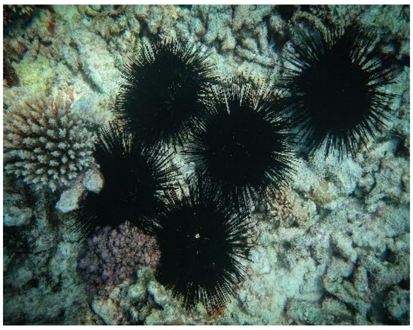
## SedBudget: Indian Ocean field data collection protocol (Version 1; Jan 2023)



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## 1. Context and approach

The methodology described in this document is aimed at supporting estimates of biogenically-generated reef sediment production on Indian Ocean coral reefs (although many of these methods are also appropriate for Pacific reef assessments). The methodologies described relate to those taxa and processes that have been reported to be the dominant sediment contributors to reef, beach and island systems in the Indian Ocean region. Whilst the relative abundance of specific sedimentary constituents inevitably varies between locations and habitats (Gischler 2006), the major sediment constituents in reef-island sediments in this region have been shown to be coral, *Halimeda* spp., crustose coralline algae (CCA), molluscs (bivalves and gastropods), and benthic foraminifers, with echinoid tests and spines as a variably important secondary component (Perry et al. 2015; East et al. 2016; Jorry et al. 2016). It is this suite of regionally relevant taxa which directly or indirectly contribute to the production of these sediment constituents, that are the focus within this approach.

SedBudget has thus been set up to provide a framework for estimating rates of sediment generation from these major taxa that facilitate the release of biogenic sedimentary constituents within coral reef habitats. It is also designed to provide estimates of the contributions to different sediment grain-size classes within the pebble grade and below size classes (i.e., <64 mm based on the Udden-Wentworth grain size classification). The approach is broadly similar to that used in the ReefBudget system (Perry et al. 2012; Perry et al. 2018) in that it is census-based and the underpinning metrics are user-adaptable. In the case of SedBudget, benthic producer data is collected from replicate (n=10) 0.5 x 0.5 m quadrats placed at 1 m intervals i.e., with a 0.5 m spacing between each, along 10 m long transects (these can be conducted along the same transects as ReefBudget surveys where those are also being undertaken). A benthic data entry spreadsheet is needed for each transect line (e.g., Site X, transect 1). Fish census data should be collected from belt transects positioned in close proximity to the benthic survey lines, with data for relevant fish recorded in a separate spreadsheet (only one spreadsheet is needed for each study site). Site location, transect number, GPS coordinates and any other relevant site notes (depth etc) should be entered in the first tab of the data entry spreadsheets ('Overview'). After surveying and spreadsheet data entry, data from the 'Summary data' tabs from the sheets for both the benthic (multiple sheets per site) and fish survey (single sheet per site) then need to be copied to a habitat/site-level master summary spreadsheet (e.g., Site X master summary sheet), which is set to accommodate data from up to six transect lines.

For each study site, the following three spreadsheets are thus required:

- 'Indian Ocean – SedBudget benthic data entry' sheet
- 'Indian Ocean – SedBudget fish data entry' sheet
- 'Indian Ocean – Master summary sheet'

**It is strongly recommended that a master copy of the benthic data entry sheet is set up at the start of each project and populated with details of as many of the relevant taxa (and any necessary underpinning metrics) known to be present in a study area. Copies for each site can then be made as needed. This speeds up the post-fieldwork data entry process considerably, with any additional (rare) species encountered only needing to be added on an ad-hoc basis for any given transect.**

**Although 10 quadrats are recommended per transect line the data entry tabs are set up to accommodate <10 quadrats where transects could not be completed for logistical/time reasons.**

Notes:

1. At present the method only provides estimates of sediment generation associated with either the release of carbonate as a by-product of bioerosion or that associated with the post-mortem direct input of skeletal (i.e., shelly) material. Inputs associated with physical framework damage from waves or storms (coral rubble generation etc) cannot yet be accounted for as basic parameter data is absent, although these physical processes primarily generate material of >64 mm in size.

2. Efforts to develop methodologies to account for inputs that are at present challenging to constrain due to a paucity of underpinning data, e.g., from branching crustose coralline algae, articulated red coralline algae, echinoid tests and spines, are on-going and will be added to future revised versions.
3. This initial iteration of SedBudget should thus be seen as a first step to developing this important field of enquiry, and at the end of this handbook we highlight those taxa and processes for which we consider methodological developments/refinements to be most urgently needed. Inputs and ideas for adaptation from the user community are most welcome and we encourage you to get in touch via email: c.perry@exeter.ac.uk
4. Potentially useful taxa and species guides to support in situ surveys are listed in Appendices 2-7.
5. Aligned methodologies for the Caribbean and Pacific regions are currently under development.

**Equipment**. The following items are needed to complete the surveys as recommended.

- 10 m transect line
- 0.5 x 0.5 m quadrat
- Short (~1 m) flexible measuring tape
- 15 cm ruler
- Underwater camera
- Dive slate and pencil
- Small hand-held sieve (2 mm mesh size) and plastic sampling beaker
- 3 x 25 ml falcon tubes per transect for sediment samples for foraminifera analysis
- Any necessary species ID sheets for in-water identification.

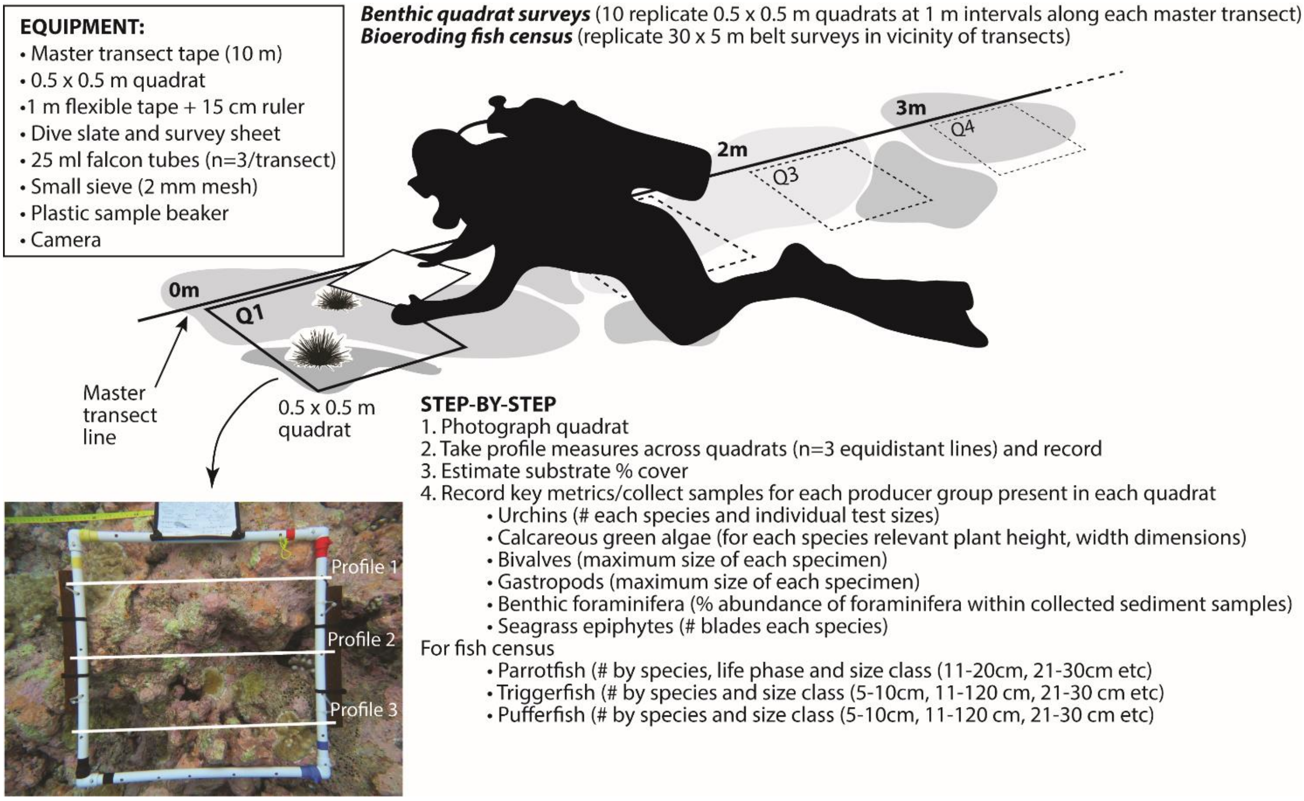



***Figure 1.*** *Cartoon illustrating the approaches used in data collection and the main equipment items needed (inset shows quadrat and spacing of profile survey lines). Quadrats can be placed at intervals either along the same transect side (as shown in figure) or in a checkerboard style if deemed more appropriate to the site.*

## 2. Field approach and data collection

The following section provides an explanation of the recommendations for data collection and spreadsheet data entry. Note that it is recommended that fish surveys within the study area are conducted prior to benthic transect work being started in order to minimise disturbance to the fish. Below, we thus describe the fish data collection approach first, and then that for the benthic data collection.

### 2.1 Fish data collection

***2.1.1 Parrotfish***. Estimates of sediment generation by parrotfishes are based on the same underlying approaches used for bioerosion rates in the ReefBudget methodology (Perry et al. 2012), the rationale for this being that there is no evidence of intestinal dissolution of ingested reef substrates in the guts of parrotfishes, and so bioerosion rate can be taken as a proxy for sediment generation (Perry et al. 2020). These erosion (and thus sediment generation) rates (in kg $CaCO_3$ $m^{-2}$ $yr^{-1}$) are based on empirical data that has been collected for a wide range of parrotfish species and use measures of bite rates, proportions of bites leaving scars, and scar volumes by species and body size (see Lange et al. 2020 and ReefBudget homepage for a summary). For sediment production estimates, it is also necessary to factor in the proportions of sediment produced in different sediment grain-size classes. For this, use is made of existing published data for a range of Indo-Pacific fish species (Hoey & Bellwood 2008), which more recently (Yarlett et al. 2021) also factor for different size classes of fish. These data currently exist for several *Scarus* spp. and *Chlorurus* spp. in the Indo-Pacific region, although either sister- or closely functionally-related species (see Choat et al. 2012) or mean genera-level data are necessarily applied in many cases. Further data collection for a wider range of species would be a useful future area of research.

An additional aspect of the release of sedimentary carbonate from parrotfishes is that the composition of the excreted faecal material also reflects the substrates on which the parrotfishes feed. This is mostly coral substrate, but not entirely so. Account thus also needs to be made for this to support estimates of the types of carbonate sedimentary particles being generated. In this context, use can be made of data based on thin-section or electron microscopy analysis of the composition of the material excreted by a range of species and size classes of parrotfishes. For example, Yarlett et al. (2021) showed that this excreted carbonate averages ~95% coral and ~5% CCA (other constituents are minimal).

***2.1.2 Triggerfishes and pufferfishes.*** In addition to the well documented processes of sediment generation by parrotfishes, some species of both pufferfishes and triggerfishes can generate coarse sand to pebble grade sedimentary material through physical breakage of reef framework (Guzman and Lopez 1991, Glynn and Manzello 2015). This occurs either whilst fish are feeding on coral (pufferfishes) or whilst foraging for cryptic invertebrates (triggerfishes) (Perry et al. 2022). Estimates of sediment generation by triggerfishes and pufferfishes can thus be made based on similar conceptual approaches that inform estimates for parrotfishes, i.e., based on data on annual sediment generation rates for fish of a given species and size class, and the size class fractions of sediment generated. Thus, in the field, data on the numbers of fishes and their sizes can also be collected from belt transect surveys or using stationary Underwater Visual Census (UVC) methods (see field data collection description below). Resultant estimates of sediment generation are then based on species-specific erosion-rate data and on the sizes of material generated. It is important to note that estimates of sediment production rates by pufferfish and triggerfish are based on what limited data currently exists and, as this is not extensive, no relation can yet be made between sediment production and fish size. Similarly, sediment grain-size generation data are only semi-quantitative (Glynn 1972; Alvarado et al. 2017), but what data does exist is used here.

**Field data collection:** Data on the numbers of each parrotfish, pufferfish and triggerfish species (and for parrotfish their life phase) and size class (currently collected in size bins; 11-20 cm, 21-30 cm, 31-40 cm, etc) are collected from a survey area close to the benthic transects in a given study location – either along belt transects (e.g., 30 x 5 m) or using a stationary UVC methodology.

**Data entry:** Data on the numbers of each species present (by size class and, additionally for parrotfish by life phase) are then entered into the 'Fish' tab (see Fig. 2) of the 'SedBudget fish data entry' sheet. The spreadsheet is set up to accommodate data from up to 6 survey transects. Information on the number of transects and the transect survey area ($m^2$) should first be entered top left of sheet (see Fig. 2) with data then entered below on the numbers of each species, life phase and size class recorded.

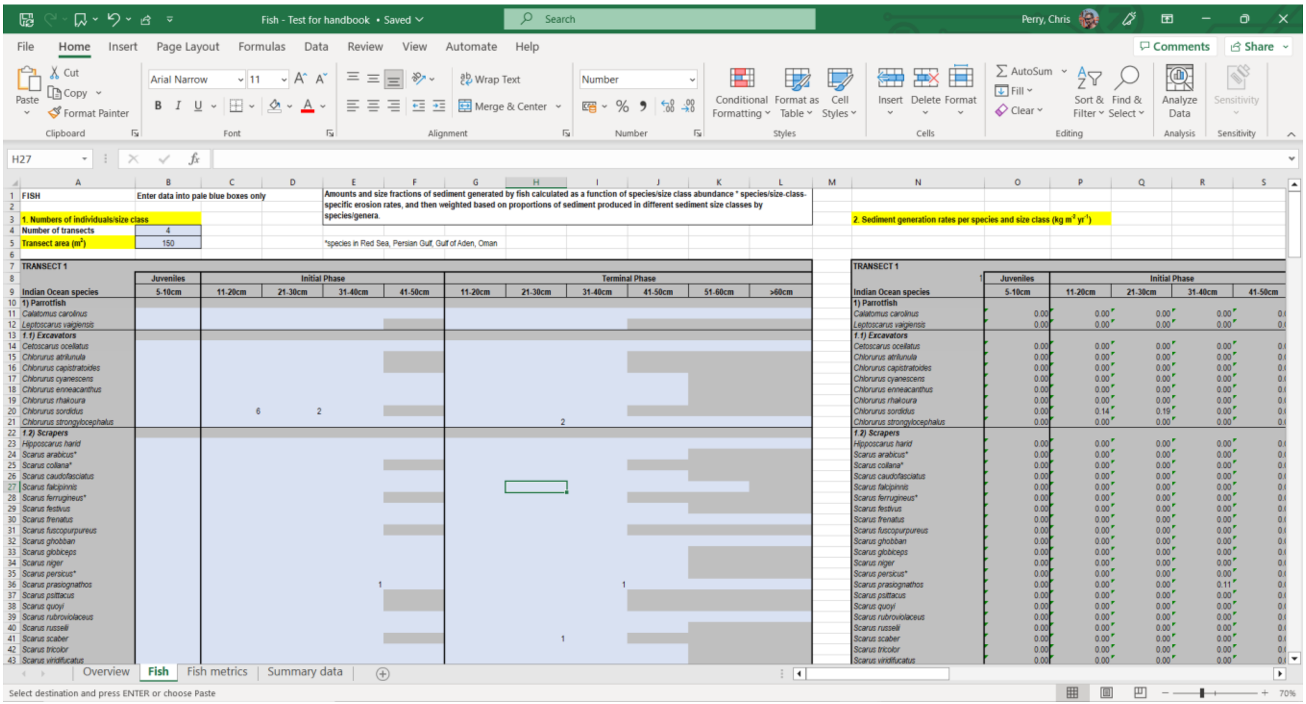


***Figure 2.*** *Census-data entry section for parrotfish in the 'Fish' data entry tab. Pufferfish and triggerfish data are entered in the same tables beneath the parrotfish for each transect.*

These data will then generate an estimate (middle set of tables on the 'Fish' tab – see Fig. 3) of total sediment generation by each species for a given transect, and then in the right hand set of tables (see Fig. 4) estimates of the amount of sediment generated within different sediment grain-size classes. The metrics underpinning these calculations are provided in the 'Fish metrics' tab and are user-changeable where local datasets exist. The 'Summary data' tab then provides total transect level rates of sediment production for each fish group by grain-size fraction class (highlighted in the orange rows; Fig. 5). These data can then be copied across manually into the 'Fish-derived sediment' sections of the 'Indian Ocean – Master summary sheet' (see Fig. 6).

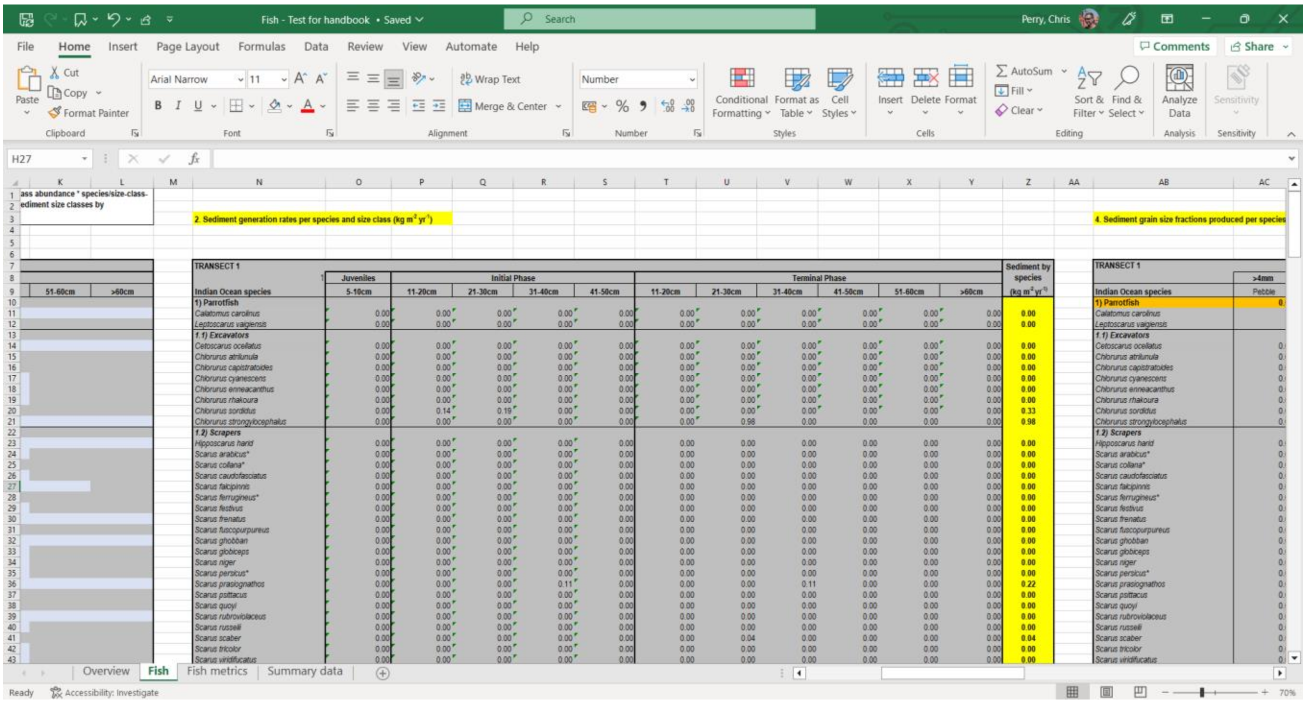



***Figure 3.*** *Sediment production section of the 'Fish' data entry tab.*

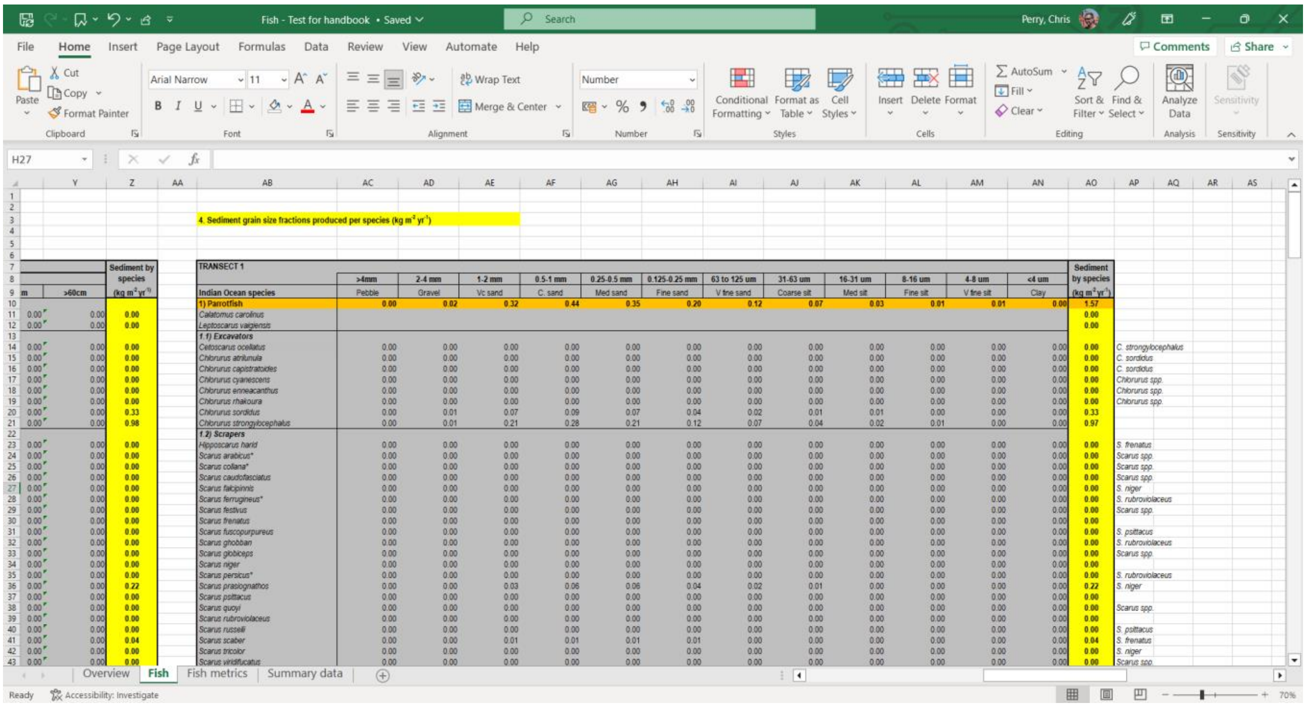
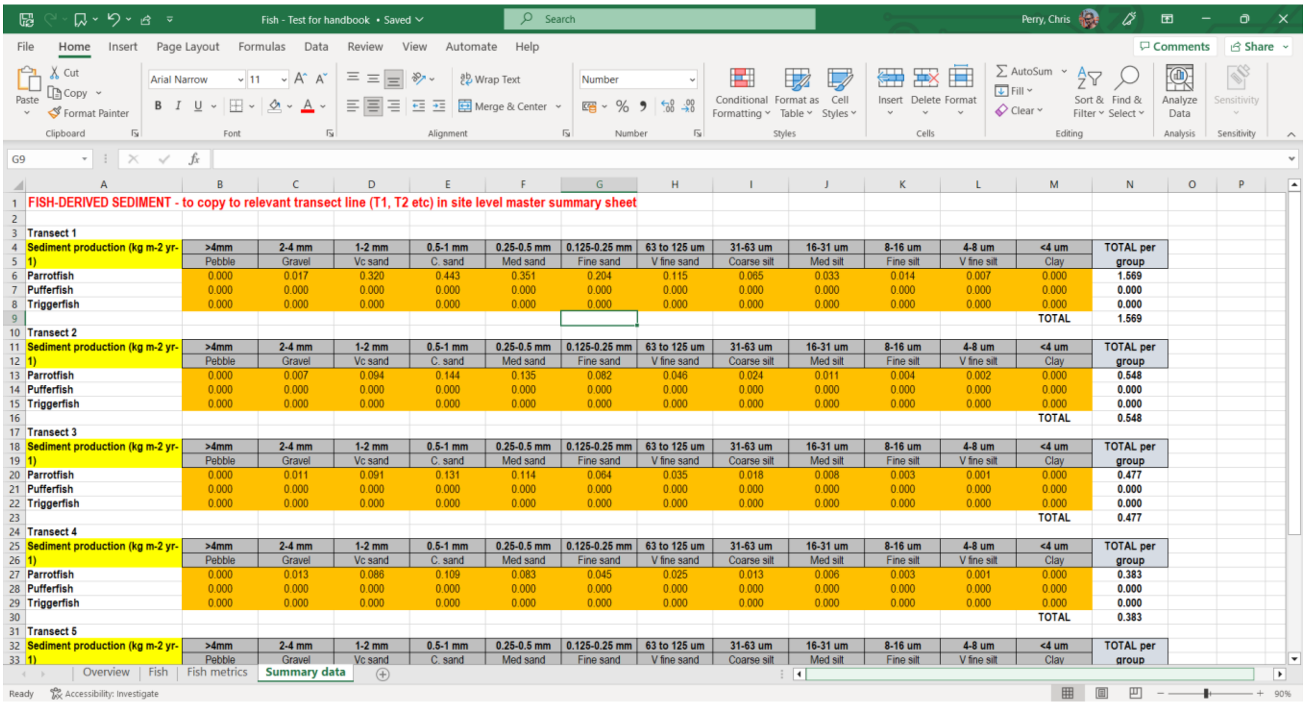


