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Carbonate Budget Assessments in the U.S. Pacific Islands

**Report of Methods Comparison
Results and Summary of
Standard Operating Procedures**

Carbonate Budget Assessments in the U.S. Pacific Islands: Report of Methods Comparison Results and Summary of Standard Operating Procedures

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Cover: A diver measures a coral colony during a carbonate budget assessment.

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Executive Summary

This technical memorandum summarizes 2021 through 2022 results from the NOAA Pacific Islands Fisheries Science Center carbonate budget assessment methods development effort and establishes standard operating procedures for conducting carbonate budget assessments as part of NOAA's National Coral Reef Monitoring Program (NCRMP) in the U.S. Pacific Islands.

Carbonate budget assessments evaluate the ability of reefs to maintain complex, three-dimensional habitat. To do so, these census-based techniques calculate net carbonate production rates by summing reef-building rates from benthic taxa that produce carbonate frameworks (corals and calcifying algae) and subtracting reef erosion rates from taxa that remove it (macrobioeroders, microbioeroders, urchins, and parrotfish). The resulting estimate of carbonate budget states reflects the overall balance of these habitat-altering processes and provides a quantitative metric for evaluating ecosystem condition and function. These assessments align well with long-term monitoring programs like NCRMP because they incorporate multiple ecological data sets into an integrated indicator value. Since 2013, NCRMP monitoring in the U.S. Atlantic and Caribbean has included carbonate budgets conducted according to the widely-used ReefBudget methodology (Perry et al. 2008). However, these assessments have not previously been incorporated into NCRMP in the U.S. Pacific Islands due to logistical challenges associated with adding time-consuming ReefBudget surveys to an already task-loaded program.

In 2021, we initiated efforts to develop a carbonate budgets methodology for Pacific NCRMP that sought to improve survey efficiency by integrating with and leveraging existing Pacific NCRMP data and methods. We compared three data collection approaches at fixed sites around O'ahu and the Marianas Archipelago: (1) the traditional Indo-Pacific ReefBudget methodology, (2) an NCRMP-intermediate methodology that integrates components of both ReefBudget and NCRMP survey design (in-water benthic and urchin transects and fixed-site stationary point count fish surveys), and (3) an NCRMP-leveraged methodology that derives benthic, urchin, and fish data exclusively from existing NCRMP surveys (Structure-from-Motion photogrammetry and stratified random stationary point count fish surveys). We also compared the Indo-Pacific ReefBudget databases used to calculate taxon-specific calcification and erosion rates to NCRMP-customized databases for Pacific species. All approaches tested were able to resolve site-level differences in net carbonate production rates with no significant differences across methods. Of the input data sets used for carbonate budget calculations, only NCRMP-leveraged benthic gross production rates derived from Structure-from-Motion imagery were comparable to ReefBudget in both accuracy and total effort required. By contrast, NCRMP-leveraged urchin and fish survey methods were less favorable because they resulted in slightly reduced accuracy of urchin and fish densities relative to ReefBudget and NCRMP-intermediate methods and/or required substantial additional data processing effort. Production and erosion rates calculated using NCRMP-customized taxon-specific calcification and erosion rate databases were generally lower than rates calculated using the geographically broader Indo-Pacific ReefBudget databases.

The final carbonate budget assessment methodology we propose for Pacific NCRMP optimizes both accuracy and efficiency by deriving benthic data from Structure-from-Motion imagery, urchin data from in-water belt transects, and fish data from fixed-site stationary point count surveys and utilizing NCRMP-customized calcification and erosion rates databases. This approach will be operationalized as part of Pacific NCRMP missions starting in FY24.

Introduction

The immense wealth of marine biodiversity, essential habitat, and cultural and ecosystem services provided by coral reefs ultimately depends upon the production and persistence of three-dimensional calcium carbonate reef frameworks. Coral reef frameworks are produced by the growth of corals, crustose coralline algae, and other marine calcifiers, and persist when rates of carbonate production outpace rates of physical erosion from storms, chemical dissolution, and biological erosion from corallivorous fish, urchins, macrobioeroders, and microbioeroders. The relative rates of gross carbonate production and carbonate erosion and resulting net rate of carbonate production—the reef’s *carbonate budget*—thus offer a metric for assessing coral reef functional status, growth potential, and capacity for maintaining complex habitats (Lange et al. 2020). Tracking these metrics becomes increasingly critical under a rapidly changing climate as ocean warming, ocean acidification, and sea-level rise threaten to reduce rates of coral and crustose coralline algae calcification, accelerate rates of erosion, and thereby jeopardize the persistence of coral reef habitat (Januchowski-Hartley et al. 2017; Perry and Morgan 2017; Perry, et al. 2018; Lange and Perry 2019).

Carbonate budget assessments offer a quantitative approach for estimating rates of biological carbonate production and erosion and the balance between these processes. While carbonate budgets can be calculated using several techniques, census-based methods are becoming increasingly popular due to their utilization of data and metrics that are commonly collected in long-term coral reef monitoring efforts and integration of multiple ecological data streams into a single reef status indicator value. The most widely used census-based carbonate budget methodology, ReefBudget (Perry et al. 2008), employs organism size and abundance data to sum the individual contributions of carbonate producing and carbonate eroding taxa and estimate site-level carbonate budgets. Census-based carbonate budget assessments have been conducted for numerous coral reef sites in the Atlantic/Caribbean (Perry et al. 2013; Courtney et al. 2016; Manzello et al. 2018; Perry et al. 2018) and western and central Indian Ocean (Herrán et al. 2017; Perry and Morgan 2017; Perry et al. 2018; Lange and Perry 2019; Ryan et al. 2019; Lange et al. 2022) and at a handful of locations in the Red Sea (Roik et al. 2018), western Pacific (Woesik and Cacciapaglia 2018), and eastern Pacific (Manzello et al. 2017). Collectively, these assessments highlight significant spatial heterogeneity in carbonate budget states across reef habitats, geographic regions, and ocean basins (Lange et al. 2020). However, beyond a handful of rapid imagery-based assessments (Courtney et al. 2022), the status and trends in carbonate budget states throughout most of the U.S. Pacific Islands region remain largely unknown.

Tasked with monitoring the status and trends of U.S. coral reef ecosystems, NOAA’s National Coral Reef Monitoring Program (NCRMP) provides a strategic scientific and operational framework for collecting sustained, national-level data on coral reef carbonate budgets (NOAA Coral Program 2021). As such, ReefBudget assessments have been part of NCRMP in the U.S. Atlantic and Caribbean since 2013 (Manzello et al. 2018; Morris et al. 2022; Webb et al. 2023). However, carbonate budget assessments have not previously been implemented as part of NCRMP in the U.S. Pacific Islands, where coral reef states and territories span large spatial gradients in environmental conditions and coral reef community states and thus likely vary in their rates of carbonate production and erosion (Williams et al. 2011; Smith et al. 2020; Barkley et al. 2022; Huntington et al. 2022). Integrating ReefBudget-style carbonate budget surveys into Pacific NCRMP has proved challenging for a variety of reasons. First, ReefBudget and NCRMP

methodologies for benthic and fish data collection differ in survey design, survey area, and metrics assessed; estimating carbonate budgets using traditional ReefBudget approaches thus requires supplementary field data collection in addition to routine NCRMP surveys. Second, ReefBudget field assessments take more time (approximately 2–5 additional dive hours required per site) than NCRMP missions can generally support (~2 hours per site maximum). Third, executing field surveys requires coral, algae, urchin, and fish identification, necessitating a high level of involvement and coordination from all three Pacific NCRMP science teams (benthic, fish, and climate; see NOAA Coral Program 2021). Finally, a number of common U.S. Pacific Islands coral and fish species are not included in ReefBudget databases, making it difficult to accurately calculate carbonate production and erosion at sites where these species are abundant.

In 2021, we initiated efforts to develop, test, and pilot a new NCRMP carbonate budget methodology for the U.S. Pacific Islands. We sought to retain comparability with national and international ReefBudget methods and data sets while also addressing the unique opportunities and challenges posed by Pacific NCRMP operations. This technical memorandum (1) describes the carbonate budget assessments methodologies developed, tested, and considered for inclusion in NCRMP monitoring, (2) summarizes initial results of the 2021 through 2022 pilot assessments and methods comparison conducted at sites around O‘ahu and the Marianas Archipelago, and (3) establishes Pacific NCRMP standard operating procedures for conducting future carbonate budget assessments.

Methods

Overview of methods comparison

Census-based carbonate budget assessments require: (1) benthic, urchin, and fish field survey data to quantify the cover or abundance of carbonate producing and eroding taxa; and (2) databases of taxon-specific production and erosion rates for all calcifying and eroding organisms observed. As part of our methods comparison and pilot survey effort, we developed, tested, and compared (1) field methodologies for collecting benthic, urchin, and fish survey data and (2) taxon-specific calcification and erosion rates databases. Our approach is summarized below and described in further detail in the following methods sections.

1. *Field survey methods*: to assess potential approaches for collecting carbonate budget census data as part of Pacific NCRMP, we compared the following suite of field data collection methodologies:
 - **Indo-Pacific ReefBudget methodology**: surveys conducted following the established approach for the Indo-Pacific region outlined by Perry et al. (2018).
 - **NCRMP-intermediate methodology**: as an intermediate between Indo-Pacific ReefBudget and NCRMP-leveraged methodologies, this method utilizes elements of both approaches to address potential concerns with or to test alternate techniques for using existing NCRMP survey design and data sets to calculate carbonate budgets.
 - **NCRMP-leveraged methodology**: data extracted entirely from data streams currently collected on Pacific NCRMP missions: fixed-site Structure-from-Motion (SfM) photogrammetry (Rodriguez et al. 2021) and stratified random stationary point count fish surveys (Ayotte et al. 2015).

Field surveys for each methodology were designed around existing NCRMP mid-depth (~15 m) climate fixed sites. Fixed sites are designated on the benthos as a 10 m × 5 m box with a stainless steel reference stake on the upper left (inshore) corner and calcification accretion units (CAUs) deployed at 5-m increments around the perimeter (Figure 1A). Additional fixed sites occasionally surveyed during NCRMP operations are set up according to the Scripps Institution of Oceanography site design, where no CAUs are deployed, and two or three pins are installed across a 10-m centerline. For these sites, the centerline with pins was treated as equivalent to the inshore 10-m side of the fixed site rectangle (Figure 1B).

2. *Taxon-specific calcification and erosion rates*: to select the best taxon-specific calcification and erosion rates databases for Pacific NCRMP carbonate budget assessments, we compared carbonate production and erosion rates generated from the following databases:
 - **Indo-Pacific ReefBudget databases**: Indo-Pacific calcification and bioerosion, urchin erosion, and parrotfish erosion rates databases from Perry et al. (2018).
 - **U.S. Pacific Islands (NCRMP) databases**: coral and crustose coralline algae calcification rates and parrotfish foraging metrics and erosion rates databases developed specifically for U.S. Pacific Islands species.

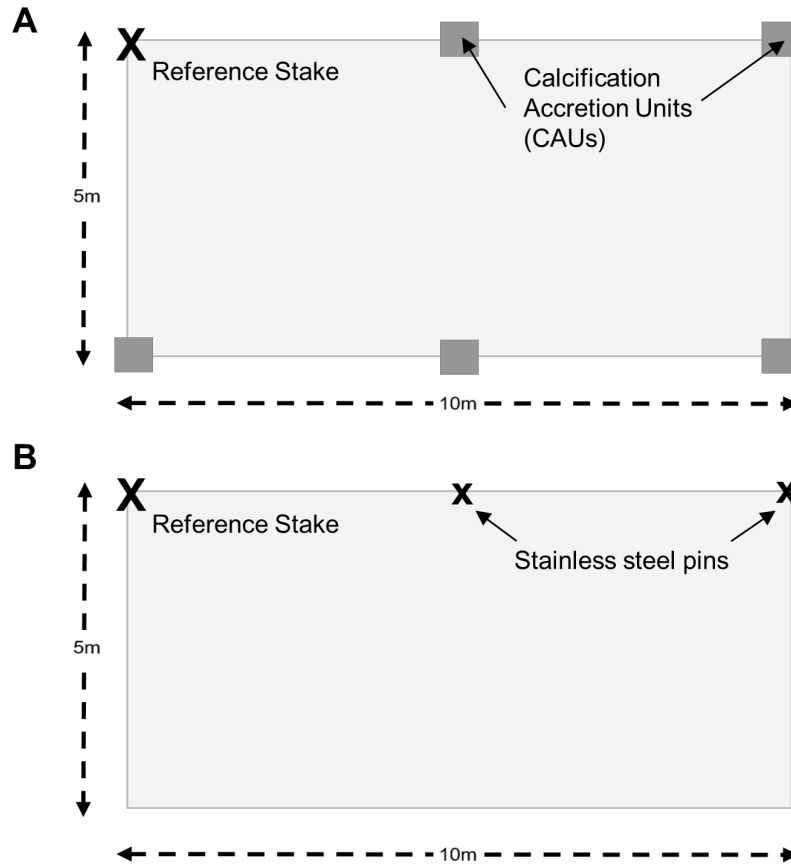


Figure 1. Fixed site benthic box design (10 m × 5 m) of A) each mid-depth NCRMP permanent site, showing the corner reference stake and five calcification accretion units (CAUs) and B) Scripps Institution of Oceanography site design, with a reference stake and 2–3 stainless steel pins (middle pin is not consistently installed). The reference stake is oriented inshore, and the 10-m edges of the fixed site box run parallel to shore.

We applied the same data processing procedure to data generated using all methods and databases. Carbonate production and erosion were calculated following ReefBudget protocol (Perry et al. 2018) using the *reefbudgetR* package, a customized R package developed by PIFSC for Pacific NCRMP from the Indo-Pacific ReefBudget Excel data entry spreadsheets.

Carbonate budget assessments also generate several additional metrics including hard coral cover, rugosity, urchin abundance and density, and fish biomass that are used in production and erosion calculations. These ancillary metrics may be useful for other research or monitoring applications.

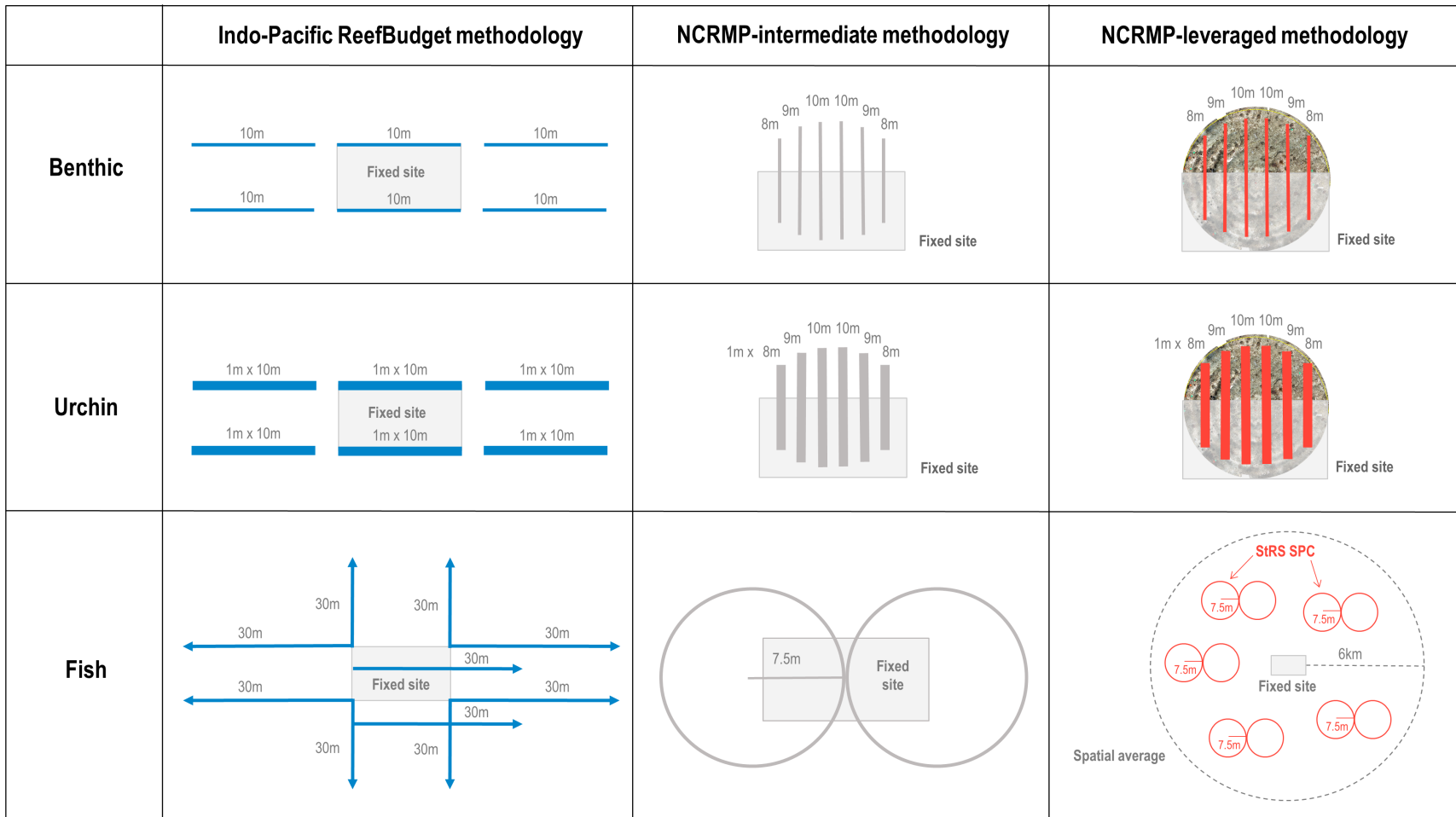


Figure 2. Overview of benthic, urchin, and fish survey methods tested as part of the carbonate budget pilot assessments. “Fixed site” designates the 10 m × 5 m benthic box at each mid-depth NCRMP permanent site (Figure 1). Survey design schematics are color-coded by methodology and are not drawn to scale. For NCRMP-leveraged methodology fish surveys, StRS SPC refers to stratified random sampling stationary point count surveys. See methods section for additional information on each survey methodology.

Benthic production

Field data collection

Indo-Pacific ReefBudget methodology (IPRB)

Following IPRB methodology, benthic survey data were collected by divers along six 10-m transects per site. Transects were laid out in two parallel rows of three—the middle transects in each row were overlaid on the inshore and offshore 10-m edges of the fixed site box with 5-m spacing between adjacent transects (Figure 2). Along each transect, the surface cover (cm) of every benthic component located directly beneath the transect tape was measured with a flexible measuring tape. Data were collected on the following benthic components: hard scleractinian corals (identified to genus/species and morphology), crustose coralline algae (CCA), macroalgae, turf algae, sand, rubble, carbonate hard substrate, non-carbonate hard substrate (e.g., basaltic surfaces), or other (including cyanobacteria, soft coral, seagrass, sponges, zoanthids, corallimorphs, or other invertebrates).

The surface cover of coral colonies with open branching morphologies (e.g., *Acropora intermedia*, *Pocillopora grandis*) was estimated by multiplying the total number of branches directly beneath the transect tape by the average branch diameter. This approach minimizes potential over-estimation of live coral cover that can occur when draping the tape over an entire branching colony (where void space is included in the surface cover measurement). Surface cover of colonies with closed branching morphologies (e.g., *Acropora humilis*, *Pocillopora damicornis*; where void space between branches is minimal and all substrate beneath the transect tape is coral skeleton) was measured by draping the tape over the entire colony.

NCRMP-intermediate methodology

Under the NCRMP-intermediate methodology, benthic data were collected along transects whose endpoints fell roughly on the circumference of the circular fixed-site SfM footprint (Figure 2). This approach enables us to evaluate two major concerns with the use of SfM-derived data for carbonate budget assessments: (1) the impact of shrinking the area of reef footprint surveyed from ~40 m × 5 m (covered by IPRB methodology) to a 12-m diameter circular area (covered by SfM), and (2) the introduction of any bias in SfM-derived data relative to diver-collected data. Using this approach, divers collected in-water benthic data along the same set of transects that were later surveyed virtually using SfM as part of the NCRMP-leveraged approach.

To ensure that transects fell within the 12-m SfM circular footprint, a master transect tape was first established along the inshore, 10-m edge of the fixed site box (Figure 1). Six 8-m to 10-m perpendicular transects (2 × 8 m, 2 × 9 m, and 2 × 10 m) were then laid out at predetermined distances along the master transect tape with 1.5-m spacing between transects (shorter transects closer to the edges, longer transects towards the center of the circle). Benthic data were collected along the six perpendicular transects according IPRB methodology. Yellow dive weights were placed at the beginning and end of each transect; these weights were included in subsequent SfM imagery collection to mark the locations of diver-collected transects.

NCRMP-leveraged methodology

The NCRMP-leveraged methodology for benthic data collection utilizes fixed-site SfM imagery already collected as part of NCRMP monitoring efforts (Figure 2). Imagery was collected at each site following the spiral survey method outlined in Rodriguez et al. (2021). The images were processed with Agisoft Metashape photogrammetry software to produce a scaled digital elevation model (DEM) and corresponding orthomosaic for each site (Torres-Pulliza et al. in review). Benthic data were extracted from these two high resolution reef models in ArcGIS Pro 3.0.3 using a customized tool that replicates in-water benthic data collection in the SfM environment (see [Appendix A](#) for full standard operating procedure). The orthomosaic image was used to visually characterize the benthos while the DEM was used to estimate surface cover of benthic components. In-water transect locations from the NCRMP-intermediate methodology were replicated virtually using the yellow dive weights as transect end markers. The benthic components of each transect were measured following IPRB methodology, with the exception that total surface cover for corals with open branching morphologies was calculated as the sum of the diameter of each branch directly beneath the transect (rather than using the coarser estimated diameter of all branches).

Rugosity and coral cover calculations

Rugosity: based on IPRB methodology (v 1.3)¹, rugosity (R_j) is calculated for each transect as the sum of individual surface cover (x_i , in cm) of all observed benthic components divided by the transect linear length (L_j , in cm):

$$R_j = \frac{\sum_{i=1}^n x_i}{L_j}$$

Coral cover: coral percent cover for each transect (C_j) is calculated as the summed surface cover of all corals (x_i , where $x_i = \text{coral}$) divided by total transect cover of all benthic components:

$$C_j = \frac{\sum_{i=1, x_i = \text{coral}}^n x_i}{\sum_{i=1}^n x_i}$$

Gross carbonate production calculations

Coral and crustose coralline algae calcification rates databases

A customized calcification rates database was developed for the U.S. Pacific Islands based on the existing IPRB calcification database (v 1.3)². Where possible, the spatial extent of the database of published coral extension rates and densities was limited to studies from the western, central, or south Pacific Ocean. Genus and/or species average calcification rates and densities were then calculated at taxonomic levels used by the NCRMP benthic team. This database improves regional estimates of coral calcification rates and increases integration with existing NCRMP

¹ Accessed from https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/reefbudget/documents/Indo-Pacific_Carbonate_Production_v1.3-Jan23.xlsx

² Accessed from https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/reefbudget/documents/IP_Calcification_and_bioerosion_rates_database_v1.3.xlsx

benthic data collection. When Pacific growth rate data were not available for a particular genus/species, Indo-Pacific rates were substituted for the closest genus and morphology pair in the IPRB database. CCA growth rates were estimated using a Pacific-wide average of CAU accretion data (Barkley et al. 2022).

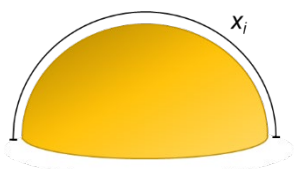
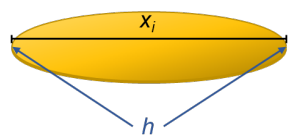
To determine whether the calcification rate database led to differing gross carbonate production rates, benthic data were processed using (1) the IPRB calcification database and (2) the U.S. Pacific Islands NCRMP calcification database for each survey site and field methodology tested.

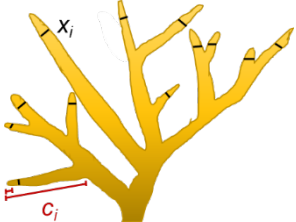
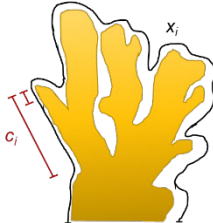
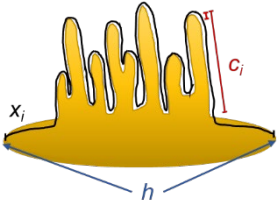
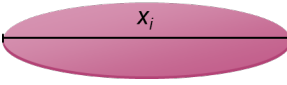
Coral and crustose coralline algae production rates

Colony-level production rates: based on the IPRB methodology, the equations in Table 1 are used to calculate colony-level carbonate production rates for coral and CCA. Following IPRB methodology, production rates for all other benthic components were assumed to be zero.

