


ReefBudget: Methodology

(*Eastern Tropical Pacific* version 1.0, February 2024)

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1 Census-based approaches to quantifying reef carbonate budgets

This Eastern Tropical Pacific (ETP) *ReefBudget* methodology follows the framework production states approach (Perry et al. 2008) and is an extension of the *ReefBudget* methodology previously developed to support estimates of net biologically-driven carbonate budgets (kg $CaCO_3$ m^{-2} yr^{-1}) on Indo-Pacific reefs (see http://geography.exeter.ac.uk/reefbudget/). It uses a census-based approach to quantify cover/abundance of carbonate producing (corals and crustose coralline algae (CCA)) and bioeroding taxa (urchins, parrotfish and micro- and macro-endolithic taxa), and integrates these data with published and field-derived measures of species/genera specific carbonate production and erosion rates to support resultant budget calculations. The methodology can be applied to different reef zones and depths as necessary to support spatial upscaling efforts.

While similar to the Indo-Pacific methodology, there are important differences in this ETP version that have been integrated to factor for the somewhat unique aspects of ETP reefs. The first relates to the often monospecific nature of many ETP reefs which are commonly dominated by expanses stands of species of *Pocillopora*. These extensive fields of coral often comprise of colonies that display highly complex micro-branching surfaces with complex micro-scale topographic relief. These would represent a challenge to accurately survey in the field within dive time constraints. Thus, a modified approach to the field census methodology normally used in *ReefBudget* has been developed for relevant species so that carbonate production from these corals can be more feasibly included in the field data collection. This methodology is described in Section 3. The second modification relates to the need to include within the fish census additional species of pufferfishes and triggerfishes, which are known to be key agents of substrate erosion on ETP reefs.

These modifications aside, carbonate production by corals and CCA are, as with other versions of *ReefBudget*, calculated using geometric relationships derived from individual colony morphology, and not from calculated rugosity at the transect level. Calculations are supported by relevant coral growth rate and skeletal density data drawn wherever possible from ETP specific studies. Framework erosion by microborers (e.g., cyanobacteria, fungi) and macroborers (e.g., sponges, polychaete worms, bivalves) is calculated based on published rates (still limited in the ETP region for entire boring assemblages) and as a function of the proportion of substrate in each transect available for bioerosion. The method does not attempt to estimate sediment production rates *per se*, but to some extent this can be estimated for grazing bioeroders (urchins and parrotfish). Other aspects of sediment production and post-depositional lithification are not presently quantified within this approach.

Key points:

- This ETP *ReefBudget* methodology arises from field-testing a revised version of the Indo-Pacific methodology on several coral reefs along the Mexican Pacific coast during 2022-23. The methodology takes account of differences in the availability of data on growth/erosion rates, and inherent reef community differences within the region.
- At present the protocol and supporting online database and spreadsheets are drawn where possible from ETP reefs, but some use of wider Indo-Pacific data has been necessary. However, as more data on coral growth rates etc become available, there is the potential to further adapt this approach to become sub-region specific to reflect the strong N-S environmental gradient, and the impacts of upwelling along the coast.
- As for other versions of the *ReefBudget* methodology, the proposed methods can be applied to any reef site and zone, but variations in depth and regional growth rates need to be considered. If using the pre-set regional average data and calculations in the default spreadsheets, it is suggested that sites are limited to < 10 m depth, because this is the depth interval from across which the majority of data is drawn.
- Data should ideally be collected along depth contours parallel to the reef crest. If there are obvious differences in coral or fish community composition between areas of reef within the same zone, the establishment of multiple survey sites should be considered.

2 Site selection, characteristics and transect placement

2.1 Site characteristics

In order to provide a general characterisation of each study area, the following types of data should be recorded/collected at each site.

1. **Management status** – i.e., whether the site is in a no-take marine protected area, if certain activities are restricted within the site, etc.
2. **Local environmental variables** – whether there are nearby inputs of freshwater, sediment, nutrients, wave exposure, etc.
3. Estimates of **sediment thickness**. This can be done by probing pockets/veneers of sediment accumulated on the reef while conducting surveys.

2.1 Transect placement

At each survey depth a minimum of four (preferably six) 10 m transects should be established as 'master' survey lines along which all data (except parrotfish data) are collected.

- Each transect should be established either along depth contours parallel to the reef front/crest or along discrete (depth-consistent) reef structures (e.g., spurs, patch reefs) as deemed most appropriate to the site and the study.
- Transects should be placed approximately 5-10 m apart.
- Each transect should ideally (if permitting allows) be marked at the start and end with a fixed marker pin (Fig. 2.1). This provides the opportunity to establish a series of long-term monitoring sites as a resource for either subsequent budget assessments or other forms of reef monitoring.
- Marker pins should be more than 10 m apart, and the tape used for the survey line should be pulled taut and secured tightly.
- Each measuring tape used should have a ~50 cm length of 'leader' cord attached at the start of the tape – this ensures that the start point of each measured transect (where marker stakes are placed to avoid areas of live coral) is not biased by the presence of available substrate for peg deployment (Fig. 2.1).
- A map of the location and the layout of transects relative to notable aspects of the gross reef structure, in addition to global positioning system co-ordinates of the transects, is highly recommended.

Fig 2.1*| Survey tape attached to marker stake showing 50 cm long 'leader' cord from clip to main tape.*

3 Determining rates of benthic carbonate production

Coral reefs are 3-dimensional, rugose structures, and their topographical complexity often varies both within and between reefs as a function of benthic composition (e.g., abundance of different coral morpho-taxa) and geomorphological structure (e.g., spurs and grooves). Therefore, in order to accurately determine the surface area covered by calcifying biota, this topographical complexity must be accounted for. However, the most commonly used methods of point-intercept or line-intercept transects struggle to accurately account for the three-dimensional complexity of coral reefs, and the organisms that occur on cryptic surfaces (Goatley and Bellwood 2011). Reef rugosity has most commonly been measured by running a chain or weighted rope of known length (d1) over the substrate conforming to the topography and measuring the planar distance covered by the chain (d2). Rugosity can then be determined as d1/d2 (Hubbard et al. 1990; Mallela and Perry 2007). While this rugosity index can be applied as a conversion factor to individual transects to derive a more accurate measure of the true surface area covered by reef taxa, it is important to note that this method alone would not account for differences in benthic community diversity and composition driven by complexity, such as canopy effects (e.g. shading of the substrate by large coral colonies), and true measurement of the abundance of organisms on vertical or overhanging surfaces.

In order to combat these problems, the *ReefBudget* approach uses a variation of the chain-intercept method as described in Goatley and Bellwood (2011), where organisms on all surfaces under the master survey line are assessed. The *ReefBudget* method thus integrates the chain transect method with a line-intercept transect (Box 1). Using a tape laid out to conform to the true surface profile of the reef, all overhangs, vertical surfaces and horizontal surfaces can be surveyed (i.e., if the transect line crosses over a table coral, the upper and lower surfaces of the coral, plus the benthos under the canopy, and potentially the benthos on the central pillar of the table coral should be recorded). This level of accuracy is best achieved by using a ~1 m length of flexible tape, and recording the distance covered by each taxa/substrate category as encountered as the diver moves along the transect. This methodology is typically considerably more time consuming than standard point-intercept or line-intercept methods (particularly in high complexity reefs), but provides far more accurate data on the actual surface area covered by, and abundance of, each benthic component on the reef. It also ensures that benthic cover on cryptic surfaces is accurately included. The complimentary collection of swath-type video footage or sequential photographs for each transect is recommend to provide a record of substrate characteristics and information on gross transect morphology.

For the purposes of framework budget estimates, the key requirement is to quantify the abundance and morphology of corals and other calcareous encrusters. Collection of abundance data on other non-carbonate producing groups is also readily incorporated into the surveys, and can provide an essential context for understanding resultant budgetary data (for example, on reefs that have undergone phase shifts to macroalgal dominance). Data on the following groups are collected:

- Coral to species or genera[1] and morphological group (a generic 'hard coral' category is also provided that will calculate the carbonate production rate based on *mean* coral extension rates and density, but colony morphology has to be recorded).
- Crustose coralline algae (CCA) crusts (including non-differentiated other encrusters e.g., serpulids, bryozoans).
- Rubble
- Sediment
- Rock/limestone pavement
- Macroalgal cover[2] (it is useful to differentiate between fleshy and coralline algae, and we suggest *Halimeda* spp. as well as other articulate coralline algae are recorded separately)
- Turf algal cover

- Sponges (both eroding and non-eroding)
- Soft coral cover[2]
- Anenomes
- Corallimorpharians
- Clams and other sessile invertebrates

[1] The Indo-Pacific coral finder (https://www.byoguides.com/coralfinder/) provides a useful field guide to the main genera of interest. For a more in-depth and broader cover of coral species and identification, the Australian Institute of Marine Science (AIMS) has an extensive online library of images and distributions of corals from across the wider Indo-Pacific (http://coral.aims.gov.au/), and Glynn et al. (2017) also has useful identification and species data.

[2] We recommend looking under any macroalgal or soft coral canopy to determine if there is living CCA beneath the algal canopy. In these cases a mixed classification is recorded so the most accurate assessments of CCA cover/production or macroalgal cover are obtained.

BOX 1| Benthic Surveys – Recommended field methodology

(1) Insert a marker stake into the reef (not directly into a living coral colony) and then lay out the 10 m master transect line along the depth contour (parallel to the reef crest) before fixing to a second marker stake and pulling taut (the two stakes should be a little >10 m apart – Figs. 3.1 A, B).

(2) Record data on survey sheets using recommended taxa specific codes (see Appendix A). It is essential that the correct coding system is followed on data entry because these codes link to the taxon and morphologically specific extension rates, density data, any conversion metrics and the equations required to calculate carbonate production estimates.

(3) Measure the surface distance (cm's) covered by each benthic component directly beneath the master tape as the diver moves along the 10 m survey transect (Figs. 3.1 C). This is best done using a short (~1 m) length of flexible tape that can be laid out to conform to the exact surface profile of the reef (Figs. 3.1 D). The full size of each colony to the nearest centimetre should be recorded. Care should be taken to include measures of the surface cover within all cracks and crevices along the linear transect. However, the monospecific nature of many ETP reefs, the micro-topographic relief of many of the common coral taxa, and their complex intergrown nature can make this challenging. Hence for several genera and species the ETP version of *ReefBudget* has been modified so that for some species only the surface profiles of the colonies need be measured – the calculation system then factors for the micro-topographic relief of these species based on extensive in-field measures of the relationship between the surface contour distance and true colony surface cover. This surveying "rule" is applied to the following corals: all *Pocillopora* (*Pocillopora verrucosa*, *Pocillopora damicornis*, *Pocillopora capitata*, *Pocillopora eydouxi* (*grandis*), *Pocillopora meandrina*, *Pocillopora effusus*, *Pocillopora inflata*, *Pocillopora woodjonesi*), all columnar and plating forms of the following species of *Pavona* (*Pavona clavus*, *Pavona maldivensis*, *Pavona varians*), and all columnar forms of the following species of *Porites* (*Porites panamensis*). Relevant conversion factors are listed in the coral production sheets (but can be user adapted as appropriate).

