ReefBudget: Methodology

(*Indo-Pacific* version)

Development of this methodology was originally funded by the Ecosystem Services for Poverty Alleviation (ESPA) programme ‘Sustainable Poverty Alleviation from Coastal Ecosystem Services’ project (NE-K010484-1). The ESPA programme is funded by the Department for International Development, the Economic and Social Research Council, and the Natural Environment Research Council

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1 Census-based approaches to quantifying reef carbonate budgets

The Indo-Pacific *ReefBudget* methodology follows the framework production states approach (Perry et al. 2008) and is an extension of the methodology developed to support estimates of net biologically-driven carbonate budgets (kg $CaCO_3$ m^{-2} yr^{-1}) on Caribbean reefs (see http://geography.exeter.ac.uk/reefbudget/ and Perry et al. (2012)). 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 current format of the original Caribbean methodology, there are some important differences in this Indo-Pacific version. First, carbonate production by corals and coralline algae is calculated using geometric relationships derived from individual colony morphology, rather than calculated using rugosity at the transect level. These calculations are supported by relevant coral growth rate and skeletal density data from Indo-Pacific studies. Second, framework erosion by microborers (e.g., cyanobacteria, fungi) and macroborers (e.g., sponges, polychaete worms, bivalves) is calculated based on published rates 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 methodology arises from field-testing a revised version of the Caribbean *ReefBudget* methodology on coral reefs in East Africa, Chagos and the Maldives in both lagoonal and fore-reef environments during 2013-2018. The methodology has thus been refined over a number of years and differences to the Caribbean method take account of differences in the availability of data on growth/erosion rates, and inherent reef community differences between the regions.

- At present the protocol and supporting online database and spreadsheets are drawn from the entire Indo-Pacific. However, as more data on coral growth rates etc. become available, there is the potential to adapt this approach to become more region specific.

- As for the Caribbean *ReefBudget* methodology, these methods can in principle 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 data and calculations in the default spreadsheets, it is suggested that sites are limited to between 2 and 10 m depth, because this is the depth interval from across which the majority of data is drawn.

- Data should 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.
- 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.

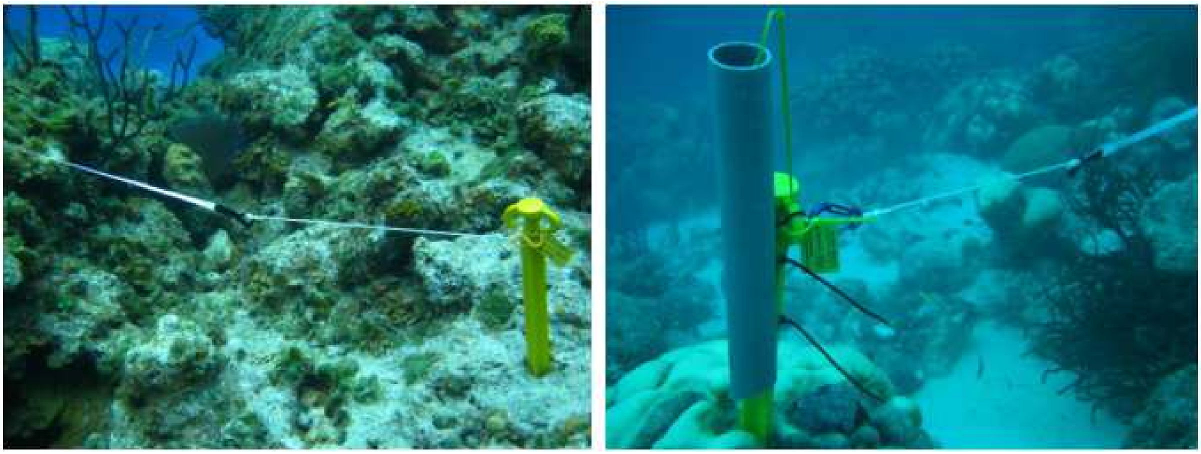


Fig 2.1| *Survey tape attached to marker stake showing 50 cm long 'leader' cord from clip to main tape.*

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 each taxon, 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 within each linear 1 m of 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 purpose 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 readily incorporated into the surveys, and may provide an essential context for understanding resultant budgetary data (for example, on reefs that have undergone phase shifts to macroalgal dominance). We recommend that data on the following groups are collected:

Essential categories to collect for Indo-Pacific* ReefBudget *framework calculations

- Coral to 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

Desirable

- 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 across the Indo-Pacific (http://coral.aims.gov.au/).

[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 growth rates, density and equations required to calculate carbonate production estimates.

(3) Measure the surface distance (cm's) covered by each benthic component directly beneath the master tape within each linear 1 m of 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). When the tape crosses a coral colony that is >1 m in size (i.e., it stretches across two linear metres of the master tape) it is necessary to record the full size of the colony to the nearest centimetre (i.e., if the colony is 115 cm this should be recorded as 115 cm, not 100 cm and 15 cm). In these cases, assign the colony to the metre in which the majority of the colony lies. Care should be taken to include measures of the surface cover within all cracks and crevices along the linear transect.

(4) Where the transect crosses areas of complex living coral cover (e.g., branching *Acropora*, overlapping table corals) the methodology is most effective if as reliable an estimate as possible is made of the distance covered by living tissue under the transect line.

(5) Where the tape crosses open branching corals, the diameter of these 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.

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

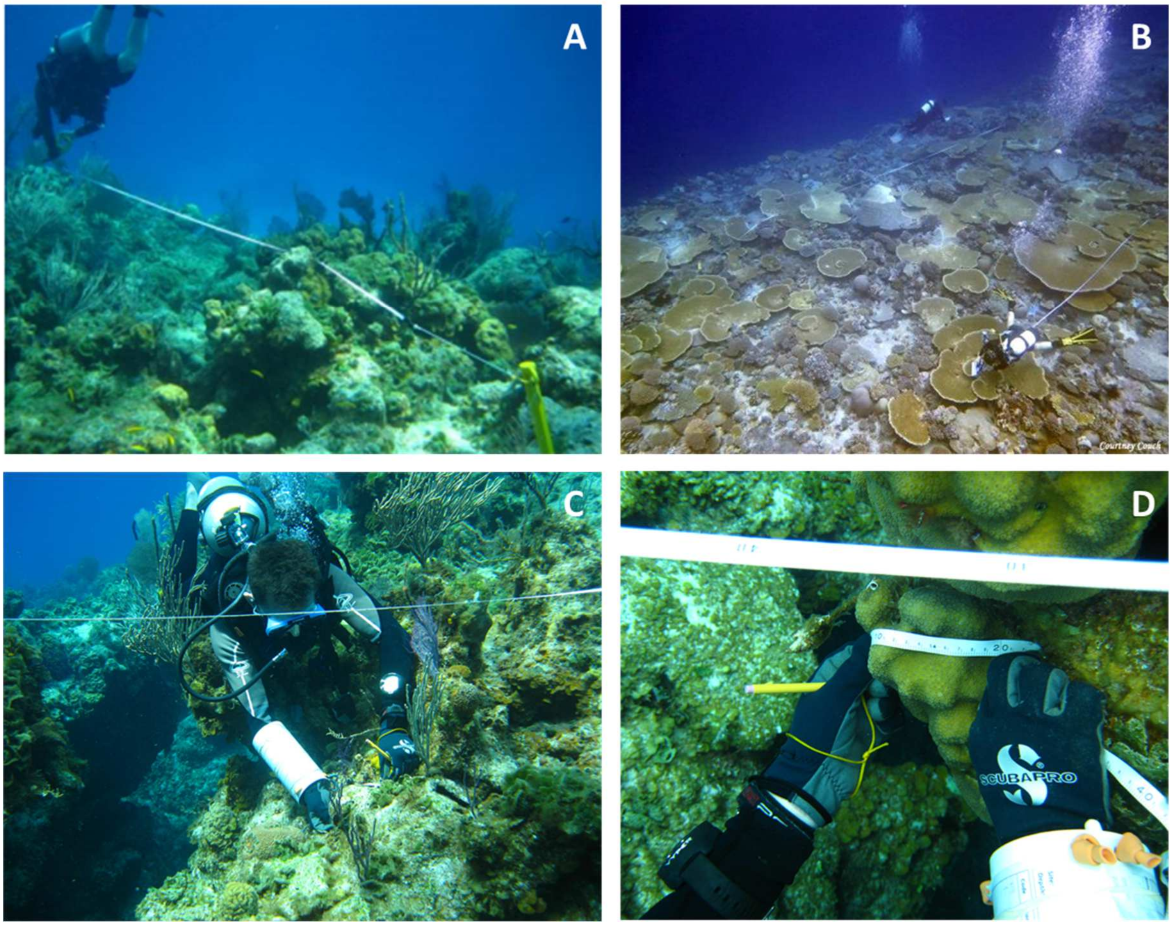


Fig 3.1| *(A, B) Master transect line, attached to a fixed marker stake, being laid out; (C) Diver recording linear distance cover by each benthic component immediately beneath the main 10 m transect line; (D) Care should be taken to ensure that the flexible substrate measuring tape conforms to the exact 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 *Pocillopora* and *Stylophora* which are calculated with the branching formula below, as for these taxa the submassive category is used to differentiate thickly branched growth forms from the more delicate ones.

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 on branching corals during surveys is time-consuming. Therefore, in order to calculate the amount of each colony that represents growing axial branch tips, we measured the size of branching colonies and the length of growing tips of each colony across 337 colonies in northern Mozambique (238 *Acropora*, 50 *Pocillopora*, 26 *Porites*, 23 other – Table 1) and these conversion factors are used for all branching and columnar taxa 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*

Genera	Morphology	Growing tips: colony size	95% CI	N
Acropora	arborescent	0.059	0.009	28
	branching, corymbose	0.190	0.012	145
	digitate	0.253	0.016	65
Millepora	branching	0.241	0.049	7
Pocillopora	branching	0.364	0.027	33
	submassive	0.338	0.032	17
Porites	branching	0.221	0.056	21
	columnar	0.214	0.060	5
Seriatopera	branching	0.141	0.023	6
Stylophora/Stylocoeniella	branching, submassive/columnar	0.327	0.064	10

Note that the above calculations and conversion factors are already integrated into the Default 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 '*Indo-Pacific 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 Indo-Pacific average growth rates and skeletal densities for each coral genus and morphology in question and Indo-Pacific average CCA calcification rates from 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. The online supporting file '*IP Calcification and bioerosion rates_database*' summarizes currently available coral growth and skeletal density data (we are aware of) for Indo-Pacific corals and CCA, as well as available macro- and microbioerosion rates. 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).

3.2 Coral growth rates and density measures

The collection of new data on rates of coral linear extension and density from each reef site used for budget estimates is clearly a problematic issue, because it requires significant amounts of coral sampling, analysis, and time. In the Caribbean, there is relatively low coral diversity and a relatively extensive (compared to other regions) dataset of both coral growth rate and density data (see original *ReefBudget*). The Indo-Pacific provides a very different situation, with well-developed reefs along wider longitudinal (~32°E to ~78°W) and latitudinal (~ 30°N to ~30°S) gradients, experiencing an arguable broader range of environmental conditions and with much higher biodiversity of corals (~1400 species compared to ~70 in the Caribbean). These factors mean that currently available data on growth rate and density gathered on one species in the Eastern Pacific may not accurately represent the same, or similar species in the Red Sea or Western Indian Ocean. Furthermore, the number of species for which there are well-replicated data at different geographic locations is, unsurprisingly, very small compared to Caribbean species (the massive corals *Porites lobata* and *lutea* are an exception, because they are often used in paleoclimate studies). Additionally, difficulties in accurately identifying many corals to species level in the field suggests that the use of genera level rates and growth form averages from across the Indo-Pacific region are at present a necessary requirement. Where no taxa specific rates are available, mean values for all hard corals (coded HC) of each growth form currently substitute for these missing rates (see '*IP Calcification and bioerosion rates_database*' file). These constraints need to be acknowledged in any assessments of carbonate production rates.

