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Assessing coral reef health in the North Ari Atoll (Maldives) using the FoRAM Index

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Tropical marine ecosystems are richly diverse, but are experiencing growing pressure from coastal development and tourism. Assessing the status of coral reef communities along gradients of human pressure is necessary to predict recovery capacity of reefs exposed to acute events such as mass bleaching or storm destruction. Islands in the central Maldives Archipelago, which experience three different management regimes (four for each category: local community, uninhabited, and resort islands), were sampled during the International Union for Conservation of Nature (IUCN)-REGENERATE Cruise in 2015. Assessments were carried out using the FoRAM Index (FI), based on relative abundances of larger foraminiferal shells in reef sediments.

Overall, FI values (> 5) indicate that water quality currently should support active accretion by reef-building corals and larger benthic foraminifers. The highest median FI values (5.9) were recorded from sites associated with the uninhabited islands. Slightly, but significantly lower medians were recorded at sites near community and resort islands (FI = 5.3 and 5.1, respectively) that host permanent human settlement, indicating possible local deterioration of water quality by disposal of domestic wastes. Note that the FI was designed to assess suitability of local water quality and not to assess responses to regional to global changes associated with temperature stress or ocean acidification.

1. Introduction

Coral reefs are important ecosystems that are threatened worldwide. Their study can provide fundamental insights for their conservation and can drive management actions before it is too late. These ecosystems may appear healthy long after serious degradation has occurred (McClanahan et al., 2011), similar to forests that may appear healthy but have lost their ability to provide ecosystem services or have undergone changes in species composition (Millennium Ecosystem Assessment, 2005). Severely overfished reefs can be dominated by high live coral cover long after fish biomass has declined, then undergo a rapid phase shift following a major stress event (Hughes, 1994). Live coral cover is a widely used metric for coral reef condition, yet it has been shown not to differ between reefs exposed to different fishing pressure (Hughes, 1994; McClanahan et al., 2011). Thus, for sustainable management, additional approaches are essential to evaluate the condition of coral reef ecosystems (Sandin et al., 2008).

Defining reference conditions against which changes can be measured is often difficult because the different components of ecosystems often respond differently to changes in physical and biotic processes (Dayton et al., 1998). Coral reef condition greatly depends upon reef characteristics, ecological characteristics, disturbance regime, and anthropogenic influences (Sandin et al., 2008; Graham et al., 2011). Reefs exposed to high human pressure or in proximity to human population centers may be expected to show slower recovery due to pollution, terrestrial run off and exploitation (Sandin et al., 2008).

Much of the understanding of coral reefs and their resilience comes from the Caribbean and Australia's Great Barrier Reef (Hughes, 1994; Mumby et al., 2007; Sweatman et al., 2011; De'ath et al., 2012). In contrast, much less is known about the condition of coral reefs in the Indian Ocean. Coral reefs in the Maldives are some of the most diverse in the Indian Ocean, hosting > 250 species of corals and 1200 species of fish (Naseer and Hatcher, 2004). Their remote oceanic location, combined with a fishery that historically has not been based on reef fish, place them among the reefs with limited local anthropogenic disturbances worldwide.

Given the logistic and economic constraints for broad-scale environmental management, understanding the ecological factors driving reef resilience (i.e., recovery capacity) is of paramount importance for the appropriate management of Maldivian reefs, and in guiding

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investments in efforts aimed at enhancing resilience. Disturbances to Maldivian reefs have increased in the recent years as the consequences of crown-of-thorn starfish outbreaks and nutrification associated with disposal of human wastes (Morri et al., 2010), resulting in spatial variation in recovery and condition of reefs (McClanahan, 2000; Edwards et al., 2001; McClanahan and Muthiga, 2014; Morri et al., 2015). The extent to which current condition and recovery potential vary among Maldivian reefs is poorly understood, especially in the context of anthropogenic pressure.

Foraminifera, unicellular protists, are very sensitive to changing environmental conditions and their shells are a standard tool for paleo/oceanographic reconstruction. Hallock et al. (2003) developed the Foraminifera in Reef Assessment and Monitoring (FoRAM) Index (FI) to meet the need for bioindicators for coral reefs as expressed by the U.S. Environmental Protection Agency (Kurtz et al., 2001). Hallock (2012) summarized applications of this index in different habitats, reefs and countries, concluding that its applicability has proven far beyond that originally proposed, despite some regional limitations. Use of the FI has been also proposed as a low-cost approach to reef health assessment that could have application in countries with strong human resources and limited technological resources (Hallock et al., 2006).

The FoRAM Index is based on the observation that large benthic foraminifera hosting algal endosymbionts, which are abundant on healthy coral reefs, require water-quality conditions similar to those required by corals (e.g., Hallock, 1984; Hallock et al., 2003; Fujita et al., 2014). The input of nutrients into coral reef environments allows the proliferation of small heterotrophic foraminifera, whose shells numerically overwhelm those of symbiont-bearing taxa (Cockey et al., 1996). Under extreme local nutrification, where organic-rich conditions can result in intermittent hypoxia in the sediments (i.e., eutrophication), a few species of small, stress-tolerant foraminifera can become dominant (e.g., Alve and Bernhard, 1995; Carnahan et al., 2009). The advantage of benthic foraminifera as bioindicators is that their relatively short life cycles and sensitivity to changing environmental conditions allow them to respond more quickly than corals to changes in water quality. Therefore, foraminiferal-shell proportions in reef sediments provide a simple yet sensitive tool to differentiate between chronic reef decline and acute coral-specific mortality events (Cockey et al., 1996; Hallock et al., 2003). If chronic nutrification is present, it can reduce the potential for coral recruitment and thus reef resilience, such that a coral reef will be unlikely to recover and may continue to decline following an acute mortality event (Hallock et al., 2003; Ramirez et al., 2008).

This study evaluates the FI in islands from the North Ari Atoll in the Maldives, to assess spatial variation in current reef condition within the context of different human pressures. Specifically, the FI was determined for sediments in the vicinity of islands with different human population levels and under different management regimes, to test if it can predict reef resilience in the Maldives.

