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ARTICLE

Handheld-LIBS and 3DXCT reconstruction of historical sedimentation impacts on coral growth in Baler, Aurora, Philippines

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ABSTRACT

Annual growth bands in corals record changes in the marine environment and the corals' responses to them. In this study, we measured geochemical proxies of terrestrial sedimentation and compared them with coral growth parameters in coral core collected from Baler, Aurora, Philippines. Terrestrial sedimentation input was traced using Ti/Ca, Mn/Ca, and Ba/Ca ratios measured by handheld laser-induced breakdown spectroscopy (hLIBS), and coral growth was quantified by the calcification rate derived from 3D X-ray computed tomography (3DXCT) images of the core. High Ti/Ca, Mn/Ca, and Ba/Ca ratios indicate increased terrestrial input. Their peaks tended to coincide with lower linear extension and calcification rates. Increased sedimentation may smother corals and limit nutrient availability, reducing calcium carbonate availability for coral skeletons and leading to slower growth. Sedimentation peaks also coincided with major typhoons in Baler, including Pepang (1983), Konsing (1984) Reming (1996), Pining (1997), Luding (1999), Chedeng (2003), Kabayan (2015), Karen (2016), and Jolina (2017). The results suggest that typhoon-driven sedimentation may contribute to slower coral growth at Baler and highlight the need to better understand its impacts on the coastal environment in the context of climate change.

INTRODUCTION

The Philippines, comprising over 7,100 islands, has the third-largest coral reef area in the world and is renowned for its coral and shorefish diversity (Licuanan et al. 2019; Carpenter and Springer 2005). Philippine coral reefs and coastal ecosystems provide one of the major sources of sustenance to the country's people (White et al. 2000).

Coral reefs are essential to the ecosystem health and economy of many tropical and subtropical nations (Shaish et al. 2010; Hughes et al. 2003), and have been negatively impacted by a combination of human and natural disturbances (Prouty et al. 2014; Nguyen et al. 2013; Roberts et al. 2017). These main disturbances include changes in water velocity, sedimentation, turbidity, salinity, and sea-surface temperature (Hongo et al. 2012). The calcification process is the core of these dynamic and intricate ecosystems. The coral-algal symbiosis considerably increases sustained calcification, which must occur quickly to withstand biological erosion and physical forces such as waves and tropical cyclones (Hongo et al. 2012; Lough and Cantin 2014; Dixon et al. 2022).

Corals are susceptible to natural and anthropogenic disturbances, such as runoff, storms, disease, rising water temperatures, and ocean acidification (Crabbe and Smith 2005). Typhoons can lower sea-surface temperature, introduce vertical mixing, alter salinity, and make shallow reef water turbid. They also increase runoff, nutrients, and suspended sediment, which can suppress coral growth and overprint skeletal geochemistry (Zhou et al. 2012; Hanan et al 2015). Besides introducing terrestrial sedimentation to the marine environment, typhoons can also redistribute sediments as well as flush and export suspended sediment out of reef systems (Braithwaite 2016). Excessive sedimentation has been shown to decrease the light available for photosynthesis, inhibit recruitment, reduce growth, and cause stress and mortality in a wide variety of corals (Hairsine 2017). Certain large corals, such as *Porites* spp., exhibit seasonal patterns of density bands that can be dated and provide a historical record of calcification (Lough and Cooper 2011). Each band serves as a page in the environmental archive, specifying information on past growth responses (linear area, skeletal density, mineralization rate), and can be used to study coral

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KEYWORDS

Coral growth, terrestrial sedimentation, handheld-LIBS, 3DXCT, paleoceanography

growth in response to environmental changes (Lough and Cooper 2011). Climate change and the increasing intensities of typhoons pose a significant threat to these reefs (Villanoy et al. 2012). Coral reefs in Baler frequently bear the brunt of typhoons, and their health is crucial to the region's marine ecosystem by providing food and shelter for a diverse range of fish species (Raquino et al. 2015).

Analyses of coral cores for paleoenvironmental reconstruction traditionally require extensive sample preparation, laborious wet chemistry, and partial or total destruction of the sample (Lough and Cooper 2011). Here, we present handheld Laser Induced Breakdown Spectroscopy (hLIBS) as a rapid, minimally destructive alternative for providing elemental information that will help reconstruct various natural and anthropogenic climate and environmental changes. Particularly, we aim to demonstrate the impact of terrestrial sedimentation inputs on coral growth in Baler, Aurora, by analyzing the coral core's morphology using 3D X-ray computed tomography and measuring elemental proxies for sedimentation using hLIBS. This study aims to provide valuable insights into the history and impacts of natural disasters on coral reef ecosystems in the Philippines, which ultimately affect the country's food supply and economy.

MATERIALS AND METHODS

Study Site

Aurora Province lies on the eastern side of Luzon Island, Philippines. The Municipality of Baler has a total land area of 9,255 hectares divided into 13 barangays, five of which are coastal communities (Buhangin, Pingit, Reserva, Sabang, and Zabal). The populace's livelihoods primarily depend on natural resources, such as agriculture, fisheries, and tourism, with the majority engaged in various agricultural and fisheries activities. Baler is a coastal community vulnerable to climate change (stronger typhoons, floods, sea-level rise, landslides, etc.) (Orencio and Fujii 2012), and the negative impacts on the province's resources are worsening poverty in the area (Grefalda et al. 2020). Baler has a vast marine fishery resource, but the fishing industry remains underdeveloped. Baler Bay serves as a marine fishing ground that supports the local marginal fisherfolk (Grefalda et al. 2020). Baler, Aurora faces the Pacific Ocean with no barriers to shield it from typhoons coming from the east and experiences two main wind currents: north-easterly monsoon (*Amihan*) from November to April, and the south-westerly monsoon (*Habagat*) for the rest of the year (Grefalda et al. 2020). The area experiences two rainfall maxima, in July and December, with December as the wettest month (280 to 650 mm of rain per month), and April the driest (median rainfall of 110 mm) (Corporal-Lodangco et al. 2017).