3.3 Crustose coralline algal growth and density measures

Far fewer published data are available for CCA growth rates and density than for corals, making quantitative estimates of CCA production less reliable. Studies in the Indo-Pacific used *Porites* blocks or PVC substrates, which were deployed in reef settings from 6 months to 5 years and analysed for lateral and vertical growth of algal patches or directly for annual calcium carbonate production (e.g. Pari et al. 1998, 2002; Kennedy et al. 2017; Lewis et al. 2017; Morgan and Kench 2017). Strikingly, calcification rates were on average 5 times higher in studies that deployed substrates for less than one year, indicating faster growth in the initial settling period. In the default mode, the spreadsheet therefore uses an average of rates from studies that investigated growth over >1 year only (see '*IP Calcification and bioerosion rates_database*' file). It is recommended, where possible, that simple experimental substrates are deployed for periods of 12-24 months in order to quantify calcification rates by calcareous encrusters within the study site in question (Box 2).

BOX 2| CCA growth experiment – Recommended field methodology

A wide range of potential substrates have been deployed in past experiments to quantify CCA production rates (Kennedy et al. 2017). Deployment of either lightly sanded PVC pipe (Fig. 3.2 A) or small plastic cards (such as those used for bank or library cards) ~ 8 x 5 cm (Fig. 3.2 B) in the proximity of each transect line are recommended (n = 6-9 pipes, or 5-6 cards), both for ease of deployment and because community recruitment closely matches that observed on surrounding natural substrates. These experimental substrates can be monitored to document CCA settlement and growth either through being photographed frequently (~every 3 months) or via a subset being retrieved approximately every 6-12 months for analysis (depending on the number of pipes/tiles and the amount of encrusting growth). Pipes/cards should be retrieved only after a bag has been secured around them with cable tie. These substrates can then be examined visually to ascertain percent cover and thickness of calcareous encrusters (and photographed in detail), and a weight per unit area derived. This is achieved by dissolving the CCA crust in 10% hydrochloric acid and dividing the dry weight by the surface area of the internal and external portions of the 10 cm length of pipe (see Morgan and Kench (2014) for further details), or by the surface area of cards (further differentiated by surface orientation if appropriate).

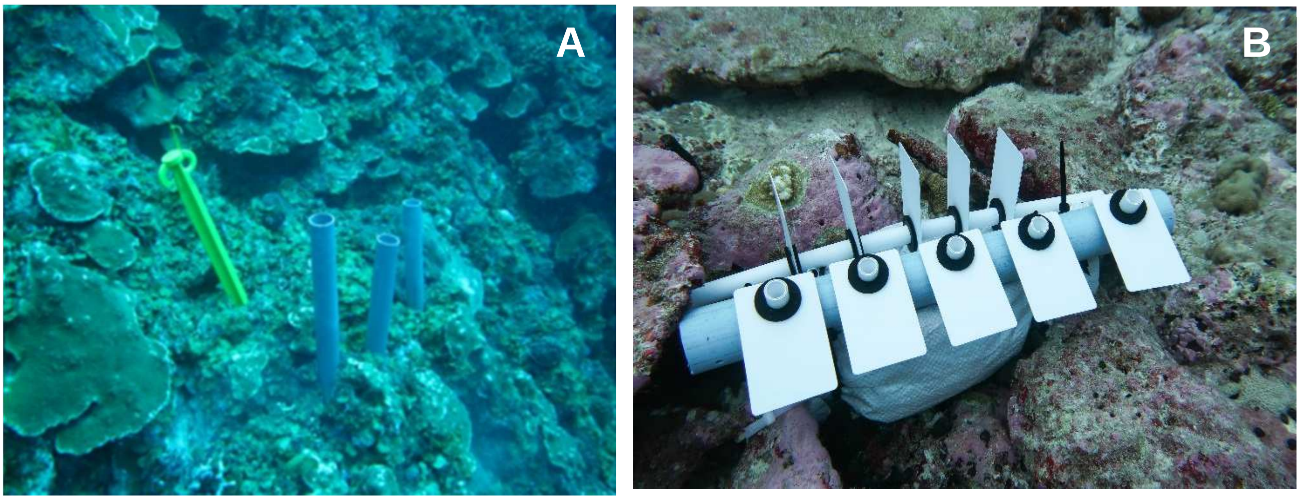


Fig 3.2| *(A) Array of PVC settlement pipes placed in the reef framework with an adjacent marker stake; (B) Array of PVC cards (in both horizontal and vertical orientations) deployed on a reef.*

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). Bak (1994) suggests that the main agents of echinoid bioerosion belong to the family Diadematidae, (*Diadema* spp., and *Echinothrix* spp.), and the genera *Echinometra*, *Echinostrephus*, and *Eucidaris*. 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 or 10 x 2 m belt transects along the 'master' transect lines (Box 3). Abundance/size data are then combined with published Indo-Pacific 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 six species of urchins across 9 studies in the Indian and Pacific Oceans, including the eastern tropical Pacific.

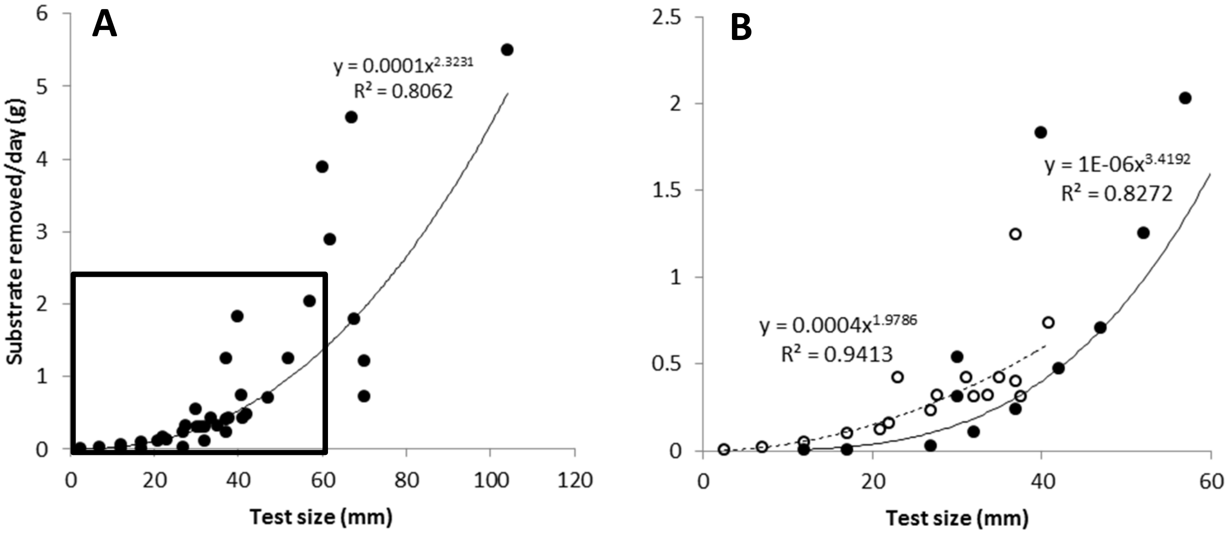


***Fig. 4.1**| (A) Bioerosion rates (substrate removed/day (g)) for urchins across a range of test sizes (Indo-Pacific data only). Data aggregated from: Russo 1980; Downing and El-Zahr 1987; McClanahan and Muthiga 1988; Bak 1990; Mokady et al. 1996; Conand et al. 1997; Mills et al. 2000; Carreiro-Silva and McClanahan 2001; Herrera-Escalante et al. 2005. (B) Close up of bioerosion rates for Diadematidae (solid circles) and Echinometra mathaei (open circles).*

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

$$\text{Bioerosion rate (g urchin}^{-1}\text{ day}^{-1}\text{)} = 1*10^{-4}.x^{2.323}$$

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

However, a more detailed assessment of the data suggests that at the genus/family level the relationship between test size and bioerosion rate may differ. In general, *Echinometra mathaei* tend to have higher bioerosion rates than Diadematidae in the smaller size classes (Fig. 4.1B). Separate equations are therefore used in the 'Data Analysis IndEQ' tab within the '*Indo-Pacific Urchin Erosion*' spreadsheet that can be downloaded from the *ReefBudget* website:

- Diadematidae (*Diadema* spp. and *Echinothrix* spp.):
  $$\text{Bioerosion rate (g urchin}^{-1}\text{ day}^{-1}\text{)} = 1*10^{-6}.x^{3.4192}$$
- *Echinometra mathaei*: Bioerosion rate (g urchin^{-1} day^{-1}) = $4*10^{-4}.x^{1.9786}$
- Other: General urchin bioerosion rate (g urchin^{-1} day^{-1}) = $1*10^{-4}.x^{2.323}$

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).

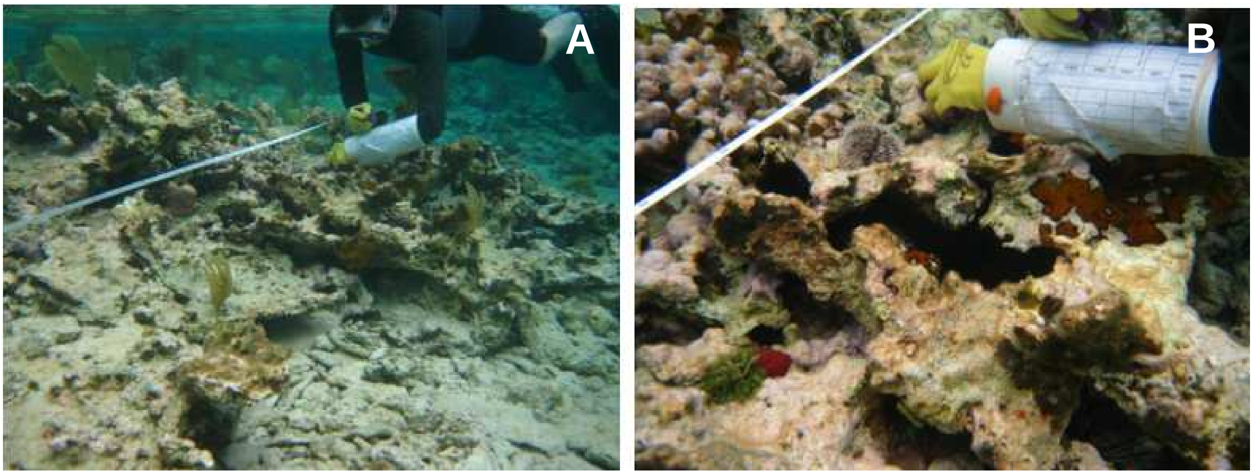


Fig. 4.2| *(A) Diver surveying urchins within an area 1 m either side of the master transect line; (B) Abundance and size class data for each species are recorded on the relevant survey sheet.*

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 '*Indo-Pacific 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 (e.g., parrotfish, triggerfish). However, there are only 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 that 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). Excavating parrotfish on Indian and Pacific Ocean reefs primarily are of the genus *Chlorurus*, while most scrapers are *Scarus* spp., although *Cetoscarus bicolor* and larger individuals of both *Scarus rubroviolaceus* and *S. ghobban* are also considered to have an excavating mode of feeding (Bellwood and Choat 1990; Ong and Holland 2010). While other fish families undoubtedly contribute to erosion, the *ReefBudget* methodology concentrates on quantifying erosion rates by parrotfish because this is the major eroding group.

