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Unprecedented decline in modern coral reef communities could indicate the onset of the Anthropocene

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Abstract

Coral reefs have experienced widespread and accelerated decline, driven by a combination of global and local anthropogenic stressors. To contextualize these changes, we compared the composition of coral reef communities on Curaçao between 1973 and 2023 with that of corals preserved in fossil reefs from the Last Interglacial period (128–116 ka). These fossil reefs, exposed along the island's leeward coast, provide a multi-millennial baseline of ecological variability. Here we show that the ecological transformation observed on modern reefs over the past five decades is unmatched when compared to the relatively stable community structure maintained for more than 12,000 years during the Last Interglacial. We propose that the global, rapid, and well-documented collapse of tropical coral reef ecosystems since the mid-20th century represents a stratigraphically relevant signal of anthropogenic change. We surmise that a well-characterized reef site—such as Curaçao—could, in principle, serve as the Global Boundary Stratotype Section and Point (GSSP) marking the onset of the Anthropocene.

Keywords: Coral reef decline; Last Interglacial; Anthropocene; Paleoecology; Caribbean reefs

Coral reefs are among the most diverse marine ecosystems , supporting millions of people through services such as tourism, food security, and coastal protection (*1–4*). A combination of global (e.g., ocean warming and acidification (*6*)) and local (e.g., overfishing and pollution (*7*)) stressors led global coral cover to decline by 50% between 1957 and 2007, and mass coral bleaching events and climate-driven disturbances have further accelerated the loss of coral cover worldwide (*9*) . These trends have been particularly severe in the Caribbean, where local pressures—such as disease outbreaks (e.g., black- and white-band disease (*10*, *11*)), hurricane impacts, nutrient enrichment, and the overharvesting of herbivores—have intensified the effects of global change and accelerated regional reef degradation.

Although the global decline of coral reefs is well documented, it remains unclear how recent changes compare to those in the geological past. Are the losses observed over the past few decades truly without precedent, or do they echo patterns seen during earlier periods of environmental stress?

The geological record provides a means of evaluating whether recent reef degradation exceeds the range of natural variability. Fossil reefs, particularly from the Pleistocene, can serve as ecological baselines against which modern reef assemblages can be compared (*13–15*). The Last Interglacial (LIG, 128–116 ka) represents the most recent period in Earth's history with global atmospheric temperatures exceeding modern values, smaller polar ice sheets, and sea levels several metres higher than today (*16*, *17*). Understanding how coral reefs responded to such conditions may provide critical context for interpreting the magnitude and significance of recent ecological change.

The island of Curaçao, in the southern Caribbean (Figure 1), offers a unique opportunity to compare modern and fossil reef dynamics (*14*, *18*). Along its coast, well-preserved LIG reef stratigraphic sequences are exposed in erosional gullies and cliff faces (*19–22*), providing a stratigraphically ordered, high-resolution record of coral community composition and structure. These outcrops allow the reconstruction of ecological change across early, middle, and late phases of the LIG. In parallel, Curaçao's modern reefs are comprehensively surveyed , with quantitative ecological data available starting from 1973. Together, these datasets create a natural laboratory for evaluating whether the recent reef degradation exceeds the bounds of natural variability.

Beyond establishing ecological baselines, comparisons between fossil and modern reefs can inform the ongoing debate surrounding the Anthropocene—a proposed new geological epoch defined by pervasive and lasting human impacts on the Earth system (*23–25*). For the Anthropocene to be formally recognized within the Geological Time Scale, it must be distinguished from the Holocene by a clear, datable, and globally synchronous marker known as a Global Boundary Stratotype Section and Point (GSSP), or "golden spike" (*26*). This marker must capture a geologically distinct signal—whether biotic, sedimentary, or geochemical—that can be identified across multiple stratigraphic records worldwide but formally designated at a single reference site. Despite the growing scientific consensus around the Anthropocene as a concept, the Subcommission on

Quaternary Stratigraphy rejected the formal proposal to define the Anthropocene as a new epoch, with a mid-20th century start (*27*).

