Supplementary Material

Contents

Sampling design: sites per island

Figure S1. The relationship between sampling effort (i.e., the number of sites per island) and the amount of nearshore habitat, represented here by the length of each island's 10 m isobath. For the Main Hawaiian Islands, only leeward coastline was considered since all study sites were located on the leeward side of islands to control for wave energy. Leeward coastline was defined as the length of the continuous 10 m isobath with an average long-term wave energy of < 10 kW/m using data from Wedding et al. 2018. The full length of the 10 m isobath was used for the Northwest Hawaiian Islands since sites were not confined to the leeward side of atolls in this region. Logistical constraints limited sampling effort in the Northwest Hawaiian Islands to 4-5 sites per island. Additional sites from the island of Hawai‘i were surveyed, but low image quality necessitated the exclusion of several sites from this analysis. For those reasons, Hawai‘i, Pearl and Hermes, French Frigate Shoals, and Lisianski are under-sampled compared to a fully balanced design.

Sites were surveyed between July 2016 and August 2017 as part of five separate research expeditions. Scripps researchers, in collaboration with NOAA, surveyed sites in the Northwest Hawaiian Islands as part of the 2016 Hawaiian Archipelago Reef Assessment and Monitoring (HARAMP) cruise from July to September 2016. The 100 Island Challenge team at Scripps surveyed sites on O‘ahu in March 2017 and on Moloka‘i, Kaho‘olawe, and Lāna‘i in April 2017. A separate team of researchers from Scripps and The Nature Conservancy surveyed sites along the Kona coast of Hawai‘i in April 2017. Finally, researchers from the Smith Lab at Scripps led a research expedition to Maui from July to August 2017 as part of an annual monitoring program. Sites were surveyed using similar methods across research expeditions.

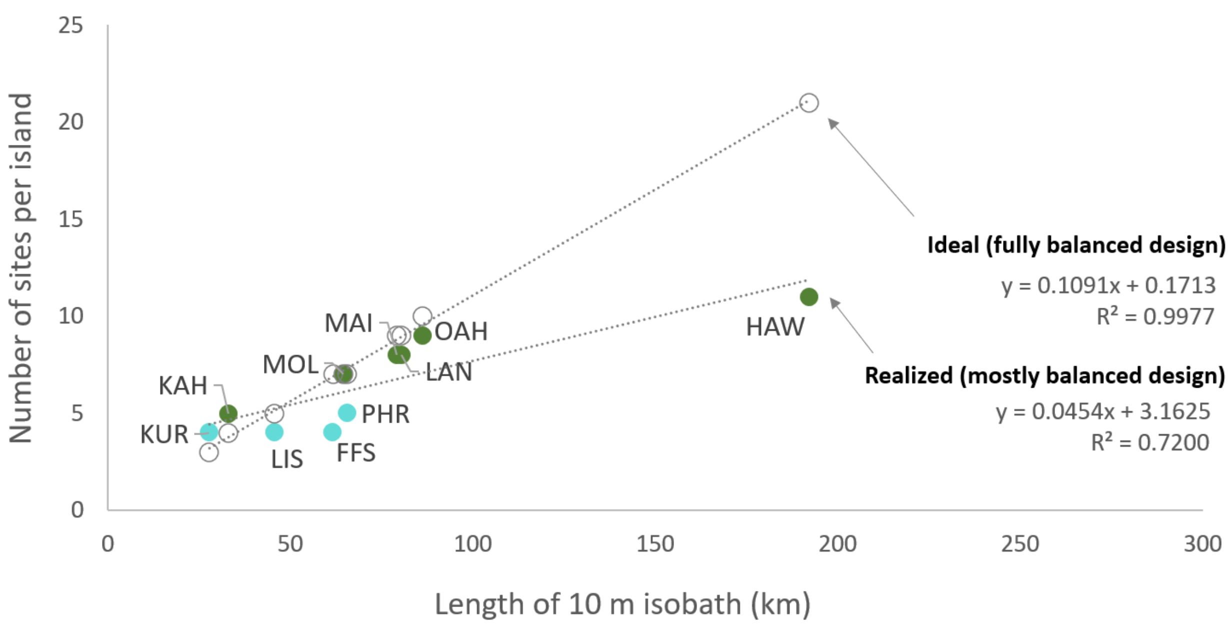
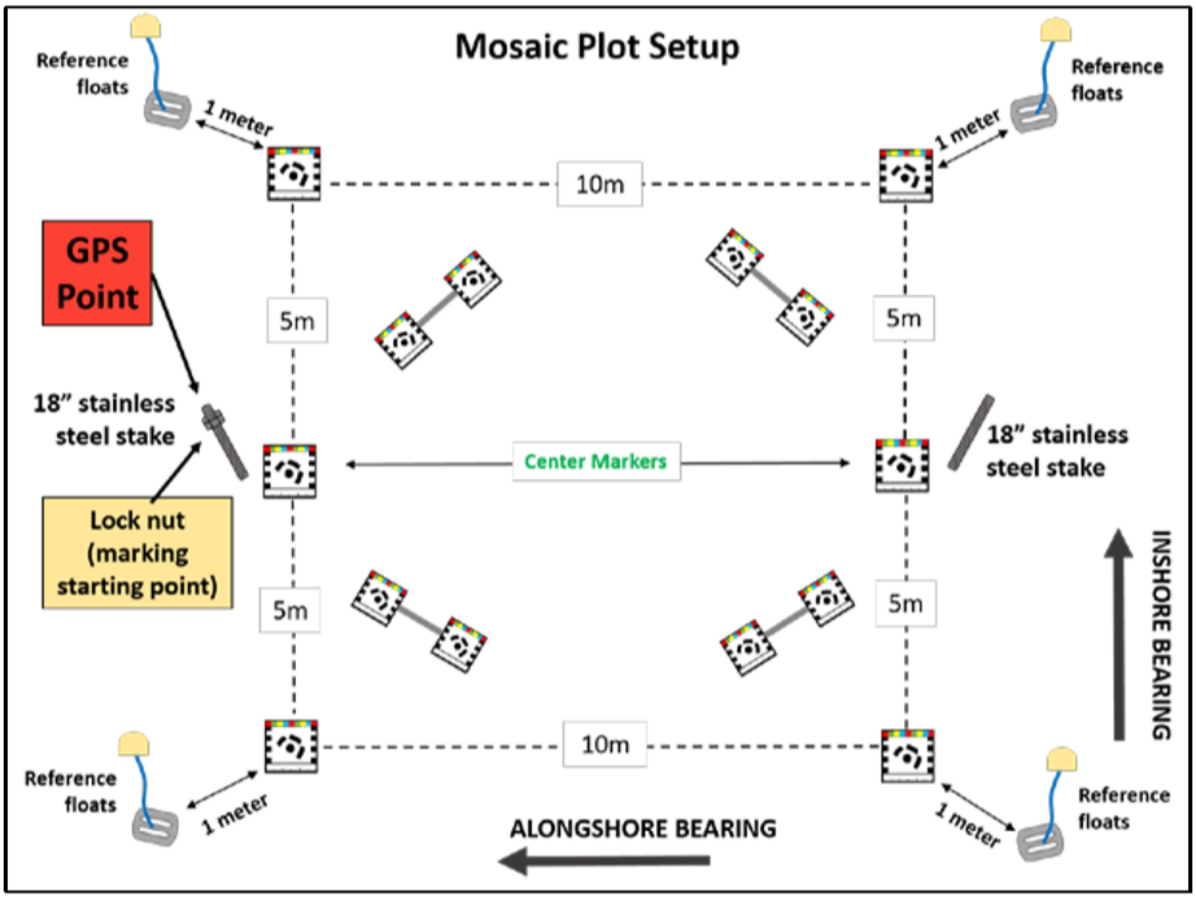


