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Responses of reef bioindicators to recent temperature anomalies in distinct areas of the North Ari and Rasdhoo atolls (Maldives)

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ABSTRACT

Assessments of reef sediments in the North Ari Atoll (Maldives) were conducted in 2015 and 2018 on reefs of three islands with different management strategies: community, resort, and uninhabited. Indices applied were the Foraminifera in Reef Assessment and Monitoring Index (FI) and the Sediment Constituents Index (SI). Both indices are based on shells or fragments of functional groups, which for the FI are foraminiferal shells and for the SI are sediment components. The FI is considered to be an indicator of water quality and the SI an indicator of water quality, community structure, and processes such as grazing and bioerosion. Both indices indicated that environmental deterioration occurred between 2015 and 2018, likely related to the intense temperature anomaly in March–June 2016 that caused widespread coral bleaching and mortality. Median FI declined from 5.1 to 4.0 overall, indicating that water quality still supports reef accretion, though the replacement of coral cover by algae and sponges likely provides more food sources for smaller, faster-growing foraminiferal species. The median SI values similarly declined from 3.8 to 3.0, reflecting a decrease in identifiable coral fragments and an increase in unidentifiable clasts, likely indicative of increased bioerosion. Although a minor component, molluscan fragments also increased by 25%, likely in response to more algal cover for grazers. In 2015, the FI and SI data indicated that the island management regime contributed to the reef health status. Uninhabited islands were associated with higher indices compared to resort and community islands. A clear distinction between management regimes was not observed in 2018, because a major decrease in FI (median: 4.9 in 2015, 2.9 in 2018) was recorded offshore from an agricultural settlement on the previously "uninhabited" island surveyed. These observations support the usefulness of these indices in reef assessment, and provide additional understanding that the FI can respond to a coral-mortality event that alters food sources in the benthic community.

1. Introduction

Coral reefs are among the most diverse, complex and vulnerable ecosystems on Earth, and their status is influenced by a wide range of environmental variables (e.g., Reaka-Kudla, 1997; Langdon and Atkinson, 2005; Anthony et al., 2008, 2011; Meissner et al., 2012). These environmental factors include increasing occurrences of regional temperature anomalies associated with El Niño-Southern Oscillation (ENSO) events (e.g., Jokiel and Coles, 1990; Hoegh-Guldberg, 1999, Wilkinson et al., 1999; Graham et al., 2015), and anthropogenic impacts (e.g., Sandin et al., 2008, Morri et al., 2010; Pisapia et al., 2017a,b). In particular, environmental pressure on coral reefs drastically increased with the most recent El Niño event that produced anomalously elevated sea-surface temperatures (SST) that persisted

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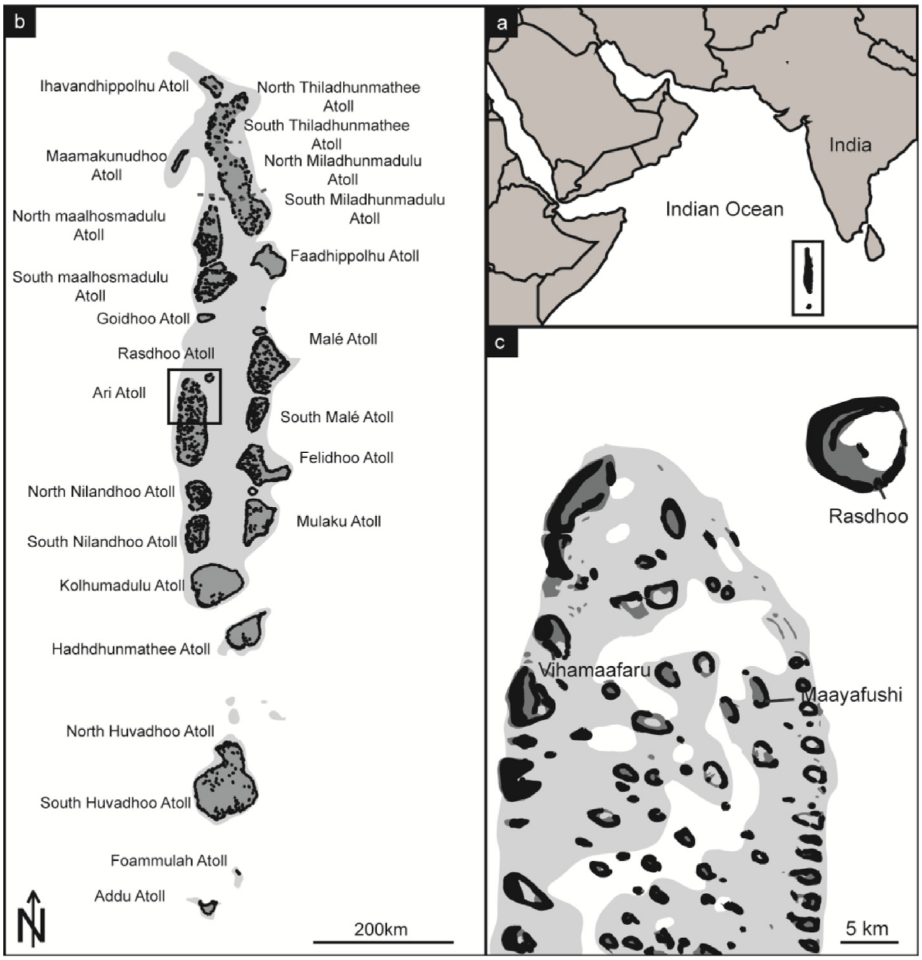