(4) Where the tape crosses open branching corals, the diameter of branches should be measured and then the total number of living branches that intersect below the guide tape should be counted e.g., if branches average 2 cm diameter, and 15 branches intersect the line, the total living cover for that colony would be recorded as 30 cm. This avoids over-estimating living coral cover as might occur if a tape is draped over the entire colony. Dead branches should be counted in the same way and recorded accordingly.

(5) In contrast to some benthic surveys the distance covered by sand and rubble should be included in the measures made.

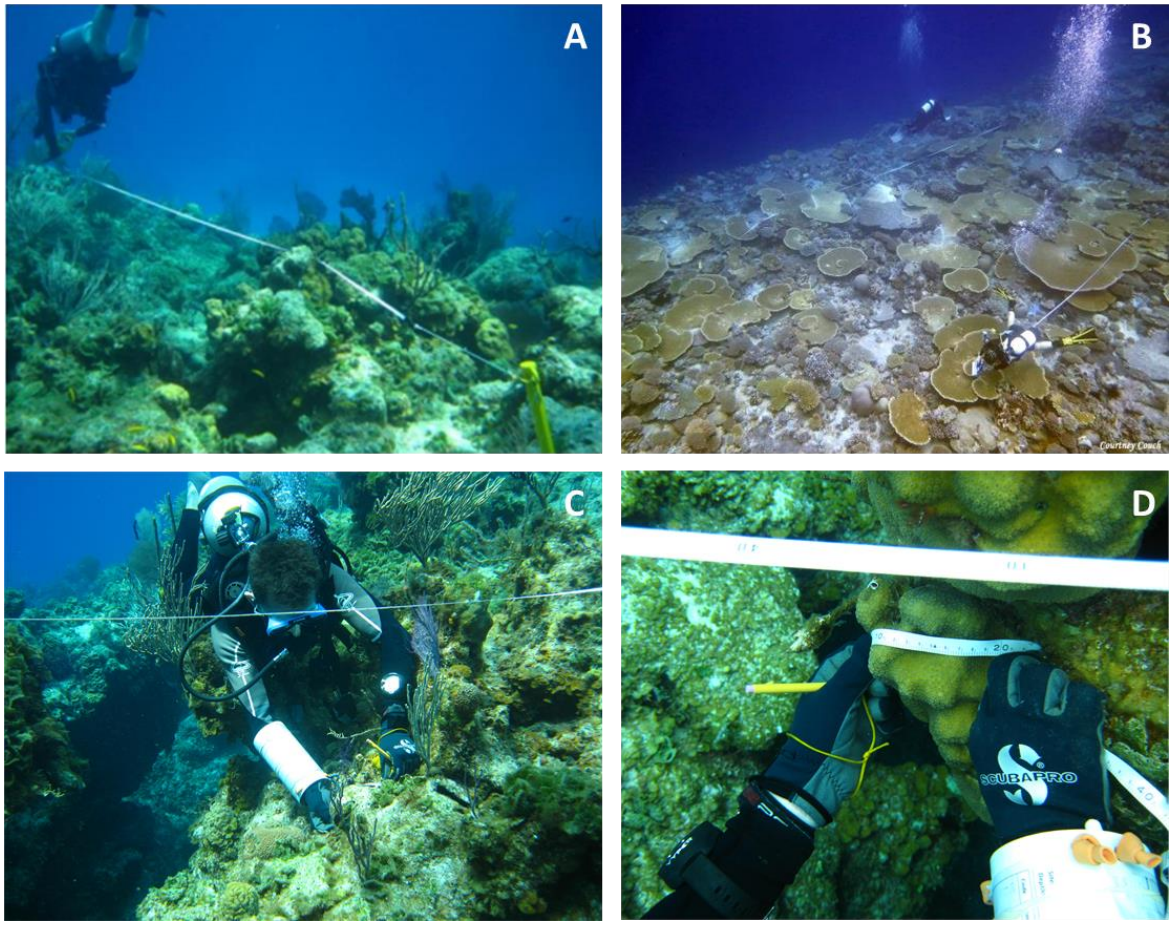


Fig 3.1| *(A, B) Master transect line, attached to a fixed marker stake, being laid out; (C) Diver recording linear distance cover by each benthic component immediately beneath the main 10 m transect line; (D) Care should be taken to ensure that the flexible substrate measuring tape conforms to the exact surface of the reef beneath the master transect line.*

3.1 Calculating coral carbonate production rates based on colony size and morphology

In order to derive accurate estimates of carbonate production, the density ($g.cm^{-3}$) of the particular primary (coral) or secondary producer (crustose coralline algae) in question needs to be combined with measures of the linear growth rate ($cm.yr^{-1}$), the geometric shape and the current size of each colony/crust. This produces a production rate for each colony in kg $CaCO_3$ yr^{-1}. These data can then be combined with the planar area of each transect (normally 10 m x 1 cm) to produce a carbonate production rate for the reef in kg $CaCO_3$ m^{-2} yr^{-1}, where m^{-2} refers to planar reef area.

In the *ReefBudget* calculations the following assumptions about colony morphology are made: massive colonies are assumed to grow uniformly in a hemispherical fashion; encrusting, foliose and plating colonies are assumed to be growing primarily at the edge of the colony (and at 10% of this growth rate across the remainder of the colony); and for branching and columnar colonies, the proportion of the colony area of growing branch tips is assumed to be growing at published rates, and the remainder of the colony at 10% of these rates. For corals with multiple plates, fronds or tables, it is thus important to measure each plate or frond separately.

Resultant carbonate production equations are:

Massive:

$$CP_i = \left(\left(g + \left(\frac{x}{\pi}\right)\right)^2 \pi - \left(\frac{x}{\pi}\right)^2 \pi\right).d$$

Submassive:

$$CP_i = g.x.d$$

An exception are submassive/finely branched *Pocillopora* for which rates are calculated with the branching formula below.

Encrusting/plating/foliose:

$$CP_i = h.(g.d) + 0.1g.x.d$$

Branching/corymbose/columnar:

$$CP_i = (x.c_a.g.d) + (x - c_a.x).0.1g.d$$

Where CP_i = carbonate production for colony *i*, *g* = growth rate, *x* = surface length of colony, *d* = skeletal density, *h* = the number of colony "edges" (normally 2), and c_a = proportion of colony that are growing axial branches. Measuring the linear surface of growing tips relative to total branch length on complex micro-relief branching or submassive corals, and for columnar growth form corals during surveys is time-consuming. Therefore, in order to calculate the amount of each colony that represents growing axial branch tips, we used the same conversion factor approach to that used in the Indo-Pacific version of *ReefBudget* based on measures made on a range of coral colonies in the wider IP region; Table 1. These conversion factors are used for relevant species of *Pavona*, *Pocillopora*, *Porites* and *Psammocora* in the calculation of carbonate production.

To calculate the production for a single transect over a year, the following equation is used:

$$CP_j = \sum_{i=1}^{n} CP_1 + CP_2 + \cdots + CP_n$$

Where CP_j is the total carbonate production of both corals and crustose coralline algae for transect *j* in kg $CaCO_3$ yr^{-1}.

To estimate the production rate of the reef, the following equation is used:

$$Gprod_j = CP_j/(\frac{10000}{l})$$

Where $Gprod_j$ is the carbonate production rate of both corals and crustose coralline algae for transect *j* in kg $CaCO_3$ m^{-2} yr^{-1}, and *l* is the transect length in centimetres.

Table 1| *Ratio of growing axial branches/tissue to colony size relevant to ETP coral taxa*

Genera	Morphology	Growing tips: colony size	95% CI	N
Pocillopora	branching	0.364	0.027	33
Porites	columnar	0.214	0.060	5

Note that the above calculations and conversion factors are already integrated into the calculation spreadsheets. For branching and columnar growth forms of genera that do not appear in the table above we currently use average conversion factors for the relevant morphologies. Additional site-specific data can be collected as needed.

The data entry sheets '*ETP Carbonate Production'* can be downloaded from the *ReefBudget* website. General site data and details of transects conducted should be completed on the 'Site Description' tab, and census data within each linear meter of transect added into the 'Data Entry' tab. The 'Analysis' tab then calculates the percent cover and carbonate production (where applicable) for each genus/morphotype for each transect. There is also a tab to calculate micro- and macro-bioerosion (see sections 4.3 & 4.4 for details). All data are then summarised in the 'Results' tab, which gives transect and site level data on total carbonate production, production by major coral guilds, life-history strategies (after Darling et al. (2012), derived from Coral Trait Database: https://coraltraits.org/traits/233) and genera. It also provides percent cover data for the same categories.

The spreadsheets have been pre-set to use where possible ETP specific average growth rates and skeletal densities for each coral species and morphology in question (augmented as needed by wider Indo-Pacific data) and an average CCA calcification rate from regional studies that investigated growth over >1 year. All rates can be manually modified in the 'Calcification Rates' tab if more local or depth-specific data are available. **NB. This is an issue that may need careful site consideration in the ETP region because of potential differences arising from latitudinal variations and the influence of upwelling in some locations.**

NB. The online supporting file '*ETP Coral-CCA growth and density metrics database*' summarizes currently available coral growth and skeletal density data (we are aware of) for ETP corals. These have been ordered approximately north to south by country to aid any selective regional use of the data. We are aware of only limited ETP specific data on CCA calcification rates (also listed in this spreadsheet) but use of these is currently made. It is an on-going intention to continue to add any newly available data to this resource. If you aware of relevant data that does not appear here, please forward such information to Chris Perry (c.perry@exeter.ac.uk) and Ines Lange (i.lange@exeter.ac.uk).

4 Determining rates of reef framework bioerosion

Bioerosion is defined as the corrosion of hard substrates by living agents (Neumann 1966). A wide variety of organisms contribute to this process, including not only particular species of fish and urchins, but also a variety of endolithic organisms (Golubic et al. 1981; Perry et al. 2008). These include boring sponges, bivalves, worms, cyanobacteria, chlorophytes, rhodophytes and fungi.

4.1 Urchin bioerosion

One group of major bioeroding grazers are the Echinoidea (sea urchins). These comprise two groups, one of which consists of species that live on soft bottoms and primarily ingest sediment and have negligible impact on carbonate budgets, and a second group which feed by scraping algae and other organisms off hard substrate (Bak 1990). In the ETP region, the following are the major bioeroding urchin species, *Diadema mexicanum*, *Eucidaris galapagensis*, *Eucidaris thouarssi*, *Centrostephanus coronatus* and *Toxopneustes roseus*. These urchins can erode coral reef substratum either by burrowing behaviour, which weakens the reef structure and increases a reef's susceptibility to storm damage, or directly through abrading the hard substrate through feeding behaviour. The *ReefBudget* methodology includes estimations of the latter of these two mechanisms of erosion.

In order to quantify echinoid bioerosion, *ReefBudget* uses a census-based approach and collects data on the abundance and size of urchins within 10 x 1 m belt transects along the 'master' transect lines (Box 3). Abundance/size data are then combined with published ETP region urchin erosion rate data. This approach is predicated on the premise that the rate of erosion by urchins is a function of species and size, with larger individuals causing more erosion (Bak 1994). A variety of techniques have been used to estimate bioerosion rates by urchins, including quantifying the $CaCO_3$ content of the gut (e.g., Conand et al. 1997) or faecal pellets (e.g., Glynn et al. 1979), both with or without estimations of reworked sediment, spine abrasion and gut turnover (e.g., Stearn et al. 1977; Griffin et al. 2003). This makes it difficult to compare the urchin bioerosion rates derived from different studies. However, evaluating published data on erosion rates against test size across all urchin species suggest a relatively tightly correlated plot. Figure 4.1A shows the aggregated bioerosion rates relative to test size for all bioeroding species of urchins across 6 studies in the ETP region.