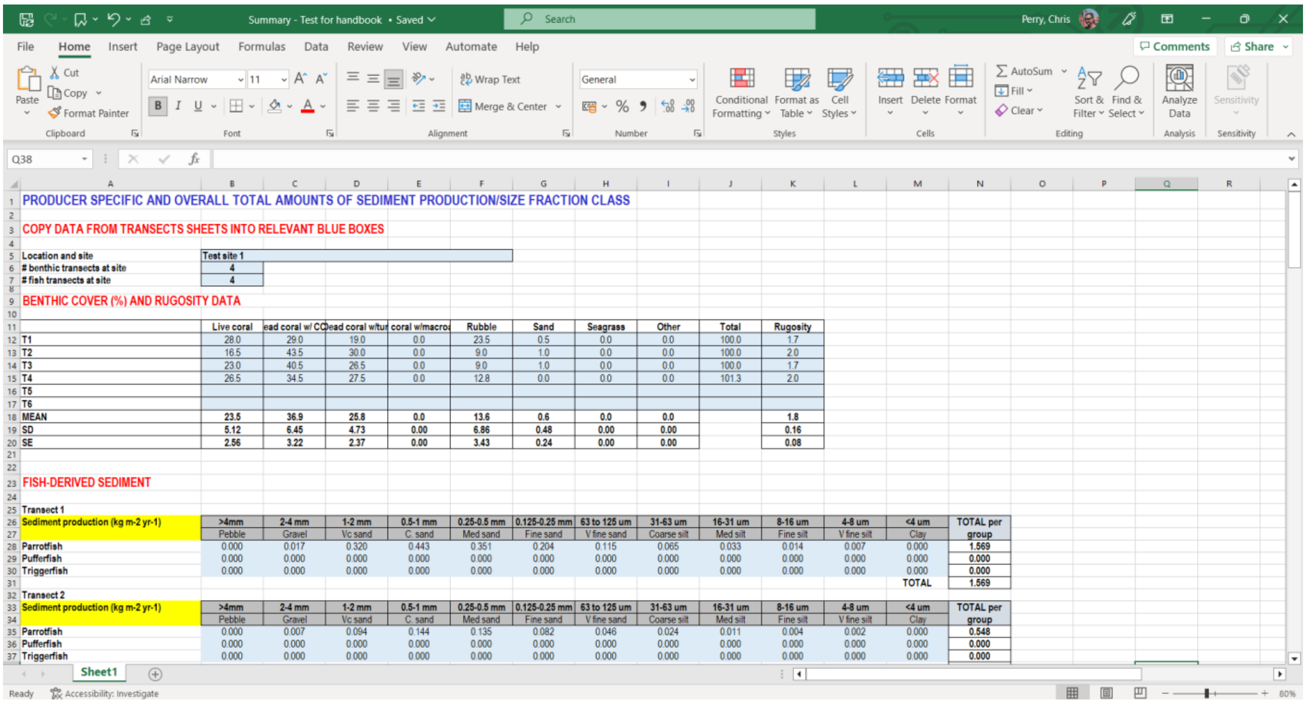

***Figure 4.*** *Sediment production by grain-size class fraction section of the 'Fish' data entry tab.*



FISH-DERIVED SEDIMENT - to copy to relevant transect line (T1, T2 etc) in site level master summary sheet

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transect 1 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.017 | 0.320 | 0.443 | 0.351 | 0.204 | 0.115 | 0.065 | 0.033 | 0.014 | 0.007 | 0.000 | 1.569 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 1.569 |
| Transect 2 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.007 | 0.094 | 0.144 | 0.135 | 0.082 | 0.046 | 0.024 | 0.011 | 0.004 | 0.002 | 0.000 | 0.548 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 0.548 |
| Transect 3 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.011 | 0.091 | 0.131 | 0.114 | 0.064 | 0.035 | 0.018 | 0.008 | 0.003 | 0.001 | 0.000 | 0.477 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 0.477 |
| Transect 4 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.013 | 0.086 | 0.109 | 0.083 | 0.045 | 0.025 | 0.013 | 0.006 | 0.003 | 0.001 | 0.000 | 0.383 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 0.383 |
| Transect 5 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |

**Figure 5.** *'Summary data' tab with production rates autocompleted from each transect. These data (highlighted in orange) should then be manually copied across to the site-level 'Indian Ocean – Master summary sheet' (see Fig. 6 below). For the fish data the entire summary data above can be copied across as one block.*



PRODUCER SPECIFIC AND OVERALL TOTAL AMOUNTS OF SEDIMENT PRODUCTION/SIZE FRACTION CLASS

COPY DATA FROM TRANSECTS SHEETS INTO RELEVANT BLUE BOXES

| | |
|---|---|
| Location and site | Test site 1 |
| # benthic transects at site | 4 |
| # fish transects at site | 4 |

BENTHIC COVER (%) AND RUGOSITY DATA

| | Live coral | ead coral w/ CC | Dead coral w/tur | coral w/macro | Rubble | Sand | Seagrass | Other | Total | Rugosity |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 28.0 | 29.0 | 19.0 | 0.0 | 23.5 | 0.5 | 0.0 | 0.0 | 100.0 | 1.7 |
| T2 | 16.5 | 43.5 | 30.0 | 0.0 | 9.0 | 1.0 | 0.0 | 0.0 | 100.0 | 2.0 |
| T3 | 23.0 | 40.5 | 26.5 | 0.0 | 9.0 | 1.0 | 0.0 | 0.0 | 100.0 | 1.7 |
| T4 | 26.5 | 34.5 | 27.5 | 0.0 | 12.8 | 0.0 | 0.0 | 0.0 | 101.3 | 2.0 |
| T5 | | | | | | | | | | |
| T6 | | | | | | | | | | |
| MEAN | 23.5 | 36.9 | 25.8 | 0.0 | 13.6 | 0.6 | 0.0 | 0.0 | | 1.8 |
| SD | 5.12 | 6.45 | 4.73 | 0.00 | 6.86 | 0.48 | 0.00 | 0.00 | | 0.16 |
| SE | 2.56 | 3.22 | 2.37 | 0.00 | 3.43 | 0.24 | 0.00 | 0.00 | | 0.08 |

FISH-DERIVED SEDIMENT

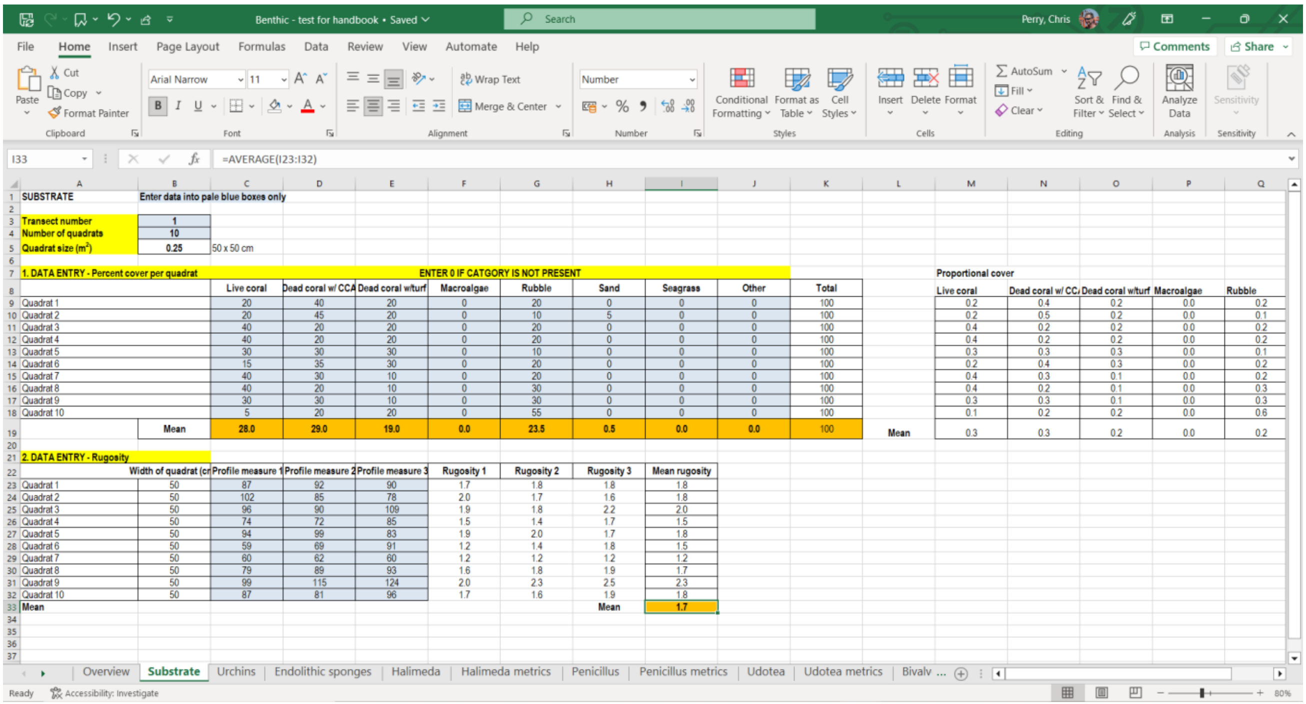
| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Transect 1 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.017 | 0.320 | 0.443 | 0.351 | 0.204 | 0.115 | 0.065 | 0.033 | 0.014 | 0.007 | 0.000 | 1.569 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 1.569 |
| Transect 2 | | | | | | | | | | | | | |
| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
| Parrotfish | 0.000 | 0.007 | 0.094 | 0.144 | 0.135 | 0.082 | 0.046 | 0.024 | 0.011 | 0.004 | 0.002 | 0.000 | 0.548 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

**Figure 6.** *'Indian Ocean – Master summary sheet' data entered for parrotfish, pufferfish and triggerfish.*

## 2.2 Benthic data collection

**2.2.1 Benthic composition and rugosity.** In order to provide benthic data for contextualisation of the sediment generation data, and to provide metrics that feed into some of the sediment generation estimates, basic benthic cover and substrate rugosity data should first be recorded for each quadrat. It is recommended that a photograph of each quadrat is taken initially for any subsequent data verification/checking. Each quadrat should then be examined to quantify the relative % cover of the following major substrate categories: live coral, dead coral w/coralline algal (CCA) crust, dead coral w/ turf, macroalgae, coral rubble, sand and seagrass. This can either be done visually in the field with the aid of a visual % cover estimator chart (see Appendix 1), or post-surveying by point counting benthic categories in quadrat images (e.g., using the Freeware software JMicrovision, CPCe, CoralNet). In addition, an estimate of mean substrate rugosity should be made for each quadrat by measuring over the surface profile of the quadrat (using a flexible ~1 m long tape measure and ensuring that the tape conforms to the surface of the substrate) at three equidistant points (see Fig. 1, inset). Rugosity is then calculated as the profile measure divided by the width of the quadrat (50 cm).

**Data entry:** These % cover estimates and profile measurements (Profile measure 1, Profile measure 2 etc) should be entered into the 'Substrate metrics' tab (Fig. 7) of the 'Indian Ocean – SedBudget data entry' sheet and are automatically pulled across into the sediment production sheets and where relevant to production estimates, e.g., for endolithic sponges. The mean rugosity and % benthic cover data are also automatically pulled across into the final 'Summary' tab (Fig. 8) and these can then be copied across manually into the separate 'Indian Ocean – Master summary sheet' (Fig. 9).



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SUBSTRATE | Enter data into pale blue boxes only | | | | | | | | | |
| Transect number | 1 | | | | | | | | | |
| Number of quadrats | 10 | | | | | | | | | |
| Quadrat size (m²) | 0.25 | 50 x 50 cm | | | | | | | | |
| 1. DATA ENTRY - Percent cover per quadrat | | | | | ENTER 0 IF CATGORY IS NOT PRESENT | | | | | |
| | | Live coral | Dead coral w/ CCA | Dead coral w/turf | Macroalgae | Rubble | Sand | Seagrass | Other | Total |
| Quadrat 1 | | 20 | 40 | 20 | 0 | 20 | 0 | 0 | 0 | 100 |
| Quadrat 2 | | 20 | 45 | 20 | 0 | 10 | 5 | 0 | 0 | 100 |
| Quadrat 3 | | 40 | 20 | 20 | 0 | 20 | 0 | 0 | 0 | 100 |
| Quadrat 4 | | 40 | 20 | 20 | 0 | 20 | 0 | 0 | 0 | 100 |
| Quadrat 5 | | 30 | 30 | 30 | 0 | 10 | 0 | 0 | 0 | 100 |
| Quadrat 6 | | 15 | 35 | 30 | 0 | 20 | 0 | 0 | 0 | 100 |
| Quadrat 7 | | 40 | 30 | 10 | 0 | 20 | 0 | 0 | 0 | 100 |
| Quadrat 8 | | 40 | 20 | 10 | 0 | 30 | 0 | 0 | 0 | 100 |
| Quadrat 9 | | 30 | 30 | 10 | 0 | 30 | 0 | 0 | 0 | 100 |
| Quadrat 10 | | 5 | 20 | 20 | 0 | 55 | 0 | 0 | 0 | 100 |
| | Mean | 28.0 | 29.0 | 19.0 | 0.0 | 23.5 | 0.5 | 0.0 | 0.0 | 100 |

| Proportional cover | | | | | |
|---|---|---|---|---|---|
| | Live coral | Dead coral w/ CC/ | Dead coral w/turf | Macroalgae | Rubble |
| | 0.2 | 0.4 | 0.2 | 0.0 | 0.2 |
| | 0.2 | 0.5 | 0.2 | 0.0 | 0.1 |
| | 0.4 | 0.2 | 0.2 | 0.0 | 0.2 |
| | 0.4 | 0.2 | 0.2 | 0.0 | 0.2 |
| | 0.3 | 0.3 | 0.3 | 0.0 | 0.1 |
| | 0.2 | 0.4 | 0.3 | 0.0 | 0.2 |
| | 0.4 | 0.3 | 0.1 | 0.0 | 0.2 |
| | 0.4 | 0.2 | 0.1 | 0.0 | 0.3 |
| | 0.3 | 0.3 | 0.1 | 0.0 | 0.3 |
| | 0.1 | 0.2 | 0.2 | 0.0 | 0.6 |
| Mean | 0.3 | 0.3 | 0.2 | 0.0 | 0.2 |

| 2. DATA ENTRY - Rugosity | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Width of quadrat (cr | Profile measure 1 | Profile measure 2 | Profile measure 3 | Rugosity 1 | Rugosity 2 | Rugosity 3 | Mean rugosity |
| Quadrat 1 | 50 | 87 | 92 | 90 | 1.7 | 1.8 | 1.8 | 1.8 |
| Quadrat 2 | 50 | 102 | 85 | 78 | 2.0 | 1.7 | 1.6 | 1.8 |
| Quadrat 3 | 50 | 96 | 90 | 109 | 1.9 | 1.8 | 2.2 | 2.0 |
| Quadrat 4 | 50 | 74 | 72 | 85 | 1.5 | 1.4 | 1.7 | 1.5 |
| Quadrat 5 | 50 | 94 | 99 | 83 | 1.9 | 2.0 | 1.7 | 1.8 |
| Quadrat 6 | 50 | 59 | 69 | 91 | 1.2 | 1.4 | 1.8 | 1.5 |
| Quadrat 7 | 50 | 60 | 62 | 60 | 1.2 | 1.2 | 1.2 | 1.2 |
| Quadrat 8 | 50 | 79 | 89 | 93 | 1.6 | 1.8 | 1.9 | 1.7 |
| Quadrat 9 | 50 | 99 | 115 | 124 | 2.0 | 2.3 | 2.5 | 2.3 |
| Quadrat 10 | 50 | 87 | 81 | 96 | 1.7 | 1.6 | 1.9 | 1.8 |
| Mean | | | | | | | Mean | 1.7 |

*__Figure 7.__ 'Substrate metrics' tab for estimating benthic cover and substrate rugosity.*