Sample Collection

Coral core samples were collected from Baler Bay, Aurora, Philippines (N 15°45'31.2", E 121°37'47.9") (Figure 1), approximately 525 m offshore, in October 2018 using a diver-operated hydraulic drill rig (5.8 cm internal diameter). Drilling was done perpendicular to *Porites lutea* (*Porites* spp.) coral growth, with a single coral core collected per colony, to minimize coral damage. Baler 2 coral core, the same core sample used in Bautista VII et al. (2021a; 2021b), is used in this study.

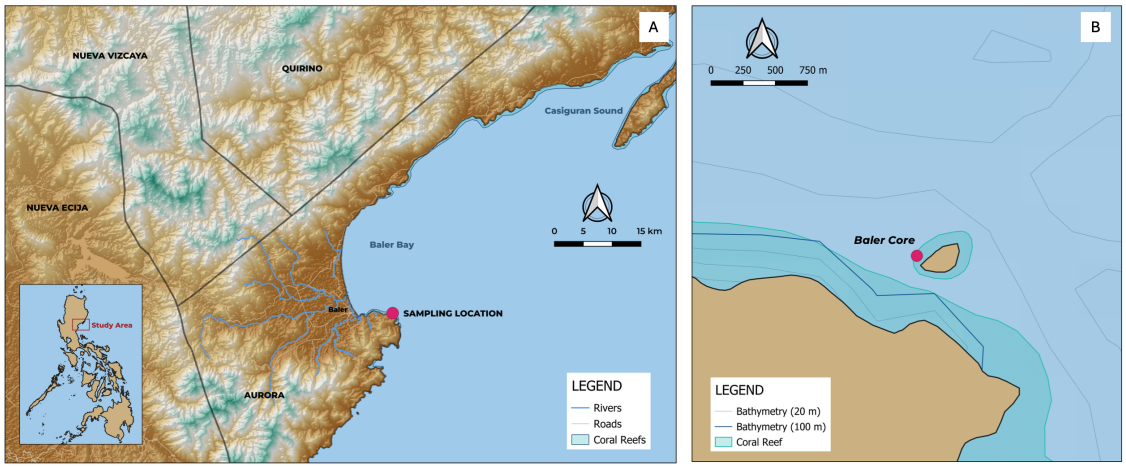


Figure 1: Regional location map (**A**) and sampling location of the Baler coral (**B**) (Digital elevation model from USGS Landsat 2 (2020) and bathymetry data from General Bathymetric Chart of the Oceans (2026)).

Sample Preparation

After sample collection, the coral cores were sliced into 5 mm-thick slabs using a custom-made circular saw. The coral slabs from both coral cores were cleaned with ultrapure water (18.2 MΩ-cm resistivity) and then dried in a clean oven overnight at 40 °C. The slabs were then packaged, labeled, and stored until analysis.

Three-dimensional X-ray Computed Tomography and Coral Age Model

Coral core slabs were analyzed by three-dimensional (3D) X-ray computed tomography (3DXCT; North Star Imaging X5000) in the Industrial Technology Development Institute – Advanced Device and Materials Testing Laboratory (ITDI-ADMATEL). Compared with conventional X-ray, 3DXCT provides higher-resolution grayscale images, with each pixel corresponding to a spatial resolution of 54 µm (Bautista et al. 2021). These high-resolution grayscale images allow clearer visualization of the coral density bands, which were then used as the basis for developing the age model of the coral core. The measurement parameters for the 3DXCT analysis of the 5 mm-thick coral slabs were as follows: 115 kV, 300 µA, 34.5 µm focal spot size, microfocus focal spot mode, and a frame rate of 12.5 fps. A 2D slice of the 3DXCT image of the Baler 2 coral slab is shown in Figure 2, whereas its age model or chronology has previously been established using 3DXCT and sea surface temperature records (Bautista VII et al. 2021a, 2021b; Bauyon et al. 2022).

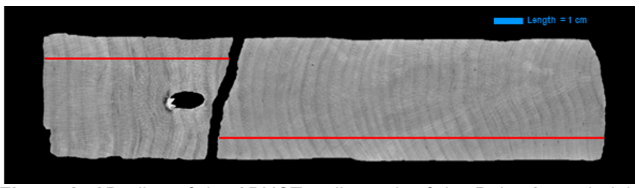


Figure 2: 2D slice of the 3DXCT radiograph of the Baler 2 coral slab sample. The red line shows the profile along which gray values were extracted.

Handheld LIBS Analysis and Terrestrial Sedimentation Proxies

Handheld laser-induced breakdown spectroscopy (SciAps Z300, Massachusetts, USA) was used for the elemental analysis of the coral cores. The coral slab was analyzed at 3 mm intervals limited by hLIBS laser aperture size, with 5-6 mJ/pulse, 50Hz rep rate, and 3B at 1064nm. Each measurement point was read thrice using the Geochem Z-300 internal calibration (Pandhija and Rai 2008; Gonçalves et al. 2021), and cross-validated against the certified reference materials (CRMs) GSD-1 and GSR-12. The measured elemental concentrations of Ti, Mn, Ba, and Ca were then averaged and used for terrestrial sedimentation proxies calculation.

Terrestrial sedimentation was investigated using the following geochemical ratios derived from elemental concentrations measured by hLIBS: Ti/Ca (Gauchery et al. 2021; Chagué 2020), Mn/Ca, and Ba/Ca (Leonard et al. 2019; Lewis et al. 2018; Jiang et al. 2017). Higher Ti/Ca ratios indicate a greater influx of terrigenous sediment to the reef. Titanium is a common component of terrigenous (detrital) sediments and is widely used as a tracer of terrestrial input. High Ti/Ca ratios in coral cores could indicate high river runoff and sediment input (Rothwell and Croudace 2015). The Mn/Ca ratio provides insights into sediment-related processes and redox conditions. Higher Mn/Ca ratios may indicate more oxidized conditions associated with sediment deposition. The Ba/Ca ratio can reflect riverine input of terrigenous material, such as sediment, nutrients, and pollutants and higher Ba/Ca ratios suggest an increased influence of terrestrial sources (Jiang et al. 2017; Jupiter et al. 2008). Calculated sedimentation proxies were plotted on a time-series graph.