2. Materials and methods

2.1. Sampling sites and sample treatment

This study surveyed islands in the North Ari Atoll in the central Maldives archipelago from 22nd April–6th May 2015, including four community islands: Rasdhoo, Bodufolhudhoo, Feridhoo and Maalhos; four uninhabited islands: Gaathafushi, Alikoirah, Vihamafaru and Madivaru; and four resort islands: Velidhu, Kandholhudhoo, Maayafushi, and Madoogali (Fig. 1, geographical coordinates of each island are shown in Figs. 2–4). Community and resort islands are densely populated. For example, Rasdhoo, the capital of the North Ari Atoll, is 0.57 km long and 0.40 km wide, and hosts a permanent population of 867 people. Velidhu is 0.35 km long and 0.27 km wide, and may daily host several hundred tourists.

At each island reef, three sites were randomly chosen. Sediment samples (0–1 cm surface interval) were collected into 15 ml falcon tubes by SCUBA divers; collection sites were consistently at 10 m water depth in areas without coral or algal cover. Three replicate samples for each site were taken along reef slopes at 50 m distance one from another, for a total of 108 samples (Figs. 2–4). The islands of Vihamaafaru were sampled twice, first at 10 m depth on reef terraces and then at 10 m depth on the slope for comparison. Samples were treated with rose Bengal to ascertain that dead specimens had living counterparts. In the laboratory all samples were dried in open air and weighed.

2.2. Sediment texture

Subsamples of all samples were 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 was calculated, allowing the median grain size to be determined for each sample (Table 1, Supplementary Material-1).

2.3. Foraminiferal investigations

Because cohesive mud-sized particles were scarce in the sediments samples, the subsamples for foraminiferal investigations were not sieved, thus retaining very small, stress tolerant taxa such as *Bolivina*. This procedure was adopted to investigate the complete foraminiferal assemblage. Subsamples were split using a standard splitter to acquire a split of approximately 1 g. The sediment from that split was placed on a gridded tray and examined under a binocular microscope; 150–200 foraminiferal specimens were picked following the standard protocol. Dix (2001) demonstrated that this amount provides a statistically valid compromise between the precision of larger samples and processing costs in low diversity samples, or when not identifying to species level (Hallock et al., 2003). The picked benthic foraminiferal specimens were classified to genus and into one of three functional groups (symbiont-bearing, stress-tolerant, or other smaller taxa) and counted (Supplementary Material-2).

The FI was calculated based on functional groups according to Hallock et al. (2003), as modified by Carnahan et al. (2009). For each sample, the FI was determined by the equation:

$$FI = (10 \times P_s) + (P_o) + (2 \times P_h)$$

where $Ps = N_s/T$, N_s represents the number of symbiont-bearing foraminifera and T is total fauna; $Po = N_o/T$, where N_o represents the number of stress tolerant foraminifera; and $Ph = N_h/T$, where N_h represents the number of other small foraminifera. FI values < 2 indicate ecological conditions unfavorable for calcifying organisms that host algal endosymbionts (and therefore not conducive to reef growth), values between 2 and 4 indicate marginal conditions, and values > 4 indicate ecological conditions generally favorable for calcifying organisms that host algal endosymbionts, and therefore that support reef growth.

During specimen counting, the degree of bioclast preservation was also evaluated (Barbosa et al., 2009; Hallock, 2012). For example bioclasts corroded or rounded may indicate prolonged reworking by currents (e.g., heavily broken specimens and missing or eroded tubulospines in calcarinids). Both means and medians of the FI were calculated, the latter to minimize the influence of local microenvironments that can result in an anomalously high or low FI values (Table 1, Supplementary Material-1).

2.4. Water samples

Water samples were collected into plastic bottles by divers, and were taken both at the sea surface and at the sea floor from the same locations where sediments were collected. Immediately after collection the pH, temperature and conductivity of the water samples were

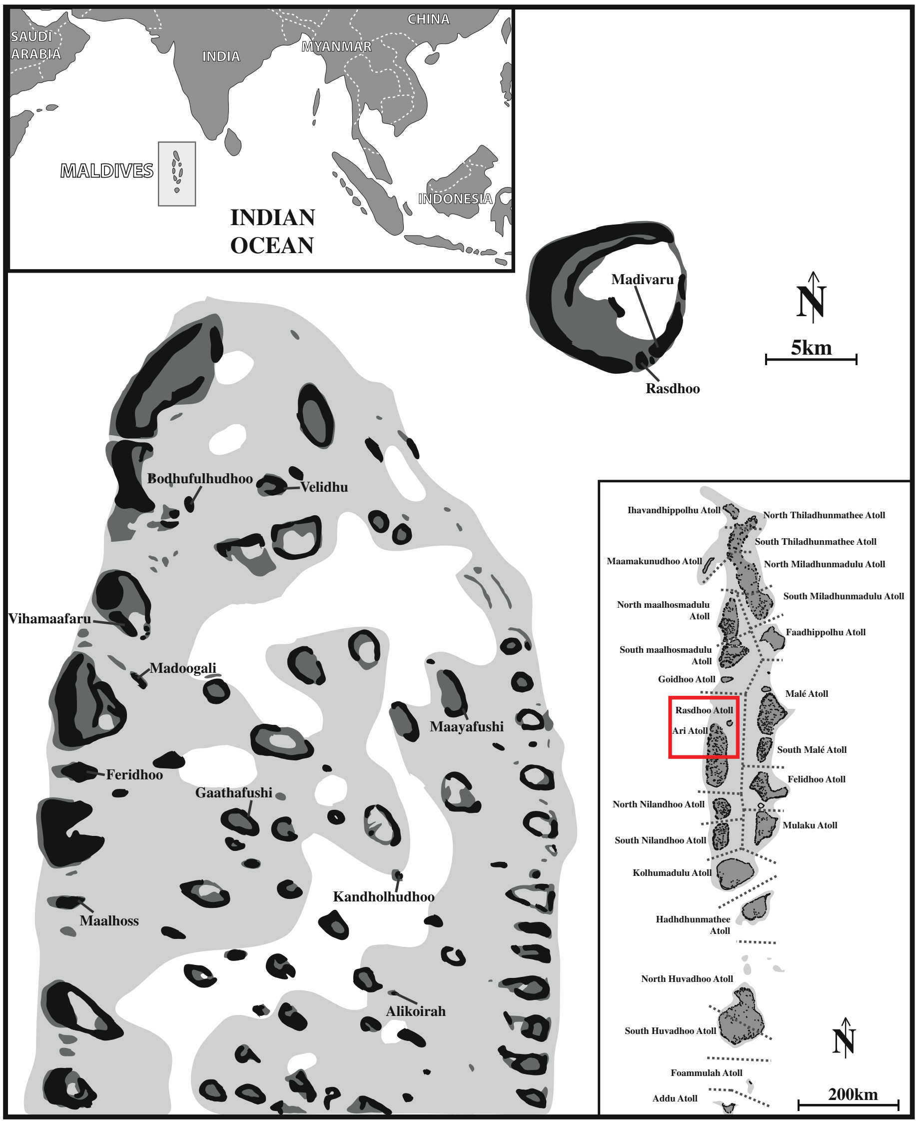

Fig. 1. Location map of North Ari (Alifu Alifu) Atoll, in the Maldives showing the investigated islands.

