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## EXPLORING THREE-DIMENSIONALITY AND HETEROGENEITY: MALDIVIAN CORAL REEFS POST-THERMAL ANOMALIES

### INDAGARE LA TRIDIMENSIONALITÀ E L'ETEROGENEITÀ: LE SCOGLIERE CORALLINE MALDIVIANE DOPO LE ANOMALIE TERMICHE

**Abstract** - Increasing anthropogenic pressures and global warming pose severe threats to coral reefs worldwide, leading to the loss of their three-dimensional structure and biodiversity. The rugosity index (RI) has been applied to Maldivian reefs surveyed over time, particularly after the severe thermal anomaly of 2016, to assess the effect of coral mortality on the three-dimensional structure of reefs. RI assessments were conducted on both lagoon and ocean reefs at various depths. Although ocean reefs exhibited greater resilience to the thermal anomaly compared to lagoon reefs, a reduction in three-dimensionality was observed in all reefs after 2016, regardless of depth. A slight increase in reef heterogeneity was observed in the subsequent years. RI represents a valuable tool for quickly monitoring the three-dimensionality of coral reefs. Because of the additional information it provides on reef health, the RI should be integrated with the other commonly adopted ecological indices in tropical reef monitoring programs.

**Keywords:** Rugosity Index, three-dimensionality, coral reefs, Maldives, thermal anomalies.

**Introduction** - Coral reefs play essential ecological and economic roles: they correspond to less than 1% of the ocean floor, and yet these environments are home to more than 25% of all marine fish species, as well as many other marine animals (Spalding, 2001), protect tropical coastlines and coastal settlements from storms, and provide social, economic, and cultural services with an estimated value of more than \$1 trillion globally (Heron *et al.*, 2017).

Their ecological role is due to their high three-dimensional structure formed through phenotypic plasticity and intraspecific variation in corals (Todd, 2008). Greater structural complexity leads to greater niche diversity, consequently accounting for greater specific diversity. Species richness is highly correlated with substrate roughness (Luckhurst, 1978).

Coral reefs are the result of a dynamic balance between bioconstruction and erosion. However, this balance may shift towards net coral reef erosion due to widespread mortality of stony corals, for example, after severe bleaching events (Sheppard *et al.*, 2002). Following a mass mortality event, the decrease in live hard coral cover on coral reefs does not immediately translate into a loss of available habitat for associated communities because the reef structure can persist long after the corals have died (Alvarez-Filip *et al.*, 2009).

Maldivian coral reefs are affected by both natural and anthropogenic pressures (Montefalcone *et al.*, 2020). The effects of global ocean warming, particularly severe thermal anomalies, are leading to an increase in the severity, duration and frequency of coral bleaching events, resulting in a progressive degradation of coral reefs. Two major heat anomalies caused bleaching and mass coral mortality in the Maldives in 1998 and 2016 (Montefalcone *et al.*, 2018). The 2016 event had a lower impact but lasted longer.

The main objectives of this study are: (a) compare the rugosity indices (RI) in the years following the 2016 bleaching event; (b) investigate differences in three-dimensionality between ocean and lagoon reefs; and (c) evaluate the relationship between three-dimensionality and heterogeneity of coral reefs.

**Materials and methods** - Spatial and temporal variability of reef rugosity in the central Maldivian atolls, including North Malé, South Malé, Ari, Felidhoo, and Rasdhoo atolls, were investigated. An equal number of ocean and lagoon reefs was randomly selected and surveyed annually from 2018 to 2022, between April and May, utilising the chain transect method to collect data on the reefs' rugosity. A chain of fixed length (200 cm) with negative buoyancy was placed along the reef contour, and its projection was measured with a meter to calculate the rugosity index (RI) as the ratio of the chain's length to its projection. The rugosity index ranges from 1, for flat reefs or sandy bottoms, to values greater than 1, indicating higher rugosity.