In addition to the morphologies already included in the IPRB approach, a laminar columnar growth equation was developed for Pacific NCRMP surveys to model *Porites rus* and *Porites monticulosa* calcification. To determine the proportion of laminar vs. columnar growth, divers recorded the total surface distance (x_i) and the length of surface distance composed of laminar plates for 50 *P. rus* colonies. Based on these field measurements, the laminar columnar growth model assumes that ~55% of the surface distance measured for an individual colony represents laminar growth ($0.55x_i$) and ~45% represents columnar growth ($0.45x_i$). Because laboratory studies also show that columns and plates grow at different rates (Lenz and Edmunds 2017; Padilla-Gamiño et al. 2012), different extension rates ($g_{i,LA}$ and $g_{i,CO}$) are applied for each morphological component. The laminar and columnar portions of growth are then summed to estimate the total production for each colony.

Table 1. Equations used to calculate colony-level carbonate production rates (p_i in g CaCO₃ yr⁻¹) for each coral morphology and CCA (i). x_i = surface cover (in cm), g_i = taxon-specific linear extension rate (in cm yr⁻¹), d_i = taxon-specific skeletal density (in g cm⁻³), c_i = taxon-specific proportion of colony growing axial branches, and h = number of colony edges.

Coral Morphology or Calcifier Type (Morphology Code)	Description	Schematic and Production Equation
Massive (MD) Mounding Lobate (ML) Free-living (FR)	Colonies are treated as hemispheres with uniform growth.	 $p_i = d_i \cdot \left[\left(g_i + \frac{x_i}{\pi} \right)^2 \left(\pi - \pi \left(\frac{x_i}{\pi} \right)^2 \right) \right]$
Encrusting (EM) Plating (PL) Foliose (FO) Table (TB)	Growth is assumed to occur at published rates at the colony edges (assume $h = 2$ edges per colony) and at 10% of these rates across the rest of the colony.	 $p_i = h \cdot g_i \cdot d_i + 0.1 \cdot (x_i \cdot g_i \cdot d_i)$

Coral Morphology or Calcifier Type (Morphology Code)	Description	Schematic and Production Equation
Branching (BR) <i>open branching morphology</i>	Assumes large void space between branches. Growth is assumed to occur at published rates at the colony branch tips and at 10% of these rates across the rest of the colony.	 $p_i = (x_i \cdot c_i \cdot g_i \cdot d_i) + 0.1 \cdot g_i \cdot d_i \cdot (x_i - x_i \cdot c_i)$
Branching (BR) <i>closed branching morphology</i>	Assumes minimal void space between branches or columns. Growth is assumed to occur at published rates at the colony branch tips and at 10% of these rates across the rest of the colony.	 $p_i = (x_i \cdot c_i \cdot g_i \cdot d_i) + 0.1 \cdot g_i \cdot d_i \cdot (x_i - x_i \cdot c_i)$
Laminar columnar (LC)	Colony growth is assumed to have both laminar and columnar components that grow at different rates, where $g_{i, LA}$ = laminar extension rate (in cm yr^{-1}) and $g_{i, CO}$ = columnar extension rate (in cm yr^{-1}).	 $p_i = [h \cdot g_{i, LA} \cdot d_i + 0.1 \cdot (0.55x_i \cdot g_{i, LA} \cdot d_i)] + [(0.45x_i \cdot c_i \cdot g_{i, CO} \cdot d_i) + 0.1 \cdot g_{i, CO} \cdot d_i \cdot (0.45x_i - 0.45x_i \cdot c_i)]$
Crustose coralline algae (CCA)	Growth is assumed to be the product of extension, density, and surface cover.	 $p_i = x_i \cdot g_i \cdot d_i$

Transect-level gross production rates: to calculate the total annual carbonate production per transect (P_j , in kg CaCO₃ yr⁻¹), colony-level production (p_i) is summed for all corals and CCA:

$$P_j = \sum_{i=1}^n p_i$$

Gross production rate per unit area ($G_{prod,j}$, in kg CaCO₃ m⁻² yr⁻¹) is calculated using the following equation, where L_j is the transect length (in cm):

$$G_{prod,j} = P_j \left(\frac{10000}{L_j} \right)$$

Site-level mean and error gross production rates: site-level production rate (G_{prod} , in kg CaCO₃ m⁻² yr⁻¹) and error ($\sigma_{G_{prod}}$) are calculated as the average and standard deviation production rates, respectively, across all transects per site (n , typically $n = 6$):

$$G_{prod} = \frac{1}{n} \sum_{j=1}^n G_{prod,j}$$

$$\sigma_{G_{prod}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (G_{prod,j} - G_{prod})^2}$$

Macrobioerosion and microbioerosion

Field data collection

Macrobioerosion (from bivalves, gastropods, endolithic sponges, polychaete worms, sipunculid worms, decapods, and cirripeds) and microbioerosion (from cyanobacteria, green and red algae, fungi, and bacteria) rates are derived from benthic survey data (Figure 2). The abundance of these taxa are not directly enumerated from benthic surveys; instead, the IPRB approach uses published Indo-Pacific macrobioerosion and microbioerosion rates and the amount of erodible carbonate substrate available to calculate transect-level and site-level bioerosion.

Macrobioerosion and microbioerosion rate calculations

Macrobioerosion rates

Transect-level macrobioerosion rates: macrobioerosion rates are calculated using the following formula: $E_{macro,j}$ = transect-level macrobioerosion (in kg m⁻² yr⁻¹), R_j = transect rugosity, m_{macro} = Indo-Pacific macrobioerosion rate (0.209 ± 0.129 kg m⁻² yr⁻¹), and $C_{macro,j}$ = percent cover of benthic substrate available for macrobioerosion (total percent cover of carbonate rock, dead

coral, rubble, turf, calcifying algae, macroalgae, sponges, cyanobacteria, and substrate beneath articulated algae):

$$E_{macro,j} = R_j \cdot m_{macro} \cdot \frac{C_{macro,j}}{100}$$

Site-level mean and error macrobioerosion rates: macrobioerosion rates per unit area (E_{macro} , in kg CaCO₃ m⁻² yr⁻¹) and error ($\sigma_{E_{macro}}$) are calculated as the average and standard deviation macrobioerosion rate, respectively, across all transects per site (typically n = 6):

$$E_{macro} = \frac{1}{n} \sum_{j=1}^n E_{macro,j}$$

$$\sigma_{E_{macro}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (E_{macro,j} - E_{macro})^2}$$

Microbioerosion rates

Transect-level microbioerosion rates: microbioerosion rates are calculated using the following formula: $E_{micro,j}$ = transect-level microbioerosion (in kg m⁻² yr⁻¹), R_j = transect rugosity, m_{micro} = Indo-Pacific microbioerosion rate (0.262 ± 0.180 kg m⁻² yr⁻¹), and $C_{micro,j}$ = percent cover of benthic substrate available for microbioerosion (total percent cover of carbonate rock, dead coral, rubble, turf, cyanobacteria, macroalgae, and substrate beneath articulated algae; coral and CCA calcification rates are assumed to already account for microbioerosion):

$$E_{micro,j} = R_j \cdot m_{micro} \cdot \frac{C_{micro,j}}{100}$$

Site-level mean and error microbioerosion rates: microbioerosion rates per unit area (E_{micro} , in kg CaCO₃ m⁻² yr⁻¹) and error ($\sigma_{E_{micro}}$) are calculated as the average and standard deviation microbioerosion rate, respectively, across all transects per site (typically n = 6):

$$E_{micro} = \frac{1}{n} \sum_{j=1}^n E_{micro,j}$$

$$\sigma_{E_{micro}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (E_{micro,j} - E_{micro})^2}$$

Urchin erosion

Field data collection

Indo-Pacific ReefBudget methodology (IPRB)

Urchin surveys were conducted over a 1-m wide belt along the same transects used for IPRB benthic surveys (Figure 2). Along each transect, divers recorded the number and test size (size of the urchin exoskeleton excluding spines) for the following genera: *Echinostrephus*, *Echinothrix*, *Diadema*, *Echinometra* (including *Echinometra mathaei*), and *Parasalenia*. Test sizes were measured with a scale bar on the side of dive slates and binned into 20 mm classes: 0–20 mm, 21–40 mm, 41–60 mm, 61–80 mm, 81–100 mm, 101–120 mm, 121–140 mm, and 141–160 mm.

NCRMP-intermediate methodology

NCRMP-intermediate urchin surveys (1 m × 8-10 m belt transects) were conducted along the same transects surveyed for the benthic methodology following the IPRB procedure described above (Figure 2).

NCRMP-leveraged methodology

Extraction of urchin data from SfM imagery was conducted for O‘ahu sites using ArcGIS Pro and NOAA Video and Image Analytics for Marine Environments (VIAME) software. In ArcGIS Pro, virtual benthic transects laid in each fixed-site orthomosaic were cropped to the extent of the belt transect survey area (1 m × 8-10 m) and exported as individual jpeg images for each transect. Belt transect images were uploaded to VIAME, and all visible urchins were identified to genus/species and sized with a bounding box. The total length of each urchin (length of the test plus spines) was estimated to be the largest dimension of the bounding box.

Urchin erosion calculations

Urchin erosion rates database

Due to the paucity of studies on erosion rates for bioeroding urchin taxa, the IPRB database (v 1.3)³ and equations were used to calculate urchin erosion rates.

Urchin erosion rates

Urchin erosion rates were calculated following IPRB methodology (v 1.3)⁴. The equations in Table 2 were used to calculate carbonate erosion rates for each urchin taxon and test size bin.

To calculate urchin erosion rates from NCRMP-leveraged SfM data, taxon-specific equations were first used to convert total size of each urchin observed to test size. Conversion equations were derived for *Diadema*, *Echinometra*, *Echinostrephus*, and *Echinothrix* species based on field measurements of both length parameters for individuals of each genus, where divers measured total length and test length of 187 urchins (*Echinothrix* = 49, *Diadema* = 5, *Echinometra* = 91,

³ Accessed from https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/reefbudget/documents/Indo-Pacific_Urchin_Erosion_v1.3.xlsx

⁴ Accessed from https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/reefbudget/documents/Indo-Pacific_Urchin_Erosion_v1.3.xlsx

Echinostrephus = 42) at two O‘ahu sites (Kewalo and Reef Runway). Total urchin lengths estimated in VIAME were then converted to test length using species-specific equations (Table 2). Test sizes were binned into 20 mm size classes for each taxon.

Table 2. Equations used to convert urchin test length to carbonate erosion rate and total length to test length (for SfM-derived urchin data) for each bioeroding urchin taxon. For erosion rates, e_i = erosion rate (in $\text{kg m}^{-2} \text{yr}^{-1}$), n_i = number of urchins observed per transect, t_i = median urchin test size bin diameter (in mm), A_j = transect area (in m^2). For length conversion equations, t_i = test size (mm) and l_i = total size (in mm).

Urchin genus	Erosion rate	Total length to test length conversion equation
<i>Diadema</i>	$e_i = \frac{365 \cdot n_i \cdot 0.000003t_i^{3.2887}}{1000 \cdot A_j}$	$t_i = 0.33l_i + 2.49$
<i>Echinometra</i>	$e_i = \frac{365 \cdot n_i \cdot 0.0003t_i^{1.9671}}{1000 \cdot A_j}$	$t_i = 0.69l_i - 6.08$
<i>Echinostrephus</i>	$e_i = \frac{365 \cdot n_i \cdot 0.00004t_i^{2.6025}}{1000 \cdot A_j}$	$t_i = 0.38l_i + 10.30$
<i>Echinothrix</i>	$e_i = \frac{365 \cdot n_i \cdot 0.000003t_i^{3.2887}}{1000 \cdot A_j}$	$t_i = 0.52l_i + 4.07$
Other eroding urchins	$e_i = \frac{365 \cdot n_i \cdot 0.00004t_i^{2.6025}}{1000 \cdot A_j}$	$t_i = 0.54l_i + 1.30$

Transect-level urchin erosion rates: urchin erosion rates for each transect ($E_{urchin,j}$, in $\text{kg m}^{-2} \text{yr}^{-1}$) were calculated by summing the individual erosion rates for each taxon and test size bin.

$$E_{urchin,j} = \sum_{i=1}^n e_i$$

Site-level mean and error urchin erosion rates: site urchin erosion rate per unit area (E_{urchin} , in $\text{kg CaCO}_3 \text{m}^{-2} \text{yr}^{-1}$) and error ($\sigma_{E_{urchin}}$) were calculated as the average and standard deviation urchin erosion rate, respectively, across all transects per site (typically $n = 6$):

$$E_{urchin} = \frac{1}{n} \sum_{j=1}^n E_{urchin,j}$$

$$\sigma_{E_{urchin}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (E_{urchin,j} - E_{urchin})^2}$$

Parrotfish erosion

Field data collection

Indo-Pacific ReefBudget methodology (IPRB)

Parrotfish belt transects were conducted according to IPRB methodology. At each site, eight to ten replicate (30-m × 5-m) belt surveys were conducted both perpendicular and parallel to shore. Adjacent transects were treated as replicates: six replicate transects were conducted parallel to shore where each diver pair were 5 m apart from each other. The four remaining replicate transects were conducted perpendicular to shore (both offshore and towards shore directions) where each diver pair was 10 m apart from each other (Figure 2). The parallel transect placements closely followed IPRB methodology, and the perpendicular transect placements were incorporated to survey adjacent areas offshore and inshore of the NCRMP fixed site box.

While looking a distance roughly 8 m ahead, divers recorded the species and life phase (initial or terminal) of every parrotfish individual encountered along the transect (for O‘ahu and the Mariana Archipelago: *Scarus*, *Hipposcarus*, *Chlorurus*, *Calotomus*, and *Cetoscarus* spp.) and visually-estimated total length. Fish lengths were binned into the following size classes: 0–10 cm, 11–20 cm, 21–30 cm, 31–40 cm, 41–50 cm, and 51–60 cm. Divers completed 8 to 10 transects in a single dive and recorded the general habitat type that dominated over 50% of each transect. Divers ceased surveying if the transect ran into expansive sand habitat or large changes in depth (> 5 m), and a shortened transect was recorded. It took 7 minutes to survey each 30-m transect.

NCRMP-intermediate methodology

Stationary point count (SPC) surveys were conducted at each fixed site following NCRMP standard operating procedures (Ayotte et al. 2015; Heenan et al. 2017). SPC surveys utilize a visually-estimated “snapshot” approach to record and size fish (including parrotfish) observed within a pair of 15-m diameter cylinders. At each fixed site, a 30-m transect line was laid out and centered with the fixed site box (Figure 2); divers began by recording general habitat type that dominated over 50% of their transect survey area from a predetermined category list (aggregate reef, pavement, pavement with sand channels, spur and groove, etc.). The methodology consists of two components: first, an enumeration period during the first five minutes of the survey during which each diver listed all species observed within their cylinder. Second, during a tallying period, divers recorded the number and visually-estimated total length of all individuals within their cylinder, working through their recorded species list one at a time through a series of rapid visual sweeps. Species that were enumerated in the first 5 minutes but were no longer present during the tallying period were counted and sized according to memory and were circled to denote their absence. As new species entered the cylinder after the first 5 minutes, they were identified, sized, and counted in their own category. Adjacent cylinders were treated as replicates and were averaged. While all species were recorded to maintain consistency with NCRMP fish surveys, only parrotfish data were used in subsequent site-level abundance, biomass, and bioerosion calculations.

NCRMP-leveraged methodology

NCRMP SPC surveys were conducted using a stratified random sampling design, where sites were pre-allocated to strata based on the area of hard bottom substrate and historical data variance. Stratified random sampling SPC (StRS SPC) surveys were conducted at sites in less than 30 m depth as part of routine NCRMP operations (Ayotte et al. 2015; Heenan et al. 2017). Parrotfish abundance, biomass, and bioerosion estimates associated with each stratified randomly selected site were calculated by averaging site-level data (averages of paired cylinders per site). Then abundance, biomass, and bioerosion estimates from all StRS SPC sites located within 6 km of each fixed site box were averaged (Figure 2). The sites within 6 km of their respective fixed sites were further subsetted by excluding all non-aggregate reef habitat types (excluding pavement and reef rubble habitats) as parrotfish are not known to actively forage in these areas (Carlson et al. 2017; Davis et al. 2017). The NCRMP-intermediate fixed SPC sites were not included in the averaged NCRMP-leveraged StRS SPC estimates.

Parrotfish biomass calculations

Individual fish biomass: individual parrotfish total length (TL_i) was recorded for all NCRMP-intermediate and NCRMP-leveraged SPC surveys, while individual parrotfish total lengths were binned (i.e., 10 cm bins) for IPRB belt transects. To remain consistent across methodologies, the total length used to calculate biomass for each individual was treated as the midpoint of each size class bin. For example, if the individual was binned in the 11–20 cm bin for IPRB belt transects, 15 cm was used in the biomass calculations. If the individual sized for NCRMP-intermediate or NCRMP-leveraged SPC was 12 cm, the individual was binned in the 11–20 cm size class and hence, 15 cm was used in the biomass calculations. Parrotfish biomass was calculated using length-to-weight conversion parameters from the FishBase database (Froese and Pauly 2017; Heenan et al. 2017). The wet weight of each individual parrotfish was calculated from fork length using the following equation: w_i = wet weight (in g), TL_i = total length (in cm), cf_i = length conversion factor (total length to fork length), and a and b are length-to-weight coefficients:

$$w_i = a \cdot (TL_i \cdot cf_i)^b$$

Species biomass: biomass (b_i , in kg) was calculated for the number of individuals observed (n_i) across each species and size class using the following equation:

$$b_i = \frac{n_i \cdot w_i}{1000}$$

Survey-level biomass: survey-level (transect or cylinder) biomass per unit area ($B_{fish,j}$, in kg ha^{-1}) was calculated by summing biomass (b_i , in kg) across all species and dividing by transect survey area (A_j , in m^2):

$$B_{fish,j} = \frac{1000}{A_j} \left(\sum_{i=1}^n b_i \right)$$

Site-level mean and error biomass: site-level mean biomass (B_{fish} , in kg ha^{-1}) and standard deviation ($\sigma_{B_{fish}}$) were calculated by averaging biomass ($B_{fish,j}$) across all replicate IPRB belt

transects (n = 10) or replicate NCRMP-intermediate fixed site SPC cylinders (n = 2) or by averaging across all NCRMP-leveraged StRS SPC transects (n = 1–40) within a 6-km radius of each fixed site.

$$B_{fish} = \frac{1}{n} \sum_{j=1}^n B_{fish,j}$$

$$\sigma_{B_{fish}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (B_{fish,j} - B_{fish})^2}$$

Parrotfish erosion calculations

Parrotfish foraging metrics

Bioerosion estimates of individual parrotfishes are calculated using several parameters including an individual's bite rate, the volume removed per bite, and the proportion of bites that leave scars. These metrics vary by species, life phase, and size of an individual. To calculate erosion rates of surveyed parrotfish, a two-step process was implemented: (1) calculate foraging metrics (bite rate, bite volume, proportion of scars) using total length of each fish, (2) calculate erosion rates using these foraging metric inputs for each fish observed. To calculate foraging metrics, two databases were used: (1) the existing IPRB parrotfish erosion rates database (v1.4)⁵, and (2) a new database consisting of allometric foraging equations for herbivorous fishes in the Pacific synthesized by Kindinger et al. (in review; henceforth referenced as Kindinger et al. database).

Four functional group metrics were assigned for each species (i.e., excavators, scrapers, browsers, others) depending on how deeply they cut into the substrate when they feed. For some species, assignments of functional groups varied with life phase and changed at a specific size. During the calculation of foraging metrics, if data were missing for a select parrotfish species in the IPRB database, then values were assigned from their respective sister species (i.e., groupings based on clades from Choat et al. (2012) and Bonaldo et al. (2014); see IPRB parrotfish erosion rates database for sister species assignments). The IPRB database grouped foraging metrics predominantly by sister species. When species-specific foraging metric equations were missing in the Kindinger et al. database, then genus level equations were used.

The IPRB database models foraging metrics per species within a functional group as a function of body size in total length. The IPRB database modeled each data set in the literature that informed foraging metrics for each species separately which resulted in multiple models and multiple types of curves for some species (e.g., power, exponential; Table 3). Each foraging metric was calculated using one or more combinations of the equations listed in Table 3 for each species from thorough literature reviews. For the species with more than one equation, multiple values for each foraging metric were calculated and then averaged (see IPRB parrotfish erosion

⁵ Accessed from https://geography.exeter.ac.uk/media/universityofexeter/schoolofgeography/reefbudget/documents/Indo-Pacific_Parrotfish_Erosion_v1.4.xlsx

rates database v1.4 to view specific equations, calculations, species-specific foraging metric values, and averaged foraging metric values for each species or sister species groupings).

Kindinger et al. modeled foraging metrics per species and per genus within a functional group as a function of body size in total length. Foraging metrics were calculated for each species based on equations derived from thorough literature reviews. Contrary to the IPRB method, to calculate each foraging metric, the Kindinger et al. database combined all data for all parrotfish species with existing data into one model with a meta-analytic approach. Hence, one equation was applied across all species for each foraging metric. Among bite rates, they also considered an effect of sea-surface temperature (SST) given the geographical spread of data they compiled and synthesized. For the scope of this project, best-fit bite rate models including SST were used. If a species-specific foraging metric was not accounted for, the genus level equations from Kindinger et al. were used.

Bite rates (bites min^{-1}), volume removed per bite (cm^3), and proportion (or probability) of bites leaving scars for each parrotfish species were calculated using the formulas from the two different databases in Table 3.

Table 3. Equations used to calculate foraging metrics using two different databases per species of parrotfish: TL_i = total length (in cm; mid-point of each size bin), SST_i = sea surface temperature (in °C), and a , b , c , SST are input constants. The constants used in each equation for both databases are literature-derived species-specific constants.

Foraging Metric	IPRB Database*	Kindinger et al. Database
Bite rates (bites min ⁻¹)	$br_i = a \cdot TL_i^b$ $br_i = a \cdot TL_i^2 + b \cdot TL_i + c$	$br_i = e^{a+(TL_i \cdot b)+(SST \cdot SST_i)}$
Bite volume (cm ³ per bite)	$v_i = a \cdot TL_i^b$ $v_i = a \cdot e^{b \cdot TL_i}$	$v_i = a \cdot TL_i^b$
Scars (IPRB – proportion; Kindinger et al. - probability)	$s_i = a \cdot e^{b \cdot TL_i}$ $s_i = a \cdot \ln(TL_i) - b$ $s_i = a + b \cdot \log(TL_i)$ $s_i = a + b \cdot \ln(TL_i)$ $s_i = a \cdot TL_i^b$ $s_i = a \cdot TL_i - b$	$s_i = \frac{e^{a+(TL_i \cdot b)}}{1 + e^{a+(TL_i \cdot b)}}$

*IPRB database foraging metric equations vary based on the study from which the equations were derived. Multiple values for each parrotfish species were derived from these foraging metric equations and were then averaged to determine final foraging metric rate. Refer to the existing Indo-Pacific ReefBudget parrotfish erosion rates database (v1.4) to view the combination for species-specific equations, sister species groupings, and averaged species-specific or sister-species foraging metric values.

Parrotfish erosion rates

Individual parrotfish erosion rates: using the formula below, erosion rates (r_i , in kg individual⁻¹ yr⁻¹) for each parrotfish species and size class were estimated from foraging metrics calculated with each database: d = substrate density (g cm³), br_i = bite rate (bites min⁻¹), s_i = proportion of bites leaving scars, v_i = bite volume (cm³), h = mean daylight period (hours day⁻¹), and f = percent of daylight spent feeding:

$$r_i = 365 \cdot \frac{d \cdot br_i \cdot s_i \cdot v_i \cdot 60 \cdot \left(h \cdot \frac{f}{100} \right)}{1000}$$

Mean daylight period (h) was assumed to be 12 hours, percent of day spent feeding (f) was assumed to be 83.3% (Bellwood 1995), and substrate density (d) was set to the IPRB default (1.47 g cm⁻³).