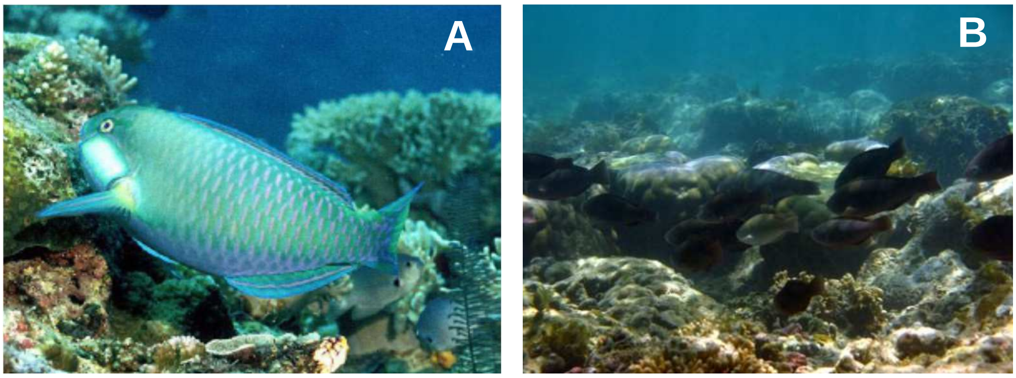


Fig 4.3| *(A) Chlorurus strongylocephalus – an excavating parrotfish species, individuals of which can remove up to 480 kg of reef substrate per year; (B) a school of Scarus frenatus – a scraping parrotfish that can remove up to 25 kg of substrate per year.*

In light of this, it is pertinent to note that parrotfish size and species 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, linked to their feeding functional group (Bruggemann et al. 1996; Hoey and Bellwood 2008). 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). The key parameters that are needed to assess parrotfish bioerosion are thus: species, life phase, fish size and abundance. In this context the *ReefBudget* methodology calculates bioerosion rates for each individual parrotfish 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 parrotfish populations, and it is recommended that an underwater visual census along belt transects conducting instantaneous parrotfish counts (i.e., not timed transects) is used (Box 4). In order to appropriately sample the parrotfish 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, parrotfish 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).
(2) Observations should be made between 10 am and 5 pm (the period of maximum feeding activity; Bellwood 1995).
(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 and total length of each parrotfish (Fig. 4.4 A). Total length is estimated within the following classes: 5-10 cm; 11-20 cm; 21-30 cm, 31-40 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 parrotfish 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.

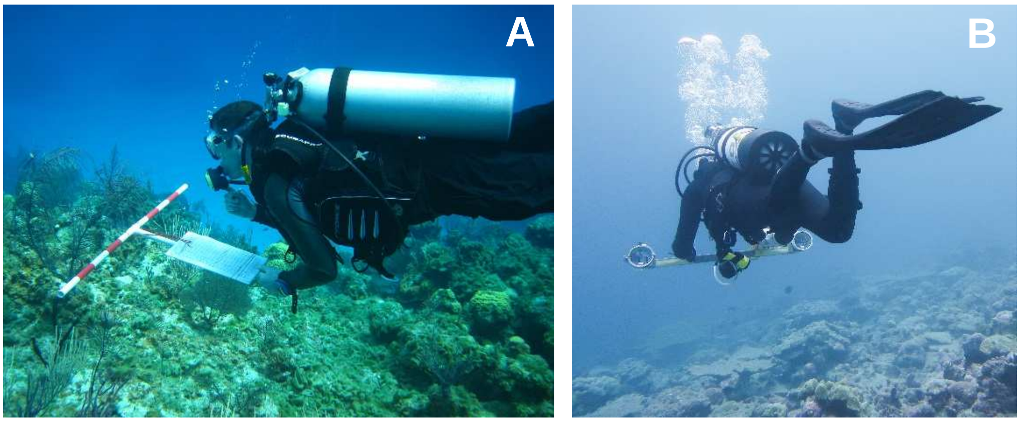


Fig 4.4| *(A) Diver surveying belt transects; (B) Diver using a stereo-video system*

4.2.1 Calculation of the amount of fish bioerosion

The method proposed for calculating bioerosion by fish is based on a model that 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 parrotfish species. Currently, this data is very patchy and exists for only a subset of species, but additional data can be added as it becomes available, or if collected as part of the same study (Box 5). An online resource (see '*IP Parrotfish erosion rates_database'* on the *ReefBudget* website) is provided that summarizes available published and unpublished data on bite rates, bite volumes and proportion of bites leaving scars for Indo-Pacific parrotfish species. However, due to the paucity of data it is currently necessary to integrate data from sister species and clades (grouped according to Choat et al. (2012)), where their size range and morphology correspond, and to use averaged values from these. Species without available data were substituted with species of similar size and feeding mode instead of exclusively looking at phylogenetic relationships. Currently, the calculations are only available for fish sizes up to 60 cm; in regions with very large parrotfish, bite volume data may have to be extrapolated to larger size classes and the associated uncertainty acknowledged. Of the three parameters, bite volume likely introduces the biggest error term to the annual carbonate erosion estimate, as measurements in the field have been proven to be very difficult due to shallow bite depth and variable substrate morphology (e.g. Yarlett et al. 2018).

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). The following equation is then used to calculate species specific erosion rates for the median value within each size class:

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

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 1.47 g cm^{-3}, which is the average over all available coral taxa and growth form density data in the '*IP Calcification and bioerosion rates_database'* 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| Bite rate and bite volume – 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

Data entry sheets for calculating '*Indo-Pacific Parrotfish Erosion'* 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 parrotfish species and size class are added on the 'Data Entry' tab. The 'Density' and 'Biomass' tabs provide an overview of parrotfish 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.

N.B. At the moment, the parrotfish data entry sheet is set up for Indian Ocean species only. Values for the calculations take into account published bite rates and volumes from the Great Barrier Reef and the Central Pacific to increase data coverage and thereby provide averages for all Indo-Pacific species. If the model is to be used in the Pacific, local species have to added to the ‘Data Entry’ tab and the upper table of the ‘Equations’ tab, and model assumptions of the respective parrotfish group in the lower tables will have to be assigned.

The largest parrotfish species, *Bolbometopon muricatum*, is not included in the *ReefBudget* methodology. The belt transect method used for counts of most species of parrotfish is not suitable to obtain estimates of populations of these large, mobile schooling species. Bellwood et al. (2003) estimated that an average sized *B. muricatum* can consume over 5 tonnes of structural reef carbonate per year. This value is based on high substrate density estimates of 2.44 g cm^{-3}. When the average density over all available coral data in the ‘*IP Calcification and bioerosion rates_database’* resource (1.47 g cm^{-3}) is used, the more conservative erosion estimate is 3428 kg yr^{-1} ind^{-1}. If *B. muricatum* is known to occur at the study site we recommend conducting an additional appropriate sampling strategy as follows, adapted from Bellwood et al. (2003).

BOX 6| *Bolbometopon muricatum* abundance – Recommended field methodology

(1) Conduct at least 6 timed transects of 5 m width and 20 minutes duration, swimming steadily throughout.
(2) Take GPS points at the start and the end of each transect to obtain transect length. This can also be achieved by attaching a GPS unit to a surface marker buoy and using the ‘track’ function.
(3) Record only the abundance of *B. muricatum*
(4) Bioerosion for each transect by *B. muricatum* is calculated using the formula below. This is then averaged over all transects to provide a site mean bioerosion rate.

$$\text{Bioerosion rate (kg m}^{-2}\text{ year}^{-1}) = 3428 * N_{BM}/\text{transect area}$$

Where 3428 is the amount of bioerosion per year by an average *B. muricatum* in kilograms, assuming a substrate density of 1.47 g cm^{-3}, and N_{BM} is the number of individuals surveyed.

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 Indo-Pacific, there are different contributions from macroborers, with worms providing a larger contribution, particularly in the first few years that substrate is available for colonisation (Sammarco and Risk; Tribollet and Golubic 2005; Carreiro-Silva and McClanahan 2012, however see Pari et al. 2002; Chen et al. 2013). In general, the proportion of substrate infested by sponges is reported to range from 30-80% across the Indo-Pacific, with higher values in sites of increased eutrophication or under protection from fishing (Carreiro-Silva and McClanahan 2012). Worms (both polychaetes and sipunculids) can contribute up to ~ 50% of the macro-bioeroder community by volume (Osorno et al. 2005; Tribollet and Golubic 2005; Carreiro-Silva and McClanahan 2012). Bivalves and decapods generally have small contributions to the macro-bioeroder community, but contributions can be high in some settings. Approaches to measuring rates of macro-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).

One issue that arises when assessing macroboring rates in the Indian and Pacific Oceans is that the macroborer community is generally less well characterised than that of 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, instead of conducting an intensive search of the substrate for clionaid sponges as described in the Caribbean *ReefBudget* approach, the Indo-Pacific methodology 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. While both live and soft corals can prevent settlement of most bioeroding sponges, live corals are often colonised by other bioeroders, particularly polychaete worms.

4.3.1 Calculation of the amount of macrobioerosion

Estimates of macrobioerosion are automatically calculated in the '*Indo-Pacific 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 not available to bioeroders (non-carbonate rock and sand) is excluded. The spreadsheets are pre-set with an average macrobioerosion rate based on all currently available published data for the Indo-Pacific region (see '*IP Calcification and bioerosion rates_database'* file on the *ReefBudget* website).

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 '*Indo-Pacific 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 not available to bioeroders (mud, sand, non-carbonate rock) is excluded. The spreadsheets are pre-set with an average microbioerosion rate based on all currently available published data for the Indo-Pacific region (see '*IP Calcification and bioerosion rates_database'* file on the *ReefBudget* website).

5 Explanations for accompanying Excel spreadsheets

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

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

The '*Indo-Pacific Urchin Erosion*' spreadsheet calculates urchin erosion using either a general equation, or individual equations for two main categories of urchins (Diadematidae and *Echinometra mathaei*). 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.

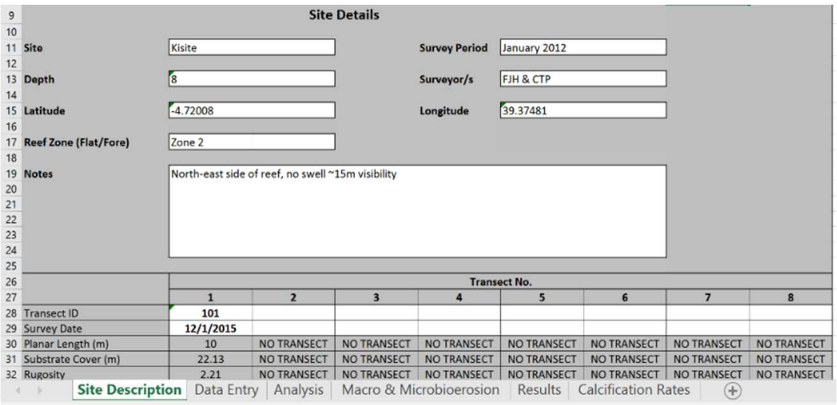
The '*Indo-Pacific Parrotfish Erosion'* spreadsheet calculates bioerosion by parrotfish surveyed to species and life-phase within 10 cm size categories. It reports density, biomass and bioerosion of parrotfishes at the species and transect level.

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

5.1 'Indo Pacific Carbonate Production' spreadsheet

5.1.1 <u>Site description</u>

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



Site Details

Site Kisite

Survey Period January 2012

Depth 8

Surveyor/s FJH & CTP

Latitude -4.72008

Longitude 39.37481

Reef Zone (Flat/Fore) Zone 2

Notes North-east side of reef, no swell ~15m visibility

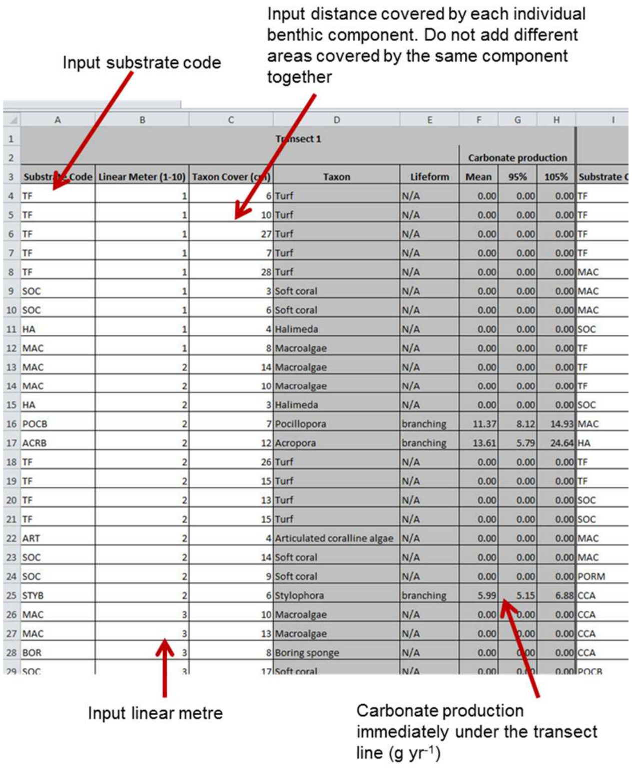
	Transect No.							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Transect ID	**101**							
Survey Date	**12/1/2015**							
Planar Length (m)	10	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Substrate Cover (m)	22.13	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Rugosity	2.21	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT

Fig 5.1.1| *Example of the 'Site Description' tab in the 'Indo-Pacific 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 <u>Data entry</u>

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**.