Some geochemical features of coral reefs have been considered as potential GSSP for the Anthropocene, as their skeletons record chemical changes in ocean water, potentially preserving evidence of anthropogenic pollutants and nuclear fallout (*28*), The abrupt, widespread, and well-documented ecological collapse of tropical coral reefs was not considered in this context, but it may offer a biologically grounded and stratigraphically persistent signal of planetary change. For such a signal to contribute meaningfully to the formalization of the Anthropocene, it must be shown to exceed the bounds of natural variability observed in prior warm intervals of Earth's history.

Here, we evaluate that possibility by comparing the recent ecological trajectory of Curaçao's coral reefs with their fossil counterparts from the Last Interglacial. Given the exceptional preservation, stratigraphic continuity, and well-documented ecological record on Curaçao, this site may also offer a suitable candidate section for defining the Global Boundary Stratotype Section and Point (GSSP) for the Anthropocene.

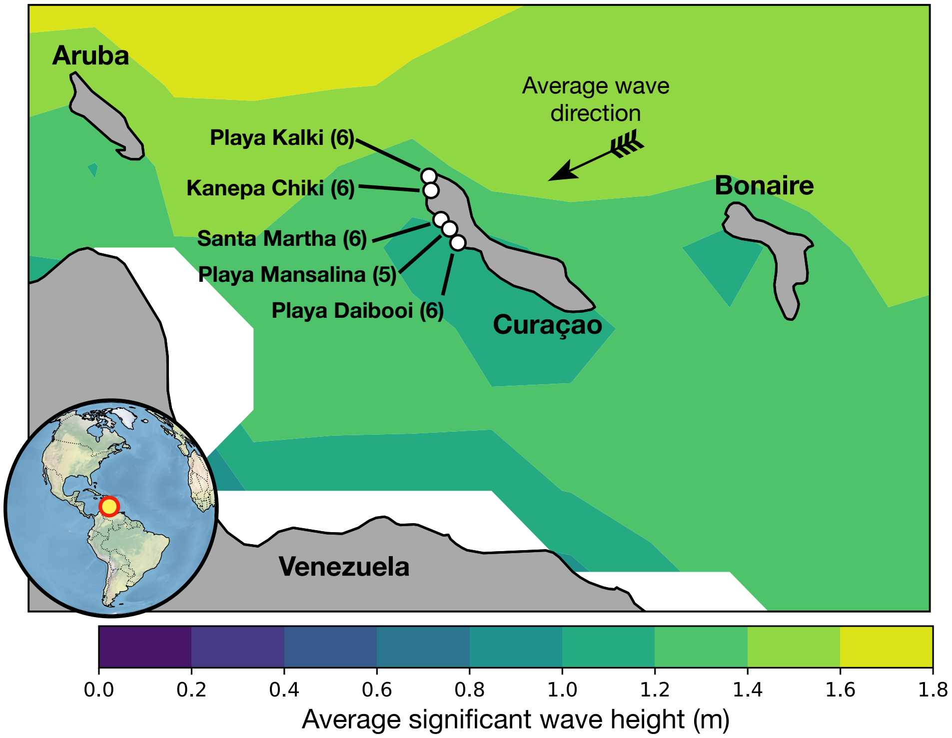

Figure 1. Study area along the leeward coast of Curaçao. Sites where LIG reefs have been surveyed are indicated by white circles and the number of point intercept transects (PITs) at each site are in parentheses. Modern reef surveys span the entire leeward coast of Curaçao (sites not shown). Background color represents the average significant wave height (Jan 1st, 1980 to Jan 31st, 2024) from the Copernicus Marine Environment Monitoring Service WAVeReanalYSis(*29*) (white areas indicate no data in the model).

Results

We analyzed data from quantitative ecological surveys conducted between 1973 and 2023 on Curaçao's shallow coral reefs at 10 m depth. In 1973, coral cover exceeded 60%, with large *Orbicella* spp. colonies dominating the benthic community (Figure 2A,C). Over the following three decades, coral cover declined steadily to ~20%, corresponding to an annual loss rate of 1.4% (Figure 2A,B). This initial decline coincided with the outbreak of white-band disease, which decimated *Acropora* populations across the Caribbean(*30*, *31*), and with the mass mortality of the herbivorous sea urchin *Diadema antillarum*, leading to reduced grazing pressure and macroalgal overgrowth on Curaçaoan reefs (*32*).