Erosion rates (e_i , in kg m⁻² yr⁻¹) were then summed for each parrotfish species and size class across the number of individuals observed (n_i):

$$e_i = n_i \cdot r_i$$

Survey-level erosion rates: survey-level (transect or cylinder) erosion rates ($E_{fish,j}$, in kg m⁻² yr⁻¹) were calculated by summing erosion rates across all species (e_i) and dividing by survey area (A_j , in m²):

$$E_{fish,j} = \frac{\sum_{i=1}^n e_i}{A_j}$$

Site-level mean and error erosion rates: site-level mean parrotfish erosion rates (E_{fish}) and standard deviation ($\sigma_{E_{fish}}$) were calculated by averaging erosion rates ($E_{fish,j}$) across all replicate IPRB belt transects ($n = 10$) or replicate NCRMP-intermediate fixed site SPC cylinders ($n = 2$) surveyed per site, or averaging across all NCRMP-leveraged StRS SPC transects ($n = 1-40$).

$$E_{fish} = \frac{1}{n} \sum_{j=1}^n E_{fish,j}$$

$$\sigma_{E_{fish}} = \sqrt{\frac{1}{n-1} \sum_{j=1}^n (E_{fish,j} - E_{fish})^2}$$

Net carbonate production

Site-level net carbonate production rates: the net production rate for each site (G_{net}) is calculated as site-level mean gross production rate (G_{prod}) less rates of macrobioerosion (E_{macro}), microbioerosion (E_{micro}), urchin erosion (E_{urchin}), and parrotfish erosion (E_{fish}):

$$G_{net} = G_{prod} - E_{macro} - E_{micro} - E_{urchin} - E_{fish}$$

Site-level net carbonate production rates error: the standard deviation of site-level net carbonate production (σ_{Gnet}) is calculated as the square root of the summed squared standard deviation for each site-level mean:

$$\sigma_{Gnet} = \sqrt{(\sigma_{Gprod})^2 + (\sigma_{Emacro})^2 + (\sigma_{Emicro})^2 + (\sigma_{Eurchin})^2 + (\sigma_{Efish})^2}$$

Net carbonate production: NCRMP-proposed methodology

Based on the efficiency of the survey methods tested in the field and comparison of the data generated using each method, net carbonate production rates were also calculated for each site using the combination of methods we ultimately propose for NCRMP carbonate budget assessments (see [discussion](#) for additional rationale on the selection of these methods). No new field data were generated for this methodology; rather, the NCRMP-proposed methodology selects the benthic, urchin, and fish data collection techniques from the NCRMP-intermediate and NCRMP-leveraged methodologies that optimize both efficiency of data collection in the field and comparability of calculated carbonate production and erosion rates to traditional IPRB surveys. The NCRMP-proposed methodology net carbonate production rate calculations use the following data sets:

- **Benthic data (G_{prod} , E_{macro} , and E_{micro}):** NCRMP-leveraged methodology
- **Urchin data (E_{urchin}):** NCRMP-intermediate methodology
- **Fish data (E_{fish}):** NCRMP-intermediate methodology

Pilot survey sites and summary of dive operations

Field surveys were conducted at 16 sites in 2021–through 2022: 6 sites around O‘ahu in 2021 and 10 sites in the Mariana Archipelago (Guam = 4 sites, Saipan = 2 sites, Pagan = 2 sites, and Maug = 2 sites) in 2022 as part of the NCRMP-Marianas mission on NOAA Ship Rainier (Figure 3, Table 4). Sites were selected to maximize latitudinal gradients, windward and leeward sides of islands, variability in coral cover and fish biomass, and anthropogenic impacts to the greatest extent possible within operational and weather constraints.

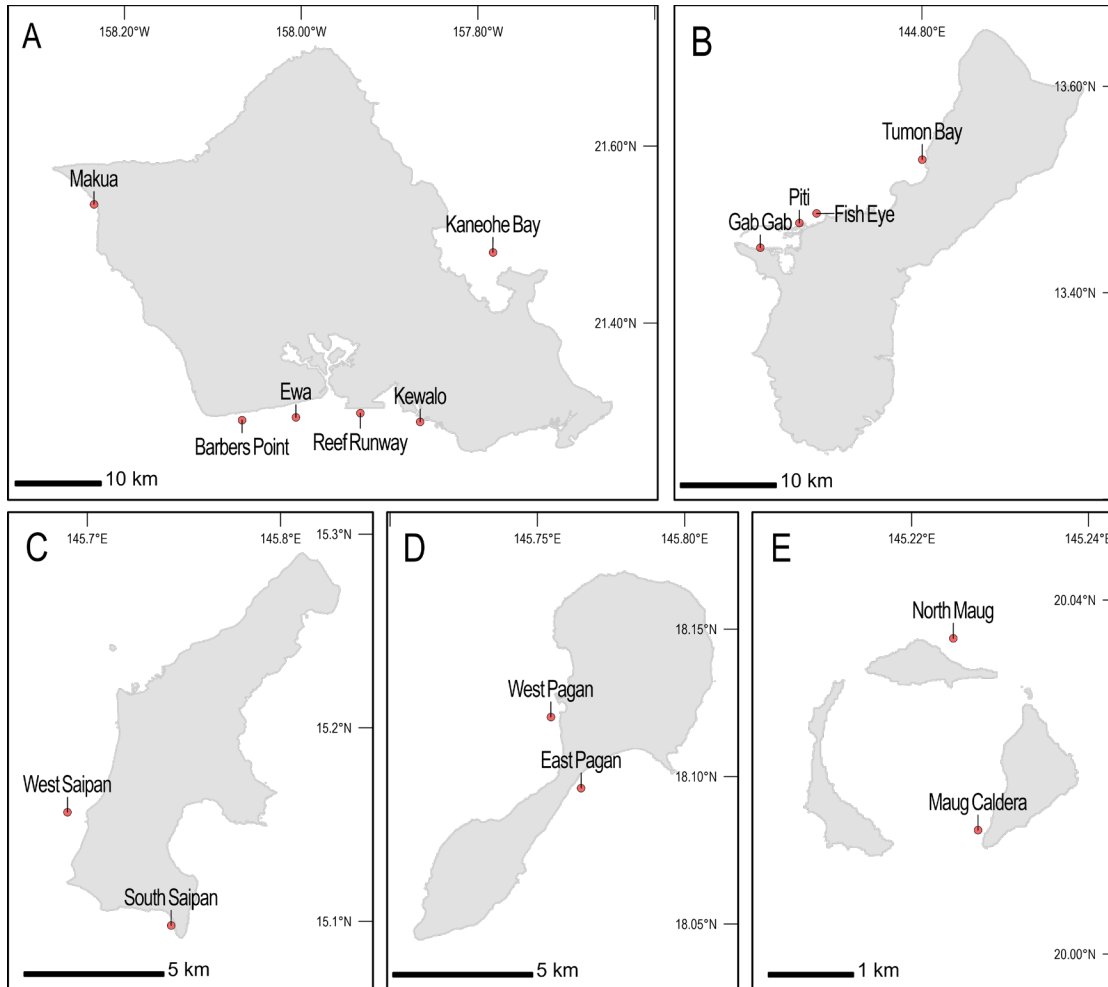


Figure 3. Carbonate budget pilot assessment sites conducted at A) O’ahu (2021) and B-E) the Mariana Archipelago (2022): B) Guam, C) Saipan, D) Pagan, and E) Maug. See Table 4 for additional information on survey sites.

Field data collection methodologies were tested over a two-day period at each site. IPRB benthic, urchin, and fish surveys and NCRMP-intermediate fish surveys were conducted on one day, and NCRMP-intermediate benthic and urchin surveys were conducted on the other. Fish surveys were conducted on the first or third dive of the day, and the order of IPRB surveys and NCRMP-intermediate surveys rotated between sites to minimize any bias in fish counts that might occur between the first dive at a site (when fish divers were the first divers on site that day) and the third dive (after divers had been in the water for benthic and fish surveys and could potentially influence fish abundance). The dive teams executing the full suite of carbonate budget methodologies were composed of two fish divers and four or five divers trained in coral, algae, and urchin identification. For the NCRMP-leveraged methodology, fixed-site SfM imagery was collected by the climate team following the completion of in-water benthic and urchin surveys, and StRS SPC surveys were conducted separately by the fish team during the same field mission.

All benthic, urchin, and fish data collection methodologies were tested at each site, with the exception that NCRMP-leveraged urchin data were not collected for sites in the Marianas (due to

processing time limitations). For Marianas sites, NCRMP-intermediate urchin erosion rates from each site were substituted in net production calculations for NCRMP-leveraged methodology.

Table 4. Site information for pilot assessment surveys conducted around O‘ahu (2021) and the Mariana Archipelago (Guam, Maug, Pagan, Saipan; 2022). Site design refers to the layout of any existing installations at the survey site: NCRMP sites include a 10 m × 5 m fixed site box with a reference stake and CAUs. Scripps Institution of Oceanography (SIO) sites are marked with two or three stainless steel pins along the 10-m centerline of the survey site (see Figure 1).

Island	Year	Site ID	Site Name	Latitude (°N)	Longitude (°E)	Depth (m)	Site Design
O‘ahu	2021	OCC-OAH-005	Kaneohe Bay	21.4798	-157.7830	12.5	NCRMP
O‘ahu	2021	OCC-OAH-010	Kewalo	21.2884	-157.8653	12.2	NCRMP
O‘ahu	2021	OCC-OAH-012	Makua	21.5341	-158.2344	14.6	NCRMP
O‘ahu	2021	OCC-OAH-038	Reef Runway	21.2981	-157.9330	9.5	SIO
O‘ahu	2021	OCC-OAH-039	Ewa	21.2934	-158.0060	10.3	SIO
O‘ahu	2021	OCC-OAH-040	Barbers Point	21.2903	-158.0670	11.0	SIO
Guam	2022	OCC-GUA-015	Tumon Bay	13.5290	144.8004	14.3	NCRMP
Guam	2022	OCC-GUA-024	Gab Gab	13.4436	144.6433	6.1	SIO
Guam	2022	OCC-GUA-025	Piti	13.4675	144.6812	12.2	SIO
Guam	2022	OCC-GUA-026	Fish Eye	13.4768	144.6978	11.6	SIO
Maug	2022	OCC-MAU-002	North Maug	20.0357	145.2247	13.7	NCRMP
Maug	2022	OCC-MAU-019	Maug Caldera	20.0140	145.2275	10.4	SIO
Pagan	2022	OCC-PAG-006	East Pagan	18.0961	145.7649	15.5	NCRMP
Pagan	2022	OCC-PAG-013	West Pagan	18.1202	145.7546	17.4	NCRMP
Saipan	2022	OCC-SAI-009	South Saipan	15.0979	145.7434	17.4	NCRMP
Saipan	2022	OCC-SAI-012	West Saipan	15.1564	145.6898	12.5	NCRMP

Statistical analyses

All statistical analyses were conducted in R (version 4.1.3). For data derived using the three benthic methodologies, the impact of survey method (IPRB, NCRMP-intermediate, NCRMP-leveraged), region (O‘ahu, Marianas), site (nested within region), and their interactions on the response variables of hard coral cover (C_j), rugosity (R_j), macrobioerosion ($E_{macro,j}$), and microbioerosion ($E_{micro,j}$) were evaluated using three-way nested Analysis of Variance (ANOVA) tests with post hoc Tukey Honestly Significant Difference (HSD) tests. For gross carbonate production ($G_{prod,j}$), the calcification database used (IPRB, NCRMP) to calculate coral and CCA production was also considered as an additional explanatory variable in a four-way nested ANOVA. The six benthic transects surveyed per site were treated as replicates for each site. All

data were square-root transformed to meet ANOVA assumptions of normality and homogeneity of variance, and model residuals were evaluated with quantile-quantile plots.

Because NCRMP-leveraged urchin data were not collected for the Marianas, statistical analyses of urchin densities and erosion rates calculated using the three urchin methodologies were run separately for each region. For O‘ahu sites, densities of all bioeroding urchins, boring genera (*Echinometra* and *Echinostrephus*), and non-boring genera (*Echinothrix* and *Diadema*) did not meet parametric ANOVA assumptions and were therefore evaluated with Scheirer-Ray-Hare tests (nonparametric equivalents of two-way ANOVA tests; factors: method, site, and their interactions) with post hoc Dunn’s tests. Urchin erosion rates ($E_{urchin,j}$) for O‘ahu were evaluated with two-way ANOVA tests on square-root transformed data. Urchin densities (for all bioeroding urchins) and erosion rates for the Mariana Archipelago were evaluated with Scheirer-Ray-Hare tests. The six urchin transects surveyed per site were treated as replicates for each site.

To test the variance in the biomass and erosion rate data derived using the three fish methodologies, the impact of survey method, region, and site (nested within region) on the response variables of biomass ($B_{fish,j}$) and erosion rates ($E_{fish,j}$) was evaluated using nested ANOVA tests with post hoc Tukey HSD tests, as well as with Scheirer-Ray-Hare tests (factors: method, site, and their interactions) with post hoc Dunn’s tests. For erosion rates ($E_{fish,j}$), the foraging metrics used to calculate parrotfish erosion (IPRB, Kindinger et al.) were also considered as an additional explanatory variable in three-way nested ANOVA and Scheirer-Ray-Hare tests. Site-level biomass met ANOVA assumptions of normality and homogeneity of variance, which were evaluated with model residuals and quantile-quantile plots. Site-level erosion data did not meet parametric assumptions, even after transformations were applied; hence, nonparametric Scheirer-Ray-Hare tests were performed.

Net carbonate production rates (G_{net}) were evaluated across four data collection methodologies (Indo-Pacific ReefBudget, NCRMP-intermediate, NCRMP-leveraged, NCRMP-proposed), regions, and sites (nested within region) using three-way nested ANOVA tests on untransformed data. Interaction terms were dropped to avoid overfitting the model, as sample sizes were smaller due to the fact that net production is calculated at the site level rather than at the transect level.

Results

Coral cover, rugosity, and gross carbonate production rates

Hard coral cover varied significantly between survey methods, regions, and sites (Figure 4, Table 5). NCRMP-leveraged coral cover was lower by $3.8 \pm 1.5\%$ (\pm standard error) than cover estimated by IPRB (Tukey HSD; $p = 0.05$) and by $5.5 \pm 0.9\%$ compared to NCRMP-intermediate methods ($p < 0.001$). Rugosity varied significantly across methods, region, sites, and the interaction between sites and methods. NCRMP-leveraged rugosity values were higher than both in-water approaches by an average of 0.30 ± 0.04 ($p < 0.001$) across sites.

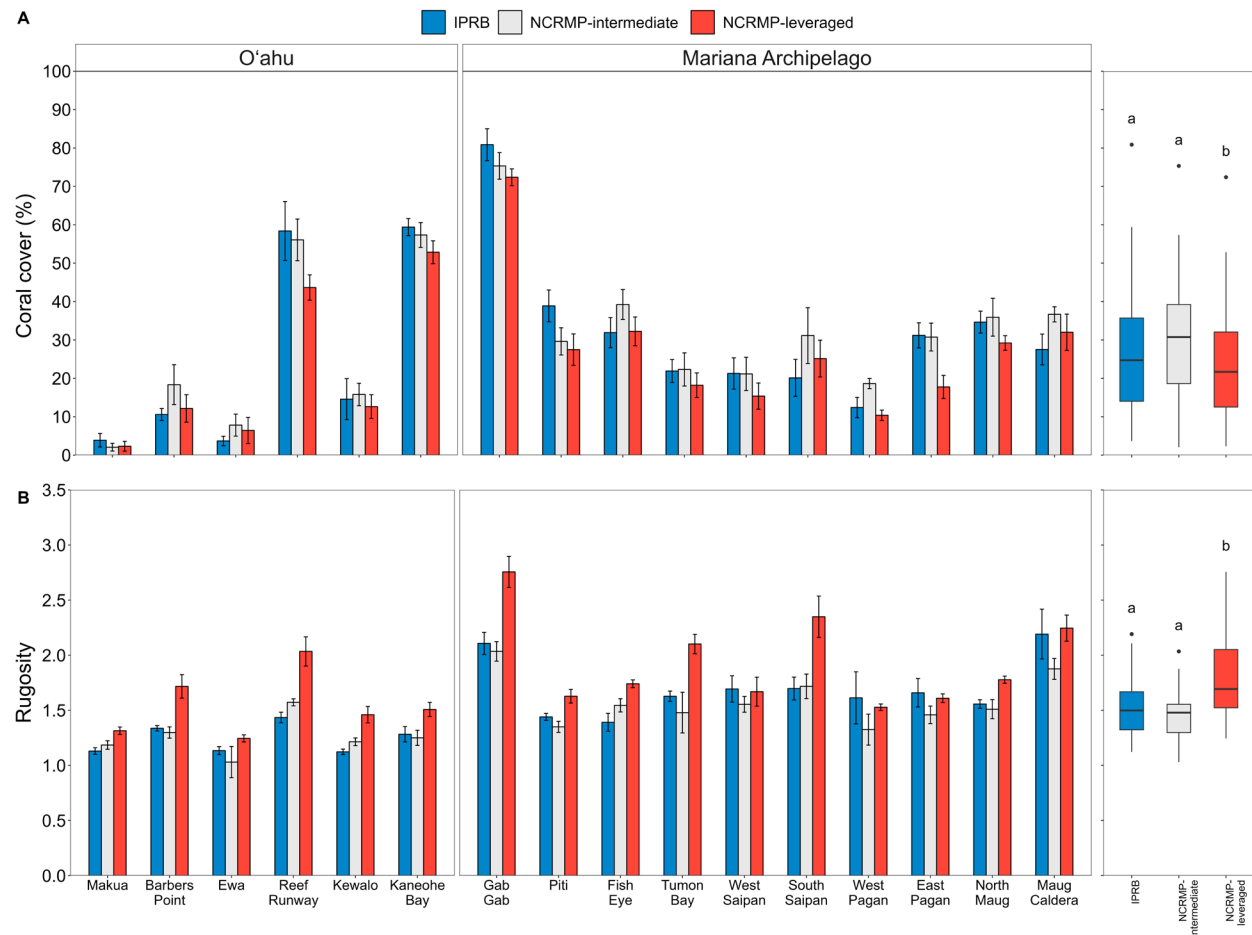


Figure 4. Comparison of mean \pm standard error (A) hard coral percent cover and (B) rugosity estimated at 16 sites across O'ahu and the Marianas using three benthic methodologies ($n = 6$ transects per site): Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, and NCRMP-leveraged. Boxplots show comparison of values generated by each method, and letters indicate significant differences between methods (from Tukey HSD tests).

Gross carbonate production rates did not differ across methods but varied significantly across regions, sites, and the interactions between region/site and method (Figure 5, Table 5).

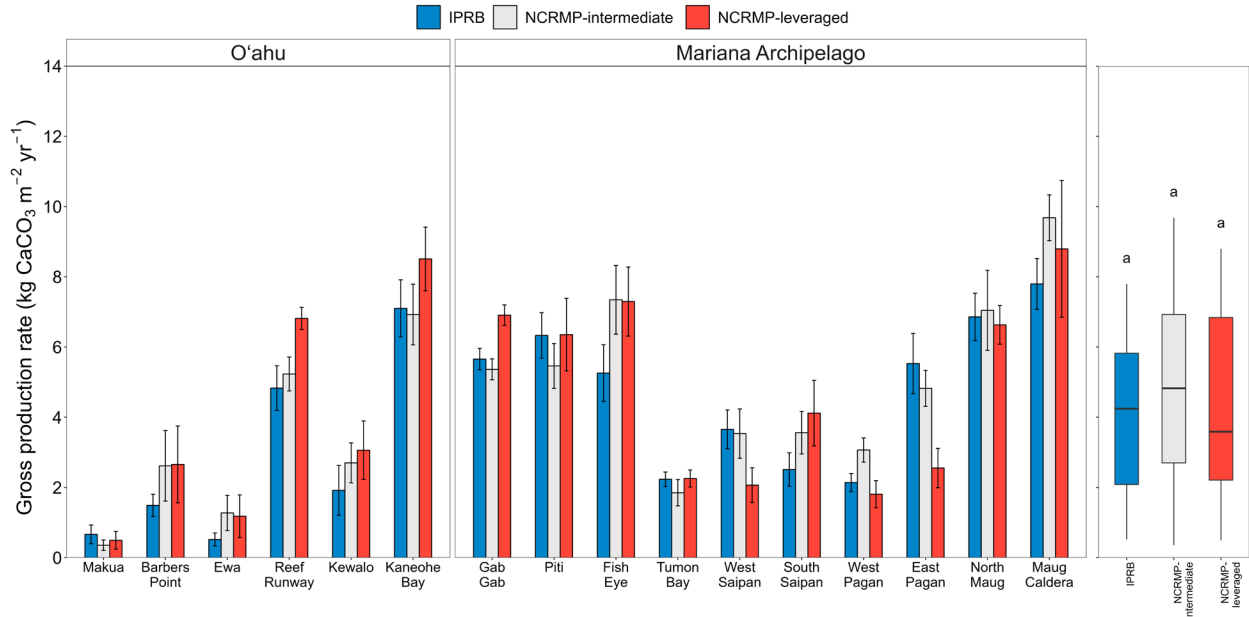


Figure 5. Comparison of mean \pm standard error gross production rates estimated at 16 sites across O‘ahu and the Mariana Archipelago using three benthic methodologies ($n = 6$ transects per site): Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, and NCRMP-leveraged. Boxplots show comparison of values generated by each method, and letters indicate significant differences between methods (from Tukey HSD tests).

Production rates generated using the NCRMP calcification rates databases were lower than those generated using the IPRB database by an average (\pm standard error) of $0.42 \pm 0.04 \text{ kg m}^{-2} \text{ yr}^{-1}$ (Tukey HSD; $p = 0.008$; Figure 6, Table 5).

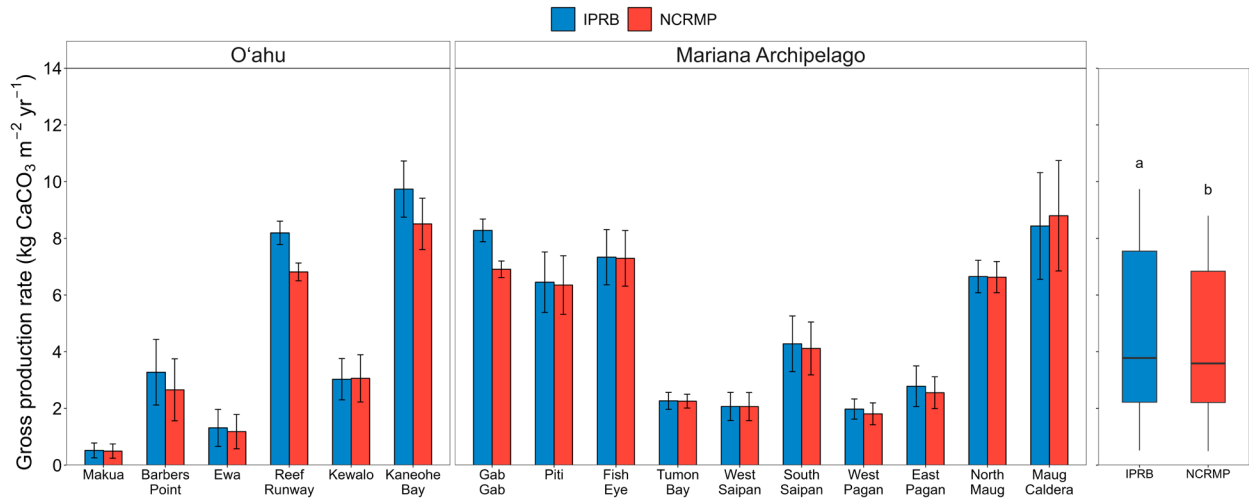


Figure 6. Comparison of mean \pm standard error gross production rates calculated at 16 sites across O‘ahu and the Mariana Archipelago ($n = 6$ transects per site) using the Indo-Pacific ReefBudget (IPRB) calcification database v1.3 and Pacific NCRMP database (NCRMP). NCRMP-leveraged benthic data are shown. Boxplots show comparison of gross production rates generated using each database, and letters indicate significant differences between databases (from Tukey HSD tests).

Macrobioerosion and microbioerosion

Macrobioerosion and microbioerosion rates varied by method, region, site within region, and the interaction between method and region (Figure 7, Table 5). For both bioerosion metrics, NCRMP-leveraged rates calculated were significantly higher than IPRB and NCRMP-intermediate measurements (Tukey HSD; $p < 0.001$). The average (\pm standard error) site-level difference between NCRMP-leveraged and IPRB/NCRMP-intermediate bioerosion rates was $0.07 \pm 0.01 \text{ kg m}^{-2} \text{ yr}^{-1}$ for macrobioerosion and $0.08 \pm 0.01 \text{ kg m}^{-2} \text{ yr}^{-1}$ for microbioerosion. There was no difference between the two in-water methods ($p > 0.50$).