Fig. 1. Location map showing the investigated Islands in the Rasdhoo and North Ari (Alifu Alifu) Atolls. Dashed lines represent governmental and administrative boundaries, solid lines represent atoll boundaries.

from March to mid-May 2016 and inducing severe coral bleaching nearly worldwide (NOAA Coral Reef Watch., 2015).

Numerous kinds of organisms are associated with coral-reef ecosystems, including soft and hard corals, mollusks, crustaceans, sponges, algae, fishes, turtles, marine mammals and biomineralized microorganisms (e.g., Reaka-Kudla, 1997; Hallock et al., 2003), which result in complex interactions. Reef communities are intertwined such that the introduction and/or disappearance of species, or even a change in their abundance, may significantly alter the balance of the whole ecosystem following equilibrium and non-equilibrium dynamics (Karlson and Hurd, 1993).

The most accepted metric to assess the status of a coral reef is the living coral cover. However, the simple evaluation of this parameter may mask on-going variations in ecological processes, recruitment, or species assemblages (e.g., Hughes et al., 2010; McClanahan et al., 2011). Therefore, additional approaches can provide a more comprehensive view of the overall state of a reef (Sandin et al., 2008).

The Foraminifera in Reef Assessment and Monitoring Index (FI) was developed by Hallock et al. (2003) and successively revisited by Hallock (2012) and Prazeres et al. (2019) as a supplementary method to assess the status of coral reefs of the western Atlantic and Caribbean on multi-year timescales. Despite some regional limitations (e.g., Hallock, 2012 and references therein), since its development the FI has been used worldwide as a low-cost reef-assessment tool (Pisapia et al., 2017b; Prazeres et al., 2019; and references in both). The FI is based on the presence and abundance of foraminiferal taxa attributed to three functional groups (symbiont-bearing, stress-tolerant and other small foraminifera) in sediments collected within reefs (between 5 and 15 m water depth). The proportions of the three groups provide a simple but sensitive and efficient tool to discriminate between healthy reefs, reefs in chronic decline and acute coral-specific mortality events (Cockey et al., 1996; Hallock et al., 2003; Hallock, 2012; Pisapia et al., 2017b and references therein).

Based upon studies of changes in constituents of Florida reef sediments (Lidz and Hallock, 2000; Daniels, 2005; Ramirez et al. 2008) proposed the Sediment Constituent Index (otherwise called SEDCON Index or SI) as a tool to evaluate changes in community structure and accretion potential, ranging from a reef-building mixotrophic assemblage dominated by coral fragments and symbiont-bearing foraminifers, to a hard-ground assemblage dominated by unidentifiable fragments and with heterotrophic contributors including smaller foraminifers and molluscan fragments. Similarly to the FI, the SI constituent proportions were proposed to reflect water quality and other environmental changes over years, related to the reduced accretion potential associated with chronic decline in water quality or more acute stress events (Ramirez et al., 2008). Ramirez et al. (2008) found that sediment composition is strongly influenced by sediment texture and therefore, both local hydrodynamics and major storms. To date, the SI has not been applied outside the Florida reef tract as it was only used to reveal changes. As such, originally proposed thresholds for Florida were used in this study (Daniels, 2005; Ramirez et al., 2008).