Data analysis was performed using R software, examining differences in RI according to depth (3 levels: 5, 10, and 20 m), site type (2 levels: ocean vs lagoon), and year (4 levels: 2018, 2019, 2021, 2022), along with their interactions, using a three-way ANOVA, after checking for normality and homoscedasticity assumptions through Kolmogorov-Smirnov and Bartlett test, respectively. The normality assumption was not fulfilled even after data transformation, while homogeneity of variance was met. Since ANOVA is robust to violation of normal distribution of the response variable, untransformed data were analysed, setting  $\alpha = 0.01$  to compensate for a potential increased likelihood of Type I error. Post-hoc analyses were performed using the Kruskal-Wallis and pairwise-Wilcox tests. Data are visualised through barplots at each depth, comparing reef types across the study years.

**Results** - The three-way ANOVA revealed a significant effect of the interaction between site type and year ( $p$ -value  $< 0.001$ ), as well as differences in the rugosity index (RI) across the sampled depths ( $p$ -value  $\ll 0.001$ ; Tab 1). At 20 m depth, the three-dimensionality of ocean and lagoon reefs was consistently lower compared to the other depths, while at 5 and 10 m, it was comparable.

Tab. 1 - Analysis of variance.  
*Analisi della varianza.*

Response: IR					
	Df	Sum Sq	Mean Sq	F value	Pr(>F)
DEPTH	1	2.117	2.11693	15.8727	7.097e-05 ***
TYPE	1	0.199	0.19906	1.4926	0.222012
DATE	1	0.003	0.00293	0.0219	0.882263
DEPTH: TYPE	1	0.157	0.15741	1.1802	0.277484
DEPTH: DATE	1	0.006	0.00631	0.0473	0.827848
TYPE: DATE	1	0.934	0.93391	7.0025	0.008224 **
DEPTH: TYPE: DATE	1	0.342	0.34173	2.5623	0.109651
Residuals	1512	201.655	0.13337		
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Signif. Codes:	0 '***'	0.001 '**'	0.01 '*'		

Change in the RI over time at the three depths indicated a similar response to environmental variability or potential pressures. Lagoon reefs exhibited higher three-dimensionality compared to ocean reefs in 2018 at 5 m depth ( $p$ -value  $< 0.001$ ), although this difference disappeared in the subsequent years. Lagoon reefs at 5 m experienced a significant decrease in three-dimensionality between 2018 and 2019 ( $p$ -value  $\ll 0.001$ ), followed by a notable increase between 2019 and 2021 ( $p$ -value  $< 0.001$ ), and then remained stable in 2022. The RI in 2022 was significantly lower than in 2018 ( $p$ -value  $\ll 0.001$ ).

In contrast, ocean reefs at 5 m depth witnessed a considerable loss of their three-

dimensionality between 2018 and 2019 ( $p$ -value  $\ll 0.001$ ), followed by a significant increase in RI between 2019 and 2021 ( $p$ -value  $< 0.001$ ). No further significant changes were observed between 2021 and 2022. The three-dimensionality of ocean reefs at 5 m remained comparable between 2018 and 2022.

Significant differences in the RI were observed at greater depths (10 and 20 m). Three-dimensionality remained comparable between lagoon and ocean reefs in 2018, 2019, and 2022. However, in 2021, ocean reefs exhibited higher rugosity compared to lagoon reefs ( $p$ -value  $< 0.01$ ). At 10 m, lagoon reefs experienced a significant loss ( $p$ -value  $< 0.001$ ) in rugosity between 2018 and 2019, followed by a remarkable increase ( $p$ -value  $\ll 0.001$ ) between 2019 and 2021. Subsequently, between 2021 and 2022, another significant decrease in reef rugosity was observed in lagoon reefs ( $p$ -value  $\ll 0.001$ ). RI in 2018 and 2022 was comparable.

In contrast, the RI of ocean reefs was significantly higher ( $p$ -value  $\ll 0.001$ ) in 2018 compared to the following years, with a significant increase observed from 2019 to 2021 ( $p$ -value  $\ll 0.001$ ). However, the three-dimensionality decreased ( $p$ -value  $< 0.001$ ) in 2022 and was lower than in 2018 ( $p$ -value  $< 0.001$ ).

The RI did not exhibit differences between ocean and lagoon reefs across the years at 20 m depth. Both lagoon and ocean reefs experienced a highly significant loss of their three-dimensionality between 2018 and 2019 ( $p$ -value  $\ll 0.001$ ), followed by a substantial increase between 2019 and 2021 ( $p$ -value  $\ll 0.001$ ). Furthermore, a significant decrease in rugosity was observed between 2021 and 2022 ( $p$ -value  $< 0.001$ ). The RI in 2022 was statistically lower than in 2018 ( $p$ -value  $< 0.001$ ).

