ReefBudget: Methodology

Caribbean Version 2

Development of this methodology was originally funded by The Leverhulme Trust (International Research Network Programme). This is an updated version (v2, June 2019) of the original Caribbean methodology.

Please acknowledge *ReefBudget* in any publications resulting from the use of this methodology as follows:

Perry CT and Lange ID (2019) ReefBudget Caribbean v2: online resource and methodology. Retrieved from http://geography.exeter.ac.uk/reefbudget/

1 Census-based approaches to quantifying reef carbonate budgets

This revised version of the Caribbean *ReefBudget* methodology has been adapted from an updated methodology recently developed for use on Indo-Pacific reefs to support estimates of net biologically-driven carbonate budgets (kg $CaCO_3$ m^{-2} yr^{-1}) (see http://geography.exeter.ac.uk/reefbudget/ and Perry et al. (2012)). It uses a census-based approach to quantify cover/abundance of carbonate producing (corals and crustose coralline algae (CCA)) and bioeroding taxa (urchins, parrotfish and micro- and macro-endolithic taxa), and integrates these data with published and field-derived measures of species/genera specific carbonate production and bioerosion rates to support resultant budget calculations. The methodology can be applied to different reef zones and depths as necessary to support spatial upscaling efforts.

While similar to the current format of the original Caribbean methodology, there are some important differences in this new version and in the Indo-Pacific version. First, carbonate production by corals and coralline algae is calculated using geometric relationships derived from individual colony morphology, rather than calculated using rugosity at the transect level. These calculations are supported by relevant coral growth rate and skeletal density data from Caribbean studies. Second, framework erosion by microborers (e.g., cyanobacteria, fungi) is calculated within the main census sheets based on published rates and as a function of the proportion of substrate in each transect available for bioerosion. As in the original Caribbean methodology however separate census data are still collected to estimate erosion rates by endolithic sponges (as a proxy for macro- endolithic erosion), parrotfish and urchins. The method does not attempt to estimate sediment production rates *per se*, but to some extent this can be estimated for grazing bioeroders (urchins and parrotfish). Other aspects of sediment production and post-depositional lithification are not presently quantified within this approach.

Key points:

- This new version of *ReefBudget* arises from adaptations made to the methodology to support its application on Indo-Pacific reefs sites. This new methodology thus reflects refinements that have been made over a number of years, but which have been designed to provide more accurate estimates of both production and erosion within the constraints of existing underpinning empirical datasets. Further refinements to the method are anticipated as new data arises.

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

- As for the original Caribbean *ReefBudget* methodology, these methods can in principle be applied to any reef site and zone, but variations in depth and regional growth rates need to be considered. If using the pre-set data and calculations in the default spreadsheets, it is suggested that sites are limited to between 2 and 10 m depth, because this is the depth interval from across which the majority of data is drawn.

- Data should be collected along depth contours parallel to the reef crest (or as appropriate to the site). If there are obvious differences in coral or fish community composition between areas of reef within the same zone, the establishment of multiple survey sites should be considered.

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

The 'Caribbean *Carbonate Production template v2*' spreadsheet is where all benthic data is entered. It calculates percent cover of each category, carbonate production and microbioerosion. It also provides summary data for each transect by coral genus, morphology, life-history strategy (sensu Darling et al. 2012) and other categories.

The '*Urchin data entry template*' calculates urchin erosion using either a general equation, or individual equations for two main categories of urchins (*Diadematidae* and *Echinometra*). It reports urchin density and bioerosion by size class, group and transect. If relevant, urchin density by species can be obtained from one of the tabs.

