Pattern and intensity of human impact on coral reefs depend on depth along the reef profile and on the descriptor adopted

Ettore Nepote, Carlo Nike Bianchi,Mariachiara Chiantore, Carla Morri,Monica Montefalcone*

DiSTAV, Department of Earth, Environment and Life Sciences, University of Genoa, Corso Europa 26, 16132 Genoa, Italy

*Corresponding author: montefalcone@dipteris.unige.it

Abstract

Coral reefs are threatened by multiple global and local disturbances.The Maldives,already heavily hitby the 1998 mass bleaching event,arepresently affectedby growing tourism and coastal development. Most studies investigating effects of local coastal impacts assess the response of reef communities only along the horizontal distance from the impact source.This study investigated in 2012 the environmental status of a Maldivian coral reef, where an international touristic airport has been recently (2009-2011) built, along a depth gradient (5 to 20 m depth)and considering the change in cover of five different descriptors:hard corals, soft corals, other invertebrates, macroalgae and abiotic attributes.Eight reefs in areas not affected by any coastal development were used as controls.Results showed that hard coral cover, the most widely used descriptor in impact studies, was not sufficient to detect subtle indirect effects that occur deeper along the reef profile.

Keywords

Impact assessment, non-taxonomic descriptors,depth gradient, underwater visual survey, ACI design, Maldives.

Introduction

Multiple global and local disturbances represent serious threats to coral reefsworldwide (Carpenter et al. 2008). The bleaching event of 1998caused mass coral mortality in the largest majority of tropical regions, implying a severe reduction in hard coral cover (Baker et al. 2008), and high spatial variability in recovery and shifts in taxonomic composition had been reported afterward (van Woesiket al. 2011; Johns et al., 2014). Local impacts such as overfishing,mass tourism, and coastal development may actin a synergistic mannerwith global impacts (Ban et al. 2014).

The greatest ecological threats that tourism and growing human population pose on coastal ecosystemsconsist of the infrastructure and transport arrangements required to support them(Davenport and Davenport 2006). In particular, dredging,development of touristic resorts and other coastalfacilities contribute to substantial, often irreversible, environmental degradation, due to land reclamation and to the consequent flow of sediments.Sediment causes an increase in water turbidity thatreduces light penetration and therefore worsens environmental conditions for zooxanthellate corals (Fabricius 2005).

As a consequence, any local impact deriving from land reclamation and coastal construction is supposed to have a direct effect on the state of shallow corals, but also indirect effects along a reef profile due to the sliding of sediments at greater depths (Rogers 1990).Yet, most studies dealing with the impact of coastal development have been performed considering only its effect along a horizontal distance from the impact source (Erftemeijer et al. 2012).

In this paper, we investigated the effectsof the recent construction of an international touristic airport on the status of the adjacent reefin an island of the Maldives, taking into account different depth zonesfrom the outer flat to the slope. The status of the impacted reefwas compared with that of nearby Maldivian reefs unaffected by coastal constructions. The Maldives are among the areas most severely affected by the 1998 bleaching episode (Bianchi et al. 2003), and theircoral reefs are still in the recovery process (Lasagna et al. 2010). A recent overview of reef communities in the Maldives is provided by Jimenez et al. (2012). As the Maldives are experiencing a tumultuous growth of urbanisation, costal development and, especially, tourism (de-Miguel-Molina et al. 2011; Jaleel 2013), local action is urged to prevent irreversible reef degradation (Kennedy et al. 2013): this notwithstanding, environmental impact assessment in the Maldives is still inadequate (Zubair et al. 2011).

Material and methods

Study area

In May 2012weinvestigated 9 reefslocated in Ariand South MaléAtolls (Fig. 1).We chose as impact site the rear reef of the island of Maamigili (Ari), where the MaamigiliVilla International Airport (Fig. 2)had been recentlybuilt (2009: beginning of the construction; the 1stof October 2011: day of opening). This airport and other infrastructures (such as a harbour) required land reclamation over the reef flat for a distance of about 360 m along most of the island perimeter.We compared the status of this reef with that of other 8 randomly selected reefs, to be used as control sites (Table 1). Control sites were selected among the two reef typologiesthat occur in the Maldivian atolls(Lasagna et al. 2010): 4 were outer reefs (ocean-facing sides of the atoll rim, and therefore exposed to wave action), and 4 inner reefs (lagoon patch-reefs or lagoon-facing sides of the atoll rim, sharing similar environmental features with the impacted reef).