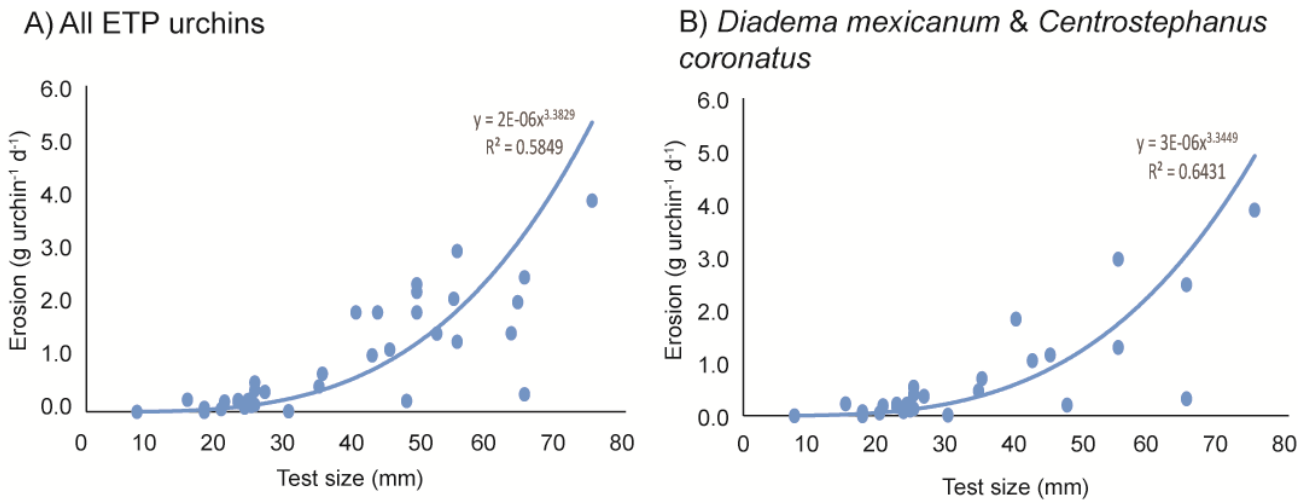


Fig. 4.1| *(A) Bioerosion rates (substrate removed/day (g)) for all urchins across a range of test sizes (ETP data only). (B) Bioerosion rates (substrate removed/day (g)) for Diadema mexicanum and Centrostephanus coronatus only. Data from: Glynn 1988; Herrera-Escalante et al. 2006; Alvarado 2012; López-Pérez and López-López 2016; Obonaga et al. 2017; Toro-Farmer et al. 2004; Reyes-Bonilla & Calderon Aguilera 1999.*

From this perspective, a single rate per urchin test size can be applied as follows:

$$\text{Bioerosion rate (g urchin}^{-1}\text{ day}^{-1}) = 2*10^{-6}.x^{3.3829}$$

where *x* is the test diameter of an urchin in millimetres.

However, more extensive data is available for two of the ETP species (*Diadema mexicanum* and *Centrostephanus coronatus*, both in the family Diadematidae) and for these two species use can be made of a separate relationship between test size and bioerosion rate (Fig. 4.1B). Separate equations are therefore used in the 'Data Analysis IndEQ' tab within the '*ETP Urchin Erosion*' spreadsheet that can be downloaded from the *ReefBudget* website:

Diadematidae (*Diadema mexicanum* and *Centrostephanus coronatus*):

$$\text{Bioerosion rate (g urchin}^{-1}\text{ day}^{-1}) = 3*10^{-6}.x^{3.3449}$$

where *x* is the test diameter of an urchin in millimetres.

BOX 3| Urchin Surveys – Recommended field methodology

(1) Conduct a 1 or 2 m wide belt transect along each 10 m transect line (Fig 4.2 A).

(2) The number and size classes of each bioeroding urchin species are recorded. Size classes are the width of the test (shell excluding any spines): 0-20 mm, 21-40 mm, 41-60 mm, 61-80 mm, 81-100 mm etc. A scale bar on the side of a dive slate can help discriminate categories (Fig 4.2 B).

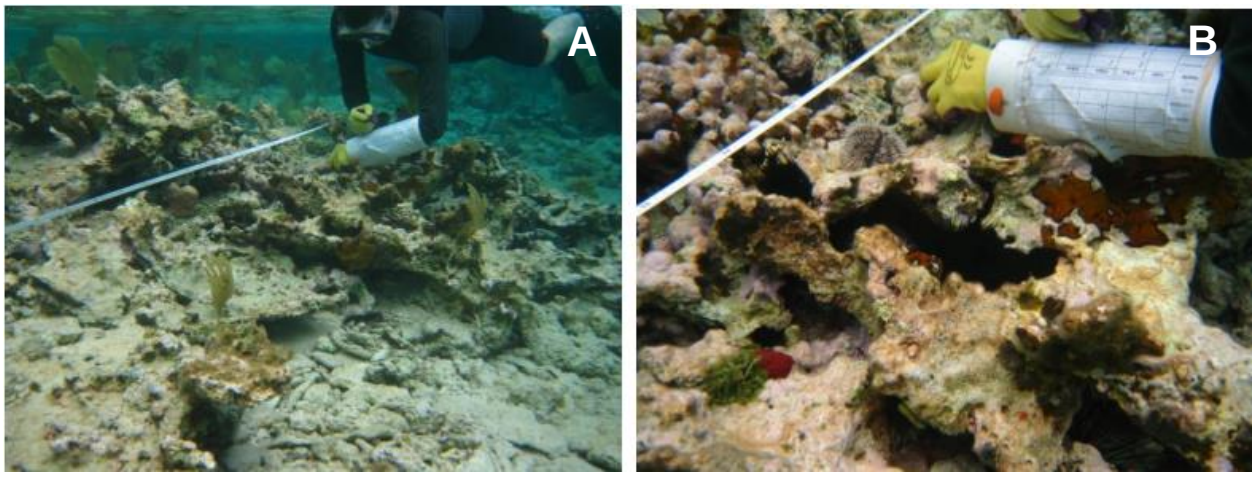


Fig. 4.2| *(A) Diver surveying urchins within an area 1 m either side of the master transect line; (B) Abundance and size class data for each species are recorded on the relevant survey sheet.*

4.1.1 Calculation of the amount of urchin bioerosion

The rate of bioerosion per urchin per day (g) is calculated using the relevant equations and the median of each size class. This rate is then multiplied by the number of individuals in each size class to yield the total daily rate of bioerosion per size class for each species. The total daily rate per size class is then multiplied by 365 to yield the total bioerosion rate per size class per year. Total bioerosion per size class per year is then summed to yield the total bioerosion by each species per year and these can be summed to yield a total rate for all urchins for the transect. Total erosion is then divided by the transect area to yield urchin bioerosion per metre squared, and converted to kg m^{-2} $year^{-1}$. The data entry sheets '*ETP Urchin Erosion*' can be downloaded from the *ReefBudget* website.

4.2 Fish bioerosion

There are a number of fish families whose feeding techniques contribute to the erosion of reef framework on ETP reefs (e.g., parrotfish, triggerfish and pufferfish). However, there are only a few species which actively erode the reef substratum because many species ingest unattached or reworked sediment and do not erode the reef framework directly. There has been substantial research undertaken on the different feeding modes of herbivorous reef fish, and these have been categorised into three main functional groups: grazers that primarily consume macroalgal fronds; scrapers that remove epilithic algae and sediment from the substrate surface; and excavators which remove part of the reef substratum (Bellwood and Choat 1990). While each of these three groups are important to the resilience and long-term maintenance of coral reefs, only the latter two have significant impacts on reef carbonate budgets, and excavators contribute to a much larger extent than scrapers. Most species that exhibit these forms of feeding are parrotfish (subfamily Scarinae, family Labridae). However, whilst bioeroding species of parrotfishes do occur on ETP reefs, species diversity is far lower than elsewhere in the Indo-Pacific, being represented by only four species of *Scarus*; *Scarus rubroviolaceus*, *Scarus ghobban*, *Scarus compressus* and *Scarus perrico*. In addition, it has been well-documented that species of pufferfishes, specifically *Arothron meleagris* and *Arothron hispidus*, play a key role in framework erosion on ETP reefs (Glynn et al. 1972, Reyes-Bonilla & Calderon-Aguilera 1999, Palacios et al. 2014), and that three species of triggerfish also contribute to fish bioerosion; *Sufflamen verres*, *Pseudobalistes naufragium* and *Balistes polylepis* (Alvarado et al. 2017). The ETP version of *ReefBudget* thus factors for erosion by each of these species.

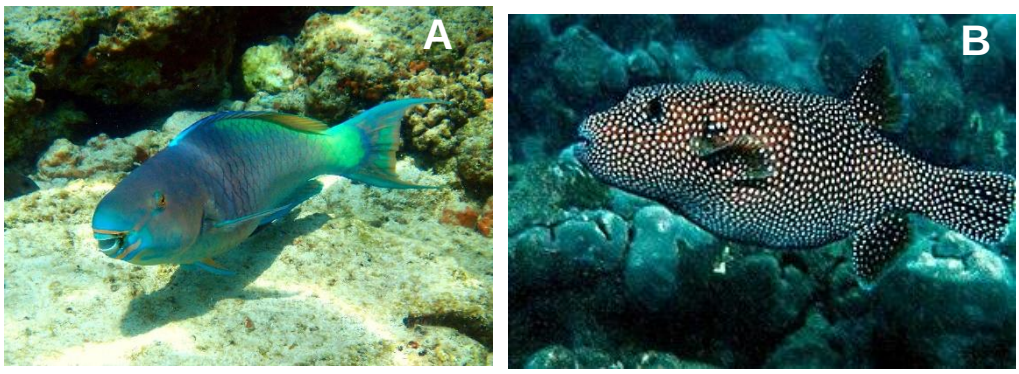


Fig 4.3| *(A) Scarus rubroviolaceus – a bioeroding parrotfish species, individuals of which can remove up to 295 kg of reef substrate per year; (B) Arothron meleagris – a common substrate eroding species of pufferfish on ETP reefs, individuals can remove up to 31 kg of substrate per year.*

Fish size and species for all these groups (parrotfishes, pufferfishes and triggerfishes) are important factors in controlling bioerosion rates. Numerous authors have reported higher bioerosion rates for larger fish (Bellwood 1995; Bruggemann et al. 1996; Ong and Holland 2010), and differences between the eroding capacities of similar sized fish of different species of parrotfishes, linked to their feeding functional group (Bruggemann et al. 1996; Hoey and Bellwood 2008). For parrotfishes, life stage and size are also important, because feeding rates may be higher in initial phase than in terminal phase fish, and usually decrease with size (Bruggemann et al. 1994a, 1994b; Mumby 2006; Lokrantz et al. 2008 but see Afeworki et al. 2013 and Yarlett et al. 2018). Whether this applies to pufferfishes and triggerfishes is unclear. Regardless, the key parameters that are needed to assess bioerosion rate are: species, life phase (for parrotfish species), fish size and abundance. In this context the *ETP ReefBudget* methodology calculates bioerosion rates for each individual fish within a size class for a particular species, and then combines this with abundance figures to yield rates per size class for each species. Various methods have been used to visually assess fish populations, and it is recommended that an underwater visual census along belt transects conducting instantaneous counts (i.e., not timed transects) is used (Box 4). In order to appropriately sample the fish population, we recommend replicate transects of at least 30 m in length, preferably 50 m (Samoilys and Carlos 2000) depending on the size of the reef. Therefore, fish erosion rates at

each transect will not be directly comparable with the benthic transects and when calculating carbonate budgets should only be applied at the wider site level.