Diagram of site setup *in situ*

Figure S2. A diagrammatic overview of procedures for delineating each site *in situ*. Each site was (typically) marked by two stainless steel pins, one of which corresponded to a GPS point. A diver placed six calibration tiles to delineate the boundaries of a 10 x 10 m site, along with reference floats 1 m away from each corner of the site. These floats marked the boundaries of image collection by the diver, and ensured a minimum 1 m buffer around the edge of the site, which is marked by the calibration tiles. After marking the boundaries of the site, the diver measured the depth of each calibration tile and placed four 50 cm scale bars within the site. These bars were used during model post processing to scale the model, while the depth values taken at each of the calibration tiles were used to orient the model with respect to the sea surface. The second diver swam in a gridded pattern over the site, capturing images while swimming in both the alongshore and inshore directions to ensure maximum photo coverage. Each dive typically lasted about 50 to 60 minutes.



Overview of the Virtual Profile Gauge tool in Viscore

Viscore's Virtual Profile Gauge tool (VPG) is designed to mimic a profile gauge, a commonly used apparatus for measuring the contour of surfaces that has been used to measure the structural complexity of reefs *in situ* (McCormick 1994). A profile gauge consists of a series of parallel rods in a linear frame. When placed on the substrate, the rods slide independently to rest on the shallowest object beneath, approximating the contour of the substrate along a line. Measuring the substrate along a line is advantageous because it produces an easily interpretable, one-dimensional metric of complexity that can be interrogated to explore cross-scale patterns of 3D structure. One-dimensional measures of 3D structure also have direct analogues to standard *in situ* monitoring tools, such as a chain and tape or profile gauge. Specifically, VPG uses a series of virtual cylindrical rods to measure the vertical height of the point cloud along virtual transects. Viscore allows users to select the number of rods per transect, the length of the transects, the number of transects, and the orientation of the transects with respect to the point cloud (Figure S3).

Before VPG analysis can be performed, the point cloud must be scaled and oriented with respect to the surface using measurements made *in situ*. Viscore allows users to manually adjust the scale of the point cloud using *in situ* distance measurements, and to orient the point cloud with respect to the sea surface using four or more *in situ* depth measurements. Following current field protocols for surveying a site, divers place four 50 cm scale bars within the boundaries of the site and record the depth at six points (the four corners of the site and two points midway along the site's inshore boundaries). Point cloud orientation is particularly important because VPG's virtual rods extend orthogonally from the hypothetical sea surface to the model below. All virtual rods have the same diameter and are directly adjacent to each other so that the height of the point cloud is continuously assessed along the length of each transect (Figure S4A).