While disease and herbivore loss initiated the decline, mounting anthropogenic pressures likely amplified its severity. Although the island's population remained relatively stable (*33*), the number of tourist arrivals more than tripled between 1995 and 2019, reaching 1.29 million annual visitors (*34*) (Figure 2B). Coastal development and the discharge of insufficiently treated sewage, particularly near urban centers (*35*), likely contributed to eutrophication and localized reef degradation. Concurrently, the effects of global climate change intensified the pressure on Curaçao's reefs. Marine heatwaves triggered coral bleaching events in 1987, 1990, 1995, and 1998 (*36*), while several hurricanes and tropical storms—including Lenny (1999), Ivan (2004), and Omar (2008)—inflicted direct physical damage on reef structures(*37*) (Figure 2B). After 2003, coral cover continued to decline, albeit at a slower pace of 0.6% per year (Figure 2A), with another severe bleaching event in 2010, causing a 1% loss of live coral cover in only a few months (*36*). Although overall community composition remained relatively stable, average colony size decreased (Figure 2C,D) due to the loss of large *Orbicella* spp. colonies (*38*).

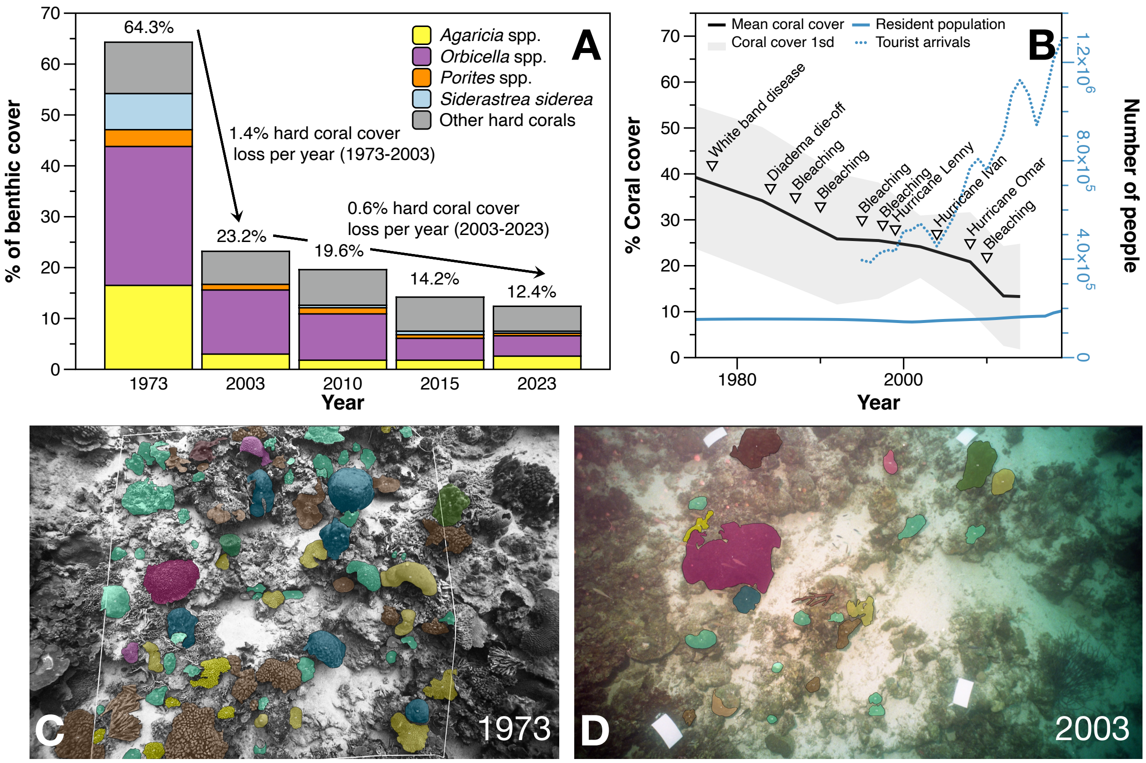

Figure 2. A) Changes in hard coral cover (%) and trends in hard coral cover loss (% year^{-1}) from 1973 to 2023 at 10m depth on the shallow reefs of Curaçao. B) Time series of hard coral cover (%) from 1973 to 2014 based on permanent quadrats on the leeward coast of Curaçao (data from De Bakker et al., 2016(*38*)). The black line indicates the average % coral cover from four depths (10 m, 20 m, 30 m, and 40 m) each sampled at four sites and the gray band indicates 1 standard deviation of the mean; triangles above the line show major events affecting the Curaçao reefs. Blue lines show the number of tourist visits(*34*) (dotted line) and the resident population in Curaçao(*33*) (continuous line). C) and D) visual examples of hard coral cover in 1973 and 2003 of the same photo quadrat on Curaçao. Colors indicate different coral genera identifiable in the quadrats.