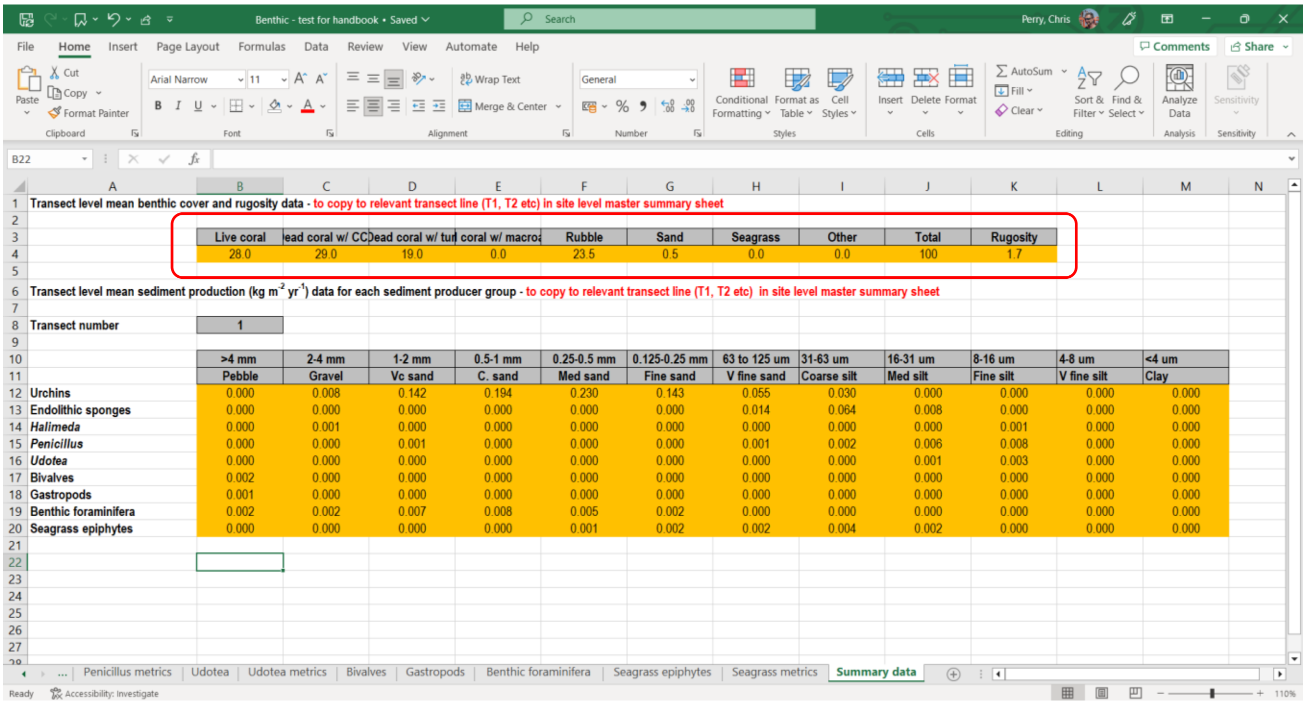



**Figure 8.** *'Summary data' tab with benthic metrics at the top.*

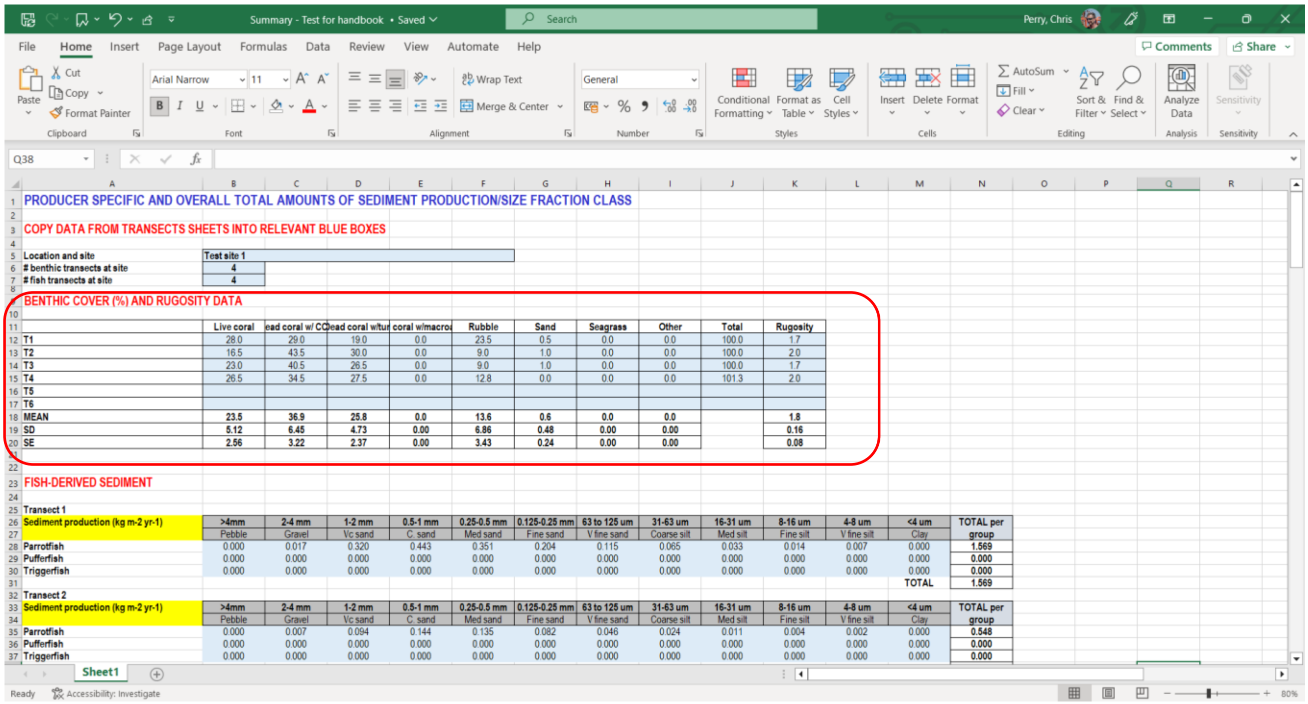



**Figure 9.** *'Indian Ocean – Master summary sheet' showing copied transect level benthic cover data at the top.*

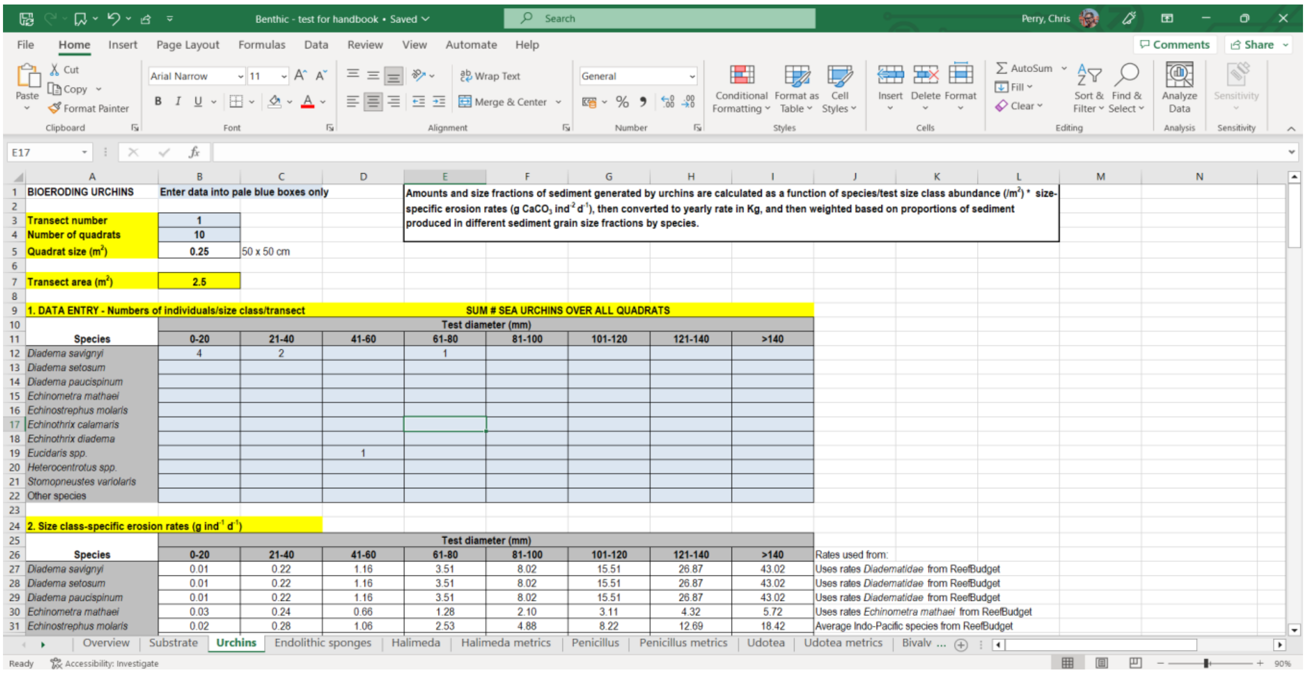
***2.2.2 Urchins.*** Estimates of sediment generation by urchins are also based on the same underlying principles used in the ReefBudget methodology for bioerosion (Perry et al. 2018), that being the collection of data on urchin species and test sizes. A number of studies have quantified substrate erosion rates for different urchin species and test size classes (e.g., Bak 1990; Griffin et al. 2003; Alvarado et al. 2016), based either on the collection of faecal pellets produced per individual per unit of time or on gut content analysis. The resultant bioerosion rate, which is calculated as a function of established relationships based on test size, can then be taken as an estimate of the total sediment generation rate (kg $CaCO_3$ $m^{-2}$ $yr^{-1}$). There is again a further need to also consider the proportion of sediment produced in different sediment grain-size fractions. Such data for urchin sediment production is not extensive. In the Indian Ocean region, data for specimens of different test sizes only exists for the species *Echinometra mathaei* (Chazottes et al. 2004). Thus, additional data from across a wide range of test-size classes of the species *Diadema antillarum* and for small *Echinometra lucunter* collected from the Bahamas (Hale et al. in prep) are currently applied to the most relevant Indian Ocean counterpart species to provide current best estimates of the proportion of sediment generated in different grain-size classes.

As for parrotfishes, an additional aspect of the release of sedimentary carbonate in excreted faecal material relates to the substrates on which the urchins feed. Only a couple of known studies have examined this issue. Hunter (1977) showed that *Diadema antillarum* faecal pellets comprised on average ~47% coral and 53% CCA grains, while work by Chazottes et al. (2004) on *Echinometra mathaei* showed that faecal pellets comprised on average ~61% coral, 35% CCA, and ~4% 'other' grains (mostly foraminifera and molluscs). Additional data for different species and size classes would thus be a useful future area of research for urchins as well, but for now the existing sediment size percentages are used within the 'Indian Ocean – Master summary sheet' to estimate the proportional contributions to coral and CCA particle generation by urchin erosion.

NB. For urchins there is a pressing need to develop a methodology to additionally support estimates of sediment inputs from urchin tests and spines since they can sometimes be common in reef sediment. Ideally this needs to factor for all urchin species in a habitat and not just the bioeroders. Methodologies based on assessments of urchin test size as a function of age/growth rates and test and spine $CaCO_3$ content are thus currently being explored.

**Field data collection:** Counts should be made of every urchin within each quadrat along each transect. These data should be recorded for each species in the relevant size-class bins (0-20 mm, 21-40 mm, 41-60 mm, etc).

**Data entry:** Data are then summed over all quadrats along the transect and entered into the relevant tab of the sediment production template – 'Urchins' (see Fig. 10). The transect number, the number of quadrats counted and the quadrat survey area ($m^2$) should be entered top left of sheet (see Fig. 10) with data then entered by species and test size-class bin.




| Species | 0-20 | 21-40 | 41-60 | 61-80 | 81-100 | 101-120 | 121-140 | >140 |
|---|---|---|---|---|---|---|---|---|
| *Diadema savignyi* | 4 | 2 | | 1 | | | | |
| *Diadema setosum* | | | | | | | | |
| *Diadema paucispinum* | | | | | | | | |
| *Echinometra mathaei* | | | | | | | | |
| *Echinostrephus molaris* | | | | | | | | |
| *Echinothrix calamaris* | | | | | | | | |
| *Echinothrix diadema* | | | | | | | | |
| *Eucidaris spp.* | | | 1 | | | | | |
| *Heterocentrotus spp.* | | | | | | | | |
| *Stomopneustes variolaris* | | | | | | | | |
| Other species | | | | | | | | |

| Species | 0-20 | 21-40 | 41-60 | 61-80 | 81-100 | 101-120 | 121-140 | >140 | Rates used from: |
|---|---|---|---|---|---|---|---|---|---|
| *Diadema savignyi* | 0.01 | 0.22 | 1.16 | 3.51 | 8.02 | 15.51 | 26.87 | 43.02 | Uses rates *Diadematidae* from ReefBudget |
| *Diadema setosum* | 0.01 | 0.22 | 1.16 | 3.51 | 8.02 | 15.51 | 26.87 | 43.02 | Uses rates *Diadematidae* from ReefBudget |
| *Diadema paucispinum* | 0.01 | 0.22 | 1.16 | 3.51 | 8.02 | 15.51 | 26.87 | 43.02 | Uses rates *Diadematidae* from ReefBudget |
| *Echinometra mathaei* | 0.03 | 0.24 | 0.66 | 1.28 | 2.10 | 3.11 | 4.32 | 5.72 | Uses rates *Echinometra mathaei* from ReefBudget |
| *Echinostrephus molaris* | 0.02 | 0.28 | 1.06 | 2.53 | 4.88 | 8.22 | 12.69 | 18.42 | Average Indo-Pacific species from ReefBudget |

***Figure 10.*** *Census data entry section of the 'Urchins' data entry tab.*

These data will then generate an estimate (at bottom of the tab – see Fig. 11) of total sediment generation by urchins for the relevant transect and the mean proportional contributions to different sediment grain-size classes. The summary data are then autocompleted in the final summary tab (highlighted in the orange row) for each transect (see Fig. 8). These data can then be manually copied across into the benthic producer section of the 'Indian Ocean – Master summary sheet' (Fig. 12).

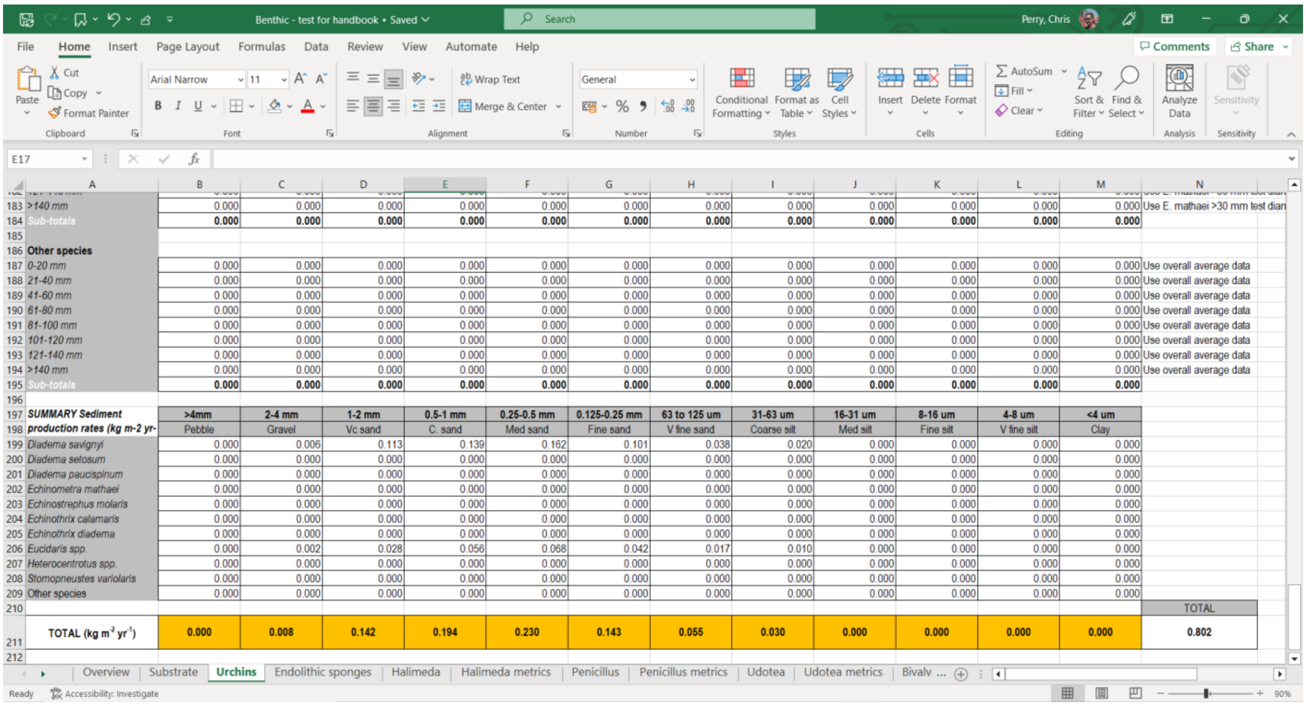


***Figure 11.*** *Summary sediment production section of the 'Urchins' data entry tab.*

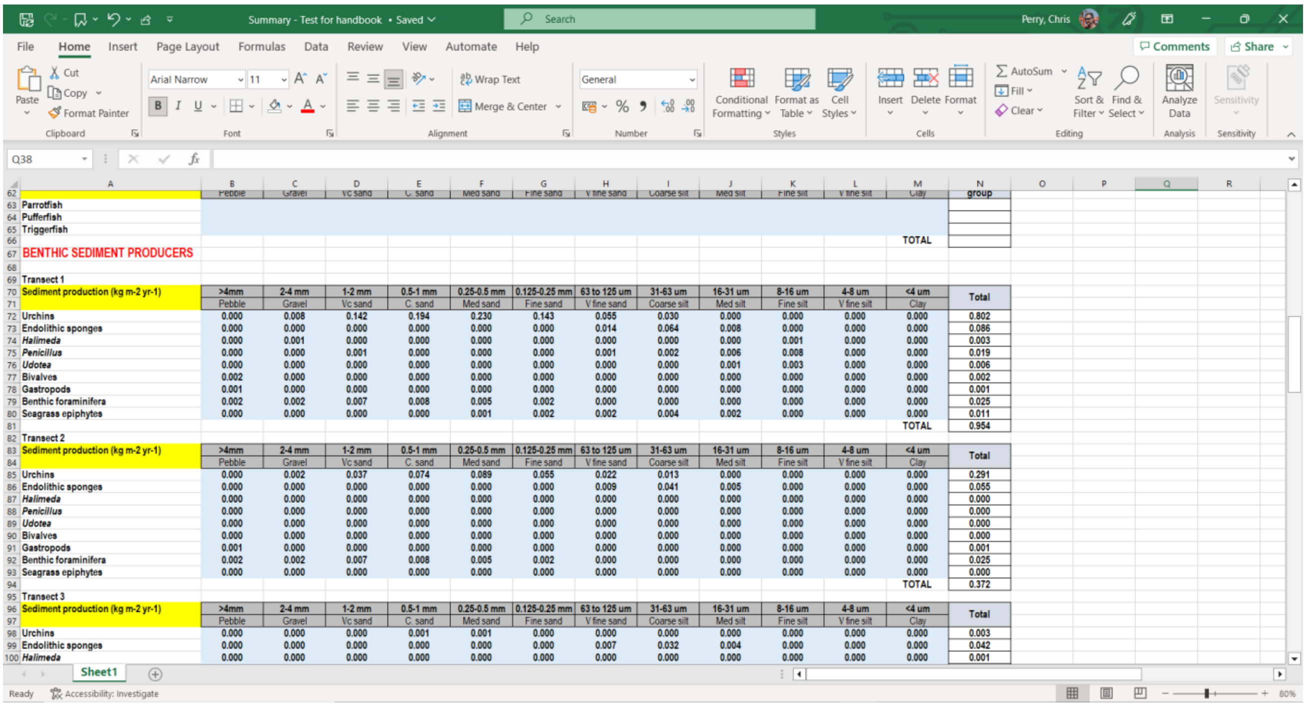


***Figure 12.*** *Benthic data entry section of 'Indian Ocean – Master summary sheet'.*

***2.2.3 Endolithic sponges.*** Endolithic sponges generate fine-grained 'chips' of sediment during the process of chamber excavation, and these are subsequently expelled into the surrounding water through their exhalent oscules. This bioerosion process thus provides a source of fine-grained (mostly <0.1 mm in size) carbonate sediment (Fütterer 1974) and various studies using experimental substrates have provided estimations of rates of endolithic sponge erosion (e.g., Tribollet & Golubic 2005; Osorno et al. 2012; Carreiro-Silva & McClanahan 2012). Meaningful contributions to fine-grained sediment budgets can thus be assumed in environments where endolithic sponges are common. However, because the erosion process involves chemical substrate dissolution, bioerosion rates estimated based on techniques such as buoyant weight loss do not directly equate to a measure of sediment generation. Estimates of sponge-derived sediment generation thus require some understanding of the proportions of eroded substrate that is lost to dissolution during chamber excavation (the difference then being the remaining solid material that is expelled as sediment).

Only limited data on this relationship exists, but published studies on Pacific species suggest that on average ~35% of sponge eroded material is lost to dissolution (Nava & Carballo 2008; Zundelevich et al. 2007). This provides a basis for estimating sponge-derived sediment generation from experimentally-derived erosion rate data, which can be applied as a function of available erodible substrate per unit area (calculated here on the basis of proportional cover of dead in-situ coral and coral rubble). Published data on the grain sizes of sediment generated by endolithic sponges are equally sparse, but Fütterer (1974) provided an overview of the size-class contributions from one Pacific site, and unpublished data provided by Didier de Bakker also quantifies the proportional contributions made to different grain-size classes for a wide range of Caribbean sponge species. A mean of all data is presently applied to Indian Ocean estimates.

**Field data collection:** Estimates of endolithic sponge-derived sediment generation rates for Indian Ocean sites are based on the proportion of available (to endolithic sponge exploitation) substrate in each quadrat (already entered in the 'Substrate metrics' tab) and to which experimentally derived published rates of erosion for the region are applied. Thus, beyond the substrate categorisation process and the selection of an appropriate annual erosion rate (from locally collected experimental data or from existing literature), no additional field data needs to be collected.

**Data entry:** Estimates of endolithic sponge erosion are made by entering data into the relevant sediment production tab – 'Endolithic sponges' (see Fig. 13) as following:
1. Record transect number and # of quadrats counted (top left of tab – see Fig. 13).
2. If possible enter a local or regional erosion rate (kg $CaCO_3$ $m^{-2}$ $yr^{-1}$) (Column B, Row 14) – this should ideally be an erosion rate for sponges only (not other endoliths such as worms or gastropods that do not generate sediment). It is likely that such rates will need to be drawn from published experimental bioerosion block deployments.

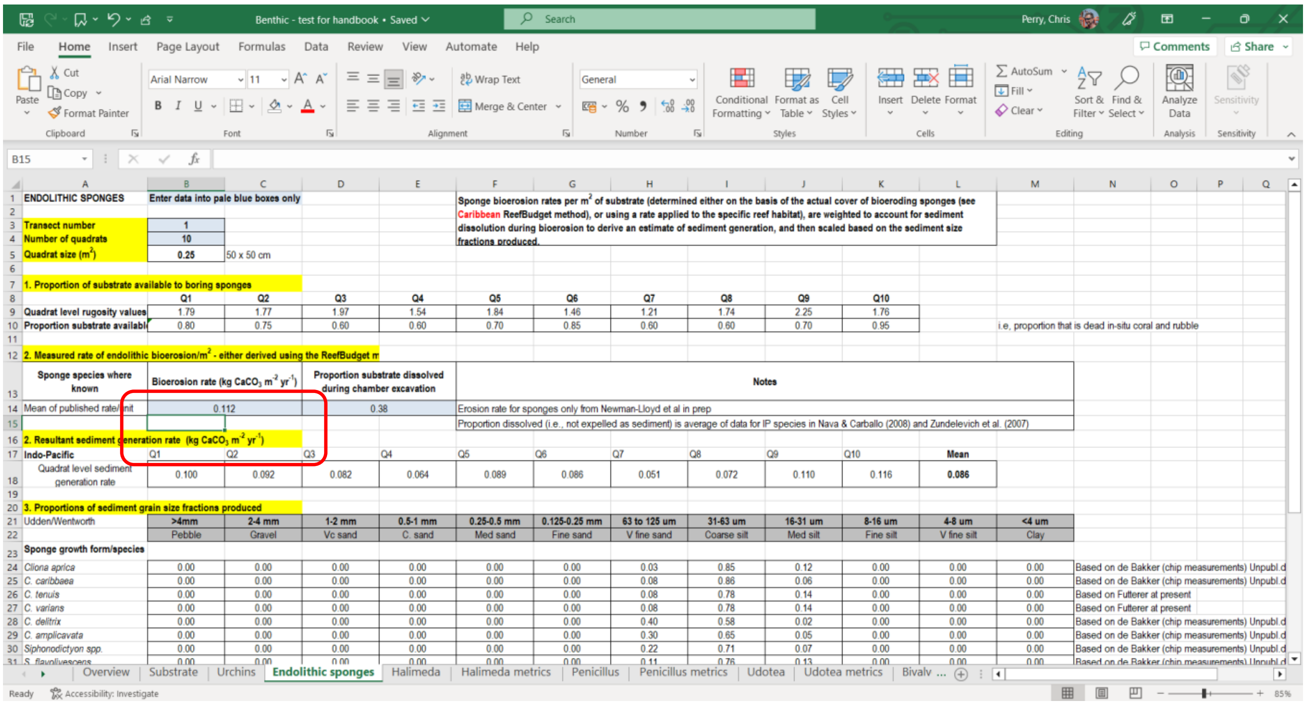



*Figure 13. Census data entry section of the 'Endolithic sponges' data entry tab.*

The tab will then generate an estimate (at bottom of the tab – see Fig. 14) of the total sediment generation by endolithic sponges for the relevant transect and the mean proportional contributions to different sediment grain-size classes. The summary data (highlighted in the orange row) are then autocompleted in the final summary tab for each transect (Fig. 8), and can then be copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

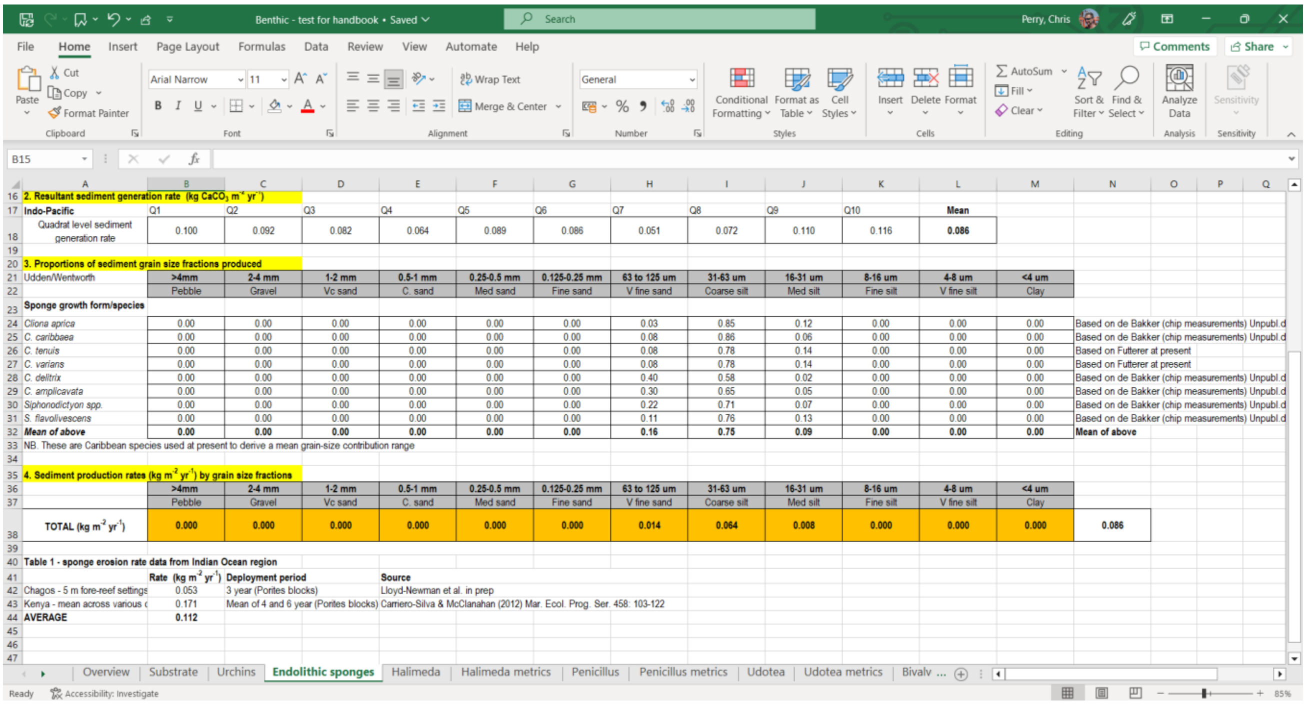



*Figure 14. Summary sediment production section of the 'Endolithic sponges' data entry tab.*

***2.2.4 Sediment generation by species of calcareous green algae.*** Various approaches have previously been used to estimate carbonate production of different calcifying green algae species including *Halimeda* spp., *Penicillus* spp., *Rhipocephalus* spp. and *Udotea* spp.. This has typically involved either sampling plants from known unit areas of reefs, staining and counts of plant segment production, and/or assessments of plant abundance and carbonate content (e.g., Neumann & Land 1975; Drew 1983; Mülter 1988; Payri 1988). These approaches have mostly involved some form of plant removal. The aim for SedBudget has been to limit destructive sampling where possible, whilst also building on aspects of the approaches used in these previous studies. In essence, estimates of green algae carbonate (and thus sediment) production require data on the abundance of plants per unit area of habitat, data on the carbonate content of each of those plants, and data on the annual plant turnover rate (number of crops per year) (see also Freile et al. 2004). The approach used here is thus based on the in-situ measurement of plant dimension metrics and supported by either published data or limited local data collection to parametrise the calculation of carbonate production rates. This specific method was first applied to *Halimeda* spp. (Perry et al. 2016) in the Maldives and then expanded to include species of *Penicillus*, *Rhipocephalus* and *Udotea* (Perry et al. 2019) in the Caribbean. For each group, species-specific relationships between plant biovolumes and carbonate content are used to estimate the amount of carbonate per plant per quadrat. This is comparable to approaches used to quantify biovolumes of corals (Naumann et al. 2009). Species-specific crops-per-year data are then used to estimate annual production rates. In addition, data on the proportional contributions of the carbonate derived from each plant post-mortem to different sediment grain-size classes is needed.