measured with a multiparameter meter Orion™ Star A325. The model sensor for pH was the Orion™ Ross Ultra™ 8107UWMMD and the sensor for conductivity was the Orion™ DuraProbe™ 013010MD. The temperature range was 0–100 °C, the pH range was 0–14 with pH precision of 0.01 using National Bureau of Standards as pH scale. The Orion™ Star A325 was calibrated daily. Two points of calibration were performed for the pHNBS with two buffer solutions (pH of 4.01 and 7.00). One point of calibration was performed for conductivity with a buffer solution of 1413 µS/cm. Dissolved oxygen was measured with DO600 Waterproof ExStik® II Dissolved Oxygen Meter, which has an auto-calibration function. The calibration was performed daily. These parameters were chosen to facilitate comparison with previous studies on the FI (e.g., Hallock et al., 2003; Ramirez et al., 2008; Barbosa et al., 2009). Averages for each island are in Table 2 and the complete data set in Supplementary Material-3.

2.5. Data analyses

Water-sample, grain-size and foraminiferal data (FI) were statistically treated to determine correlations among parameters. A Principal Components Analysis (PCA) was conducted to investigate how FI and water-sample data varied among resort, community and uninhabited islands. In Fig. 5, spatial variation at the site level (n = 3 per island) are shown for the first two components; vectors represent the relative contribution of each variable to the observed variation among sites.

Since symbiont-bearing foraminifera are larger compared to stress-tolerant and other smaller taxa, a PCA was also performed to compare the FI Index with sediment texture and to investigate whether those parameters vary with management regime. Both PCA calculations were performed using the Software PRIMER 6 (Clarke and Gorley, 2006); prior to PCA analyses, data were normalized.

3. Results

Benthic foraminiferal assemblages in the North Ari Atoll are typical of tropical warm-water coral reefs. The assemblages are rich and diverse; 118 genera were identified following Loeblich and Tappan (1994) and classified according to the three functional groups (Supplementary Material-2). The symbiont-bearing functional group was dominated by *Amphistegina* spp., *Calcarina defrancii*, and *Neorotalia calcar*, with *Sorites* spp. and *Peneroplis* spp. occurring less commonly. Stress-tolerant species were generally rare, and included *Ammonia* sp., elphidids and bolivinids. Other small foraminifera that were moderately abundant included miliolids, planorbulinids, textulariids, and cibicidids.

The FI calculated for samples collected along the reefs of the community islands (Fig. 2a–d) revealed values between 3.8 and 9.5, with a median of 5.3 (Tables 1, 2). The FI values from the resort islands

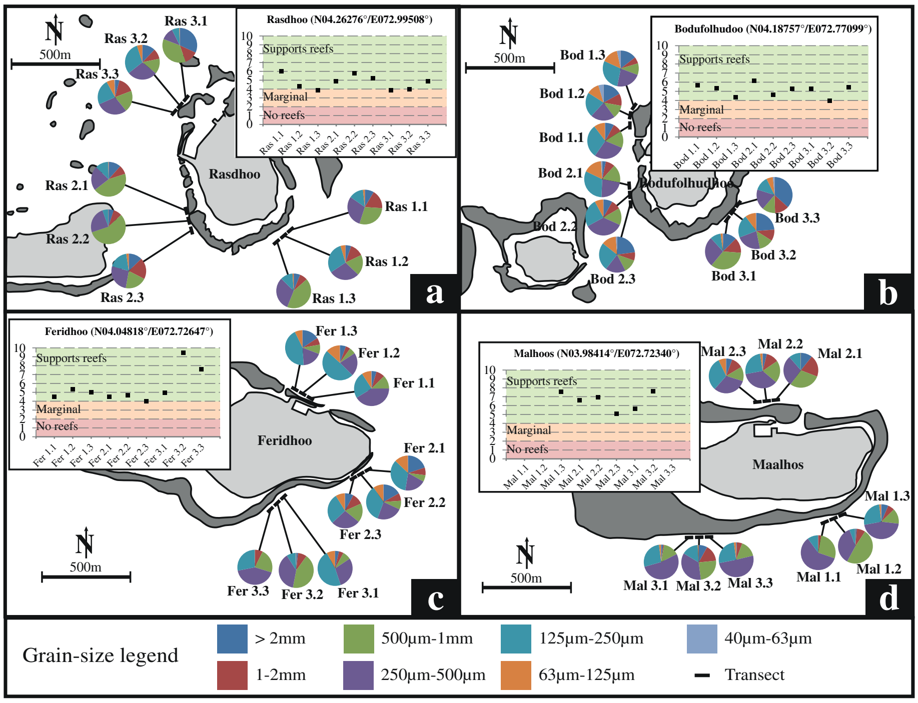

Fig. 2. The FoRAM Index from community islands. The FI is calculated for the transects sampled along the reefs in the island of Rasdhoo (a), Bodufolhudhoo (b), Feridhoo (c) and Maalhos (d). Panel (a) modified after Pisapia et al., 2017 (cruise report).

(Fig. 3a–d) ranged from 3.4 to 9.2, with a median of 5.1. The FI from the uninhabited islands varied from a low of 3.4 to a high of 9.6 (Fig. 4a–d), with median of 5.9.