To evaluate whether ecological changes comparable to those on modern reefs occurred in the geological past, we analyzed 29 point intercept transects (PITs) across five fossil reef sites along the leeward coast of Curaçao (Figure 1). These outcrops expose stratigraphically ordered reef frameworks, with older reef structures at the base and younger sequences toward the top, corresponding to the early, middle, and late phases of the Last Interglacial (LIG, 128–116 ka)—a period characterized by global temperatures and sea levels equal to or exceeding present-day conditions. Hard coral cover averaged 26.4% during the early LIG, declined slightly to 23.7% in the mid-LIG, and rose again to 28.7% in the late LIG (Figure 3D). These millennial-scale fluctuations were modest in magnitude and accompanied by reversible shifts in community composition. Notably, the mid-LIG was marked by a transient increase in *Acropora palmata* abundance and a decline in *Orbicella* spp., followed by a return to *Orbicella*-dominated assemblages in the late LIG (Figure 3E).

These community shifts occurred against a backdrop of regional environmental fluctuations during the Last Interglacial, as documented in previous studies (*39*–*41*). Strontium/calcium-derived sea surface temperature (SST) reconstructions from *Diploria* corals on neighboring Bonaire indicate that SSTs were slightly cooler than present at the onset of the interglacial (~128 ka) (*39*, *41*), followed by a sharp thermal drop of 2.1 ± 0.7 °C around 126 ka, and a rapid return to modern-like conditions thereafter (*40*) (Figure 3B). The same proxies suggest that while temperature seasonality during the early and late LIG was comparable to modern values, it was notably amplified between 126 and 124 ka (*41*). Salinity reconstructions from the same corals indicate a temporary freshwater pulse around 125.8 ka, followed by increasing salinity toward the end of the interglacial (*40*) (Figure 3A).

Sea-level variability during the LIG may have also influenced reef development on Curaçao. While local sea level in the southern Caribbean was likely shaped by glacial isostatic adjustment and rose gradually throughout the interglacial, stratigraphic evidence from Curaçao's reef terraces suggests minor internal sea-level fluctuations (Figure 3C). These may align with a brief global sea-level fall of approximately 1 m recorded in the Bahamas around 124–125 ka, possibly linked to asynchronous melting of Northern and Southern Hemisphere ice sheets (*42*, *43*). Although wind and wave energy reconstructions for the LIG remain sparse, climate model simulations centered at 127 ka indicate weaker trade winds in the Southern Caribbean (*44*) but more favorable conditions for tropical cyclone genesis across the broader Caribbean basin (*45*). These fluctuations in sea level and storm dynamics may have contributed to mid-LIG shifts in coral community composition observed in the fossil record.

Despite these climatic and oceanographic fluctuations, the LIG coral communities on Curaçao exhibited only moderate and reversible ecological responses. During the mid-LIG, a shift in community composition occurred, with a temporary increase in *Acropora palmata* coinciding with reduced *Orbicella* spp. cover (Figure 3E). This transition may reflect opportunistic colonization by *A. palmata* following storm disturbances, consistent with its known capacity to proliferate via fragmentation. However, this shift did not result in sustained coral loss. As environmental conditions stabilized toward the end of the interglacial, coral cover increased (Figure 3D), and *Orbicella* spp. once again dominated the reef framework. Overall, LIG reef communities displayed resilience to regional environmental variability, maintaining ecological structure over millennial timescales.

