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Coral Distribution on Artificial Structures in Bonaire, Leeward Antilles

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Abstract: Distribution patterns of live scleractinian coral colonies on vertical faces of concrete blocks were compared with distribution patterns of environmental parameters known to affect coral recruitment and growth. Coral coverage was not random across the blocks and among regions of their faces. Variations in colonization did not correspond to differences in substrate type, illuminance, and water motion intensity. Coral distribution significantly correlated with blocks location and faces orientation, and these correlations depended on prevailing current direction. These correlations and dependencies are consistent with the hypothesis that the coral coverage was detrimentally affected by a low quality of water flow from the local marine port.

Keywords: Colonization, environmental factors, reef conservation, reef management, reef restoration, scleractinia, sedimentation, water quality.

INTRODUCTION

Physical environmental factors play a crucial role in coral settlement, survival, growth, and development. Such factors as increase in water temperature and acidity, or increase in strength and frequency of storms affect coral reefs on global and regional scales [1]. Factors such as coastal currents, water turbidity, and sedimentation have more localized effects [2, 3]. Even small local variations in physical environmental parameters may cause significant differences in coral reef establishment and persistence [4, 5].

It is often difficult to determine the effect of a specific environmental factor on coral communities due to many uncontrolled or unknown factors and because the age and history of the coral is usually unknown [6]. These difficulties are minimized in experimental settings where corals develop on simple artificial structures such as tiles and racks, in selected environments [7]. These studies provide data on settlement and initial survival, usually not on the subsequent growth and development of corals [8]. Some long term data are available from studies of coral reef development on artificial structures with well known history such as submerged constructions and ship wrecks [9, 10]. However, these data are often difficult to interpret because of the complexity of the structures and a multitude of environmental factors.

A rare opportunity to investigate long term coral development on simple artificial structures is provided by the boat mooring blocks installed along the coast of Kralendijk, Bonaire, Leeward Antilles. These are concrete blocks with dimensions of 1 m x 1 m x 1 m that were deployed by Bonaire National Marine Park between 1994 and 1996. The mooring blocks were installed on a flat bottom between the shore and the natural fringing reef, with about 50 m between the moorings. Their vertical faces are now partially covered with coral colonies that developed since the installation.

These simple structures have the same physical and chemical composition, surface texture, color, and deployment configuration. This setup allows for comparison of limited number of physical environmental parameters that vary among sites. Variables associated with the block locations consist of different depths, distances from the shore and from the reef, and locations of the blocks along the shore. Variations between the block faces consist of different exposure to light and currents due to different orientations.

The purpose of this study was to investigate the long-term relationship between the physical environmental factors and patterns of the coral distribution. The percentage of live coral coverage on the block faces was the dependent variable. This measure is a good estimate of the total amount of live coral in this study because only massive and encrusting coral species (of mostly genus *Diploria* with some *Porites* and *Agaricia* and much less significant contribution of other genera) have developed on the mooring blocks, with branching and columnar species absent.

The results of this study may contribute to the understanding of small-scale environmental effects on coral reef development, and may be helpful in future restoration projects.

MATERIALS AND METHODS

Study Site

This study focused on boat moorings used for rental by private yachts because these moorings are the most permanent compared to other moorings that are used by

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Fig. (2). The inshore and the southern offshore mooring areas and direction of sediment spreading.

Light

Light data were collected between Sep. 25, 2010, and Apr. 2, 2011, using HOBO Pendant® Temperature/Light Data Loggers 64K (Onset Computer Corporation, Pocasset, MA). The loggers continuously recorded light intensity every minute.

The light data were collected in three locations - around mooring 190 in the southern offshore area, mooring 340 in the northern offshore area, and mooring 205 in the inshore area (Fig. **1**). At each location, five loggers were installed, facing northward, eastward, southward, westward, and upward. The loggers were installed on metal rods fastened to the bottom, near the block faces to measure the illuminance of each face with corresponding orientation.

The recordings were transferred weekly to a computer. After transferring the data, the loggers were reset, cleaned of sedimentation and growth, and randomly repositioned and reoriented.

