that the coral reefs of the Persian Gulf may be among the first reefs in the world to disappear. Mass coral bleaching events have been frequently reported from the Persian Gulf in the past three decades [15,24,27,30,31]. Three back-to-back bleaching events have happened before this in the southern Persian Gulf in 2010, 2011, and 2012 [27]. However, it seems that the northern Persian Gulf is becoming a major bleaching hotspot.

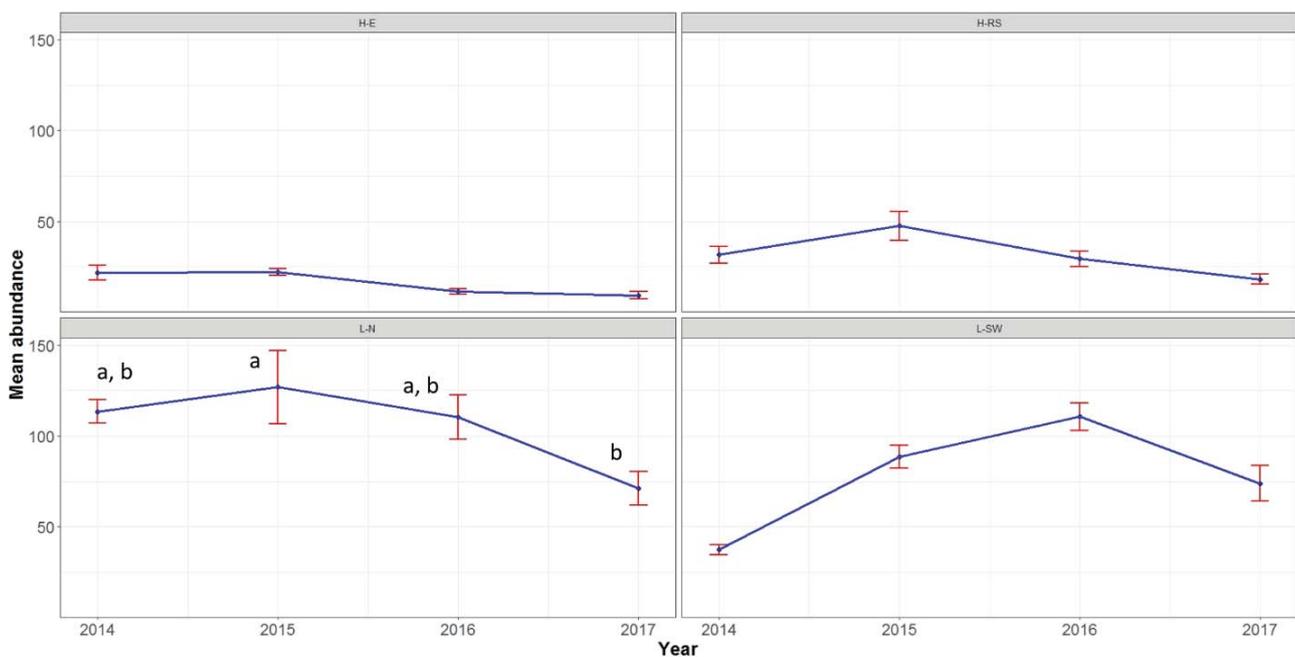
The four consecutive bleaching events in the northern Persian Gulf happened just one year after the 2012 massive bleaching that resulted in the bleaching of 84% of the corals [29]. For example, 100% of the corals at *H-E* were to some degree bleached in 2012. On the other hand, in 2014, 69% of

the corals at *H-E* did not show any sign of bleaching unlike the other three sites where at best <15% of their coral communities were unbleached. This suggests that reef-building corals at *H-E* (and likely other sites) managed to recover fast from the 2012 bleaching. Fast recovery may be a characteristic of the Persian Gulf corals, particularly at Hormuz Island because despite four consecutive bleaching events, there was no increase in coral mortality intensity and decline in coral abundances at *H-E* and *H-RS*. Another reason may be that the intensities of the bleaching events were not much higher than the maximum monthly mean temperatures of the sites for a long enough time to kill the corals. This needs to be further studied. However, the back-to-back bleaching events from 2014 to 2017 left almost no unbleached coral colony at none of the study sites (except a few massive *Porites* colonies at *H-E*) by the end of the 2017 bleaching. In fact, at all sites, except *H-E*, 73%-86% of the coral colonies were severely bleached. Even the percent of severely bleached corals significantly increased at *H-E* in 2017. The corals at the *L-N* and *L-SW* sites, which did not show mortality in the first three years, showed significant increases in percent of coral colonies with 81-100% mortality in 2017. This confirms previous studies that suggested consecutive bleaching events can lead to coral reef degradation because they do not give the bleached corals enough time to recover and produce larvae in order to return the reefs to their original, pre-bleached state [27,48]. Bleaching events may have long-term dramatic impacts on coral reef ecosystems and services that can be observed years later [14,49-51].