Maldivian reefs are among the most diverse within the Indian Ocean. They host over 250 species of corals and 1200 species of fish (Naseer and Hatcher, 2004). They are considered generally healthy, supporting active accretion by reef-builders, although indications of deterioration have been noted by studies of coral cover and foraminiferal assemblages in some locations (Moritz et al., 2017; Pisapia et al., 2017a). In particular, Pisapia et al. (2017b) reported lower FI values from reefs near islands hosting permanent human settlements (community and resorts), compared to uninhabited islands.

A survey carried out in 2018 by a Training Through Research expedition organized within the framework of the "Conférence Universitaire de Suisse Occidentale" (CUSO) in the Maldives targeted the islands of Rasdhoo (community), Maayafushi (resort) and Vihamaafaru (previously uninhabited but by 2018 semi-uninhabited, with the presence of agricultural crops) to investigate the reef status following the 2016 El Niño event. We present here the results from assessment of the FI and SI found during the 2018 survey compared with those obtained from a pre-bleaching survey performed during the International Union for Conservation of Nature (IUCN) REGENERATE cruise in April–May 2015 (Moritz et al., 2017¸ Pisapia et al., 2017a,b).

2. Material and methods

The islands of Rasdhoo (community), Maayafushi (resort) and Vihamaafaru (semi-uninhabited) located respectively in the Rasdhoo and North Ari atolls, were surveyed during the CUSO Maldives Training Through Research expedition from 1 to 8 September 2018 (Fig. 1). At each island, two reef sites were chosen (Fig. 2, black lines) based upon the locations of sites sampled during the IUCN REGENERATE cruise in 2015 (Fig. 2, red lines; Pisapia et al., 2017a,b). Samples were treated following the procedure described in Pisapia et al. (2017b). The 0–1 cm sediment surfaces were collected at 10 m water depth into 15 ml falcon tubes by SCUBA divers, avoiding areas with coral or algal cover. Three replicates for each site were taken along the reef slopes at 25 m distance apart, for a total of 18 samples. Samples were placed in a rose Bengal-alcohol solution (2 g/l) to ascertain that dead species had living counterparts. All samples were left to dry at room temperature and weighed.

The FI assessment was done on a 1 g aliquot of sediment, dry split with a standard splitter, for each sample. Since the proportion of sediments < 63 μm was negligible, the samples were not subsequently wet sieved. Sediments were placed on a gridded picking tray, examined with a stereomicroscope, and 150–200 specimens were picked from the dead assemblage (unstained specimens) of each sample, following the standard protocol of Hallock et al. (2003). The picked foraminiferal specimens (Supplementary Material 1) were grouped into the three functional groups (symbiont-bearing, stress tolerant and other small foraminifera, following Pisapia et al. 2017b) and counted. The FI for each sample was calculated according to the equation in Table 1 and the median for each site was calculated. According to Pisapia et al., (2017b) and confirmed by Prazeres et al., (2019), calcarinids have been retained in the calculation of the FI as in an oligotrophic environment, like the Maldives, they are a sensitive component of the assemblages.

Similarly to above, 1 g of dry sediment was used for the SI calculation for each sample. A total of 300 sediment components were identified and counted from the size fractions between 0.5 and 2 mm. The functional groups used to calculate the SI are noted in Table 2. The SI for each sample was calculated according to the equation in Table 1 and the median for each site was calculated.

The remaining sediments were used to quantify sediment textures. This portion of the samples was dry sieved using standard mesh sizes of 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm, 0.040 mm and $<$ 0.040 mm. Each fraction was weighed and the weight percentage of each fraction calculated, allowing the median grain size to be determined for each sample.

A Principal Components Analysis (PCA), using FI, SI and grain-size data from 2015 and 2018 and combining the type of management and the year, was obtained with PRIMER v7 (Clarke and Gorley, 2015). Grain-size data from 2015 and 2018 were normalized and the PCA was run to identify possible differences within the data.

3. Results

The benthic foraminiferal assemblages identified in the samples from the Rasdhoo and North Ari atolls (Supplementary Material 1) were similar to those reported by Pisapia et al. (2017b). However, the proportions of the functional groups differed between 2015 and 2018. Symbiont-bearing species decreased in relative abundance and both stress-tolerant and other small foraminiferal species increased in the 2018 samples, compared to the samples collected in 2015 (Supplementary Material 1).