BOX 4| Fish census – Recommended field methodology

(1) Conduct replicate belt transects of at least 30 m length by 5 m width. The spreadsheet has the capacity to accommodate data input from up to 10 transects and the higher the level of replication the better given the roaming nature of fish.

(2) Observations should be made between 10 am and 5 pm (the period of maximum feeding activity; Bellwood 1995), and when possible spread across the feeding day.

(3) Each transect should be conducted by a diver running out a tape or line of the desired length across the reef zone and waiting for ~5 minutes after laying the line before conducting the survey to allow fish to return to normal activity after the transect line has been set.

(4) The diver then swims slowly along the line noting the species, life phase (for parrotfish) and total length of each fish (Fig. 4.4 A). Total length is estimated within the following classes: 5-9 cm; 10-19 cm; 20-29 cm, 30-39 cm etc. It is recommended that at the start of each day training of size estimations is conducted by estimating lengths of a random selection of PVC pipe at ~ 3-5 m distance while in the water until the observer estimates are consistently ± 2 cm (McClanahan et al. 2007).

(5) An alternative approach is to use a calibrated stereo-video system (DOV) to record fish individuals while swimming along the same number and length of transects (Fig. 4.4 B). Fish can be identified from the video, and the length of each is calculated by a program overlaying pictures from both cameras. This method is considerably more cost-intensive but saves underwater working time and allows one to go back to the recording to look at other species if desired.

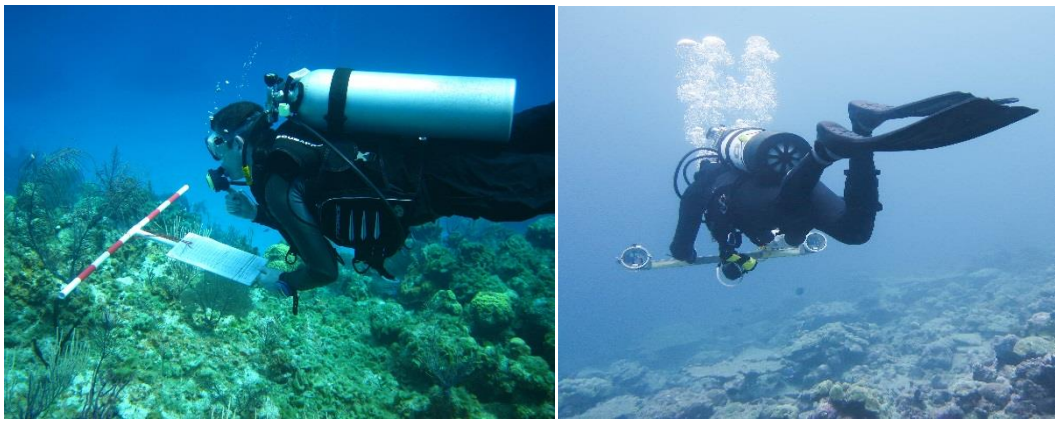


Fig 4.4| *(A) Diver surveying belt transects; (B) Diver using a stereo-video system*

4.2.1 Calculation of the amount of fish bioerosion

The method proposed for calculating bioerosion by fish on ETP reefs is based on the same principles used in other *ReefBudget* systems. For parrotfish, the model uses total length and life phase to predict bite rates (bites hr^{-1}), bite volume (cm^3) and proportion of bites leaving scars for each species. Daily bite numbers and volume removed per day by each individual fish are calculated from bites rates and volumes by integrating length of day, as defined in the 'Site Description' tab (default 12 h), and diurnal feeding activity (83-88%, Bellwood, 1995). Available published data used in the calculations are listed in the '*Equations*' tab of the '*ETP Fish Erosion sheet*' on the *ReefBudget* website. Of the three parameters, bite volume likely introduces the biggest error term for parrotfish species to the annual carbonate erosion estimate, as measurements in the field have been proven to be very difficult due to shallow bite depths and variable substrate morphology (e.g. Yarlett et al. 2018). The following equation is used to calculate parrotfish species specific erosion rates for the median value within each size class:

Bioerosion rate (kg.ind^{-1}yr^{-1}) = $v.s_{prop}.br.d*365$

Where v is bite volume (cm^3), s_{prop} is the proportion of bites leaving scars, br is bite rate (bites day^{-1}) and d is substratum density (default 1.46 g cm^{-3}, which is the average over all available coral taxa and growth form density data in the '*ETP coral growth and density data*' resource).

A comparison of published parrotfish erosion rates shows a considerable range in magnitude. There is evidence to suggest that feeding rates may differ across zones and locations (Hoey and Bellwood 2008) and with season and temperature (Ong and Holland 2010; Afeworki et al. 2013). Bite volume has been shown to be affected by food type and water depth (Ong and Holland 2010) as well as microtopography (convex, flat, concave surfaces) (Bellwood and Choat 1990). Therefore, to increase the accuracy of the model predicting bite rates and volumes from parrotfish size, it may prove useful to quantify feeding rates and measure bite scars at the survey sites (Box 5). This may be particularly important in regions or sites where parrotfishes can be abnormally large or towards range limits. Obtained rates can be entered into the spreadsheets in place of the current bite rates.

BOX 5| parrotfish bite rates and bite volumes – Recommended field methodology

(1) Identify a focal fish, and follow it for a minimum of 2 minutes, or until it has conducted several bite forays (a patch of closely spaced bites, followed by movement to another patch). This ensures it has acclimatised to the presence of the observer and is behaving naturally. Use your discretion – for some individuals more than 2 minutes of acclimatisation may be necessary.

(2) Note total length, life phase and species. Then observe the fish for at least 3 minutes (preferably 5 min), noting how many bites are taken, and how many bites leave visible scars (if possible).

(3) Length, width and, where possible, depth of bites for each species and size class can be measured during additional observations using callipers. As the depth for scrapers and small excavators can be very shallow (<0.1 mm), assumptions of 0.1 mm depth for small excavators and large *S. rubroviolaceus* and 0.05 mm for shallower scrapes can be used if necessary (Yarlett et al. 2018). Grazing scars can occur as 1 mark or 2 marks (made by the upper and lower jaws). In the latter case, both marks should be measured and the volume combined. Bite volume is calculated as length*width*depth.

Fig 4.4| *(A)* Example of grazing scars on a small *Porites* colony

For most species of pufferfishes and triggerfishes published data on rates of erosion is far from extensive, and well below the level of detail collected to date for parrotfishes. Rate calculations are thus based more simply on reported rates by fish size class. All currently available published data used in the calculations are listed in the '*Equations*' tab of the '*ETP Fish Erosion sheet*' on the *ReefBudget* website).

Data entry sheets for calculating fish erosion rates (*'ETP fish erosion rates'*) can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted, including length and width, should be completed on the 'Site Description' tab. Census data on fish species and size class are added on the 'Data Entry' tab. The 'Density' and 'Biomass' tabs provide an overview of fish density and biomass for each species and size class per transect and per hectare, and the 'Bioerosion Rate' tab provides bioerosion rates by species in kg m^{-2} yr^{-1} for each transect. The 'Equations' tab is where alterations can be made to bite rates, percent of bites

leaving scars and bite volumes. The 'Results' tab provides site average and transect level data on total bioerosion, abundance and biomass.

4.3 Macroborer (sponges, bivalves, worms) bioerosion

Macroborers are defined as those eroders which produce boreholes with diameters >1 mm and include endolithic sponges, polychaete and sipunculid worms, bivalves, decapods and cirripeds. Of these groups, sponges have received the greatest attention because, on a reef-wide basis (and especially within the Caribbean), they typically dominate the macroboring community, comprising 75-90% by proportion of substrate infestation (e.g., Highsmith 1981; Kiene and Hutchings 1994; Perry 1998). In the ETP region endolithic sponges are also certainly very common although often highly cryptic (see review of Alvarado et al. 2017), but boring bivalves are often the most abundant and destructive endolithic bioeroders. As in the wider Indo-Pacific polychaete and sipunculan worms also commonly contribute, and locally decapods may be important to coral framework abrasion. Approaches to measuring rates of macroendolithic bioerosion have primarily relied on two methods: (1) the use of experimental coral blocks left exposed for long periods (Kiene and Hutchings 1994; Osorno et al. 2005; Tribollet and Golubic 2005; Carreiro-Silva and McClanahan 2012); and (2) estimates of internal rates of bioerosion using cored or slabbed corals from which x-rays or CT scans have been taken to determine annual growth rates against which measures of internal substrate removal can be calibrated (e.g., DeCarlo et al. 2015). Calculated macroendolithic rates for ETP reefs are generally sparse, but all available data do point to much higher rates that in many other regions.

From the perspective of assessing endolithic bioeroder abundance in the ETP, as indeed in other parts of the wider Indo-Pacific, a key further challenge is that the macroborer community is generally less visually apparent compared to the Caribbean. This is particularly true of clionaid sponges, which are generally cryptic and difficult to identify in the field (Schönberg 2015). To this end, and as used in the Indo-Pacific *ReefBudget* approach, the ETP methodology necessarily utilizes published rates of total macrobioerosion alongside data on substrate available for bioerosion derived from the benthic transects. This consists of all dead carbonate substrate available to bioeroding organisms, including that covered by macroalgae or algal turf, and live coral cover.

4.3.1 Calculation of the amount of macrobioerosion

Estimates of macrobioerosion are automatically calculated in the '*ETP Carbonate Production'* spreadsheet, in the 'Macro & Microbioerosion' tab, based on published rates of macrobioerosion (where available, locally derived rates can be manually entered into the spreadsheet) and factored for available surface area of the reef. All substrate available to macrobioeroders is included. The spreadsheets are pre-set with an average macrobioerosion rate based on all currently available published data for the ETP region. Note that currently the rate used is an average of all reported rates for different groups or combined groups as reported in Alvarado et al (2017) – and that these rates are very substantially higher than the rates applied in the wider Indo-Pacific *ReefBudget* methodology. These higher rates are however reasonable to apply because endolithic macrobioerosion is known to generally proceed at a higher rate that elsewhere in the Indo-Pacific (Alvarado et al. 2017).

4.4 Endolithic microborer (cyanobacteria, chlorophytes, fungi) bioerosion

The carbonate substrate of reefs can be degraded by the activities of photosynthetic cyanobacteria, chlorophytes and rhodophytes, and heterotrophic fungi and bacteria (Golubic et al. 1981). As with macrobioerosion, assessments of microbioerosion have tended to rely on deploying experimental substrates, predominately dead *Porites* sp. blocks (e.g., Chazottes et al. 1995; Chazottes et al. 2002; Tribollet and Golubic 2005). Most studies have chosen to examine either the bathymetric ranges of individual species, or community composition and succession dynamics of different taxa rather than determining total rates of microboring. Despite data on these

processes being sparse, microbioerosion has the potential to contribute to a non-negligible amount of bioerosion on coral reefs, since the published rates are within similar ranges to those of macroborers.