Water-sample parameters were generally similar across all islands categories (Table 1, Supplementary Material-3). Temperature (~3 °C range), salinity (33–35‰) and pH (7.89–8.22) were relatively consistent from site to site, with the exception of elevated salinity (39‰) at the Maayafushi sites and the highest mean temperature (31.8 °C) at Kandholudoo (Table 1). Mean pH and DO values were slightly higher at the surface than at 10 m. While DO varied substantially (~4–10 mg·L^{-1}), such variability is consistent with normal daily fluctuation in clear, shallow water.

The PCA indicated correlations between T, DO and FI (Fig. 5). There was a clear clustering of the island data in two distinct groups (Fig. 5). One group included sites where the lowest salinities were recorded (33.1‰), including Kandholudoo, a resort island, and Alikoirah, an uninhabited island. Those sites were separated by temperature, as anomalously high temperatures (up to 31.8 °C) were recorded at Kandholudoo (Supplementary Material-3). The other group included sites from all three management regimes (Fig. 5, right side). This clustering appears to be associated with salinity and pH. Resort and uninhabited islands formed separate subclusters in the analysis, while community islands overlapped the other two.

The grain-size distributions varied (Figs. 2a–d to 4a–d), though median grain sizes were predominantly medium (250–500 µm) to coarse (500 µm–1 mm) sands (Fig. 6). No clusters were seen in the data and the grain-size vectors had similar lengths, with no relationship to management regime (Fig. 6). The FI vector was very short; showing a weak and negative correlation to the fine sand vector.

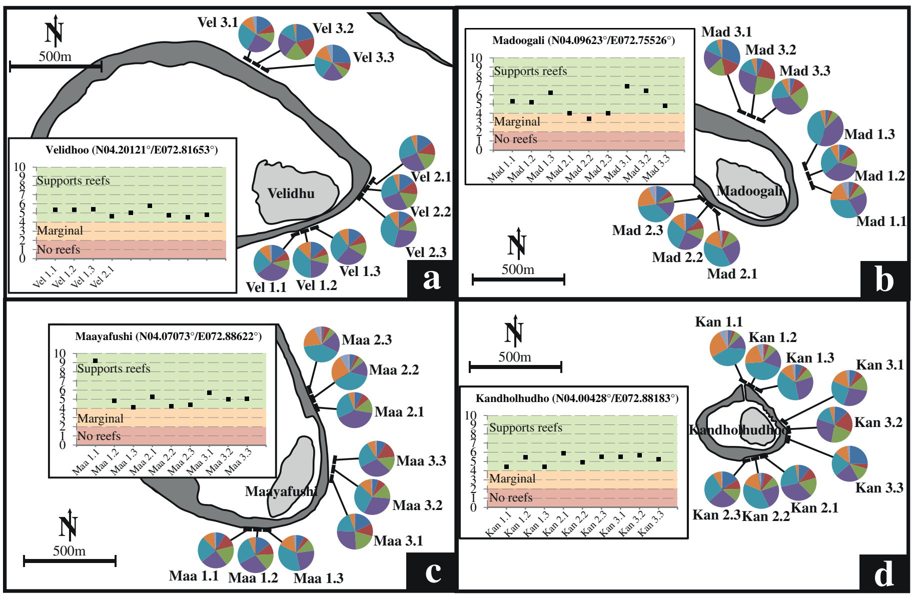

Fig. 3. The FoRAM Index from resort islands. The FI calculated for the transects sampled along the reefs of the resort island Velidhu (a), Madoogali (b), Maayafushi (c), and. Kandholhudhoo (d). See Fig. 2 for legend. Panel (a) modified after Pisapia et al., 2017 (cruise report).

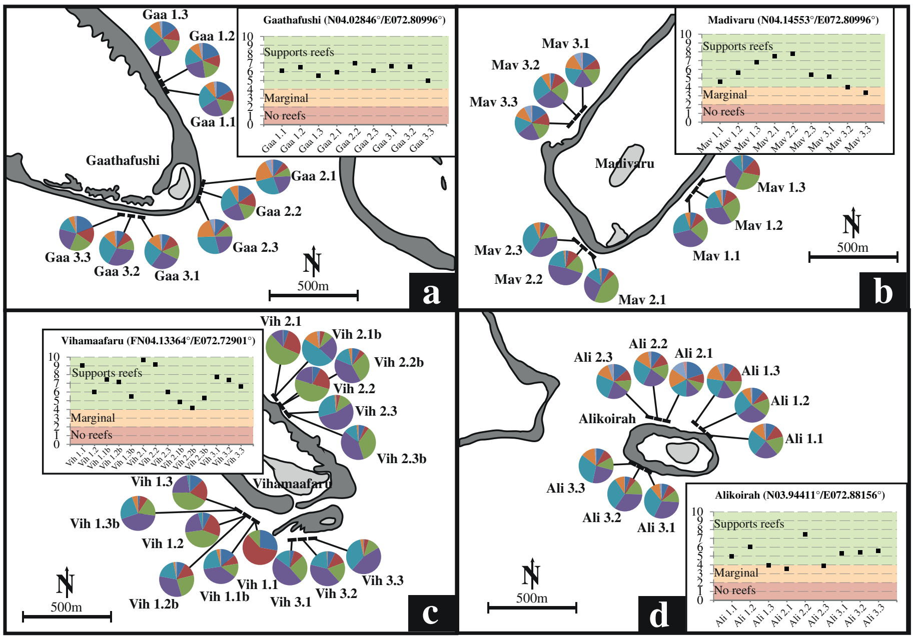

Fig. 4. The FoRAM Index from uninhabited islands. The FI calculated for the transects sampled along the reefs of the uninhabited island Gaathafushi (a), Madivaru (b), Vihamafaru (c), and Alikoirah (d). See Fig. 2 for legend. Panel (a) modified after Pisapia et al., 2017 (cruise report).

Table 1
Mean pH, temperature (T), Conductivity, dissolved oxygen (DO), salinity and FI in the investigated islands.