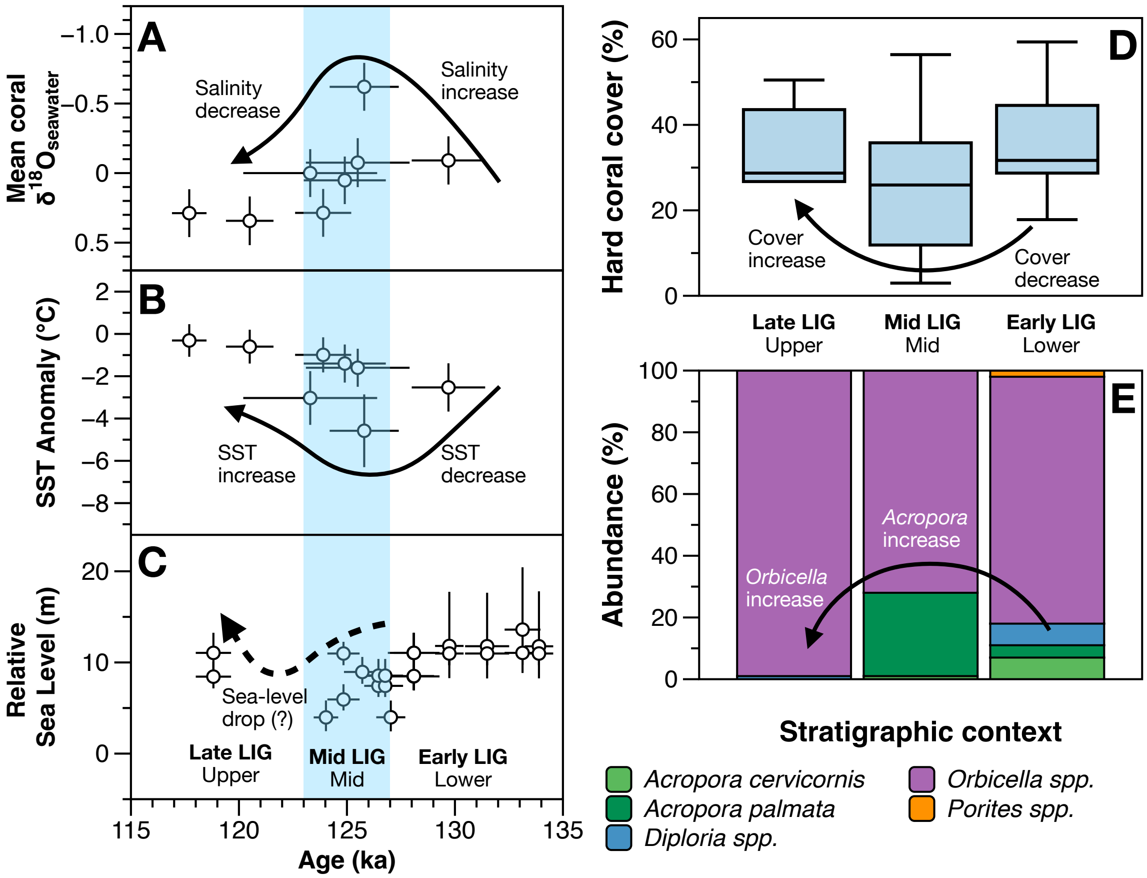

Figure 3. Mean coral δ18Oseawater for Bonaire corals (*40*) using the Sr/Ca-SST relationship of −0.066 (*46*) and corresponding coral δ18O-SST relationship of −0.196‰ per °C (*46*). B) Mean coral Sr/Ca-SST anomaly for Bonaire corals (*40*) calculated using the same annual mean Sr/ Ca-SST used in A). Interpretations of oscillations in A) and B) are based on the discussions in Brocas et al. (*40*, *41*) . C) Sea-level index points (*19*, *47–49*) for the Northern part of the island of Curaçao, filtered to avoid inclusion of sites with differential tectonic uplift. Horizontal error bars in A-C represent 2-sigma age errors, while vertical error bars represent 1-sigma errors. D) Whisker plots of hard coral cover across the 5 sites on Curaçao surveyed and three stages of LIG reef growth indicated in (E). E) Community abundance at each stage of LIG reef growth, focusing on the main hard coral constituents of each stage.