**Note that in contrast to taxa considered up to this point in the methodology, for the calcareous green algae there is a need for users to select what they deem to be the most appropriate underpinning metrics to use e.g., on plant volume : carbonate content relationships, turnover rates etc. Data known to us are listed in the supporting metrics tab for each producer group (see Fig. 15 for an example for *Halimeda*), but users will need to select what they feel is the most appropriate data (or to collect new data at their sites of interest using relevant experimental approaches e.g., those in Perry et al. 2016; 2019).**

***Halimeda* spp..** Plant biovolume: Carbonate content relationship data has now been collected for several common species of *Halimeda* (and this and other available underpinning metrics are provided in the 'Halimeda metrics' tab; see Fig. 15). Such data can, in full or in part, also be locally collected for specific species, or for those species for which no data currently exists, using the approach described in Perry et al. (2019). Where this approach is needed/preferred, the volumetric space or biovolume of *Halimeda* spp. can be broadly defined by the volume of an inverted elliptical cone, determined as:

$$V = \frac{1}{3} \pi a b h$$

Where, a = the length of the minor axis (i.e., of the minimum plant width), b = the length of the major axis (i.e., of the maximum plant width), and h = the height of the plant.

The carbonate content of each *Halimeda* plant can then be determined based, first, on counts of the total number of segments in each plant and, second, by establishing the mean segment carbonate content. On this basis, an average relationship between plant volume and carbonate content can be determined and applied to data on plant dimensions collected in field surveys. This avoids the need to harvest all *Halimeda* plants in each quadrat. Published or locally collected crops-per-year data can then be used to make estimates of annual carbonate production rates (as described in Perry et al. 2016).

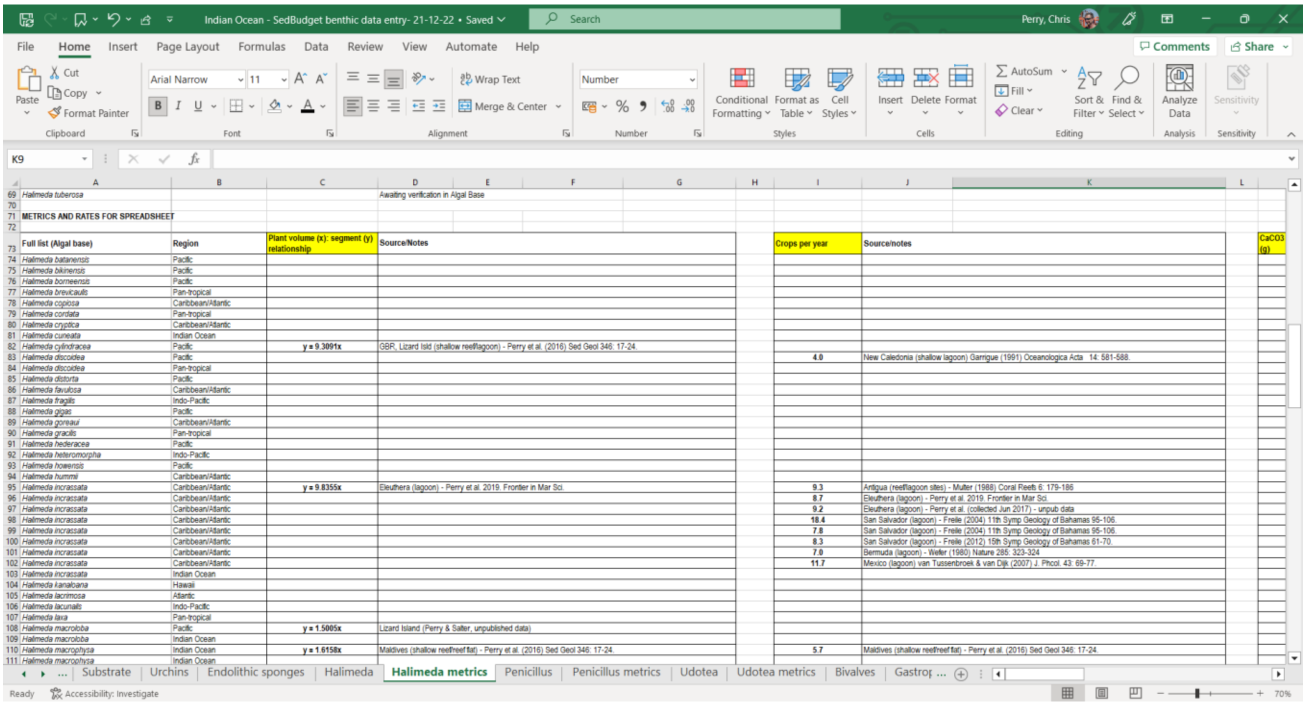


***Figure 15.*** *'Halimeda metrics' tab with site- and species-specific metrics used for the sediment generation rate estimates.*

**Field data collection:** Based on the above approach, data should be collected in the field on the primary plant dimensions (mm) that are needed to calculate plant volume, these being for each *Halimeda* plant present in a quadrat: the plant height (h) and the minimum and maximum plant widths (a and b, respectively). This information, including the species name, should be recorded for every plant within each 0.5 x 0.5 m quadrat along a transect line. Where plants intersect the edges of a quadrat they would be recorded and measured as being within the quadrat only if their holdfast is location inside the quadrat margins.

**Data entry:** The transect number and number of quadrats examined should first be entered in the blue boxes on the top left of the tab (Fig. 16). A list of all species present within the study area should then be entered (Rows 11 to 18; Fig. 16) along with, for each species present, the basic metrics on the plant biovolume: plant segment relationship (Column D), numbers of crops per year (Column G) and average segment carbonate content (Column J) (see Fig. 16). The available underpinning metrics can be drawn from the 'Halimeda metrics' tab or can be determined locally where needed.

Rows 23-30 should also contain data on species-specific proportional contributions of plants to different grain-size fractions (available data is on the 'Halimeda metrics' tab, or ideally can be collected locally).

**NB. It is most efficient to populate a location-specific master data entry sheet with the above information for all species present within a study area before starting the field data entry.**

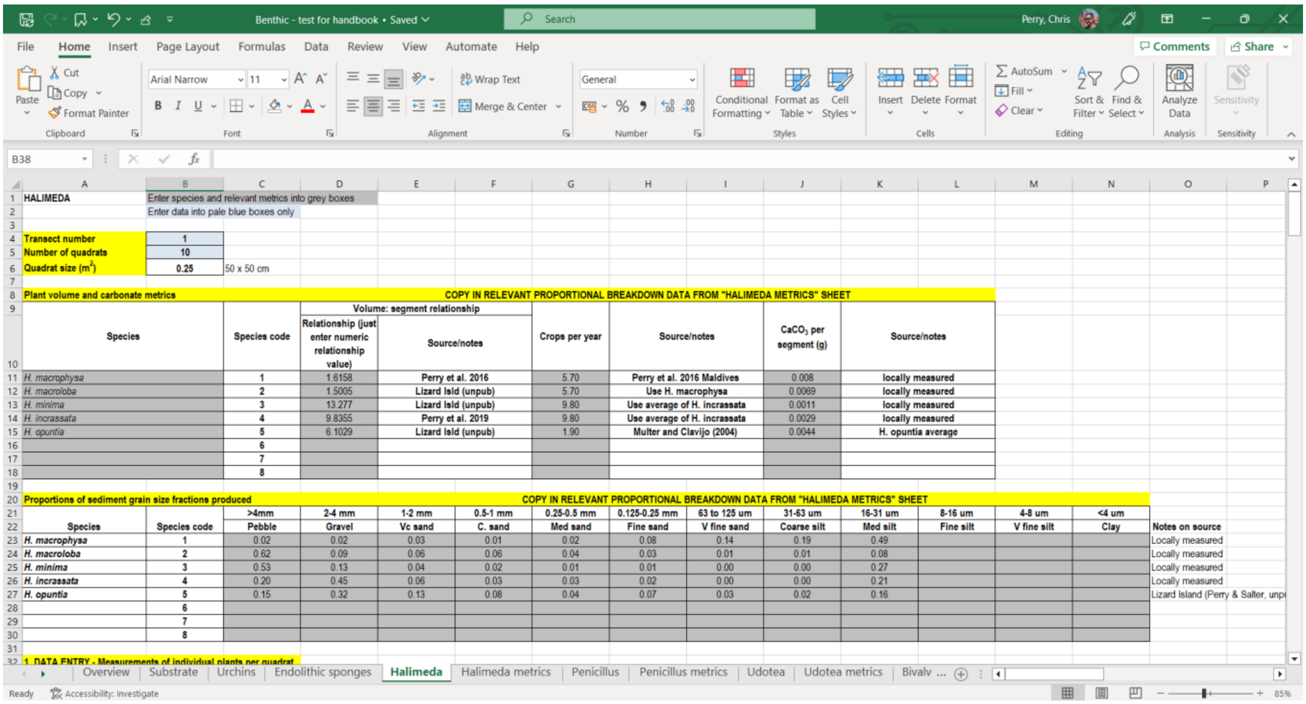


***Figure 16.*** *Section of the 'Halimeda' data entry tab for entering underpinning species-specific metrics.*

Once the data entry spreadsheet has been populated with the underpinning metrics, the measured dimension of each plant per quadrat can be entered, using the species code number (Column C, Rows 11-18), and then the h, a, b dimensions (in mm) in Columns C-E respectively (see Fig. 17). The sheet is set up with 10 quadrats that can be populated with data, and sediment production rates and proportions of sediment in different size class fractions will be automatically calculated based on the principles described above. The summary of production and grain-size contribution data (highlighted in orange row; Fig. 18) are then autocompleted in the final summary tab for each transect (Fig. 8), and can be copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

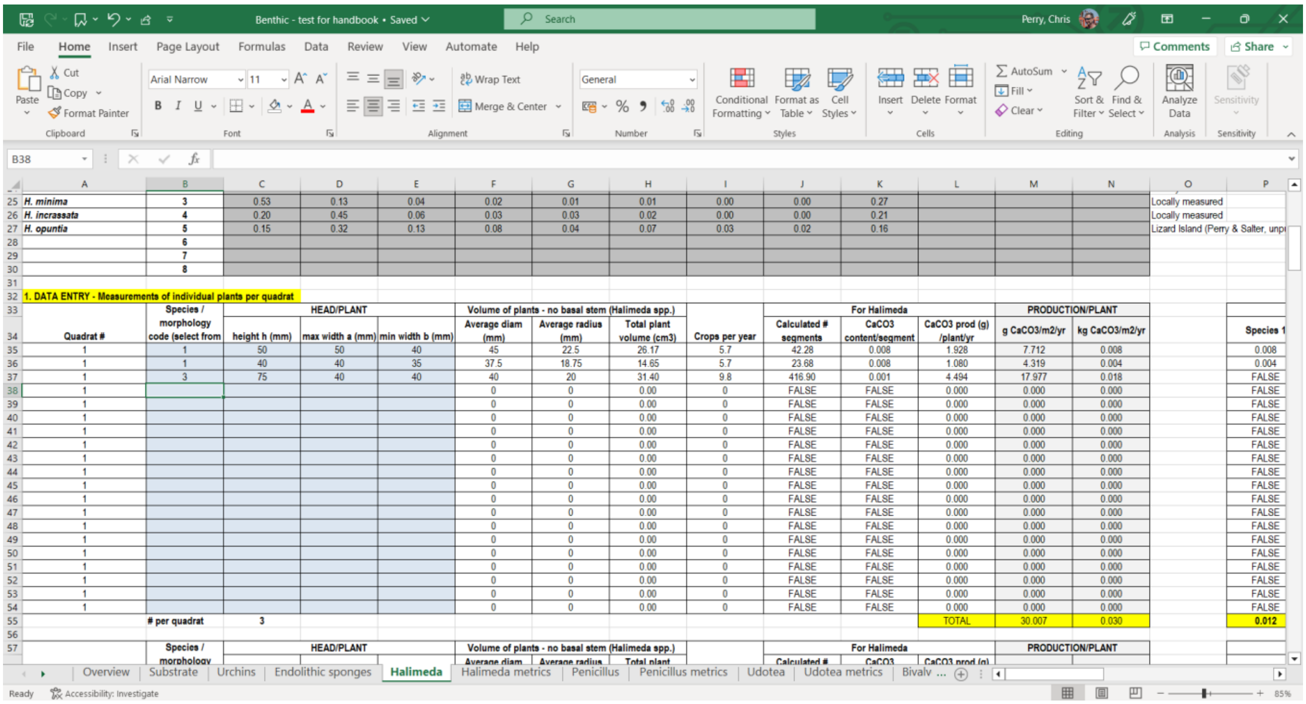


***Figure 17.*** *Census data entry section of the 'Halimeda' data entry tab.*

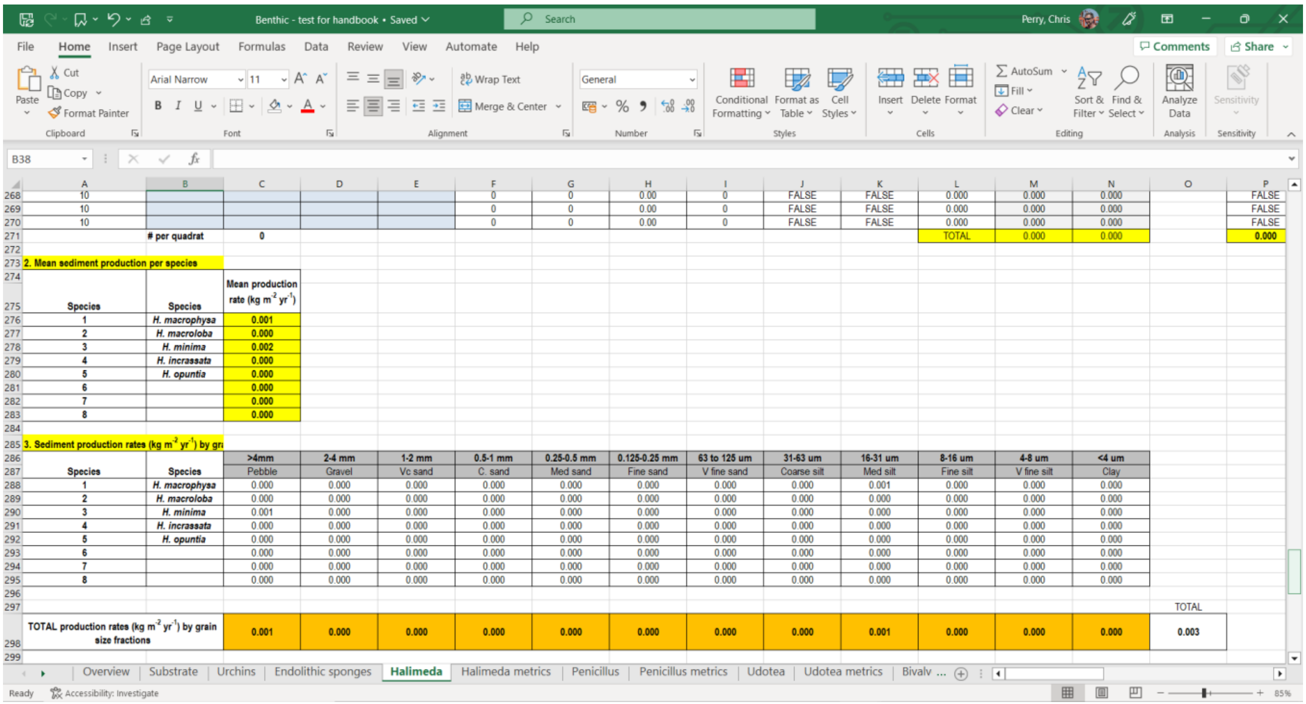



***Figure 18.*** *Summary sediment production section of the 'Halimeda' data entry tab.*

***Penicillus* spp.**. Data on plant biovolume: carbonate content relationships exist for a couple of common species of *Penicillus* (this and other available underpinning metrics are provided in the 'Penicillus metrics' tab). However, where such relationship data is needed (for a site or species not presently analysed) a similar approach to that used for *Halimeda* spp. (above) can be used. For *Penicillus* spp. the growth morphology and the resultant volumetric space are best defined by the sum of the volume (V) of an inverted elliptical cone (for the head) and a cylinder (for the stem) (see Perry et al. 2019), which can be determined as:

$$V = (\tfrac{1}{3} \pi a b h) + (\pi r^2 s)$$

Where, a = the length of the minor axis (i.e., of the minimum head width), b = the length of the major axis (i.e., of the maximum head width), h = the height of the head, s = height of the stem, and r = the radius of the stem (calculated in the spreadsheets from in-field measures of the plant diameter, d).

The carbonate content (g) of each plant can then be determined based on weight loss of whole plants after treatment in acid (see Perry et al. 2019). On this basis, an average relationship between plant volume and carbonate content can be determined and applied to data on plant dimensions collected in field surveys. Published or locally collected crops-per-year data can then be used to make estimates of annual carbonate production rate (as described in Perry et al. 2016).

**Field data collection:** Based on the above approach, data should be collected in the field on the primary plant dimensions (mm) that are needed to calculate plant volume, these being for each *Penicillus* plant present in a quadrat both the stem dimensions, i.e., stem height (s) and stem width (d), and the head dimensions, i.e., height (h), and minimum width (a) and maximum width (b) dimensions. This information, including the species, should be recorded for every plant within each 0.5 x 0.5 $m^2$ quadrat along a transect line. Where plants intersect the edges of a quadrat they would be recorded and measured as being within the quadrat only if their holdfast is located inside the quadrat margins.

**Data entry:** The transect number and number of quadrats examined should first be entered in the blue boxes top left of tab (Fig. 19). The data entry tab should then be populated with a list of the *Penicillus* species present within the study area (Rows 11 to 14; Fig. 19) and, accompanying this, for each species present, the following underpinning metrics should be added: i) the relevant plant biovolume: carbonate content relationship (Column D), and ii) the number of crops per year (Column G) (see Fig. 19). These underpinning metrics can be drawn where available from the 'Penicillus metrics' tab or can be locally determined where needed.

Rows 19-22 should also contain data on the species-specific proportional contributions of plants to different grain-size fractions (available data is on the 'Penicillus metrics' tab, or can be locally collected).

**NB. It is most efficient to populate a location-specific master data entry sheet with the above information for all species present within a study area before starting the field data entry.**

Once the data entry spreadsheet has been populated with the underpinning metrics, the measured dimension of each plant per quadrat can be entered, using the species code (Column C; Fig. 19), and then the relevant plant stem and head dimensions (in mm) in Columns C-G, respectively (see Fig. 19). The sheet is set up to enter data for up to 10 quadrats, and from these sediment production rates and proportions of sediment in different size-class fractions will be automatically calculated based on the principles described above. The summary production and grain-size contribution data (highlighted in orange row; Fig. 20) are then autocompleted in the final summary tab for each transect (Fig. 8) and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

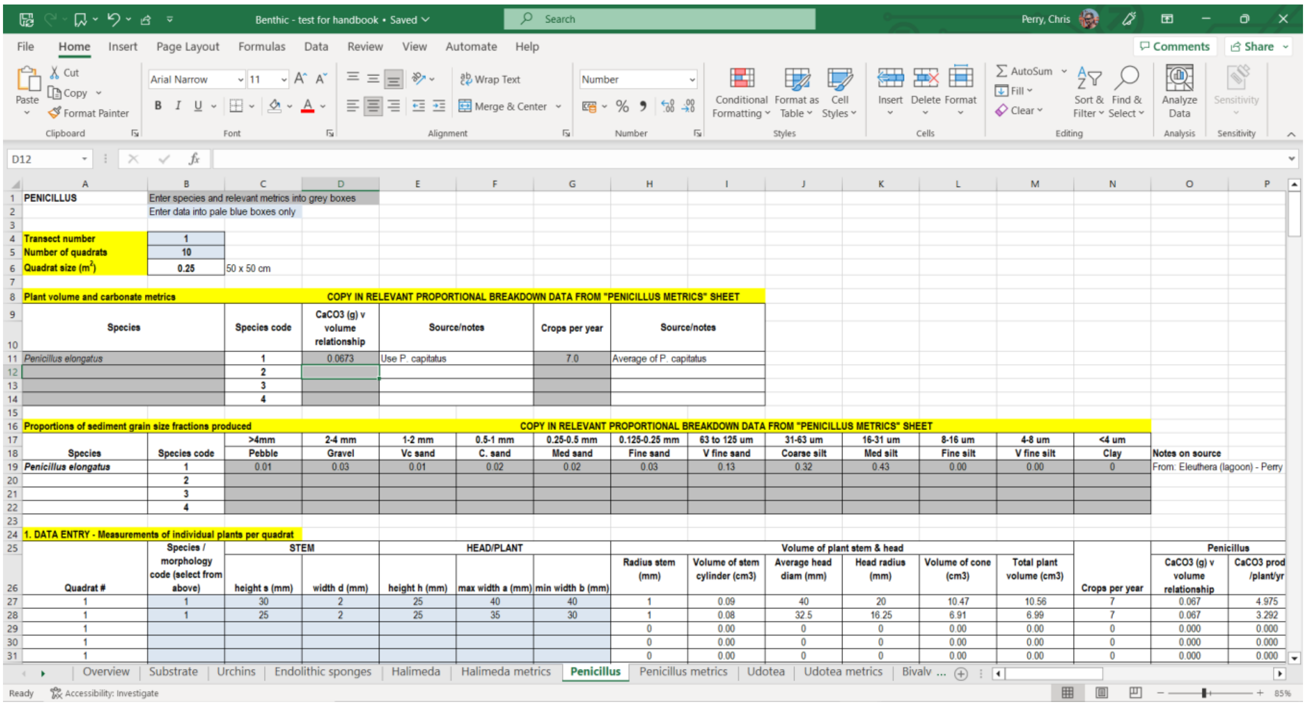


***Figure 19.*** *Census data entry section of the 'Penicillus' data entry tab.*

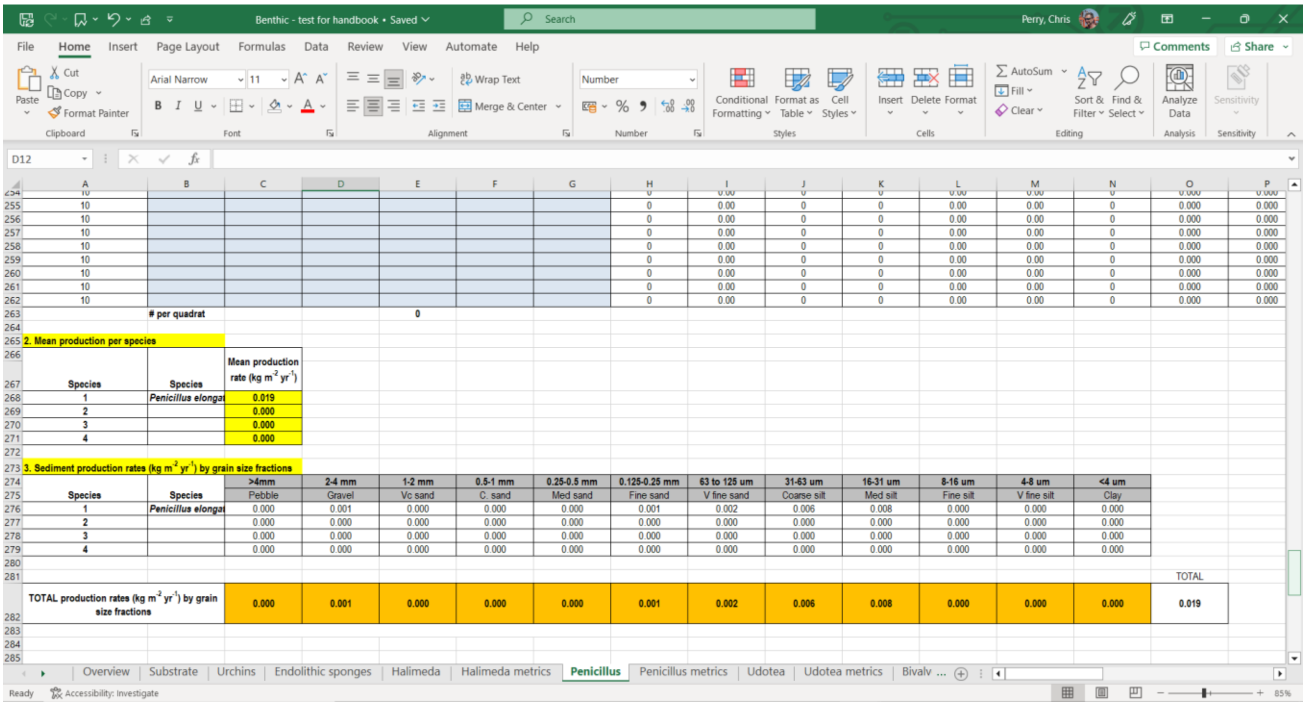



***Figure 20.*** *Summary sediment production section of the 'Penicillus' data entry tab.*

***Udotea* spp.** Specimens of *Udotea* exhibit two basic growth morphologies, some such as *Udotea cyathiformis* have a vase-shaped growth morphology to the main 'head', while others such as *Udotea flabellum* have a flatter triangular shaped head. Data on plant biovolume: carbonate content relationships for species of both growth forms have been established (Perry et al. 2019) and along with other underpinning metric data are available in the tab 'Udotea metrics'. However, additional relationship data e.g., for a specific study location or species, can be collected using a similar approach to that used for *Halimeda* and *Penicillus* spp.. For vase-shaped species of *Udotea*, the growth morphology and resultant volumetric space is best defined by the sum of the volume (V) of an inverted elliptical cone (for the head) and a cylinder (for the stem) (Perry et al. 2019), and which can be determined as:

$$V = (\tfrac{1}{3} \pi a b h) + (\pi r^2 s)$$

Where, a = the length of the minor axis (i.e., of the minimum head width), b = the length of the major axis (i.e., of the maximum head width), h = the height of the head, s = height of the stem, and r = the radius of the stem (calculated in the spreadsheets from in-field measures of the plant diameter, d).