Sites	Avg. depth (in m)	Avg. pH	Avg. T in °C	Avg. conduct. (ms/cm)	Avg. DO (mg·L^{-1})	Avg. salinity (‰)	Med. FI
Rasdhoo	10	8.17	30.08	51.96	5.35	34.32	4.9
Feridhoo	10	8.04	30.30	51.61	5.94	33.92	5.0
Maalhoss	10	8.01	30.71	51.56	6.12	33.88	6.9
Bodhufolhudhoo	10	8.16	30.38	51.47	4.75	33.82	5.3
Community	10	8.10	30.37	51.65	5.55	33.98	5.3
Community	Surface	8.15	30.37	51.67	7.56	34.03	
Velidhoo	10	8.15	28.89	51.79	5.65	34.06	5.0
Maadoogali	10	ND	30.02	51.81	4.81	34.07	5.2
Maayafushi	10	8.05	29.89	58.51	5.09	39.08	5.0
Kandholhudhoo	10	8.03	31.76	50.50	6.13	33.11	5.48
Resort	10	8.08	30.39	53.15	5.42	35.08	5.1
Resort	Surface	8.16	30.59	53.02	8.25	34.98	
Vihamaafaru	10	8.05	30.15	51.21	5.55	33.61	6.3
Gaathafushi	10	8.04	30.97	51.75	5.63	34.03	6.15
Alikoirah	10	8.04	29.9	50.52	5.28	33.14	5.2
Madivaru	ND	ND	ND	ND	ND	ND	5.4
Uninhabited	10	8.04	30.37	51.16	5.48	33.59	5.9
Uninhabited	Surface	8.13	30.70	51.12	7.68	33.56	

ND = No Data.

Table 2
Medians calculated for the investigated sediment grain-size categories and for the FI.

Medians										
	Dry sed.	> 2 mm	1–2 mm	500 µm–1 mm	250–500 µm	125–250 µm	63–125 µm	40–63 µm	< 40 µm	FI
Community	4.11	0.28	0.35	0.71	1.05	1.02	0.145	0.01	0	5.28
Resorts	5.86	0.42	0.47	0.66	1.42	1.71	0.67	0.09	0.01	5.07
Uninhabited	5.59	0.46	0.55	0.95	1.6	1.26	0.39	0.07	0.01	5.94

4. Discussion

Previous studies on total benthic foraminiferal assemblages in the North Ari Atoll were conducted by Parker and Gischler (2011) and Stotz et al. (2014). Parker and Gischler investigated the > 125 µm size fraction and identified 92 genera from reef crests, back reefs and lagoons. The somewhat larger number of genera identified in this study (118) was likely the result of assessment of all grain sizes, thereby retaining the smallest taxa such as the bolivinids.

4.1. Limitation of the FI

The FI index has been applied in coastal environment around the world including Puerto Rico, Florida, Brazil, Pacific Islands, Australia, and Greece. Limitations of the FI have been identified in some studies, such as in Indonesia where large calcarinids may thrive in mesotrophic waters and increase in abundance with macroalgal cover (Renema and Troelstra, 2001). This limitation can be overcome by excluding calcarinids from the symbiont-bearing category. Another exception is for

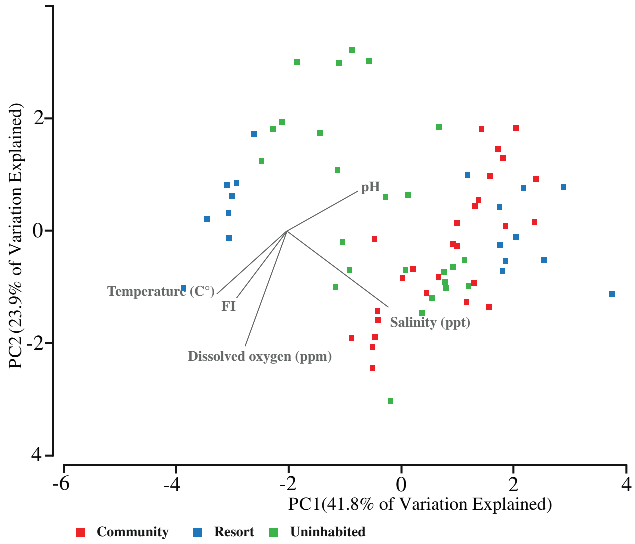

Fig. 5. Principal component analysis (PCA) of water-sample and FI data from community islands in red, resorts islands in blue, and uninhabited islands in green. Vectors represent the relative contribution of each variable to the observed variation among sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

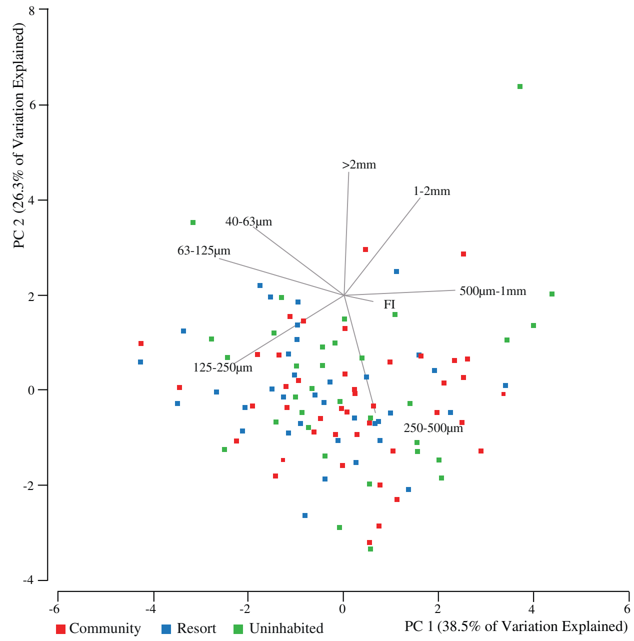

Fig. 6. Principal component analysis (PCA) of grain-size and FI data from community islands in red, resorts islands in blue and uninhabited islands in green. Vectors represent the relative contribution of each variable to the observed variation among sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Brazilian reefs that are characterized by unique canopy structures, where the FI appears to be more dependent on sediment texture (Barbosa et al., 2009, 2012). An additional limitation of this index is in higher energy environments where larger foraminifera have been major sediment producers in the past. In such cases, relict shells may dominate sediments even where water quality is in decline. To avoid this bias we have carefully checked that the genera considered in this study had living counterparts (i.e., rose Bengal stained specimens in the samples).

4.2. *FI and water parameters*

Although the FI can vary with parameters such as distance from the coast (Narayan and Pandolfi, 2010), sediment texture, hydrodynamic regime and light penetration (Barbosa et al., 2009), several studies have demonstrated that the FI is primarily related to water quality (Uthicke and Nobes, 2008; Uthicke et al., 2010; Koukousioura et al., 2011; Velásquez et al., 2011; Reymond et al., 2012; Oliver et al., 2014).