Input substrate code

Input distance covered by each individual benthic component. Do not add different areas covered by the same component together

			Transect 1					
					Carbonate production			
Substrate Code	Linear Meter (1-10)	Taxon Cover (cm)	Taxon	Lifeform	Mean	95%	105%	Substrate C
TF	1	6	Turf	N/A	0.00	0.00	0.00	TF
TF	1	10	Turf	N/A	0.00	0.00	0.00	TF
TF	1	27	Turf	N/A	0.00	0.00	0.00	TF
TF	1	7	Turf	N/A	0.00	0.00	0.00	TF
TF	1	28	Turf	N/A	0.00	0.00	0.00	MAC
SOC	1	3	Soft coral	N/A	0.00	0.00	0.00	MAC
SOC	1	6	Soft coral	N/A	0.00	0.00	0.00	MAC
HA	1	4	Halimeda	N/A	0.00	0.00	0.00	SOC
MAC	1	8	Macroalgae	N/A	0.00	0.00	0.00	TF
MAC	2	14	Macroalgae	N/A	0.00	0.00	0.00	TF
MAC	2	10	Macroalgae	N/A	0.00	0.00	0.00	TF
HA	2	3	Halimeda	N/A	0.00	0.00	0.00	SOC
POCB	2	7	Pocillopora	branching	11.37	8.12	14.93	MAC
ACRB	2	12	Acropora	branching	13.61	5.79	24.64	HA
TF	2	26	Turf	N/A	0.00	0.00	0.00	TF
TF	2	15	Turf	N/A	0.00	0.00	0.00	TF
TF	2	13	Turf	N/A	0.00	0.00	0.00	SOC
TF	2	15	Turf	N/A	0.00	0.00	0.00	SOC
ART	2	4	Articulated coralline algae	N/A	0.00	0.00	0.00	MAC
SOC	2	14	Soft coral	N/A	0.00	0.00	0.00	MAC
SOC	2	9	Soft coral	N/A	0.00	0.00	0.00	PORM
STYB	2	6	Stylophora	branching	5.99	5.15	6.88	CCA
MAC	3	10	Macroalgae	N/A	0.00	0.00	0.00	CCA
MAC	3	13	Macroalgae	N/A	0.00	0.00	0.00	CCA
BOR	3	8	Boring sponge	N/A	0.00	0.00	0.00	CCA
SOC	3	17	Soft coral	N/A	0.00	0.0	0.00	POCB

Input linear metre

Carbonate production immediately under the transect line (g yr^{-1})

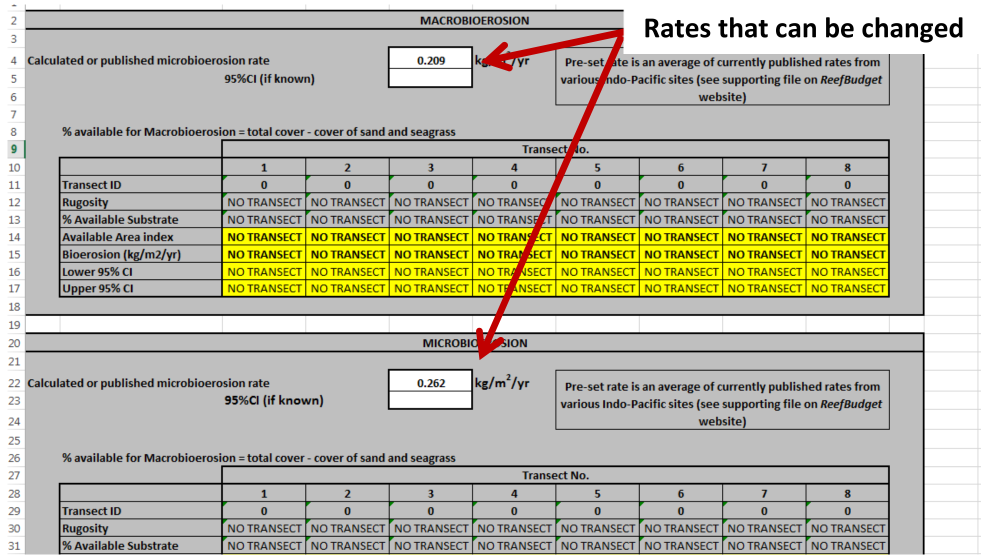
Fig 5.1.2| *Example of the 'Data Entry' tab in the 'Indo-Pacific carbonate production' spreadsheet*

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 have to be updated.

5.1.4 Macro- & Microbioerosion

This tab calculates macro- and microbioerosion. The white cells are published rates of erosion summarized 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.



Rates that can be changed

MACROBIOEROSION

Calculated or published microbioerosion rate 0.209 kg/m^2/yr

95%CI (if known)

Pre-set rate is an average of currently published rates from various Indo-Pacific sites (see supporting file on *ReefBudget* website)

% available for Macrobioerosion = total cover - cover of sand and seagrass

	Transect No.							
	1	2	3	4	5	6	7	8
Transect ID	0	0	0	0	0	0	0	0
Rugosity	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
% Available Substrate	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Available Area index	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Bioerosion (kg/m2/yr)	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Lower 95% CI	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
Upper 95% CI	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT

MICROBIOEROSION

Calculated or published microbioerosion rate 0.262 kg/m^2/yr

95%CI (if known)

Pre-set rate is an average of currently published rates from various Indo-Pacific sites (see supporting file on *ReefBudget* website)

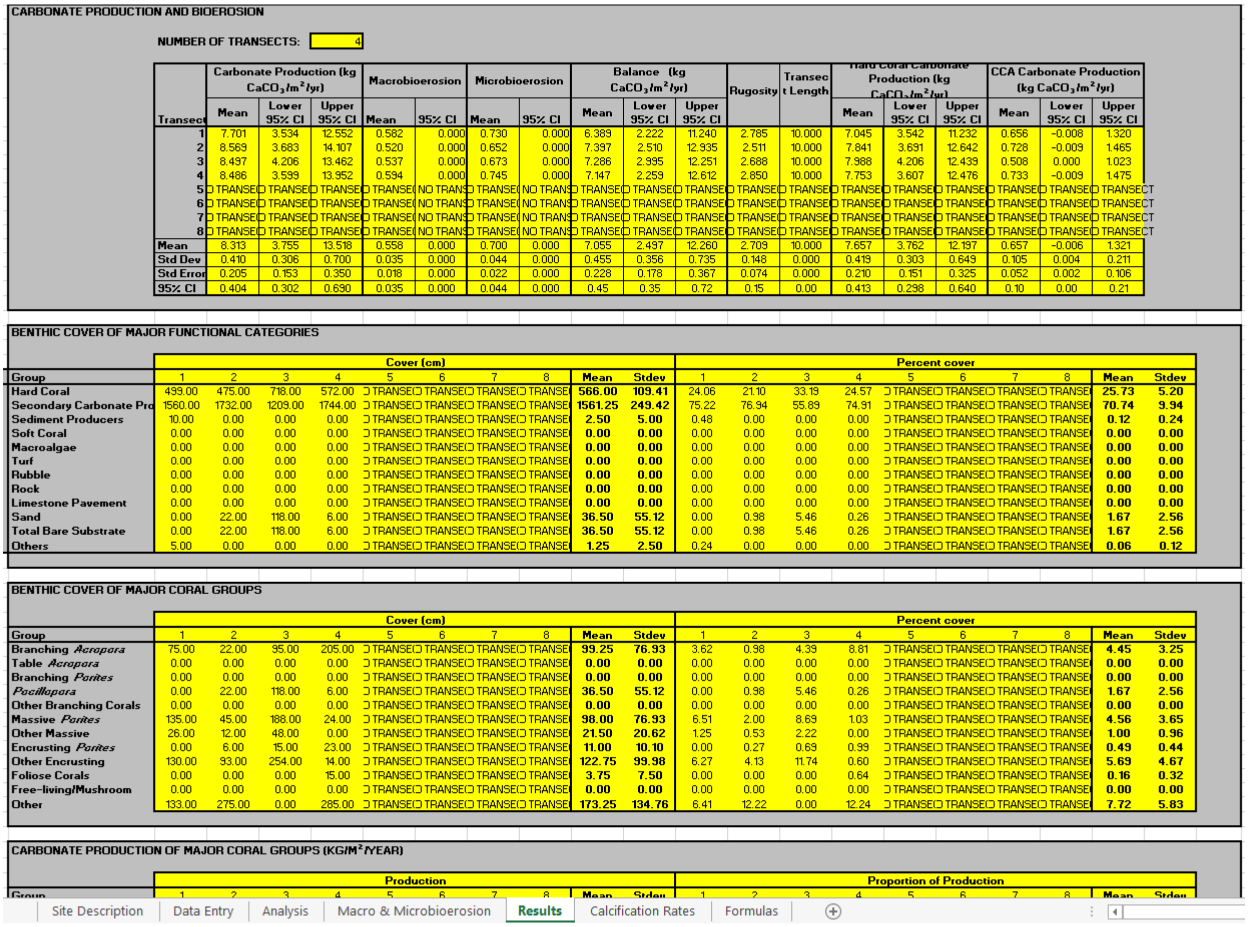
% available for Macrobioerosion = total cover - cover of sand and seagrass

	Transect No.							
	1	2	3	4	5	6	7	8
Transect ID	0	0	0	0	0	0	0	0
Rugosity	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT
% Available Substrate	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT	NO TRANSECT

Fig 5.1.3| *Example of the 'Macro & Microbioerosion' tab in the 'Indo-Pacific 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.**



CARBONATE PRODUCTION AND BIOEROSION

NUMBER OF TRANSECTS: 4

	Carbonate Production (kg $CaCO_3/m^2/yr$)			Macrobioerosion		Microbioerosion		Balance (kg $CaCO_3/m^2/yr$)			Rugosity	Transect Length	Hard Coral Carbonate Production (kg $CaCO_3/m^2/yr$)			CCA Carbonate Production (kg $CaCO_3/m^2/yr$)		
Transect	Mean	Lower 95% CI	Upper 95% CI	Mean	95% CI	Mean	95% CI	Mean	Lower 95% CI	Upper 95% CI			Mean	Lower 95% CI	Upper 95% CI	Mean	Lower 95% CI	Upper 95% CI
1	7.701	3.534	12.552	0.582	0.000	0.730	0.000	6.389	2.222	11.240	2.785	10.000	7.045	3.542	11.232	0.656	-0.008	1.320
2	8.569	3.683	14.107	0.520	0.000	0.652	0.000	7.397	2.510	12.935	2.511	10.000	7.841	3.691	12.642	0.728	-0.009	1.465
3	8.497	4.206	13.462	0.537	0.000	0.673	0.000	7.286	2.995	12.251	2.688	10.000	7.988	4.206	12.439	0.508	0.000	1.023
4	8.486	3.599	13.952	0.594	0.000	0.745	0.000	7.147	2.259	12.612	2.850	10.000	7.753	3.607	12.476	0.733	-0.009	1.475
5	D TRANSE	D TRANSE	D TRANSE	D TRANSE	NO TRANS	D TRANSE	NO TRANS	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSECT
6	D TRANSE	D TRANSE	D TRANSE	D TRANSE	NO TRANS	D TRANSE	NO TRANS	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSECT
7	D TRANSE	D TRANSE	D TRANSE	D TRANSE	NO TRANS	D TRANSE	NO TRANS	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSECT
8	D TRANSE	D TRANSE	D TRANSE	D TRANSE	NO TRANS	D TRANSE	NO TRANS	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSE	D TRANSECT
Mean	8.313	3.755	13.518	0.558	0.000	0.700	0.000	7.055	2.497	12.260	2.709	10.000	7.657	3.762	12.197	0.657	-0.006	1.321
Std Dev	0.410	0.306	0.700	0.035	0.000	0.044	0.000	0.455	0.356	0.735	0.148	0.000	0.419	0.303	0.649	0.105	0.004	0.211
Std Error	0.205	0.153	0.350	0.018	0.000	0.022	0.000	0.228	0.178	0.367	0.074	0.000	0.210	0.151	0.325	0.052	0.002	0.106
95% CI	0.404	0.302	0.690	0.035	0.000	0.044	0.000	0.45	0.35	0.72	0.15	0.00	0.413	0.298	0.640	0.10	0.00	0.21