Field activities

In the 9 selected sites data were collected by SCUBAdiving in 3 distinct depth zones: i) outer flat, at around 5 m depth; ii) upper slope, ca. 10 m depth; and iii) 'ten-fathom terrace' at about 20 m (Bianchi et al. 1997). Ateach depth,6replicate cover estimationswere performed using the plan viewtechnique of Wilson et al. (2007), over a 5 m × 5 m area. In particular, we estimated the cover of 5 benthic descriptors(Lasagna et al. 2008): 1) hard (zooxanthellate) coral; 2) soft (zooxanthellate) coral; 3)(azooxanthellate, suspension-feeding) invertebrates; 4) macroalgae; 5) abiotic attributes (sand, rock, coral rubble).

Data analysis

Lack of information on reef status before the construction of the airport prevented the application of a rigorous beyond-BACI design (Underwood 1992). We therefore adopted an ACI (Azzurro et al. 2010) and asymmetrical design, where the differences between the impactsite and the 8 controls were only tested in the "after" condition. Five analyses of variance (ANOVAs) were performed separately for each benthic descriptorin the three depth zones investigated. Prior to the analysis, the homogeneity of variances was tested by Cochran’s test and, if necessary, data were appropriately transformed. After subtraction of the variance among controls ($MS_{AmongCtr}$) from the total variance among sites (MS_{site}), impact effect ($MS_{IvsAmongCtr}$) has been tested versus the variance among controls ($MS_{AmongCtr}$) or the variance among residual (MS_{Res}), when the former was not significant.

A multivariate analysis (MDS) for each depth was also performed taking into account the five benthic descriptorsaltogether.The resemblance matrix was based on Bray-Curtis similarity onln(x+1)transformed data.Differences between outer and inner sites (impact site excluded) and between controls and impact were tested with a multivariate analysis of variance by permutations (PERMANOVA). This method analyses the variance of multivariate data explained by one or more explanatory factors and gives *p*-values calculated using all possiblepermutations (Clarke and Warwick 1994). We used "Condition" as factor with 3 levels: inner, outer and impact.

Results and Discussion

The ordination model for the 5 m depth sites showed that the impact sitewas distinctly separated from both the inner and the outer controls (Fig. 3a); paradoxically, the MDS plot showed it closer to the outer rather than to the inner sites, to which it belongs. PERMANOVA indicated that the pairwise difference between the impact site and both the inner and the outer controls was very significant ($p<0.01$); inner and outer controls were also different among them ($p<0.05$). According to the ANOVAs, the difference between impact and controls was mostly due to the highly significant ($p<0.001$) decrease of hard coral cover (Fig. 4a) and increase of abiotic attributes (Fig. 4e); cover of macroalgae was significantly ($p<0.05$) higher in the impact site than at the inner controls (Fig. 4d). Reduction of hard coral cover and augmentation of non-living substrate is an expected consequenceof a large coastal construction (Price et al. 2014): this mechanical impact resulted here greater on a protected reef than that exerted by oceanic waveson Maldivian outer reefs (Lasagna et al. 2010). Higher abundance of macroalgae with respect to inner controls was presumably related to the enhanced flow of loose sediment caused by costal work, as sediments deposing over the algal matrix suppress fish herbivory (Goatley and Bellwood 2013).

In the ordination model for the 10 m depth, the impact site is slightly separated from the controls (Fig. 3b): however, according to PERMANOVA, the difference between the impact site and the controls is still very significant ($p<0.01$), whereas no difference was found between outer and inner controls. ANOVA indicated the cover of other invertebrates as highly significantly (*p*<0.001) higher in the impact site than in the remaining inner sites (Fig. 4c). These filter-feeder invertebrates (mostly sponges) may take proportional advantages over algae and corals thanks to the increased turbidity and particulate organic matter content of the water column due to the re-suspension and sliding down of sediments operated by the coastal work on the flat (Fabricius 2005).