4.4.1 Calculation of the amount of microbioerosion

Estimates of microbioerosion rates are automatically calculated in the '*ETP Carbonate Production'* spreadsheet, in the 'Macro & Microbioerosion' tab, based on published rates of microbioerosion (where available, locally derived rates can be manually entered into the spreadsheet) and factored for available surface area of the reef. All substrate available to microbioeroders is included. The spreadsheets are pre-set with an average microbioerosion rate based on all currently available published data for the wider Indo-Pacific region due to the lack of any ETP specific data (see 'IP Calcification and bioerosion rates_database' file on the *ReefBudget* website).

5 Explanations for accompanying Excel spreadsheets

Three spreadsheets are provided for the *ETP ReefBudget* methodology to calculate estimates of carbonate production and bioerosion.

The '*ETP Carbonate Production*' spreadsheet is where all benthic data is entered. It calculates percent cover of each category, and carbonate production and macro- & microbioerosion rates. It also provides summary data for each transect by coral genus, morphology, life-history strategy (sensu Darling et al. 2012) and other categories.

The '*ETP Urchin erosion*' spreadsheet calculates urchin erosion using either a general equation, or individual equations for the two species of Diadematidae which occur in the region. It reports urchin density and bioerosion by size class, group and transect. If relevant, urchin density by species can be obtained from one of the tabs.

The '*ETP Fish Erosion'* spreadsheet calculates bioerosion by parrotfish, pufferfish and triggerfish surveyed to species within 10 cm size categories. It reports density, biomass and bioerosion fishes at the species and transect level.

Grey and yellow cells should not be manipulated. Yellow cells are the results of formula; white cells are where values can be manipulated.

5.1 'ETP Carbonate Production' spreadsheet

5.1.1 Site description

This tab contains instructions for filling out the spreadsheet and space for a description of the study site and period.

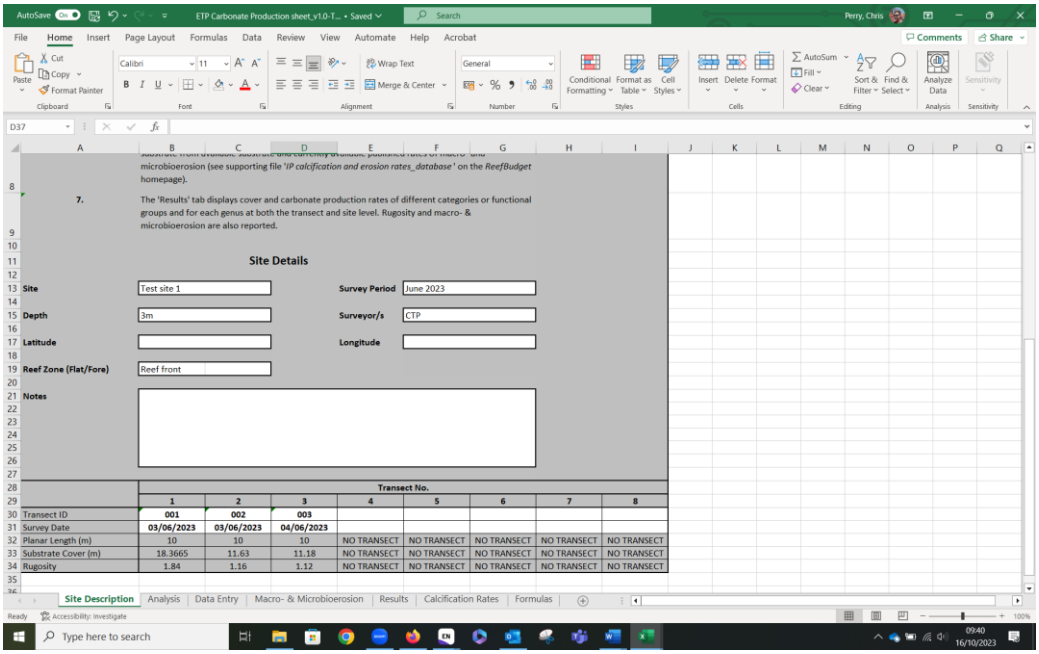
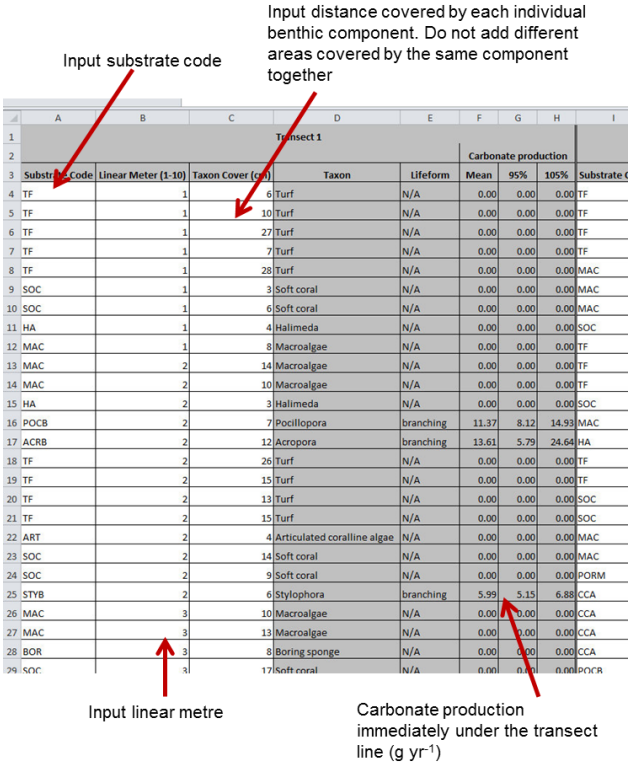


Fig 5.1.1| *Example of the 'Site Description' tab in the 'ETP carbonate production' spreadsheet*

The calculations in the spreadsheet automatically adjust for varying numbers of transects up to a maximum of 8 per site, and also for situations where it may not be possible to complete a full 10 m transect. In the site description tab, it is essential to **allocate a Transect ID** and a **survey date** for each transect in order for the calculations to work correctly.

5.1.2 Data entry

This tab is for entering the data for each transect. It is important to ensure that the **correct codes** are used, and that at least the **final linear metre** is entered into the linear metre column (e.g., if a full transect has been done, this should be 10). **Do not add together measurements of the same benthic category, enter each colony/patch as a separate row**.



	A	B	C	D	E	F	G	H	I
1				Transect 1					
2						Carbonate production			
3	Substrate Code	Linear Meter (1-10)	Taxon Cover (cm)	Taxon	Lifeform	Mean	95%	105%	Substrate (
4	TF	1	6	Turf	N/A	0.00	0.00	0.00	TF
5	TF	1	10	Turf	N/A	0.00	0.00	0.00	TF
6	TF	1	27	Turf	N/A	0.00	0.00	0.00	TF
7	TF	1	7	Turf	N/A	0.00	0.00	0.00	TF
8	TF	1	28	Turf	N/A	0.00	0.00	0.00	MAC
9	SOC	1	3	Soft coral	N/A	0.00	0.00	0.00	MAC
10	SOC	1	6	Soft coral	N/A	0.00	0.00	0.00	MAC
11	HA	1	4	Halimeda	N/A	0.00	0.00	0.00	SOC
12	MAC	1	8	Macroalgae	N/A	0.00	0.00	0.00	TF
13	MAC	2	14	Macroalgae	N/A	0.00	0.00	0.00	TF
14	MAC	2	10	Macroalgae	N/A	0.00	0.00	0.00	TF
15	HA	2	3	Halimeda	N/A	0.00	0.00	0.00	SOC
16	POCB	2	7	Pocillopora	branching	11.37	8.12	14.93	MAC
17	ACRB	2	12	Acropora	branching	13.61	5.79	24.64	HA
18	TF	2	26	Turf	N/A	0.00	0.00	0.00	TF
19	TF	2	15	Turf	N/A	0.00	0.00	0.00	TF
20	TF	2	13	Turf	N/A	0.00	0.00	0.00	SOC
21	TF	2	15	Turf	N/A	0.00	0.00	0.00	SOC
22	ART	2	4	Articulated coralline algae	N/A	0.00	0.00	0.00	MAC
23	SOC	2	14	Soft coral	N/A	0.00	0.00	0.00	MAC
24	SOC	2	9	Soft coral	N/A	0.00	0.00	0.00	PORM
25	STYB	2	6	Stylophora	branching	5.99	5.15	6.88	CCA
26	MAC	3	10	Macroalgae	N/A	0.00	0.00	0.00	CCA
27	MAC	3	13	Macroalgae	N/A	0.00	0.00	0.00	CCA
28	BOR	3	8	Boring sponge	N/A	0.00	0.00	0.00	CCA
29	SOC	3	17	Soft coral	N/A	0.00	0.00	0.00	POCB

Fig 5.1.2| *Example of the 'Data Entry' tab in the 'Indo-Pacific carbonate production' spreadsheet*

5.1.3 Analysis

This tab contains the calculations for benthic carbonate production for each colony of each coral genera and morphology across all transects. Cover immediately under the transect line (cm), percent cover (%), planar production (i.e. the production immediately under the transect line; kg $CaCO_3$ yr^{-1}) and carbonate production per m^2 (kg $CaCO_3$ m^{-2} yr^{-1}). **This sheet should not be altered**, except if the **life history strategies** of specific taxa need to be updated.

5.1.4 Macro- & Microbioerosion

This tab calculates macro- and microbioerosion. The white cells are published rates of erosion – for macrobioerosion summarized in a table to the right of the data entry section, and for microbioerosion in the supporting '*IP Calcification and bioerosion rates_database'* file on the *ReefBudget* website. **Rates can be changed if desired**, and the spreadsheet will automatically calculate the erosion using these new rates.