BENTHIC COVER OF MAJOR FUNCTIONAL CATEGORIES

	Cover (cm)										Percent cover									
Group	1	2	3	4	5	6	7	8	Mean	Stdev	1	2	3	4	5	6	7	8	Mean	Stdev
Hard Coral	499.00	475.00	718.00	572.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**566.00**	**109.41**	24.06	21.10	33.19	24.57	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**25.73**	**5.20**
Secondary Carbonate Pro	1560.00	1732.00	1209.00	1744.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1561.25**	**249.42**	75.22	76.94	55.89	74.91	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**70.74**	**9.94**
Sediment Producers	10.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**2.50**	**5.00**	0.48	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.12**	**0.24**
Soft Coral	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Macroalgae	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Turf	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Rubble	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Rock	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Limestone Pavement	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Sand	0.00	22.00	118.00	6.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**36.50**	**55.12**	0.00	0.98	5.46	0.26	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1.67**	**2.56**
Total Bare Substrate	0.00	22.00	118.00	6.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**36.50**	**55.12**	0.00	0.98	5.46	0.26	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1.67**	**2.56**
Others	5.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1.25**	**2.50**	0.24	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.06**	**0.12**

BENTHIC COVER OF MAJOR CORAL GROUPS

	Cover (cm)										Percent cover									
Group	1	2	3	4	5	6	7	8	Mean	Stdev	1	2	3	4	5	6	7	8	Mean	Stdev
Branching *Acropora*	75.00	22.00	95.00	205.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**99.25**	**76.93**	3.62	0.98	4.39	8.81	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**4.45**	**3.25**
Table *Acropora*	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Branching *Porites*	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Pocillopora	0.00	22.00	118.00	6.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**36.50**	**55.12**	0.00	0.98	5.46	0.26	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1.67**	**2.56**
Other Branching Corals	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Massive *Porites*	135.00	45.00	188.00	24.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**98.00**	**76.93**	6.51	2.00	8.69	1.03	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**4.56**	**3.65**
Other Massive	26.00	12.00	48.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**21.50**	**20.62**	1.25	0.53	2.22	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**1.00**	**0.96**
Encrusting *Porites*	0.00	6.00	15.00	23.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**11.00**	**10.10**	0.00	0.27	0.69	0.99	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.49**	**0.44**
Other Encrusting	130.00	93.00	254.00	14.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**122.75**	**99.98**	6.27	4.13	11.74	0.60	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**5.69**	**4.67**
Foliose Corals	0.00	0.00	0.00	15.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**3.75**	**7.50**	0.00	0.00	0.00	0.64	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.16**	**0.32**
Free-living/Mushroom	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**	0.00	0.00	0.00	0.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**0.00**	**0.00**
Other	133.00	275.00	0.00	285.00	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**173.25**	**134.76**	6.41	12.22	0.00	12.24	D TRANSE	D TRANSE	D TRANSE	D TRANSE	**7.72**	**5.83**

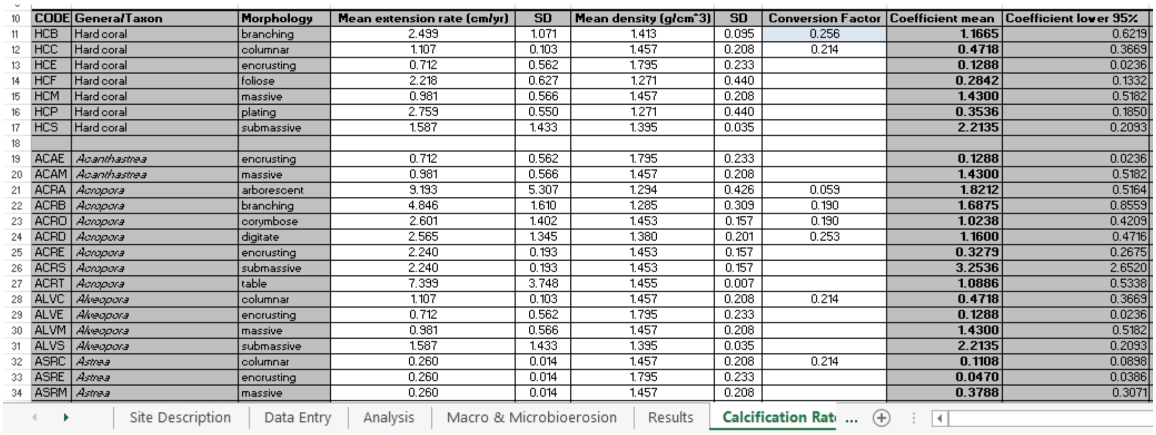
CARBONATE PRODUCTION OF MAJOR CORAL GROUPS (KG/M²/YEAR)

	Production										Proportion of Production									
Group	1	2	3	4	5	6	7	8	Mean	Stdev	1	2	3	4	5	6	7	8	Mean	Stdev

Fig 5.1.4| *Example of the 'Results' tab in the 'Indo-Pacific 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 '*IP Calcification and bioerosion rates_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.



10	CODE	General/Taxon	Morphology	Mean extension rate (cm/yr)	SD	Mean density (g/cm^3)	SD	Conversion Factor	Coefficient mean	Coefficient lower 95%
11	HCB	Hard coral	branching	2.499	1.071	1.413	0.095	0.256	**1.1665**	0.6219
12	HCC	Hard coral	columnar	1.107	0.103	1.457	0.208	0.214	**0.4718**	0.3669
13	HCE	Hard coral	encrusting	0.712	0.562	1.795	0.233		**0.1288**	0.0236
14	HCF	Hard coral	foliose	2.218	0.627	1.271	0.440		**0.2842**	0.1332
15	HCM	Hard coral	massive	0.981	0.566	1.457	0.208		**1.4300**	0.5182
16	HCP	Hard coral	plating	2.759	0.550	1.271	0.440		**0.3536**	0.1850
17	HCS	Hard coral	submassive	1.587	1.433	1.395	0.035		**2.2135**	0.2093
18										
19	ACAE	*Acanthastrea*	encrusting	0.712	0.562	1.795	0.233		**0.1288**	0.0236
20	ACAM	*Acanthastrea*	massive	0.981	0.566	1.457	0.208		**1.4300**	0.5182
21	ACRA	*Acropora*	arborescent	9.193	5.307	1.294	0.426	0.059	**1.8212**	0.5164
22	ACRB	*Acropora*	branching	4.846	1.610	1.285	0.309	0.190	**1.6875**	0.8559
23	ACRO	*Acropora*	corymbose	2.601	1.402	1.453	0.157	0.190	**1.0238**	0.4209
24	ACRD	*Acropora*	digitate	2.565	1.345	1.380	0.201	0.253	**1.1600**	0.4716
25	ACRE	*Acropora*	encrusting	2.240	0.193	1.453	0.157		**0.3279**	0.2675
26	ACRS	*Acropora*	submassive	2.240	0.193	1.453	0.157		**3.2536**	2.6520
27	ACRT	*Acropora*	table	7.399	3.748	1.455	0.007		**1.0886**	0.5338
28	ALVC	*Alveopora*	columnar	1.107	0.103	1.457	0.208	0.214	**0.4718**	0.3669
29	ALVE	*Alveopora*	encrusting	0.712	0.562	1.795	0.233		**0.1288**	0.0236
30	ALVM	*Alveopora*	massive	0.981	0.566	1.457	0.208		**1.4300**	0.5182
31	ALVS	*Alveopora*	submassive	1.587	1.433	1.395	0.035		**2.2135**	0.2093
32	ASRC	*Astrea*	columnar	0.260	0.014	1.457	0.208	0.214	**0.1108**	0.0898
33	ASRE	*Astrea*	encrusting	0.260	0.014	1.795	0.233		**0.0470**	0.0386
34	ASRM	*Astrea*	massive	0.260	0.014	1.457	0.208		**0.3788**	0.3071

Fig 5.1.5| *The 'Calcification Rates' tab in the 'Indo-Pacific carbonate production' spreadsheet*

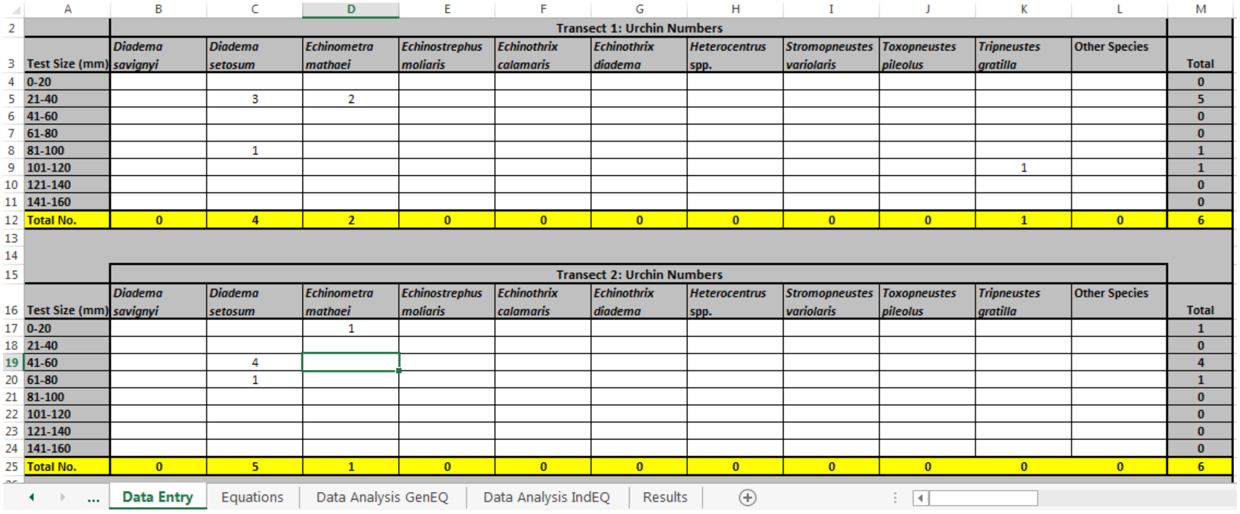
5.2 ‘Indo-Pacific Urchin Erosion’ spreadsheet

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 ‘*Indo-Pacific 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.