Linear Extension Rate

Annual linear extension (or growth) rate was calculated as the distance between two points (Δlength; in mm) measured with a 1-mm-precision steel ruler. The age dates of the two points were then used to determine the elapsed time (Δtime; in yr). The linear extension rate is calculated by dividing the length between the two points and the time elapsed between them (Δlength/Δtime; in mm yr^{-1}).

Coral Density

Gray values measured from the 3DXCT analysis were used as a proxy for density values. Gray value (GV) measures the lightness or darkness of a pixel from the 3DXCT image. This value is related to the total X-ray absorption through the given sample, which can be related to the density and thickness of the sample. Thus, for our coral slabs, which are of fixed thickness, denser parts register higher gray values in a negative X-ray image, and vice versa. Given this, GV serves as a proxy-derived relative density variation, rather than independently calibrated absolute skeletal density values. The GV profile was also validated by comparing the extracted 3DXCT density pattern with the visible high- and low-density banding observed in both the 3DXCT images and the corresponding flatbed X-ray images (Bauyon et al. 2022). Gray values (GV) from the resulting 3DXCT image were determined per pixel from top to bottom of the coral slab (i.e., along the superimposed red line in Figure 2) using the built-in 3DXCT software. Mean coral skeletal densities typically range from 0.99 to 2.01 g cm^{-3} (Ng et al. 2019), gray values from 3DXCT analysis are scaled down values between 1 and 2 using linear scaling in Microsoft Excel.

Calcification Rate

Calcification rate, defined as the product of linear extension and coral skeletal density, was approximated using gray values derived from 3DXCT as proxies for coral density. Because of these limitations, GV values were rescaled to a range of 1–2, similar to reported coral densities, was used only to aid comparison. The rescaled values are not absolute densities in g cm^{-3} and should not be interpreted as a direct conversion. The calcification rate was then calculated by multiplying the linear extension rate (L) by the linear-scaled gray density values (D) (Equation 1):

$$Calcification\ Rate\ =\ L\ x\ D \quad \text{(Equation 1)}$$

Where L is the linear extension growth rate (mm yr^{-1}) and D is the linear scaled gray values (dimensionless).

Statistical Analysis

Spearman's rank correlation (rho) was used to test the relationship between the sedimentation proxies (Mn/Ca, Ba/Ca, and Ti/Ca) and the growth parameters (linear extension rate and calcification rate) using Jamovi 2.6.26 (Jamovi Project, Sydney, Australia). This statistical method was used because it measures the strength and direction of the association between two variables without assuming a specific linear relationship. Spearman's rank correlation allows us to examine the potential connection between sedimentation rates and coral growth more flexibly, considering any possible nonlinear relationships that may exist.

RESULTS AND DISCUSSION

Sedimentation Rates and Typhoon Events

Based on the computed coral age, sedimentation proxy data for the Baler 2 coral span the years 1977 to 2018. Measured Ti/Ca, Ba/Ca, and Mn/Ca sedimentation rates ranged from 3.5×10^{-4} to 3.57×10^{-3}, 7.2×10^{-3} to 2.4×10^{-2}, and 5×10^{-5} to 1.5×10^{-4}, respectively. These values are higher than reported Ba/Ca ratio ranges in *Porites* spp. corals from Hainan Island, China (1.69×10^{-5} to 3.448×10^{-5}) and Sanya Bay, China (8.875×10^{-6} to 1.813×10^{-5}) (Jiang et al. 2017). The Mn/Ca ratios are also higher than those in *Porites* spp. corals in Hainan, China (2.824×10^{-7} to 7.824×10^{-6}), Caribbean Sea (5.209×10^{-8} to 9.239×10^{-6}), Mediterranean Sea (2.056×10^{-6} to 7.128×10^{-6}) and Galapagos Islands (6.854×10^{-8} to 1.508×10^{-7}) (Jiang et al. 2017). These differences may reflect environmental differences.

Figure 3 shows that sedimentation rates fluctuate over time, with Ti/Ca exhibiting the most pronounced fluctuations. Furthermore, comparing the sedimentation proxies used in this study reveals that each proxy exhibits similar peaks and troughs. Peaks are taken to indicate periods of increased terrestrial input (Figure 3). For instance, peak number 5, Luding (1999), has Ti/Ca =0.0035, Mn/Ca = 0.00009, and Ba/Ca= 0.015, and may reflect flooding and landslides caused by past extreme weather events, such as typhoons, in the area.

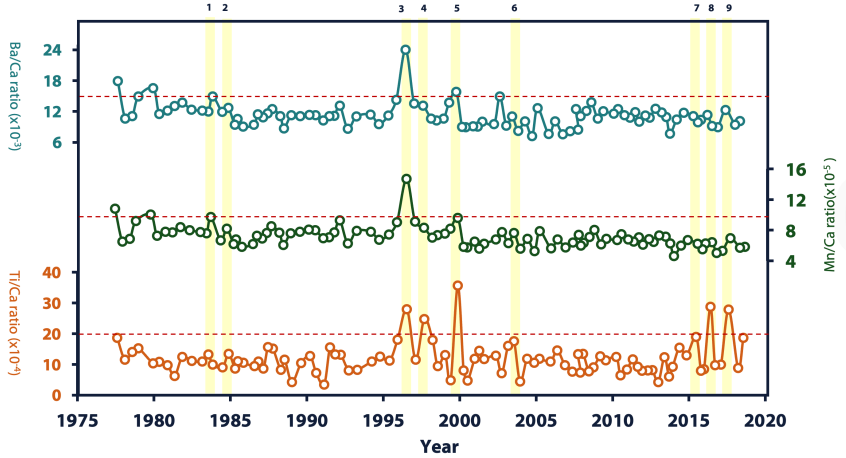


Figure 3: Sedimentation proxies Ba/Ca, Mn/Ca, and Ti/Ca in the Baler 2 coral core. The red lines mark the upper quantile line of the sedimentation proxy values. Yellow lines labelled with numbers indicate identified corresponding typhoon occurrences in Table 1.