The FI is based on the relative abundances of benthic foraminiferal shells in the sediments, which accumulate over weeks to years and therefore, are representative of the environmental conditions over a time of weeks to years (Hallock et al., 2003; Ramirez et al., 2008). Although the FI and water-quality parameters can be strongly linked, our water-parameter data were snapshot measures representative only of the environmental conditions at the time of measurements. Moreover, the only parameters that we measured that can be somewhat related to nutrient regime were DO and pH. These parameters can vary widely as a function of temperature, water motion, and especially with rates of photosynthesis, which are dependent upon time of day.

All the means of the water parameters we measured fall within typical ranges for reef environments and within ranges previously recorded in the Maldives and, more widely, in the Indian Ocean and adjacent regions (e.g., Ramamirtham, 1968; Wild et al., 2010; Zweng et al., 2013; Lauvset et al., 2015. Thus, it is not surprising that the parameters we measured do not correlate strongly with the FI (Fig. 5).

4.3. *FI and sediment texture*

Hallock et al. (2003), Ramirez et al. (2008), and Carnahan et al. (2009) all cautioned that coarser sediments could have higher FI indices compared to finer sediments. Although larger foraminifera can be abundant in coarse sediments, Hallock et al. (2003) and Ramirez et al. (2008) demonstrated that, in ecosystems where environmental conditions are conducive for higher abundances of smaller foraminifera, they are not overwhelmed by the shells of larger species even in coarse sediments. However, as noted above, Barbosa et al. (2009) showed that along the coast of Brazil, the distribution of symbiont-bearing foraminifers can be controlled by the sedimentation regime where corals form extensive canopies at the sea surface. Barbosa et al. also demonstrated that some coral species can thrive in muddy sediments that are not tolerated by symbiont-bearing foraminifera. Uthicke et al. (2010) and Narayan and Pandolfi (2010) also suggested that values of FI negatively correlate with increasing amounts of fine sediments. Given that the samples from the Maldives sampling sites were overwhelmingly dominated by medium-to-coarse, sand-sized sediments, sediment texture did not appear to be an important influence on the FI data that we collected (Fig. 6).

4.4. *The FoRAM Index and its application to the Maldives*

Since neither the water parameters measured nor the sediment texture significantly influenced the FI in the North Ari Atoll, we compared the FI across the management regimes. The management system of the Maldives includes 1) resort reefs, which are conservation areas where fishing is prohibited but non-extractive activities are allowed (e.g., diving); 2) uninhabited islands, where fishing and other extractive activities are allowed but do not host permanent human settlement; and 3) community islands, where fishing and other extractive activities are allowed and host permanent human settlement often without waste management (Ministry Of Environment and Energy, MOEE, 2011). This regulation regime provided an appropriate setting in which to investigate if anthropogenic threats affect the current condition of reefs (Sandin et al., 2008; Rizzari et al., 2015; McClanahan, 2011).

Previous studies have assessed the FI across a range of anthropogenic influences. Uthicke and Nobes (2008) demonstrated that FI can reflect nutrient flux and light availability along water-quality gradients in the Great Barrer Reef. Koukousioura et al. (2011) documented the FI at sites in the Aegean Sea, reporting that the FI was 6.8–8.2 in pristine regions and 2.0–3.4 close to sewage outfalls. Velásquez et al. (2011) enigmatically found that FIs in a Marine Protected Area (MPA) were lower than in the non-MPA areas sampled, but the difference was attributed to the intense tourism in protected areas. Emrich et al. (2017), from work at Caye Caulker, Belize, reported a significant negative correlation between FI and fecal sterols, which they assessed as indicators of sewage pollution.

The median FI values > 5 indicate that water quality around the reefs in the North Ari Atoll currently should support relatively healthy reefs (Tables 1, 2). However, the FI values overall were somewhat lower near community and resort islands that host permanent human activity, indicating potential for deterioration in environmental conditions in some restricted areas (Fig. 2a–d).

The FI values overall varied from 3.4 to 9.6 and sometimes varied within the replicates from an island. Given that range of variability and the limited number of samples per site (n = 3), medians were considered to be more reliable indicators of central tendency than means. Moreover, the degree of preservation of the bioclasts was evaluated in an effort to exclude less reliable values, following recommendations of Barbosa et al. (2009) and Hallock (2012). Some samples from Ferhidhoo (e.g., 3.2 and 3.3) displayed very high FI values, and the bioclasts contained in the sediments were generally corroded or rounded, indicating reworking by currents. These observations suggest that such sediments underwent reworking by currents for a more prolonged time and, therefore, their FI values were considered to be biased (Supplmentary Material-1). In some samples from Malhoos (e.g., 1.1 and 1.2), fewer than 50 benthic foraminiferal shells were found and therefore, following Ramirez et al. (2008), those samples were not included in the FI calculation. All bioclasts from Maalhos were also generally corroded and eroded, further indicating that their FI values were not reliable. However, the good preservation of calcarinids and other shells indicate that the FI from all other samples from Feridhoo, Rashdoo and Bodhufulhudhoo can be considered as reliable and representing accumulation time of weeks to months.

For the community islands, the somewhat lower FI values may be related to the limited means of domestic waste disposal, as the consequent accumulation of waste close to an island can induce very local nutrification (Boblme, 2010). As noted above, Emrich et al. (2017), from work at Caye Caulker, Belize, reported a significant negative correlation between FI and fecal sterols. Nevertheless, the overall mean FI was 5.1, and the authors concluded that, for reef areas with limited adjacent land area and that are relatively exposed to waves or currents, the influence of local sewage pollution can be quite limited in extent, even if quite severe nearshore. The medium-to-coarse sediment texture, which was recorded at nearly all sites in North Ari Atoll, also indicates an active hydrodynamic regime that can similarly limit the extent of influence of local domestic waste.

The highest values of FI (median 5.9) were observed near the uninhabited islands, indicating suitable water quality for healthy reefs (Fig. 3a–d). The islands with consistently high FI values are Vihamafaru and Gaatafushi, where preservation of bioclasts was overall very good, indicating limited reworking of sediments.