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

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

2 Site selection, characteristics and transect placement

2.1 Site characteristics

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

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

2.2 Transect placement

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

- Each transect should be established either along depth contours parallel to the reef front/crest or along discrete (depth-consistent) reef structures (e.g., spurs, patch reefs) as deemed most appropriate to the site.
- Transects should be placed approximately 5-10 m apart.
- Each transect should ideally (if permitting allows) be marked at the start and end with a fixed marker pin (Fig. 1). This provides the opportunity to establish a series of long-term monitoring sites as a resource for either subsequent budget assessments or other forms of reef monitoring.
- Marker pins should be more than 10 m apart, and the tape used for the survey line should be pulled taut and secured tightly.
- Each measuring tape used should have a ~50 cm length of 'leader' cord attached at the start of the tape – this ensures that the start point of each measured transect (where marker stakes are placed to avoid areas of live coral) is not biased by the presence of available substrate for peg deployment (Fig. 1).
- A map of the location and the layout of transects relative to notable aspects of the gross reef structure, in addition to global positioning system co-ordinates of the transects, is highly recommended.

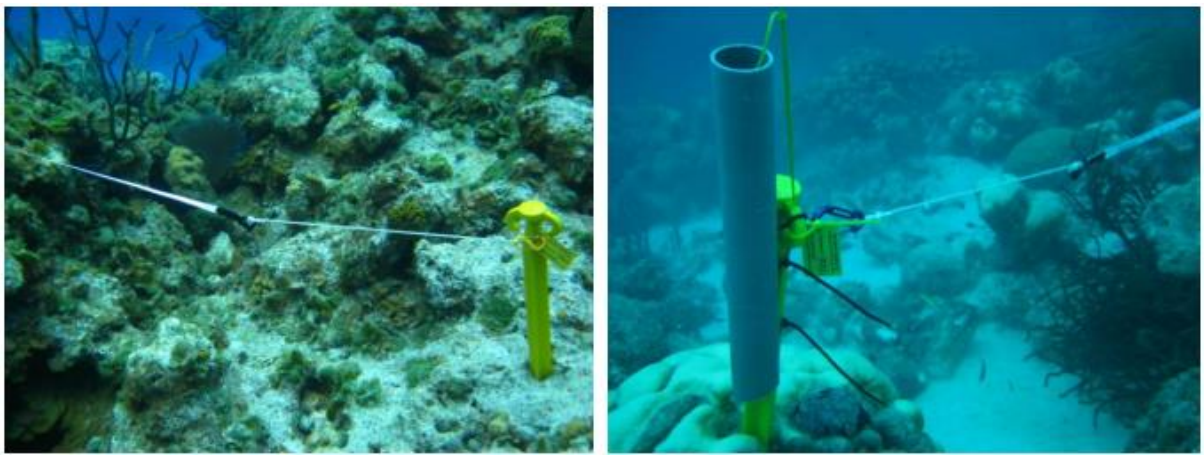


Fig 1| *Survey tape attached to marker stake showing 50 cm long 'leader' cord from clip to main tape.*

3 Determining rates of benthic carbonate production

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

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

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

Essential categories to collect for Caribbean* ReefBudget *framework calculations

- Coral to species[1] (or if not possible genera) and morphological group level (a generic ‘hard coral’ category is also provided that will calculate the carbonate production rate based on *mean* coral extension rates and density, but colony morphology has to be recorded).
- Crustose coralline algae (CCA) crusts (including non-differentiated other encrusters e.g., serpulids, bryozoans).
- Rubble
- Sediment
- Rock/limestone pavement

Desirable

- Macroalgal cover[2] (it is useful to differentiate between fleshy and coralline algae, and we suggest *Halimeda* spp. as well as other articulate coralline algae are recorded separately)
- Turf algal cover
- Sponges (both eroding and non-eroding)
- Soft coral cover[2]
- Anenomes
- Corallimorpharians
- Clams and other sessile invertebrates

[1] The online guide to Caribbean corals and sponges, *Coralpedia* (https://coralpedia.bio.warwick.ac.uk/) provides a useful field guide for Caribbean coral species genera.

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

BOX 1| Benthic Surveys – Recommended field methodology

(1) Insert a marker stake into the reef (not directly into a living coral colony) and then lay out the 10 m master transect line along the depth contour (parallel to the reef crest) before fixing to a second marker stake and pulling taut (the two stakes should be a little >10 m apart – Figs. 2 A, B).