Currents

Currents data were collected between Jul. 2, 2010, and Aug. 29, 2012, on random days and at random time between 08:00 and 17:00. The data were collected near the southern offshore mooring 190, the northern offshore mooring 340, and the inshore mooring 205 (Fig. **1**). The currents were measured by a SCUBA diver hovering about 0.5 m above the bottom and drifting with the current. While passively drifting, the diver dropped two small weights one minute apart. The distance between the weights and their relative position provided measurement of the currents' velocity and direction.

Integrated Water Motion

To estimate integrated water motion caused by wave surge, tides, and currents, data on galvanic corrosion rates were collected [11, 12]. To compare between the three mooring areas, the data were collected at the southern offshore moorings 110 and 190, the northern offshore mooring 370, and the inshore moorings 115 and 205 (Fig. **1**), in seven random 15–32 day periods between May 12, 2012, and Oct. 27, 2012. Zinc-copper galvanic pairs were attached to re-bars on top of the mooring blocks at the beginning of each period and removed at the end of each period. All zinc pieces used for each period were cut from the same zinc rod. After the removal, zinc pieces were cleaned for three

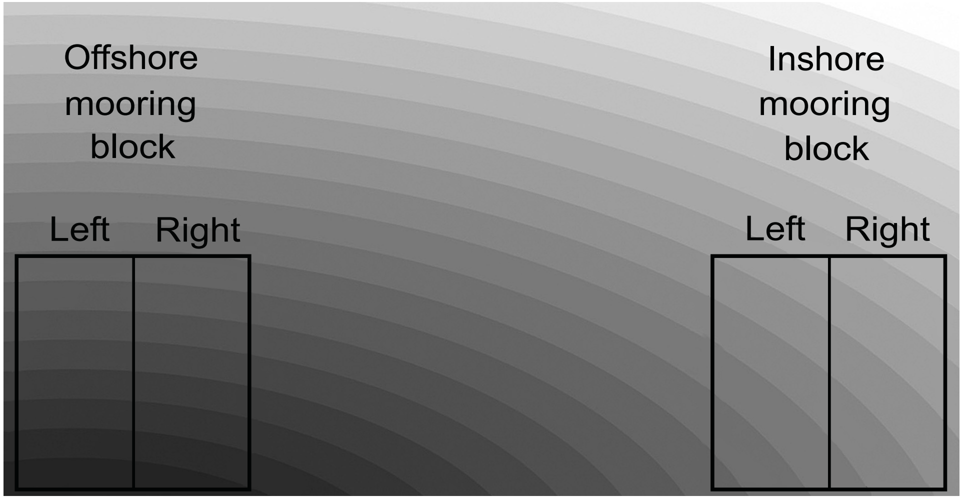

Fig. (3). Cross-section view of the suspended sediment plume drifting from the port in the direction with the current.

Table 1. Coral coverage on exposed mooring block faces by mooring areas.

Mooring Area	Number of Faces	Mean Coverage, %	Minimum Coverage, %	Maximum Coverage
Inshore	61	25.4	1	49
Southern offshore	32	12.3	0	27
Northern offshore	34	20.7	1	44

Table 2. Coral coverage by mooring area and orientation; mean coral coverage, %, (number of faces).

Mooring Area	Face Orientation			
	North	East	South	West
Inshore	24.8 (14)	25.8 (17)	27.3 (12)	24.2 (18)
Southern offshore	13.0 (9)	13.7 (10)	9.7 (8)	11.8 (5)
Northern offshore	25.1 (8)	21.0 (7)	21.0 (9)	16.6 (10)

minutes in 10% HCl solution. Weights of zinc pieces before and after each period were recorded.

Statistical Analysis and Plume Model

InStat software (GraphPad Software, La Jolla, CA) was used to calculate summary statistics and to run statistical tests. Vertical and horizontal distribution of suspended sediments in the "marine snow" plume was assumed qualitatively to be a normal Gaussian distribution (Fig. **3**).