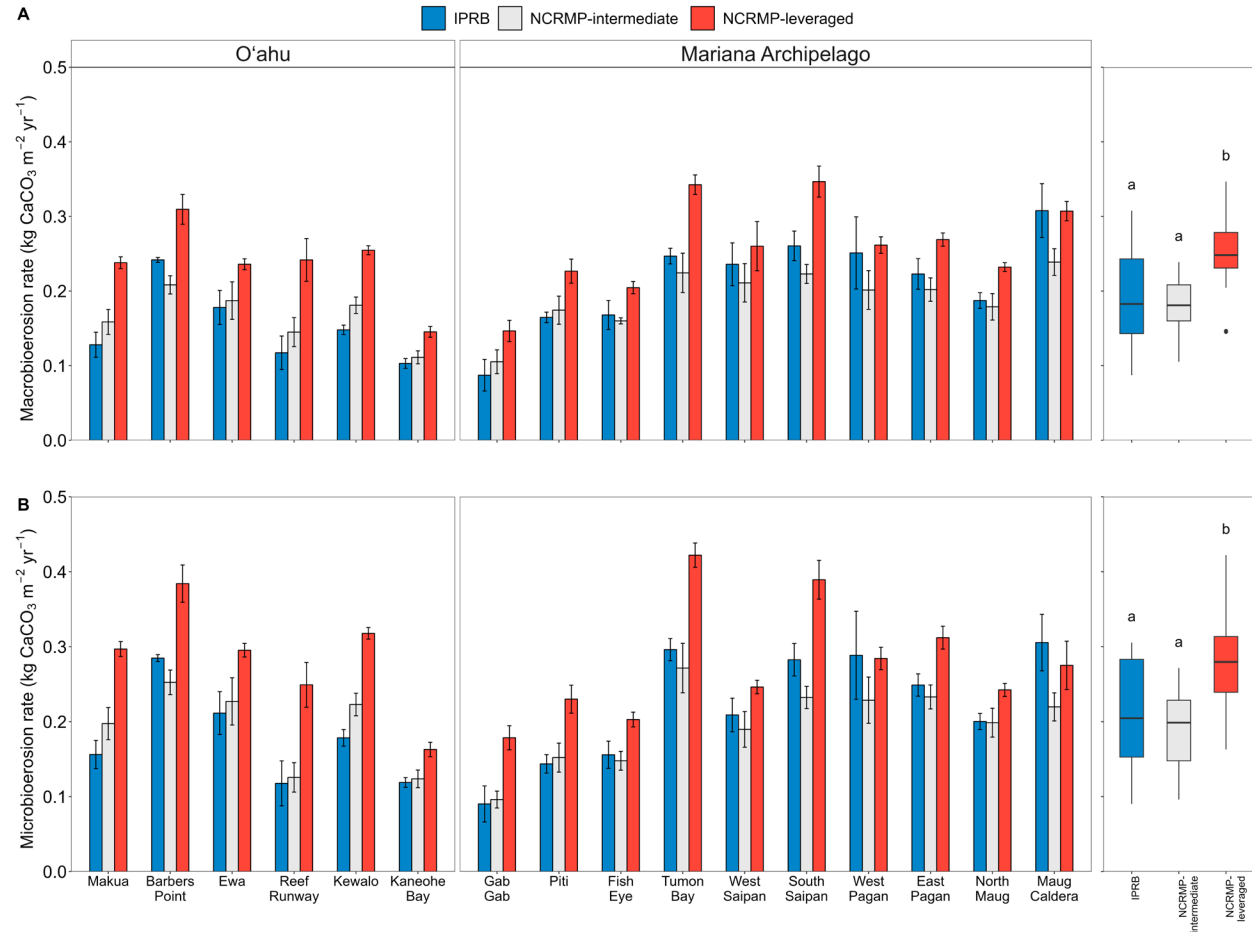


Figure 7. Comparison of mean \pm standard error (A) macrobioerosion and (B) microbioerosion rates estimated at 16 sites across O'ahu and the Mariana Archipelago using three benthic methodologies ($n = 6$ transects per site): Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, and NCRMP-leveraged. Boxplots show comparison of values generated by each method, and letters indicate significant differences between methods (from Tukey HSD tests).

Urchin density and erosion

Urchin densities varied significantly across O‘ahu sites but were not significant across methods (Figure 8, Table 5). Boring urchins (*Echinometra* spp. and *Echinostrephus* spp.) were the most abundant urchins observed, and densities observed in NCRMP-intermediate surveys were significantly higher than NCRMP-leveraged data (Dunn’s Test; $p = 0.009$). Non-boring urchin densities (mainly *Echinothrix* spp.) varied across sites but were similar across methods. In the Marianas where urchins were generally less abundant, urchin densities varied by site but not by method (Figure 8, Table 5).

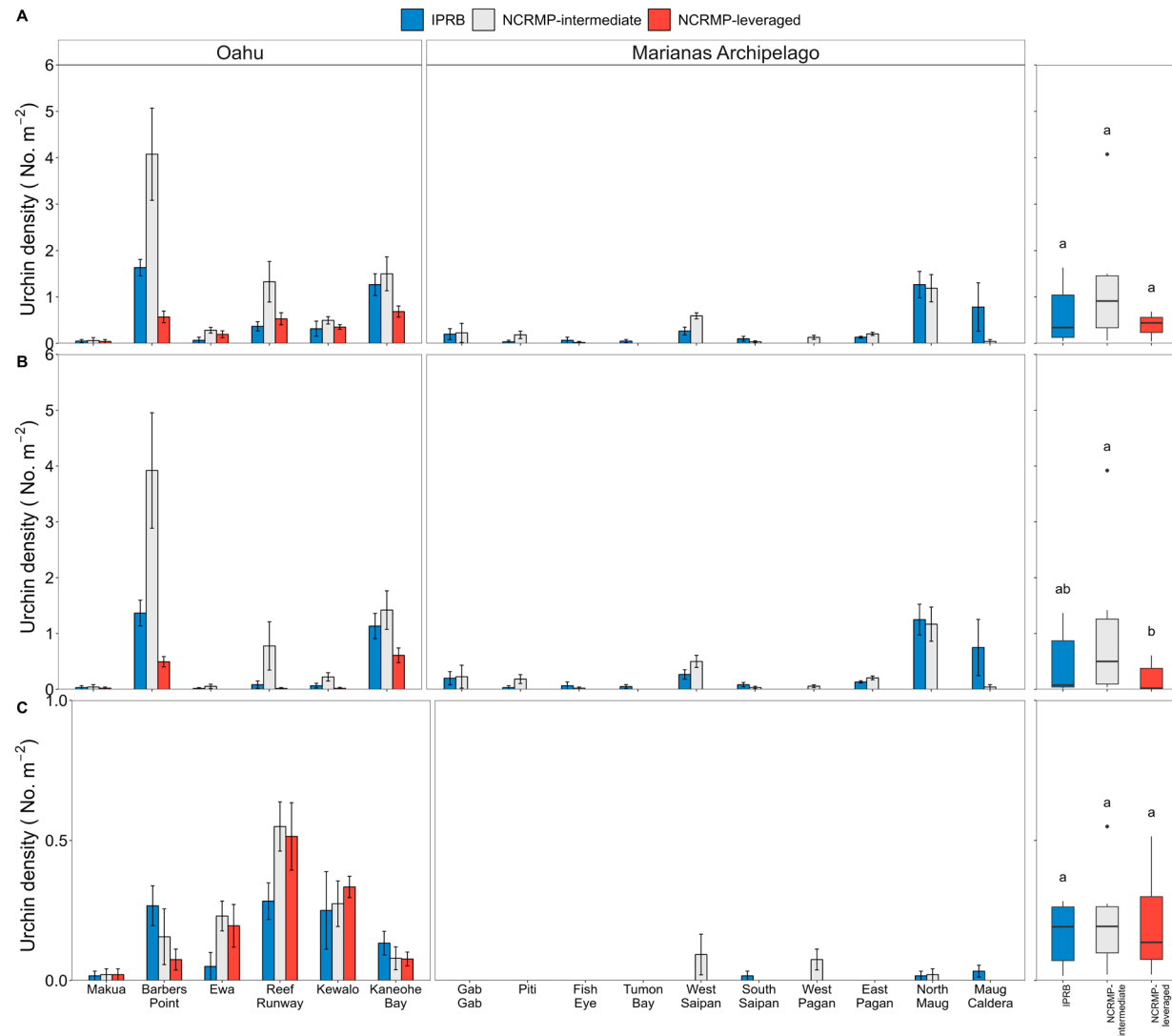


Figure 8. Comparison of mean \pm standard error urchin density for (A) all bioeroding urchins, (B) boring urchins and (C) non-boring urchins measured at 16 sites across Oahu and the Marianas Archipelago using three survey methodologies ($n = 6$ transects per site): Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, and NCRMP-leveraged (only). Boxplots show comparison of rates from each method (Oahu only), and letters indicate significant differences between methods (from Dunn’s tests).

Across O‘ahu sites, urchin erosion rates varied significantly by site, method, and their interactions (Figure 9, Table 5). Erosion rates calculated from NCRMP-intermediate surveys

were higher by an average (\pm standard error) of $0.32 \pm 0.21 \text{ kg m}^{-2} \text{ yr}^{-1}$ than rates calculated from IPRB (Tukey HSD; $p = 0.02$). There was no difference between NCRMP-leveraged data and both in-water methods ($p > 0.10$). In the Marianas, urchin erosion rates varied by site but not between the Indo-Pacific Reef-Budget and NCRMP-intermediate methods.

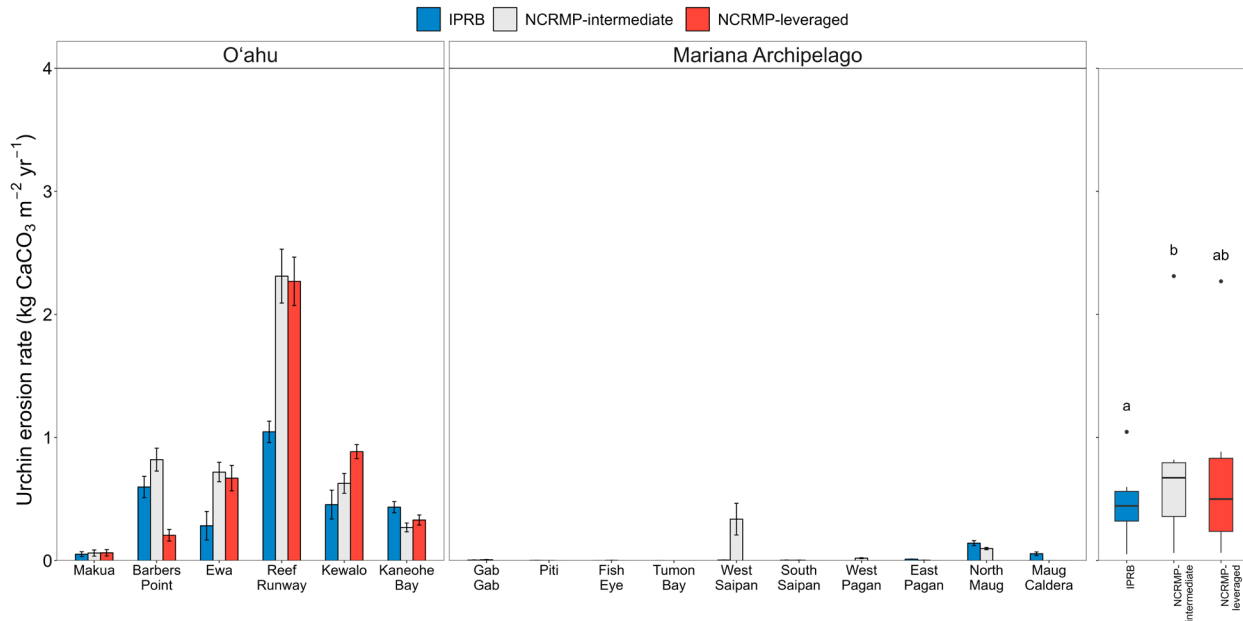


Figure 9. Comparison of mean \pm standard error urchin carbonate erosion rates estimated at 16 sites across O'ahu and the Mariana Archipelago. Urchin erosion rates were estimated using three methodologies ($n = 6$ transects per site): Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, and NCRMP-leveraged (O'ahu only). Boxplots show comparison of rates generated by each method (O'ahu only), and letters indicate significant differences between methods (from Tukey HSD tests).

Parrotfish biomass and erosion

Parrotfish biomass did not vary by method but did vary significantly between regions and sites (Figure 10, Table 5), where biomass estimates from O‘ahu were lower compared to estimates from the Mariana Archipelago (Tukey HSD; $p < 0.001$).

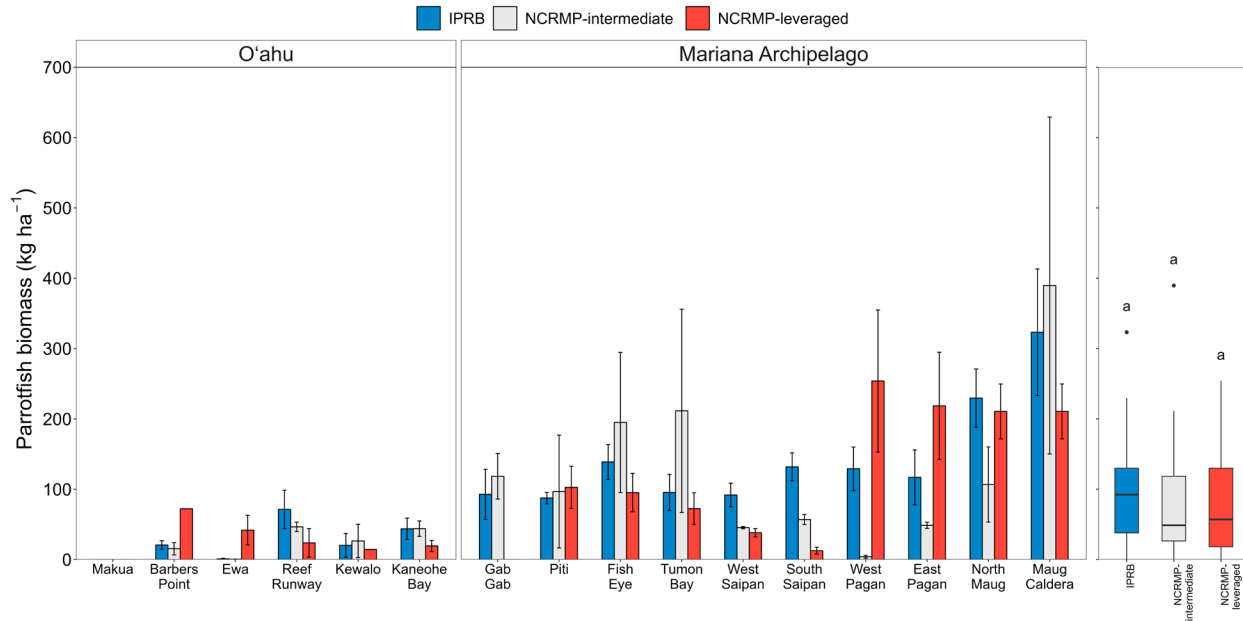


Figure 10. Comparison of mean \pm standard error parrotfish biomass estimated at 16 sites across O‘ahu and the Mariana Archipelago. Parrotfish biomass was estimated from data collected using three field survey methodologies: Indo-Pacific ReefBudget parrotfish belt surveys (IPRB), NCRMP-intermediate, and NCRMP-leveraged. Boxplots show comparison of rates generated from each method, and letters indicate significant differences between methods (from Tukey HSD tests).

Parrotfish erosion rates varied significantly across sites and databases for the Marianas, and only by site for O‘ahu sites (Figure 11, Table 5). Erosion rates estimated from parrotfish surveyed by method did not statistically differ ($p > 0.05$, Table 5). Erosion rates generated from foraging metrics calculated with the Kindinger et al. database were not statistically different from the IPRB database at O‘ahu sites. In contrast, erosion rates for Marianas sites generated from the Kindinger et al. database were lower than rates resulting from the IPRB database by an average (\pm standard error) of $1.82 \pm 0.62 \text{ kg m}^{-2} \text{ yr}^{-1}$ (Scheirer-Ray-Hare; $p < 0.001$; Figure 12, Table 5).

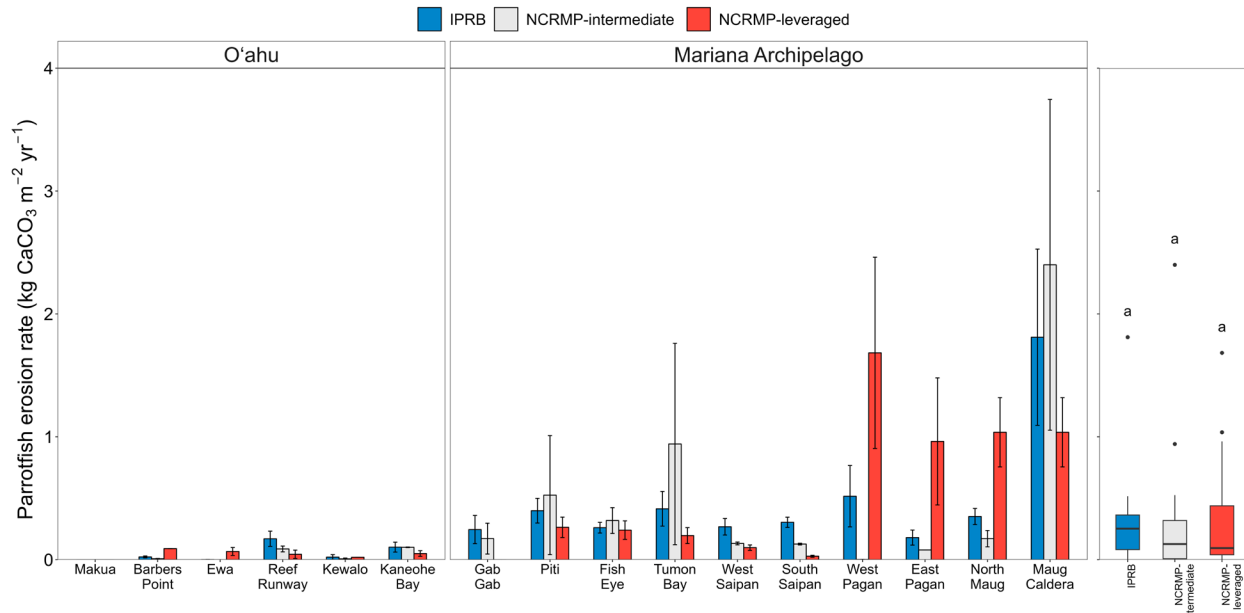


Figure 11. Comparison of mean \pm standard error parrotfish erosion rates estimated at 16 sites across O‘ahu and the Mariana Archipelago. Parrotfish erosion rates were estimated from data collected using three field survey methodologies: Indo-Pacific ReefBudget parrotfish belt surveys (IPRB), NCRMP-intermediate, and NCRMP-leveraged. Boxplots show comparison of rates generated from each method, and letters indicate significant differences between methods (from Tukey HSD tests).

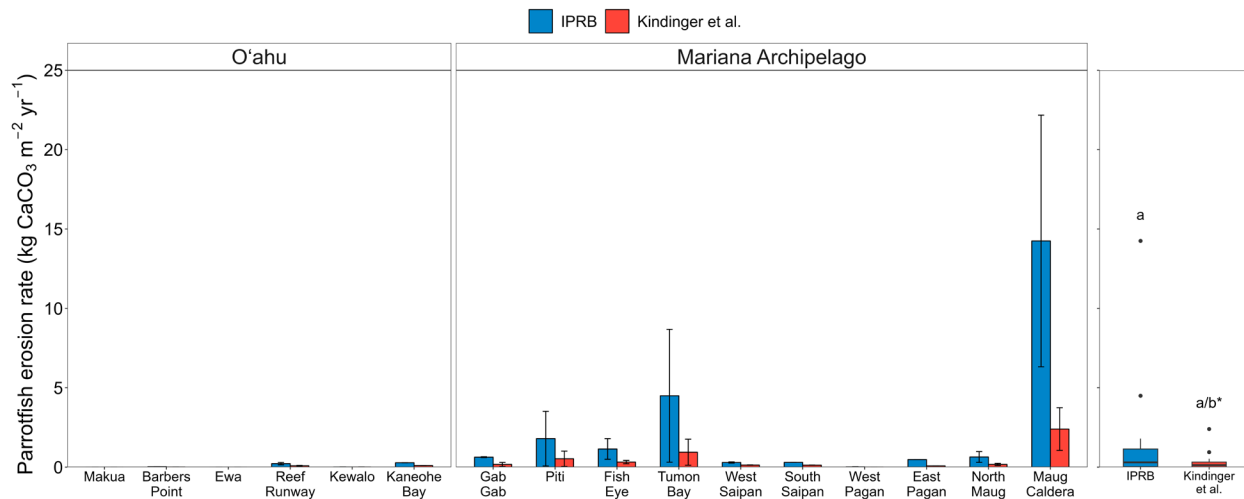


Figure 12. Comparison of mean \pm standard error parrotfish erosion rates calculated at 16 sites across O‘ahu and the Mariana Archipelago using the Indo-Pacific ReefBudget (IPRB) fish erosion rates database v1.4 and erosion rates calculated from Kindinger et al. (in review) foraging parameters. Parrotfish data shown were collected using fixed SPC surveys. Boxplots show comparison of rates generated using each database. Letters indicate significant differences between methods (from Tukey HSD tests); a/b* indicates that erosion rates from Marianas sites differed significantly by databases, while there were no differences between databases for O‘ahu sites.

Net carbonate production

Net carbonate production rates varied by region and site but did not differ based on the field data collection methodologies used (Figure 13, Table 5). Net carbonate production rates calculated

using the NCRMP-proposed methodology did not significantly differ from estimates generated using IPRB surveys (Tukey HSD; $p = 0.62$), the NCRMP-intermediate methods ($p = 0.98$), and the NCRMP-leveraged techniques ($p = 0.88$).

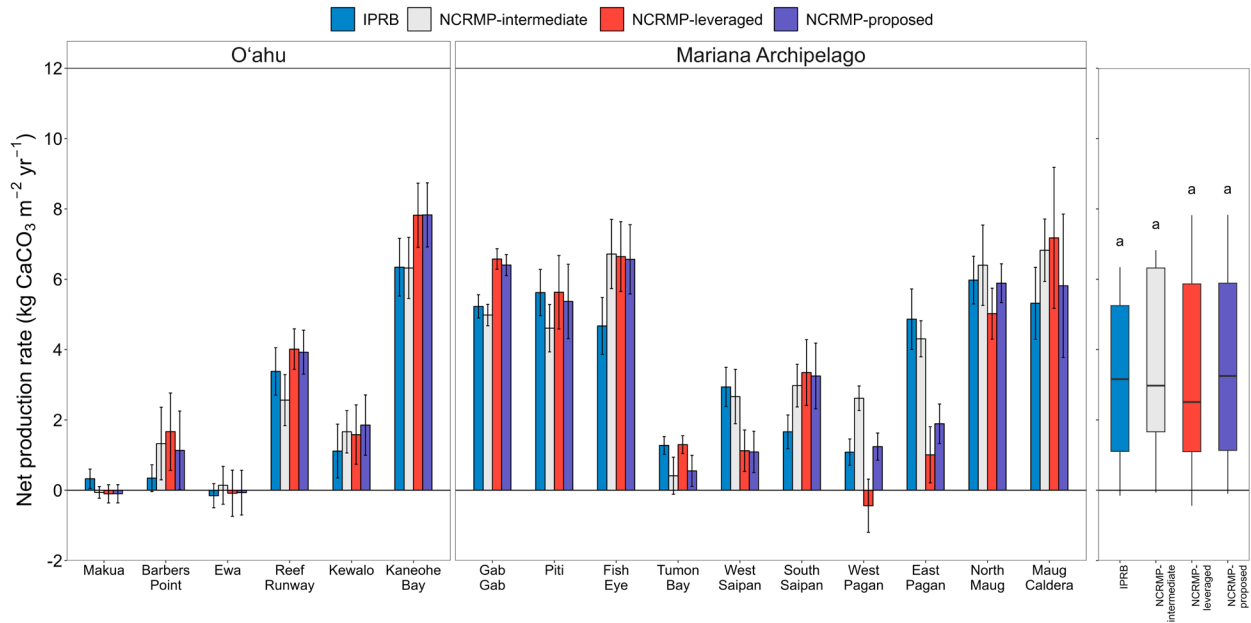


Figure 13. Comparison of mean \pm standard deviation net carbonate production rates estimated at 16 sites across O'ahu and the Mariana Archipelago using four methodologies: Indo-Pacific ReefBudget (IPRB), NCRMP-intermediate, NCRMP-leveraged, and NCRMP-proposed. Boxplots show comparison of net production rates generated by each method, and letters indicate significant differences between methods (from Tukey HSD tests).

Table 5. Summary of statistical test results for all parameters. F values are reported for ANOVA tests and H values are reported for Scheirer-Ray-Hare tests.