(2) Record data on survey sheets using recommended taxa specific codes (see Appendix 1). It is essential that the correct coding system is followed on data entry because these codes link to the taxon and morphologically specific growth rates, density and equations required to calculate carbonate production estimates.

(3) Measure the surface distance (cm's) covered by each benthic component directly beneath the master tape within each linear 1 m of the 10 m survey transect (Fig. 2C). This is best done using a short (~1 m) length of flexible tape that can be laid out to conform to the exact surface profile of the reef (Fig. 2D). When the tape crosses a coral colony that is >1 m in size (i.e., it stretches across two linear metres of the master tape) it is necessary to record the full size of the colony to the nearest centimetre (i.e., if the colony is 115 cm this should be recorded as 115 cm, not 100 cm and 15 cm). In these cases, assign the colony to the metre in which the majority of the colony lies. Care should be taken to include measures of the surface cover within all cracks and crevices along the linear transect.

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

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

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

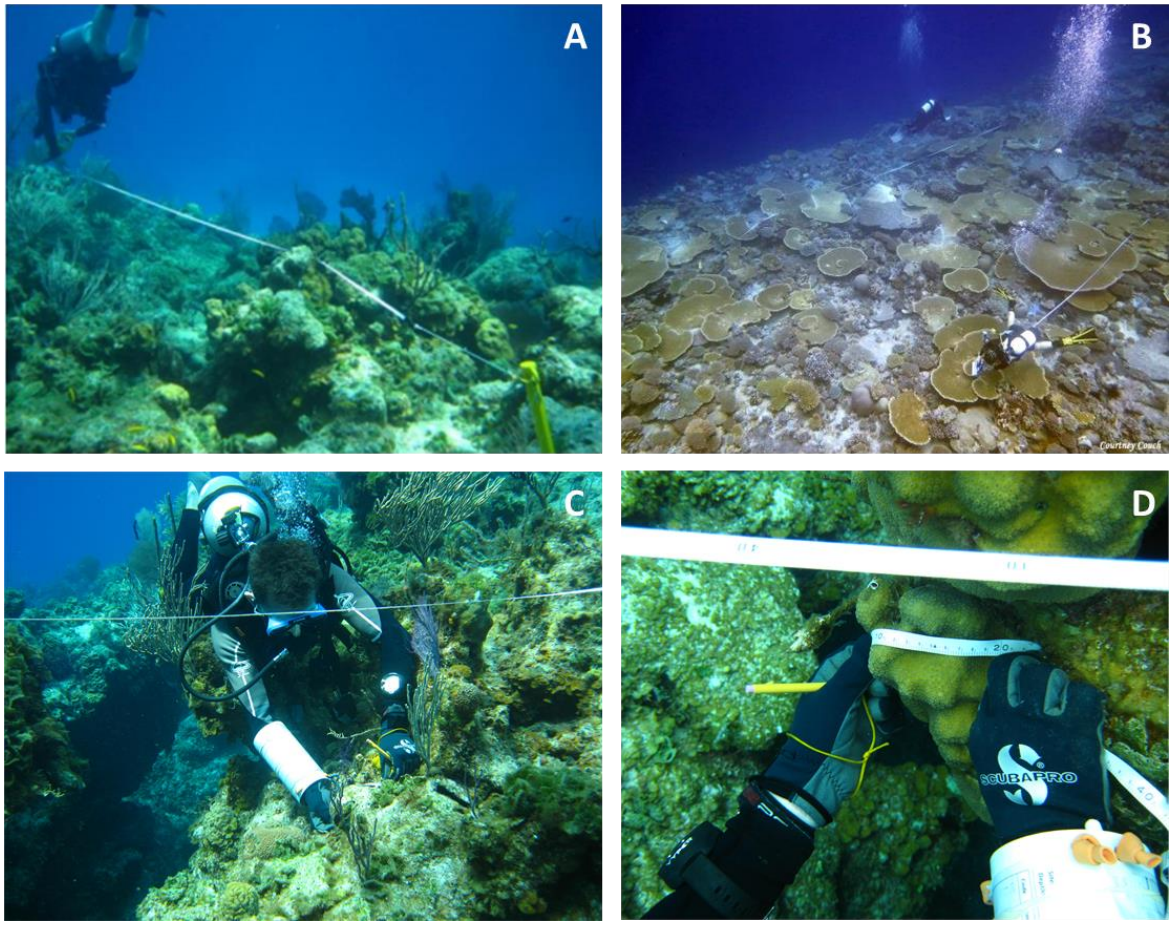


Fig 2| *(A, B) Master transect line, attached to a fixed marker stake, being laid out; (C) Diver recording linear distance cover by each benthic component immediately beneath the main 10 m transect line; (D) Care should be taken to ensure that the flexible substrate measuring tape conforms to the exact surface of the reef beneath the master transect line.*

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

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

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

NB. Emerging photogrammetry based methods are starting to provide interesting insights into areas of relatively higher or lower growth across individual colonies and may support further future modifications.

Resultant carbonate production equations are:

Massive:

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

Submassive:

$$CP_i = g.x.d$$

Encrusting/plating/foliose:

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

Branching/corymbose/columnar:

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

Where CP_i = carbonate production for colony *i*, *g* = growth rate, *x* = surface length of colony, *d* = skeletal density, *h* = the number of colony "edges" (normally 2), and c_a = proportion of colony that are growing axial branches.

NB. Measuring the linear surface of growing tips on branching corals during surveys is time-consuming. Therefore, in order to calculate the amount of each colony that represents growing axial branch tips, the size of branching and bladed colonies and the length of their growing tips have been measured for a number of key species at sites in Mexico (see – Table 1) and these conversion factors are used for all branching and columnar taxa in the calculation of carbonate production. In a few cases these conversions are currently based on Indo-Pacific taxa and where used are explained in the 'Conversion rates' tab in the benthic substrate calculation file.