In the 2015 samples, symbiont-bearing foraminifera were dominated by *Amphistegina* spp., with *Calcarina defrancei*, *Neorotalia calcar, Sorites* spp., *Peneroplis* spp. and *Borelis* sp. less commonly occurring. Stress-tolerant taxa included calcareous bolivinids, elphidids and very rare *Ammonia* spp., and agglutinated taxa such as *Eggerelloides* spp. (Pisapia et al., 2017b). In the samples from 2018, *Calcarina defrancei*, and *Neorotalia calcar* were largely missing. The median FI in the samples declined from ∼ 5 in 2015 to ∼ 4 in 2018 at Rasdhoo and Maayafushi. At Vihamaafaru, the overall median FI decreased from 5.4 in the 2015 samples to 4.2 in 2018. However, the overall median masked a notable difference in the data (Fig. 2–2b and c, Table 3) from the sites Vih 1.1, 1.2 and 1.3 (in 2015, median FI = 7.2; in 2018, FI = 4.2) compared to the sites Vih 2.1, 2.2, 2.3 (in 2015, median FI = 4.9; in 2018, FI = 2.9) The northeastern site (Vih 2) is just offshore from a small agricultural settlement that was not present in 2015 (Fig. 2a).

The most abundant sediment constituents in the 2018 data set were unidentified fragments (50% overall), followed by coral fragments (20%), molluscan fragments (8%), symbiont-bearing foraminifera (7%), corallinae and calcareous algal fragments (combined ∼ 8%), and other categories (combined $<$ 7%). The overall relative abundance of coral fragments was higher in 2015 (28%), while unidentified fragments (45%), molluscan fragments (6.4%) and symbiont-bearing foraminifera (5.8%) were less abundant. Other components remained relatively unchanged. Between 2015 and 2018, the median SI showed an overall decline (3.8 to 3.0), with 3.7 to 3.0 at Rasdhoo; 3.6 to 3.0 at Maayafushi and 4.1 to 3.5 at Vihamaafaru (Fig. 2; Table 3, Supplementary Material 1).

In the PCA plot, PC1 and PC2 explained 62% of the data variance (Fig. 3, Supplementary Material 3). The plot revealed a clear separation between the samples collected in 2015 and 2018, correlating with higher FI and SI values in 2015.

4. Discussion

The FI reflects the environmental conditions over temporal scales of months to years, since it is based on time-averaged assemblages (Hallock et al., 2003; Ramirez et al., 2008). Because the FI can be influenced to some degree by sediment texture, Hallock et al. (2003) recommended that grain-size analyses be carried out on subsamples of sediments analyzed using the FI. Moreover, because seasonal changes in wind direction and storm activity can influence sediment components, Hallock (2012) recommended that between-year comparisons be carried out during the same season, when possible. The FI has been generally linked to water quality (Ramirez et al., 2008; Uthicke and Nobes, 2008; Uthicke et al., 2010; Koukousioura et al., 2011; Velásquez et al., 2011; Reymond et al., 2012; Hallock 2012; Oliver et al., 2014). Pisapia et al. (2017b) showed that the *in-situ* water parameters measured during the 2015 sampling campaign in the Maldives fall not only within typical ranges for reefs but also within ranges previously documented in the Maldives and adjacent regions of the Indian Ocean (e.g., Ramamirtham, 1968; Wild et al., 2010; Zweng et al., 2013; Lauvset et al., 2015). Therefore, their study demonstrated that water parameters measured at the time of sampling did not significantly influence the FI in the North Ari Atoll. As previously mentioned, the FI is representative of longer term conditions and not a snapshot of the current