For species with fan-shaped heads, plant volumetric space can be defined by the sum of the volume (V) of a triangular prism (for the head) and a cylinder for the stem (Perry et al. 2019), which can be determined as:

$$V = (0.5 h a b) + (\pi r^2 s)$$

Where, h = head height, a = maximum width of the plant head, and b is fixed at 0.5 mm to represent head thickness (b does not need recording in the field or entering in the spreadsheet for fan-shaped species), s = stem height, r = stem radius (calculated in the spreadsheets from in-field measures of the plant diameter, d).

The carbonate content (g) of each plant can then be determined based on weight lost after acid treatment (see Perry et al. 2019). On this basis, an average relationship between plant volume and carbonate content can be determined and applied to data on plant dimensions collected in field surveys. Published or locally collected crops-per-year data can then be used to make estimates of annual carbonate production rates (as described in Perry et al. 2016).

**Field data collection:** Based on the above approach, data should be collected in the field on the primary plant dimensions (mm) that are needed to calculate plant volumes, these being for each *Udotea* plant present in a quadrat (regardless of growth form) the relevant stem dimensions i.e., height (s) and width (d), and then the head dimensions: for vase-shaped species : height (h), minimum width (a) and maximum width (b) dimensions, or for fan-shaped species: the height (h) and width (a) of the head (see Figure 2 in Perry et al. 2019). This information, including the species name, should be recorded for every plant within each 0.5 x 0.5 m quadrat along a transect line (recommended 10 quadrats per transect). Where plants intersect the edges of a quadrat they would be recorded and measured as being within the quadrat only if their holdfast is located inside the quadrat margins.

**Data entry**: The transect number and number of quadrats examined should first be entered in the blue boxes top left of tab (Fig. 21). The data entry tab should then be populated with a list of the *Udotea* species present within the study area (Rows 11 to 14; Fig. 21) and, accompanying this, for each species present, the following underpinning metrics should be added: i) the relevant plant biovolume: carbonate content relationship (Column E), and ii) the number of crops per year (Column H) (see Fig. 21). These underpinning metrics can be drawn where available from the 'Penicillus metrics' tab or can be locally determined where needed.

Rows 19-22 should also contain data on species-specific proportional contributions of plants to different grain-size fractions (available data is on the 'Udotea metrics' tab, or can be collected locally).

**NB. It is most efficient to populate a location-specific master data entry sheet with the above information for all species present within a study area before starting the field data entry.**

Once the data entry spreadsheet has been populated with the underpinning metrics, the measured dimension of each plant per quadrat can be entered, using the species code (Column C), and then the relevant plant stem and head dimensions (in mm) for vase-shaped species in Columns C-G (see Fig. 21) or for fan-shaped species in columns C-F (see Fig. 21). The sheet is set up with 10 quadrats that can be populated with data and then sediment production rates and proportions of sediment in different size-class fractions will be calculated based on the principles described above. The summary production and grain-size contribution data (highlighted in orange row; Fig. 22) are then autocompleted in the final summary tab for each transect (Fig. 8), and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

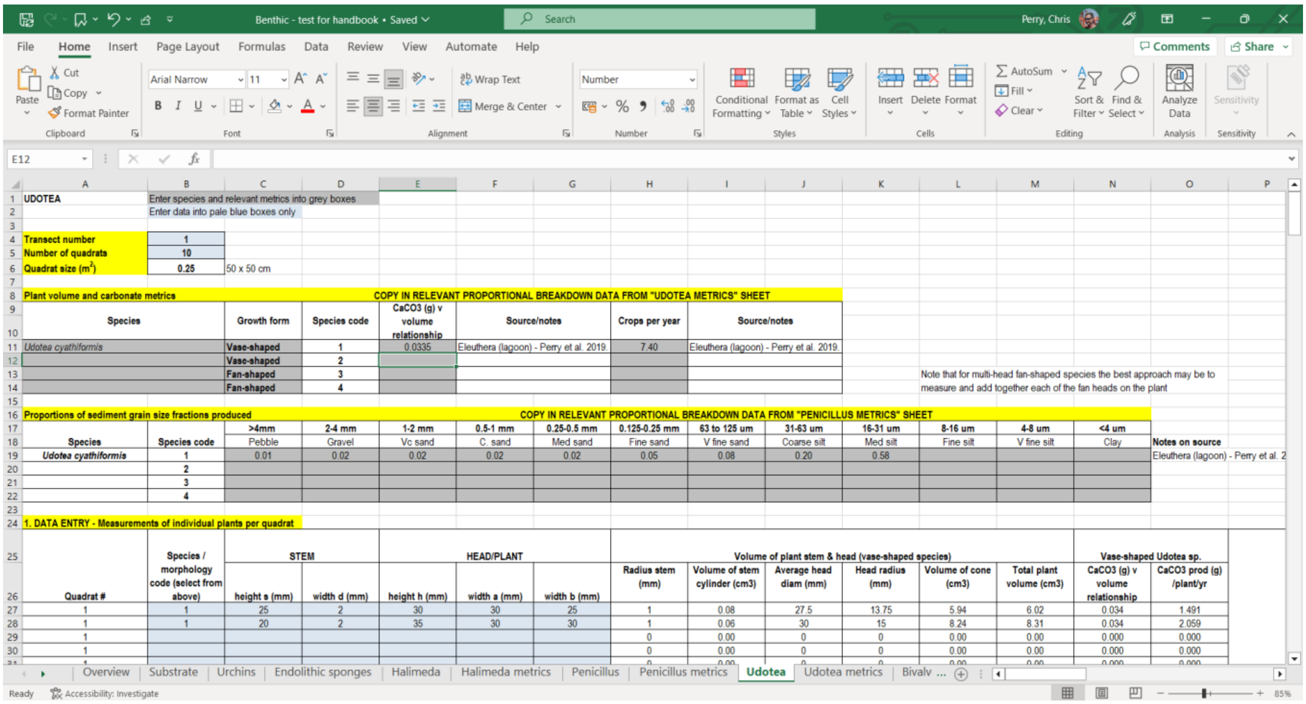



***Figure 21.*** *Census data entry section of the 'Udotea' data entry tab.*

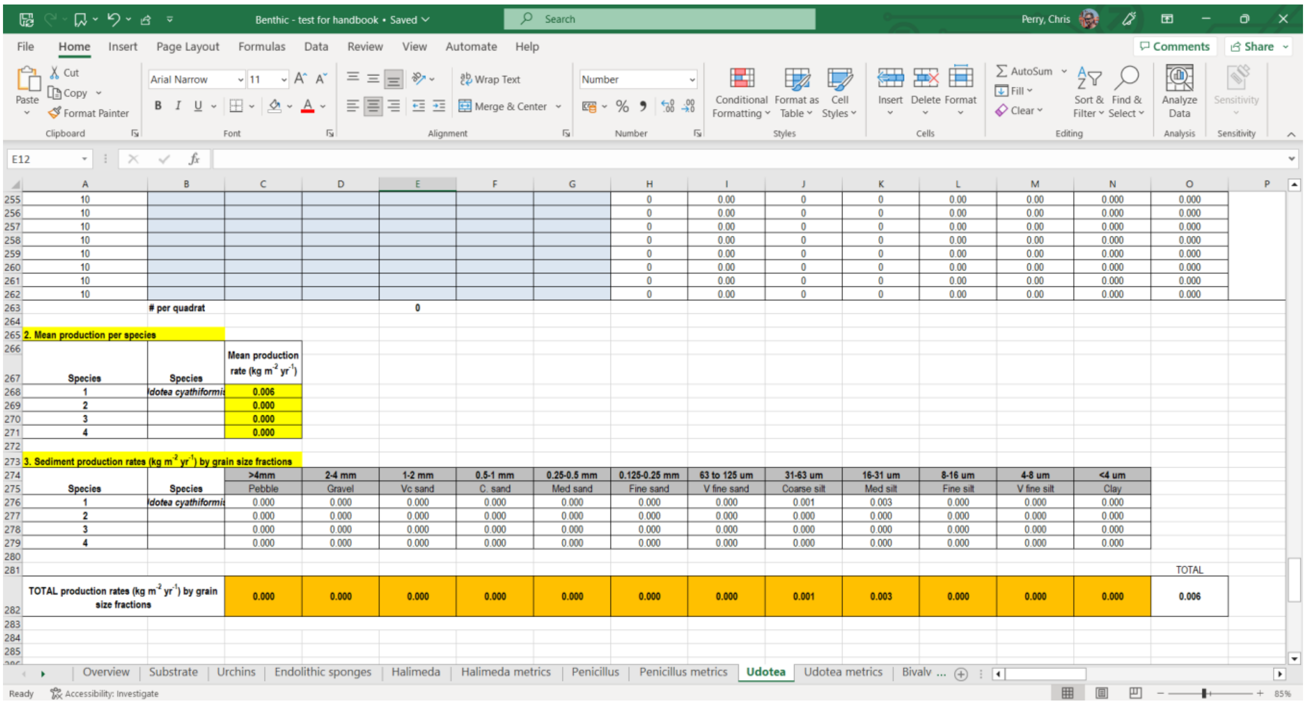



***Figure 22.*** *Summary sediment production section of the 'Udotea' data entry tab.*

***2.2.5 Bivalves.*** Bivalves represent important producers of skeletal sedimentary carbonate in some reef habitats, and most especially in those dominated by sediment substrates as many bivalves are infaunal. Estimating sediment generation rates is, however, made complex by the fact that annual carbonate production rates for a given species are scarce. The approach used here thus represents a current working approach and is based on counts of the number of living infaunal or epifaunal bivalves per 0.5 x 0.5 m quadrat, with an average annual carbonate production rate per individual applied (based on the data provided in Bosence 1989 – these are listed at the bottom of the 'Bivalves' tab) and a future option may be to revise this to include counts at the genera level.

**Field data collection:** Based on the above approach, counts are made of the number of living infaunal (within sediment) and epifaunal bivalves per 0.5 x 0.5 m quadrat (recommended 10 quadrats per transect), and the maximum size of each specimen should also be recorded. Depending on the nature of the substrate different approaches to these counts may wish to be considered. In framework-dominated habitats with only a very thin sediment veneer, counts of the numbers of bivalves found within the entire quadrat may well be feasible based simply on visual inspection. In sediment dominated environments where the sediment extends to more than a few cm's of depth it would be more appropriate to place a smaller (e.g., 0.25 x 0.25 m) quadrat within the main quadrat, to extract all the sediment to a specified depth of 10-15 cm using a smaller beaker, and to then sieve this in a hand-held 2 mm mesh-size sieve in-water. Bivalve specimens present can then be counted and measured (and photographed) and the numbers scaled to the 0.5 x 0.5 m quadrat area. Users are free to choose how many quadrats this process is repeated for – but the number of quadrats examined needs to be noted in the top left of the data entry sheet. We suggest to include even specimens well in excess of 4 mm.

**Data entry:** The transect number and number of quadrats examined should first be entered in the blue boxes top left of tab (Fig. 23), and an average annual carbonate production (growth) rate per individual added in Row 14, Column C (note this is pre-set with the average data from various genera listed at the bottom of the sheet and are derived from Bosence 1989). The number of bivalves counted in each quadrat should then be entered in the relevant quadrat boxes in Row 10 (use a '0' where no shells were present in a quadrat). The size data recorded in the field should then be used to populate Row 21 with data on the numbers of shells counted in each grain-size class. A total sediment production rate and the proportion of shells in different size-class fractions will be automatically calculated based on the principles described above. The resultant summary production and grain-size contribution data (highlighted in orange row; Fig. 23) are then autocompleted in the final summary tab for each transect (Fig. 8) and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

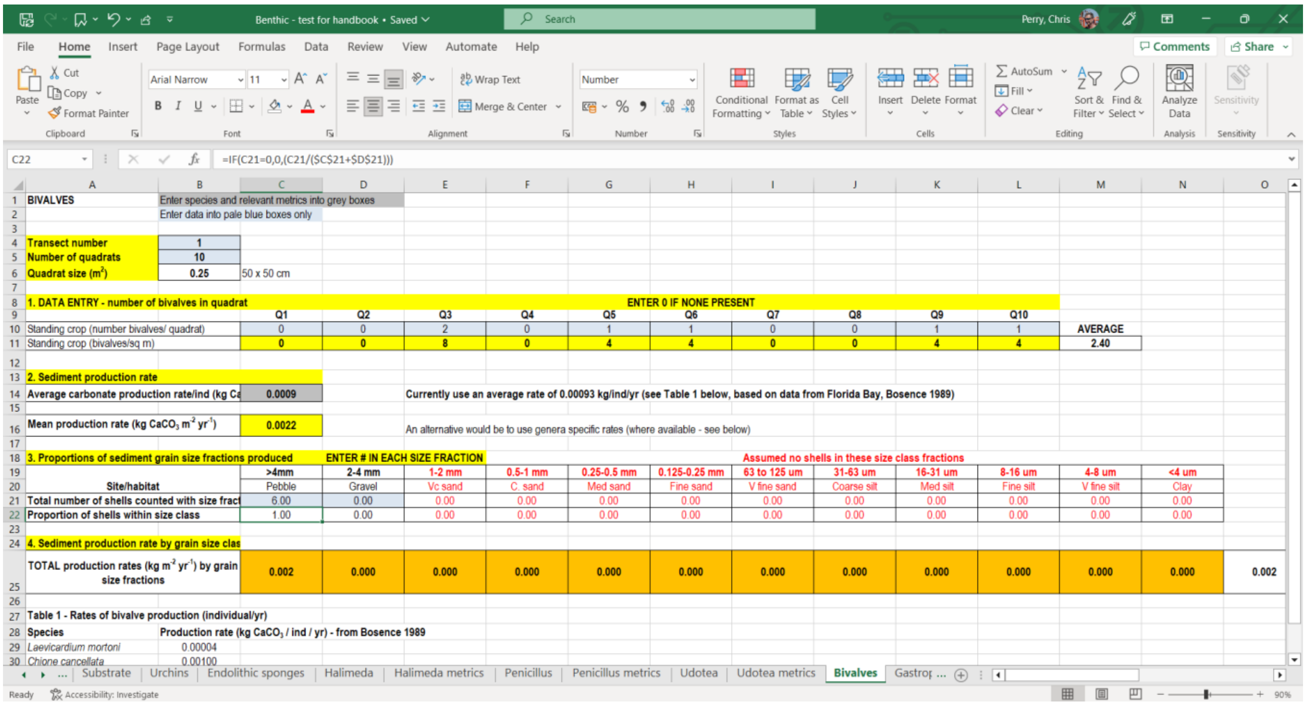



***Figure 23.*** *Census data entry section and summary production data on the 'Bivalves' data entry tab.*

***2.2.6 Gastropods.*** Gastropods also represent important contributors of skeletal sedimentary carbonate in some reef habitats, and again probably most especially in those dominated by sedimentary substrates. Estimating sediment generation rates is made slightly easier than for bivalves as many reefal gastropods tend to be epifaunal, although as for bivalves, annual production rates for a given species are not abundant. The approach used here thus again represents a current working approach and is simply based on counts of the number (and size) of living gastropods per 0.5 x 0.5 m quadrat, with an average annual carbonate production rate per individual applied (based on the data provided in Bosence 1989 – these are listed at the bottom of the 'Gastropods' tab), and a future option may be to revise this to include counts at the genera level.

**Field data collection:** Based on the above approach, counts are made of the number of living gastropods (check to ensure shells are alive and not inhabited by hermit crabs) per 0.5 x 0.5 m quadrat (recommended 10 quadrats per transect), and the maximum size of each specimen should also be recorded. We suggest to include even specimens well in excess of 4 mm.

**Data entry:** The transect number and number of quadrats examined should first be entered in the blue boxes top left of tab (Fig. 24), and an average annual carbonate production (growth) rate per individual added in Row 14, Column C (note this is pre-set with the genera level average data from Bosence 1989). The number of gastropods counted in each quadrat should then be entered in the relevant quadrat boxes in Row 10 (use a '0' where no shells are present in a quadrat). The size data recorded in the field should then be used to populate Row 21 with data on the numbers of shells counted in each grain-size classes. A total sediment production rate and the proportion of shells in different size class fractions will be automatically calculated based on the principles described above. The resultant summary production and grain-size contribution data (highlighted in orange row;

Fig. 26) are then autocompleted in the final summary tab for each transect (Fig. 8) and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

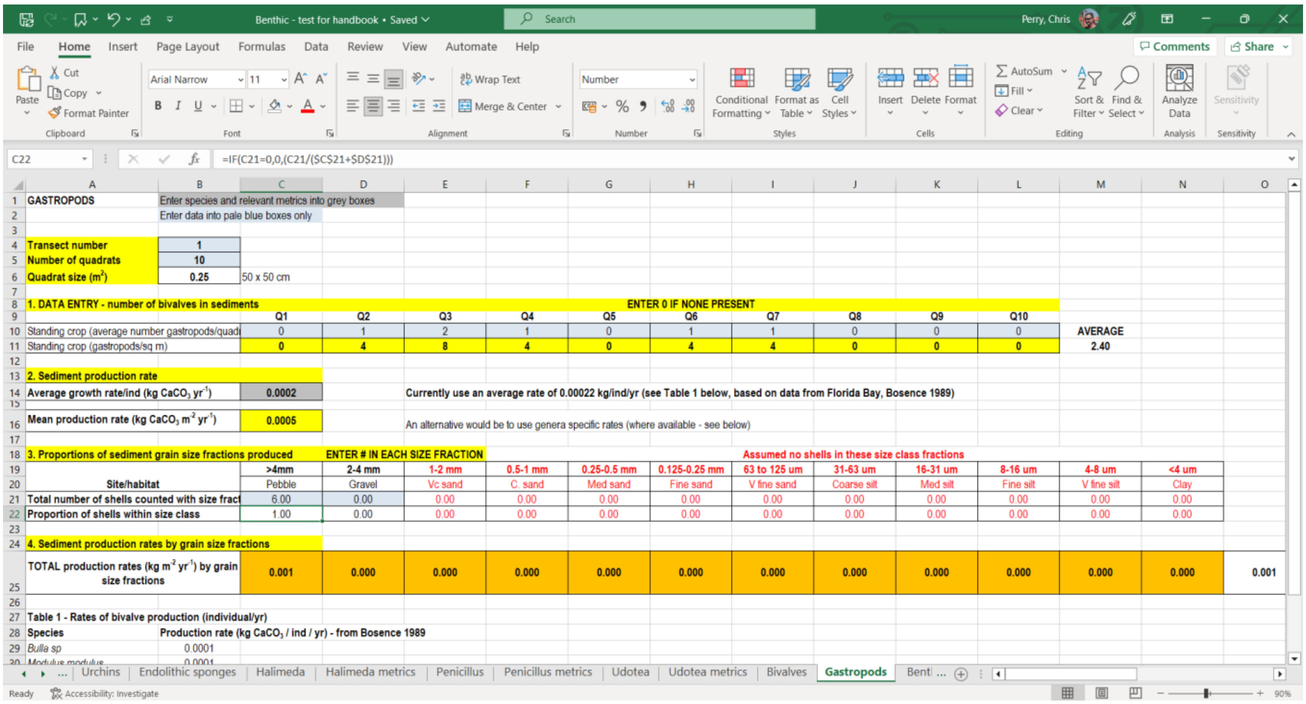



***Figure 24.*** *Census data entry section and summary production data on the 'Gastropods' data entry tab.*

***2.2.7 Benthic foraminifera.*** Benthic foraminifera are major sediment producers in many reef systems. However, their generally small size and the challenges of measuring populations and test sizes in-situ make estimates of sediment production based only on in-field data collection highly problematic. In this initial iteration of SedBudget we thus adopt an approach proposed by Langer et al. (1997), hereafter termed the '% abundance method'. Using this methodology, foraminifera test production rates are estimated as a function of the proportion of tests counted in sediment samples collected from each transect, multiplied by a set productivity value depending on reef zone (in reef framework and rubble habitats, 6 g $m^{-2}$ $yr^{-1}$; for lagoonal sand-dominated habitats, 1.2 g $m^{-2}$ $yr^{-1}$; see Langer et al. 1997). This approach clearly lacks detail on the taxa present and their grain size contributions, the latter being especially useful for consistency with the other methodologies in SedBudget. Our approach here is thus based on counts of foraminifera tests at the family level being made within size-fraction sieved samples such that the proportional contributions of foraminifera tests to different sediment grain-size fractions can also be accounted for.

Note 1: Whilst counts at family level are not strictly needed for the existing methodology (and a total count of foraminifera present per size class fraction can be entered if preferred in Row 30; see fig. 25), family level data collection is recommended to allow retrospective calculations to be made once a more refined version of the carbonate production method is developed – see note 2.