The impact site appeared as a tight cluster within inner controls in the ordination model relative to 20 m depth (Fig. 3c). Consistently, PERMANOVA showed that the impact site was significantly different from the outer controls (p<0.05), but not from the inner controls (p=0.06). Two differences between the impact site and the inner controls were evidenced by ANOVAs: the cover of other invertebrates in the impact site was significantly (*p*<0.05) lower (Fig. 4c); the abundance of abiotic attributes was highly significantly (*p*<0.001) greater (Fig. 4e). Maldivian reef profiles usually show a steeper inclination at 7-15 m depth (Lasagna et al. 2010), and a terrace at about 20 m depth (Bianchi et al. 1997): this causes greater sediment deposition on the comparatively levelled substrate at 20 m than on the reef wall at 10 m, and explains both the increased amount of abiotic attributes (mostly sand) and the decreased cover of non coral invertebrates (other invertebrates), whose filter-feeding apparatus may get clogged by sediment (Bell et al. 2015).

Conclusions

The comparatively high amount of abiotic attributes observed at all depths and in all sites is indicative that Maldivian reefs are not completely recovered yet by the bleaching of 1998, which caused widespread coral mortality (Bianchi et al. 2006). However, the fact that in all control sites corals were always the descriptors exhibiting the highest cover values (about 20 to 65%) is a positive sign of recovery (Morri et al. 2010). Notwithstanding apparent hysteresis, the risk of phase shift seems averted (Montefalcone et al. 2011).

Reefs still in the process of recovery, however, may be more vulnerable to further disturbances. This study is the first to attempt quantifying the impact of a local anthropogenic disturbance of the still recovering Maldivian reefs. Although the construction of Maamigili Villa International Airport is too recent to draw robust conclusions, the impact it caused at 5 m reef was such to hamper the recovery of an inner reef, maintaining it in a regressive stage even more severe than the one exhibited by outer reefs exposed to the mechanical damage by oceanic waves (Graham et al. 2014). The impact there implied reduction of hard coral cover, increase of algal cover, and dramatic augmentation of non-living substrate. At 10 m and 20 m depth, the impact was less obvious by hard coral and abiotic attributes, but still detectable if different descriptors, namely other invertebrates, were considered. Reef profile played a major role in determining pattern and intensity of the impact at different depths. While hard corals are widely used as the main indicators of coral reef status (Chabanet et al. 2005), our study suggested that other descriptors may provide integrative information to identify indirect and more subtle effects that may occur deeper. Coral reef recovery dynamics in an era of global change are hardly predictable (Graham et al. 2011): selecting an array of different descriptors and considering different depth zones, where corals may find refuge from climate impacts (Smith et al. 2014), may serve as guidelines for the efforts of minimising the impact of local human interventions on coral reefs.

Acknowledgements

Albatros Top Boat (Verbania and Malè) sponsored and organized our scientific cruise in the Maldives. In particular, we gratefully acknowledge the general manager of Albatros, Donatella 'Dodi' Telli, for her assistance. The sponsor had no role in study design, data analysis, manuscript preparation, or the decision to publish. Giulia Gatti, Alberto Maradini, Alberto Rovellini, Aurora Truccolo participated in field activitiesand helped collecting data.

References

Azzurro E., Matiddi M., Fanelli E., Guidetti P., La Mesa G., Scarpato A. and Axiak V. (2010) Sewage pollution impact on Mediterranean rocky-reef fish assemblages. Marine Environmental Research 69, 390-397.

Baker A.C., Glynn P.W. and Riegl B. (2008) Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine Coastal and Shelf Science 80, 435-471.

Ban S.S., Graham N.A.J. and Connolly S.R. (2014) Evidence for multiple stressor interactions and effects on coral reefs. Global Change Biology 20, 681-697.