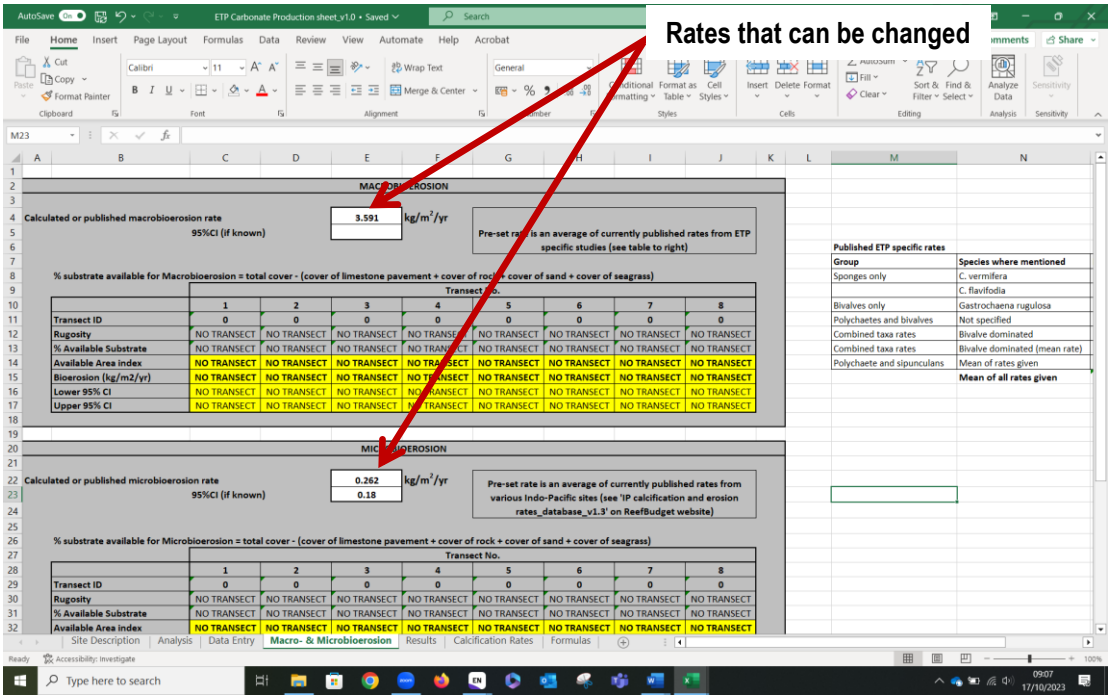


Fig 5.1.3| *Example of the 'Macro & Microbioerosion' tab in the 'ETP carbonate production' spreadsheet*

5.1.5 Results

This tab provides an extensive list of different categories. For gross carbonate production and erosion the top table provides a summary of rates. Below this there are tables that report cover and carbonate production by major functional categories, major coral groups, life-history strategies and genera. **This sheet should not be altered.**

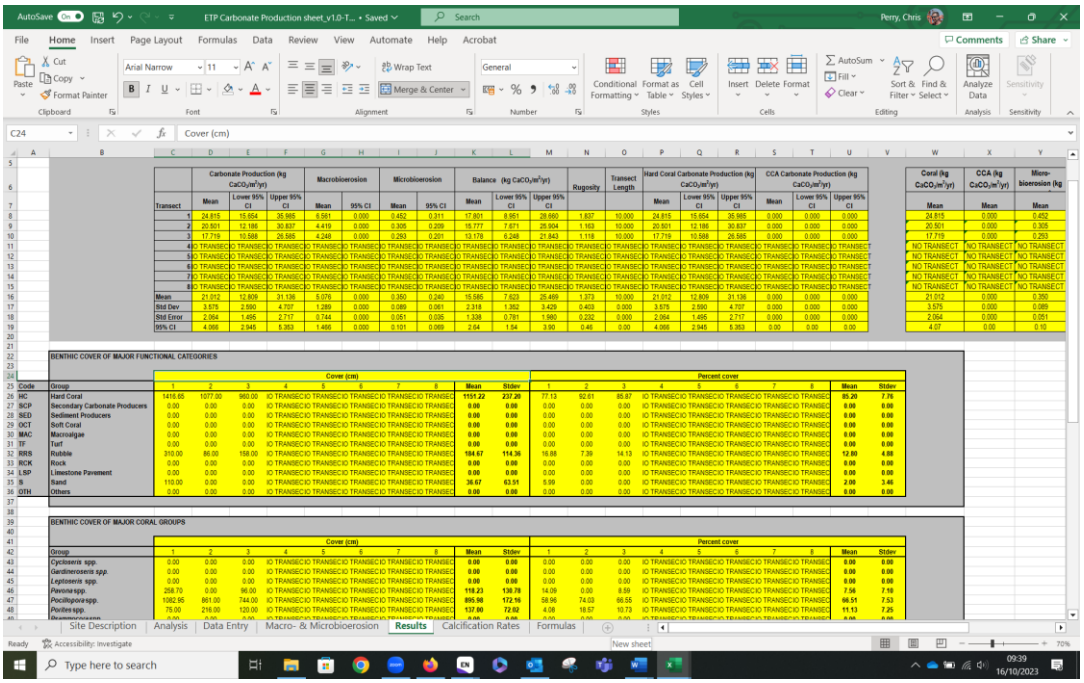


Fig 5.1.4| *Example of the 'Results' tab in the 'ETP carbonate production' spreadsheet*

5.1.6 Calcification Rates

This tab contains the linear extension and density values for each coral genera and morphology combination, which are means calculated from published studies, listed in the '*ETP coral growth and density metrics database*' excel file, along with the conversion factor for complex corals where required. **These can all be changed by the user if desired**. There is currently no facility for changing the base equations of the geometric shapes the colony production is calculated from.

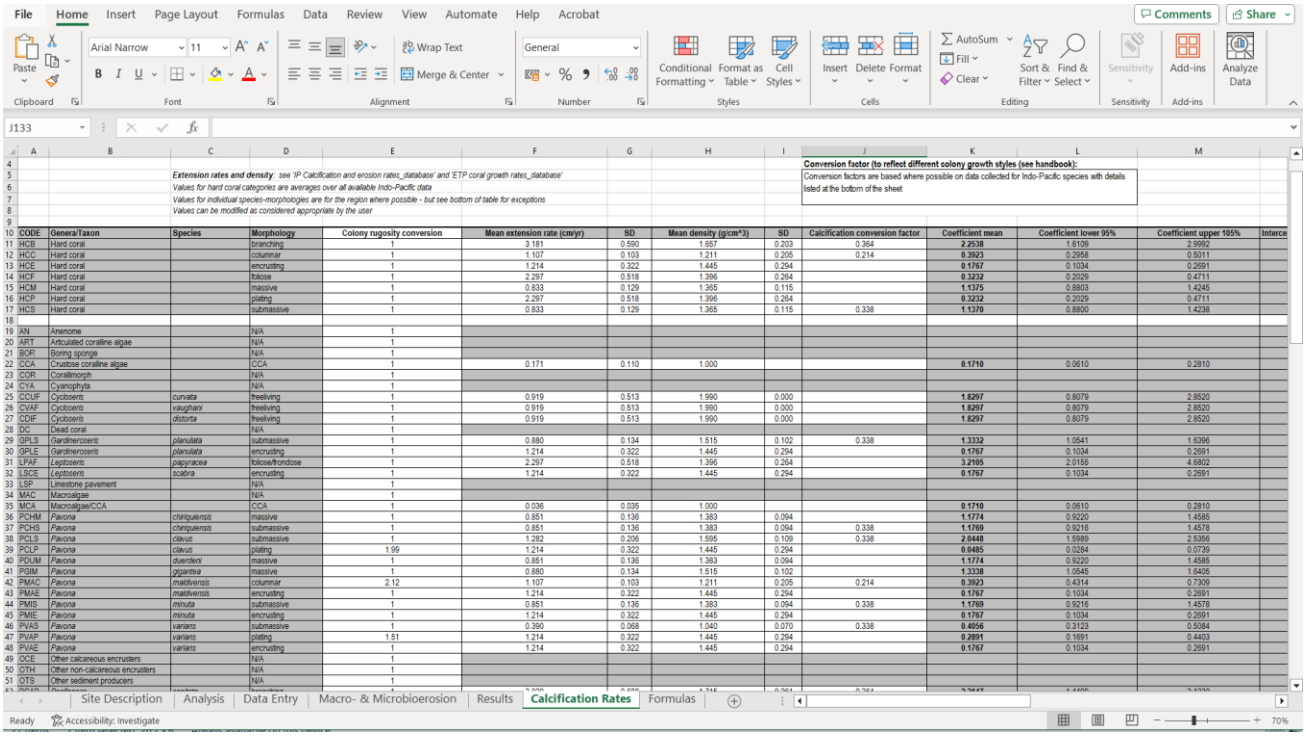


Fig 5.1.5| *The 'Calcification Rates' tab in the 'ETP carbonate production' spreadsheet*

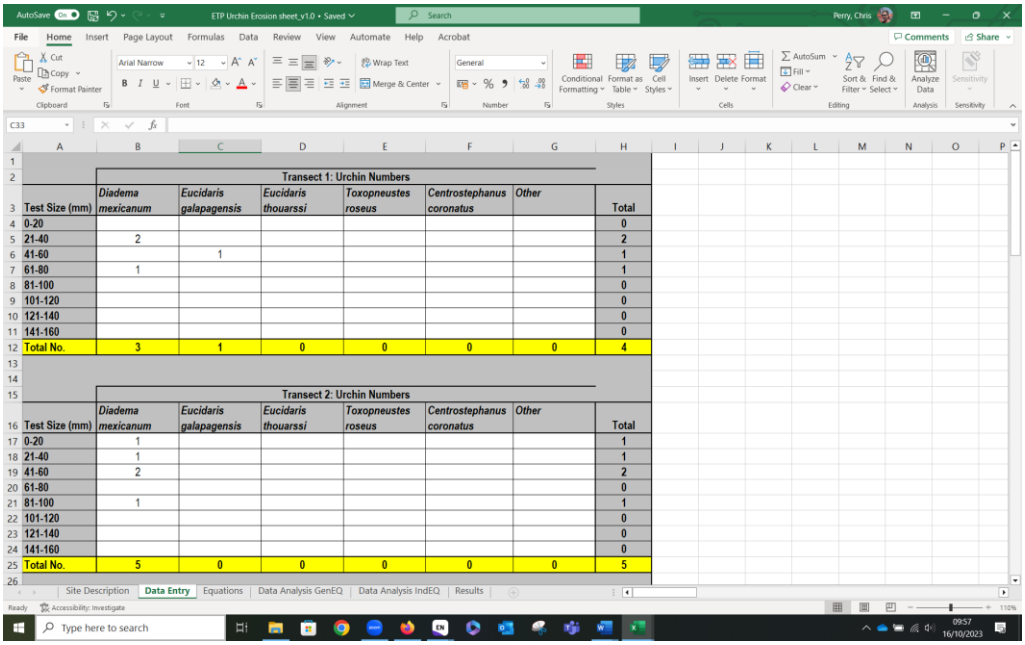
5.2 'ETP Urchin Erosion' spreadsheet

5.2.1 Site description

This tab contains instructions for filling out the spreadsheet to calculate bioerosion of reef substrate by urchins. It is very similar to the '*ETP Carbonate Production*' sheet. **Transect ID and the length and width of transects must be entered** for the formulas to work correctly.

5.2.2 Data Entry

The number of urchins in each size category for each species should be entered for each transect. If there were no urchins present (either in a size category or an entire transect) the **cells can be left blank** and the formula will still work. Non-eroding urchins are present in this data entry tab, but are not used to calculate urchin bioerosion.



	A	B	C	D	E	F	G	H
1								
2		Transect 1: Urchin Numbers						
3	Test Size (mm)	*Diadema mexicanum*	*Eucidaris galapagensis*	*Eucidaris thouarssi*	*Toxopneustes roseus*	*Centrostephanus coronatus*	*Other*	Total
4	0-20							0
5	21-40	2						2
6	41-60		1					1
7	61-80	1						1
8	81-100							0
9	101-120							0
10	121-140							0
11	141-160							0
12	Total No.	3	1	0	0	0	0	4
13								
14								
15		Transect 2: Urchin Numbers						
16	Test Size (mm)	*Diadema mexicanum*	*Eucidaris galapagensis*	*Eucidaris thouarssi*	*Toxopneustes roseus*	*Centrostephanus coronatus*	*Other*	Total
17	0-20	1						1
18	21-40	1						1
19	41-60	2						2
20	61-80							0
21	81-100	1						1
22	101-120							0
23	121-140							0
24	141-160							0
25	Total No.	5	0	0	0	0	0	5
26								

Fig 5.2.1| *The 'Data Entry' tab in the 'ETP Urchin Erosion' spreadsheet*

5.2.3 Equations

This tab contains the equations, and the amount of carbonate an urchin in each size category will consume. **These can be adjusted if desired.**

5.2.4 Data Analysis GenEQ & Data Analysis IndEQ

These two sheets contain the formulas necessary to calculate the abundance, density and bioerosion by urchins either using the general equation for all urchins (GenEQ), or the individual equations for the two separate groups (IndEQ). If required, total urchin abundance should be obtained from the 'Data Analysis GenEQ' tab.