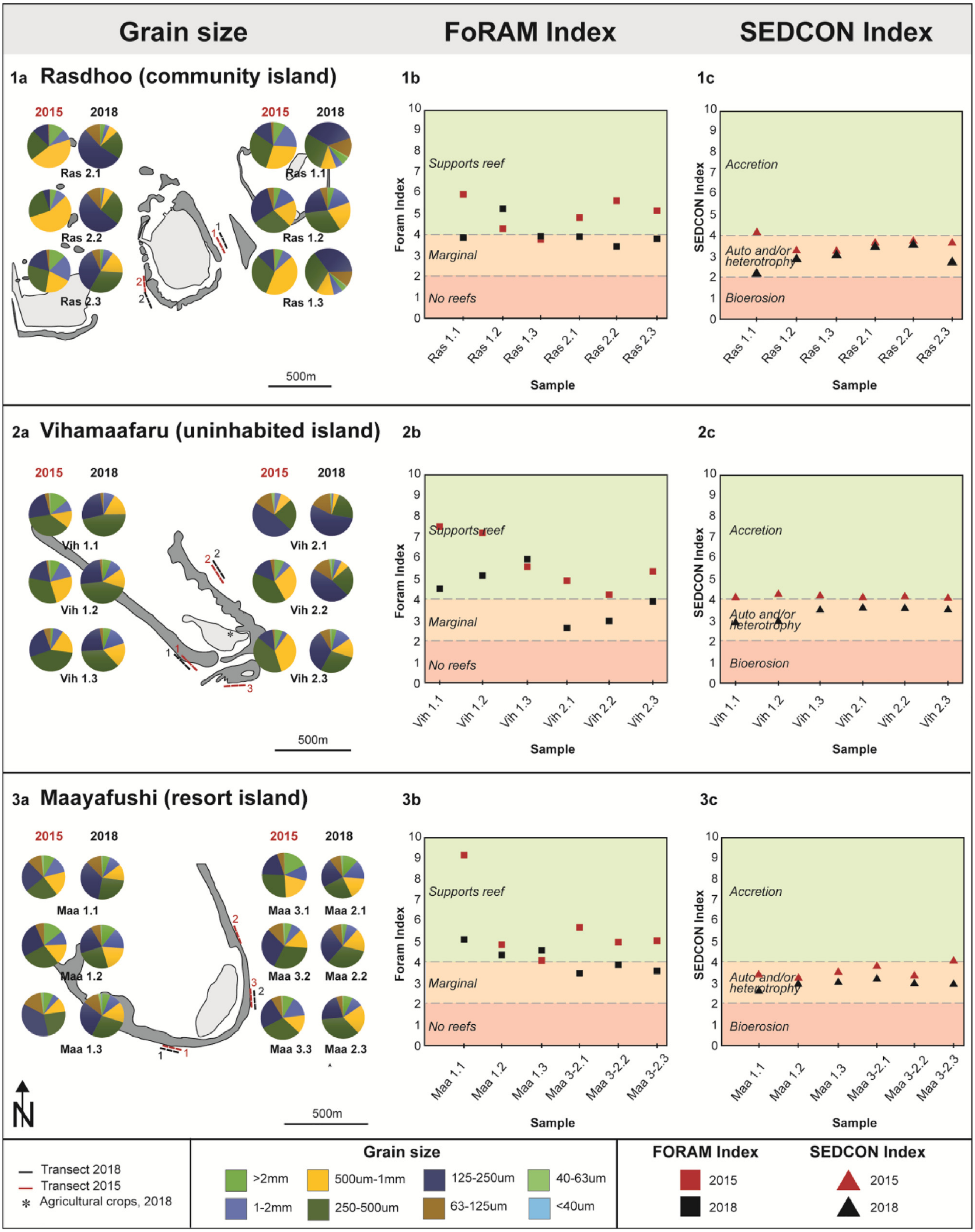

Fig. 2. The FI and SI values in 2015 and 2018 from (a) Rasdhoo, community island; (b) Vihamaafaru, semi-uninhabited island; and (c) Maayafushi, resort island. Pie charts represent the sediment grain size percentages from 2015 and 2018. Numbers next to the transect lines represent transect numbers.

situation. Similarly, the SI reflects processes affecting the macrobenthos on multi-year time scales, such as changes in nutrient input or coral mortality that promote increased influence of bioerosion, grazing by gastropods and urchins, and calcareous algal production, with a consequent variation in the carbonate production (Daniels, 2005; Ramirez et al., 2008). Therefore, water parameters are not discussed here.

Using the FI, Pisapia et al. (2017b) reported that the Maldivian reefs

Table 1
Equations and parameters used to calculate the FI and SI (modified after Ramirez et al., 2008).