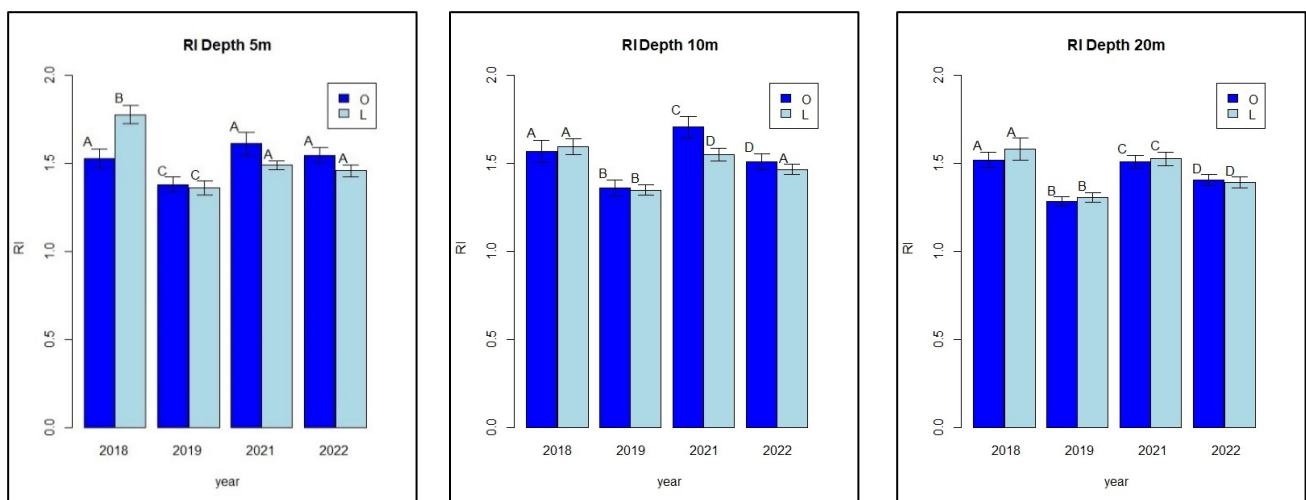


Fig. 1 - Barplot Rugosity Index (RI) at the three depths of 5, 10, and 20 m.

*Barplot dell'Indice di Rugosità (RI) alle tre profondità di 5, 10 e 20 metri.*

**Discussion and conclusions** - The rugosity index serves as a valuable tool for quickly assessing reef three-dimensionality, indicative of reef health and biodiversity. Highly three-dimensional reefs support diverse marine life and are essential for ecosystem resilience.

Ocean reefs exhibited greater resilience than lagoon reefs, attributed to ocean currents that clear coral rubble, facilitating new colony establishment. After 2019, ocean reefs displayed a faster increase in three-dimensionality, emphasising their capacity to recover from disturbances.

Reefs at varying depths respond similarly to mass mortality events, with comparable erosion and accretion rates. While lagoon and ocean reefs exhibited different three-dimensionality at 5 m after the 2016 severe thermal anomaly, these differences

diminished in the following years. At major depths, the three-dimensionality was always comparable between lagoon and ocean reefs.

Our results do not indicate a significant increase in the three-dimensionality of Maldivian reefs in recent years, even though other studies have observed a rapid recovery of Maldivian coral reefs following bleaching events (Pisapia *et al.*, 2016). This discrepancy can be attributed to the fact that the reefs exhibiting a faster recovery are predominantly dominated by tabular *Acropora* species, known for their exceptionally rapid growth rates compared to other coral morphologies. When the tabular colonies expand, increasing the total cover of corals on reefs, they lead to a reduction in the reef's three-dimensional structure, especially when adjacent colonies overlap their fans, with a parallel reduction in both reef heterogeneity and species richness. For this reason, the rugosity index must be integrated with other ecological indices to define better the state of health of coral reefs, such as, for instance, the hard coral cover and the BioConstruction Potential Index (Montefalcone *et al.*, 2018).

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