5.2.5 Results

This tab gives the results from using either the general or individual equations for the site, each transect and each size category.

5.3 'ETP Fish Erosion' spreadsheet

5.3.1 Site description

This tab contains instructions for filling out the spreadsheet to calculate the bioerosion of reef substrate by fish. It is very similar to the previous sheets. **Transect ID and the length and width of transects must be entered** for the formulas to work correctly. The mean daylight period can also be changed (currently set to a default of 12 hours).

5.3.2 Data Entry

Enter the number of each species for each size class for each transect. Again, if no individuals were present, cells should be left blank.

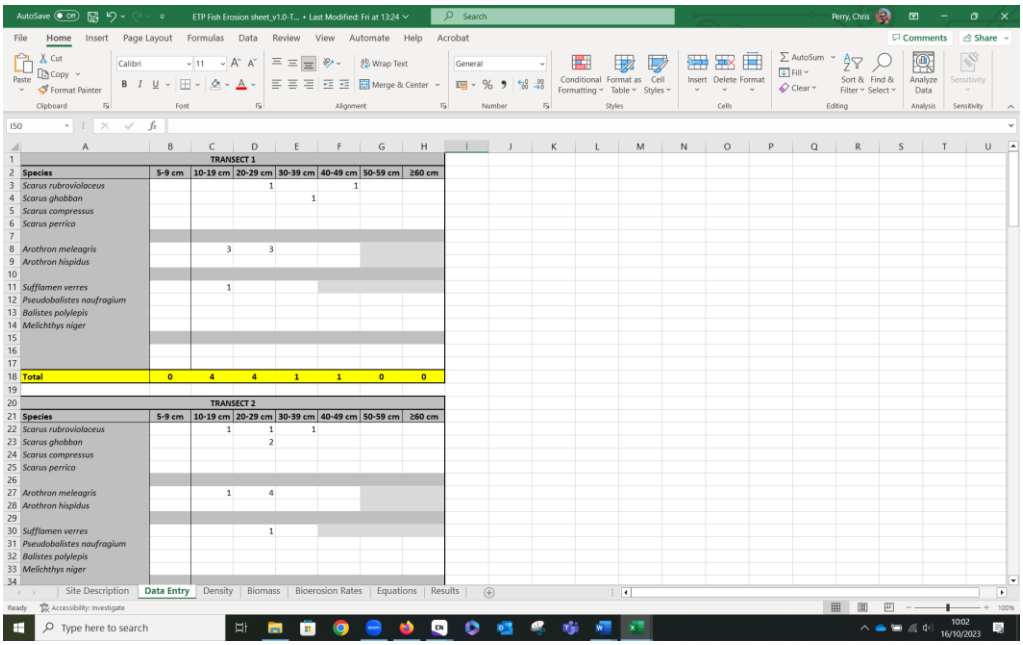


Fig 5.3.1| *The 'Data Entry' tab in the 'ETP Fish Erosion' spreadsheet*

5.3.3 Density, Biomass & Bioerosion Rates

These tabs calculate the density (individuals hectare^{-1}), biomass (kg hectare^{-1}) and bioerosion (kg $CaCO_3$ m^{-2} year^{-1}) for each species and size class at each transect. Biomass is calculated using the formula:

$$\text{Biomass (kg m}^{-2}) = (a.(c.TL)^b)/1000$$

where a and b are averages of length-weight relationships published at fishbase.org (Froese & Pauly 2018), weighted by the number of replicates and the goodness of fit in each study. TL is the total length of the fish in cm and c a conversion factor in case the relationships were derived from standard length instead of total length. Relationships used in the '*ETP Fish Erosion*' spreadsheet for parrotfishes are stated in the supporting '*IP Parrotfish erosion_ database*' file on the *ReefBudget* website, the value is divided by 1000 to convert the weight from g to kg. Where there was no published relationship available for a particular species, the relationship for a species within the same genera, of similar size and geographic range was used.

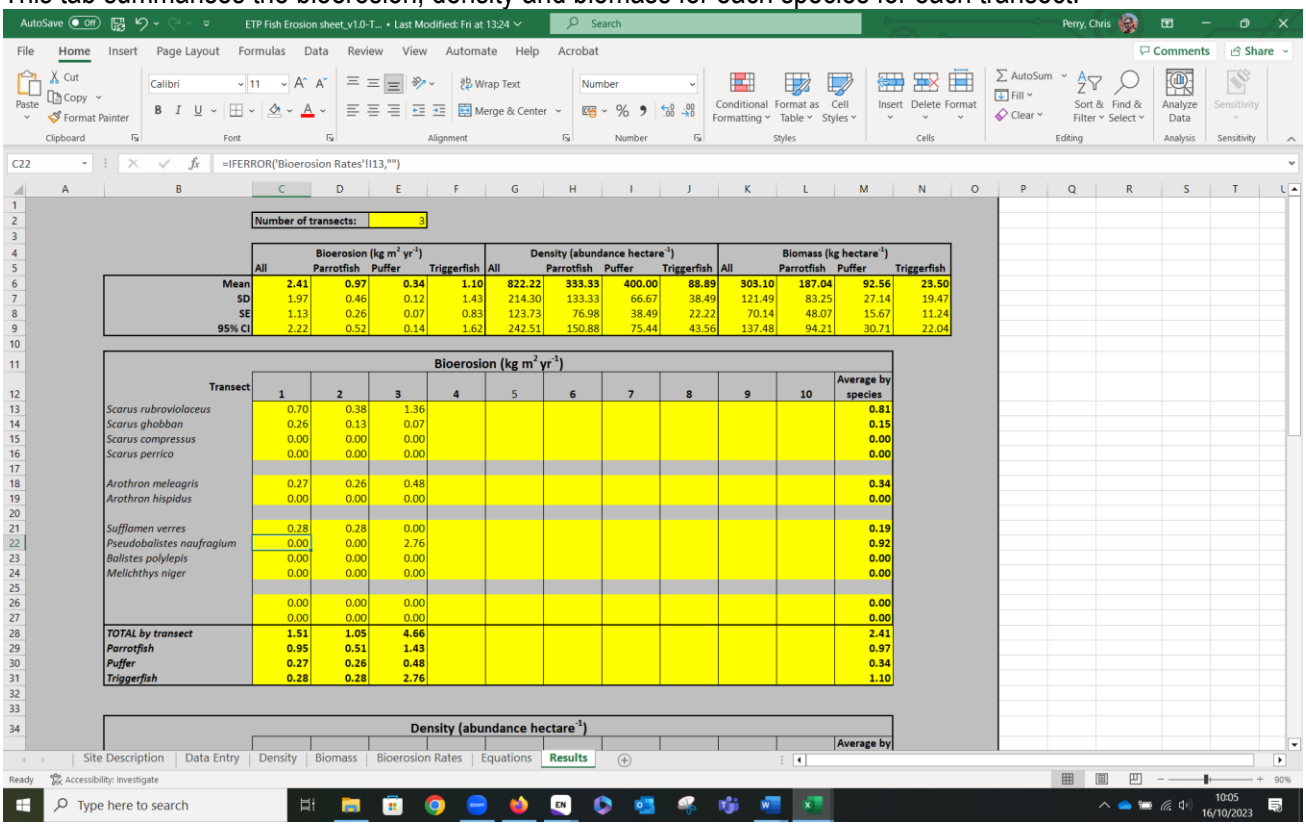
5.3.4 Equations

This tab contains the size class specific erosion rates for individual parrotfishes, and the data used to calculate these rates (Fig 5.3.2). This includes for parrotfishes: Proportion of bites leaving scars; Substrate density (g cm^{-3}); Bite rate (bites minute^{-1}); and volume removed per bite (cm^3) which **can be changed** as deemed appropriate. It also contains size class specific erosion rates for species of pufferfishes and triggerfishes that are used in the

calculations. Again, these **can be changed** as deemed appropriate Currently, the sheet is pre-set to provide average values from all available data with sources summarised in the sheets.

5.3.5 Results

This tab summarises the bioerosion, density and biomass for each species for each transect.



Number of transects: 3

	Bioerosion (kg m^2 yr^{-1})				Density (abundance hectare^{-1})				Biomass (kg hectare^{-1})			
	All	Parrotfish	Puffer	Triggerfish	All	Parrotfish	Puffer	Triggerfish	All	Parrotfish	Puffer	Triggerfish
Mean	2.41	0.97	0.34	1.10	822.22	333.33	400.00	88.89	303.10	187.04	92.56	23.50
SD	1.97	0.46	0.12	1.43	214.30	133.33	66.67	38.49	121.49	83.25	27.14	19.47
SE	1.13	0.26	0.07	0.83	123.73	76.98	38.49	22.22	70.14	48.07	15.67	11.24
95% CI	2.22	0.52	0.14	1.62	242.51	150.88	75.44	43.56	137.48	94.21	30.71	22.04

Bioerosion (kg m^2 yr^{-1})

Transect	1	2	3	4	5	6	7	8	9	10	Average by species
Scarus rubroviolaceus	0.70	0.38	1.36								0.81
Scarus ghobban	0.26	0.13	0.07								0.15
Scarus compressus	0.00	0.00	0.00								0.00
Scarus perrico	0.00	0.00	0.00								0.00
Arothron meleagris	0.27	0.26	0.48								0.34
Arothron hispidus	0.00	0.00	0.00								0.00
Sufflamen verres	0.28	0.28	0.00								0.19
Pseudobalistes naufragium	0.00	0.00	2.76								0.92
Balistes polylepis	0.00	0.00	0.00								0.00
Melichthys niger	0.00	0.00	0.00								0.00
	0.00	0.00	0.00								0.00
	0.00	0.00	0.00								0.00
TOTAL by transect	**1.51**	**1.05**	**4.66**								**2.41**
Parrotfish	**0.95**	**0.51**	**1.43**								**0.97**
Puffer	**0.27**	**0.26**	**0.48**								**0.34**
Triggerfish	**0.28**	**0.28**	**2.76**								**1.10**

Density (abundance hectare^{-1})

Average by

Fig 5.3.2| *The 'Results' tab in the 'ETP Fish erosion' spreadsheet showing total erosion rates, fish density and biomass and species level contributions to total fish erosion.*

6. References

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Appendix A: Benthic category codes and example data recording sheet

Benthic categories are listed in the table below. Most codes are of the following construction: 3 letters to denote the genus or taxa, and a final letter to denote morphology for corals. The exception is for corals with a free-living morphology (no morphology letter), and for some other non-coral taxa (e.g., DC – Dead coral, TF – turf algae, HA – *Halimeda*). The example survey sheet can be downloaded from the *ReefBudget* website http://geography.exeter.ac.uk/reefbudget/ in .pdf form.