To determine the position of the substrate under each rod, Viscore records the depth (Z coordinate) of the shallowest point encountered within the diameter of the rod, and uses the center of the rod as the XY coordinates. This approach is necessary because the point cloud is made up of ideal mathematical points separated by empty space. As the diameter of a profile gauge rod approaches zero, the likelihood increases that the rod will fail to encounter any point in the point cloud. In practice, we have found that profile gauge rods with a diameter of ≥0.25 cm are sufficient to avoid this issue. The output of VPG is a .csv file where each row contains the XYZ coordinates of a profile gauge rod terminus, along with its associated transect number, rod number, and rod spacing (i.e., resolution).

Calculating linear rugosity

Linear rugosity is calculated using the .csv output described above. This point data is used to calculate the length of the reef contour along each transect by summing the Euclidean distance between points. For each transect, contour distance is divided by transect length to calculate linear rugosity (Rugosity = Contour Distance / Transect Length). To determine the true length of the transect in three-dimensional space, we calculated transect length in this study as the length of the best fit regression of transect points. This approach allowed us to accounts for the slope of the substrate. However, in other circumstances that approach would not be appropriate, such as when measuring the same location to detect change in rugosity over time. When measuring the same location repeatedly over time, using the "horizontal distance" traversed by the profile gauge in XY space as denominator of linear rugosity would be more advisable since it would create consistent profile gauge lengths in each timestep. Since no single approach is correct in all circumstances, the choice of how to calculate linear rugosity is dependent on the user's study goals and entirely independent from the mechanics of the VPG tool.

Following the approach in our study, a linear rugosity value of 1 indicates that the substrate has no surface roughness (i.e., that the reef contour is equivalent to the best fit line along the transect), although the substrate may have an overall slope. Values of linear rugosity greater than 1 occur when the reef contour is longer than the overall transect, and progressively higher linear rugosity values correspond to greater levels of structural complexity.

Accounting for missing or erroneous points

Point clouds are approximations of reality, and cannot reliably reconstruct all aspects of the substrate. For example, sections of the substrate that are difficult to photograph or that appear in too few photographs (e.g., holes, crevices, overhangs, or the interstitial space within a coral colony) may not be resolved using Structure from Motion, creating gaps in the point cloud reconstruction. Point cloud gaps may also arise if photographs are taken without enough overlap (i.e., if a diver swam too fast or if camera passes were too far apart). In addition, blurry or low-quality photographs, or the movement of sessile organisms such as macroalgae or gorgonians, may result in low confidence or erroneous "floating points" in point cloud reconstructions.

If a virtual profile gauge rod is positioned over a gap in the point cloud, or if the width of the rod is too small relative to the resolution of the point cloud, that virtual rod will not intersect the point cloud. When this occurs, VPG records a special value to denote the missing point that can be easily identified and filtered in post-processing. When calculating linear rugosity from VPG output data, segments of each transect with missing values are excluded from rugosity calculations (Figure S4B). Where VPG encounters floating points, users must manually identify these instances and replace that point's depth with a special value in the .csv output file to signify a missing point. For this reason, it is not advisable to use VPG to measure rugosity when models have more than a few floating points. In those instances, the photographs that are causing reconstruction errors should be identified, and the model reconstructed without those photos to minimize the number of floating points. Alternatively, if the point cloud was exported from Agisoft Metashape with information about point confidence (i.e., the confidence in the accuracy of each point in the point cloud in 3D space), then this value can be used to automatically filter out points that are likely erroneous.

Sub-setting virtual profile gauges to simulate coarser levels of resolution

Measurements of structural complexity are highly scale dependent, and it is thus important to account for the scale at which linear rugosity is measured. VPG resolution (i.e., the spacing of virtual profile gauge rods) is analogous to the minimum grain size for the purpose of rugosity calculations. The reef contour data that is generated by VPG and used to calculate rugosity can be sub-sampled to simulate rugosity measurements from coarser levels of resolution, which allows users to easily measure linear rugosity of the same surface at multiple scales. To simulate coarser levels of resolution, the user selects a sub-set interval n, which divides each profile gauge into segments of n virtual rods. For example, if the user wishes to simulate 2 cm resolution from a VPG output file with 1 cm resolution, the first two virtual rods on the transect would be joined together, followed by the next two and the next two. The rod with the shallowest depth in each rod pairing would be used as the that segment's new Z coordinate, while the center of the segment would be used for the new XY coordinates. Summing the distance between each segment's new XYZ coordinate generates a sub-sampled contour distance, which is used in concert with the profile gauge length to calculate linear rugosity at that new resolution.

Accounting for substrate slope

The slope of a forereef is an important component of coral reef benthic structural complexity that has been shown to explain variation in coral reef fish assemblages (Jankowski et al. 2015). However, forereef slope occurs over larger spatial scales (100s of meters to kilometers) than those of interest in this analysis, which focuses on the contribution of biotic and abiotic objects (i.e., coral colonies, boulders, channels, spur and groove formations, etc.) to structural complexity between the scales of 0.5 cm and 2.56 m.

Still, it is important to account for the effect of steep substrate slope on linear rugosity measurements, since a steep substrate slope can obscure the linear rugosity signal of smaller reef structures. This concept is demonstrated in Figure S5. If the reef substrate has a non-zero slope, the apparent length of the profile gauge along the substrate will be longer than the horizontal distance covered by that profile gauge. A non-zero substrate slope will inflate the minimum value of rugosity to be greater than 1, assuming the horizontal length of the profile gauge is used as the denominator to calculate rugosity. This "slope effect" will cause the minimum value of rugosity to increase as the substrate slope becomes steeper. For example, a sandy substrate (i.e., otherwise "flat" ecologically) with a slope of 45 degrees would have a rugosity value of 1.41, while the same sandy bottom habitat would have rugosity value close to 1 when the effect of the underlying substrate slope is filtered out.