RESULTS

Coral Coverage Patterns

Mooring Areas

Coral coverage on exposed mooring block faces was compared between the three areas (Table **1**). Kruskal-Wallis test (nonparametric ANOVA) showed significant differences among the median coverage (KW = 22.7, $P < 0.0001$). Dunn's multiple comparisons post-test showed that the median coverage was significantly higher for the inshore than the southern offshore ($P < 0.001$) and for the northern offshore than the southern offshore ($P < 0.01$) mooring areas. Coverage was not significantly different between the inshore and the northern offshore mooring areas.

Face Orientation

Coral coverage in each mooring area was compared among the faces oriented toward north, east, south, and west (Table **2**). Kruskal-Wallis test failed to detect significant differences among orientations in every mooring area (inshore: KW = 0.3943, P = 0.9414; southern offshore: KW = 1.834, P = 0. 6076; northern offshore: KW = 2.220, P = 0.5280).

Coral coverage differences among orientations were significant when compared by mooring areas. The coral coverage on northerly faces in the inshore mooring area was significantly higher than that of southerly faces in the southern offshore mooring area (Mann-Whitney test: U = 19, P = 0.0126).

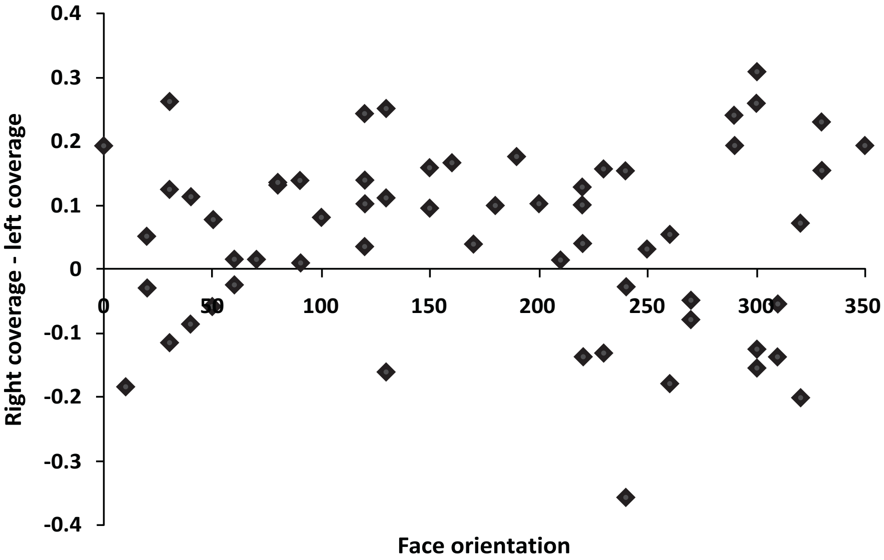

Fig. (4). Coral coverage difference between right and left halves of mooring block faces in the inshore mooring area, by face orientation.

Table 3. Daily light intensity between 06:00 and 18:00 by mooring area and orientation; mean daily light intensity, lux (number of days).

Mooring Area	Face Orientation			
	North	East	South	West
Inshore	1,907 (139)	2,824 (137)	2,876 (138)	2,873 (143)
Southern offshore	1,387 (105)	2,049 (106)	2,195 (119)	1,390 (90)
Northern offshore	1,639 (76)	2,469 (75)	1,691 (87)	1,402 (83)

Right and Left Halves

Coral coverage in each mooring area was compared between the right and the left halves of the faces. No significant differences were detected in the southern offshore area (Wilcoxon matched-pairs signed-ranks test: N = 32, W = -12, P = 0.9181) or in the northern offshore area (Wilcoxon matched-pairs signed-ranks test: N = 34, W = 93, P = 0.4316). But the coral coverage on the right halves of block faces in the inshore area was significantly higher than that on their left halves (Wilcoxon matched-pairs signed-ranks test: N = 61, W = -769, P = 0.0058).

Differences between the coverage on right and left halves of the mooring block faces in the inshore area depended on the face orientation (Fig. **4**). Coral coverage on the right halves of the faces oriented down the shoreline (80° - 250°) was significantly higher than that on their left halves (Wilcoxon matched-pairs signed-ranks test: N = 30, W = -276, P = 0.0047). However, there was no significant difference between right and left half coverage on the faces oriented up the shoreline (260° - 70°) (Wilcoxon matched-pairs signed-ranks test: N = 31, W = -118, P = 0.2516).