Note 2: One issue with the '% abundance method', although being the only current working approach that is viable, is that it only crudely accounts for site-relevant productivity rates. Consequently, we are looking to develop an alternative approach aligned to the 'simple method' (after Hallock 1981) described by Narayan et al. (2022), whereby the carbonate production rate per foraminifera genera is estimated as a function of the current standing crop of foraminifera and then factoring for genera-specific turnover rates and the mass of a typical individual of that genera in a specific size class (Narayan et al. 2022). Once refined, this alternative methodology will appear in a revised iteration of the SedBudget methodology.

**Field data collection:** Based on the current '% abundance method', it is suggested that 3 (~25 ml) surficial sediment samples are collected using falcon-type tubes from within one or more randomly selected quadrats along each transect. Post-collection, samples can be combined into a single aggregated sample before freshwater rinsing over an 8 mm sieve to remove larger particles and a 63-µm sieve to remove the finest size-class fractions (to which foraminifera make little or no contribution). The remaining sample can then be dried and bagged for subsequent (post-fieldwork) analysis.

**Lab-based microscopy analysis.** Prior to analysis, the samples collected from each transect can be run through a riffle splitter if needed to create a randomised but smaller, i.e., more manageable, sediment sample for microscopy analysis (ideally aiming for a single post-splitting sample of ~50g). This sample should be dry sieved through a sieve stack (base pan, 125 µm, 250 µm, 500 µm, 1 mm, etc up to 4 mm). Each size-class fraction should then be weighed, and the weight recorded in the data entry spreadsheet. A grain classification analysis of each size class fraction should then be undertaken, separating benthic foraminifera tests from all other grain types (Appendix 7 provides a visual guide to the major Indian Ocean genera). This sorting should be done under a light microscope using a picking tray and fine paint brush to sift sediment grains. Examples of useful sorting items (small sieves, splitter, sample tray and fine brushes and even small microscope) are available here: http://www.microslides.kreativika.sk/?q=allproducts. We recommend 100 grains per size class fraction are classified into foraminifera (by family) and non-foraminifera categories, and the numbers recorded in the spreadsheet. In some cases, and especially for larger size class fractions, fewer than 100 grains may be available, in which case all grains should be counted and these again classified into foraminifera and non-foraminifera categories. This provides a % contribution of foraminifera tests at family level to each size class fraction, and from this both total and size-class specific production estimates can be derived based on the Langer et al. (1997) method.

**Data entry:** The transect number should first be entered in the blue box top left of tab (Fig. 25), and then the relevant foraminifera productivity conversion metric added (Row 9, Column C). The weight (g) of each sieved size fraction should be added (Row 15, Columns D-J). Note that we assume no data is collected from samples <63 µm due to the challenges of picking and identifying under a binocular microscope. After counting and classification of grains into foraminifera (by family group) and non-foraminifera categories for each sieved size class fraction, the total number of grains counted per size class fraction should be recorded (Row 18, Columns C-I), and the numbers of each foraminifera family genera counted in the size class fraction also recorded (Row 21-33, Columns C-I). If family level data are not recorded, the total numbers of foraminifera per sediment grain size class can be added under 'Other taxa' in Row 30. A total foraminifera test production rate and the production rate within each size-class fraction will then be automatically calculated based on the principles described above. The resultant summary production and grain-size contribution data (highlighted in orange row; Fig. 25) are then autocompleted in the final summary tab for each transect (Fig. 8) and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

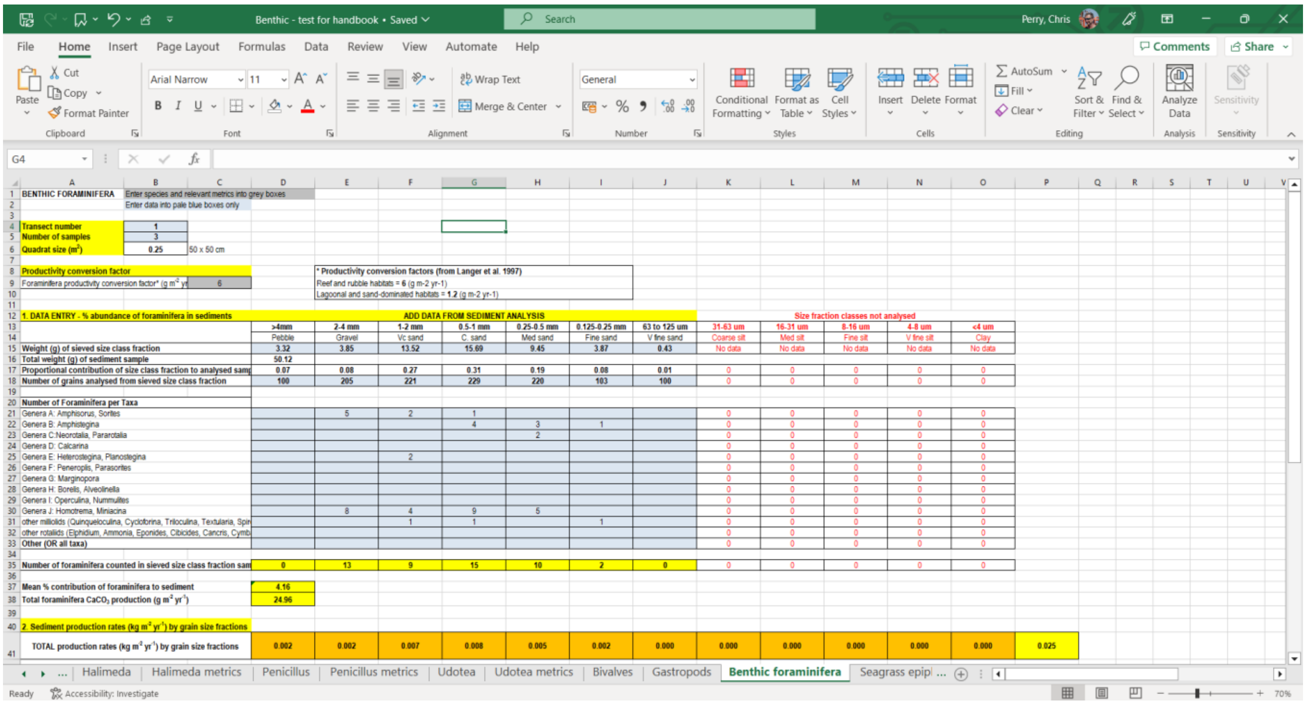


***Figure 25.** Census data entry section and summary production data on the 'Benthic foraminifera' data entry tab.*

***2.2.8 Seagrass epibionts.*** The calcareous epiphytes that colonise seagrass blades can locally make an important contribution to carbonate sediment production through their post-mortem release (Corlett & Jones 2007). Several studies have quantified resultant production rates and these show that blade density and the amount of carbonate per blade are important controls on epiphytic carbonate production (Nelsen & Ginsburg 1986; Perry & Beavington-Penney 2005). The approach used here is underpinned by data generated in these previous studies (specifically on epiphyte carbonate values and crops per year – see 'Seagrass metrics' tab for published data for different species and locations of seagrass). By making counts of seagrass blade density per unit area of habitat, seagrass epiphytic calcium carbonate per blade can then be determined. If needed, local measures of epiphytic carbonate content can be readily obtained from local collection of blades following the methods in Nelsen & Ginsburg (1986).

**Field data collection:** Based on the above approach, counts should be made of the total number of seagrass blades per species per 0.5 x 0.5 m quadrat (recommended 10 quadrats per transect).

**Data entry:** The transect number and number of quadrats examined should first be entered in the blue boxes top left of tab (Fig. 26), and the species present listed in Rows 10-12. A published or locally obtained crops-per-year rate should be entered for each species present (Column D, Rows 10-12, as appropriate), and published or locally collected data on mean epibiont weight per blade for each species present be added as well (Column E, Rows 10-12, as appropriate) (Fig. 26). Rows 18-20 (as appropriate to the number of species present) should also have data entered on the proportional contributions made by epibionts to each grain-size fraction after their release from the seagrass blades (the only known data, from Perry et al. 2019, is pre-entered but is user-changeable if it is locally determined). Existing known relevant metrics are provided on the 'Seagrass metrics' tab. Field counts of the number of seagrass blades per quadrat should then be entered (Row 24-26, Columns C-L).

**NB. It is most efficient to populate a location-specific master data entry sheet with the above information for all species present within a study area before starting the field data entry.**

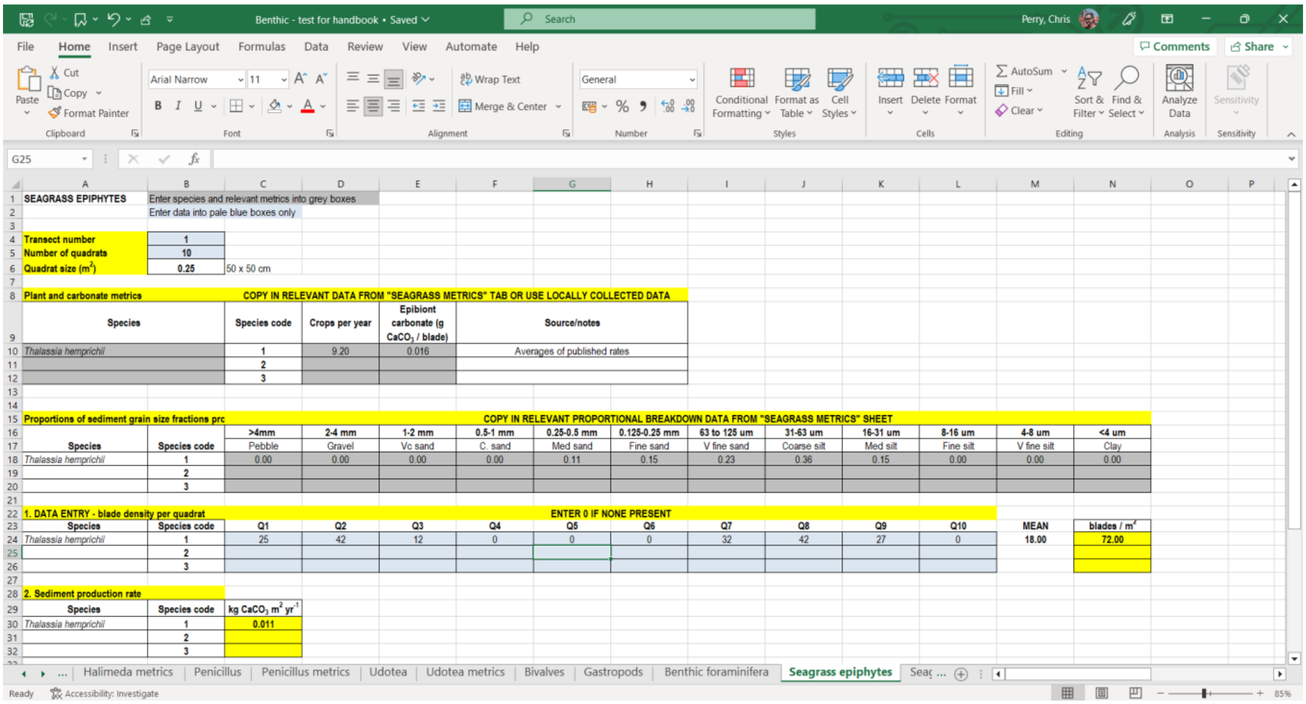



*Figure 26.* *Census data entry section on the 'Seagrass epiphytes' data entry tab.*

A total sediment production rate and the proportional contributions to different size-class fractions will be automatically calculated based on the principles described above. The resultant summary production and grain-size contribution data (highlighted in orange row; Fig. 27) are then autocompleted in the final summary tab for each transect (Fig. 8) and can then be manually copied across to the 'Indian Ocean – Master summary sheet' (Fig. 12).

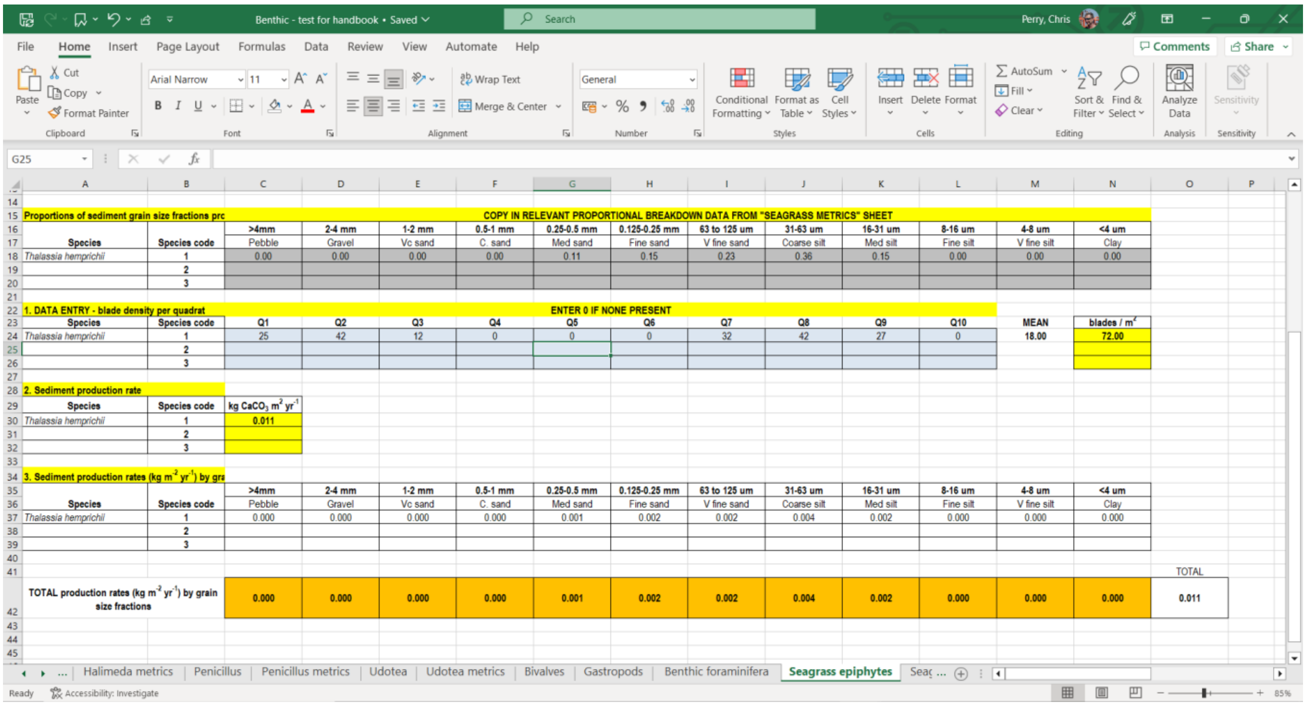


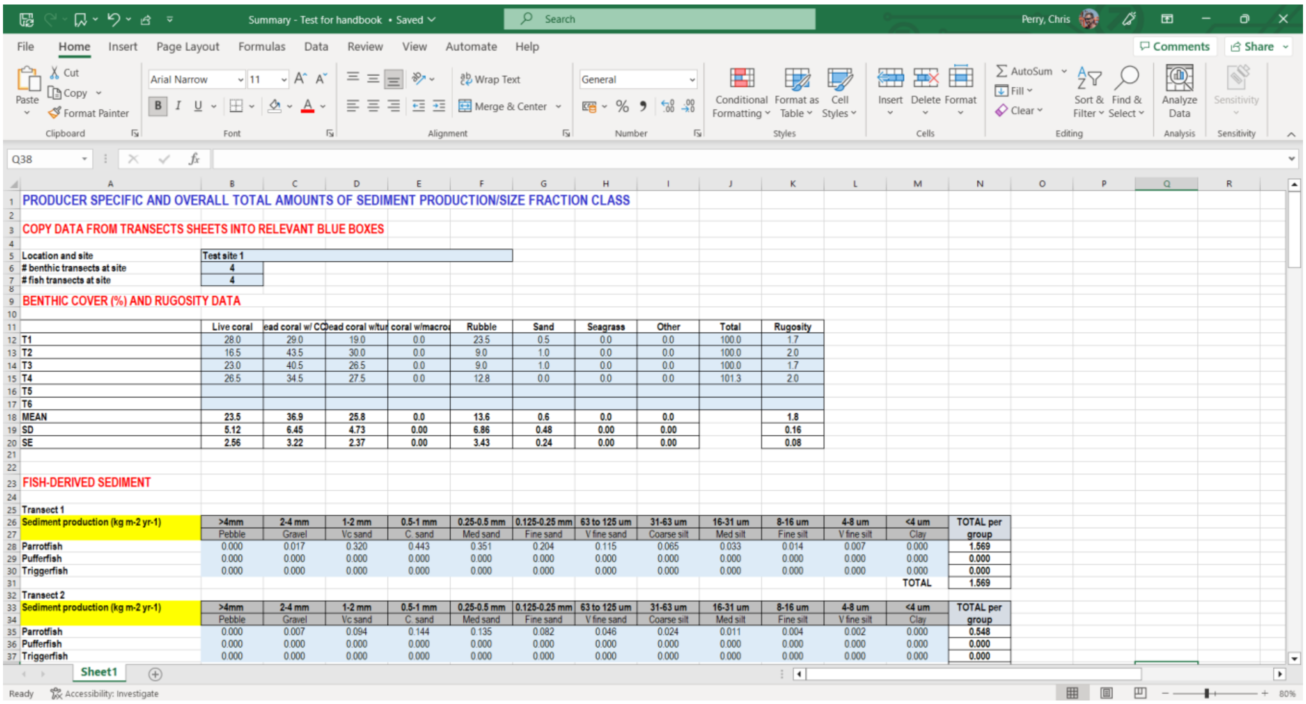

*Figure 27.* *Summary production data on the 'Seagrass epiphytes' data entry tab.*

## 3. Summary of data and outputs

As outlined above, the sediment production rate by grain-size class data – which are automatically pulled across into the 'Summary data' tabs for fish (Fig. 5) and benthic producers (Fig. 8) should be manually copied across to the 'Indian Ocean – Master summary sheet' – renamed to the study site name or code (Fig. 28). The site name and number of transects examined should be entered at the top left, and additionally summary benthic cover and rugosity data for each transect can be copied across from the benthic sheets. Data for each producer group should be entered into the relevant transect lines. Fish data are entered at the top of the sheet (Fig. 28) and benthic data below this (Fig. 29). The sheet is set to accommodate data from up to 6 transect lines per site.

The summary spreadsheet will then calculate a mean sediment production rate (± SD and SE) for each producer group present within each transect.

Lower down the sheet in rows 150-176 (see Fig. 30), two tables summarise this data: Table 1 summarises total sediment production by transect and overall for the site, and Table 2 summarises sediment production rate by producer group and grain-size class fraction.



PRODUCER SPECIFIC AND OVERALL TOTAL AMOUNTS OF SEDIMENT PRODUCTION/SIZE FRACTION CLASS

COPY DATA FROM TRANSECTS SHEETS INTO RELEVANT BLUE BOXES

| | |
|---|---|
| Location and site | Test site 1 |
| # benthic transects at site | 4 |
| # fish transects at site | 4 |

BENTHIC COVER (%) AND RUGOSITY DATA

| | Live coral | ead coral w/ CC | ead coral w/tur | coral w/macro | Rubble | Sand | Seagrass | Other | Total | Rugosity |
|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 28.0 | 29.0 | 19.0 | 0.0 | 23.5 | 0.5 | 0.0 | 0.0 | 100.0 | 1.7 |
| T2 | 16.5 | 43.5 | 30.0 | 0.0 | 9.0 | 1.0 | 0.0 | 0.0 | 100.0 | 2.0 |
| T3 | 23.0 | 40.5 | 26.5 | 0.0 | 9.0 | 1.0 | 0.0 | 0.0 | 100.0 | 1.7 |
| T4 | 26.5 | 34.5 | 27.5 | 0.0 | 12.8 | 0.0 | 0.0 | 0.0 | 101.3 | 2.0 |
| T5 | | | | | | | | | | |
| T6 | | | | | | | | | | |
| MEAN | 23.5 | 36.9 | 25.8 | 0.0 | 13.6 | 0.6 | 0.0 | 0.0 | | 1.8 |
| SD | 5.12 | 6.45 | 4.73 | 0.00 | 6.86 | 0.48 | 0.00 | 0.00 | | 0.16 |
| SE | 2.56 | 3.22 | 2.37 | 0.00 | 3.43 | 0.24 | 0.00 | 0.00 | | 0.08 |

FISH-DERIVED SEDIMENT

Transect 1

| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parrotfish | 0.000 | 0.017 | 0.320 | 0.443 | 0.351 | 0.204 | 0.115 | 0.065 | 0.033 | 0.014 | 0.007 | 0.000 | 1.569 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| | | | | | | | | | | | | TOTAL | 1.569 |

Transect 2

| Sediment production (kg m-2 yr-1) | >4mm Pebble | 2-4 mm Gravel | 1-2 mm Vc sand | 0.5-1 mm C. sand | 0.25-0.5 mm Med sand | 0.125-0.25 mm Fine sand | 63 to 125 um V fine sand | 31-63 um Coarse silt | 16-31 um Med silt | 8-16 um Fine silt | 4-8 um V fine silt | <4 um Clay | TOTAL per group |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parrotfish | 0.000 | 0.007 | 0.094 | 0.144 | 0.135 | 0.082 | 0.046 | 0.024 | 0.011 | 0.004 | 0.002 | 0.000 | 0.548 |
| Pufferfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Triggerfish | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

***Figure 28.*** *Site-level 'Master summary spreadsheet'. Information on the site and benthic cover and rugosity data are added at the top. Fish data can be copied across into the section below this.*

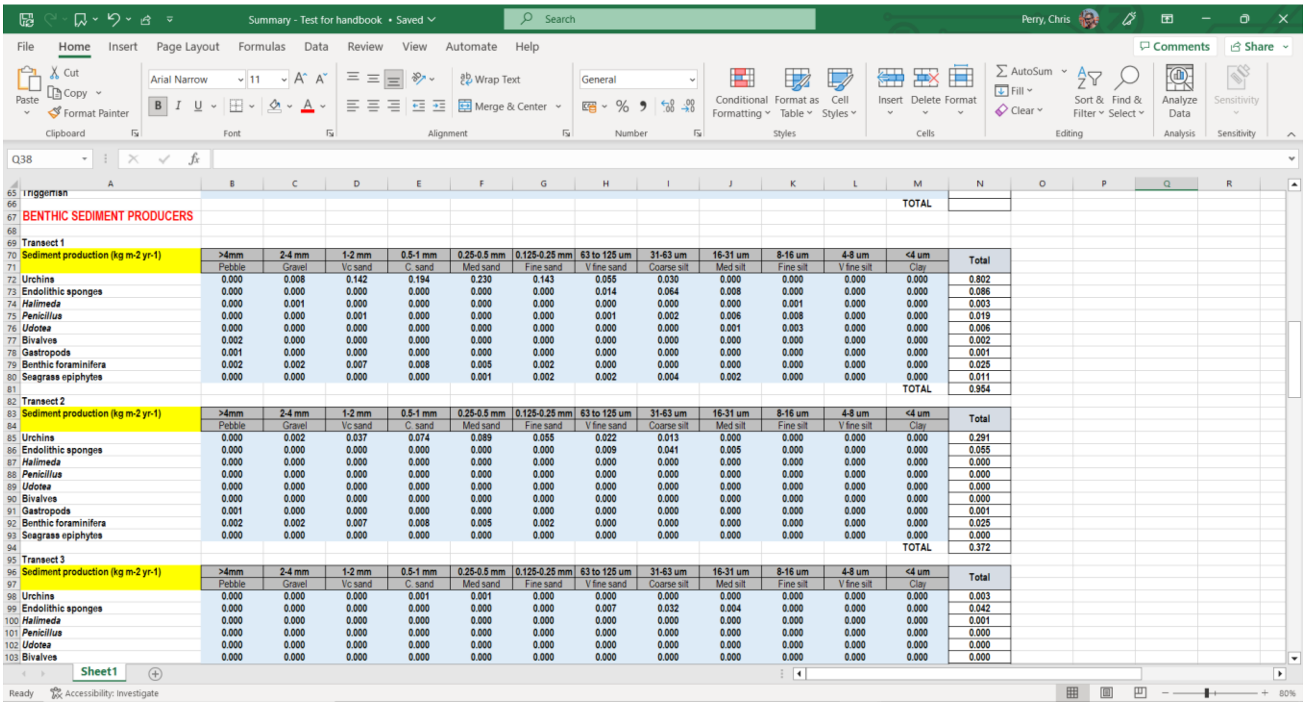



***Figure 29.*** *Site-level 'Master summary spreadsheet' showing the section where benthic production rate data should be added.*