$FI = (10*P_s) + (P_o) + (2*P_h)$	
	$P_s = N_s/T$
Where	$P_o = N_o/T$
	$P_h = N_h/T$
	T = total number of specimens counted (150–200)
	N_s = number of symbiont-bearing Foraminifera
And	N_o = number of stress-tolerant Foraminifera
	N_h = number of other small, heterotrophic Foraminifera
$SI = (10*P_c) + (8*P_f) + (2*P_{ah}) + (0.1*P_u)$	
	$P_c = N_c/T$
Where	$P_f = N_f/T$
	$P_{ah} = N_{ah}/T$
	$P_u = N_u/T$
	T = total number of grains counted (3 0 0)
	N_c = number of coral fragments
And	N_f = number of symbiont-bearing Foraminifera
	N_{ah} = number of coralline and calcareous algae, heterotrophic skeletal grains (e.g., molluscs, echinoids, worm tubes, bryozoans, smaller Foraminifera)
	N_u = number of not identified fragments

(having overall values > 5) appeared to be healthy and that water quality supported active accretion by reef-building corals and larger benthic foraminifers. They also showed that healthier conditions prevailed around uninhabited islands and that islands hosting permanent human settlement showed some local deterioration in water quality. Our results revealed that both FI and SI values decreased between 2015 and 2018 (pre- and post-2016 bleaching). Therefore, by using these two indices, we have the unique opportunity to observe and document some of the complex physical and ecological interactions that control reef equilibrium.

A factor that can influence both indices is grain size (Hallock et al., 2003; Ramirez et al., 2008; Carnahan et al., 2009; Barbosa et al., 2009). In particular, higher values of FI can be expected to positively correlate with coarser grain size (Hallock et al., 2003; Ramirez et al., 2008) and negatively with fine grain size (e.g., Narayan and Pandolfi, 2010). The positive correlation with grain size can occur because the hydrodynamic processes that remove finer grains, which include smaller foraminiferal tests, can concentrate the larger tests of symbiont-bearing foraminifera. Their proportions in medium to coarse-sized sand grains can vary from 20% to 95% (Hohenegger, 2006).

The PCA plot (Fig. 3) shows a clear separation between 2015 and 2018 samples. In the 2015 samples, the median grain size at the Rasdhoo was coarser (0.5–1 mm) than in 2018 (median 0.25–0.5 mm). At Maayafushi, the median was 0.25–0.5 mm both years. At Vihamaafaru, a reduction in grain size can be seen in the 2018 samples from the northeastern site (Vih 2), where median values of FI also decreased from 4.2 to 2.9. This decline may be related to the installment of a small agricultural site on the northeastern side of the island (Fig. 2a). While no seawater nutrient data are available, we assume there would be some increase in nutrients due to an anticipated increase in organic matter related to the agricultural practices. Furthermore, the island management regime does not seem to influence either the FI or SI, as no clear separation is visible (Fig. 3).

Based on our observations, the reduction in grain size is indicative of an intensification of bioerosion possibly resulting from the ENSO pulse that occurred in 2015–2016 that caused extensive coral mortality. Indeed, dead corals are subject to more intense bioerosion than living ones, especially by fish and urchins grazing on algae growing on the dead coral, as well as by recruitment of bioeroding sponge species on dead coral skeletons. A perturbation such as a severe ENSO-induced bleaching can cause direct mortality, in addition to disease-related mortality (Glynn and Manzello, 2015). The consequent change in substratum may have created more suitable niches for smaller foraminifera, resulting in lower FI values in 2018. This is an important observation because Cockey et al. (1996) and Hallock et al. (2003) predicted that the FI should not be influenced by coral mortality. Generally, coral mortality results in an increase in benthic cover by filamentous and fleshy algae (e.g., Clarke et al., 2000), therefore, there will be more food available for heterotrophic species, including not only smaller, faster-growing foraminiferal species, but also grazers such as urchins, as well as some taxa of fish and gastropods.

The decrease in the SI between 2015 and 2018 was likely the consequence of increased bioerosion associated with boring sponges (by chemical secretion) and the grazers noted above (Dorgan, 2015). The effect of wave erosion can be excluded as the sample positions are below the wave base in the Maldives (Kench et al., 2006). The lower SI values in the 2018 data are consistent with the lower FI values, and reflect the deterioration of the reef environment, which is also indicated by the increase in unidentifiable fragments compared to coral fragments.