Bell J.J., McGrath E., Biggerstaff A., Bates T., Bennett H., Marlow J., Shaffer M. (2015) Sediment impacts on marine sponges. Marine Pollution Bulletin 94, 5-13.

Bianchi C.N., Colantoni P., Geister J. and Morri C. (1997) Reef geomorphology, sediments and ecological zonation at Felidu Atoll, Maldive Islands (Indian Ocean). In Lessios H.A. and Macintyre I.G. (Eds) Proceedings of the 8thInternational Coral Reef Symposium. Panama: Smithsonian Tropical Research Institute, pp. 431-436.

Bianchi C.N., Morri C., Pichon M., Benzoni F., Colantoni P., Baldelli G. and Sandrini M. (2006) Dynamics and pattern of coral recolonization following the 1998 bleaching event in the reefs of the Maldives. In Suzuki Y., Nakamori T., HidakaM.,KayanneH., Casareto B.E., NadaokaK., Yamano H. and Tsuchiya M.(Eds) Proceedings of the 10th International Coral Reef Symposium.Tokyo, Japan: Japanese Coral Reef Society, pp. 30-37.

Bianchi C.N., Pichon M., Morri C., Colantoni P., Benzoni F., Baldelli G. andSandrini M. (2003) Le suivi du blanchissement des coraux aux Maldives: leçons à tirer et nouvelles hypothèses. Oceanis 29 (3-4), 325-354.

Carpenter K.E., Abrar M., Aeby G., Aronson B.R., Banks S., Bruckner A., Chiriboga A., Cortès J., Delbeek C.J., De Vantier L., Edgar J.G., Edwards J.A., Fenner D., Guzmàn M.H., Hoekesema W.B., Hodgson G., Johan O., Licuanan Y.W., Livingstone R.S., Lovell E.R., Moore J.A., Obura O.D., Ochavillo D., Polidoro A.B., Precht W.F., Quibilan M.C., Reboton C., Richards T.Z., Rogers A.D., Sanciangco J., Sheppard A., Sheppard C., Smith J., Stuart S., Turak E., Veron E.N.G., Wallace C., Weil E. and Wood E. (2008)One third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321, 560-563.

Chabanet P., Adjeroud M., Andréfouët S., Bozec Y.M., Ferraris J., Garcìa-Charton J.A. Schrimm M. (2005) Human-induced physical disturbances and their indicators on coral reef habitats: A multi-scale approach. Aquatic living resource 18, 215-230.

Clarke K.R. and Warwick R.M. (1994) Change in marine communities: An approach to statistical analysis and interpretation. Natural Environment Research Council, UK,: 144.

Davenport J. and Davenport J.L. (2006) The impact of tourism and personal leisure transporton coastal environments: Aa review.Estuarine Coastal and Shelf Science67, 280-292.

De-Miguel-Molina B., De-Miguel-Molina M., Rumiche-Sosa M. (2011)Does luxury indicate sustainability?An analysis of the Maldives.Electronic Journal of Business Ethics and Organization Studies 16 (1), 21-32.

Erftemeijer P., Riegl B., Hoeksema B.W. and Todd P.A. (2012) Environmental impacts of dredging and other sediment disturbances on corals: a review. Marine Pollution Bulletin 64, 1737-1765.

Fabricius K.E. (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50, 125-146.

Goatley C.H.R. and Bellwood D.R. (2013) Ecological consequences of sediment on high-energy coral reefs.PLoS ONE 8, e77737.

Graham N.A.J., Chong-Seng K.M., Huchery C., Januchowski-Hartley F.A. and Nash K.L. (2014) Coral reef community composition in the context of disturbance history on the Great Barrier Reef, Australia. PLoS ONE 9, e101204.

Graham N.A.J., Nash K.L. and Kool T.J. (2011) Coral reef recovery dynamics in a changing world.Coral Reefs 30, 283-294.

JaleelA. (2013) The status of the coral reefs and the management approaches: the case of the Maldives. Ocean & Coastal Management 82, 104-118.