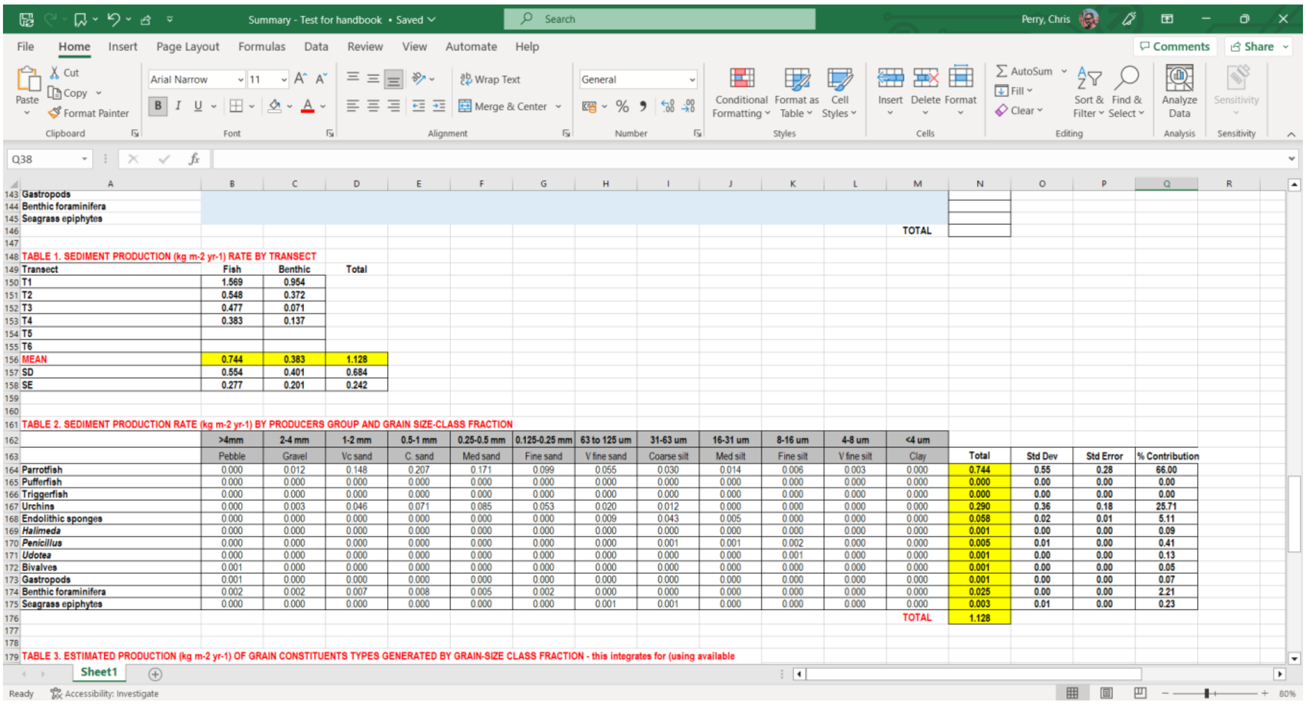



***Figure 30.*** *Summary section of 'Master summary sheet' showing Table 1 (total sediment production by transect) and Table 2 (sediment production rate by producer group and size class fraction).*

Perhaps most importantly, however, the final section of the summary spreadsheet (Table 3) then also provides an estimate of what the production values from different producers will equate to in terms of the predicted abundance of different sediment constituent types - both as a total and by grain-size class (Fig. 31). These two aspects of sediment production (the rate of sedimentary material production and the contribution to different sediment constituent types) differ where inputs derive from indirect sources such as bioerosion – because in contrast to direct skeletal inputs from, for example, shelly fauna, the process of bioerosion releases substrate of different compositions into the sediment reservoir. Thus, for example, coral sedimentary material primarily derives from a combination of parrotfish erosion, urchin erosion and endolithic sponge erosion. Known data on the proportional constituent contributions from these bioerosion sources are listed (see Tables i-iii at the bottom of the spreadsheet) and means of available data are used in the sediment constituent production calculations (but can be changed as deemed appropriate to the study location). Resultant data in this final section of the spreadsheet are thus a best estimate of what should be going into the local sediment reservoir in terms of the types of sediment constituents. Such data could be usefully compared against existing reef, beach or island sediments, but also used to model sediment transport potential, e.g., for shoreline sediment supply studies.

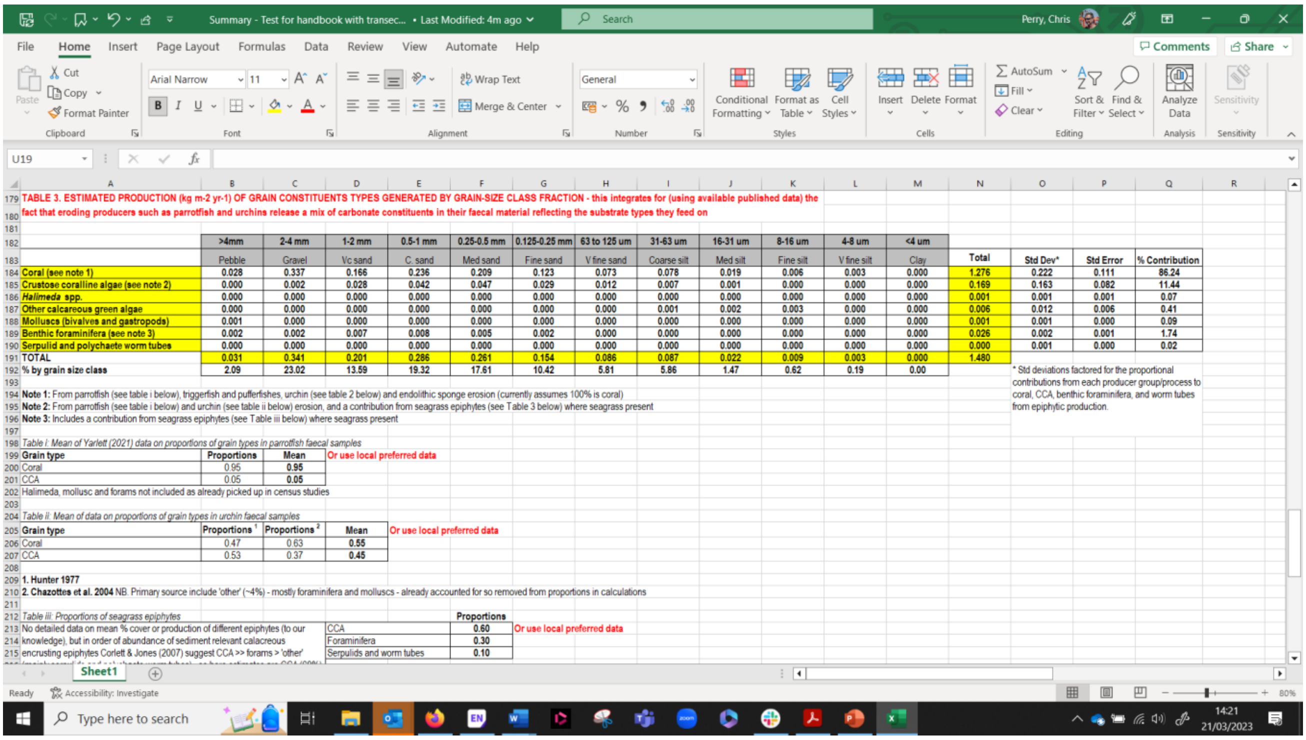


TABLE 3. ESTIMATED PRODUCTION (kg m-2 yr-1) OF GRAIN CONSTITUENTS TYPES GENERATED BY GRAIN-SIZE CLASS FRACTION - this integrates for (using available published data) the fact that eroding producers such as parrotfish and urchins release a mix of carbonate constituents in their faecal material reflecting the substrate types they feed on

| | >4mm | 2-4 mm | 1-2 mm | 0.5-1 mm | 0.25-0.5 mm | 0.125-0.25 mm | 63 to 125 um | 31-63 um | 16-31 um | 8-16 um | 4-8 um | <4 um | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pebble | Gravel | Vc sand | C. sand | Med sand | Fine sand | V fine sand | Coarse silt | Med silt | Fine silt | V fine silt | Clay | Total | Std Dev* | Std Error | % Contribution |
| Coral (see note 1) | 0.028 | 0.337 | 0.166 | 0.236 | 0.209 | 0.123 | 0.073 | 0.078 | 0.019 | 0.006 | 0.003 | 0.000 | 1.276 | 0.222 | 0.111 | 86.24 |
| Crustose coralline algae (see note 2) | 0.000 | 0.002 | 0.028 | 0.042 | 0.047 | 0.029 | 0.012 | 0.007 | 0.001 | 0.000 | 0.000 | 0.000 | 0.169 | 0.163 | 0.082 | 11.44 |
| *Halimeda* spp. | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.001 | 0.07 |
| Other calcareous green algae | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.002 | 0.003 | 0.000 | 0.000 | 0.006 | 0.012 | 0.006 | 0.41 |
| Molluscs (bivalves and gastropods) | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.000 | 0.09 |
| Benthic foraminifera (see note 3) | 0.002 | 0.002 | 0.007 | 0.008 | 0.005 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.026 | 0.002 | 0.001 | 1.74 |
| Serpulid and polychaete worm tubes | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.02 |
| TOTAL | 0.031 | 0.341 | 0.201 | 0.286 | 0.261 | 0.154 | 0.086 | 0.087 | 0.022 | 0.009 | 0.003 | 0.000 | 1.480 | | | |
| % by grain size class | 2.09 | 23.02 | 13.59 | 19.32 | 17.61 | 10.42 | 5.81 | 5.86 | 1.47 | 0.62 | 0.19 | 0.00 | | | | |

* Std deviations factored for the proportional contributions from each producer group/process to coral, CCA, benthic foraminifera, and worm tubes from epiphytic production.

**Note 1:** From parrotfish (see table i below), triggerfish and pufferfishes, urchin (see table 2 below) and endolithic sponge erosion (currently assumes 100% is coral)
**Note 2:** From parrotfish (see table i below) and urchin (see table ii below) erosion, and a contribution from seagrass epiphytes (see Table 3 below) where seagrass present
**Note 3:** Includes a contribution from seagrass epiphytes (see Table iii below) where seagrass present

*Table i: Mean of Yarlett (2021) data on proportions of grain types in parrotfish faecal samples*

| Grain type | Proportions | Mean |
|---|---|---|
| Coral | 0.95 | **0.95** |
| CCA | 0.05 | **0.05** |

Or use local preferred data

Halimeda, mollusc and forams not included as already picked up in census studies

*Table ii: Mean of data on proportions of grain types in urchin faecal samples*

| Grain type | Proportions [1] | Proportions [2] | Mean |
|---|---|---|---|
| Coral | 0.47 | 0.63 | **0.55** |
| CCA | 0.53 | 0.37 | **0.45** |

Or use local preferred data

**1. Hunter 1977**
**2. Chazottes et al. 2004** NB. Primary source include 'other' (~4%) - mostly foraminifera and molluscs - already accounted for so removed from proportions in calculations

*Table iii: Proportions of seagrass epiphytes*

No detailed data on mean % cover or production of different epiphytes (to our knowledge), but in order of abundance of sediment relevant calacreous encrusting epiphytes Corlett & Jones (2007) suggest CCA >> forams > 'other'

| | Proportions |
|---|---|
| CCA | **0.60** |
| Foraminifera | **0.30** |
| Serpulids and worm tubes | **0.10** |

Or use local preferred data

***Figure 31.*** *Final section of the 'Master summary spreadsheet' showing Table 3 which provides transect level and total estimates of production by carbonate sedimentary constituent type (rate of production and % contribution to sediment).*

## 4. Notes and current limitations

As outlined at the start of this document this initial iteration of SedBudget should be seen as a first step to developing this important field of enquiry, and feedback and inputs from the user community are most welcome. Clearly, there are a wide range of areas where additional datasets would help to improve these sediment production rate estimates. Some such data may inherently arise as wider applications of the methodology are undertaken because, where possible, site-relevant collection of supporting metrics would clearly be advantageous. This would help add additional datasets to augment existing known metrics, e.g., on species turnover rates, carbonate content metrics, etc, and we would welcome any additional information that can be added to the metric tabs (please email; c. perry@exeter.ac.uk). In other cases, clear species data gaps exist, and these would benefit from more focused research. Examples include, but are not limited to:

- Methodologies for estimating production from articulated red calcareous algal species (e.g., *Amphiroa*)
- Methodologies for estimating production associated with branched crustose coralline algae such as *Lithothamnium* spp.
- Methodologies to support estimates of sediment inputs from urchin tests and spines, and ideally to factor for all urchins in a habitat and not just the bioeroding species.
- Data and methodologies for better estimating production rates by key genera of bivalves and gastropods.
- More refined methodologies for estimating sediment generation by benthic foraminifera.

## 5. References


Alvarado, J. J., Cortés, J., Guzman, H., & Reyes-Bonilla, H. (2016). Bioerosion by the sea urchin *Diadema mexicanum* along Eastern Tropical Pacific coral reefs. Marine Ecology, 37(5), 1088-1102. doi:https://doi.org/10.1111/maec.12372

Alvarado, J. J., Grassian, B., Cantera-Kintz, J. R., Carballo, J. L., & Londoño-Cruz, E. (2017). Coral Reef Bioerosion in the Eastern Tropical Pacific. In P. W. Glynn, D. P. Manzello, & I. C. Enochs (Eds.), Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic Environment (pp. 369-403). Dordrecht: Springer Netherlands.

Bak, R. P. M. (1990). Patterns of echinoid bioerosion in two Pacific coral reef lagoons. Marine Ecology Progress Series, 66, 267-272.

Bosence, D. (1989). Biogenic carbonate production in Florida Bay. Bulletin of Marine Science, 44, 419-433.

Carreiro-Silva, M., & McClanahan, T. R. (2012). Macrobioerosion of dead branching *Porites*, 4 and 6 years after coral mass mortality. Marine Ecology Progress Series, 458, 103-122. doi:10.3354/meps09726

Chazottes, V., Chevillotte, V., & Dufresne, A. (2004). Caractérisation de la production particulaire par l'oursin Echinometra mathaei sur les récifs Indo-Pacifiques : influence des peuplements coralliens et implications sur la dynamique sédimentaire. Geobios, 37(1), 13-22. doi:10.1016/j.geobios.2003.01.008

Choat, J. H., Klanten, O. S., Van Herwerden, L., Robertson, D. S., & Clements, K. D. (2012). Patterns and processes in the evolutionary history of parrotfishes (Family Labridae). Biological Journal of the Linnean Society, 107, 529–557.

Corlett, H., & Jones, B. (2007). Epiphyte communities on *Thalassia testudinum* from Grand Cayman, British West Indies: Their composition, structure, and contribution to lagoonal sediments. Sedimentary Geology, 194(3-4), 245-262. doi:10.1016/j.sedgeo.2006.06.010

Drew, E. A. (1983). Halimeda biomass, growth rates and sediment generation on reefs in the Central Great Barrier Reef Province. Coral Reefs, 2, 101-110.

East, H. K., Perry, C. T., Kench, P. S., & Liang, Y. (2016). Atoll-scale comparisons of the sedimentary structure of coral reef rim islands, Huvadhu Atoll, Maldives. Journal of Coastal Research, 75(sp1), 577-581. doi:10.2112/si75-116.1

Freile, D. (2004). Carbonate productivity rates of *Halimeda* in two different locations, San Salvador Islad, Bahamas. 11th Symposium of the Geology of the Bahamas and other regions, 95-106.

Futterer, D. K. (1974). Significance of the boring sponge *Cliona* for the origin of fine grained material of carbonate sediments. Journal of Sedimentary Petrology, 44, 79-84.

Gischler, E. (2006). Sedimentation on Rasdhoo and Ari Atolls, Maldives, Indian Ocean. Facies, 52(3), 341-360. doi:10.1007/s10347-005-0031-3

Glynn, P. W., & Manzello, D. P. (2015). Bioerosion and Coral Reef Growth: A Dynamic Balance. In Coral Reefs in the Anthropocene (pp. 67-97). Dordrecht: Springer.

Glynn, P. W., Stewart, R. H., & McCosker, J. E. (1972). Pacific coral reefs of Panamá: Structure, distribution and predators. Geologische Rundschau, 61(2), 483-519. doi:10.1007/BF01896330

Griffin, S. P., Garcia, R. P., & Weil, E. (2003). Bioerosion in coral reef communities in southwest Puerto Rico by the sea urchin *Echinometra viridis*. Marine Biology, 143(1), 79-84. doi:10.1007/s00227-003-1056-1

Guzman, H. M., & Lopez, J. D. (1991). Diet of the corallivorous pufferfish *Arothron meleagris* (Pisces: Tetraodontidae) at Gorgona Island, Colombia Revista de Biologia Tropical, 39, 203-206.

Hallock, P. (1981). Production of carbonate sediments by selected large benthic foraminifera on two Pacific coral reefs. Journal of Sedimentary Petrology, 51, 467-474.

Hoey, A. S., & Bellwood, D. R. (2008). Cross-shelf variation in the role of parrotfishes on the Great Barrier Reef. Coral Reefs, 27(1), 37-47. doi:10.1007/s00338-007-0287-x

Hunter, I. (1977). Sediment production by *Diadema antillarum* on a Barbados fringing reef. Paper presented at the Third International Coral reef Symposium, University of Miami.

Jorry, S. J., Camoin, G. F., Jouet, G., Roy, P. L., Vella, C., Courgeon, S., . . . Borgomano, J. (2016). Modern sediments and Pleistocene reefs from isolated carbonate platforms (Iles Eparses, SW Indian Ocean): A preliminary study. Acta Oecologica, 72, 129-143. https://doi.org/10.1016/j.actao.2015.10.014

Lange, I. D., Perry, C. T., & Alvarez-Filip, L. (2020). Carbonate budgets as indicators of functional reef “health”: A critical review of data underpinning census-based methods and current knowledge gaps. Ecological Indicators, 110, 105857. https://doi.org/10.1016/j.ecolind.2019.105857

Langer, M. R., Silk, M. T., & Lipps, H. R. (1997). Global ocean carbonate production and carbonate dioxide production: the role of reef foraminifera. Journal of Foraminiferal Research, 27, 271-277.

Multer, G. (1988). Growth rate, ultrastructure and sediment contribution of *Halimeda incrassata* and *Halimeda monile*, Nonsuch and Falmouth Bays, Antigua, W.I. Coral Reefs, 6, 179-186.

Narayan, G. R., Reymond, C. E., Stuhr, M., Doo, S., Schmidt, C., Mann, T., & Westphal, H. (2022). Response of large benthic foraminifera to climate and local changes: Implications for future carbonate production. Sedimentology, 69(1), 121-161. https://doi.org/10.1111/sed.12858

Naumann, M. S., Niggl, W., Laforsch, C., Glaser, C., & Wild, C. (2009). Coral surface area quantification–evaluation of established techniques by comparison with computer tomography. Coral Reefs, 28(1), 109-117. doi:10.1007/s00338-008-0459-3

Nava, H., & Carballo, J. L. (2008). Chemical and mechanical bioerosion of boring sponges from Mexican Pacific coral reefs. Journal of Experimental Biology, 211(Pt 17), 2827-2831. doi:10.1242/jeb.019216

Nelsen, J., & Ginsburg, R. N. (1986). Calcium carbonate production by epibionts on *Thalassia* in Florida Bay. Journal of Sedimentary Petrology, 56, 622-628.

Neumann, A., & Land, L. (1975). Lime mud deposition and calcareous algae in the Bight of Abaco, Bahamas: a budget. Journal of Sedimentary Petrology, 45, 763-786.

Osorno, A., Peyrot-Clausade, M., & Hutchings, P. A. (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(2), 292-303. doi:10.1007/s00338-005-0478-2

Payri, C. (1988). Halimeda contribution to organic and inorganic production in a Tahitian reef system. Coral Reefs, 6, 251-262.