To account for the slope of the substrate, we measured linear rugosity in the alongshore direction at all sites, which tended to have a more gradual slope than the inshore direction. We also used the distance traversed by the best fit regression of profile gauge points as our measure of profile gauge length, which incorporates substrate slope into the linear rugosity calculation. This allowed us to focus on smaller-scale processes that create reef structure on the order of magnitude of mm to m.

Figure S3. An example of Viscore's Virtual Profile Gauge tool (VPG) in action. The tool allows users to measure the linear rugosity of a point cloud along a series of transects, represented here by orange lines. VPG uses virtual rods to measure the depth of the substrate. By determining the coordinates of rod depths in XYZ space, the tool allows users to calculate the distance along the reef contour, which is then divided by the length of the transect. Users select the number of virtual rods per transect (point gauge resolution), the number of transects, and the length and orientation of the transects with respect to the point cloud.

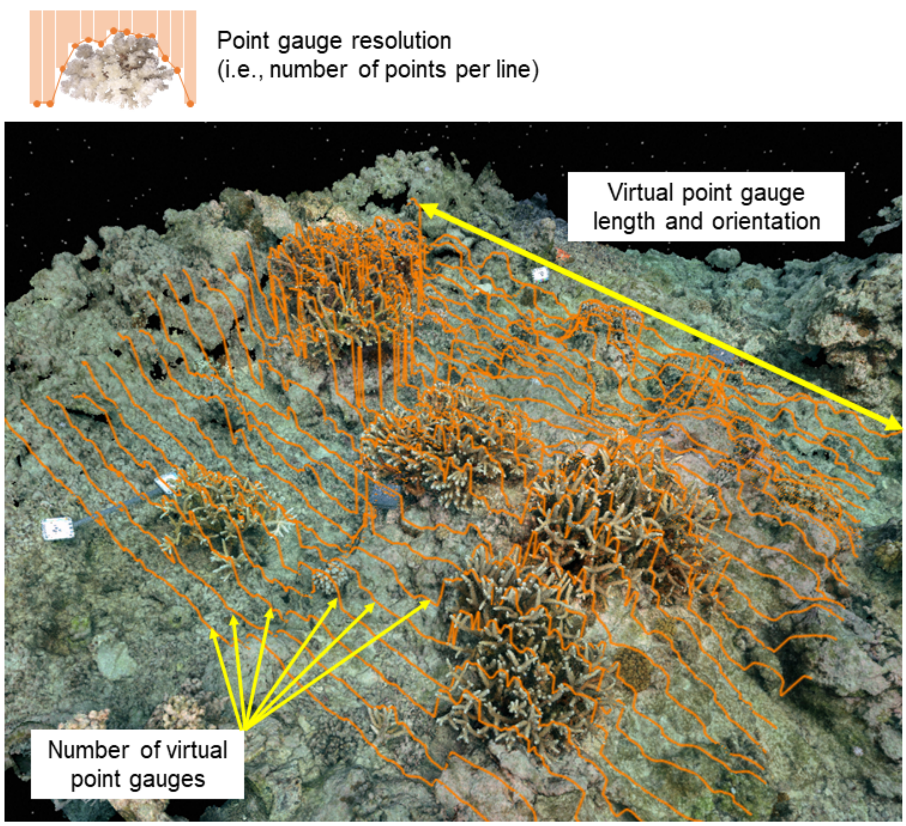


Figure S4. A) A conceptual diagram illustrating how the Virtual Profile Gauge tool (VPG) measures the linear rugosity of the point cloud. Each yellow bar represents a virtual rod that is dropped onto the point cloud from above (the diameter of these rods is the VPG resolution). Each rod terminates as soon as it intersects the point cloud, and the Z coordinate of that point is recorded as the depth of the substrate within that rod (represented here by the blue point at the end of each rod). VPG produces an output file with the XYZ coordinates of each rod terminus, where the XY coordinates correspond to the center of each rod. The sum of Euclidean distances between these points is the contour distance (blue line) along the point cloud (gray line). Since the profile gauge rods rest on the shallowest point beneath, the line connecting them rarely intersects with the substrate beneath, although intersections are possible. In this way, the VPG behaves just as a real profile gauge would if it were placed on the substrate *in situ*. In this study, the length of the transect was calculated as the length of the best fit regression of all VPG points (orange line), however it can also be calculated as the horizontal length of the VPG transect. Linear rugosity is calculated as the ratio of contour distance to transect length. B) For models with gaps or missing points, we calculated the contour distance over sections of the point cloud where data exists (i.e., C_1, C_2, C_3). These contours are summed together to generate a total contour distance. The regression through all VPG points is used to determine the full length of the transect, and then the segments of the transect where data exists (i.e., T_1, T_2, T_3) are summed to calculate a transect length that accounts for model gaps.