Upper and Lower Halves

Coral coverage in each mooring area was compared between the upper and the lower halves of the faces. Coral coverage on the upper halves of the block faces was significantly higher than that on their lower halves in all three mooring areas (inshore area, Wilcoxon matched-pairs signed-ranks test: N = 61, W = 1587, P < 0.0001; southern offshore area, Wilcoxon matched-pairs signed-ranks test: N = 32, W = 418, P < 0.0001; northern offshore area, Wilcoxon matched-pairs signed-ranks test: N = 34, W = 515, P < 0.0001).

The ratios of lower half to upper half coverage was significantly different between the three areas (Kruskal-Wallis test: KW = 6.063, P = 0.0482). Dunn's multiple comparisons post-test did not find which pair's medians of the ratio are significantly different. Because the medians for the two offshore areas were very close to each other, 0.360 and 0.365, they were pooled together as one offshore area (N = 66, mean ± SE = 0.504 ± 0.067), which was compared against the inshore area (N = 61, mean ± SE = 0.632 ± 0.056). Mann-Whitney test of this comparison showed significant difference between the inshore and the offshore areas (U = 1504, P = 0.0142). The relative difference in coverage of live coral between upper and lower halves of the block faces was significantly greater in the offshore area than in the inshore area.

Light Intensity

Light intensities in each mooring area were compared among north, east, south, and west orientations (Table **3**).

Table 4. Average current velocity, cm×sec^{-1}.

Mooring Area	Number of Measurements	Mean Velocity	Minimum Velocity	Maximum Velocity
Inshore	98	4.85	0.2	24.5
Southern offshore	54	5.17	0.8	25.5
Northern offshore	44	5.12	0.3	17.7

Kruskal-Wallis test showed that these intensities were significantly different in every area (inshore: KW = 115.58, $P < 0.0001$; southern offshore: KW = 125.81, $P < 0.0001$; northern offshore: KW = 115.37, $P < 0.0001$).

Significant difference in light intensity was also found between mooring areas. Light intensity of the northern orientation in the inshore area was significantly lower than that in the southern orientation in the southern offshore area (Mann-Whitney test: U = 5698, $P < 0.0001$).

Currents

Velocities

Average current velocities were compared among the three mooring areas (Table **4**). No significant differences were found (Kruskal-Wallis test: KW = 2.063, P = 0.3565).

Prevailing Currents

Directions of prevailing currents in each mooring area are generally parallel to the shoreline in that area (Fig. **5**). Current velocities up the shoreline and down the shoreline were compared in each mooring area. The average velocity up the shoreline was significantly higher than that down the shoreline in the inshore (Wilcoxon signed rank test: N = 98, W = 2220, $P < 0.0001$) and in the southern offshore (Wilcoxon signed rank test: N = 54, W = 822, P = 0.0004) areas, but there was no significant difference between the directions in the northern offshore area (Wilcoxon signed rank test: N = 44, W = 199, P = 0.2480).

Zinc Corrosion (Integrated Water Motion)

Repeated measures ANOVA failed to detect a significant difference in average zinc corrosion rates among the three mooring areas (df = 34, F = 1.891, P = 0.1448).

DISCUSSION

About two decades ago, Bonaire Marine Park installed concrete mooring blocks, 1 m x 1 m x 1 m, along the shoreline of Kralendijk for yachts and boats to moor. Mixed coral colonies colonized the block faces. We find that distribution of the coral coverage is not random but instead follows patterns that this research sought to characterize and explain.

Mooring Areas

Coral coverage on the mooring blocks located close to shoreline near downtown Kralendijk (the inshore area) was about twice as much as on the adjacent blocks which are farther from the shoreline and closer to the natural reef (the southern offshore area). Because polluted rainwater enters sea water from the shore, the water near the shoreline is expected to be of a lower quality than water farther from it. Water quality is a known factor affecting coral development and poor water quality reduces coral establishment [13]. Thus higher coral coverage near the shore was unexpected and counter-intuitive. It suggests that a different factor, other than the water pollution from the shore, determined the observed pattern.