Discussion and conclusions

The ecological trajectories of fossil and modern reefs on the leeward side of Curaçao offer a striking perspective on coral reef change. Over the course of the Last Interglacial, coral communities in this area responded to environmental variability—including shifts in temperature, salinity, sea level, and possibly storm activity—with moderate changes in composition and structure that proved reversible over millennial timescales. Coral cover remained relatively stable, and community dominance by *Orbicella* spp. re-emerged as conditions stabilized. By contrast, the past five decades have seen a dramatic and sustained decline in coral cover on modern reefs, affecting multiple taxa and lacking any clear signs of recovery or functional reorganization. This contrast highlights the exceptional severity and rapidity of contemporary reef degradation.

The mid-LIG shift from long-lived, slow-growing *Orbicella* spp. to fast-growing *Acropora palmata* suggests that ancient coral communities were capable of adjusting to environmental stress through changes in life-history strategies. This transition—from a K-selected generalist (*Orbicella* spp.) to an r-selected opportunist (*Acropora palmata*) —is consistent with ecological theory predicting increased opportunism under disturbance regimes. Importantly, this shift was temporary: as conditions stabilized later in the interglacial, *Orbicella* spp. regained dominance and coral cover rebounded. In contrast, the trajectory of modern reefs shows no comparable capacity for reorganization. Since the 1970s, coral cover decline has been broad-based, marked by the loss of large colonies, reduced coral size, and persistent mortality across taxa, with little evidence of adaptive restructuring or recovery (*38*).

While comparisons between modern and fossil reef records are inherently constrained by methodological differences, these limitations are well understood. Fossil data lack the temporal resolution of modern ecological monitoring and are subject to preservation bias, including the inability to distinguish live from dead coral or detect short-lived ecological overgrowths. However, such constraints generally act to underrepresent ecological disturbance rather than exaggerate it. Moreover, the fossil record provides a unique and necessary window into the long-term dynamics of coral reef communities—one that is inaccessible through short-term ecological studies alone (*15*). Building on this perspective, our analysis of LIG reef sequences on Curaçao reveals no evidence of sustained coral loss or persistent community collapse, despite the climatic variability of that period. In contrast, the scale and speed of degradation observed on Curaçao's modern reefs—marked by sharp, island-wide coral decline over just five decades—suggest that these changes are without clear precedent in at least the past 120,000 years.

Coral reef changes such as those experienced by the leeward reefs of Curaçao are not only ecological, but also stratigraphic in nature: the abrupt, globally synchronous collapse of coral ecosystems is likely to leave a persistent and recognizable signal in the geological record. The coral reef crisis thus represents a candidate phenomenon for defining the onset of the Anthropocene. Given its global distribution (*12*, *50*, *51*), abrupt timing, and potential for preservation in carbonate deposits (*13*), it fulfills key stratigraphic criteria required for selecting a Global Boundary Stratotype Section and Point (GSSP). While other candidate signals—such as radionuclide fallout or plastic accumulation—reflect chemical or physical markers, the global decline of coral reefs provides a biologically driven, ecosystem-scale response to human activity. A well-characterized reef site such as Curaçao could, in principle, serve as the golden spike anchoring the Anthropocene within the formal geological timescale.

Methods

Modern coral reef data

The data on the historical evolution of modern reefs was obtained from several different sources. Data for 1973 were gathered from the PhD thesis of Nagelkerken (1979) (9 sites, % cover, as original per site data was lost). Data for 2003 was compiled by K. Vermonden (*52*) (island-wide average, 9 sites). Data for 2010 was compiled by M.J.A. Vermeij (CARMABI, unpublished data, island wide average, 21 sites). The 2015 dataset was compiled by the Waitt Institute (145 sites, the same dataset used in Sandin et al., 2022 (*53*)) using the Global Coral Reef Monitoring Network (GCRMN) recommended methodology for surveying Caribbean reef communities (*54*). The 2023 dataset was compiled by UvA/CARMABI (122 sites using the GCRMN methodology).