Jimenez H., Bigot L., Bourmaud C., Chabanet P., Gravier-Bonnet N., Hamel M.A., Payri C., Mattio L., Menou J.L., Naeem S., Rilwan Y., Sattar S., Scott L., Shiham A., Vigliola L., Andréfouët S. (2012)Multi-taxa coral reef community structure in relation to habitats in the Baa Atoll Man and Biosphere UNESCO Reserve (Maldives), and implications for its conservation. Journal of Sea Research 72, 77-86.

Johns K.A., Osborne K.O. and Logan M. (2014) Contrasting rates of coral recovery andreassembly in coral communities on the Great Barrier Reef.Coral Reefs 33, 553-563.

Kennedy V.E., Perry T.C., Halloran R.P., Iglesias-Prieto R., Schönberg C.H.L., Wisshak M., Form U.A., Carricart-Ganivet P.J., Fine M., Eakin M.C. and Mumby J.P. (2013) Avoiding coral reef functional collapse requires local and global action. Current Biology 23, 912-918.

Lasagna R., Albertelli G., Colantoni P., Morri C. and Bianchi C.N. (2010) Ecological stages of Maldivian reefs after the coral mass mortality of 1998. Facies 56, 1-11.

Lasagna R., Albertelli G., Giovannetti E., Grondona M., Milani A., Morri C. and Bianchi C.N. (2008) Status of Maldivian reefs eight years after the 1998 coral mass mortality. Chemistry and Ecology 24, 67-72.

Montefalcone M., Parravicini V. and Bianchi C.N. (2011) Quantification of coastal ecosystem resilience. In Wolanski E. and McLusky D.S. (Eds.) Treatise on Estuarine and Coastal Science, vol. 10. Waltham: Academic Press, pp. 49-70.

Morri C., Aliani S. and Bianchi C.N. (2010) Reef status in the Rasfari region (North Male´ Atoll, Maldives) five years before the mass mortality event of 1998. Estuarine Coastal and Shelf Science 86, 258-264.

Price A.R.G., Ghazi S.J., Tkaczynski P.J., Venkatachalam A.J., Santillan A., Pancho T., Metcalfe R. and Saunders J. (2014) Shifting environmental baselines in the Red Sea. Marine Pollution Bulletin78, 96-101

Rogers C.S. (1990) Responses of coral reefs and reef organisms to sedimentation.Marine Ecology Progress Series 62, 185-202.

SmithT.B.,GlynnP.W.,Maté J.L., TothL.T. and GyoryJ. (2014) A depth refugium from catastrophic coral bleachingprevents regional extinction. Ecology 95(6), 1663-1673.

Underwood A.J. (1992) Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. Journal of Experimental Marine Biology and Ecology 161, 145-178.

vanWoesik R., Sakai K., Ganase A.and Loya Y. (2011) Revisiting the winners and losers adecade after coral bleaching. Marine Ecology Progress Series 434, 67-76.

Wilson S.K, Graham N.A.J. and Polunin N.V.C. (2007) Appraisal of visual assessments of habitat complexity and benthic composition on coral reefs.Marine Biology 151, 1069-1076.

Zubair S., Bowen D. and Elwin J. (2011) Not quite paradise: inadequacies of environmental impact assessment in the Maldives. Tourism Management 32, 225-234.

Table heading and Figure captions

Table 1: Geographical coordinates and typology of the investigated reefs. Position of each reef was recorded using a GPS.

Figure1. Geographic location of the 9 reefs investigated in the Maldivian atolls of Ari and South Malé.

Figure 2.Changes in the Maamigili Island following the new Maamigili Villa International Airport construction.Arrow indicates the impact site adopted in this study. a)year 2001; b) year 2007; c) year 2011.Images from Google Earth®.

Figure 3. MDS plots of study sites at different depths. a) 5 m; b) 10 m; c) 20 m. Each individual symbol represents a replicate.

Figure4. Mean (±s.e.) percentcover of hard corals (a), soft corals (b), other invertebrates (c), macroalgae(d) and abiotic attributes(e) in the impact site and in the two control conditions (inner and outer reefs), separately for the three depth zones investigated (5, 10, 20 m).

Table 1.