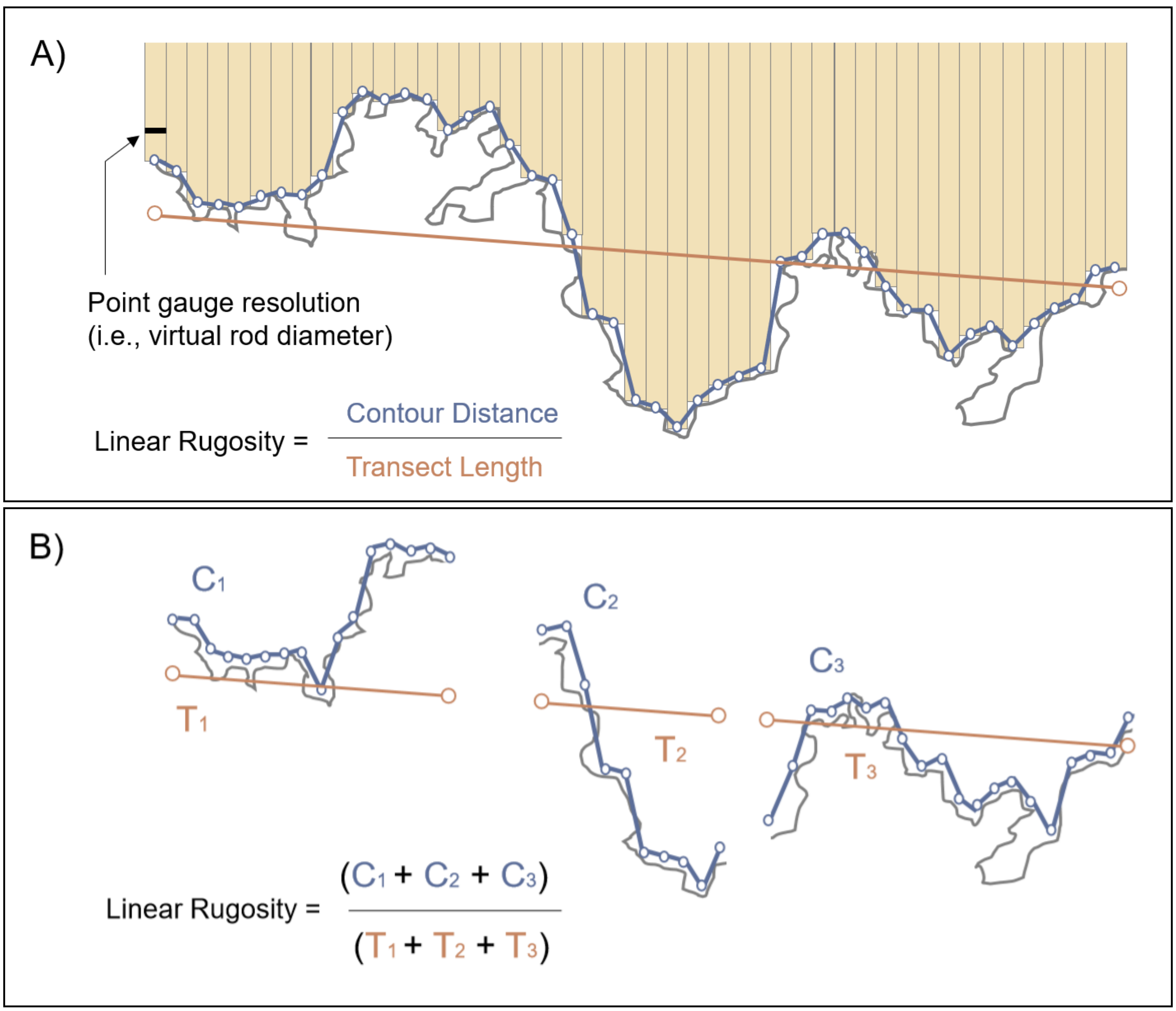
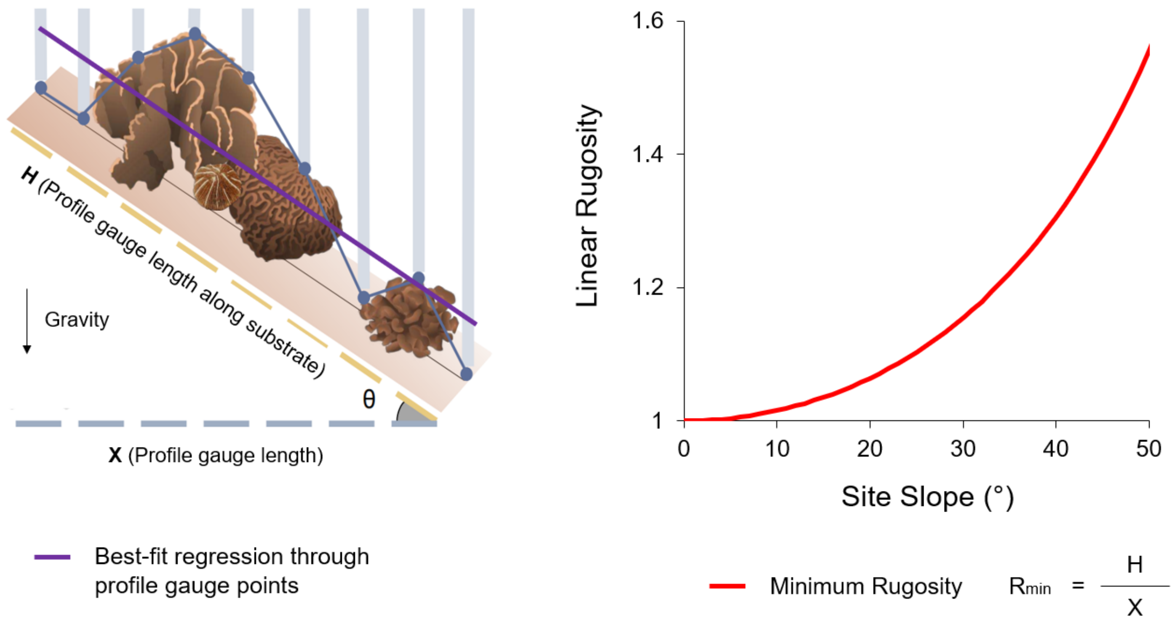