Studies have shown effects of proximity to a natural reef on coral settlement [14]. However, observed coral distribution on the mooring blocks in this study appears to be unrelated to the proximity of the natural reef. The coral coverage was significantly higher on the mooring blocks located in the northern offshore area than in the southern offshore area and was similar to the inshore area. The significant difference in coral coverage between the northern and the southern offshore areas, located equally close to the reef, suggests that the determining factor in this study was unrelated to possible biotic effects caused by reef inhabiting organisms found in other studies [15-19].

Exposure to light has been shown to affect multiple aspects of coral development [20-22]. However, factors determining coverage patterns on mooring blocks in this study appear to be unrelated to the illumination of mooring block faces. The inshore block faces which point north received only 65% of the amount of light reaching east-, south-, or west-oriented faces. If light intensity caused the differences in coral coverage, the northern faces would have significantly different amounts of coral from faces with other orientations. But no difference was found in coral coverage on faces with different orientations.

Inshore blocks received on average significantly more light than southern offshore ones and coral coverage on the inshore blocks was significantly higher than on the southern offshore ones. However, the northerly oriented faces of the inshore blocks received significantly less light than southerly oriented faces of the southern offshore blocks. In spite of this, northerly oriented faces of the inshore blocks had twice as much coral as southerly oriented faces of the southern offshore blocks. The lack of consistent relationship between coral coverage on the block faces and amounts of light reaching the faces indicates that light intensity did not determine observed coral distribution patterns in this study.

Directional water flow, i.e. current, is another factor known to affect multiple aspects of coral development [21, 23, 24]. However, the coverage patterns on mooring blocks in this study appear to be unrelated to the current velocity near the blocks. Average velocities of the currents in all three mooring areas were about 5 cm/sec, at least five times weaker than currents shown in the other studies to affect