The variable and sometimes low FI values, which were recorded in few sites in other uninhabited islands, may be differently explained. The island of Alikoirah is very close to the large resort of Meerufenfushi and is used for tourist excursions. Therefore, some nutrification associated with touristic pressure cannot be ruled out as cause for lower and variable FI values around Alikoirah. Moreover, at this site several individuals of *Acanthaster planci* were observed during the field work (Pisapia, personal observation). The presence of this corallivorous starfish has been linked to anthropogenic nutrification in other regions (Morri et al., 2010), resulting in spatial variation in recovery and condition of reefs (McClanahan, 2000; Edwards et al., 2001; McClanahan and Muthiga, 2014; Morri et al., 2015).

5. Conclusions

The high FIs documented in this study indicate that water-quality around the reefs in the North Ari Atoll should continue to support relatively healthy reefs. However, the FI values are overall somewhat lower near community and resort islands that host permanent human activity, indicating local nutrification of waters by disposal of domestic wastes. The highest median FI values were recorded from sites associated with the uninhabited islands.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.marmicro.2017.06.001.

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References

Alve, E., Bernhard, J., 1995. Vertical migratory response of benthic foraminifera to controlled oxygen concentrations in an experimental mesocosm. Mar. Ecol. Prog. Ser. 116, 137–151.
Barbosa, C.F., de Freitas Prazeres, M., Ferreira, B.P., Seoane, J.C.S., 2009. Foraminiferal assemblage and reef check census in coral reef health monitoring of East Brazilian margin. Mar. Micropaleontol. 73, 62–69.
Barbosa, C.F., Ferreira, B.P., Seoane, J.C.S., Oliveira-Silva, P., Gaspar, A.L.B., Cordeiro, R.C., Soares-Gomes, A., 2012. Foraminifer-based coral reef health assessment for Southwestern Atlantic offshore archipelagos, Brazil. J. Foraminifer. Res. 42, 169–183.
BOBLME, 2010. Coastal pollution loading and water quality criteria - Maldives. BOBLME-2010-Ecology-06 (34 pp).
Carnahan, E., Hoare, A., Hallock, P., Lidz, B., Reich, C., 2009. Foraminiferal assemblages in Biscayne Bay, Florida, USA: responses to urban and agricultural influence in a subtropical estuary. Mar. Pollut. Bull. 59, 221–233.
Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User Manual/tutorial. Primer-E Limited.
Cockey, E., Hallock, P., Lidz, B., 1996. Decadal-scale changes in benthic foraminiferal assemblages off Key Largo, Florida. Coral Reefs 15, 237–248.
Dayton, P.K., Tegner, M.J., Edwards, P.B., Riser, K.L., 1998. Sliding baselines, ghosts, and reduced expectations in kelp forest communities. Ecol. Appl. 8, 309–322.
De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. PNAS 109, 17995–17999.
Dix, T.L., 2001. The Distribution and Ecology of Benthic Foraminifera of Tampa Bay, Florida. (Ph.D. Dissertation) University of South Florida, Tampa, Florida.
Edwards, A.J., Clark, S., Zahir, H., Rajasuriya, A., Naseer, A., Rubens, J., 2001. Coral bleaching and mortality on artificial and natural reefs in Maldives in 1998, sea surface temperature anomalies and initial recovery. Mar. Pollut. Bull. 42, 7–15.
Emrich, K., Martinez-Colon, M., Alegria, H., 2017. Is untreated sewage impacting coral reefs of Caye Caulker, Belize? J. Foraminifer. Res. 47, 20–33.
Fujita, K., Nagamine, S., Yoichi, I., Yamanao, H., 2014. Distribution of large benthic foraminifers around a populated reef island: Fongafale Island, Funafuti Atoll, Tuvalu. Mar. Micropaleontol. 113, 1–9.
Graham, N.A.J., Nash, K.L., Kool, J.T., 2011. Coral reef recovery dynamics in a changing world. Coral Reefs 30, 283–294.
Hallock, P., 1984. Distribution of selected species of living algal symbiont-bearing foraminifera on two Pacific coral reefs. J. Foraminifer. Res. 14, 250–261.
Hallock, P., 2012. The FoRAM Index revisited: uses, challenges, and limitations. Proc. 12th Int. Coral Reef Symp. www.icrs2012.com/proceedings/manuscripts/ICRS2012_15F_2.pdf.
Hallock, P., Lidz, B.H., Cockey-Burkhard, E.M., Donnelly, K.B., 2003. Foraminifera as bioindicators in coral reef assessment and monitoring: the FoRAM Index. Environ. Monit. Assess. 81, 221–238.
Hallock, P., Williams, D., Fisher, E., Toler, S., 2006. Bleaching in foraminifera with algal symbionts: implications for reef monitoring and risk assessment. Anu. Inst. Geocienc. 29, 108–128.
Hughes, T.P., 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science 301, 929–933.
Koukousioura, O., Dimiza, M.D., Triantaphyllou, M.V., Hallock, P., 2011. Living benthic