Figure S5. The slope of the substrate impacts linear rugosity measurements. If the reef substrate has a non-zero slope, the apparent length of the profile gauge along the substrate (H) will be longer than the horizontal distance covered by that profile gauge (X). A non-zero substrate slope will inflate the minimum value of rugosity (R_{min}) to be greater than 1, assuming the horizontal length of the profile gauge (X) is used as the denominator to calculate rugosity. The red line in the plot to the right shows R_{min} as a function of the substrate's overall slope. The length of the profile gauge along the substrate (H) can be easily calculated as the best fit line through all profile gauge rod termini (shown below as a purple line).

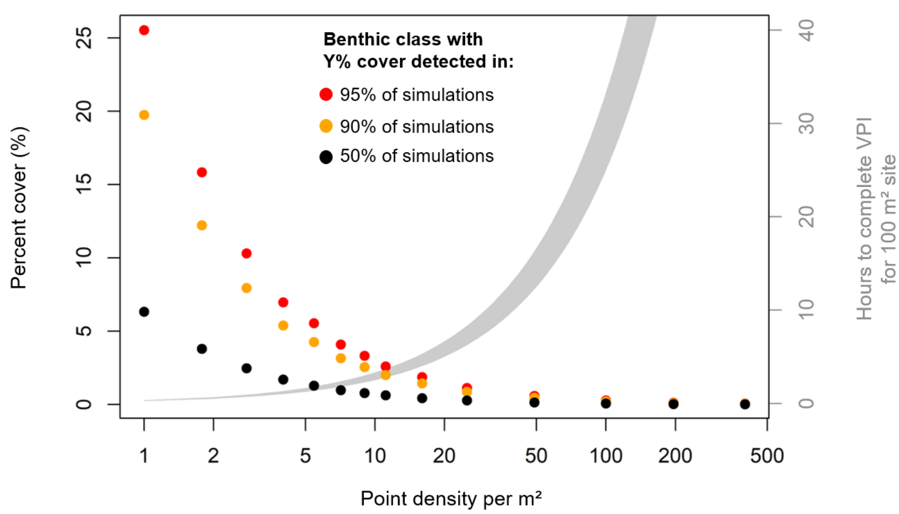


Percent cover power analysis

The Virtual Point Intercept (VPI) tool in Viscore generates a user-determined number of stratified random points within a fixed area. Once these points have been generated, their location is superimposed on the raw imagery used to construct the Structure from Motion point cloud, allowing users to identify benthic taxa directly from high quality photographs. Determining how many stratified random points to use requires a tradeoff between precision of benthic cover estimates and time spent analyzing images. In our experience, it takes a coral and algae ID expert approximately 15 to 20 minutes to identify benthic cover at 100 points. To strike an appropriate balance between precision and analysis time, we conducted a power analysis using fully annotated 3 x 3 m orthoprojections from five sites in Maui. We considered these orthoprojection annotations to be "true" representations of benthic cover on the reef for this exercise. The orthoprojections were sampled in a stratified random manner in R using various VPI point densities, from 1 to 400 points/m^2. This process was repeated 10,000 times. For each VPI point density, we calculated the percent of simulations in which a benthic class wasn't detected, and determined the relationship between this detection probability and percent cover.

Based on our results, we recommend using 25 points/m^2 for research questions focused on quantifying community composition, detecting rare taxa, or documenting benthic change over time. At this point density, we were able to detect taxa with 1.1% cover in 95% of simulations, and would expect VPI analysis to take approximately 6 to 8 hours for one 10 x 10 m site. For studies where a rapid or coarse descriptor of benthic cover is sufficient (i.e., calculating total coral cover or identifying the most dominant taxon on the reef), we suggest 10 points/m^2 as a sufficient tradeoff between precision and efficiency. At this point density, we were able to detect taxa with 3.0% cover in 95% of simulations, and would expect VPI analysis to take only 2.5 to 3.5 hours for one 10 x 10 m site. Since our study deals with large differences in total coral cover across an entire archipelago (sites ranging from 0 to 82% coral cover) rather than more minute differences in coral cover (i.e., from change over time), we felt comfortable with the precision provided by VPI at 10 points/m^2. Past studies have also found that this point density provides qualitative and reliable measures of percent cover (Dumas et al. 2009).

Figure S6. Results from a power analysis of percent cover point densities. The probability of detecting a benthic class with Y% cover is shown as a function of VPI point density. For example, a taxon that covers 1.1% of the benthos would be detected 95% of the time using a VPI point density of 25 points/m^2. The shaded gray polygon depicts the estimated amount of time it would take to complete benthic ID for a 100m^2 site as a function of VPI point density.