The upper quantiles of each sedimentation proxy, illustrated by the red line in Figure 3, provide insights into possible typhoon events responsible for significant changes and unique sedimentation events in *Porites* sp. Applying the upper quantile threshold ensures that the selected peaks represent extreme events. The occurrences of several typhoons, including Typhoon Pepang (1983), Typhoon Konsing (1984), Typhoon Reming (1996), Typhoon Pining (1997), Typhoon Luding (1999), Typhoon Chedeng (2003), Typhoon Kabayan (2015), Typhoon Karen (2016), and Typhoon Jolina (2017), were found to correlate with sedimentation proxies, especially the Ti/Ca peaks, and other outliers coincided with these following typhoons. The upper quantile also shows peaks common across the three sedimentation proxies in years 1983, 1996, and 1999, which correspond to Severe Tropical Storm Joe (Pepang), Tropical Depression Abel (Reming), and Severe Tropical Storm (Luding). Table 1 summarizes the significant typhoons identified from the high sedimentation rate peaks cross-referenced with the Department of Science and Technology – Philippine Atmospheric, Geophysical and Astronomical Services Administration's (DOST-PAGASA) comprehensive database and reported disturbances (Grefalda et al. 2024).

Table 1: Typhoon occurrences in Baler and Aurora Province from 1977 to 2018 and corresponding sedimentation rate peaks.

	NAME OF TYPHOONS	DATES	Ti/Ca	Mn/Ca	Ba/Ca
1	Severe Tropical Storm Joe (Pepang)	October 1983		0.00009	0.014
2	Severe Tropical Strom Konsing	July 1984		0.00008	
3	Tropical Depression Abel (Reming)	October 1996	0.0027	0.00014	0.024
4	Tropical Storm Pining	November 1997	0.0024	0.00008	0.017
5	Severe Tropical Storm (Luding)	August 1999	0.0035	0.00009	0.015
6	Tropical Storm Chedeng	May 2003	0.0017		
7	Tropical Storm Kabayan	October 2015	0.0018		
8	Typhoon Karen	October 2016	0.0028		
9	Severe Tropical Storm Jolina	August 2017	0.0027		

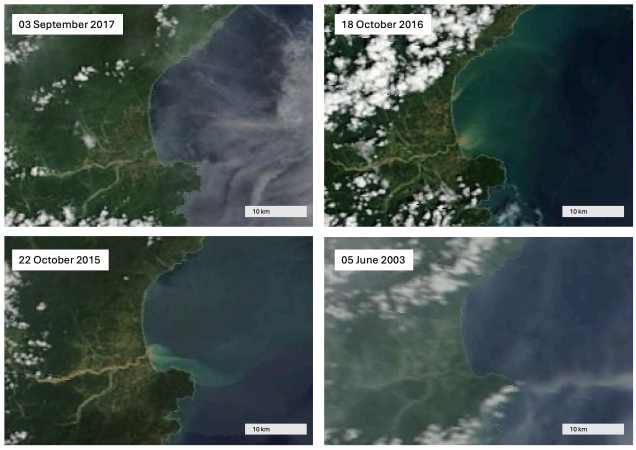


Figure 4: Select (NASA Terra/MODIS) satellite images several days after typhoon occurrences showing increased sediment plumes.

Furthermore, satellite images from selected typhoon and non-typhoon periods in 2025 and 2026 were presented as more recent analogues of typhoon-driven terrestrial sediment input to Baler Bay (Figure 5). The satellite image of 12 November 2025, after the landfall of Super Typhoon Uwan in Aurora, shows a pronounced riverine sediment plume extending into the bay, unlike the images of 4 August 2025 (rainy season) and 16 April 2026 (dry season). Similar observations from other tropical reef settings demonstrate that extreme rainfall and tropical cyclones can substantially enhance terrestrial sediment delivery to coastal reefs (Fong et al. 2020; Takesue et al. 2021), while river discharge and flood-plume sediment inputs have been recorded by coral Ba/Ca and Mn/Ca proxies (Moyer et al. 2012). In particular, typhoon-related rainfall has been associated with distinct Mn/Ca peaks, while high-resolution coral Ba/Ca records can capture tropical cyclone events (Jiang et al. 2017; Feng et al. 2024).

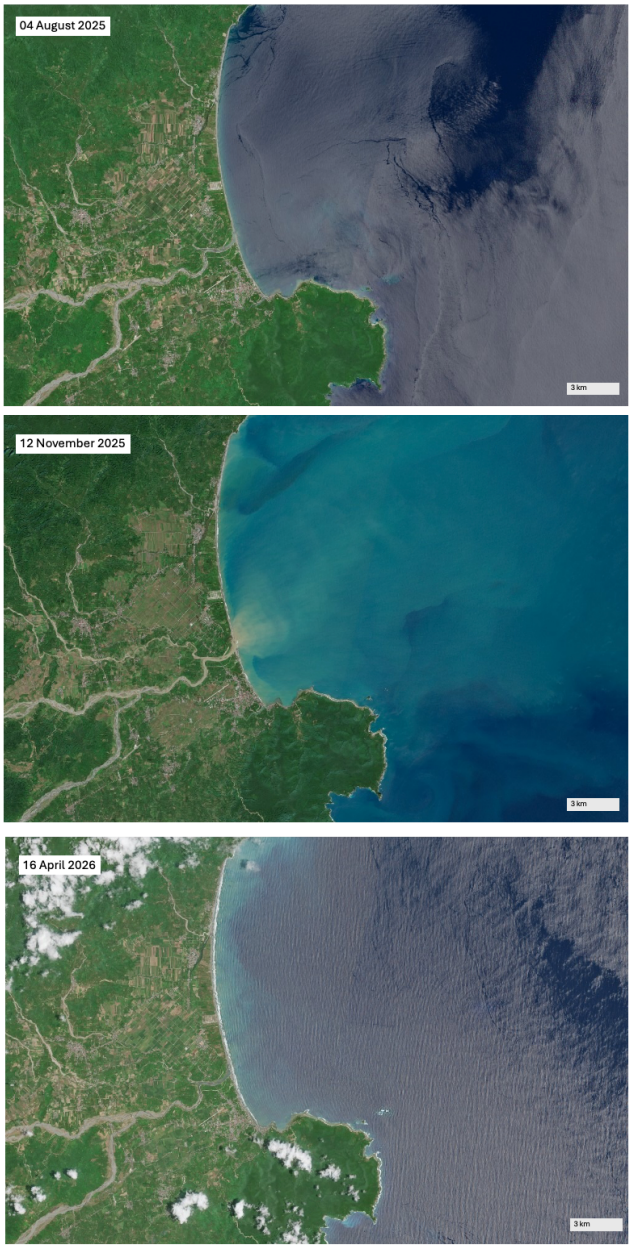


Figure 5: Sentinel-2 L2A images of Baler Bay on (A) 4 August 2025 (rainy season, no typhoon), (B) 12 November 2025 (several days after Super Typhoon Uwan), and (C) 16 April 2026 (dry season, no typhoon).