Table 1| *Ratio of growing axial branches/tissue to total colony size*

Species	Morphology	Growing tips: colony size	SD	N
Acropora cervicornis	Complex fine branching	0.024	0.055	53
Acropora palmata	Robust branching	0.152	0.092	72
Agaricia tenufolia	Platy branches/fronds	0.063	0.023	63
Eusimilia fastigata	Short branches	0.114	0.033	7
Porites divaricata	Branching	0.081	0.045	28
Porites porites	Branching	0.146	0.118	47
Millepora alcicornis	Fine branched	0.041	0.045	22
Millepora complanata	Bladed branches	0.100	0.031	41

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

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

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

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

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

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

Note that the above calculations and conversion factors are already integrated into the Default spreadsheets. Additional site-specific data can be collected as needed.

3.2 Coral growth rates and density measures

The collection of new data on rates of coral linear extension and density from each reef site used for budget estimates is clearly a problematic issue, because it requires significant amounts of coral sampling, analysis, and time. In the Caribbean, there is relatively low coral diversity and a relatively extensive (compared to other regions) dataset of both coral growth rate and density data, such that there are a higher proportion of species/genera with at least some published rates. The downloadable spreadsheets have thus been pre-set to use Caribbean average growth rates and skeletal densities for each coral species and morphology in question and average CCA calcification rates from studies that investigated growth over >1 year. However, **all rates can and should be manually modified in the 'Calcification Rates' tab if more local or depth-specific data are available**.

The online supporting files 'Caribbean coral growth rate data', and 'Caribbean coral density data' summarize currently available coral growth and skeletal density data (we are aware of) for Caribbean corals and CCA. It is an on-going intention to continue to add any newly available data to this resource. If you aware of relevant data that does not appear here, please forward such information to Chris Perry (c.perry@exeter.ac.uk).

3.3 Crustose coralline algal growth and density measures

Far fewer published data are available for CCA growth rates and density than for corals, making quantitative estimates of CCA production less reliable. In the default mode, the spreadsheet therefore uses an average of rates from studies that investigated growth over >1 year only (see '*CCA production rate*' file). It is recommended, where possible, that simple experimental substrates are deployed for periods of 12-24 months in order to quantify calcification rates by calcareous encrusters within the study site in question (Box 2).