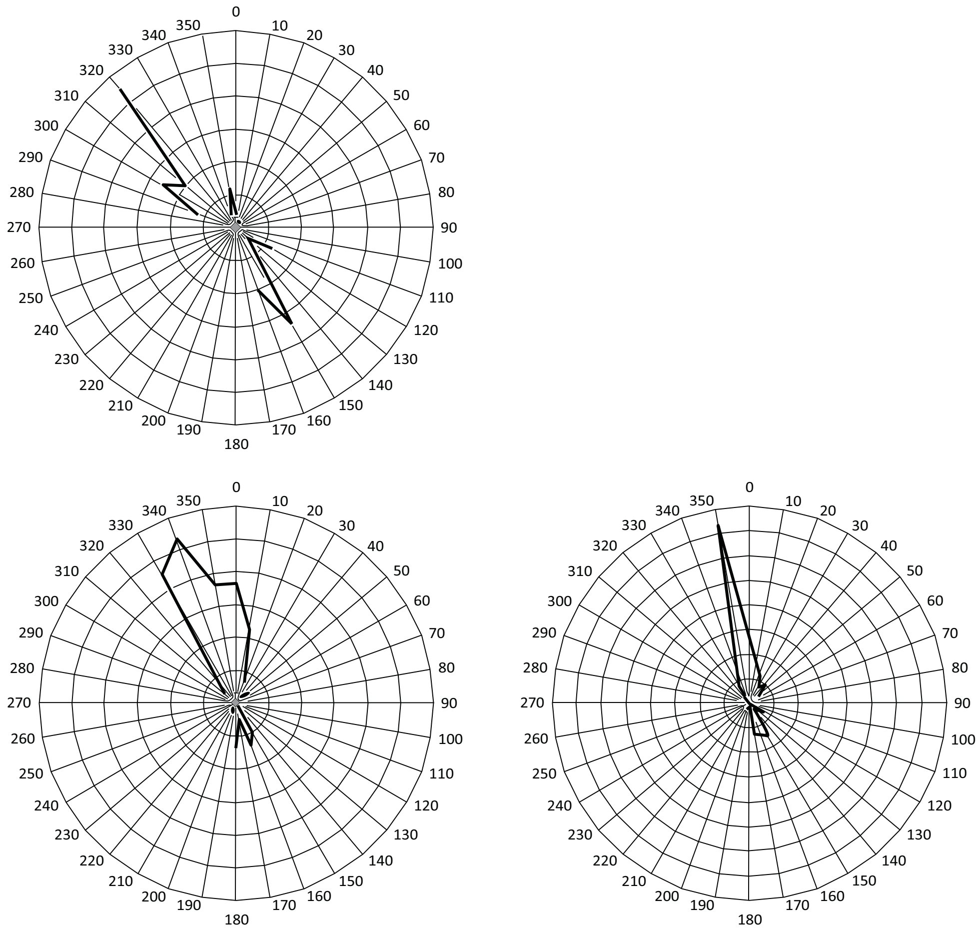

Fig. (5). Relative sum of current velocities for each current direction measured in the northern offshore (upper), southern offshore (lower left) and inshore (lower right) mooring areas.

coral recruitment, survival, or growth. Moreover, no differences in current velocities have been found among the three mooring areas.

Non-directional water motion caused by tides and waves also affects coral development [25, 26]. However, the measurements of galvanic corrosion failed to detect any difference in water motion among the mooring areas.

Additional factors that could lead to differences in coral coverage among the mooring areas are different amounts of sand surrounding mooring blocks, and different time durations the blocks were submerged. The sand might prevent coral recruitment by scouring the surface of the mooring blocks. However, the inshore moorings were located in the middle of the sand-flat, surrounded by sand, while the offshore moorings were located near the reef and surrounded by a mix of sand with hard coral rubble, small patches of live corals, sponges, and gorgonians. There was more sand around the inshore mooring blocks than around the offshore ones. If the amount of sand were preventing coral recruitment, then there would be less coral on the inshore moorings than on the offshore ones. The actual pattern was exactly opposite and thus, the sand around the moorings does not explain the coral coverage patterns.

Chronologically, all the mooring blocks in this study were installed over one year and half between 1994 and 1996. The offshore moorings were installed first, from south to north, and then the inshore moorings were installed. This timing of mooring installation does not correspond to the patterns of coral coverage present.

Another environmental factor known to detrimentally affect multiple aspects of coral development is sediment disturbance [3, 27-31]. If this was the factor determining coral coverage patterns on the mooring blocks, the disturbance affected mostly the southern offshore mooring area and to a lesser extent the inshore and the northern offshore areas. Examining the vicinity of the mooring areas suggests a possible source of such disturbance: the plume of muddy “marine snow” from the port (Fig. **2**).

The offshore moorings are located near the reef drop-off, and thus, on the axis of the plume movement. The southern offshore mooring blocks are the closest to the plume’s source, the port, and thus they would be most affected. As the plume moves farther away from its source it settles and disperses, and its effect on the blocks weakens. In addition, the lack of a prevailing current direction in the northern mooring area diminishes the plume effect in that area. The inshore mooring blocks would be less affected than the southern offshore ones because the inshore blocks are located away from the plume movement axis. Thus, the plume of sediments mechanically disturbed in the port and drifted by the prevailing currents can consistently explain the observed patterns of coral distribution among the three mooring areas.

Right and Left Halves of Block Faces

The faces of the inshore mooring blocks which were oriented against the prevailing current had significantly more coral coverage on their right halves than on their left halves. No asymmetry in the coral coverage between the right and left halves has been found in other mooring areas or on faces oriented away from the current. The plume of disturbed sediment described in the previous section can consistently explain this pattern. The suspended sediments' concentration varies horizontally and vertically, as viewed in the direction of the plume movement (Fig. **3**). The axis of the plume is near the offshore mooring area – this is where the concentration of the suspended sediment is the highest. This concentration decreases upward and sidewise. The concentration of suspended sediment differs between right and left halves of the inshore block faces oriented toward the upcoming plume: the right halves being farther from the plume axis receive less sediment than the left halves (Fig. **3**). Although this difference is not as pronounced as the difference between the inshore and the offshore block faces, it could be sufficient for coral larvae to settle preferentially on the right rather than the left halves as they explore quality of attachment sites by probing, crawling, bouncing and swimming across them [14, 32-34].