Effects of Sedimentation on Coral Growth and Calcification Rates

Massive corals such as *Porites* sp. form annual density bands that can be dated and record past calcification (Lough and Cooper 2011). Annual linear extension rate (LER) in the Baler core ranged from 3.24 to 17.15 mm yr^{-1}, with a mean of 7.20 mm yr^{-1}. The mean LER of the Baler core (7.20 mm yr^{-1}) is lower than that of *Porites* colonies from Calaguas Islands, Camarines Norte (10.4 mm yr^{-1}), Ayuku and General Islands, Surigao del Sur (11.2 mm yr^{-1}), Pamilacan, Bohol (11.0 mm yr^{-1}), and Parola Island, Spratlys (9.6 mm yr^{-1}) as reported by Manglicmot (2015).

Sedimentation proxies were compared with the calcification rate of Baler coral to assess possible sedimentation-related effects on coral growth, as shown in Figure 6. Calculated calcification rates of Baler 2 coral ranged from 5.53 to 27.80 (mean 11.88). Since LER and calcification rates are highly correlated, periods of reduced calcification generally correspond to periods of reduced linear extension. Moreover, peaks in sedimentation proxies notably coincide with the troughs of calcification rate suggesting high sedimentation rate events may have contributed to variations in Baler coral growth. Typhoons can transport terrestrial material by heavy rainfall and resuspend seafloor sediment, potentially smothering reefs (Lough and Cantin 2014; Dixon et al. 2022; Pan and Lou 2023).

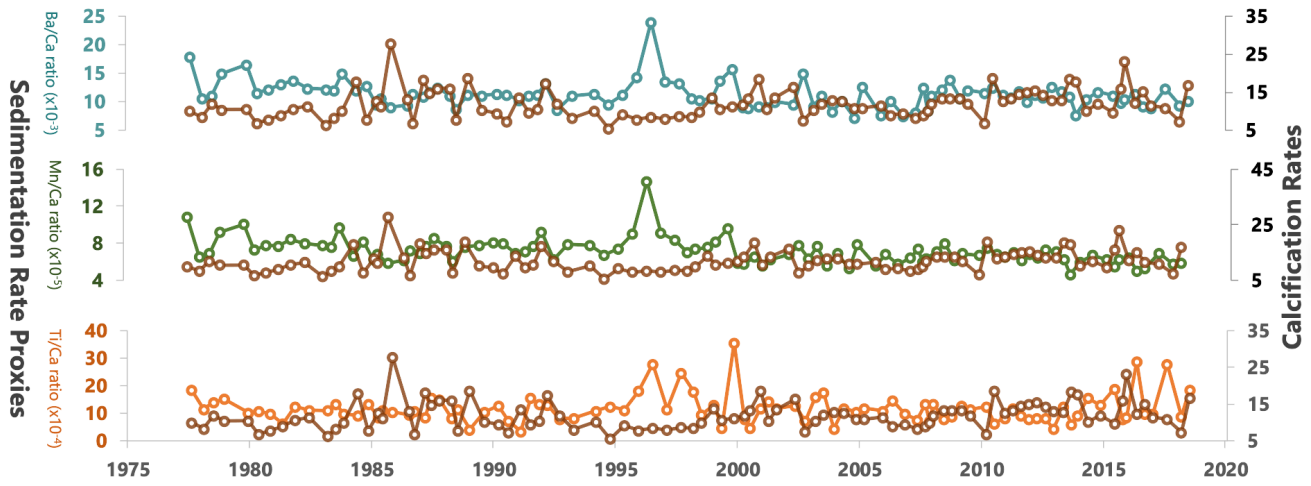


Figure 6: Sedimentation proxies and calcification rate of the Baler coral core from 1977 to 2018.

Calcification is the process by which reef-building corals deposit their calcium carbonate skeletons. This process is an indicator of coral growth and is vital for maintaining the health of reef ecosystems (Gregory et al. 2015; Shaish et al. 2010). Corals and their symbiotic algae use sunlight, carbon dioxide, and water to build calcium carbonate skeletons. Calcification rate is influenced by various factors, such as temperature, the amount of light available, the availability of essential nutrients, and the presence of stressors (Lough and Cantin 2014; Hongo et al. 2012). Low calcification rates are associated with stressors such as increased sedimentation, higher water temperatures, ocean acidification, and pollution that reduce growth and survival of corals (Pendleton et al. 2016).

Spearman's rank correlation coefficients between the sedimentation proxies and the growth parameters are given in Table 2. Spearman rho correlation coefficients between calcification rate and Ti/Ca, Mn/Ca, and Ba/Ca were -0.235, -0.301, and -0.203, respectively (-0.257, -0.305, and -0.228 for LER), respectively, indicate slight inverse correlation between the three sedimentation proxies and coral growth parameters (*i.e*, monthly linear extension rate and calcification rate). Mn/Ca shows the highest correlation with growth parameters among the three sedimentation proxies as Mn/Ca can also reflect growth-linked conditions such as seasonal light, productivity, redox and mixing as compared to Ba/Ca and Ti/Ca (Saha et al. 2016). While sedimentation negatively affects coral growth, it is not the only environmental factor contributing to coral growth. Weak correlation values between sedimentation rate and growth rate in Baler coral suggest other environmental factors, such as sea surface temperature, pH, salinity, and light, potentially played a role in Baler coral growth (Nugues and Roberts 2003).