Perry, C. T., & Beavington-Penney, S. J. (2005). Epiphytic calcium carbonate production and facies development within sub-tropical seagrass beds, Inhaca Island, Mozambique. Sedimentary Geology, 174(3-4), 161-176. doi:10.1016/j.sedgeo.2004.12.003

Perry, C. T., Edinger, E. N., Kench, P. S., Murphy, G. N., Smithers, S. G., Steneck, R. S., & Mumby, P. J. (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(3), 853-868. doi:10.1007/s00338-012-0901-4

Perry, C. T., Kench, P. S., O'Leary, M. J., Morgan, K. M., & Januchowski-Hartley, F. (2015). Linking reef ecology to island building: Parrotfish identified as major producers of island-building sediment in the Maldives. Geology, 43(6), 503-506. doi:10.1130/g36623.1

Perry, C. T., Lange, I. D., & Januchowski-Hartley, F. (2018). ReefBudget Indo Pacific: online resource and methodology. Retrieved from http://geography.exeter.ac.uk/reefbudget/

Perry, C. T., Morgan, K. M., Lange, I. D., & Yarlett, R. T. (2020). Bleaching-driven reef community shifts drive pulses of increased reef sediment generation. Royal Society Open Science, 7(4), 192153. doi:10.1098/rsos.192153

Perry, C. T., Morgan, K. M., & Salter, M. A. (2016). Sediment generation by *Halimeda* on atoll interior coral reefs of the southern Maldives: A census-based approach for estimating carbonate production by calcareous green algae. Sedimentary Geology, 346, 17-24. doi:10.1016/j.sedgeo.2016.10.005

Perry, C. T., Salter, M. A., Lange, I. D., Kochan, D. P., Harborne, A. R., & Graham, N. A. J. (2022). Geo-ecological functions provided by coral reef fishes vary among regions and impact reef carbonate cycling regimes. Ecosphere, 13(12), e4288. https://doi.org/10.1002/ecs2.4288

Perry, C. T., Salter, M. A., Morgan, K. M., & Harborne, A. R. (2019). Census estimates of algal and epiphytic carbonate production highlight tropical seagrass meadows as sediment production hotspots. Frontiers in Marine Science, 6(120). doi:10.3389/fmars.2019.00120

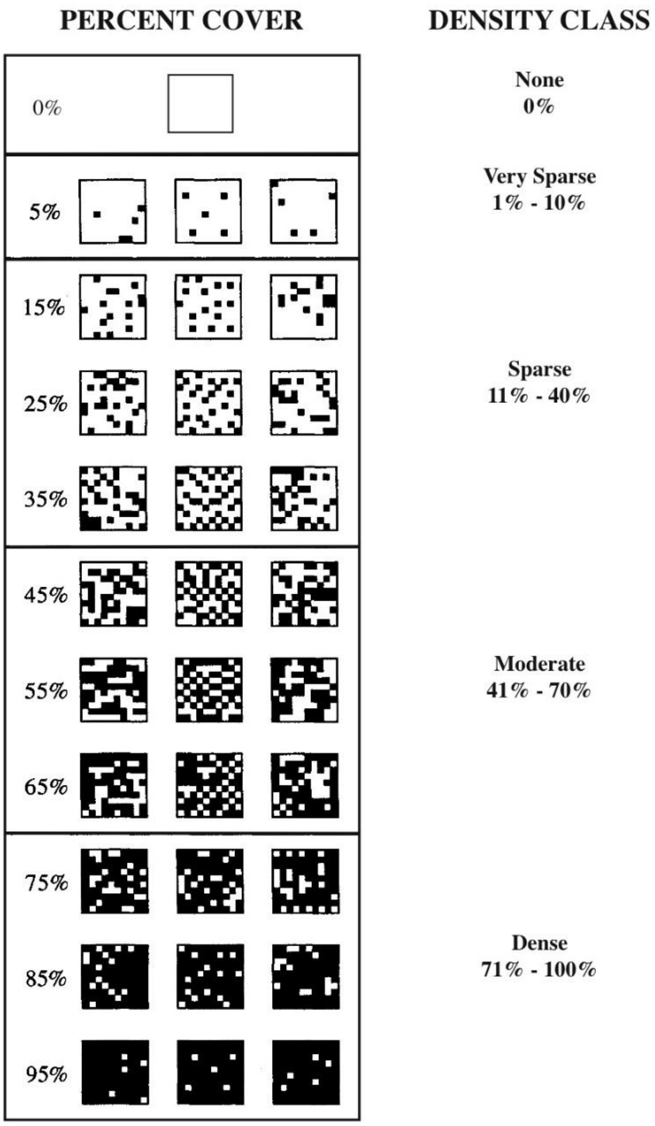
Tribollet, A., & Golubic, S. (2005). Cross-shelf differences in the pattern and pace of bioerosion of experimental carbonate substrates exposed for 3 years on the northern Great Barrier Reef, Australia. Coral Reefs, 24(3), 422-434. doi:10.1007/s00338-005-0003-7

Yarlett, R. T., Perry, C. T., & Wilson, R. W. (2021). Quantifying production rates and size fractions of parrotfish-derived sediment: A key functional role on Maldivian coral reefs. Ecology and Evolution, 11, 16250-16265. https://doi.org/10.1002/ece3.8306

Zundelevich, A., Lazar, B., & Ilan, M. (2007). Chemical versus mechanical bioerosion of coral reefs by boring sponges - lessons from *Pione cf. vastifica*. Journal of Experimental Biology, 210(1), 91-96. doi:10.1242/jeb.02627

## Appendices

**Appendix 1** – Example of visual % estimator chart (from https://nbep.files.wordpress.com/2010/08/density-class.jpg)



**Appendix 2**

The following general field guides may prove useful if needed for identification of some of the key taxa referred to in SedBudget

- Allen, GR & Steene R (1998) Indo-Pacific Coral Reef Field Guide. Tropical reef research ISBN: 981-00-5687-7.
- Coleman N (2013) Marine Life of the Maldives. Atoll Editions. ISBN: 9781876410674
- Waycott M, McMahon K, Mellors J, Calladine A. & Kleine D (2004) A Guide to Tropical Seagrass of the Indo-West Pacific. James Cook University. ISBN: 0 86443 726 9
- Littler DS, Littler MM, Bucher KE & Norris JN (1989) Marine plants of the Caribbean. Smithsonian Institute Press. ISBN: 0-87474-607-8 (although Caribbean focused has some useful images of various calcareous algae)

In addition, detailed descriptions and sometimes imagery of various types of calcareous green and red algae can be found on the Algal Base site at: https://www.algaebase.org/

The taxonomy paper by Hillis-Colinvaux provides useful descriptions of many *Halimeda* spp.

- Hillis-Colinvaux, L. (1980). Ecology and Taxonomy of *Halimeda*: Primary Producer of Coral Reefs. In J. H. S. Blaxter, F. S. Russell, & M. Yonge (Eds.), Advances in Marine Biology (Vol. 17, pp. 1-327): Academic Press.

Indian Ocean specific ID guides we have assembled are provided below in Appendices 3-7

**Appendix 3:** Fish ID based on https://www.fishbase.se and https://seatizens.sc/

**Parrotfish** (Upper picture in each box depicts the terminal phase/male, lower picture initial phase/female)

**Cetoscarus ocellatus** max 85 cm

Pink spots on head and front body, orange/pink line from mouth to anal fin

Peppered with black spots below, pale/yellow above

**Chlorurus strongylocephalus** max 70 cm

Steep profile, pink streak on scales, yellow patch on cheek

Reddish below, dark green around mouth, blue tail margins

**Chlorurus sordidus** max 40 cm

Lighter patch (blue/yellow) on tailbase, pink patch on snout (below eyelevel)

Yellow/red snout, 2 rows of white spots on dark back

**Chlorurus capistratoides** max 40 cm (CIO, WPO)
**Chlorurus atrilunula** max 30 cm (Kenya, South Africa)

Pink margin on gill cover, pinkish cheecks, blue/green bands on head, pink bars/spots on scales

Grey with 4-5 white bars, pale snout, pink tail

**Chlorurus enneacanthus** max 50 cm

Uniform blue, often in feeding groups in the shallow

**Chlorurus cyanescens** max 50 cm (WIO)

Distinct blue and yellow colouring, bump on forehead

**Calatomus carolinus** max 54 cm

Pink/orange lines from eye, teeth not fused (browser)

**Chlorurus rhakoura** max 50 cm (Eastern IO)

Ragged backfin, bump on forehead

***Scarus rubroviolaceus*** max 70 cm

Long blunt snout, long narrow tailbase. Lunate tail, yellow eye.

Red or grey, dark scale edges

***Scarus ghobban*** max 90 cm

Two short, light lines behind eye, strong lunate tail markings

Curved bars formed by large white or blue scales

***Hipposcarus harid*** max 75 cm

Long face, pink/orange margins on scales and line beak to mid body, lunate caudal fin

Brownish yellow on back, white underside

***Scarus prasiognathos*** max 70 cm
***Scarus falcipinnis*** max 60 cm (WIO)

'Pincer' marking on tail, green throat (and belly for *S. falci*)

*S. prasiognathos* (pic) more white spots than *S. falcipinnis*, lines on face, rounder profile. Form schools

***Scarus festivus*** max 45 cm (uncommon)

Sexes with similar colour, lines radiating from eye, T develops lump on forehead

***Scarus globiceps*** max 45 cm

Pink bridle over face through eye, fine spots on scales
I: undescript, similar shape, light stripes on underside

***Scarus caudofasciatus*** max 50 cm (WIO)

Lunate caudal fin, spots on pale nose, dark green around mouth, blue tail margins

Reddish-brown, light and dark bars

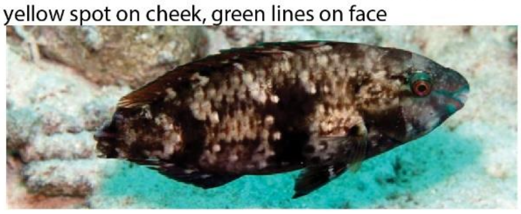
***Scarus tricolor*** max 40 cm

Strong face markings, greenish with pinkish or yellowish overlay, purple band on each caudal fin lobe

Dark body, lighter forehead, reddish tail

***Scarus russelii*** max 51 cm
***Scarus fuscopurpureus*** max 38 cm (Red Sea)

Dark purple/green at front, pale green from anal fin, yellow spot on cheek, green lines on face



*S. russelii*: reddish brown with 5 dark bars,
*S. fuscopurpureus*: more blotchy color (pic)

***Scarus frenatus*** max 47 cm

Blue-green with pink scribbles on scales, rear light, greenish band from mouth to pectoral fin

Golden scales on underside, broad dark stripes at sides

***Scarus scaber*** max 37 cm

Upper head and front body dark, blue band mouth-gill

4 yellow bars on back

***Scarus niger*** max 45 cm

Dark, bright green spots behind eye

Reddish, green bridle around mouth to or through eye

***Scarus psittacus*** max 34 cm

Dark blue/purple 'cap' on head, short blue line on chin and from upper lip to below eye, rest variable

Plain grey. Small feeding schools, ~S. globiceps, S. rivulatus

***Scarus quoyi*** max 40 cm (India & W Pacific)

Blueish/Purple, dark green 'mustache' and light green patch on cheek, light saddle on caudal fin

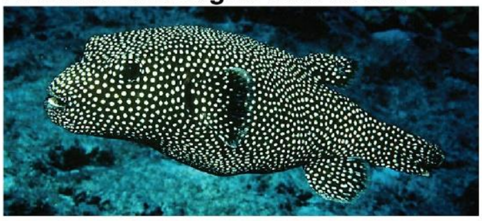
***Scarus viridifucatus*** max 40 cm

Mostly <30 cm, round body, distinct light green snout

Dark brown, sometimes with faint light bars

### Pufferfish

***Arothron meleagris*** max 50 cm



Different color morphs

***Arothron hispidus*** max 50 cm

### Triggerfish

***Sufflamen verres*** max 40 cm

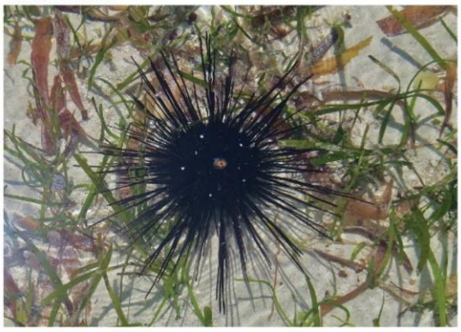
***Pseudobalistes naufragium*** max 100 cm

***Melichthys niger*** max 40 cm

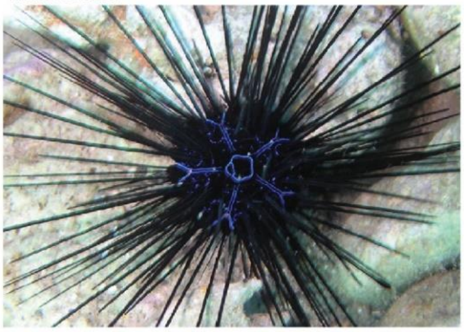
***Balistes polylepis*** max 76 cm

**Appendix 4:** Urchin ID based on https://www.marinespecies.org/ [https://www.gbif.org/](https://www.gbif.org/) and https://en.wikipedia.org/

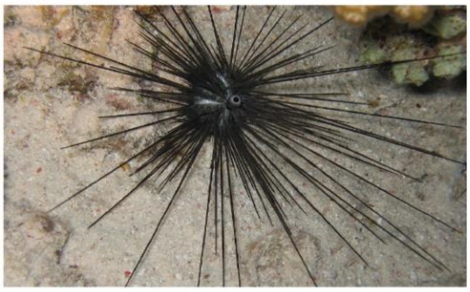
***Diadema setosum***
black/brown banded
5 white spots, orange ring on cone
max 70 mm



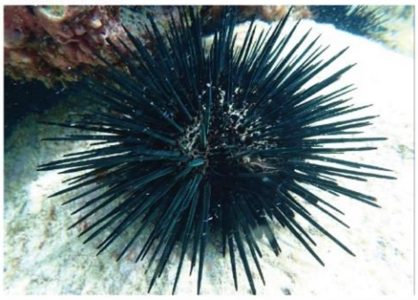
***Diadema savignyi***
black/grey/brown/purple/banded
green/blue double lines
max 90 mm



***Diadema paucispinum***
black blue/banded, very long spines
orange ring & lines
max 70 mm

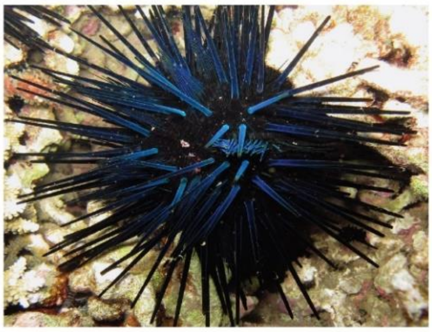


***Stomopneustes variolaris***
black, sometimes green sheen
spines stout, test visible between, apical system small
max 110 cm



***Echinometra mathaei***
purple/green,
ring at base of spine
max 50mm

***Echinothrix diadema***
blue-black spines, only banded in juveniles
small and dark anal sack
max 120 mm



***Echinostrephus molaris***
green/purple,
slender spines projecting vertically, rest short
max 23mm

***Echinothrix calamaris***
Short and long banded spines, white/red/dark
anal sack with light and dark spots
max 160 mm

***Eucidaris metularia***
red/purple, distinctly banded
spines short, stout, sometimes tapered
max 30 mm

***Heterocentrotus mamillatus***
red/brown/purple, sometimes bands
spikes tapered towards tip
max 80 mm

## Appendix 5. Calcareous green algae

***Halimeda* spp.** – descriptions and, where available imagery, from AlgalBase https://www.algaebase.org/ of common Indian Ocean *Halimeda* spp. Plants are grouped below into those broadly described as exhibiting predominantly erect, spreading or compact growth forms.

**Erect forms**


Tall, loosely organised open branches, lightly calcified segments to ~20 mm

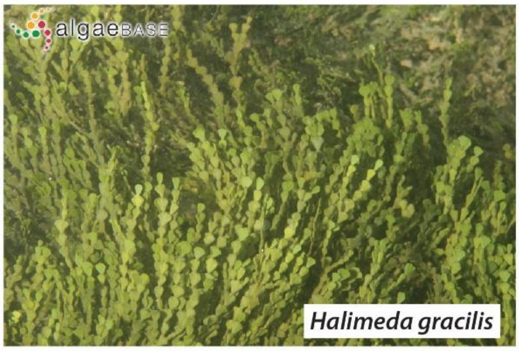

Erect, compact branched, with elongate cylindrical segments to 10 x 4 mm


Erect, compact, branching from near base, lobate often well calcified segments to ~15 mm


Erect, compact or cushion-like clumps to 12 cm tall, broadly cylindrical moderately calcified segments (sometimes slightly ribbed) to ~15 mm


Erect flat or bushy with large often lightly calcified discoidal segments (to ~40 mm)

**Sprawling forms**




Flaccid, straggling but very long branches, segments to 15 mm


Spreading or compact clumps to 15 cm tall, moderately calcified semi-circular to kidney shaped segments to 20 mm

## Compact forms

Compact cushion-like clumps, lightly calcified semi-rounded segments to 30 mm

Compact, cushion-like, often heavily calcified slightly ribbed thin segments to 16 mm

Compact, open branches, segments to ~15 mm

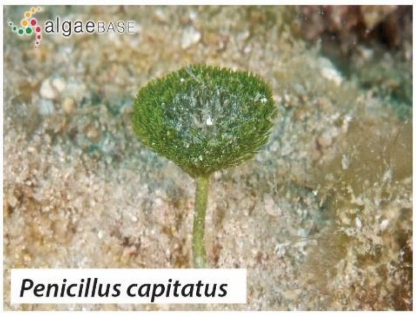
Compact to erect with moderately calcified slightly rugose large segments (to ~25 mm).

Compact, spreading, dense branches, moderately calcified discoidal and lobate segments to ~9 mm

Compact or sprawling with both erect and lateral growth. Often heavily calcified segments broadly circular and ribbed to ~11 mm wide

**Appendix 6. *Penicillus* and *Udotea* spp.** – description and image from AlgalBase https://www.algaebase.org/ of the main Indian Ocean *Penicillus* and *Udotea* spp.. *Udotea* spp. are grouped below into those described as exhibiting vase or fan-shaped  growth forms.

### *Penicillus* spp.



*Penicillus capitatus*

Narrow calcified stem with fine calcified segments forming the brush-like plant head. Plants to ~12 cm tall.

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### *Udotea* spp.

#### Vase-shaped

*Udotea cyathiformis*

Narrow calcified stem supporting calcified vase-shaped head

#### Fan-shaped

*Udotea flabellum*

Short calcified stem supporting thin ribbed, fan-shape head

*Udotea glaucescens*

Short branching calcified stem supporting multiple thin fan-shaped heads

*Udotea indica*

Short calcified stem supporting thin fan-shaped head

*Udotea orientalis*

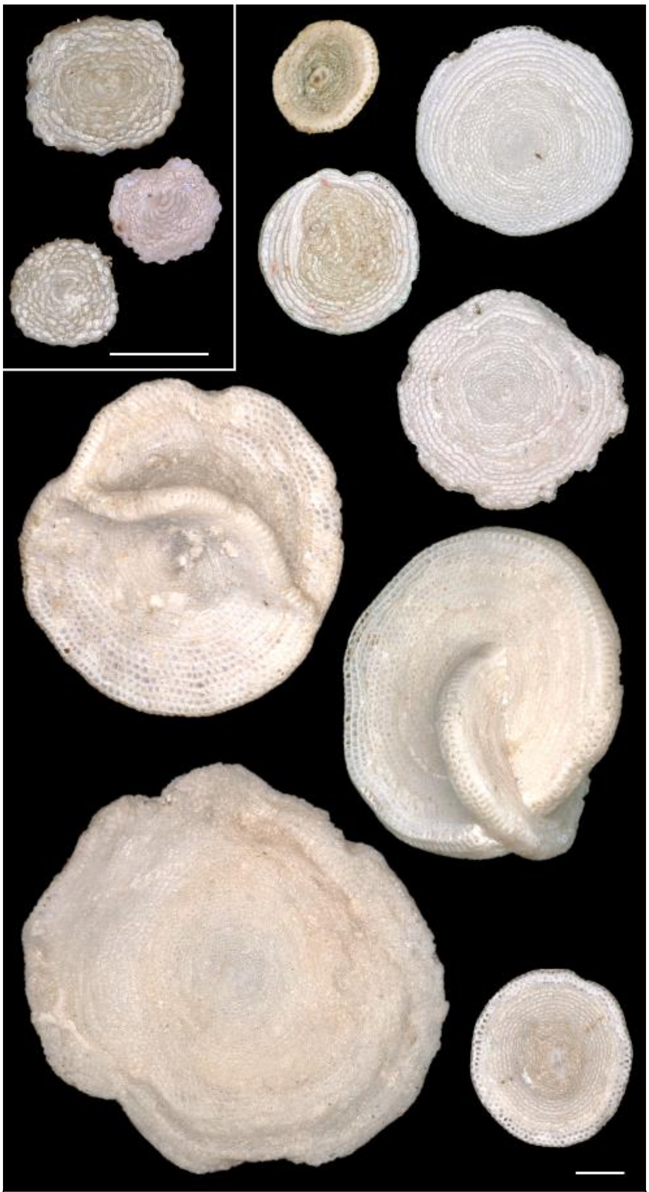
Short calcified stem supporting thin smooth fan-shape head

*Udotea wilsonii*

Short calcified stem supporting complex multi fan-shape heads

**Appendix 7. Benthic foraminifera families and genera** – images from Indian Ocean samples, collected in the Zanzibar and Chagos Archipelago, taken with a Keyence VHX-5000. Scale bars = 0.5 mm.

**A) Soritidae: *Amphisorus, Parasorites, Sorites***



Round, flat (disk-shaped), sometimes twinned or bilobated. Shell porcellaneous and smooth. Chambers arranged in annular rings, subdivided in chamberlets, with early chambers (centre) planispiral or peneropline (enrolled). Apertures (pores) form single or multiple rows of openings along outer rims. Live specimens show greenish-brown coloration of endosymbiotic microalgae through thin shell. Usually living attached to substrates such as seagrass, coral rubble, CCA or calcareous green algae, so shape may be amended to substrate. *Marginopora* spp. usually show thick and large tests with many fine pores along rims, but are very rarely found in the Indian Ocean. Often ~5 mm diameter, some species >1.5 cm.

**B) Alveolinidae: *Alveolinella, Borelis***

Fusiform (spindle-shaped), spherical to elongated, with one row of apertures or many small pores along newest (outermost) chamber rim. Shell porcellaneous, green-brown symbiont color can be visible. Often ~1 mm, up to ~1 cm.

**C) Peneroplidae: *Peneroplis***

Thin and flat, porcellaneous test, planispiral. Chambers in newer whorls often increase in width at nearly constant height. Latest whorls sometimes deroled. Apertures arranged lineraly along outer chamber rim. Symbiont color usually red-purple. Often ~0.5 mm.

**other Miliolida:**

Imperforate porcelaneous tests, multiple chambers often aranged in various planes, sometimes with yellowish tint. Aperture terminal at the end of the newest chamber.

**D) Amphistegenidae: *Amphistegina***

Trochospiral, lenticular (lentil-shaped) and bicovex solid test, with unpartitioned mostly arched chambers at the periphery. Shell walls hyaline (glassy) and perforate (fine pores all over surface). Newest chambers with curved or radial septa patterns that differ on dorsal and ventral side. Margins round to flattened, generally more spherical than Nummulitidae. Aperture slit-like on ventral side with pustules around opening. Yellow-brown to greenish symbiont color in live collected specimens. Often ~1 mm, some up to ~2 mm.

**E) Calcarinidae: *Calcarina, Neorotalia, Pararotalia***

Trochospiral coiled test, globular to flattened. Shell perforate hyaline. Undivided chambers square to rectangular or elongated, showing sharp ridge. Last whorl of *Calcarina* and *Neorotalia* spp. with spines, giving star-shape. Surface smooth or covered with small spikes or pustules. *Calcarina* spp., can show numerous and complex spines all over, but are rarely found in the Indian Ocean. Yellow-brown color of endosymbionts in specimens collected alive. Mostly <1 mm.

**F) Nummulitidae: *Heterostegina, Planostegina***

Large planispiral shells, with strongly flattened periphery. Long outer chambers mostly partitioned in chamberlets with marginal cord. Both sides showing similar patterns. Fragile chambers elongate and flatten increasingly, but are never annular. *Operculina* and *Nummulites* spp. show no subdivision of chambers, and are rare in shallow habitats. Living specimens show green-brown symbiont color. Central region may be covered with pustules. Slit-shaped apertures. Common in sandy habitats, often >1.5 mm.

**G) Homotrematidae: *Homotrema, Miniacina***

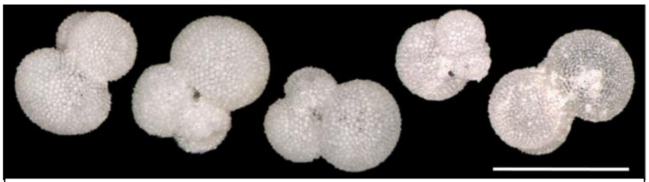
Encrusting foraminifera that grow on hard substrates in shaded areas, e.g., under coral rubble and in crevices. Tests hyaline with regular pore pattern and characteristic red coloration. Forms various colonial patterns, flat to branched.

**Other Rotaliida:**

Generally perforate hyaline shells with chambers typically enrolled/spiral, but also orbitoidal (initially spirally and then multiple chambers growing in parallel on the periphery, appearing vesicular). Central part often thickened, showing greenish or yellow-brown coloration when sampled alive.

**<u>Foraminifera not need to be counted for SedBudget:</u>**

**Planktonic foraminifera: e.g., Globigerinidae**



Thin hyaline perforated shells with large pores, partly spinose, single outer globose (spherical) chambers or arranged trochospiral. Some appear flattened with keels on periphery. Generally small, rounder and thinner-walled than benthic foraminifera, rare in shallow-water sediments.

**Agglutinated foraminifera: e.g. Textulariida**

Tests made of foreign particles, usually sediment grains, glued together by organic or calcareous cement. Shell surfaces therefore appear granular, reflecting the surrounding sediment color. Chambers often arranged uni-, bi-, or triserial. Reef-associated taxa often >1 mm.

**Further images and descriptions of benthic foraminifera appearing in the Indian Ocean:**

- foraminifera.eu
- marinespecies.org
- Parker & Gischler 2011, Marine Micropaleontology
- Weinmann & Langer 2017, Revue de Micropaléontologie
- Langer et al. 2013, Neues Jahrbuch für Geologie und Paläontologie – Abhandlungen
- Langer & Hottinger 2000, Micropaleontology
- Renema 2018, Earth-Science Reviews
- Murray 1994, Marine Micropaleontology
- Murray & Smart 1994, Journal of Micropalaeontlogy (note that *Neorotalia calcar* was here identified as *Calcarina calcar*).