Transect 1: Urchin Numbers

Test Size (mm)	*Diadema savignyi*	*Diadema setosum*	*Echinometra mathaei*	*Echinostrephus moliaris*	*Echinothrix calamaris*	*Echinothrix diadema*	*Heterocentrus spp.*	*Stromopneustes variolaris*	*Toxopneustes pileolus*	*Tripneustes gratilla*	Other Species	Total
0-20												0
21-40		3	2									5
41-60												0
61-80												0
81-100		1										1
101-120										1		1
121-140												0
141-160												0
Total No.	0	4	2	0	0	0	0	0	0	1	0	6

Transect 2: Urchin Numbers

Test Size (mm)	*Diadema savignyi*	*Diadema setosum*	*Echinometra mathaei*	*Echinostrephus moliaris*	*Echinothrix calamaris*	*Echinothrix diadema*	*Heterocentrus spp.*	*Stromopneustes variolaris*	*Toxopneustes pileolus*	*Tripneustes gratilla*	Other Species	Total
0-20			1									1
21-40												0
41-60		4										4
61-80		1										1
81-100												0
101-120												0
121-140												0
141-160												0
Total No.	0	5	1	0	0	0	0	0	0	0	0	6

Fig 5.2.1| *The ‘Data Entry’ tab in the ‘Indo-Pacific 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.

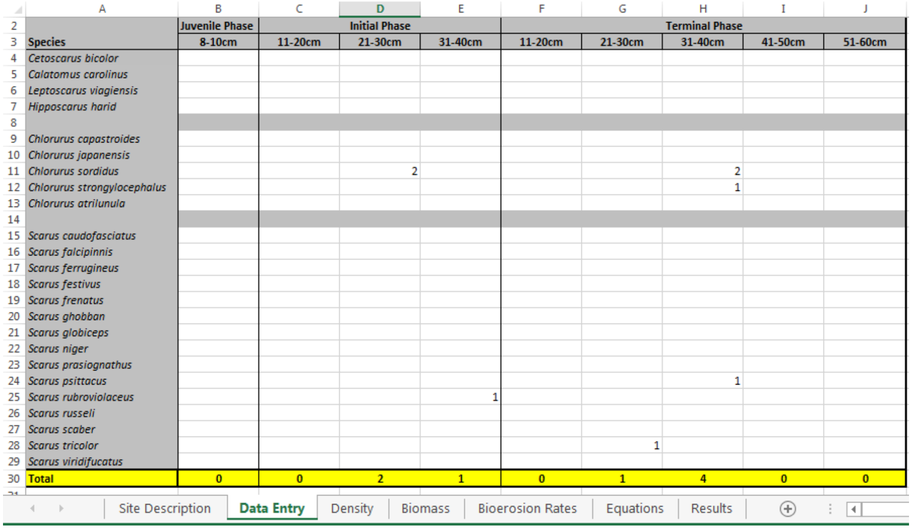
5.3 ‘Indo-Pacific Parrotfish Erosion’ spreadsheet

5.3.1 Site description

This tab contains instructions for filling out the spreadsheet to calculate the bioerosion of reef substrate by parrotfish. 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 life-history phase and size class for each transect. Again, if no individuals were present, cells should be left blank.



	Juvenile Phase	Initial Phase			Terminal Phase				
Species	**8-10cm**	**11-20cm**	**21-30cm**	**31-40cm**	**11-20cm**	**21-30cm**	**31-40cm**	**41-50cm**	**51-60cm**
Cetoscarus bicolor									
Calatomus carolinus									
Leptoscarus viagiensis									
Hipposcarus harid									
Chlorurus capastroides									
Chlorurus japanensis									
Chlorurus sordidus			2				2		
Chlorurus strongylocephalus							1		
Chlorurus atrilunula									
Scarus caudofasciatus									
Scarus falcipinnis									
Scarus ferrugineus									
Scarus festivus									
Scarus frenatus									
Scarus ghobban									
Scarus globiceps									
Scarus niger									
Scarus prasiognathus									
Scarus psittacus							1		
Scarus rubroviolaceus				1					
Scarus russeli									
Scarus scaber									
Scarus tricolor						1			
Scarus viridifucatus									
Total	**0**	**0**	**2**	**1**	**0**	**1**	**4**	**0**	**0**

Fig 5.3.1| *The ‘Data Entry’ tab in the ‘Indo-Pacific Parrotfish 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:

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

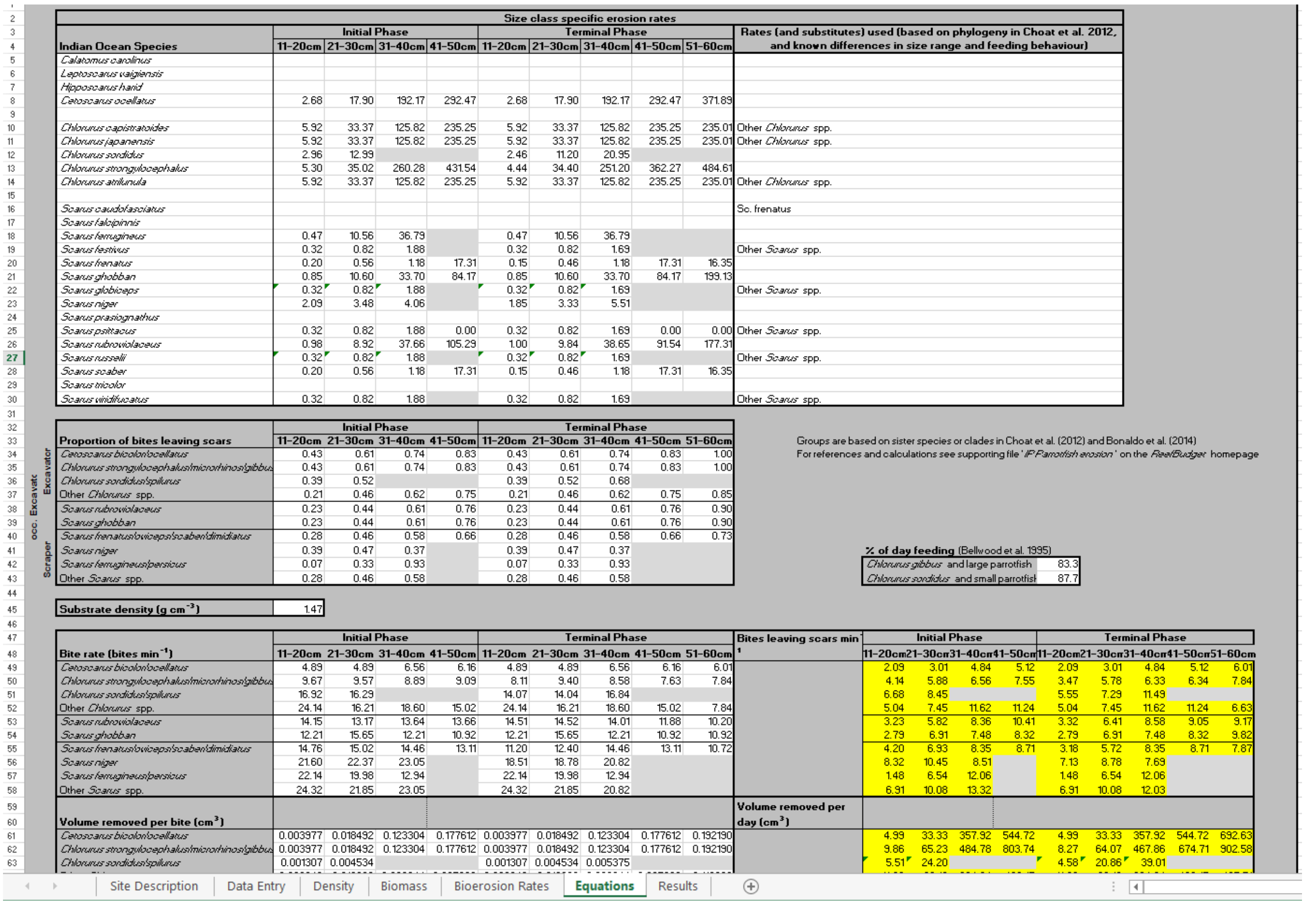
where a and b are averages of length-weight relationships published at fishbase.org (Froese & Pauly 2018), weighted by the number of replicates and the goodness of fit in each study. TL is the total length of the fish in cm and c a conversion factor in case the relationships were derived from standard length instead of total length. Relationships used in the ‘*Indo-Pacific Parrotfish Erosion*’ spreadsheet 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: Proportion of bites leaving scars; Substrate density (g cm^{-3}); Bite rate (bites minute^{-1}); and volume removed per bite (cm^{3}) which **can all be changed** as deemed appropriate. Currently, the sheet is pre-set to provide average values from all available data from the Indo-Pacific as summarized in the supporting ‘*IP Parrotfish erosion rates_database*’ file on the *ReefBudget* website.

5.3.5 Results

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



Size class specific erosion rates										
	Initial Phase				Terminal Phase					Rates (and substitutes) used (based on phylogeny in Choat et al. 2012, and known differences in size range and feeding behaviour)
Indian Ocean Species	11-20cm	21-30cm	31-40cm	41-50cm	11-20cm	21-30cm	31-40cm	41-50cm	51-60cm	
Calatomus carolinus										
Leptoscarus vaigiensis										
Hipposcarus harid										
Cetoscarus ocellatus	2.68	17.90	192.17	292.47	2.68	17.90	192.17	292.47	371.89	
Chlorurus capistratoides	5.92	33.37	125.82	235.25	5.92	33.37	125.82	235.25	235.01	Other *Chlorurus* spp.
Chlorurus japanensis	5.92	33.37	125.82	235.25	5.92	33.37	125.82	235.25	235.01	Other *Chlorurus* spp.
Chlorurus sordidus	2.96	12.99			2.46	11.20	20.95			
Chlorurus strongylocephalus	5.30	35.02	260.28	431.54	4.44	34.40	251.20	362.27	484.61	
Chlorurus atrilunula	5.92	33.37	125.82	235.25	5.92	33.37	125.82	235.25	235.01	Other *Chlorurus* spp.
Scarus caudofasciatus										Sc. frenatus
Scarus falcipinnis										
Scarus ferrugineus	0.47	10.56	36.79		0.47	10.56	36.79			
Scarus festivus	0.32	0.82	1.88		0.32	0.82	1.69			Other *Scarus* spp.
Scarus frenatus	0.20	0.56	1.18	17.31	0.15	0.46	1.18	17.31	16.35	
Scarus ghobban	0.85	10.60	33.70	84.17	0.85	10.60	33.70	84.17	199.13	
Scarus globiceps	0.32	0.82	1.88		0.32	0.82	1.69			Other *Scarus* spp.
Scarus niger	2.09	3.48	4.06		1.85	3.33	5.51			
Scarus prasiognathus										
Scarus psittacus	0.32	0.82	1.88	0.00	0.32	0.82	1.69	0.00	0.00	Other *Scarus* spp.
Scarus rubroviolaceus	0.98	8.92	37.66	105.29	1.00	9.84	38.65	91.54	177.31	
Scarus russelii	0.32	0.82	1.88		0.32	0.82	1.69			Other *Scarus* spp.
Scarus scaber	0.20	0.56	1.18	17.31	0.15	0.46	1.18	17.31	16.35	
Scarus tricolor										
Scarus viridifucatus	0.32	0.82	1.88		0.32	0.82	1.69			Other *Scarus* spp.