LIG coral reef data

We surveyed 5 sites where fossil reefs are exposed above sea level on the leeward coast of Curaçao. To capture and analyze the entire exposed LIG reef sequence at each outcrop, land-based Structure from Motion/Multi-View Stereo (SfM/MVS) surveys were conducted (see example in Figure 4A). Using a 20.1-megapixel Sony DSC-RX100M3 camera (8.8 mm focal length and resolution of 5472 x 3648 pixels) mounted on a collapsible pole, around 750 photos were collected per site. At least six ground control points (GCPs) were evenly distributed within each outcrop for georeferencing purposes. Positions and elevations of each GCP were then measured using an Emlid Reach RS2+ dual-band dGNSS receiver (Rover). Meanwhile, a second Emlid Reach RS2+ receiver (Base) recorded a daily continuous static base station log from atop the CARMABI Research Station (12.122527 N, -68.968600 E). Following data collection, sketches of significant ecological and lithological components were made for later reference.

Post-processing of dGNSS data began by correcting the Base data using the online Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) tool provided by Natural Resources Canada (NRCan). Using the corrected Base position and elevation, Rover survey logs were then post-processed using Emlid Studio Stop and Go (©Emlid Tech Kft., v. 1.3). Resulting GCP positions were then converted from WGS84 ellipsoidal height to EGM08 orthometric height[39] and the root-mean squares of all associated errors were calculated (see Supplementary Material for raw and processed dGNSS data). Next, digital twins of each site were created using the SfM/MVS software Agisoft Metashape Professional edition (version 2.1.0 build 17532), following a standard workflow for outcrop reconstruction[40]. Within each model, the above-mentioned post-processed GCPs were then manually identified. Once constructed, high-resolution orthomosaics (< 1.5 mm/pix) were then exported.

To extract paleoecological data from different parts of each outcrop captured via the digital twins, we subdivided each model into a maximum of three synchronously occurring reef subunits (lower, middle, and upper). While time-averaging is of concern when drawing ecological data from fossil reefs (*55*, *56*), we made a concerted effort to circumvent this by basing the subunits on relative elevation to the LIG coral reef terrace top as well as stratigraphic context. To further better constrain time-averaging and add replicability, three 10-m point intercept transects (PITs) were plotted horizontally with a vertical spacing of 50 cm around the vertical midpoint of each subunit. In total nine PITs were selected per outcrop and, depending on outcrop dimensions and exposure, additional sets of PITs were collected at different sections of the outcrop and treated as additional sub-sites. Drawing on the experience of previous paleoecological surveys, we utilized a PIT interval of 10 cm to achieve the most reliable ecological data(*13*, *57*, *58*). PIT data was extracted from the scaled orthomosaics in QGIS (v. 3.34.4-Prizren), where interval points were classified following a tiered scheme down to the genus level. Care was taken to only classify in-growth position coral colonies as ’live colonies’. Final site-specific, paleo benthic coverage was then calculated across each subunit by taking the average of classifications for each subunit (lower, middle, and upper).

Following benthic coverage derivation, dissimilarity was calculated across each site and respective subunit using Bray-Curtis dissimilarity of the square-root normalized genus abundance data (Figure 4B (*59*)). We then analyzed the dissimilarity within ages using a permutation test (n=10,000). The resulting p-values: lower (0.9824), middle (0.8823), and upper (0.8338) strongly support our field observations that there are 3 distinct phases of coral growth within the leeward LIG reefs of Curaçao. In order to assess the effect of stratigraphic age on the shift in hard coral cover, we fitted a Linear Mixed-Effects (LMM) model using the glmmTMB package in R (v. 4.4.3) (*60*). The model included stratigraphic age as a fixed effect and incorporated site as a random intercept to account for spatial variations across sites. None of the predictors included in the LMME were collinear with one another. Model validation diagnostics plots were obtained via the DHARMa package (*61*). Model residuals against fitted values showed homogeneity and no additional variance structure was added to the model.