Table 2: Spearman Rho correlation of sedimentation proxies vs. coral growth parameters

	Ti/Ca	Mn/Ca	Ba/Ca	Linear Extension Rate	Calcification Rate
Ti/Ca	—				
Mn/Ca	0.221	—			
Ba/Ca	0.237	0.864	—		
Linear Extension Rate	-0.257	-0.305	-0.228	—	
Calcification Rate	-0.235	-0.301	-0.203	0.977	—

High calcification rate is a positive coral response to environmental conditions, favoring growth, reproduction, species resilience and survival, and promoting adaptation (Davis et al. 2021). Severe tropical storms can, however, interfere with coral physiology, increasing susceptibility to sedimentation and elevated sea surface temperatures. Moreover, typhoons disrupt the food chain that sustains the corals and limit nutrient availability for development (Roff et al. 2015; Risk 2014).

CONCLUSION

In summary, we present a preliminary study on how coupled hLIBS and 3DXCT can provide a rapid and minimally destructive method for paleoenvironmental reconstruction of coral core samples: hLIBS serves as an accessible analytical tool for measuring geochemical proxies while 3DXCT can provide growth parameters. hLIBS analysis of the coral core measured Ti/Ca, Ba/Ca, and Mn/Ca sedimentation rates ranging from 3.5×10^{-4} to 3.57×10^{-3}, 7.2×10^{-3} to 2.4×10^{-2}, and 5×10^{-5} to 1.5×10^{-4}, respectively. These geochemical proxies provided temporal records of terrestrial sedimentation in the study area. Coincident peaks among proxies correspond to increased sedimentation rates, which may be attributed to typhoon-driven sedimentation events, including Typhoon Pepang (1983), Typhoon Konsing (1984), Typhoon Reming (1996), Typhoon Pining (1997), Typhoon Luding (1999), Typhoon Chedeng (2003), Typhoon Kabayan (2015), Typhoon Karen (2016), and Typhoon Jolina (2017). Among the three proxies, Ti/Ca exhibited the most pronounced fluctuations through time, indicating higher sensitivity to environmental changes.

Moreover, Baler 2 core had annual linear extension rates of 3.24-17.15 mm yr^{-1} (mean 7.20 mm yr^{-1}). Multiplying LER by the rescaled 3DXCT gray values gave a relative index of calcification. Baler core exhibits calcification rates from 5.53-27.80 with an average of 11.88. Comparing calcification and sedimentation rates, the two parameters show an inverse relationship: higher sedimentation rates correspond to lower coral growth. Correlation analysis indicates a slight inverse correlation between sedimentation and coral growth. While sedimentation rates negatively affect coral growth, they are not the only environmental factors contributing to coral growth; other factors, including sea surface temperature, pH, salinity, and others, would also have contributed.

This study identified sedimentation events associated with past typhoons in Baler Bay and demonstrated their possible contributions to coral growth over time through coupled hLIBS geochemical analysis and 3D-XCT imaging of the Baler 2 coral core. In future studies, the development of a density standard with a matrix comparable to coral samples may further enhance the calibration of 3DXCT-derived gray values against known density values, which would in turn improve density estimations and calcification rate calculations. In future investigations, geochemical data should also be integrated with direct river sediment discharge measurements along with other complementary remotely-sensed data such as precipitation, salinity, and seawater temperatures for more robust interpretation. The study is also limited with the 3 mm aperture size of hLIBS for temporal resolution of the geochemical proxies. Furthermore, this study highlights the vulnerability of the Baler marine environment to environmental stresses, which could be exacerbated by a changing climate.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

RNMQ: Conceptualization, Methodology, Data Curation, Investigation, Formal Analysis, Writing – original draft, review & editing**. DEMQ:** Investigation, Formal Analysis, Data Curation, Writing – original draft. **RAHM:** Methodology, Data Curation, Formal Analysis, Writing – review & editing. **DPR:** Formal Analysis, Writing – review & editing. **ATBVII:** Conceptualization, Methodology, Formal Analysis, Writing – review & editing.

REFERENCES

Bautista VII AT, Limlingan SJM, Bauyon MMT, Jagonoy AM, Racho JMD, Valdez JDG, Monsada AM, Salon BJT, Tabuso AJE, Valerio JKC, Dumalagan EE, Siringan FP. 3D X-ray computed tomography gray value and age model datasets of coral cores Baler 2 and 3 (Philippines). Data Br 2021a; 34 (106755): 1-6. https://doi.org/10.1016/j.dib.2021.106755

Bautista VII AT, Limlingan SJM, Bauyon MMT, Jagonoy AM, Racho JMD, Valdez JDG, Salon BJT, Tabuso AJE, Valerio JKC, Dumalagan EE, Kusuno H, Siringan FP, Matsuzaki H. A historical record of the impact of nuclear activities based on 129I in coral cores in Baler, Philippines: An update. J. Environ. Radioact 2021b; 227(106508): 1-6. https://doi.org/10.1016/j.jenvrad.2020.106508

Bauyon MMT, Magtaas RAH, Limlingan SJM, Jagonoy AM, Racho JMD, Valdez JDG, Monsada AM, Salon BJT, Tabuso AJE, Valerio JKC, Sarmiento KJS, Dumalagan EE Jr, Siringan FP, Bautista AT VII. Sea surface temperature reconstruction using 3D X-ray computed tomography in coral cores from Baler, Aurora, Philippines: an initial study. Mindanao J Sci Technol 2022; 20(S1):133-147.

Braithwaite CJ. Coral-reef records of Quaternary changes in climate and sea-level. Earth-Science Reviews 2016; 156: 137–154. https://doi.org/10.1016/j.earscirev.2016.03.002.