Parameter	Test	Variable	df	Test Statistic (F or H)	p-value
Hard coral cover	Three-way ANOVA	Method	2	7.85	<0.001
		Region	1	93.03	<0.001
		Site (within region)	14	66.04	<0.001
		Method × Region	2	0.10	0.90
		Method × Site (within Region)	28	0.80	0.76
Rugosity	Three-way ANOVA	Method	2	50.88	<0.001
		Region	1	179.95	<0.001
		Site (within region)	14	19.76	<0.001
		Method × Region	2	1.67	0.19
		Method × Site (within Region)	28	1.97	0.004
Gross carbonate production rate	Four-way ANOVA	Method	2	2.21	0.11
		Region	1	192.90	<0.001
		Site (within region)	14	86.005	<0.001
		Method × Region	2	4.50	0.01
		Method × Site (within Region)	28	2.64	<0.001
Macrobioerosion rate	Three-way ANOVA	Database	1	7.08	0.008
		Method	2	63.97	<0.001
		Region	1	41.18	<0.001
		Site (within region)	14	22.45	<0.001
		Method × Region	2	5.22	0.006
Microbioerosion rate	Three-way ANOVA	Method × Site (within Region)	28	0.98	0.49
		Method	2	74.12	<0.001
		Region	1	5.29	0.02
		Site (within region)	14	27.40	<0.001
		Method × Region	2	5.42	0.005
Urchin density (O'ahu)	Scheirer-Ray-Hare	Method × Site (within Region)	28	1.32	0.13
		Method	2	5.70	0.06
		Site	5	62.54	<0.001
Boring urchin density (O'ahu)	Scheirer-Ray-Hare	Method × Site	10	9.27	0.51
		Method	2	8.82	0.01
		Site	5	72.97	<0.001
Non-boring urchin density (O'ahu)	Scheirer-Ray-Hare	Method × Site	10	4.34	0.93
		Method	2	1.32	0.52
		Site	5	46.17	<0.001
Urchin density (Marianas)	Scheirer-Ray-Hare	Method × Site	10	12.41	0.26
		Method (no NCRMP-leveraged)	1	0.57	0.45
		Site	9	58.91	<0.001
Urchin erosion rate (O'ahu)	Two-way ANOVA	Method × Site	9	10.90	0.28
		Method	2	3.81	0.03
		Site	5	22.09	<0.001

		Method × Site	10	2.12	0.03
Urchin erosion rate (Marianas)	Scheirer- Ray-Hare	Method (no NCRMP-leveraged)	1	0.41	0.52
		Site	9	58.71	<0.001
		Method × Site	9	11.89	0.22
Parrotfish biomass	Two-way ANOVA	Method	2	0.39	0.68
		Region	1	43.85	<0.001
		Site (within region)	14	2.46	0.02
Parrotfish erosion rates (O‘ahu)	Scheirer- Ray-Hare	Method	2	1.93	0.38
		Database	1	0.80	0.37
		Site	5	22.81	<0.001
		Method × Site	10	7.65	0.66
		Database × Site	5	0.54	0.99
Parrotfish erosion rates (Marianas)	Scheirer- Ray-Hare	Method	2	0.22	0.90
		Database	1	9.86	0.002
		Site	9	25.96	0.002
		Method × Site	18	21.19	0.27
		Database × Site	9	1.69	0.99
Net carbonate production	Three-way ANOVA	Method	3	1.03	0.39
		Region	1	71.62	<0.001
		Site (within region)	14	32.75	<0.001

Discussion

Benthic carbonate production

Our NCRMP-leveraged approach for extracting benthic data from fixed-site SfM imagery generated gross carbonate production data that were within error of both traditional Indo-Pacific ReefBudget and our NCRMP-intermediate methodology. All three methodologies detected significant differences in rates across sites, demonstrating that our approach is sensitive enough to resolve site-level differences in benthic production. While we observed small site-level variability in production rates between the three methodologies tested, there was no systematic bias in SfM-derived rates across all sites despite the differences in survey area and in-water vs. virtual data collection techniques. Notably, however, these surveys did not include sites with abundant table *Acropora*, branching *Acropora* thickets, or walls of plating/foliose colonies, all of which may particularly challenge the accuracy of virtual transect annotation in SfM. Targeted methods comparison of these specific cases is the main priority for our final year of pilot surveys in the Pacific Remote Islands and American Samoa, and annotation protocols will be revised as needed to improve carbonate production estimates for these genera and morphologies.

While carbonate production rates did not vary significantly across approaches, NCRMP-leveraged data did introduce unidirectional, but opposing bias in live hard coral cover and rugosity measurements. NCRMP-leveraged techniques underestimated coral cover (by ~4 %) and overestimated rugosity (by ~0.3) relative to both in-water methods. Lower coral cover estimates in NCRMP-leveraged data are likely due to (1) unintentional diver bias in measuring live coral over abiotic substrate in-water, particularly in high surge or high current environments where the transect tape may move or sway and (2) difficulty resolving cryptic species in crevices, under ledges, or in shadows in imagery, especially at very structurally complex sites. Conversely, higher rugosity estimates are likely due to (1) finer resolution in NCRMP-leveraged data (1 mm resolution) relative to NCRMP-intermediate data (1 cm resolution) and (2) the ability of SfM to capture rugosity in three-dimensional structures, cracks, and crevices that are difficult for divers to access. Deviations in rugosity between methods were also particularly high at sites with high cover of branching coral morphologies such as *Porites rus* (Gab Gab, Tumon Bay, South Saipan) and *Pocillopora* spp. (Barbers Point, Reef Runway), which can be challenging to measure in-water. Ultimately, however, these biases are relatively small and appear to largely cancel out in the calculations of gross carbonate production.

Our customized NCRMP calcification rates database – which restricts the spatial domain of studies used to estimate calcification rates and calculates mean rates at NCRMP benthic taxonomic levels – produced carbonate production rates that were slightly lower than those calculated using the IPRB database. This is largely because many of the published studies included in the NCRMP database are from higher latitude, slower growing Hawaiian reefs, and calcification rates are lower for many U.S. Pacific Islands species relative to the broader Indo-Pacific (e.g., for branching *Pocillopora*, the NCRMP database calcification rate is $2.79 \text{ g cm}^{-2} \text{ yr}^{-1}$, while the IPRB database rate is $3.67 \text{ g cm}^{-2} \text{ yr}^{-1}$). While the impact of these differences in calcification rates may be relatively minor when calculating carbonate production at most sites, the cumulative effect may also be significant at sites where the genera/species with growth rates that differ across databases are particularly abundant (e.g., high *Pocillopora* cover at Reef Runway). Moreover, our new hybrid growth model for laminar columnar coral morphologies

estimates lower colony-level production for these colonies than the IPRB methodology (which assumes that all growth is columnar), resulting in lower production rate estimates for sites with high *Porites rus* cover (e.g., Gab Gab). A notable limitation for both databases is that calcification rates of all non-coral, non-CCA benthic components – including *Peyssonnelia* and *Halimeda* – are assumed to be zero. Because these calcifying algae contribute to reef framework growth (Basso 2012; Castro-Sanguino et al. 2020), it is possible that their exclusion underestimates production at sites where these taxa are prevalent. Ultimately, the accuracy of this census-based approach is also inherently limited by the accuracy of the database used; future methods improvements will explore approaches for estimating taxon-specific calcification rates at the region, island, or even site-level (e.g., by using growth rates derived from repeated SfM imagery) and expanding the number of calcifying algae taxa included in the database.

Overall, our methods comparison results offer a high level of confidence in NCRMP-leveraged benthic carbonate production data derived using SfM imagery and our NCRMP calcification rates database. Despite the differences in data collection and data processing protocols, our NCRMP-leveraged approach generates carbonate production rate estimates that are comparable to data derived using standard IPRB methodology. Critically, these data can be generated from data already collected as part of NCRMP missions and require no additional field effort. While data extraction from SfM does require significantly more annotation and processing time post-mission (~8-16 annotation and data processing person-hours per site) than do field surveys (no post-mission annotation time required), this trade-off remains preferable given that days at sea are the current limiting factor for Pacific NCRMP data collection and benthic field surveys require substantial additional dive effort (~8-12 additional person-hours per site).

Macrobioerosion and microbioerosion

Compared to in-water estimates, our NCRMP-leveraged macrobioerosion and microbioerosion rates derived from SfM imagery were consistently higher across all survey sites. These bioerosion metrics are directly derived from transect-level cover of available erodible substrate and rugosity, both of which skew higher in NCRMP-leveraged data sets. Available erodible substrate—which encompasses all non-coral carbonate substrate for macrobioerosion and all non-calcifier substrate for microbioerosion—is also elevated in NCRMP-leveraged data sets, where estimated coral cover tends to be lower. Rugosity values likely increase when estimated using SfM due to finer measurement scales in structurally complex environments. While the synergistic effect of higher rugosity and higher available substrate for erosion drives increased macrobioerosion and microbioerosion rates in NCRMP-leveraged data, the difference in rates calculated using the three methodologies (~0.07-0.08 kg m⁻² yr⁻¹) and the magnitude of these erosion rates (< 0.4 kg m⁻² yr⁻¹) compared to the other carbonate producers and eroders is relatively small. Because of this, and because macrobioerosion and microbioerosion rates are calculated from, and therefore paired with, benthic data, we believe our NCRMP-leveraged methodology offers the best approach for estimating these rates.

As a general caveat for interpretation of these data, it is important to note that all ReefBudget-style approaches utilize mean estimated rates of macrobioerosion and microbioerosion from published studies in the Indo-Pacific region. Unlike the other taxa assessed in carbonate budget surveys, the size and abundance of macrobioeroders and microbioeroders are not directly enumerated; these taxa are assumed to erode carbonate substrate at the same overall rate across

all reef sites. This assumption may be particularly problematic in the U.S. Pacific Islands since bioerosion rates are known to vary along the oceanographic and environmental gradients present (DeCarlo et al. 2015). As with our benthic carbonate production rates, desired future improvements to our erosion rate estimates include directly measuring the size and frequency of these eroding organisms, as well as measuring and incorporating site-specific rates into our erosion calculations.

Urchin erosion

Our NCRMP-leveraged urchin survey approach generated urchin erosion rates that were comparable to IPRB-derived data despite differences in urchin densities estimated from the three methods. At O‘ahu sites, urchin densities varied slightly across the three survey methods tested, largely due to greater boring urchin abundances from NCRMP-intermediate surveys at several sites (Barbers Point, Reef Runway). At these sites, survey footprint appeared to inversely impact the number of urchins observed: the smaller NCRMP-intermediate/NCRMP-leveraged footprints (which tend to be on areas of aggregate reef) concentrated urchin density relative to the larger, more variable reef benthic area surveyed by IPRB methods (which can include spur and groove habitats, sand patches, etc.). Furthermore, resolving small boring urchins hidden in recessed bore holes or under overhangs can be exceptionally difficult, if not impossible, in SfM imagery, thus resulting in much lower observed abundances of these taxa in NCRMP-leveraged data compared to in-water surveys. In the Marianas where urchins were generally less abundant across our sites, these methodological differences were less pronounced. In general, day-time urchin surveys likely underestimate urchin populations due to the fact that many urchins are nocturnal (Young and Bellwood 2011). While this could mean that our methods under-represent true site-level urchin abundances, this is a shared limitation across all carbonate budget assessments since night-time dive survey operations are not usually feasible.

Despite these differences in observed urchin densities, calculated erosion rates were similar across methods. Because the relationship between carbonate erosion and urchin test size is exponential, large non-boring urchins (like *Echinothrix* spp., which NCRMP-leveraged data can generally capture well) influence carbonate erosion rates much more than small boring urchins (like *Echinometra* spp., which NCRMP-leveraged methods tends to under-represent), ultimately minimizing the overall impact of divergent boring urchin densities across methods. Furthermore, all three methodologies were also able to detect significant differences in urchin erosion rates across sites, suggesting that any variability introduced from methodological bias is still less than the variability in site-level urchin carbonate erosion rates.

Even though NCRMP-leveraged data urchin erosion rates are comparable to those estimated from IPRB and NCRMP-intermediate methods, in-water urchin surveys are still generally preferred because (1) divers can spot cryptic boring urchins much more reliably than identifying them in SfM imagery, (2) in-water surveys can be conducted fairly efficiently (usually by a single diver within a single 30-minute dive), and (3) until automated annotation and machine learning tools become available, SfM urchin annotation remains very time-consuming. However, extracting urchin data from SfM imagery may remain a viable option for calculating erosion rates at sites where urchin densities are low if there is insufficient time to conduct in-water surveys and/or if urchin survey data are not available for historical sample periods.

Fish erosion

The objective of this study was to determine: (1) whether NCRMP-intermediate SPC surveys could produce reasonably comparable parrotfish biomass and erosion rate estimates compared to IPRB belt surveys, and (2) if the NCRMP-intermediate SPC approach could resolve site-level differences in parrotfish biomass and erosion rates. We found that NCRMP-intermediate and NCRMP-leveraged SPC surveys, both from a single survey at a fixed site and pooled surveys across stratified random sites, resulted in parrotfish biomass values that were comparable to belt surveys used by the IPRB approach. The lack of a significant methodological bias was at least partly due to the large variance among NCRMP-leveraged SPC surveys ($n = 1-40$), or lack thereof (e.g., Makua, Barbers Point, Kewalo). Despite this, there was still clear variability in mean biomass among methods at certain sites (e.g., Ewa, West Pagan, East Pagan, West Saipan). Statistically significant variability in mean biomass between regions may be attributed to several factors including (but not limited to) habitat availability for shelter and foraging (Carlson et al. 2017; Davis et al. 2017), oceanographic conditions, and human population (Williams et al. 2015). In order to attain a Pacific-wide perspective, continued sampling of parrotfish communities in areas with higher abundance and species diversity, such as the Pacific Remote Island Areas and American Samoa, will further allow us to test for differences in estimates of biomass and erosion based on method and database. Furthermore, while our results cannot be used to establish a definitive belt vs. SPC calibration (which is beyond the scope of this study), we were able to successfully generate statistically comparable parrotfish biomass estimates from both types of surveys.

Similar to mean biomass, estimates of erosion rates were statistically comparable among methodologies. Expectedly, mean biomass estimates showed a generally similar pattern in comparison to mean erosion estimates. In contrast, observed differences in parrotfish erosion estimates at both region and site level suggest high (or low) parrotfish biomass is not necessarily an indicator of high (or low) erosion estimates, as once integrated with species-specific foraging, erosion estimates may influence the outcome at the site-level (e.g., Piti, North Maug). Though not significant amongst methodologies, IPRB belt surveys generally produced higher mean erosion rates compared to NCRMP-intermediate fixed SPC and NCRMP-leveraged stratified random SPC surveys. This may be due to variation in methods of data collection between belt and SPC surveys. In addition, we recognize that the means and errors calculated from the NCRMP-leveraged stratified random SPC survey methodology are unweighted despite unequal probabilities of sampling a given site according to the underlying stratification scheme (i.e., sites are not true random).

We are selecting NCRMP-intermediate fixed SPC as the preferred NCRMP survey method for estimating parrotfish erosion for future Pacific-wide surveys because: (1) the method produced intermediate erosion estimates compared to IPRB and NCRMP-leveraged methods, (2) SPC surveys are currently used to conduct NCRMP fish assessments and will require minimal adjustments to a presently task-loaded program, and (3) conducting an SPC at the fixed site ensures parrotfish data are directly collected in conjunction with the benthic components. NCRMP-leveraged stratified random SPC surveys from ongoing NCRMP effort still offer an option for estimating fish biomass and may allow reconstruction of fish erosion estimates from historical NCRMP data (where fixed SPC data do not exist). However, this will require a thoughtful and more in-depth approach to address how to weight data summaries according to

the stratified survey design and how to strategize for the lack of SPC surveys directly near the fixed sites for historical reconstruction through time.

Erosion rate estimates in the Mariana Islands were also highly dependent on the database used to calculate individual foraging metrics. Mean erosion rates derived from Kindinger et al. were statistically lower than the rates derived from the IPRB database ($p < 0.05$; Figure 12, Table 5). Most of this variation stems from differences in estimated bite volumes for 80% of the larger-sized individuals of parrotfish species observed (e.g., 40–50 cm TL parrotfish at Maug Caldera and Tumon Bay), whereby IPRB resulted in bite volumes that were up to 0.01 order of magnitude larger. Thus, the Kindinger et al. database will continue to be used in the future because: (1) the foraging metric values were slightly more conservative than the IPRB metrics, (2) for each foraging metric, there is only one equation per species and these metrics are easily calculated across a range of fish sizes, (3) the regions we survey vary in sea surface temperature (26–30 °C); therefore, the influence of sea surface temperature on bite rates (bites min^{-1}) are accounted for among some species, and (4) the formulas are specific to Pacific Island species.

Net carbonate production

Across all survey sites, net carbonate production rates did not significantly differ between methodologies. In addition, net carbonate production rates generated using the NCRMP-proposed method—NCRMP-leveraged benthic data derived from SfM, NCRMP-intermediate in-water urchin data, and NCRMP-intermediate fish data from fixed SPC surveys—were also within error of all of the other methodologies tested. Critically, all methodologies were sensitive enough to distinguish significant differences in net production rates across regions and sites. While there was no systematic methodological bias in net production rates, we did observe small differences between methods at some sites. This variability tracks that of the benthic, urchin, and fish input data used to calculate net production rates, and largely reflects differences in site-level gross carbonate production estimates.

Pacific NCRMP carbonate budget assessment methodology

Based on the results of our methods comparison and evaluation of the efficiency of the field survey techniques tested, we propose following approach for conducting carbonate budget assessments as part of Pacific NCRMP starting in FY24 (Figure 14):

- *Benthic data*: benthic data will be derived from NCRMP-leveraged, fixed-site Structure-from-Motion models. SfM imagery will be collected and processed at fixed sites following standard vital rates (Rodriguez et al. 2021) and NCRMP (Torres-Pulliza et al. in review) protocols and annotated for carbonate budgets following the standard operating procedures presented in Appendices A and B. Carbonate production rates will be calculated using the NCRMP calcification rates database.
- *Urchin data*: urchin data will be collected using in-water belt transect surveys. Due to the time-intensive nature of laying out seven transect tapes (required as part of the NCRMP-intermediate survey design tested during the pilot), we plan to adopt an altered, more efficient transect design shown in Figure 14.
- *Fish data*: fish data will be collected using NCRMP-intermediate fixed site SPC surveys following NCRMP methodology described in Ayotte et al. (2015) and Heenan et al. (2017). Species-specific parrotfish erosion rates will be calculated using Kindinger et al. foraging parameters.

Based on the results of our methods comparison, our Pacific NCRMP carbonate budget approach can generate net carbonate production estimates that are comparable to, and within error of, data generated using the traditional IPRB approach while vastly improving the efficiency and integration of data collection with Pacific NCRMP survey design (Table 6). Our methodology leverages fixed-site SfM imagery already collected as part of Pacific NCRMP to generate benthic data; it minimizes additional field effort by integrating urchin and fish data collection into existing NCRMP survey design. While we have selected NCRMP-intermediate methodologies for urchin and fish surveys to maximize both the accuracy and efficiency of our data collection, our NCRMP-leveraged methodologies still present viable options for generating carbonate erosion data (especially for reconstructing past carbonate budgets from historical NCRMP data where in-water, fixed-site data may not exist). Critically, these methodologies now enable us to monitor coral reef carbonate production and erosion rates across the U.S. Pacific Islands region as part of Pacific NCRMP and track changes in coral reef carbonate budget states and ecosystem function under a rapidly changing climate.

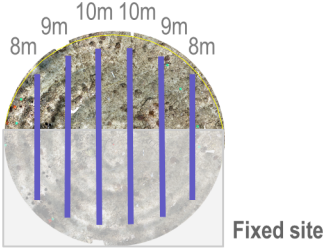

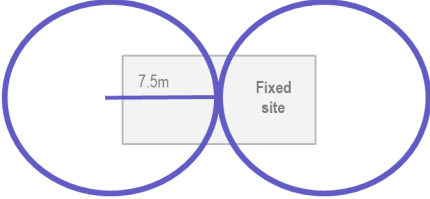
Methods Overview	Methods Schematic
<p><i>Benthic data collection</i></p> <p>Virtual benthic surveys conducted using 12 m diameter SfM models.</p> <p><i>Survey design:</i> 6 × 8–10 m transects</p> <p><i>Total linear distance surveyed:</i> 54 m</p>	
<p><i>Urchin data collection</i></p> <p>In-water urchin belt transects within and inshore of fixed site footprint.</p> <p><i>Survey design:</i> 6 × 1 m × 10 m transects</p> <p><i>Total area surveyed:</i> 60 m²</p>	
<p><i>Fish data collection</i></p> <p>NCRMP stationary point count surveys centered on fixed sites.</p> <p><i>Survey design:</i> 2 × 7.5 m radius cylinders</p> <p><i>Total area surveyed:</i> 354 m²</p>	

Figure 14. Overview of survey methods and schematic of survey designs proposed for NCRMP carbonate budget assessments. “Fixed site” designates the 10 m × 5 m benthic box at each mid-depth NCRMP permanent site (Figure 1). Methods schematics are not drawn to scale.

Table 6. Summary of estimated field time (in addition to existing NCRMP surveys), annotation time, and other requirements for each of the carbonate budgets methodologies tested. Time estimates for data collection vary based on the complexity and species diversity at each site. Limiting factor refers to the aspect of data collection that constrains the number of possible carbonate budget assessments per site year SfM=structure from motion, SPC=stationary point count.

	Indo-Pacific Reef Budget methodology	NCRMP-intermediate methodology	NCRMP-leveraged methodology	NCRMP-proposed methodology
Benthic data				
Data collection method	In-water transects	In-water transects	SfM virtual transects	SfM virtual transects
Number of additional dives and time required for field data collection (per site)	1-2 dives 6-10 person-hours	1-2 dives 6-10 person-hours	None	None
Time required for annotation (per site)	None	None	8-16 person-hours	8-16 person-hours
Urchin data				
Urchin data collection method	In-water belt transects	In-water belt transects	SfM virtual belt transects	In-water belt transects
Number of additional dives and time required for field data collection (per site)	1 dive 0.5 person-hours	1 dive 0.5 person-hours	None	1 dive 0.5 person-hours
Time required for annotation (per site)	None	None	8-16 person-hours	None
Fish data				
Fish data collection method	Belt transects	Fixed-site SPC surveys	Stratified random SPC surveys	Fixed-site SPC surveys
Number of additional dives and time required for field data collection (per site)	1 dive 1-2 person hours	1 dive 1-2 person hours	None	1 dive 1-2 person hours
Additional considerations				
Staff required (in addition to routine NCRMP)	4-5 benthic/urchin divers 2 fish divers	4-5 benthic/urchin divers 2 fish divers	1-3 benthic annotators	1-2 benthic annotators 1-2 urchin divers 2 fish divers
Maximum number of sites per year	10 sites/year	10 sites/year	20 sites/year	20 sites/year
Number of additional days at sea (DAS) required (per site)	1 DAS	1 DAS	None	0.25 DAS
Limiting factor	Field time	Field time	SfM annotation time	SfM annotation time

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Data and Code Availability

The data included in this study are archived at NOAA's National Centers for Environmental Information (<https://www.ncei.noaa.gov/>) under accession numbers 0283630 and 0283896. The R package *reefbudgetR* and supporting carbonate production and erosion rates databases used to process field data are available at <https://github.com/hannahbarkley/reefbudgetR>.

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Appendix A: Standard operating procedure for extracting benthic carbonate budgets parameters from Structure-from-Motion imagery

Created by Damaris Torres-Pulliza and Ariel Halperin

This standard operating procedure describes steps in ArcGIS Pro 2.8.0 for extracting benthic carbonate budgets data from image maps generated using Structure-from-Motion (SfM) techniques. The SfM-derived image maps consist of a Digital Elevation Model (DEM) used to estimate sub-centimeter surface distance of benthic components, and an orthomosaic used to visually characterize and annotate the benthos type (Figure 15). The combined surface cover data of individual benthic components can be analyzed using the ReefBudget framework (Perry et al. 2018) to examine how different benthic components produce or erode reef carbonate substrate.

The procedure described below outlines annotation protocols for SfM imagery generated as part of the FY21-23 carbonate budgets pilot, where yellow dive weights were captured in SfM models to mark the locations of in-water transects and facilitate the direct comparison of in-water versus SfM-derived benthic data (see methods section for full description of methodologies tested). This procedure can also be used to collect carbonate budgets benthic data from SfM imagery alone, where a digital shapefile of desired benthic transects is provided in lieu of the shapefiles derived from marked chord transects described below.

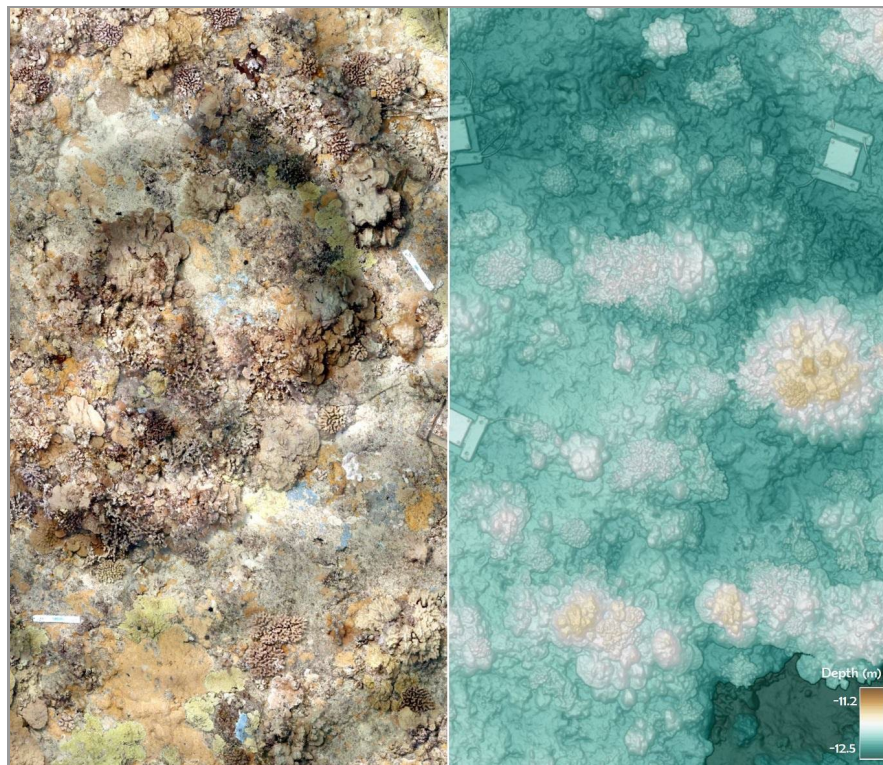


Figure 15. Example of SfM-derived image products showing a site-level 2.5D Digital Elevation Model (right) and corresponding 2D orthomosaic (left) from O‘ahu, Hawaii.