foraminifera as an environmental proxy in coastal ecosystems: a case study from the Aegean Sea (Greece, NE Mediterranean). J. Mar. Syst. 88, 489–501.
Kurtz, J.C., Jackson, L.E., Fisher, W.S., 2001. Strategies for evaluating indicators based on guidelines from the Environmental Protection Agency's Office of Research and Development. Ecol. Indic. 1, 49–60.
Lauvset, S., Gruber, N., Landschützer, P., Olsen, A., Tjiputra, J., 2015. Trends and drivers in global surface ocean pH over the past 3 decades. Biogeosciences 12, 1285–1298.
Loeblich, A.R., Tappan, H., 1994. Foraminifera of the Sahul Shelf and Timor Sea. In: Cushman Foundation Spec. Pub. No. 31, (661 pp).
McClanahan, T., 2000. Bleaching damage and recovery potential of Maldivian coral reefs. Mar. Pollut. Bull. 40, 587–597.
McClanahan, T., 2011. Coral reef fish communities in management systems with unregulated fishing and small fisheries closures compared with lightly fished reefs–Maldives vs. Kenya. Aquat. Conserv. Mar. Freshwat. Ecosyst. 21, 186–198.
McClanahan, T., Muthiga, N., 2014. Community change and evidence for variable warm-water temperature adaptation of corals in Northern Male Atoll, Maldives. Mar. Pollut. Bull. 80, 107–113.
McClanahan, T., Graham, N.A.J., MacNeil, M.A., Muthiga, N.A., Cinner, J.E., Henrich Bruggemann, J., Wilson, S.K., 2011. Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. Proc. Natl. Acad. Sci. U. S. A. 108, 17230–17233.
Millennium Ecosystem Assessment ME, 2005. Ecosystems and Human Well-being. Island Press, Washington, DC (137 pp).
Ministry Of Environment and Energy (MOEE), 2011. State of the Environment Maldives 2011. Ministry of Environment and Energy, Republic of Maldives (337 pp).
Morri, C., Aliani, S., Nike Bianchi, C., 2010. Reef status in the Rasfari region (North Malé Atoll, Maldives) five years before the mass mortality event of 1998. Estuar. Coast. Shelf Sci. 86, 258–264.
Morri, C., Montefalcone, M., Lasagna, R., Gatti, G., Rovere, A., Parravicini, V., Baldelli, G., Colantoni, P., Nike Bianchi, C., 2015. Through bleaching and tsunami: coral reef recovery in the Maldives. Mar. Pollut. Bull. 98, 188–200.
Mumby, P.J., Hastingsm, A., Edwards, H.J., 2007. Thresholds and the resilience of Caribbean coral reefs. Nature 450, 98–101.
Narayan, Y.R., Pandolfi, J.M., 2010. Benthic foraminiferal assemblages from Moreton Bay, South-East Queensland, Australia: applications in monitoring water and substrate quality in subtropical estuarine environments. Mar. Pollut. Bull. 60, 2062–2078.
Naseer, A., Hatcher, B.G., 2004. Inventory of the Maldives' coral reefs using morphometrics generated from Landsat ETM + imagery. Coral Reefs 23, 161–168.
Oliver, L., Fisher, W.S., Dittmar, J., Hallock, P., Campbell, J., Quarles, R.L., Harris, P., LoBue, C., 2014. Contrasting responses of coral reef fauna and foraminiferal assemblages to human influence in La Parguera, Puerto Rico. Mar. Environ. Res. 99, 95–105.
Parker, J.H., Gischler, E., 2011. Modern foraminiferal distribution and diversity in two atolls from the Maldives, Indian Ocean. Mar. Micropaleontol. 78, 30–49.
Pisapia, C., Rahman, M.A., Abdulla, A., Basheer, A., Caldwell, Z., Ducarme, F., Elkateb, A., Fox, M., Furby, K., Ibrahim, M., Moritz, C., Schmidt, A., Spezzaferri, S., Sweet, M., Zgliczynski, B., Grimsditch, G., 2017. Baseline assessment of coral reefs of North Ari Atoll. In: Cruise Report. IUCN and Government of Maldives, Gland, Switzerland, pp. 1–32.
Ramamirtham, C., 1968. Vertical distribution of temperature, salinity and dissolved oxygen in the Maldives region of the Indian Ocean. Indian J. Fish. 15, 27–39.
Ramirez, A., Daniels, C., Hallock, P., 2008. Applications of the SEDCON and FORAM Indices on patch reefs in Biscayne National Park, FL, USA. In: Proc. 11th Int. Coral Reef Symp. 4. pp. 77–81.
Renema, W., Troelstra, S.R., 2001. Larger foraminifera distribution on a mesotrophic carbonate shelf in SW Sulawesi (Indonesia). Palaeogeogr. Palaeoclimatol. Palaeoecol. 175, 125–146.
Reymond, C.E., Uthicke, S., Pandolfi, J.M., 2012. Tropical *Foraminifera* as indicators of water quality and temperature. Proc. 12th Int. Coral Reef Symp. http://marinepalaeoecology.org/wp-content/uploads/2011/09/Reymond-et-al.-ICRS2012.pdf.
Rizzari, J.R., Bergseth, B.J., Frisch, A.J., 2015. Impact of conservation areas on trophic interactions between apex predators and herbivores on coral reefs. Conserv. Biol. 29, 418–429.
Sandin, S.A., Smith, J.E., DeMartini, E.E., Dinsdale, E.A., Donner, S.D., Friedlander, A.M., Konotchick, T., Malay, M., Maragos, J.E., Obura, D., Pantos, O., Paulay, G., Richie, M., Rohwer, F., Schroeder, R.E., Walsh, S., Jackson, J.B.C., Knowlton, N., Sala, E., 2008. Baselines and degradation of coral reefs in the northern Line Islands. PLoS One 3 (2), e1548.
Stotz, D., Gischler, E., Parker, J.H., Klostermann, L., 2014. Changes in diversity and assemblages of foraminifera though the Holocene in an atoll from the Maldives, Indian Ocean. Mar. Micropaleontol. 106, 40–54.
Sweatman, H., Delean, S., Syms, C., 2011. Assessing loss of coral cover on Australia's Great Barrier Reef over two decades, with implications for longer-term trends. Coral Reefs 30, 521–531.
Uthicke, S., Nobes, K., 2008. Benthic foraminifera as ecological indicators for water quality on the Great Barrier Reef. Estuar. Coast. Shelf Sci. 78, 763–773.
Uthicke, S., Thompson, A., Schaffelke, B., 2010. Effectiveness of benthic foraminiferal and coral assemblages as water quality indicators on inshore reefs of the Great Barrier Reef, Australia. Coral Reefs 29, 209–225.
Velásquez, J., López-Angarita, J., Sánchez, J.A., 2011. Evaluation of the FoRAM Index in a case of conservation. Biodivers. Conserv. 20, 3591–3603.
Wild, C., Niggl, W., Naumann, M.S., Haas, A.F., 2010. Organic matter release by Red Sea coral reef organisms—potential effects on microbial activity and in situ O_2 availability. Mar. Ecol. Prog. Ser. 411, 61–71.
Zweng, M., Reagan, J.R., Antonov, J.I., Locarnini, R.A., Mishonov, A.V., Boyer, T.P., Garcia, H.E., Baranova, O.K., Johnson, D.R., Seidov, D., Biddle, M.M., 2013. World Ocean Atlas 2013, Volume 2: Salinity. NOAA Atlas NESDIS 74. pp. 39.