Carpenter KE, Springer VG. (2005). The center of the center of marine shore fish biodiversity: the Philippine Islands. Environmental Biology of Fishes 2005; 72(4): 467–480. https://doi.org/10.1007/s10641-004-3154-4

Chagué C. Applications of geochemical proxies in paleotsunami research. In: Engel M, Pilarczyk J, May SM, Brill D, Garrett E, ed(s), Geological Records of Tsunamis and Other Extreme Waves. Amsterdam: Elsevier EBooks, 2020: 381–401. https://doi.org/doi.org/10.1016/b978-0-12-815686-5.00018-3

Corporal-Lodangco IL, Leslie LM. Defining Philippine Climate Zones Using Surface and High-Resolution Satellite Data. Procedia Computer Science 2017; 114: 324–332. https://doi.org/10.1016/j.procs.2017.09.068

Crabbe MJC, Smith DJ. Sediment impacts on growth rates of *Acropora* and *Porites* corals from fringing reefs of Sulawesi, Indonesia. Coral Reefs 2005; 24: 437–441. https://doi.org/10.1007/s00338-005-0004-6

Davis KL, Colefax AP, Tucker JP, Kelaher BP, Santos IR. Global coral reef ecosystems exhibit declining calcification and increasing primary productivity. Nature Communications Earth & Environment (2021); 2(1): 1-16. https://doi.org/10.1038/s43247-021-00168-w

Dixon AM, Puotinen M, Ramsay HA, Beger M. Coral Reef Exposure to Damaging Tropical Cyclone Waves in a Warming Climate. Earth's Future 2022; 10(8): 1-17. https://doi.org/10.1029/2021ef002600

Feng C, Jiang W, Yu K, Sun Y, Xie S, Han Y, Wei C. Cumulated influence of natural and anthropogenic drivers on surface seawater barium: Evidence from a high-resolution coral record in the northern South China Sea. Science of the Total Environment 2024; 906 (167414). https://doi.org/10.1016/j.scitotenv.2023.167414.

Fong CR, Gaynus CJ, Carpenter RC. Extreme rainfall events pulse substantial nutrients and sediments from terrestrial to nearshore coastal communities: a case study from French Polynesia. Scientific Reports 2020; 10 (2955); 1-12. https://doi.org/10.1038/s41598-020-59807-5

Gauchery T, Rovere M, Pellegrini C, Asioli A, Tesi T, Cattaneo A, Trincardi F. Post-LGM multi-proxy sedimentary record of bottom-current variability and downslope sedimentary processes in a contourite drift of the Gela Basin (Strait of Sicily). Marine Geology 2021; *439 (*106564*)*:1–24. https://doi.org/10.1016/j.margeo.2021.106564

Gonçalves DA, Senesi GS, Nicolodelli G. Laser-Induced Breakdown Spectroscopy applied to environmental systems and their potential contaminants. An overview of advances achieved in the last few years. Trends in Environmental Analytical Chemistry 30 2021; e00121. https://doi.org/10.1016/j.teac.2021.e00121

Grefalda LB, Pulhin JM, Garcia JE, Inoue M. Climate Risks and Land Cover Dynamics of the Dibalo-Pingit-Zabali-Malayat River Watershed in Aurora, Philippines. Grassroots Journal of Natural Resources 2024; 7(2): 301–323. https://doi.org/10.33002/nr2581.6853.070216

Grefalda LB, Pulhin JM, Tapia MA, Anacio DB, De Luna CC, Sabino LL, Inoue M. Building institutional resilience in the context of climate change in Aurora, Philippines. Environmental Research 2020; 109584. https://doi.org/10.1016/j.envres.2020.109584

Gregory BRB, Peros M., Reinhardt EG, Donnelly JP. Middle–late Holocene Caribbean aridity inferred from foraminifera and elemental data in sediment cores from two Cuban lagoons. Palaeogeography, Palaeoclimatology, Palaeoecology 2015; 426: 229–241. https://doi.org/10.1016/j.palaeo.2015.02.029

Hairsine, PB. Review: Sediment-Related Controls on the Health of the Great Barrier Reef. Vadose Zone Journal 2017; 16(12): 1-15. https://doi.org/10.2136/vzj2017.05.0115

Hanan DSSM, Aung TT, Tin T, Salleh E. Impacts of 2009 typhoons on seawater properties and top layer ocean's structure in the Northwest Pacific Ocean. Sains Malaysiana 2015; 44(2): 167–173. https://doi.org/10.17576/jsm-2015-4402-02

Hongo C, Kawamata H, Goto K. Catastrophic impact of typhoon waves on coral communities in the Ryukyu Islands under global warming. Journal of Geophysical Research: Biogeosciences 2012; 117(G2): 1-14. https://doi.org/10.1029/2011jg001902

Hughes TP. Climate Change, Human Impacts, and the Resilience of Coral Reefs. Science 2003; 301(5635): 929–933, https://doi.org/10.1126/science.1085046.

Jiang, Q, Cao Z, Wang D, Li Y, Wu Z, Ni J. Coral Ba/Ca and Mn/Ca ratios as proxies of precipitation and terrestrial input at the eastern offshore area of Hainan Island. *J. Ocean Univ. China* 2017; 16:1072–1080. https://doi.org/10.1007/s11802-017-3265-0

Jupiter S, Roff G, Marion G, Henderson M, Schrameyer V, McCulloch M, Hoegh-Guldberg O. Linkages between coral assemblages and coral proxies of terrestrial exposure along a cross-shelf gradient on the southern Great Barrier Reef. Coral Reefs 2008; 27(4): 887–903. https://doi.org/10.1007/s00338-008-0422-3

Leonard ND, WelshKJ, Nguyen AD, Sadler J, Pandolfi JM, Clark TR, Zhao J, Feng Y, Webb GE. High resolution geochemical analysis of massive Porites spp. corals from the Wet Tropics, Great Barrier Reef: rare earth elements, yttrium and barium as indicators of terrigenous input. Marine Pollution Bulletin 2019; 149. https://doi.org/10.1016/j.marpolbul.2019.110634

Lewis SE, Lough JM, Cantin NE, Matson EG, Kinsley L, Bainbridge ZT, Brodie JE. A critical evaluation of coral Ba/Ca, Mn/Ca and Y/Ca ratios as indicators of terrestrial input: New data from the Great Barrier Reef, Australia. Geochimica et Cosmochimica Acta 2018, 237:131–154. https://doi.org/10.1016/j.gca.2018.06.017

Licuanan WY, Robles R, Reyes M. Status and recent trends in coral reefs of the Philippines. Mar Pollut Bull 2019; 142:544-550. https://doi.org/10.1016/j.marpolbul.2019.04.013

Lough JM, Cantin NE. Perspectives on massive coral growth rates in a changing ocean. Biol Bull 2014; 226(3):187-202. https://doi.org/10.1086/bblv226n3p187

Lough JM, Cooper TF. New insights from coral growth band studies in an era of rapid environmental change. Earth Sci Rev 2011; 108(3-4):170-184. https://doi.org/10.1016/j.earscirev.2011.07.001

Manglicmot, M. The linear extension rates of the massive coral *Porites* spp. from the Philippines: environmental controls, spatiotemporal trends and implications. UP IESM MS Thesis 2015.