	Initial Phase				Terminal Phase				
Proportion of bites leaving scars	11-20cm	21-30cm	31-40cm	41-50cm	11-20cm	21-30cm	31-40cm	41-50cm	51-60cm
Cetoscarus bicolor/ocellatus	0.43	0.61	0.74	0.83	0.43	0.61	0.74	0.83	1.00
Chlorurus strongylocephalus/microrhinos/gibbus	0.43	0.61	0.74	0.83	0.43	0.61	0.74	0.83	1.00
Chlorurus sordidus/spilurus	0.39	0.52			0.39	0.52	0.68		
Other *Chlorurus* spp.	0.21	0.46	0.62	0.75	0.21	0.46	0.62	0.75	0.85
Scarus rubroviolaceus	0.23	0.44	0.61	0.76	0.23	0.44	0.61	0.76	0.90
Scarus ghobban	0.23	0.44	0.61	0.76	0.23	0.44	0.61	0.76	0.90
Scarus frenatus/oviceps/scaber/dimidiatus	0.28	0.46	0.58	0.66	0.28	0.46	0.58	0.66	0.73
Scarus niger	0.39	0.47	0.37		0.39	0.47	0.37		
Scarus ferrugineus/persicus	0.07	0.33	0.93		0.07	0.33	0.93		
Other *Scarus* spp.	0.28	0.46	0.58		0.28	0.46	0.58		

Groups are based on sister species or clades in Choat et al. (2012) and Bonaldo et al. (2014)
For references and calculations see supporting file '*IP Parrotfish erosion*' on the *ReefBudget* homepage

% of day feeding (Bellwood et al. 1995)

Chlorurus gibbus and large parrotfish	83.3
Chlorurus sordidus and small parrotfisl	87.7

Substrate density (g cm^{-3})	1.47

	Initial Phase				Terminal Phase					Bites leaving scars min^{-1}	Initial Phase				Terminal Phase				
Bite rate (bites min^{-1})	11-20cm	21-30cm	31-40cm	41-50cm	11-20cm	21-30cm	31-40cm	41-50cm	51-60cm		11-20cm	21-30cm	31-40cm	41-50cm	11-20cm	21-30cm	31-40cm	41-50cm	51-60cm
Cetoscarus bicolor/ocellatus	4.89	4.89	6.56	6.16	4.89	4.89	6.56	6.16	6.01		2.09	3.01	4.84	5.12	2.09	3.01	4.84	5.12	6.01
Chlorurus strongylocephalus/microrhinos/gibbus	9.67	9.57	8.89	9.09	8.11	9.40	8.58	7.63	7.84		4.14	5.88	6.56	7.55	3.47	5.78	6.33	6.34	7.84
Chlorurus sordidus/spilurus	16.92	16.29			14.07	14.04	16.84				6.68	8.45			5.55	7.29	11.49		
Other *Chlorurus* spp.	24.14	16.21	18.60	15.02	24.14	16.21	18.60	15.02	7.84		5.04	7.45	11.62	11.24	5.04	7.45	11.62	11.24	6.63
Scarus rubroviolaceus	14.15	13.17	13.64	13.66	14.51	14.52	14.01	11.88	10.20		3.23	5.82	8.36	10.41	3.32	6.41	8.58	9.05	9.17
Scarus ghobban	12.21	15.65	12.21	10.92	12.21	15.65	12.21	10.92	10.92		2.79	6.91	7.48	8.32	2.79	6.91	7.48	8.32	9.82
Scarus frenatus/oviceps/scaber/dimidiatus	14.76	15.02	14.46	13.11	11.20	12.40	14.46	13.11	10.72		4.20	6.93	8.35	8.71	3.18	5.72	8.35	8.71	7.87
Scarus niger	21.60	22.37	23.05		18.51	18.78	20.82				8.32	10.45	8.51		7.13	8.78	7.69		
Scarus ferrugineus/persicus	22.14	19.98	12.94		22.14	19.98	12.94				1.48	6.54	12.06		1.48	6.54	12.06		
Other *Scarus* spp.	24.32	21.85	23.05		24.32	21.85	20.82				6.91	10.08	13.32		6.91	10.08	12.03		
Volume removed per bite (cm^3)										**Volume removed per day (cm^3)**									
Cetoscarus bicolor/ocellatus	0.003977	0.018492	0.123304	0.177612	0.003977	0.018492	0.123304	0.177612	0.192190		4.99	33.33	357.92	544.72	4.99	33.33	357.92	544.72	692.63
Chlorurus strongylocephalus/microrhinos/gibbus	0.003977	0.018492	0.123304	0.177612	0.003977	0.018492	0.123304	0.177612	0.192190		9.86	65.23	484.78	803.74	8.27	64.07	467.86	674.71	902.58
Chlorurus sordidus/spilurus	0.001307	0.004534			0.001307	0.004534	0.005375				5.51	24.20			4.58	20.86	39.01		

Fig 5.3.2| *The 'Equations' tab in the 'Indo-Pacific parrotfish erosion' spreadsheet showing variables used for calculations (proportion of bites leaving scars, bite rate, bite size, % of day feeding and substrate density).*

6. References

Afeworki Y, Zekeria ZA, Videler JJ, Bruggemann JH (2013) Food intake by the parrotfish *Scarus ferrugineus* varies seasonally and is determined by temperature, size and territoriality. Mar Ecol Prog Ser 489:213

Bak R (1990) Patterns of echinoid bioerosion in two Pacific coral reef lagoons. Mar Ecol Prog Ser 66:267–272

Bak RPM (1994) Sea urchin bioerosion on coral reefs: place in the carbonate budget and relevant variables. Coral Reefs 13:99–103

Bellwood D (1995) Direct estimate of bioerosion by two parrotfish species on the Great Barrier Reef, Australia. Mar Biol 121:419–429

Bellwood DR, Choat JH (1990) A functional analysis of grazing in parrotfishes (family Sacaridae): the ecological implications. Enviromental Biol Fishes 28:189–214

Bellwood DR, Hoey AS, Choat JH (2003) Limited functional redundancy in high diversity systems: Resilience and ecosystem function on coral reefs. Ecol Lett 6:281–285

Bruggemann JH, Begeman J, Bosma EM, Verburg P, Breeman AM (1994a) Foraging by the stoplight parrotfish *Sparisoma viride*. II. Intake and assimilation of food, protein and energy. Mar Ecol Prog Ser 106:57–71

Bruggemann JH, Van Oppen MJH, Breeman AM (1994b) Foraging by the stoplight parrotfish *Sparisoma viride*. I. Food selection in different, socially determined habitats. Mar Ecol Ser 106:41–55

Bruggemann JH, Van Kessel AM, Van Rooij JM, Breeman AM (1996) Bioerosion and sediment ingestion by the caribbean parrotfish *Scarus vetula* and *Sparisoma viride*: Implications of fish size, feeding mode and habitat use. Mar Ecol Prog Ser 134:59–71

Carreiro-Silva M, McClanahan TR (2001) Echinoid bioerosion and herbivory on Kenyan coral reefs: The role of protection from fishing. J Exp Mar Bio Ecol 262:133–153

Carreiro-Silva M, McClanahan TR (2012) Macrobioerosion of dead branching Porites, 4 and 6 years after coral mass mortality. Mar Ecol Prog Ser 458:103–122

Chazottes V, Campion-Alsumard TL, Peyrot-Clausade M (1995) Bioerosion rates on coral reefs: interactions between macroborers, microborers and grazers (Moorea, French Polynesia). Palaeogeogr Palaeoclimatol Palaeoecol 113:189–198

Chazottes V, Le Campion-Alsumard T, Peyrot-Clausade M, Cuet P (2002) The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). Coral Reefs 21:375-390

Chen T, Li S, Yu K (2013) Macrobioerosion in Porites corals in subtropical northern South China Sea: a limiting factor for high-latitude reef framework development. Coral Reefs 32:101–108

Choat JH, Klanten OS, Van Herwerden L, Robertson DR, Clements KD (2012) Patterns and processes in the evolutionary history of parrotfishes (Family Labridae). Biological Journal of the Linnean Society 107:529-557

Conand C, Chabanet P, Cuet P, Letourneur Y (1997) The carbonate budget of a fringing reef in La Reunion Island (Indian Ocean); sea urchin and fish bioerosion and net calcification. Proc 8th IntCoral Reef Symp 1:953-958

Darling ES, Alvarez-Filip L, Oliver TA, McClanahan TR, Côté IM (2012) Evaluating life-history strategies of reef corals from species traits. Ecol Lett 15:1378-1386

DeCarlo TM, Cohen AL, Barkley HC, Cobban Q, Young C, Shamberger KE, Brainard RE, Golbuu Y (2015) Coral macrobioerosion is accelerated by ocean acidification and nutrients. Geology 43:7-10

Downing N, El-Zahr CR (1987) Gut evacuation and filling rates in the rock-boring sea urchin *Echinometra mathaei*. Bull Mar Sci 41:579–584

Froese R, Pauly D (2018) FishBase. World Wide Web electronic publication. www.fishbase.org (08/2018)

Glynn PW, Wellington GM, Birkeland C (1979) Coral Reef Growth in the Galapagos: Limitation by Sea Urchins. Science 23:47–49

Goatley CHR, Bellwood DR (2011) The roles of dimensionality, canopies and complexity in ecosystem monitoring. PLoS One 6:e27307

Golubic S, Friedmann I, Schneider J (1981) The lithobiontic ecological niche, with special reference to microorganisms. J Sediment Res 51:475–478

Griffin SP, García RP, Weil E (2003) Bioerosion in coral reef communities in southwest Puerto Rico by the sea urchin Echinometra viridis. Mar Biol 143:79–84

Herrera-Escalante T, López-Pérez RA, Leyte-Morales GE (2005) Bioerosion caused by the sea urchin Diadema Mexicanum (Echinodermata: Echinoidea) at Bahias de Huatulco, Western Mexico. Rev Biol Trop 53 Suppl 3:263–273

Highsmith RC (1981) Coral Bioerosion: Damage Relative to Skeletal Density. Am Nat 117:193–198

Hoey AS, Bellwood DR (2008) Cross-shelf variation in the role of parrotfishes on the Great Barrier Reef. Coral Reefs 27:37–47

Hubbard DK, Miller AI, Scaturo D (1990) Production and cycling of calcium carbonate in a shelf-edge reef system (St. Croix, U.S. Virgin Islands): Applications to the nature of reef systems in the fossil record. J Sediment Res 60:335–360

Januchowski-Hartley FA, Graham NAJ, Wilson SK, Jennings S, Perry CT (2017) Drivers and predictions of coral reef carbonate budget trajectories. Proceedings Biol Sci 284:20162533

Kennedy EV, Ordoñez A, Lewis BE, Diaz-Pulido G (2017) Comparison of recruitment tile materials for monitoring coralline algae responses to a changing climate. Mar Ecol Prog Ser 569: 129–144

Kiene WE, Hutchings PA (1994) Bioerosion experiments at Lizard Island, Great Barrier Reef. Coral Reefs 13:91–98

Lewis B, Kennedy EV, Diaz-Pulido G (2017) Seasonal growth and calcification of a reef-building crustose coralline alga on the Great Barrier Reef. Mar Ecol Prog Ser 568:73-86.

Lokrantz J, Nyström M, Thyresson M, Johansson C (2008) The non-linear relationship between body size and function in parrotfishes. Coral Reefs 27:967–974

Mallela J, Perry CT (2007) Calcium carbonate budgets for two coral reefs affected by different terrestrial runoff regimes, Rio Bueno, Jamaica. Coral Reefs 26:129–145

McClanahan TR, Graham NAJ, Maina J, Chabanet P, Bruggemann JH, Polunin NVC (2007) Influence of instantaneous variation on estimates of coral reef fish populations and communities. Mar Ecol Prog Ser 340:221–234

McClanahan TR, Muthiga NA (1988) Changes in Kenyan coral reef community structure and function due to exploitation. Hydrobiologia 166:269–276

Mills SC, Peyrot-Clausade M, France Fontaine M (2000) Ingestion and transformation of algal turf by *Echinometra mathaei* on Tiahura fringing reef (French Polynesia). J Exp Mar Bio Ecol 254:71–84

Mokady O, Lazar B, Loya Y (1996) Echinoid bioerosion as a major structuring force of red sea coral reefs. Biol Bull 190:367–372

Morgan KM, Kench PS (2014) Carbonate production rates of encruster communities on a lagoonal patch reef: Vabbinfaru reef platform, maldives. Mar Freshw Res 65:720–726

Mumby PJ (2006) The impact of exploiting grazers (Scaridae) on the dynamics of caribbean coral reefs. Ecol Appl 16:747–769

Neumann AC (1966) Observations on coastal erosion in bermuda and measurements of the boring rate of the sponge, *Cliona lampa*. Limnol Oceanogr 11:92–108

Ong L, Holland KN (2010) Bioerosion of coral reefs by two Hawaiian parrotfishes: Species, size differences and fishery implications. Mar Biol 157:1313–1323

Osorno A, Peyrot-Clausade M, Hutchings PA (2005) Patterns and rates of erosion in dead Porites across the Great Barrier Reef (Australia) after 2 years and 4 years of exposure. Coral Reefs 24:292–303

Pari N, Peyrot-Clausade M, Le Campion-Alsumard TA, Hutchings P, Chazottes V, Golubic S, Le Campion J, Fontaine MF (1998) Bioerosion of experimental substrates on high islands and on atoll lagoons (French Polynesia) after two years of exposure. Mar Ecol Prog Ser. 166:119-30.