There is no or little difference in sediment concentrations between the right and the left halves of the offshore block faces because they are located at or near the plume axis; the horizontal gradient of sediment concentration is greater closer to the shore than near the plume axis (Fig. **3**). This explains why corals on the offshore block faces did not exhibit right *vs.* left differences.

Sediment concentrations in the plume do not differ between the right and the left halves of the faces oriented away from the upcoming plume because of the hydrodynamics of the water flow around the blocks [35]. That is why the corals exhibited right settlement preference only on the faces oriented against the current, *i.e.* facing into the upcoming plume.

Upper and Lower Halves of Block Faces

There was a significant difference in coral coverage between the upper and the lower halves of the block faces. The vast majority, 109 out of 127, mooring block faces had more corals on their upper than on their lower halves. This ratio held for the inshore, 51 out of 61, and for the offshore, 58 out of 66 mooring block faces.

Several environmental factors could be considered to explain this asymmetry. One such factor is the effect of waves. The faces' upper parts are closer to the surface and thus are more affected by waves than their lower parts. The enhanced water motion could be a cause of enhanced coral growth on the upper parts. But if it were so, then a stronger effect would be expected inshore than offshore because the inshore moorings are shallower than the offshore ones. The top of the inshore mooring blocks is about 2 m deep, and their base is about 3 m deep – a 50% difference, while the top of the offshore mooring blocks is at about 4 m deep and the base at about 5 m deep – only a 25% difference. Thus, the difference between upper and lower half coral coverage would be greater on the inshore than on the offshore moorings. However, as found here, the difference between upper and lower half coral coverage was significantly greater on the offshore than on the inshore moorings.

The asymmetry between the upper and lower half coverage could be caused by different light intensities. The faces' upper parts receive more light than their lower parts. Because the inshore moorings are shallower than the offshore ones, just as in the case of the wave effect described earlier, the light effect is stronger on the inshore moorings than on the offshore ones. Again, the difference between upper and lower half coral coverage would be greater on the inshore than on the offshore moorings, while the opposite pattern is found here.

Another possible explanation of the vertical asymmetry could be that sand from the bottom scours the faces' lower parts more than their upper parts. Because the inshore moorings are surrounded by larger amounts of sand than the offshore ones, the sand effect is stronger on the inshore moorings than offshore. Thus, the difference between upper and lower half coral coverage would be greater on the inshore than on the offshore moorings - opposite to the actual pattern found here.

If the asymmetry between the upper and lower half coverage were caused by any of the factors above or their combination, the asymmetry would be more pronounced in the inshore rather than the offshore areas. Contrary to this prediction, the difference between upper and lower half coral coverage was significantly greater on the offshore than on the inshore moorings. On the inshore mooring block faces, about twice as much coral covered the upper halves compared to the lower halves, but on the offshore moorings - three times as much.

The observed vertical asymmetry pattern is inconsistent with possible effects of waves, light, and sand, but it is consistent with the effects of the plume of suspended sediments described earlier. The concentration of sediments is highest at the plume's axis and drops upward and sidewise (Fig. **3**). On both the offshore and the inshore blocks, concentration of sediments is higher near the base than near the top. The vertical gradient in sediment concentration is greater near the plume axis than closer to the shore, *i.e.* greater on the offshore blocks than on the inshore ones (Fig. **3**). Accordingly, the difference in coral amounts between the upper and the lower halves of the block faces is greater on the offshore blocks than on the inshore ones.

CONCLUSION

The patterns of coral coverage distribution between the three mooring areas, as well as the horizontal and vertical patterns of coral coverage on the mooring block faces correspond to detrimental effects on coral by this plume of suspended sediment drifting along the reef from the port. They do not correspond to other factors generally known to affect coral development. This consistent correspondence strongly, albeit indirectly supports the proposed explanation of the distribution patterns. Repeated measurements of concentration of sediments suspended in water and accumulated on the mooring faces would provide more direct support for this explanation.

This study suggests a strong detrimental effect on coral development by sediment disturbance upstream of the coral site. This effect needs to be considered in coral restoration projects, and the relative position between coral sites and areas of disturbance has to be chosen accordingly.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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