Moyer RP, Grottoli AG, Olesik JW. A multiproxy record of terrestrial inputs to the coastal ocean using minor and trace elements (Ba/Ca, Mn/Ca, Y/Ca) and carbon isotopes ($\delta^{13}C$, $\Delta^{14}C$) in a nearshore coral from Puerto Rico. Paleoceanography 2012; 27(3). https://doi.org/10.1029/2011pa002249

Ng CSL, Lim JX, Sam SQ, Kikuzawa YP, Toh TC, Wee TW, Sim WT, Ng NK, Huang D, Chou LM. Variability in skeletal bulk densities of common hard corals in Southeast Asia. Coral Reefs 2019; 38(6): 1133-1143. https://doi.org/10.1007/s00338-019-01852-2

Nguyen AD, Zhao JX, Feng YX, Hu WP, Yu KF, Gasparon M, Pham TB, Clark TR. Impact of recent coastal development and human activities on Nha Trang Bay, Vietnam: evidence from a Porites lutea geochemical record. Coral Reefs 2013; 32:181-193. https://doi.org/10.1007/s00338-012-0962-4

Nugues MM, Roberts CM. Partial mortality in massive reef corals as an indicator of sediment stress on coral reefs. Mar Pollut Bull 2003; 46(3):314-323. https://doi.org/10.1016/s0025-326x(02)00402-2

Orencio PM, Fujii M. An index to determine vulnerability of communities in a coastal zone: a case study of Baler, Aurora, Philippines. Ambio 2012; 42(1):61-71. https://doi.org/10.1007/s13280-012-0331-0

Pan Y, Lou S. Hydrodynamics and water environment characteristics in coastal areas under the influences of climate change and human activities Frontiers in Marine Science 2023; 10(1199807): 1-3. https://doi.org/10.3389/fmars.2023.1199807

Pandhija S, Rai AK. Laser-induced breakdown spectroscopy: a versatile tool for monitoring traces in materials. Pramana 2008; 70(3):553-563. https://doi.org/10.1007/s12043-008-0070-8

Pendleton LH, Hoegh-Guldberg O, Langdon C, Comte A. Multiple stressors and ecological complexity require a new approach to coral reef research. Front Mar Sci 2016; 3:36. https://doi.org/10.3389/fmars.2016.00036

Prouty NG, Storlazzi CD, McCutcheon AL, Jenson JW. Historic impact of watershed change and sedimentation to reefs along west-central Guam. Coral Reefs 2014; 33(3): 733–749. https://doi.org/10.1007/s00338-014-1166-x

Raquino ME, Pajaro M, Watts P. Integrating marine biodiversity through Philippine local development plans. Manag Environ Qual 2015; 26(2):159-171. https://doi.org/10.1108/meq-09-2013-0097

Risk MJ. Assessing the effects of sediments and nutrients on coral reefs. Current Opinion in Environmental Sustainability 2014; 7: 108-117. https://doi.org/10.1016/j.cosust.2014.01.003

Roberts M, Hanley N, Williams S, Cresswell W. Terrestrial degradation impacts on coral reef health: evidence from the Caribbean. Ocean Coast Manag 2017; 149:52-68. https://doi.org/10.1016/j.ocecoaman.2017.09.005

Roff G, Chollett I, Doropoulos C, Golbuu Y, Steneck RS, Isechal AL, van Woesik R, Mumby PJ. Exposure-driven macroalgal phase shift following catastrophic disturbance on coral reefs. Coral Reefs 2015; 34(3):715-725. https://doi.org/10.1007/s00338-015-1305-z

Rothwell RG, Croudace IW. Twenty years of XRF core scanning marine sediments: what do geochemical proxies tell us? Dev Paleoenironment Res 2015; 17:25-102. https://doi.org/10.1007/978-94-017-9849-5_2

Saha N, Webb GE, Zhao JX. Coral skeletal geochemistry as a monitor of inshore water quality. Sci Total Environ 2016; 566-567:652-684. https://doi.org/10.1016/j.scitotenv.2016.05.066

Shaish L, Levy G, Katzir G, Rinkevich B. Coral Reef Restoration (Bolinao, Philippines) in the Face of Frequent Natural Catastrophes. Restor Ecol 2010; 18 (3):285-299. https://doi.org/10.1111/j.1526-100X.2009.00647.x

Takesue RK, Sherman C, Ramirez NI, Reyes AO, Cheriton OM, Ríos RV, Storlazzi CD. Land-based sediment sources and transport to southwest Puerto Rico coral reefs after Hurricane Maria, May 2017 to June 2018. Estuarine, Coastal and Shelf Science 2021; 259 (107476): 1-12. https://doi.org/10.1016/j.ecss.2021.107476.

Villanoy C, David L, Cabrera O, Atrigenio M, Siringan F, Aliño P, Villaluz M. Coral reef ecosystems protect shore from high-energy waves under climate change scenarios. Clim Change 2012; 112(2):493-505. doi: 10.1007/s10584-012-0399-3

White AT, Vogt HP, Arin T. Philippine coral reefs under threat: the economic losses caused by reef destruction. Mar Pollut Bull 2000; 40(7):598-605. https://doi.org/10.1016/s0025-326x(00)00022-9

Zhou W, Yin K, Harrison PJ, Lee, JHW. The influence of late summer typhoons and high river discharge on water quality in Hong Kong waters. Estuarine, Coastal and Shelf Science 2012; 111: 35–47. https://doi.org/10.1016/j.ecss.2012.06.004

SUPPLEMENTARY INFORMATION

Supplementary Table 1: Limits of detection of SciAps Z-300 handheld laser breakdown spectrometer expressed in ppm.

Element	Limit of Detection
Ca	50
Ti	100
Ba	50
Mn	50