Data sets needed

1. *Fixed-site digital elevation model (DEM)*: SfM-derived top-down 2.5D image with pixels representing depth
2. *Fixed-site orthomosaic*: SfM-derived top-down 2D image mosaic with pixels representing substrate RGB color
3. *Transect shapefile* (with geodatabase domains): shapefile of transects digitally traced over the orthomosaic
4. *Cameras shapefile*: used to identify and review individual raw photos building the orthomosaic. Raw imagery provides the highest pixel resolution available and allows the user to survey points along transects from different angles and exposures, aiding in accurate benthic characterization. Raw imagery can be viewed relatively easily using either Agisoft Metashape or Viscore (if available).

SfM model preparation

Prior to conducting carbonate budgets benthic data annotation, the SfM-derived image maps (DEM and orthomosaic) need to be generated in Agisoft Metashape. The SfM model build process starts by feeding the software hundreds to thousands of high-quality overlapping photos collected by divers using a ‘double spiral’ survey pattern (Rodriguez et al. 2021). The underwater imagery is automatically processed through SfM techniques in Metashape to detect and match common features seen in three or more overlapping photos, resulting in the 3D surface reconstruction of the reef scene. Further, principles of SfM and traditional photogrammetry are combined to ultimately derive geometrically accurate 3D models that retain the ground truth scale and shape. The DEM is generated by ‘anchoring’ the reconstructed 3D model in a top-down view and deriving a 2.5D grid with sub-centimeter depth values describing the reef surface structure. Lastly, the orthomosaic is derived by projecting the raw photos onto the DEM to correct for photographic distortions introduced by changes in viewing angles, resulting in a blended ortho-rectified image mosaic of the reef that retains the spatial accuracy of a map suitable for measurement. See Torres-Pulliza et al. (in review) for a detailed description of the SfM workflow.

Estimated duration

Average benthic data extraction time ranges from approximately 6–10 hours per site, depending on the size and abundance of benthic components, the relief of the site, and the visual quality of the orthomosaic and underlying raw photos.

Step 1: Start an ArcGIS Pro project

1. Open ArcGIS Pro.
2. Below 'New' on the Start page, click Map (Figure 16).
3. Name the project and hit OK.

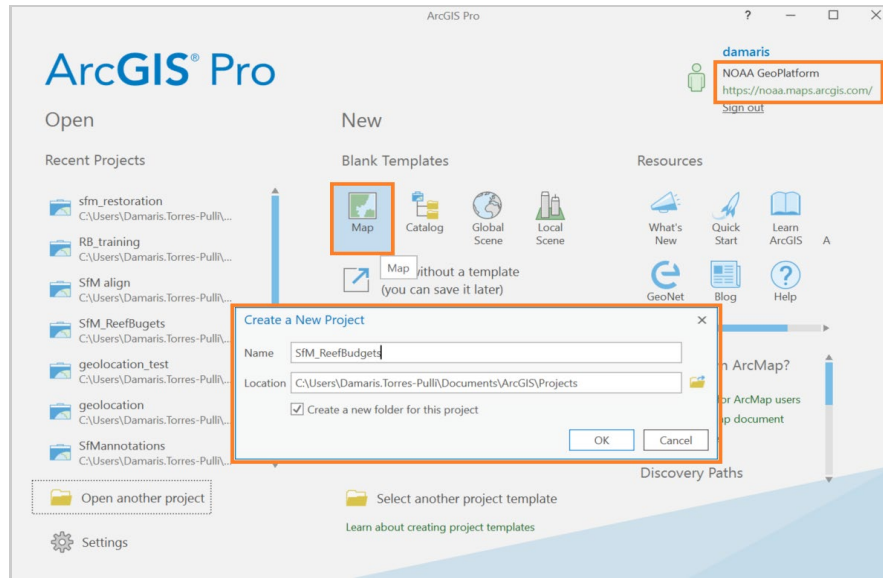


Figure 16. Screenshot from ArcGIS Pro showing creation of new map and project file.

4. The project opens to a reference map (see the Contents pane to the left). If you do not see the Contents pane, from the View tab in the Windows group, click Contents pane.
5. Because the project has no data, it uses a default template map to define a geographic coordinate system (Figure 17).

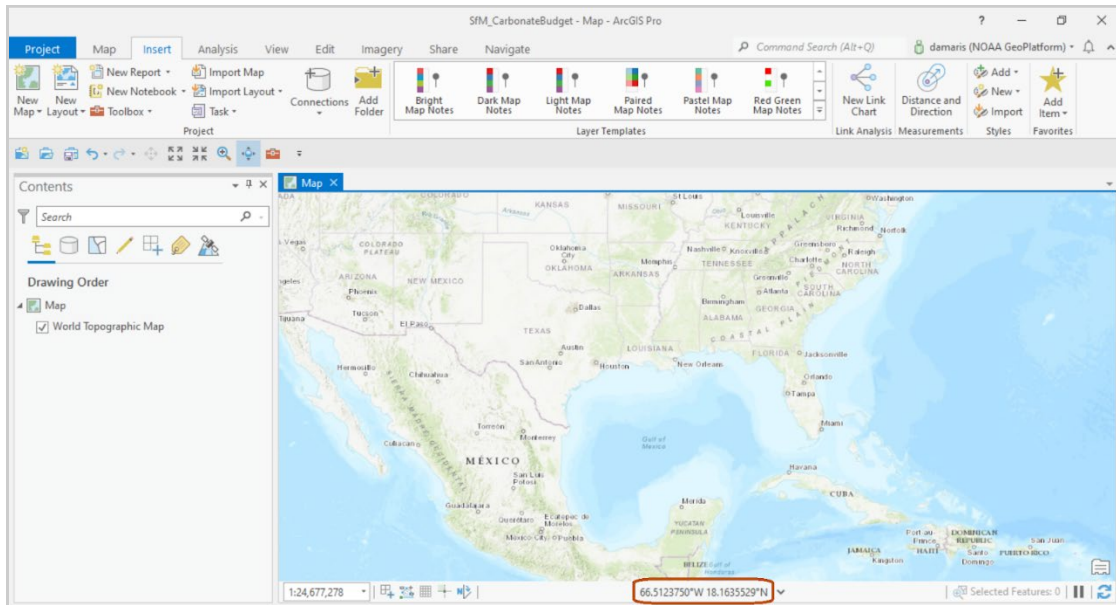


Figure 17. Screenshot from ArcGIS Pro showing default template map.

Step 2: Add data layers

1. From the Map tab in the Layers group, click Add Data.
2. Navigate to the data folder and select the spiral orthomosaic and DEM (Figure 18).
3. Click OK.
4. Optionally, add the SfM camera's shapefile to get access to the raw imagery used to build the orthomosaic. The raw photos provide the highest available resolution for visual annotations.
5. On the Contents pane, right click over the orthomosaic and select Zoom to Layer to center the view (Figure 19). You may also uncheck or remove the World basemap as it is not needed.

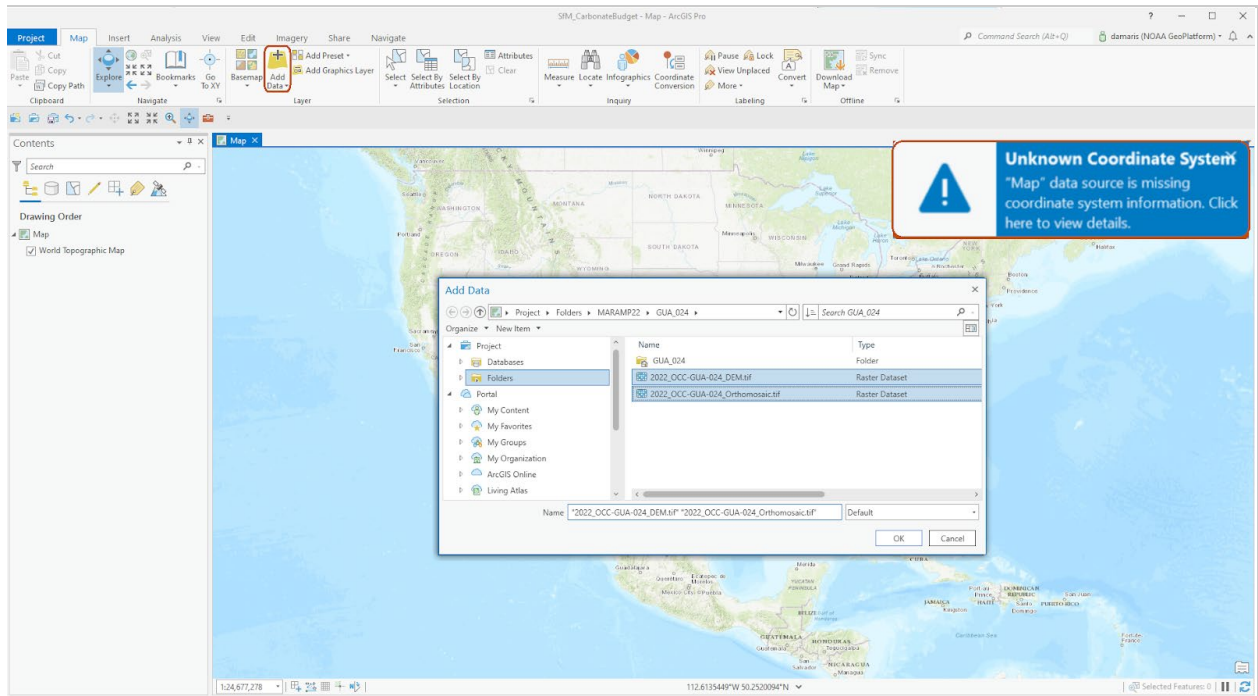


Figure 18. Screenshot from ArcGIS Pro showing how to add image layers of the orthomosaic and corresponding DEM.

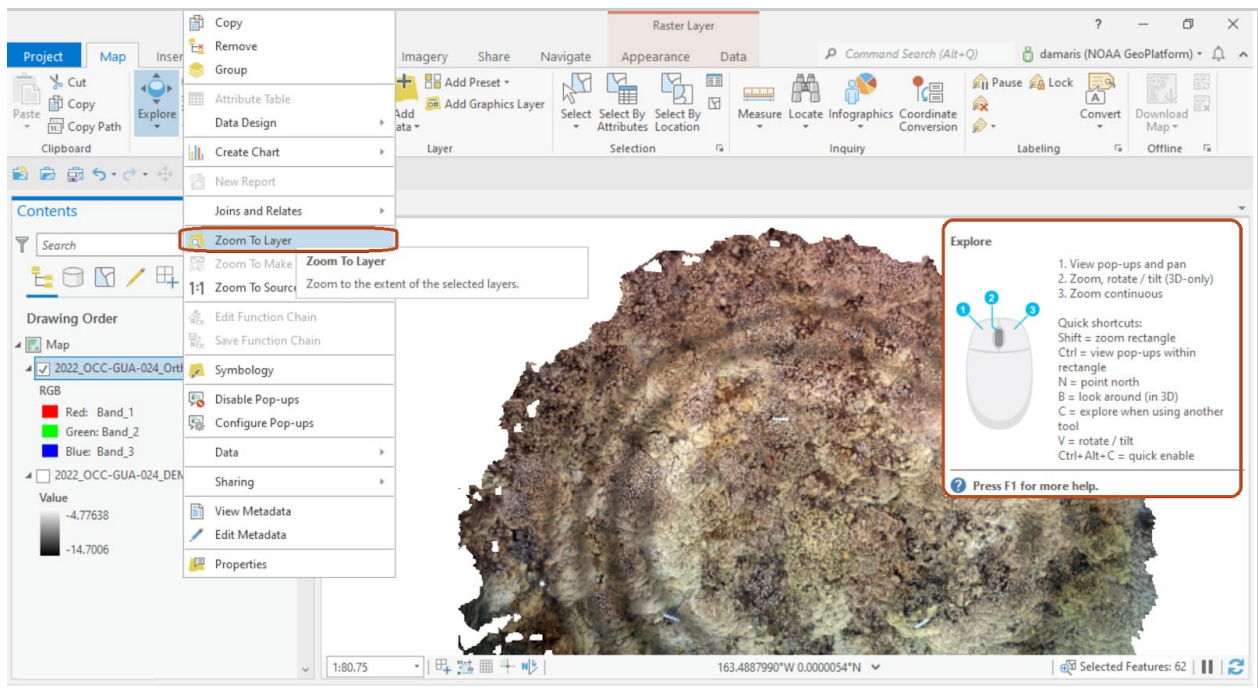


Figure 19. Screenshot from ArcGIS Pro showing how to zoom appropriately to layers of the orthomosaic and corresponding DEM.

Step 3: Define coordinate system and projection

Some images will open with an ‘unknown coordinate system’ in ArcPro (Figure 18). While unknown to ArcPro, all the SfM-derived images carry a Local Coordinate system that was defined in Metashape during model build and is expressed in meters. To transform Metashape cartesian coordinates centered at ‘0,0’ to projected coordinates:

1. On the Geoprocessing pane, in the ‘Find Tools’ search box, type **Project Raster** (Figure 20).
2. Select the DEM image as input raster.
3. Click the globe icon to the right of ‘Input Coordinate System.’ Under *Geographic Coordinate System*, navigate to World and select WGS 1984.
4. Assign an output directory and raster name that distinguishes it as ‘projected’ (i.e., add a ‘p’ to the original name).
5. Click the globe icon to the right of ‘Output Coordinate System.’ Under *Projected Coordinate System*, navigate to UTM > WGS 1984 > Northern Hemisphere > WGS 1984 UTM Zone 31N. Zone 31N denotes the UTM zone at roughly ‘0,0.’
6. If the image is geolocated and has a defined Geographic Coordinate System, use a Projected Coordinate System that is appropriate for the corresponding study area (i.e., for O‘ahu, use WGS 1984 UTM Zone 4N).
7. Leave the Output Cell Size as default, as the software reads this information directly from the image. Alternatively, modify this value if a coarser resolution is more appropriate for the analysis (i.e., change 0.001 m to 0.01 m if there is an advantage to working at centimeter scales).
8. Click Run.
9. Repeat the steps above over the orthomosaic to project it. However, make sure to leave the Cell Size as default in step 7 to take advantage of the highest resolution available for visual data extraction. The typical orthomosaic resolution the Ecosystem Sciences Division uses is 0.0005 m.

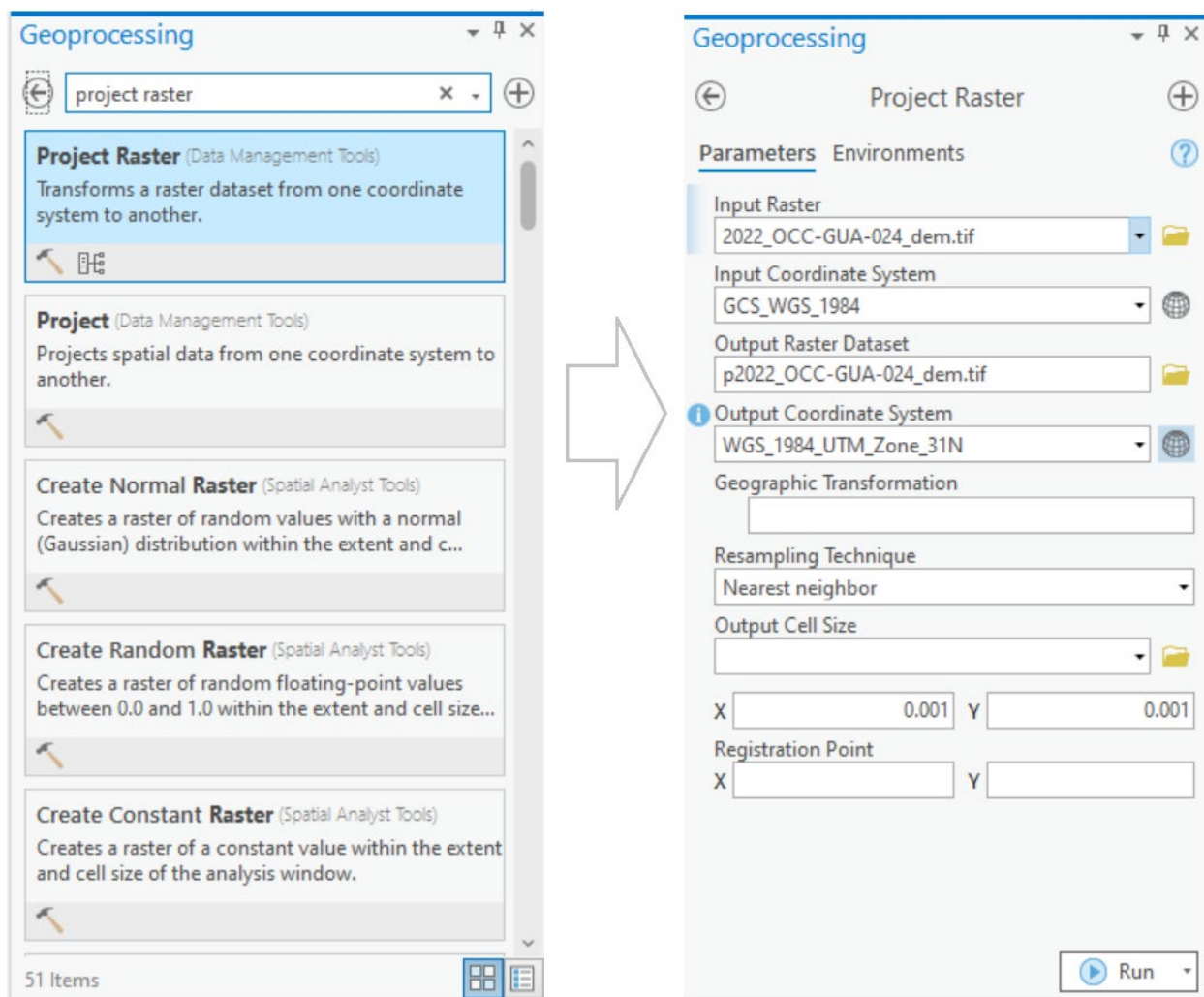


Figure 20. Screenshot from ArcGIS Pro showing how to Project Raster.

Note: The DEM has to be projected prior to annotations in order to derive surface information along the virtual transects. As a checkpoint, right click on the projected DEM and select Properties. Select the *Source* tab and under Data Source, find Vertical Units: select Meters (Figure 21). If this line of information is missing, the image needs to be projected.

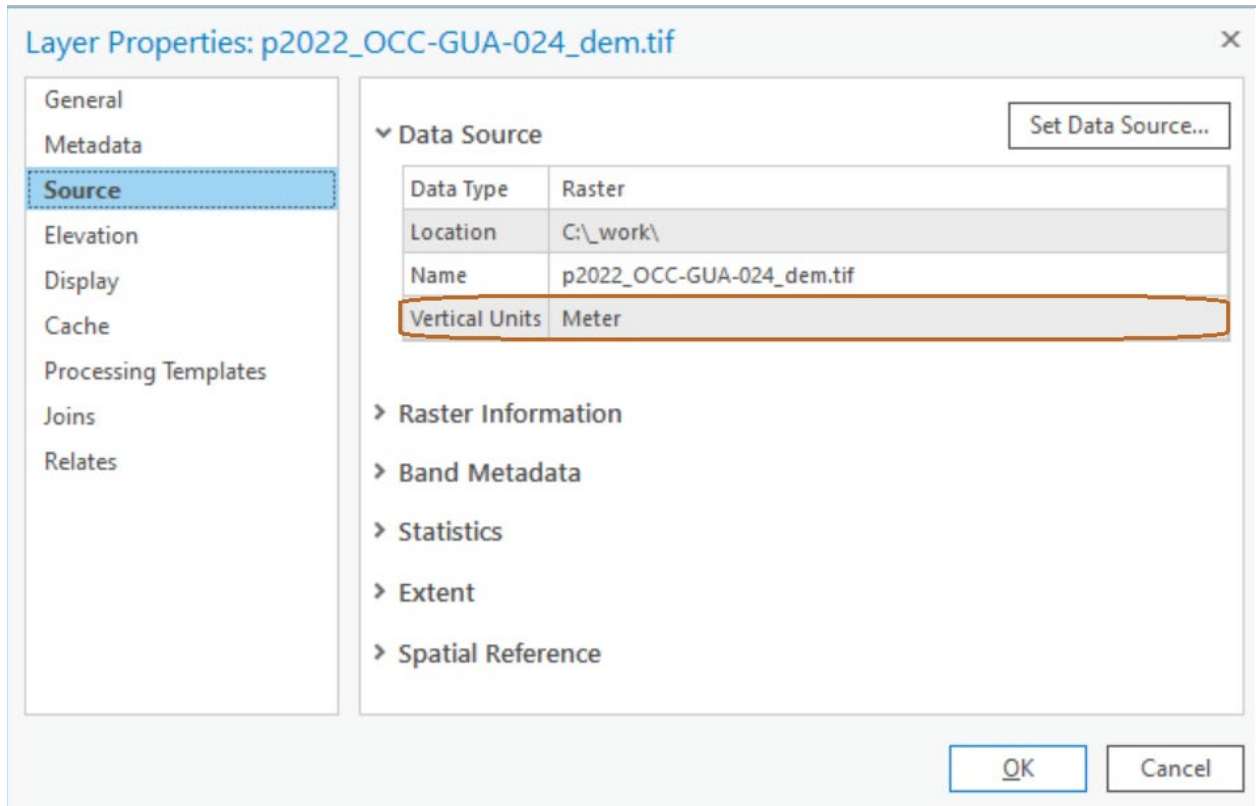


Figure 21. Screenshot from ArcGIS Pro showing image properties.

Step 4: Check image map scale

1. Hover the mouse over the image and use the middle wheel to zoom in to one of the three scale bars visible in the image.
2. From the Map tab, in the Inquiry group, click Measure > Measure Distance.
3. Using planimetric units, use the mouse to measure the distance between scale bar markers' centers to ensure spatial accuracy (Figure 22).
4. Zoom back out to the image extent.

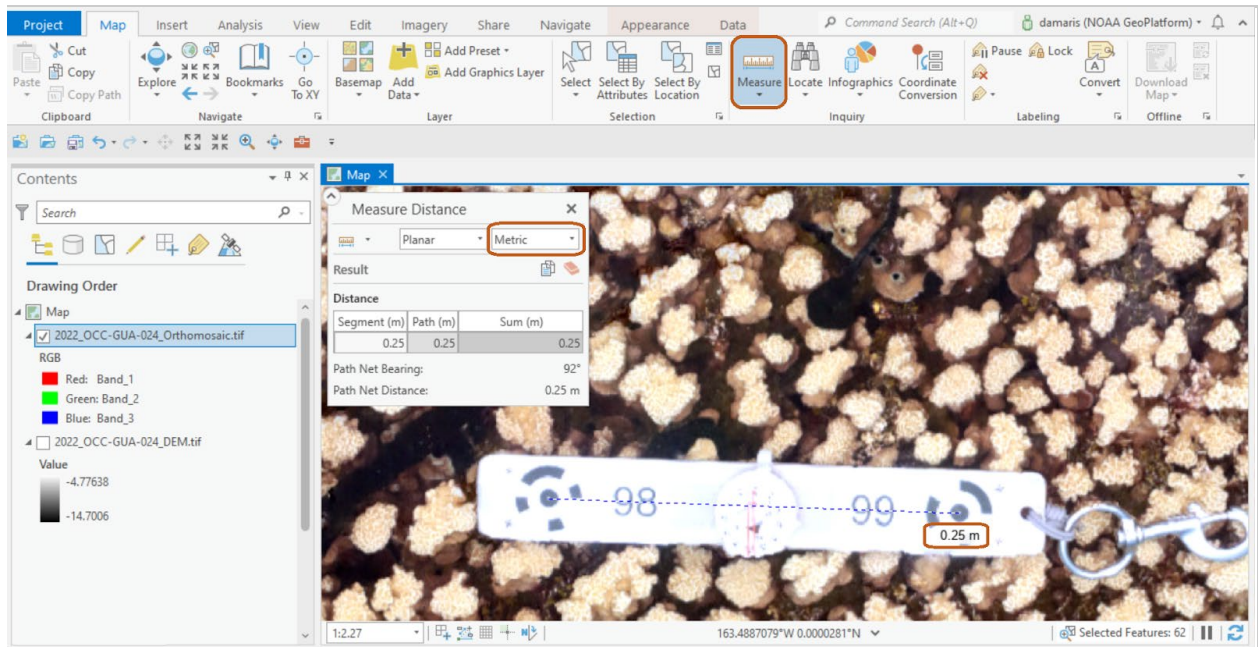


Figure 22. Screenshot from ArcGIS Pro showing how to check the image scale using the ‘Measure’ tool.