During the 2018 expedition, a parallel investigation examined corals and benthic communities to more directly quantify the effect of the 2016 ENSO-driven bleaching event. That data set revealed a significant reduction in the coral cover (Fig. 4a and b) (Caragnano et al., submitted). The loss of coral cover was also observed in other Maldivian reefs (Pisapia et al., 2019). The presence of *Acanthaster planci* increased, a corallivorous starfish linked with the anthropogenic nutrification that contributes to the disruption of reef environments (Pisapia et al., 2017b). However, the potential for these reefs to recover is promising, as indicated by the presence of abundant small (5 cm) coral colonies (Fig. 4c). Thus, even though the FI and SI show an overall environmental decline, water quality remains suitable for reef accretion as such the natural resilience of the Maldivian coral reefs is promising, unless mass coral bleaching and mortality events occur with greater frequency.

Table 2
Functional groups used for the calculations of the SEDCON Index (SI) modified after Ramirez et al. (2008).

Sediment Grains	Community Role/feeding Mode	SI Interpretation	SI Functional groups
Scleractinian corals (C)	Primary reef builders, mixotrophic	Suitable for calcification and algal symbiosis	P_c
Large symbiont bearing foraminifera (SF)	Sediment producers, mixotrophic	Calcification associated with algal symbiosis	P_f
Corallinae algae (CA)	Framework builders,autotrophic	Varies with other components	P_{ah}
Calcareous green algae (CalA)	Sediment producers, autotrophic	Nutrient signal, high carbonate saturation	P_{ah}
Molluscs (M)	Sediment producers, grazers, predators, heterotrophic	Food resources, nutrient signal	P_{ah}
Echinoids remains (ER)	Sediment producers, bioeroders, heterotrophic	Bioerosion, nutrient signal	P_{ah}
Worm tubes (WT)	Sediment producers, heterotrophic	Abundant food resources	P_{ah}
Others, e.g., small foraminifera, bryozoans, etc. (O)	Sediment producers, heterotrophic	Abundant food resources	P_{ah}
Unidentifiable (U)	Bioerosion signal	Bioerosion proxy	P_u

Table 3
Median values of grain size, FI and SI for the investigated islands.

	Dry sed	> 2mm	1–2 mm	500 µm-1 mm	250–500 µm	125–250 µm	63–125 µm	40–63 µm	< 40 µm	FI	SI
Rasdhoo – 2015	3.96	0.26	0.45	1.16	1.13	0.50	0.06	0.00	0.00	5.08	3.68
Rasdhoo – 2018	7.59	0.29	0.46	0.95	2.25	2.95	0.82	0.03	0.00	3.96	3.03
Maayafushi – 2015	5.41	0.43	0.60	0.93	1.38	1.48	0.50	0.06	0.01	5.03	3.48
Maayafushi – 2018	9.55	0.74	1.01	1.48	2.74	2.49	0.71	0.09	0.03	4.11	3.01
Vihamaafaru – 2015	6.34	0.39	0.41	1.43	2.36	1.43	0.20	0.04	0.00	5.40	4.11
Vihamaafaru – 2018	7.84	0.27	0.81	1.33	2.67	2.94	0.46	0.06	0.02	4.20	3.45

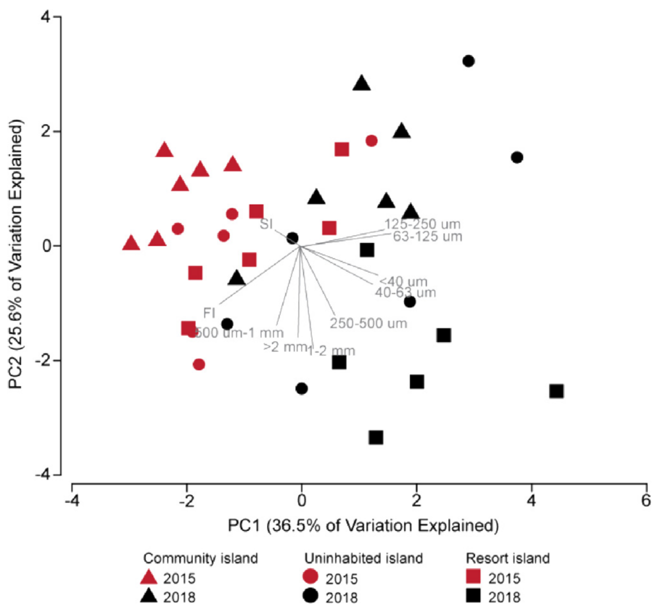

Fig. 3. Principal component analysis (PCA) of FI and SI from 2015 (red) and from 2018 (black). The vectors represent the contribution of each variable to the observed variation in the two different years of observation. The significance values for the principal components, eigenvalues and eigenvectors are reported in Supplementary material 3.