Data simulation to test fractal dimension approach

To explore the robustness of the fractal dimension approach, we measured the fractal dimension of six simulated reef profiles across 9 scale intervals. Each 10.24 m long profile was simulated using a combination of sine curves meant to generate combinations of fine-, intermediate-, and large-scale structure (Figure S7). Fine-scale sine curves were meant to simulate a reef with 25 cm diameter coral colonies and intra-colony features every 6.25 cm (Equation 1), while intermediate-scale sine curves were meant to simulate a reef with 50 cm diameter coral colonies and intra-colony features every 12.5 cm (Equation 2). Large-scale sine curves were meant to simulate underlying landscape topography, and had a period of several meters (Equation 3). For the purposes of the simulation, we interpreted values of D > 1.01 as evidence of reef structure at a given scale interval. We used the maximum value of D across scales (D_{max}) to identify the scale interval with the greatest rate of change in rugosity. Patterns of fractal dimension for these reef profiles provided context to aid in the interpretation of reef profiles obtained using Structure from Motion.

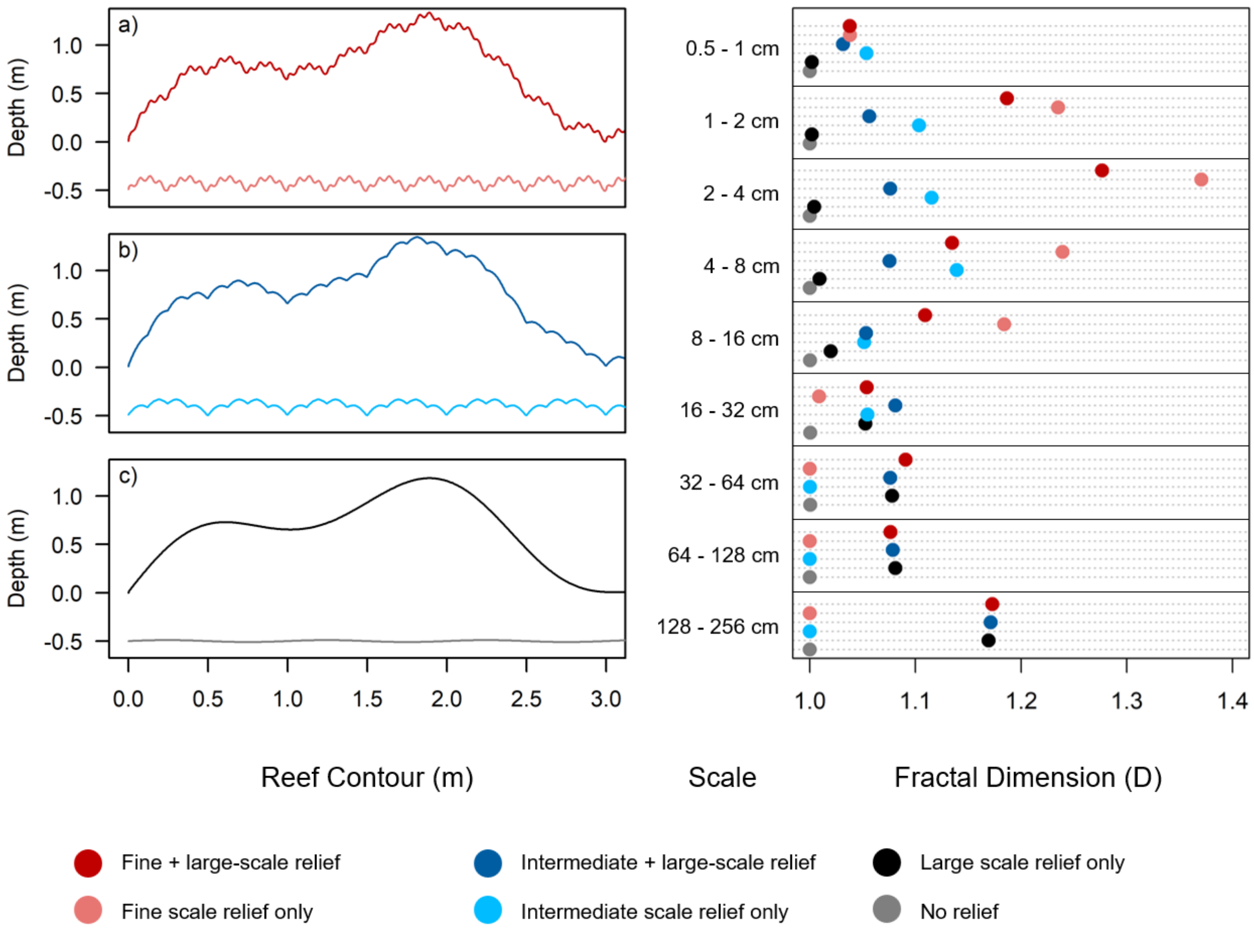
$$\textbf{Eq. 1}: \quad Y = 0.5\left(0.25\left|\sin\left(\frac{x}{16}\right)\right| + 0.05 sin\left(\frac{x}{2}\right)\right)$$

$$\textbf{Eq. 2}: \quad Y = 0.5\left(0.25\left|\sin\left(\frac{x}{32}\right)\right| + 0.1\left|\sin\left(\frac{x}{8}\right)\right|\right)$$

$$\textbf{Eq. 3}: \quad Y = \sin\left(\frac{\mathrm{x}}{200}\right) + 0.25\sin\left(\frac{x}{50}\right)$$