Pari N, Peyrot-Clausade M, Hutchings PA (2002) Bioerosion of experimental substrates on high islands and atoll lagoons (French Polynesia) during 5 years of exposure. J Exp Mar Bio Ecol 276:109–127

Perry CT (1998) Macroborers within coral framework at Discovery Bay, north Jamaica: species distribution and abundance, and effects on coral preservation. Coral Reefs 17:277–287

Perry CT, Spencer T, Kench PS (2008) Carbonate budgets and reef production states: A geomorphic perspective on the ecological phase-shift concept. Coral Reefs 27:853–866

Perry CT, Edinger EN, Kench PS, Murphy GN, Smithers SG, Steneck RS, Mumby PJ (2012) Estimating rates of biologically driven coral reef framework production and erosion: A new census-based carbonate budget methodology and applications to the reefs of Bonaire. Coral Reefs 31:853–868

Perry CT, Kench PS, O'Leary MJ, Morgan KM, Januchowski-Hartley F (2015a) Linking reef ecology to island building: Parrotfish identified as major producers of island-building sediment in the Maldives. Geology 43:503–506

Perry CT, Murphy GN, Graham NAJ, Wilson SK, Januchowski-Hartley FA, East HK (2015b) Remote coral reefs can sustain high growth potential and may match future sea-level trends. Sci Rep 5:4–11

Perry CT, Steneck RS, Murphy GN, Kench PS, Edinger EN, Smithers SG, Mumby PJ (2015c) Regional-scale dominance of non-framework building corals on Caribbean reefs affects carbonate production and future reef growth. Glob Chang Biol 21:1153–1164

Russo A (1980) Bioerosion by two rock boring echinoids (*Echinometra mathaei* and *Echinostrephus aciculatus*) on Enewetak Atoll, Marshall Islands. J Mar Res 38:99–110

Sammarco PW, Risk MJ Large-scale patterns in internal bioerosion of Porites: cross continental shelf trends on the Great Barrier Reef. Mar Ecol Prog Ser 59:145–156

Samoilys MA, Carlos G (2000) Determining methods of underwater visual census for estimating the abundance of coral reef fishes. Environ Biol Fishes 57:289–304

Schönberg CHL (2015) Monitoring bioeroding sponges: Using Rubble, Quadrat, or Intercept Surveys? The Biological Bulletin 228:137-155

Stearn CW, Scoffin TP, Martindale W (1977) Calcium Carbonate Budget of a Fringing Reef on the West Coast of BarbadosPart I - Zonation and Productivity. Bull Mar Sci 27:479–510

Tribollet A, Golubic S (2005) Cross-shelf differences in the pattern and pace of bioerosion of experimental carbonate substrates exposed for 3 years on the northern Great Barrier Reef, Australia. Coral Reefs 24:422–434

Wilson SK, Graham NAJ, Polunin NVC (2007) Appraisal of visual assessments of habitat complexity and benthic composition on coral reefs. Mar Biol 151:1069–1076

Yarlett RT, Perry CT, Wilson RW, Philpot KE (2018) Constraining species-size class variability in rates of parrotfish bioerosion on Maldivian coral reefs: implications for regional-scale bioerosion estimates. Marine Ecology Progress Series 590:155-169

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	***Taxa***
ACA	*Acanthastrea*
ACR	*Acropora*
ALV	*Alveopora*
AN	Anenome
ART	Articulated coralline algae
ASR	*Astrea*
AST	*Astreopora*
BOR	Boring sponge
CAU	*Caulastrea*
CCA	crustose coralline algae
COR	Corallimorph
COS	*Coscinaraea*
CTN	*Ctenactis*
CYA	Cyanophyta
CYC	*Cycloseris*
CYP	*Cyphastrea*
DC	Dead Coral
DIP	*Diploastrea*
ECH	*Echinophyllia*
ECP	*Echinopora*
EUP	*Euphyllia*
FAV	*Favia*
FAT	*Favites*
FUN	*Fungia*
GAL	*Galaxea*
GAR	*Gardinoseris*
GON	*Goniastrea*
GOP	*Goniopora*
HA	Halimeda
HAL	*Halomitra*
HC	Hard coral
HER	*Herpolitha*
HYD	*Hydnophora*
ISO	*Isopora*
LEP	*Leptastrea*
LET	*Leptoria*
LES	*Leptoseris*
LOB	*Lobophyllia*
LSP	Limestone pavement
MAC	Macroalgae
MCA	Macroalgae/CCA
MER	*Merulina*
MIL	*Millepora*
MON	*Montastrea*
MOP	*Montipora*
MYC	*Mycedium*
OCE	Other calcareous encrusters
OTH	Other non-calcareous encrusters
OTS	Other sediment producers
OUA	*Oulastrea*
OUL	*Oulaphyllia*
OXY	*Oxypora*
PAC	*Pachyseris*
PAV	*Pavona*
PEC	*Pectinia*
PHY	*Physogyra*

Code	***Taxa***
PAS	*Phymastrea*
PLA	*Platygyra*
PLE	Plerogyra
PLS	*Plesiastrea*
POC	*Pocillopora*
POD	*Podabacia*
POL	*Polyphyllia*
POR	*Porites*
POP	*Poritipora*
PSA	*Psammocora*
RCK	Rock
RUB	Rubble
RUBC	Rubble/CCA
RUBT	Rubble/Turf
SD	Sand
SEA	Seagrass
SER	*Seriatopora*
SID	*Siderastrea*
SOC	Soft coral
SCA	Soft coral/CCA
SP	Sponge
STC	*Stylocoeniella*
STY	*Stylophora*
SYM	*Symphyllia*
TF	Turf algae
TUR	*Turbinaria*
ZOO	Zooanthid

Morphology:	
B	Branching
E	Encrusting
C	Columnar
D	Digitate
F	Foliose/Frondose
M	Massive
O	Corymbose
P	Plating
S	Submassive
T	Table

Site:

Depth: ***Transect:***

Date:

Surveyor:

Urchins (# per 10 sq m)	0-20 mm	21-40 mm	41-60 mm	61-80 mm	81-100 mm	101-120mm
Diadema						
Echinothrix						
Echinometra						
Echinostrephus						

Diadema						
Echinothrix						
Echinometra						
Echinostrephus						

Code as genera + life form

ACA	Acanthastrea
ACR	Acropora
ALV	Alveopora
AST	Astreopora
CAU	Caulastrea
COS	Coscinaraea
CYP	Cyphastrea
DIP	Diploastrea
ECH	Echinophyllia
ECP	Echinopora
EUP	Euphyllia
FAV	Favia
FAT	Favites
FUN	Fungia
GAL	Galaxea
GAR	Gardinoseris
GON	Goniastrea
GOP	Goniopora
HAL	Halomitra
HYD	Hydnophora
LEP	Leptastrea
LET	Leptoria
LES	Leptoseris
LOB	Lobophyllia
MER	Merulina
MIL	Millepora
MON	Montastrea
MOP	Montipora
MYC	Mycedium
OUL	Oulophyllia
PAC	Pachyseris
PAV	Pavona
PLA	Platygyra
PLS	Plesiastrea
POC	Pocillopora
POR	Porites
PSA	Psammocora
SER	Seriatopera
STY	Stylophora
SYM	Symphillia
TUR	Turbinaria

HC - Hard coral

Lifeforms:

B	Branching
O	Corymbrose
C	Columnar
D	Digitate
F	Foliose
P	Plating
M	Massive
U	Mushroom
S	Submassive
T	Table
E	Encrusting

AN	Anenome
ART	Arti cora algae
CCA	Crust cora alg
CYA	Cyanophyta
DC	Dead Coral
HA	Halimeda
MAC	Macroalgae
MCA	Macroalg/CCA
OTH	Non-calca enc
RUB	Rubble
RUBC	Rubble/CCA
RUBT	Rubble/Turf
SA	Sand
SEA	Seagrass
SOC	Soft coral
SP	Sponge
TF	Turf algae

Appendix B: Common urchin species in the Indo-Pacific

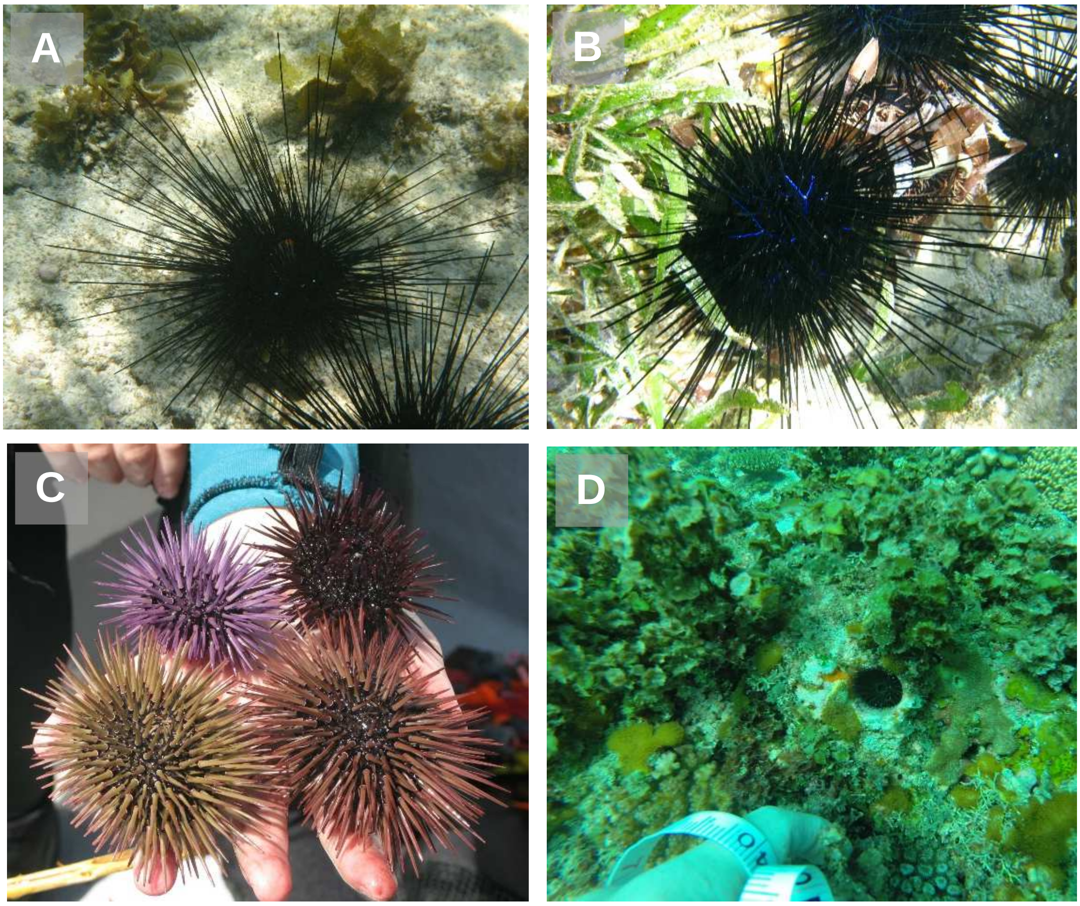


Fig. App. B: Common eroding urchin species in the Western Indian Ocean. (A) *Diadema setosum* (orange ring around anus); (B) *Diadema savingyi* (blue lines); (C) *Echinometra mathaei* in four different colour morphs; and (D) *Echinostrephus moliaris* (note hole diameter is <1 cm).