The bleaching pattern observed at *H-E* was different from the other study sites. The corals at *H-E* survived the bleaching in 2014 so that only 31% of the corals were bleached and by the end of the 2017, only 34% of the corals were severely bleached

**Table 4:** Pairwise comparisons between percent mean abundance of five mortality categories in 2017 at *L-N* and *L-SW*. Significant differences are shown with asterisks. There was no significant difference at *H-E* and *H-RS* in any year or at *L-N* and *L-SW* in 2014, 2015, and 2016.

		L-N				
2017		1%-20%	21%-40%	41%-60%	61%-80%	81%-100%
	1%-20%					*
	21%-40%					*
	41%-60%					*
	61%-80%					*
		L-SW				
2017		1%-20%	21%-40%	41%-60%	61%-80%	81%-100%
	1%-20%					*
	21%-40%					*
	41%-60%					*
	61%-80%					*



**Figure 3:** Mean abundance of coral colonies at the study sites. Significant differences between years are shown with small letters. Wherever there are no letters, it means there was no significant difference for that category between years. Similar letters mean no significant difference. Bar values represent means and error bars represent the standard error of the mean.



(against 73%–86% at other sites). One reason could be the fact that the dominant coral genus at H-E is the massive *Porites*, which accounted for > 85% of the coral cover [28]. In other sites, massive *Porites* was not the dominant genus. Massive *Porites* species are among the most tolerant reef-building coral species against elevated temperatures [52,53]. Some studies suggested that bleaching events may increase the thermotolerance capacity of the corals via acclimation/adaptation [54–56]. However, that seems to be very unlikely here (Figure 1) perhaps due to the limited capacity of tolerant corals to extreme heat stress [57]. In 2012, an elevated temperature-related White Mat Disease infected 96% all the *Porites* colonies and killed 58% of all *Porites* tissues at H-E [28]. By 2017, bleaching severity had increased; the most likely reason behind less severe bleaching at H-E compared to other sites is that the majority of the coral colonies that were vulnerable to global warming-induced bleaching died and the most tolerant colonies survived. Such huge intercolonial differences in given coral populations facing thermal stress are abundant [58,59].

No coral genus was a winner against bleaching. However, *Dipsastraea* at the site H-RS showed significant decline in percent severely bleached colonies by 2017. This did not lead to an increase of unbleached corals, but as there was no significant reduction in the population of *Dipsastraea*, it may be a sign of acclimation/adaptation induced by previous bleaching events. However, changes in coral populations can happen years later after bleaching. Interestingly, *Dipsastraea* at the site L-SW showed significant increases in its population in 2015 and 2016 compared to previous years. In both years, about 75% of *Dipsastraea* colonies were moderately bleached. Increases in abundance despite being bleached may suggest that the bleached colonies managed to reproduce larvae as did other genera around the world [60–62]. However, > 90% of fully bleached colonies showed a non-significant 27% reduction in the abundance of *Dipsastraea* in 2017, which may suggest limitations in the physiological capabilities of strong coral taxa under repeated bleaching events [57,62–64]; this was observed for the same species at the site L-N with 65% of colonies showing 81–100% mortality in 2017, whereas they were mortality-free in previous years. Similarly, significant increases in the abundance of *Acropora* at the site L-N and *Porites* at the site L-SW in 2015 and 2016 compared to the previous years, respectively, suggest either tolerance to thermal stress and successful reproduction, or fragmentation. However, their following decline shows their limitations as well. Such limitation under consecutive bleaching led to a 66% decline in *Porites* population at the site L-N and almost 100% decline of *Favites* at the site H-RS. Experimental studies showed that under two consecutive bleaching events, some species may manage to recover and survive while others may not [57,65]. Even short-term winners may become losers over time [52]. Therefore, although some tolerant colonies may survive even four back-to-back bleaching events, by increasing the number of severe bleaching events all coral taxa may be losers.

## Conclusion

In conclusion, our study shows that even the most thermotolerant coral reefs of the world can face back-to-back

bleaching events that lead to increased coral mortality and reduction in coral abundance at some sites. The significant increases in the frequency of *Acropora* coral colonies with 81%–100% mortality at the sites of Larak Island in 2017 despite being constantly minimal in the first three years highlights the fact that we cannot rely on the physiological acclimation/adaptation of corals or natural phenomena such seawater turbidity to save coral reefs. The repeated bleaching events did not seem to lead to increased tolerance of the corals of the study sites, except for *Dipsastraea* at the southwest of Larak Island that managed to significantly increase its population in 2015 and 2016. However, the non-significant 27% reduction in its abundance in 2017, when almost all colonies were severely bleached suggest that these results must be interpreted with caution. In particular that, for *Dipsastraea* at the north of Larak Island that managed to survive in the first three years, > 66% of its colonies showed 81%–100% mortality in 2017. Unfortunately, there is no effective management strategy to protect global coral reefs from climate change-induced thermal stress [7]. Therefore, as previously suggested, it seems the only way to prevent reef-building corals from reaching extinction is to substantially reduce greenhouse gas emissions, including carbon dioxide.

## Author contributions

JK designed the experiment, collected the data, wrote the paper, PTK collected the data, SHK collected the data, and FG analyzed the data.

## (Supplementary materials)

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