The fractal dimension (D) of simulated reef profiles differed depending on the scale of the underlying structures that were simulated (Figure S7). The fine-scale sine curve had D > 1.01 at five scale intervals (from 0.5-1 cm to 8-16 cm), and D_{max} occurred at the 2-4 cm scale interval (D = 1.371). Similarly, the intermediate-scale sine curve had D > 1.01 at six scale intervals (from 0.5-1 cm to 16-32 cm), with D_{max} at the 4-8 cm scale interval (D = 1.139). For the large-scale sine curve, D > 1.01 at five scale intervals (from 8-16 cm to 128-256 cm), and D_{max} occurred at the 128-256 cm scale interval (D = 1.169). The reef profile with no underlying structure never had a value of D > 1.01. Reef profiles with a combination of fine-, intermediate-, and large-scale sine curves had more nuanced patterns of fractal dimension across scales. At the largest scale intervals (between 32 and 256 cm), profiles with large-scale sine curves had nearly identical values of D, regardless of the presence or absence of fine- or intermediate-scale curves. Differences in D were more pronounced between profiles at smaller scales (between 0.5 and 16 cm), although overall trends in D were similar for profiles with fine- and intermediate-scale sine curves regardless of the presence of large-scale sine curves.

Figure S7. Simulated reef profiles with A) fine-scale relief, B) intermediate-scale relief, and C) no fine- or intermediate-scale relief. In each case, an underlying curve was added to one of the two profiles to simulate large-scale relief (red, dark blue, and black profiles respectively). Simulated reef profiles were 10.24 m long, but only the first 3 m are visualized here. D) The fractal dimension of each simulated reef profile is shown across nine scale intervals. Profiles where fine-scale relief were simulated (pink, red) have higher fractal dimension at smaller scale intervals, while the profile with only large-scale relief (black) exhibits a fractal signature only at larger scale intervals.



Full results of statistical analyses

Table S1. ANOVA results using generalized least squares when sites with >15% coral cover are grouped by their most abundant coral morphotype. Generalized least squares results were considered significant if $p < 0.01$ (n.s. = not significant, * indicates $0.001 < p < 0.01$, ** indicates $0.0001 < p < 0.001$, and *** indicates $p < 0.0001$). Post-hoc letters were determined using Tukey's test of multiple comparisons.

Scale interval (cm)	Df. (among, within)	F value	P value	Sig.	Branching *Montipora* n = 6	Encrusting *Montipora* n = 12	Branching *Porites* n = 13	Massive *Porites* n = 8
0.5 – 1	3, 35	7.4682	0.0007	**	b	ab	c	a
1 – 2	3, 35	9.5801	0.0001	**	b	ab	c	a
2 – 4	3, 35	11.9417	<0.0001	***	ab	b	c	a
4 – 8	3, 35	17.0928	<0.0001	***	a	b	c	ab
8 – 16	3, 35	20.3427	<0.0001	***	a	b	b	a
16 – 32	3, 35	14.8800	<0.0001	***	a	b	b	b
32 – 64	3, 35	5.2195	0.0051	*	a	ab	b	b
64 – 128	3, 35	1.3455	0.2783	n.s.	a	a	a	a
128 – 256	3, 35	1.0952	0.3663	n.s.	a	a	a	a

Table S2. Results of the generalized additive model (GAM), where fractal dimension at each scale interval was the response variable and coral cover, root mean square (RMS) height, and latitude were explanatory variables. Explanatory variables were considered to have a significant relationship with fractal dimension if $p < 0.01$ (n.s. = not significant, * indicates $0.001 < p < 0.01$, ** indicates $0.0001 < p < 0.001$, and *** indicates $p < 0.0001$).

Scale interval (cm)	Adj. R^2	Coral Cover			Root Mean Square (RMS) Height			Latitude		
		P value	Df	Sig.	P value	Df	Sig.	P value	Df	Sig.
0.5 – 1	0.5836	<0.0001	2.1113	***	0.0140	1.0000	n.s.	0.0009	2.6615	**
1 – 2	0.6370	<0.0001	2.1715	***	0.0499	1.9602	n.s.	0.0005	2.5051	**
2 – 4	0.6376	<0.0001	2.3361	***	0.1485	2.1711	n.s.	0.0005	2.4602	**
4 – 8	0.6657	<0.0001	2.7236	***	0.2067	2.5544	n.s.	0.0003	2.3098	**
8 – 16	0.6475	<0.0001	3.3048	***	0.1581	2.3157	n.s.	0.0007	2.1093	**
16 – 32	0.5554	0.0394	3.5131	n.s.	0.0021	2.3983	*	0.0042	2.1247	*
32 – 64	0.5110	0.6451	1.1210	n.s.	<0.0001	5.2192	***	0.0052	1.0000	*
64 – 128	0.7083	0.4369	1.0000	n.s.	<0.0001	6.0742	***	0.0279	1.0000	n.s.
128 – 256	0.6405	0.0594	1.0000	n.s.	<0.0001	4.1182	***	0.2850	1.0000	n.s.

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