Note: The DEM, derived through the Ecosystem Sciences Division SfM pipeline, should have 0.001 m pixel size. The orthomosaic is typically saved with 0.0005 m pixel size.

Step 5: Visualize the different image maps

1. Check and uncheck the orthomosaic to reveal the underlying DEM. This will confirm a one-to-one spatial correspondence between the two images and that the correct surface length will be assigned to the annotated benthic component.
2. Optionally, change the symbology of the DEM and/or orthomosaic to better visualize changes in depth and borders between benthic features. Click the DEM or orthomosaic color bar to open the Symbology options. From the Color scheme dropdown palette options, select an appropriate color range.
3. Add the site “cameras” shapefile to visualize the spiral swim path and identify photos of interest (Figure 23). If the “cameras” shapefile is displaced compared to the orthomosaic and DEM, make sure to ‘Project’ the shapefile to the same Projected Coordinate System as the image maps, as outlined in **Step 3** above.

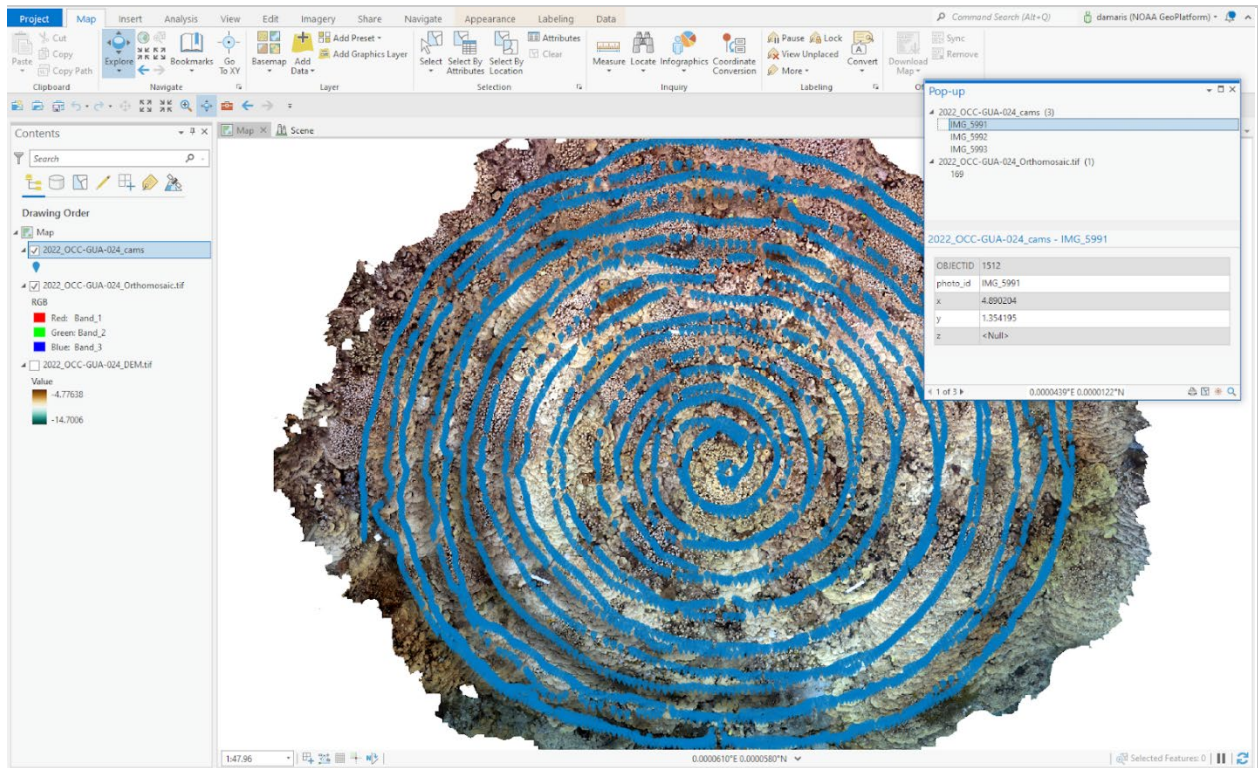


Figure 23. Screenshot from ArcGIS Pro after the ‘cameras’ shapefile has been added.

Note: Because the orthomosaic is derived from the DEM, the two image maps retain the same georeferencing added in Metashape. Consequently, even if the two image maps differ in pixel resolution, the images should overlap exactly (Figure 15). If that is not the case, or if the scale bar distance significantly differs from its expected length, the image products may need to be re-generated from the original 3D SfM model before continuing to the next steps.

Step 6: Create a shapefile

1. On the View tab in the Windows group, click Catalog Pane.
2. To create a shapefile, collapse the Database dropdown arrow, right click on the project's geodatabase, and select New > Feature Class (Figure 24).

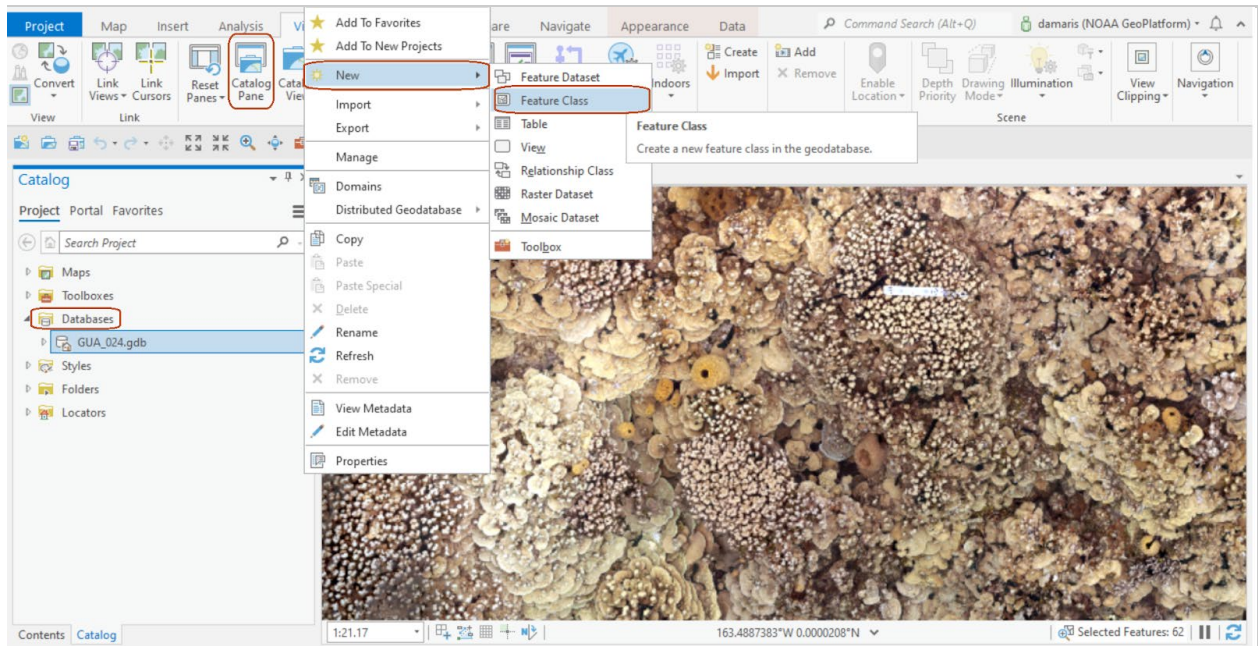


Figure 24. Screenshot from ArcGIS Pro showing how to create a new feature class.

3. In the Create Feature Class dialog, add a shapefile name, and select Line as Feature Class Type. Check the add Z Values option and click Finish. The new shapefile will be added within the project Geodatabase. Right click on the newly created Feature Class and select 'Add to current map' to see the shapefile on the Contents pane.
4. Right click on the shapefile and select Attribute table, to open it.
5. At the top left of the Attribute table area, click Field: > Add (Figure 25).

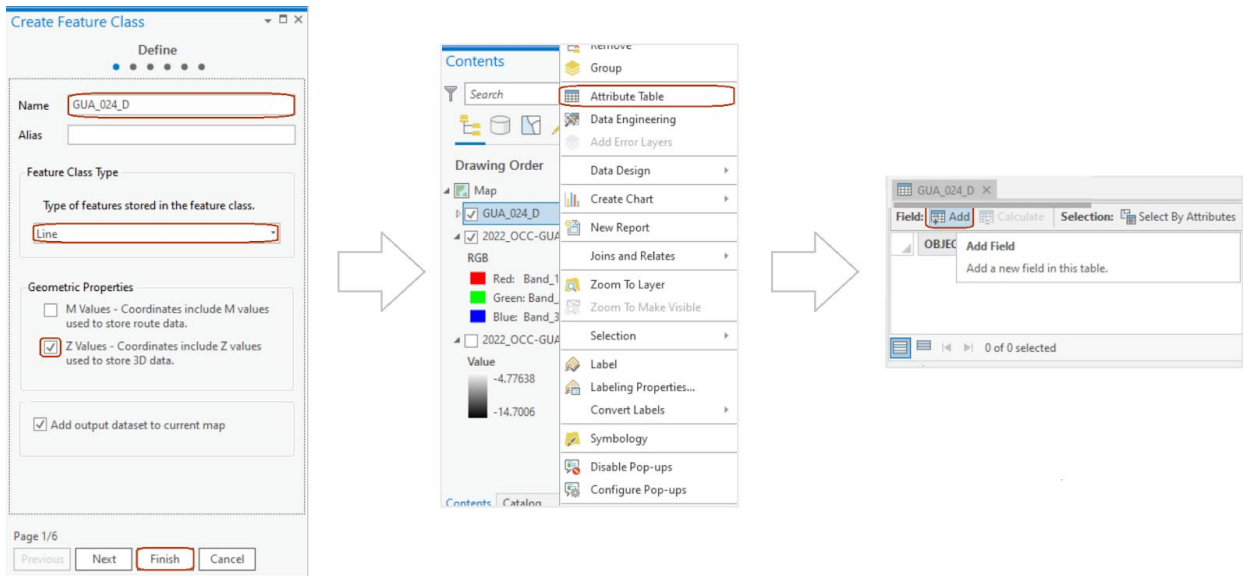


Figure 25. Screenshot from ArcGIS Pro showing how to create the transect shapefile and add fields.

6. The Fields tab will open at the top.
7. Select “Click here to add a new field” to create all the attribute fields needed. Fill the field description options accordingly. For example, fill the Field Name, Data Type, Number Format, Domain (if one is available), and Default values with their corresponding information. (Figure 26).

Note: A domain creates a drop-down menu with predefined classes for faster and more consistent annotations. See Appendix B for instructions on how to create a geodatabase domain in ArcPro to directly accommodate each project’s needs. Once a shapefile with defined attributes and domains is created, it may serve as a template for each new chord transect.

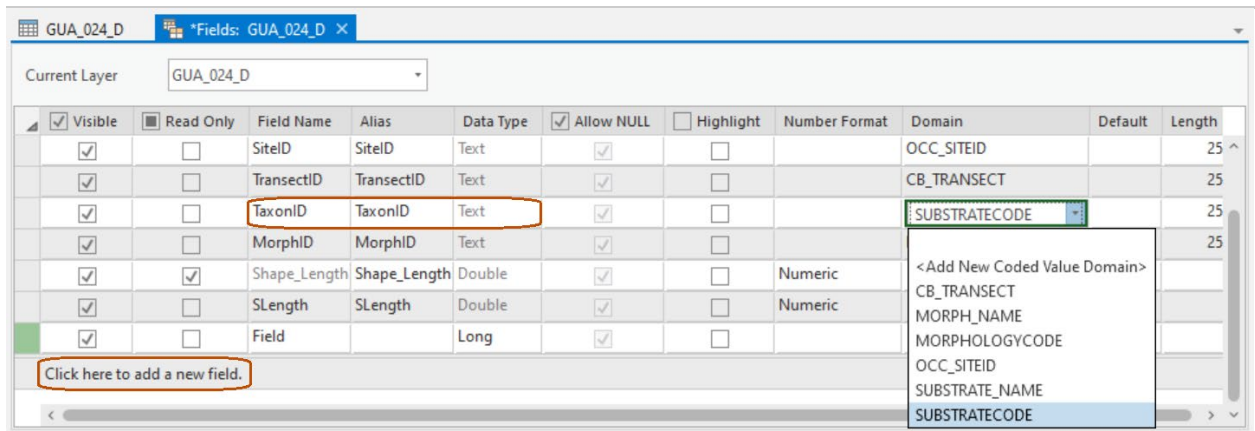


Figure 26. Screenshot from ArcGIS Pro showing how to edit field attributes, descriptions, and domains.

8. On the Fields tab, in the Changes group, click Save (Figure 27).

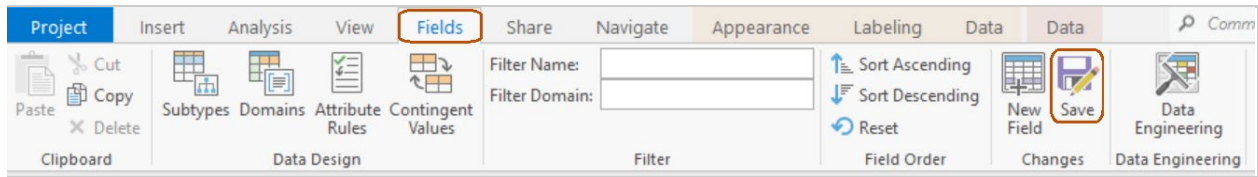


Figure 27. Screenshot from ArcGIS Pro showing how to save field edits.

Note: At this point, make sure to project the shapefile to match the coordinate projection used for the images ([Step 3](#)). Use the ‘**Project**’ tool and select one of the images under *Output Coordinate System* to mimic its geographic information.

Step 7: Lay out “ideal” digital transects over the orthomosaic within the newly created shapefile

1. On the Contents pane, check the orthomosaic checkbox to display the image.
2. On the Edit tab, in the Manage Edits group, click Edit.
3. On the Edit tab, in the Features group, click Create. The Create Features tool opens (Figure 28).

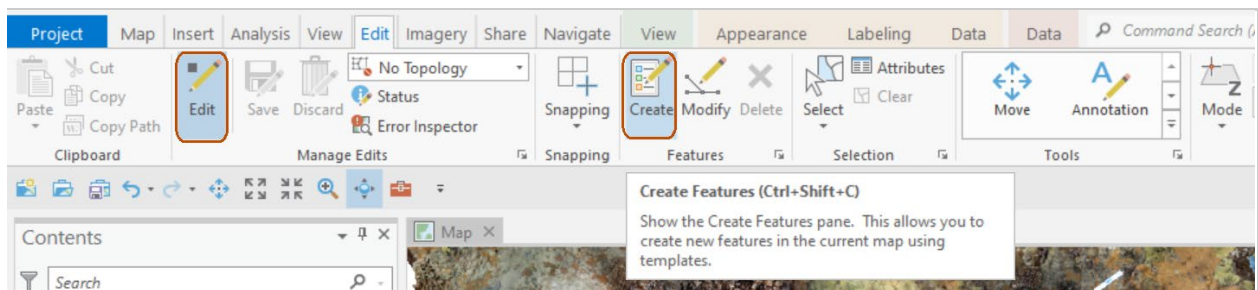


Figure 28. Screenshot from ArcGIS Pro showing how to create new features in the transect shapefile.

4. On the Create Features pane select the created shapefile to open the Create toolbox.
5. Select the Create Line tool (Figure 29).

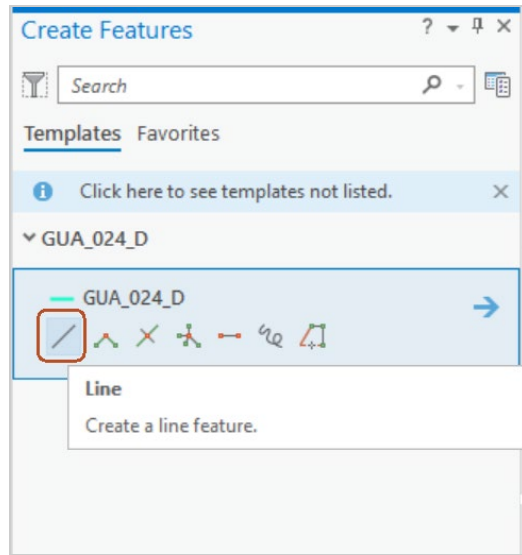


Figure 29. Screenshot from ArcGIS Pro showing how to select the line feature.

6. Place the cursor at the start of the ideal transect location (or using the yellow dive weights as reference if present, Figure 32) and click once. Then finish laying the transect line by double clicking over the corresponding yellow dive weight pair marker defining the end (Figure 30). Notice how the new transect parameters are added to the shapefile's Attribute Table automatically.
7. Repeat steps 5 and 6 from this section to draw all the “ideal” transect lines (also referred as ‘virtual transects’) and fill-in their unique **TransectID** field by double clicking on it in the Attribute Table and adding the corresponding ID value (Figure 30).

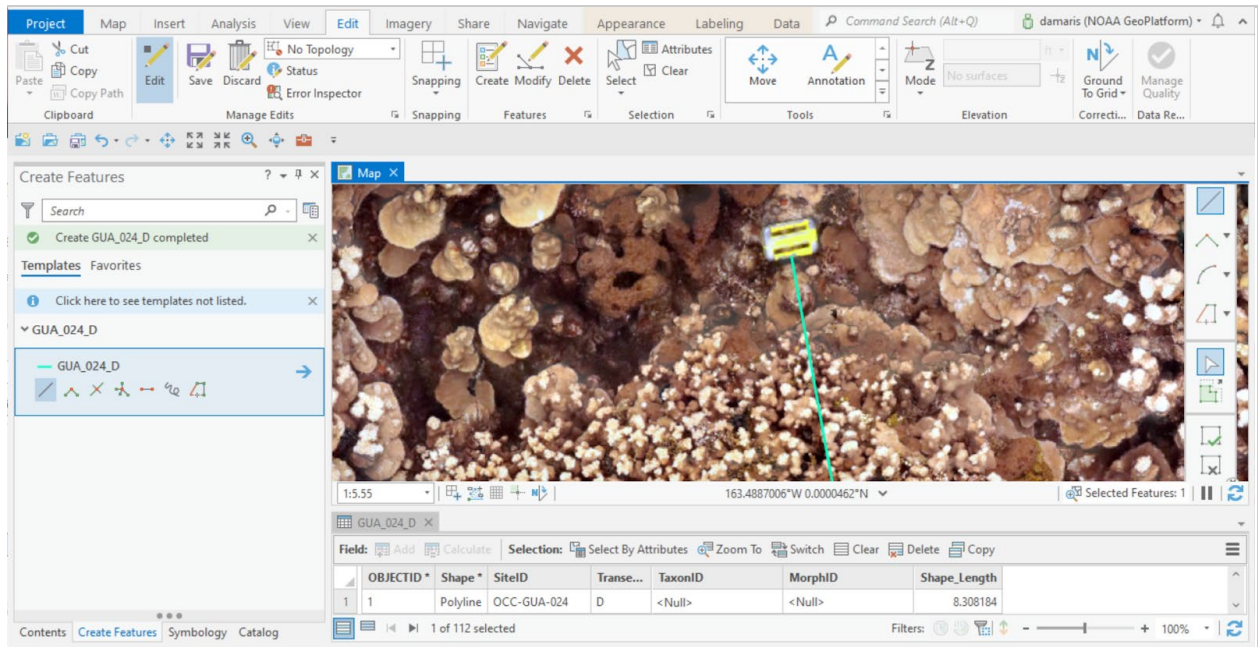


Figure 30. Screenshot from ArcGIS Pro showing how to label each new line feature within the Attribute Table of the virtual transects shapefile.

8. On the Manage Edits group, click on **Save**, and on **Edit** to stop editing.
9. Optionally, change the symbology of the lines for better visualization by clicking the line symbol and selecting a style and color from the Symbologies available.

Step 8: Separate transects shapefile into unique chord shapefiles

1. Export each transect as a separate shapefile using the ‘Export features’ command on the transects shapefile by right-clicking in the Contents pane.
2. Export each transect feature by highlighting its corresponding row in the attribute table and selecting the individual ObjectID.

Step 9: Segment each transect by benthic features

With the six benthic transects now overlaid on the orthomosaic imagery, these vector lines (virtual transects) need to be segmented to delineate the beginning and end of each benthic feature.

1. On the Edit tab, in the Manage Edits group, click **Edit**.
2. On the Edit tab, in the Feature group, click **Modify**.
3. On the Modify features toolbox, under the Divide category, select **Split**. (Figure 31).
4. On the Edit tab, in the Selection group, click **Select** and select one of the transects for editing (Figure 31). Notice that the corresponding row on the attribute table is also selected.

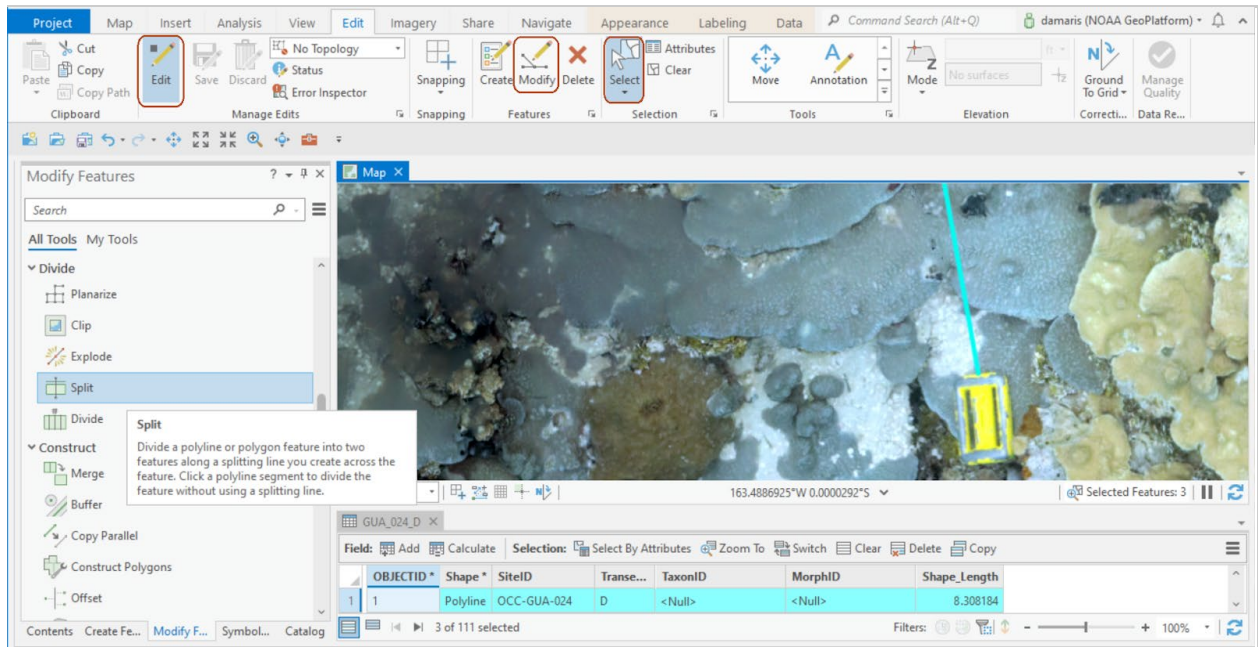


Figure 31. Screenshot from ArcGIS Pro showing how to select the split tool for a specific transect shapefile.

5. Zoom in to the image to visualize each benthic feature intercepting the selected line clearly.
6. Click on both sides of the line defining the beginning and end of each benthic feature. This will split the overarching transect shapefile into smaller segments based on where the split line [dashed line] and shapefile intersect (Figure 32).
7. Complete each segment split by double clicking anywhere on the image or right click and select Finish from the collapsed options.
8. When finished, **Save**, and stop Edits.