CODE	Genera/Taxon	Species	Morphology	CODE	Genera/Taxon	Species	Morphology
HCB	Hard coral		branching	PCAB	*Pocillopora*	*capitata*	branching
HCC	Hard coral		columnar	PDAB	*Pocillopora*	*damicornis*	branching
HCE	Hard coral		encrusting	PEFB	*Pocillopora*	*effusus*	branching
HCF	Hard coral		foliose	PELB	*Pocillopora*	*elegans*	branching
HCM	Hard coral		massive	PEYB	*Pocillopora*	*eydouxi*	branching
HCP	Hard coral		plating	PINB	*Pocillopora*	*inflata*	branching
HCS	Hard coral		submassive	PLIB	*Pocillopora*	*ligulata*	branching
AN	Anenome		N/A	PMEB	*Pocillopora*	*meandrina*	branching
ART	Articulated coralline algae		N/A	PVEB	*Pocillopora*	*verrucosa*	branching
BOR	Boring sponge		N/A	PWOB	*Pocillopora*	*woodjonesi*	branching
CCA	Crustose coralline algae		CCA	PARP	*Porites*	*arnaudi*	plating
COR	Corallimorph		N/A	PAUM	*Porites*	*australiensis*	massive
CYA	Cyanophyta		N/A	PBAE	*Porites*	*baueri*	encrusting
CCUF	*Cycloseris*	*curvata*	freeliving	PEVM	*Porites*	*evermanni*	massive
CVAF	*Cycloseris*	*vaughani*	freeliving	PLIP	*Porites*	*lichen*	plating
CDIF	*Cycloseris*	*distorta*	freeliving	PLOM	*Porites*	*lobata*	massive
DC	Dead coral		N/A	PLUM	*Porites*	*lutea*	massive
GPLS	*Gardineroseris*	*planulata*	submassive	PPAC	*Porites*	*panamensis*	columnar
GPLE	*Gardineroseris*	*planulata*	encrusting	PRUP	*Porites*	*rus*	massive
LPAF	*Leptoseris*	*papyracea*	foliose/frondose	PSVB	*Porites*	*sverdrupi*	branching
LSCE	*Leptoseris*	*scabra*	encrusting	PHAE	*Psammocora*	*haimeana*	encrusting
LSP	Limestone pavement		N/A	PHAS	*Psammocora*	*haimeana*	submassive
MAC	Macroalgae		N/A	PPRE	*Psammocora*	*profundacella*	encrusting
MCA	Macroalgae/CCA		CCA	PPRS	*Psammocora*	*profundacella*	submassive
PCHM	*Pavona*	*chiriquiensis*	massive	PSTB	*Psammocora*	*stellata*	branching
PCHS	*Pavona*	*chiriquiensis*	submassive	PSTS	*Psammocora*	*stellata*	submassive
PCLS	*Pavona*	*clavus*	submassive	RCK	Rock		N/A
PCLP	*Pavona*	*clavus*	plating	RUB	Rubble		N/A
PDUM	*Pavona*	*duerdeni*	massive	RUBT	Rubble/turf		N/A
PGIM	*Pavona*	*gigantea*	massive	RUBC	Rubble/CCA		CCA
PMAC	*Pavona*	*maldivensis*	columnar	SD	Sand		N/A
PMAE	*Pavona*	*maldivensis*	encrusting	SEA	Seagrass		N/A
PMIS	*Pavona*	*minuta*	submassive	SCA	Soft coral/CCA		CCA
PMIE	*Pavona*	*minuta*	encrusting	SOC	Soft coral		N/A
PVAS	*Pavona*	*varians*	submassive	SP	Sponge		N/A
PVAP	*Pavona*	*varians*	plating	TF	Turf		N/A
PVAE	*Pavona*	*varians*	encrusting	ZOO	Zooanthid		N/A
OCE	Other calcareous encrusters		N/A				
OTH	Other non-calcareous encrusters		N/A				
OTS	Other sediment producers		N/A				

Site: Date:
Depth: Transect: Surveyor:

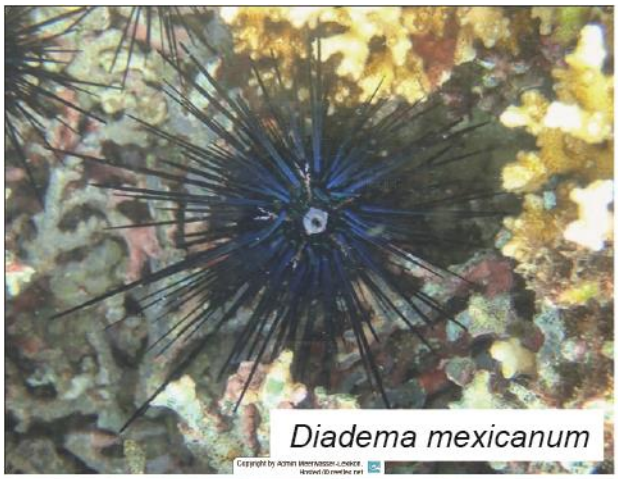
Code as genera + life form

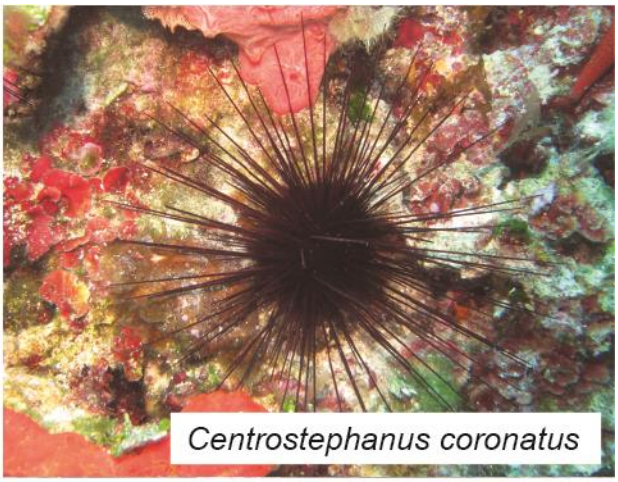
HCB	Hard coral - branching
HCC	Hard coral - columnar
HCE	Hard coral - encrusting
HCF	Hard coral - foliose
HCM	Hard coral - massive
HCP	Hard coral - plating
HCS	Hard coral - submassive
CCUF	Cycloseris curvata - foliose
CVAF	Cycloseris vaughani - foliose
CDIF	Cycloseris distorta - foliose
DC	Dead coral
GPLS	Gardineroseris planulata - submass
GPLE	Gardineroseris planulata - encrust
LPAF	Leptoseris papyracea - foliose
LSCE	Leptoseris scabra - encrust
PCHM	Pavona chiriquiensis - massive
PCHS	Pavona chiriquiensis - submass
PCLS	Pavona clavus - submass
PCLP	Pavona clavus - plating
PDUM	Pavona duerdeni - massive
PGIM	Pavona gigantea - massive
PMAC	Pavona maldivensis - columnar
PMAE	Pavona maldivensis - encrust
PMIS	Pavona minuta - submass
PMIE	Pavona minuta - encrust
PVAS	Pavona varians - submass
PVAP	Pavona varians - plating
PVAE	Pavona varians - encrust
PCAB	Pocillopora capitata - branch
PDAB	Pocillopora damicornis - branch
PEFB	Pocillopora effusus - branch
PELB	Pocillopora elegans - branch
PEYB	Pocillopora eydouxi - branch
PINB	Pocillopora inflata - branch
PLIB	Pocillopora ligulata - branch
PMEB	Pocillopora meandrina - branch
PVEB	Pocillopora verrucosa - branch
PWOB	Pocillopora woodjonesi - branch
PARP	Porites arnaudi - plating
PAUM	Porites australensis - massive
PBAE	Porites baueri - encrust
PEVM	Porites evermanni - massive
PLIP	Porites lichen - plating
PLOM	Porites lobata - massive
PLUM	Porites lutea - massive
PPAC	Porites panamensis - columnar
PRUP	Porites rus - plating
PSVB	Porites sverdrupi - branch
PHAE	Psammocora haimeana - encrust
PHAS	Psammocora haimeana - submass
PPRE	Psammocora profundacella - encrust
PPRS	Psammocora profundacella - submass
PSTB	Psammocora stellata - branch
PSTS	Psammocora stellata - submass

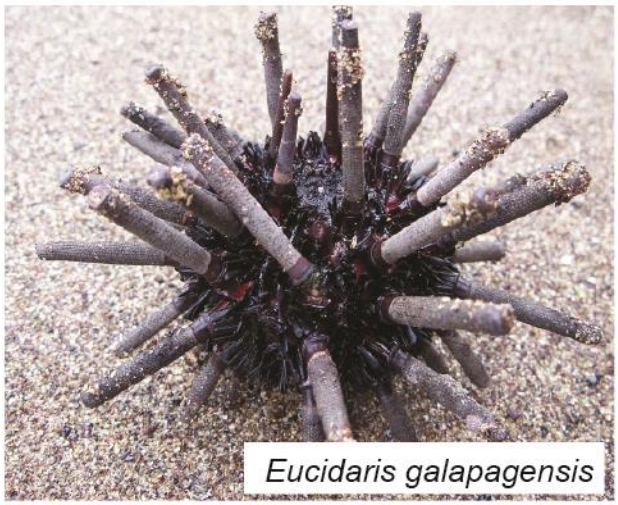
AN	Anenome	MCA	Macroalgae/CCA	SD	Sand
ART	Articulated coralline algae	OCE	Other calcareous encrusters	SEA	Seagrass
BOR	Boring sponge	OTH	Other non-calcareous encrusters	SCA	Soft coral/CCA
CCA	Crustose coralline algae	OTS	Other sediment producers	SOC	Soft coral
COR	Corallimorph	RCK	Rock	SP	Sponge
CYA	Cyanophyta	RUB	Rubble	TF	Turf
LSP	Limestone pavement	RUBT	Rubble/turf	ZOO	Zooanthid
MAC	Macroalgae	RUBC	Rubble/CCA		

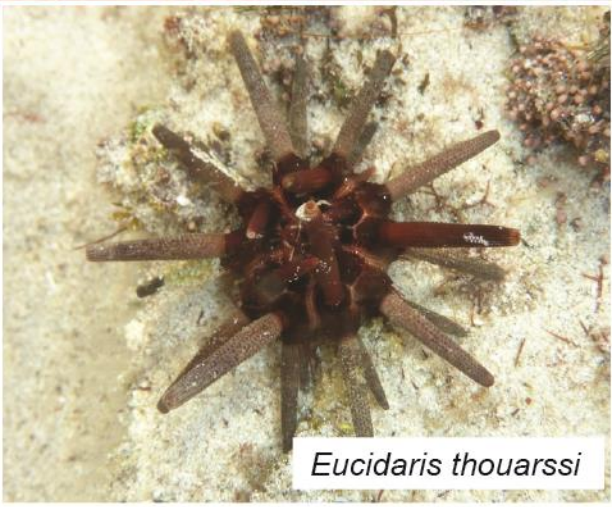
Urchins	0-20 mm	21-40 mm	41-60 mm	61 - 80 mm	81-100 mm	101 - 120 mm	121 - 140 mm
Diadema mexicanum							
Eucidaris galapagensis							
Eucidaris thouarssi							
Toxopneustes roseus							
Centrostephanus coronatus							
Other							

Appendix B: Common urchin species in the Eastern Tropical Pacific









Appendix C: Common eroding fish species in the Eastern Tropical Pacific