5. Summary and conclusions

The assessments of Maldivian water quality and consequent coral reef health in 2015 and 2018, using the FI and SI, revealed environmental deterioration, consistent with direct observations of loss of coral cover. In 2015 the healthiest condition was documented at Vihamaafaru (uninhabited island), while the most impacted was at Maayafushi (resort). Rasdhoo (community) was found in an intermediate condition. The differences between the management regimes was considered as significant, in particular the best conditions were associated with the uninhabited islands and the worst conditions with the resort islands In contrast, the FI and SI data from 2018 revealed a minimal influence of the management regime. A clear demonstration of how a small perturbation can be amplified in a nearshore reef is observed at Vihamaafaru. In 2015, the healthiest condition was observed in the western part of Vihamaafaru. Between 2015 and 2018, an agricultural site was established, and in 2018 the lowest FI (2.9) was observed. Another important observation was the notable decline of calcarinids in the 2018 samples. While the loss of this group impacts the FI calculations, their prominent decline alone is significant as it confirms their sensitive nature in the Maldives. Further investigations are planned to assess the reef health status in future years.

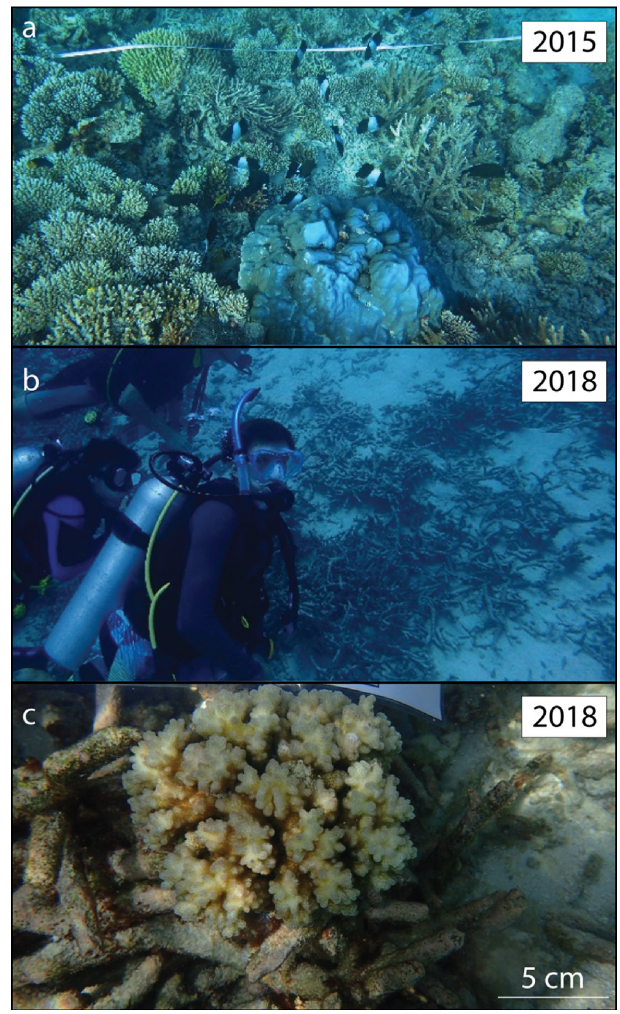

Fig. 4. Photographs of coral cover (2015–2018): (a) thriving coral in 2015, (b) dead branches of *Acropora* in 2018, (c) small coral colonies of *Pocillopora* sp. found on coral rubble along the transect in 2018.

Author contributions

VB partecipated in the cruise, contributed to sample collection, processed samples, analysed and interpreted the data, and participated in writing the paper.

SS partecipated in the cruise, processed samples, analysed and interpreted the data, led/coordinated writing the paper.

SS partecipated in the cruise, contributed to sample collection, processed samples, analysed and interpreted the data, and participated in writing the paper.

PH partecipated in the cruise, interpreted the data, and participated in writing the paper.

DB, AC, CP partecipated in the cruise, interpreted the data.

VR partecipated in the cruise, contributed to GPS positioning.

MF participated in the cruise and contributed to sample collection.

AA, AA, NDP, PD, IE, NF, MF, AF, BL, AL, MM, HN, LO, GP, AR, IS, LV participated in the cruise.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106128.

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