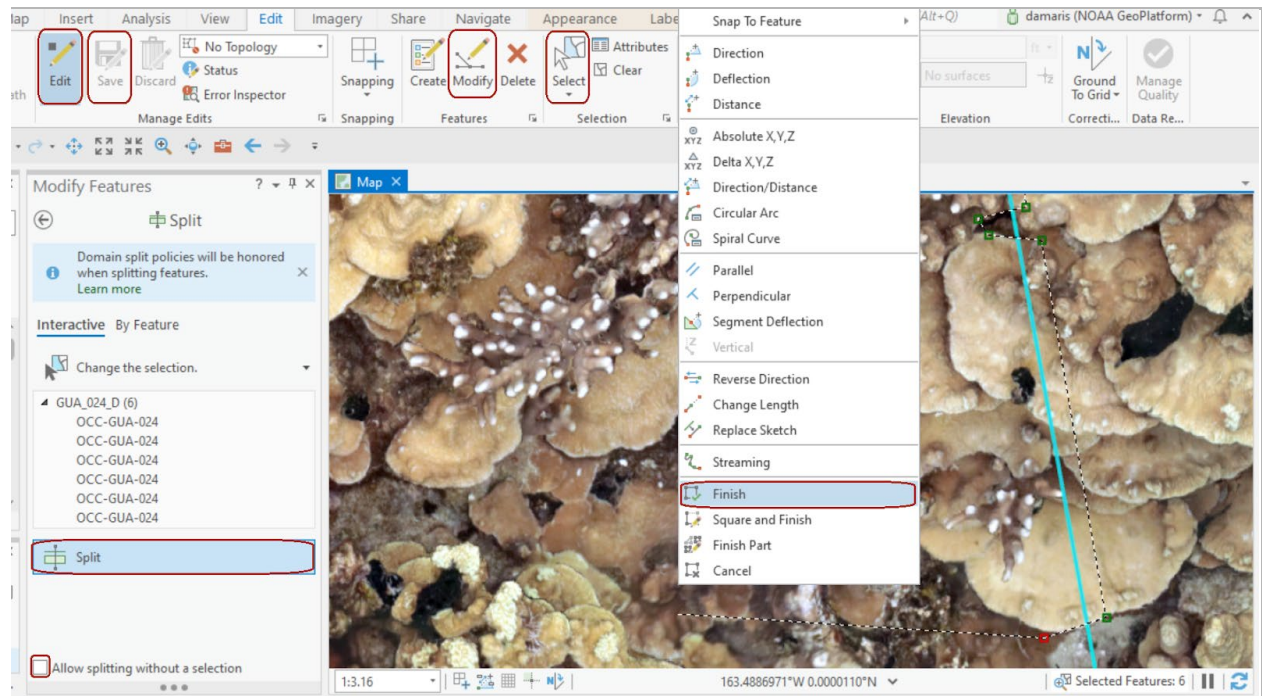


Figure 32. Screenshot from ArcGIS Pro showing how to split a specific transect shapefile into unique segments based on benthic components.

Note: With each double click, the tool will commit the split at the location where the two lines intercept, which can be at the start and end of every feature or by continuously defining multiple start and end intercepts at once. The latter allows for the splitting of various features simultaneously.

Step 10: Annotate benthic features per segment per transect

Annotate each of the transect shapefile segments to characterize the benthic type.

1. On the Edit tab, in the Manage Edits group, click **Edit**. With the Edit tool activated, the attribute table can be modified.
2. Select each divided transect segment with the **Select** tool or by clicking over each row in the attribute table.
3. On the attribute table, select the benthic class and morphology code (if applicable) from the provided drop-down lists (Figure 33).

Note: The lookup table with benthic classes should be provided from a created domain when creating the transect shapefile above in Steps 5/6.

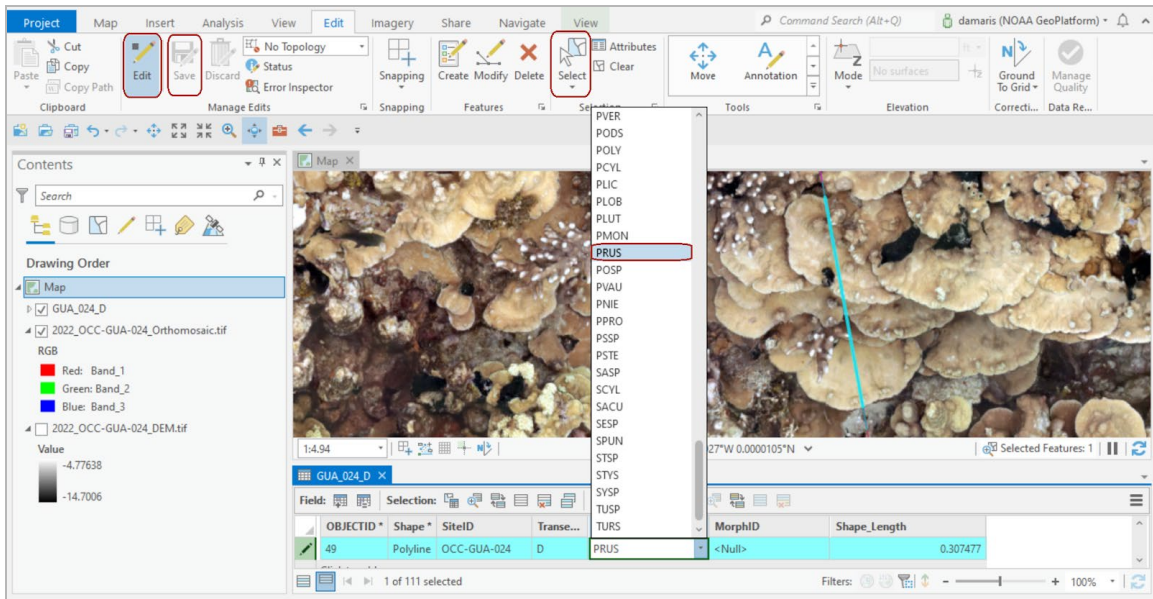


Figure 33. Screenshot from ArcGIS Pro showing how to annotate individual segments according to benthic components within the shapefile attribute table.

4. Continue until all the transect segments are coded by benthic type.
5. On the Manage Edits group, click **Save** and stop Edit.
6. Optionally, right click over the transects shapefile and select Symbology. In the Symbology toolbox, choose Unique Values as Primary symbology, and Benthos as Category field. Change the Color scheme and line width as appropriate (Figure 34).

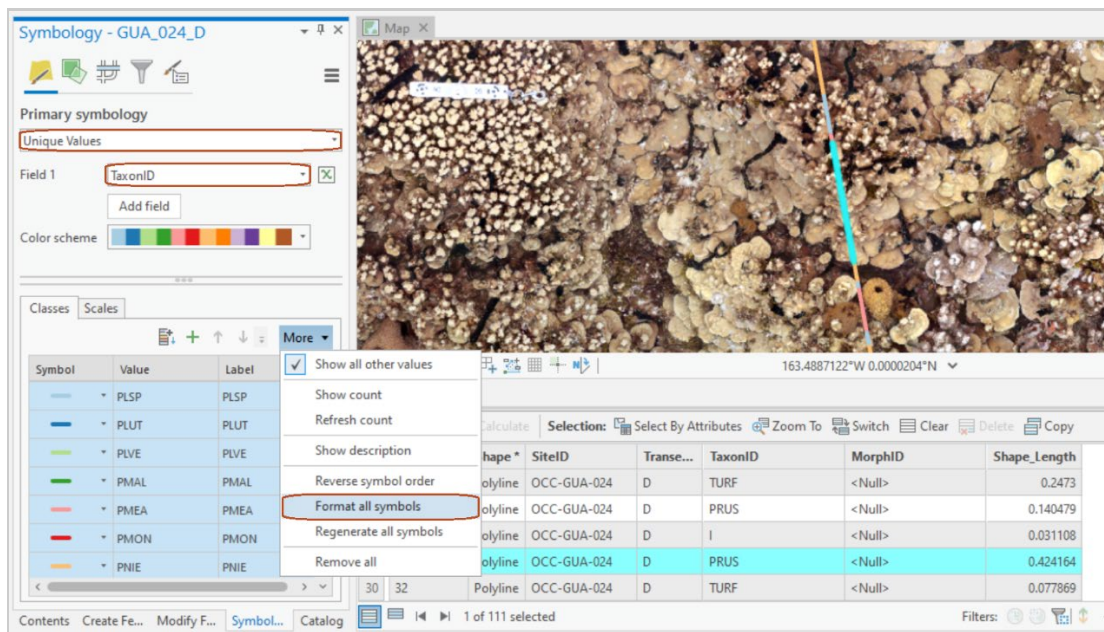


Figure 34. Screenshot from ArcGIS Pro showing how to assign color to individual segments according to benthic components within the Symbology tab.

Step 11: Extract surface length (cm) of benthic components

1. After all the above steps are completed and all segments of all transects have been classified by benthic type, on the Analysis tab, in the Geoprocessing group, click **Tools**.
2. On the Geoprocessing pane, in the 'Find Tools' search box, type **Add Surface Information** (Figure 35).
3. In the dialog, under 'Input Features' select a chord transect shapefile.
4. Under the 'Input Surface', select the corresponding DEM.
5. Check the **Surface Length** and any other parameter of interest from the options listed. Notice, on the attribute table, that the planar distance has been added automatically [Shape_Length].
6. Make sure to unselect all class features, or the tool will calculate parameters only for the selected features.
7. Click **Run**.

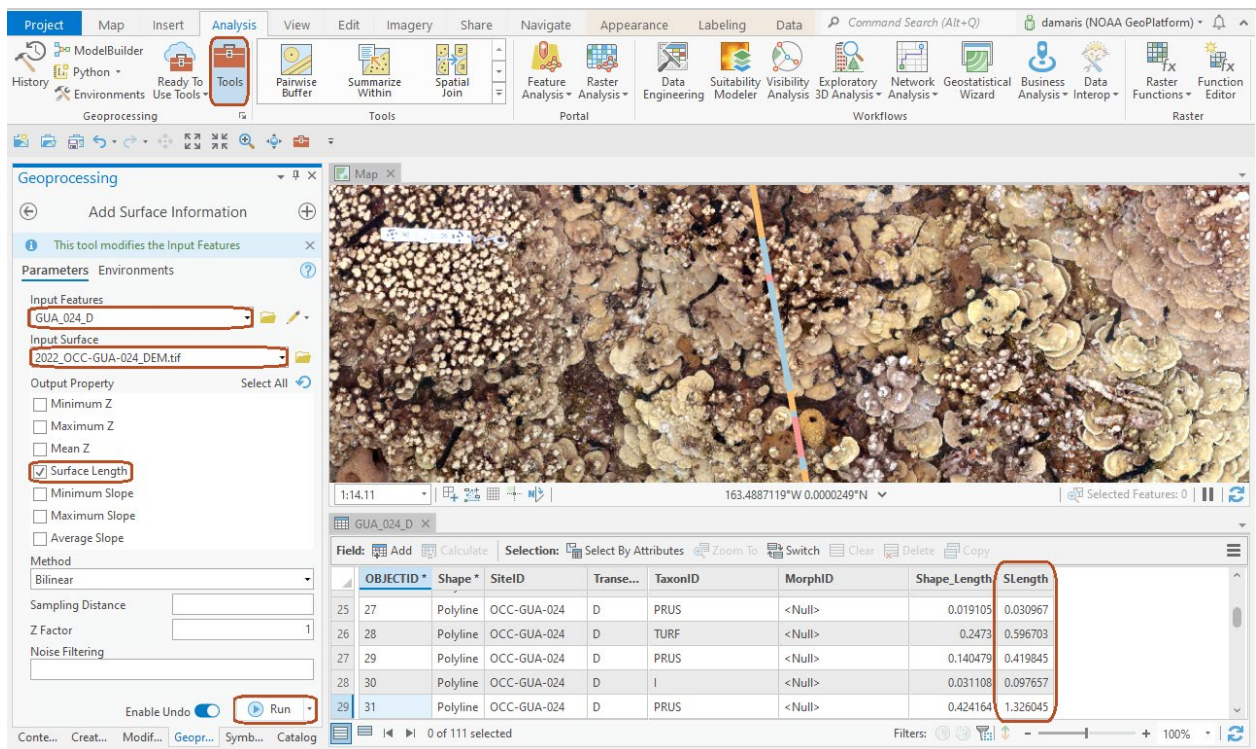


Figure 35. Screenshot from ArcGIS Pro showing how to extract the surface length of all individual segments using the 'Add Surface Information' tool.

8. A surface length [SLength] field is automatically created in the attribute table containing surface distance values per chord segment.
9. Repeat this process for each chord transect shapefile to generate surface distance
10. Save the ArcPro project.
11. When done, click on one of the attribute table fields, and press Ctrl + A, to select all.

12. Click the Copy tool button to “Copy selected rows to the clipboard” (Figure 36).

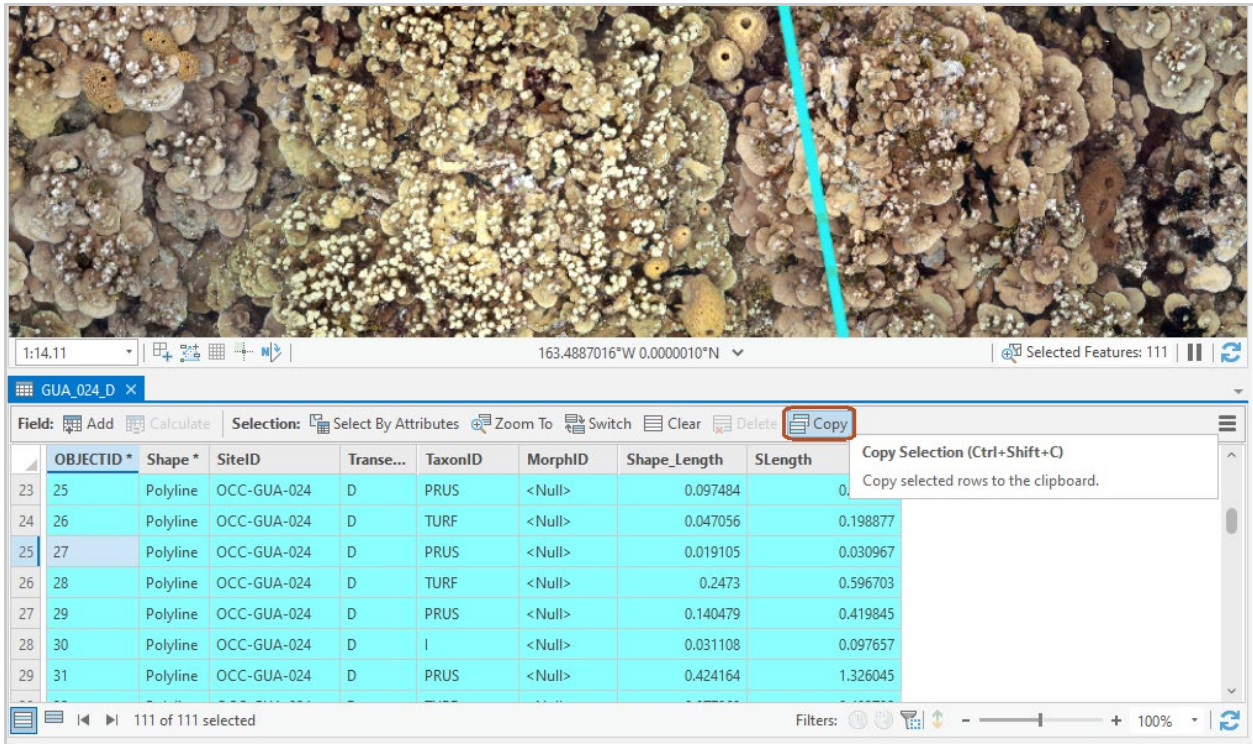


Figure 36. Screenshot from ArcGIS Pro showing how to copy the extracted data for export to MS Excel or other supported programs.

13. With the table copied, values can be pasted to an Excel spreadsheet for further data manipulation and analyses (Figure 37). For example, to derive a rugosity index per benthic type calculate [SLength / Shape_Length = Rugosity Index] or [Surface Distance / Planar Distance].

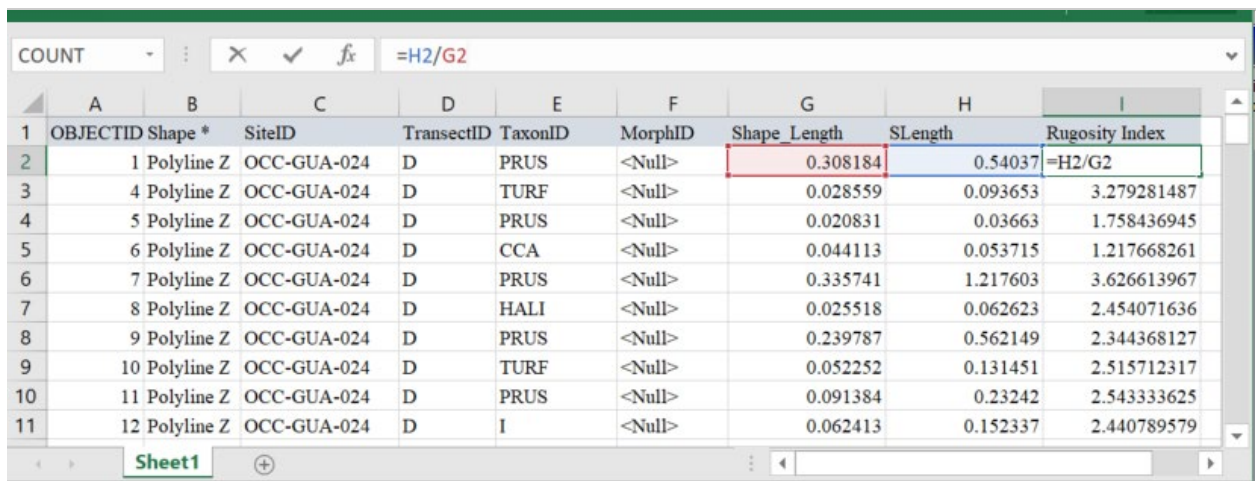


Figure 37. Screenshot from MS Excel showing the extracted data format and exemplary calculations for synthesis and analysis.

Appendix B: Creating a geodatabase with associated domains

All processes were applied in ArcGIS Pro 2.8.0. The described processes can be standardized by creating a customized ArcGIS toolbox using Model Builder.

1. Create File Geodatabase using Create File GDB (Data Management) tool.
 - a. File GDB Location: path to a folder where the geodatabase is stored.
 - b. File GDB Name: name of geodatabase.
 - c. File GDB Version: CURRENT.
2. Create a table in Excel that will be converted to your domains in the GDB (Figure 38). This step will create the attribute domains you will have in the geodatabase. Attribute domains are rules in a geodatabase used to constrain the values allowed in any particular attribute for a table or feature class within, which will let the analyst utilize a standard drop down menu. We use short codes that make conversion into our data cloud easier, although these can be full names according to what you are surveying (Figure 38). Name this table according to the geodatabase you are creating (we name according to location and year for better organization e.g., O‘AHU2021_codes).

OCC_SITEID	CB_TRANSECT	TAXON_ID	TAXON_NAME	MORPH_ID	MORPH_NAME
OCC-OAH-005	A	ACSP	Acropora sp.	BR	Branching
OCC-OAH-010	B	ACYT	Acropora cytherea	TB	Tabular
OCC-OAH-012	C	AGEM	Acropora gemmifera	EN	Encrusting
OCC-OAH-038	D	AHUM	Acropora humilus	FR	Freeliving
OCC-OAH-039	E	APAN	Acropora paniculata	MD	Mounding
OCC-OAH-040	F	COSP	Coscinaraea sp.	FO	Foliose
		CYSP	Cycloseris sp	ML	Mounding lobate
		CYPS	Cyphastrea sp.	CO	Columnar
		DIAS	Diaseris sp.		
		FUSP	Fungia sp.		
		GPLA	Gardineroseris planulata		
		LEPT	Leptastrea sp.		
		LBEW	Leptastrea bewickensis		
		LPUR	Leptastrea purpurea		
		LESP	Leptoseris sp.		
		MOSP	Montipora sp.		
		MCAP	Montipora capitata		
		MDIL	Montipora dilata		
		MFLA	Montipora flabelatta		
		MINC	Montipora incrassata		
		MPAT	Montipora patula		
		MTUR	Montipora turgescens		
		PAVS	Pavona sp.		
		PCHI	Pavona chiriquiensis		
		PDUE	Pavona duerdeni		
		PMAL	Pavona maldivensis		
		PVAR	Pavona varians		
		POCS	Pocillopora sp.		
		PDAM	Pocillopora damicornis		
		PGRA	Pocillopora grandis		
		PLIG	Pocillopora ligulata		
		PMEA	Pocillopora meandrina		
		POSP	Porites sp.		

Figure 38. Attribute domains table for the pilot study around O‘ahu in 2021. Note: only a subset of the codes are shown here.

3. Convert your Excel document to a CSV file.
4. Create attribute domains in the geodatabase using the Table to Domain (Data Management) tool.

5. Input Table: table containing coded field values and description field values
 - a. Code Field: field in the input table containing coded values (e.g., TAXON_ID)
 - b. Description Field: same field as above (TAXON_ID)
 - c. Input Workspace: the path to geodatabase created in step 1.
 - d. Domain Name: name of domain
6. Repeat the Table to Domain tool for all attribute domains you want in your column.
7. The following list domains are w added to our geodatabase: site (OCC_SITEID), transect (CB_TRANSECT), benthic taxon (TAXON_ID), and morphology (MORPH_ID) if a coral is identified.
8. Once all list domains are added, create a template polyline feature class in geodatabase using the 'Create Feature Class' (Data Management) tool.
 - a. Feature Class Location: path to geodatabase created in step 1.
 - b. Feature Class Name: template
 - c. Geometry type: Polyline
 - d. Template Feature Class (optional): Leave blank
 - e. Has M (optional): DISABLED
 - f. Has Z (optional): DISABLED
 - g. Coordinate System (optional): WGS1984 UTM Zone 4N
9. Your template feature class will automatically appear in the Table of Contents pane.
10. Add appropriate fields to the template polyline feature class and apply domain if applicable (these will be your drop down menus) using 'Add Field' (Data Management) tool (Figure 39).
 - a. Input Table: template
 - b. Field Name/Field Type/Domain: see Table 7
 - c. In this tool, when creating your fields with the drop down menus (the attribute domains you developed earlier using Excel), type the exact name of your 'Code Field' in the domain box.

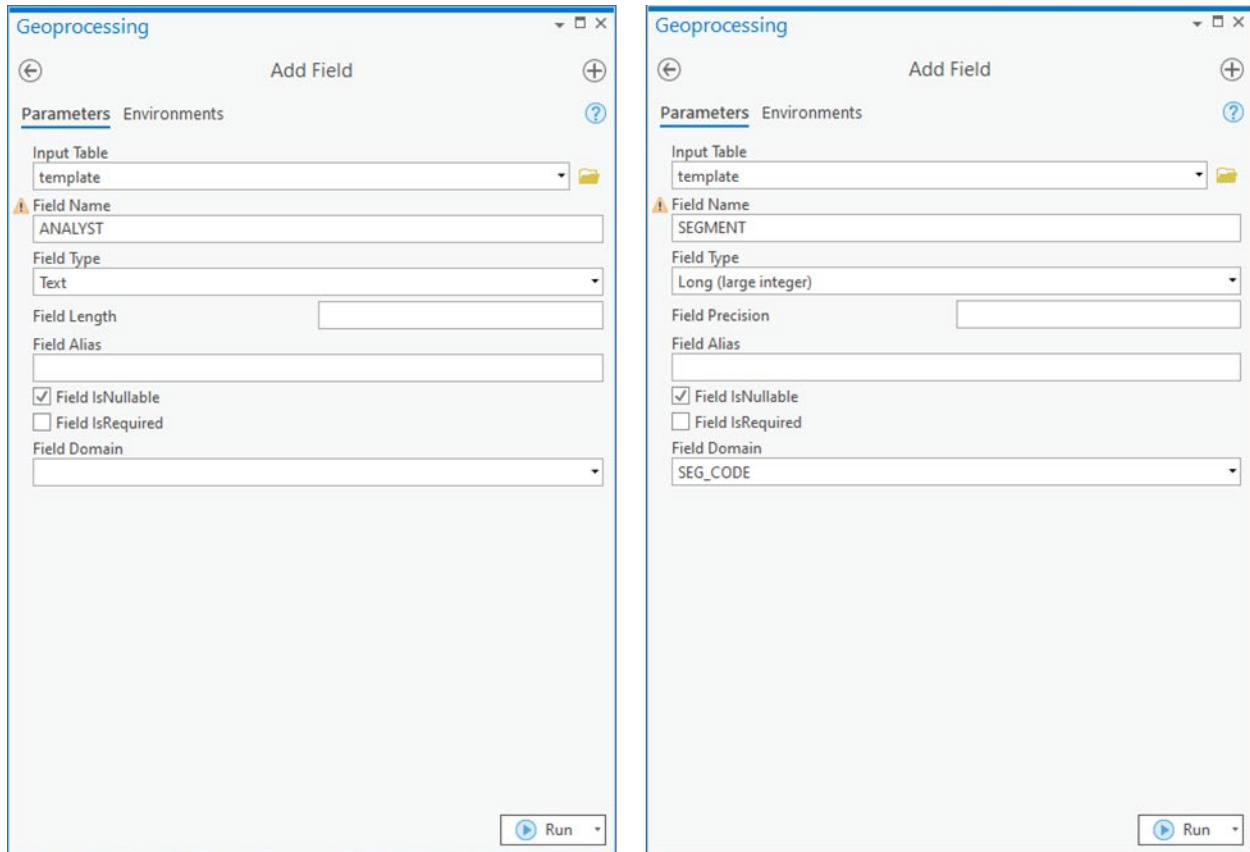


Figure 39. Screenshots from ArcGIS Pro showing how to use the Add Field tool with dropdown domains.

Table 7. Example of Field and Domain set up for attribute table with drop down menus.

Field Name	Field Type	Length	Domain
OCC_SITEID	TEXT	50	
CB_TRANSECT	TEXT	50	
TAXON_ID	TEXT	50	
MORPH_ID	TEXT	50	