Reef	**Atoll**	**Coordinates**	**Typology**
DhonkadhdhaaHau	Ari	3°32.564'N; 72°48.327'E	impact
Badhibinhau	Ari	3°52.572'N; 72°49.811'E	inner
KadholHudhoo	Ari	4°00.259'N; 72°52.830'E	inner
MaayaFushi	Ari	4°04.580'N; 72°52.704'E	inner
ThoshiganduHau	Ari	3°43.400'N; 72°48.124'E	inner
Boldhuffaru	SouthMalé	4°05.565'N; 73°23.136'E	outer
Mandhoo	Ari	3°42.478'N; 72°41.906'E	outer
RanFaru	Ari	4°01.658'N; 72°42.200'E	outer
Velassaru	SouthMalé	4°07.553' N; 73°26.186'E	outer

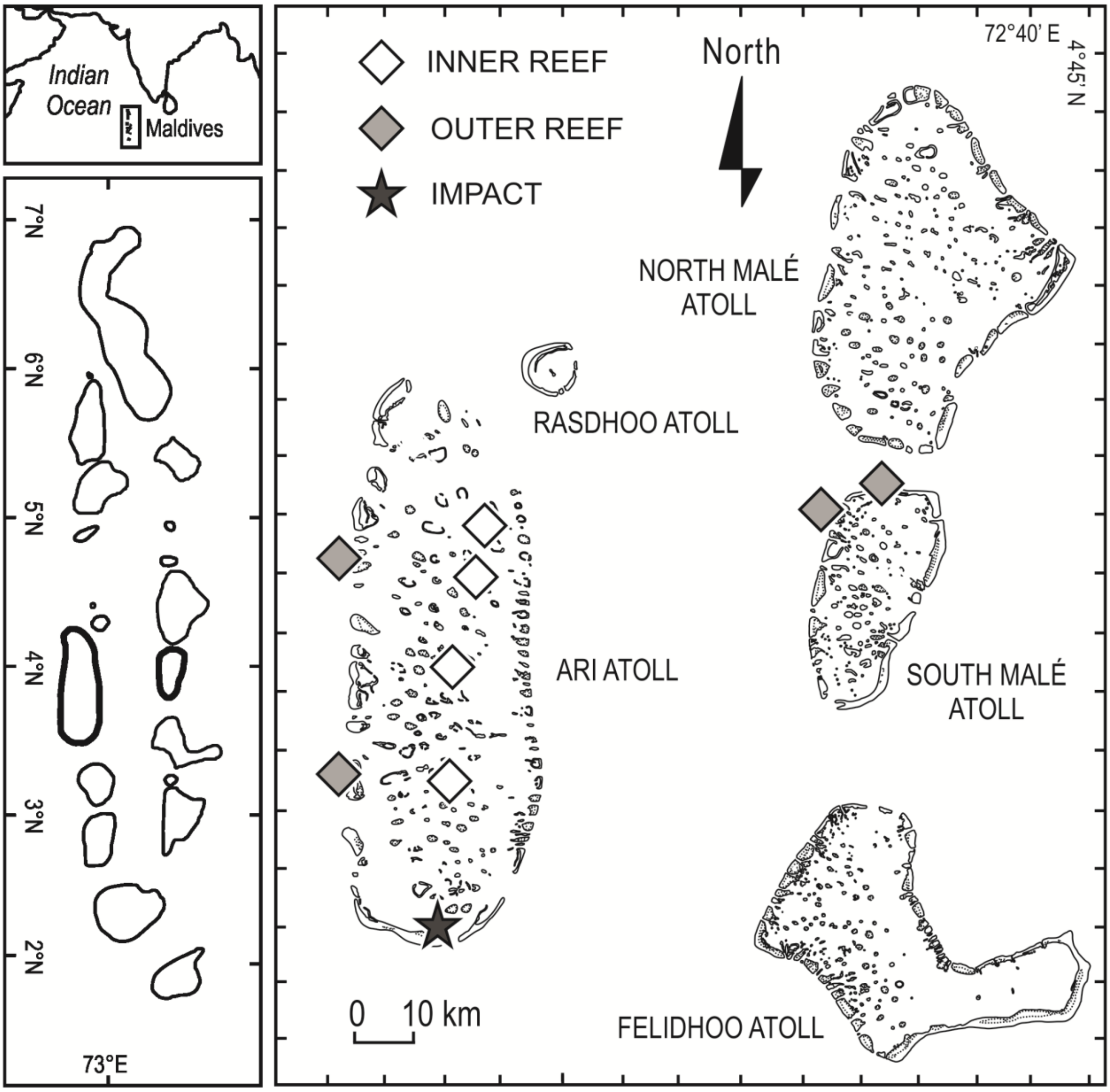

Figure 1.

Figure 2.

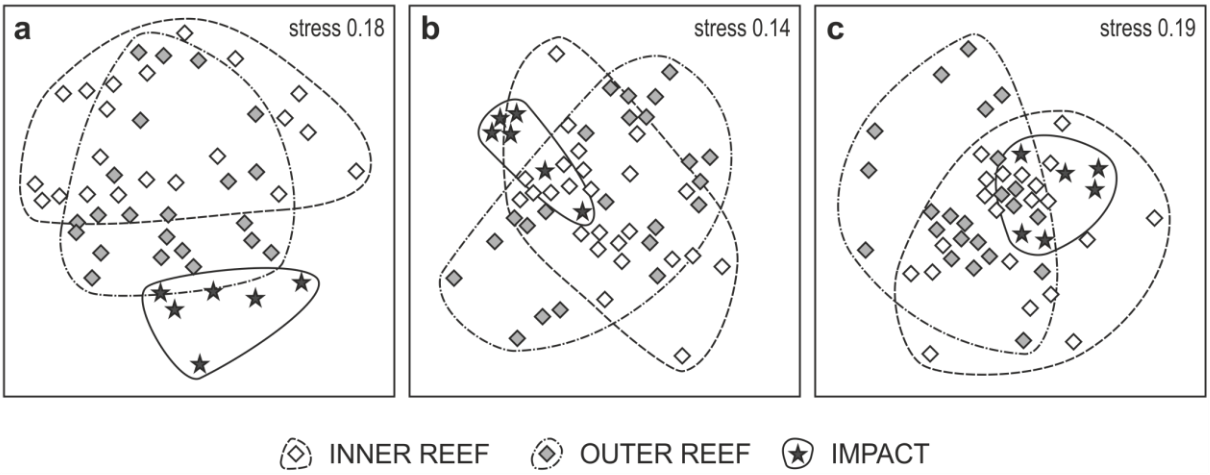

Figure 3.

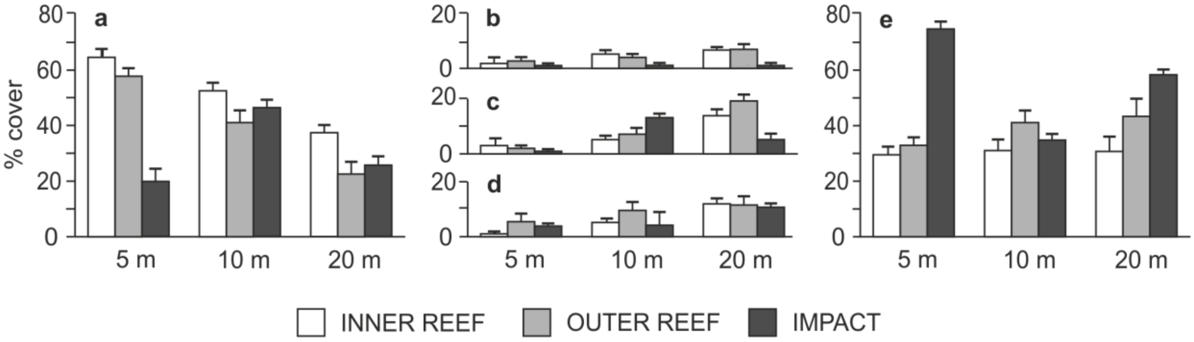

Figure 4.