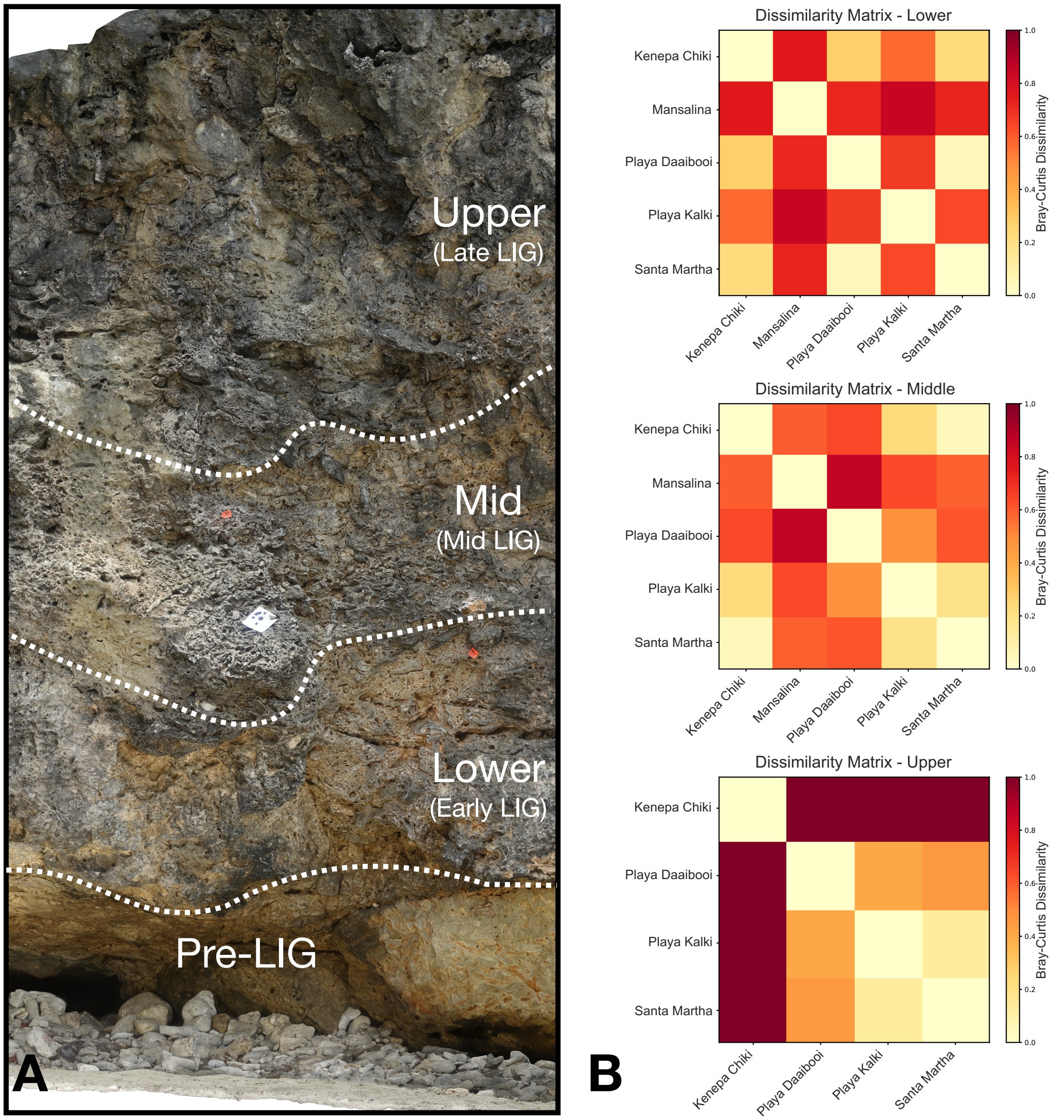

Figure 4. A) Excerpt of the digital twin of the LIG fossil reef at Playa Daaibooi. B) Dissimilarity matrices between the surveyed sites for the Lower, Mid, and Upper LIG. Kenepea Chiki serves as the one outlier in the upper record as it is dominated by a thick *A. cervicornis* rubble lay and has no in-growth position corals present.

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Author contributions

AR, PTB, and BM wrote the manuscript, based on an original idea conceived by AR and EM. AH and MV provided data on historical coral reef patterns on Curaçao. AR, PTB, YCE, SB, GS, GS, DC, and PS participated in the survey of fossil sites. PTB analyzed the fossil reef data with guidance from CW and SB. All authors contributed to the manuscript, revised it through multiple rounds, and approved the final version. ChatGPT (OpenAI) was used to support the refinement of narrative structure, clarity of expression, and adherence to journal formatting guidelines. All content generated with its assistance was critically reviewed and revised by the authors.

Conflict of interest

The authors declare no conflict of interests

Data availability

All data is available in Zenodo at this link: https://doi.org/10.5281/zenodo.15570498

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