BOX 2| CCA growth experiment – Recommended field methodology
A wide range of potential substrates have been deployed in past experiments to quantify CCA production rates (Kennedy et al. 2017). Deployment of either lightly sanded PVC pipe (Fig. 3 A) or small plastic cards (such as those used for bank or library cards) ~ 8 x 5 cm (Fig. 3 B) in the proximity of each transect line are recommended (n = 6-9 pipes, or 5-6 cards), both for ease of deployment and because community recruitment closely matches that observed on surrounding natural substrates. These experimental substrates can be monitored to document CCA settlement and growth either through being photographed frequently (~every 3 months) or via a subset being retrieved approximately every 6-12 months for analysis (depending on the number of pipes/tiles and the amount of encrusting growth). Pipes/cards should be retrieved only after a bag has been secured around them with cable tie. These substrates can then be examined visually to ascertain percent cover and thickness of calcareous encrusters (and photographed in detail), and a weight per unit area derived. This is achieved by dissolving the CCA crust in 10% hydrochloric acid and dividing the dry weight by the surface area of the internal and external portions of the 10 cm length of pipe (see Morgan and Kench (2014) for further details), or by the surface area of cards (further differentiated by surface orientation if appropriate).

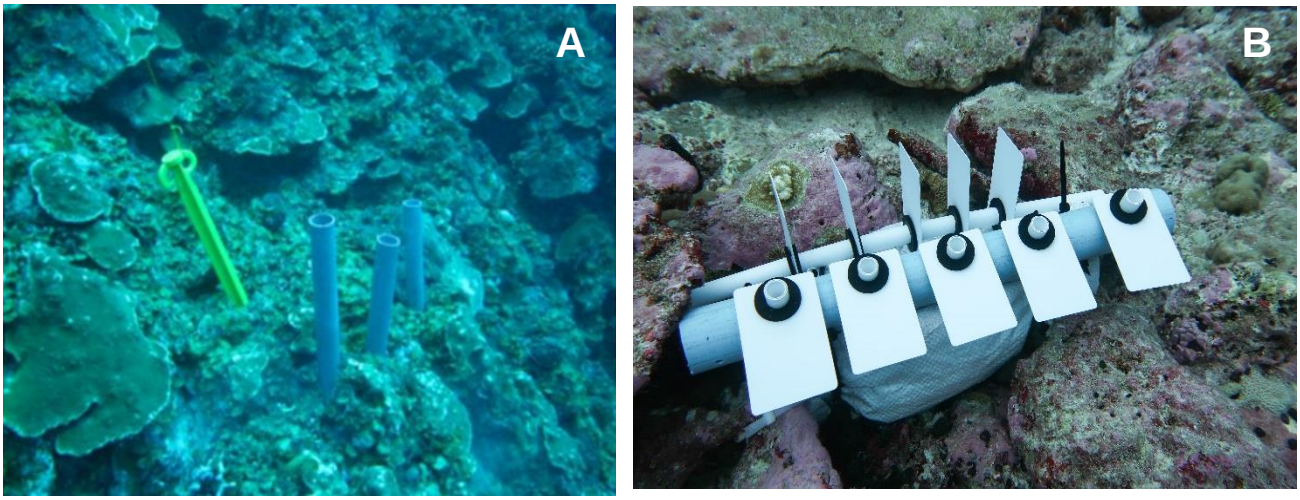


Fig 3. *(A) Array of PVC settlement pipes placed in the reef framework with an adjacent marker stake; (B) Array of PVC cards (in both horizontal and vertical orientations) deployed on a reef.*

3.4 'Caribbean Carbonate Production template v2' spreadsheet

The data entry sheets '*Caribbean carbonate production template v2*' can be downloaded from the *ReefBudget* website. General site data and details of transects conducted should be completed on the 'Site Description' tab, and census data within each linear meter of transect added into the 'Data Entry' tab. The 'Analysis' tab then calculates the percent cover and carbonate production (where applicable) for each genus/morphotype for each transect. There is also a tab to calculate micro-bioerosion (see sections 4.4 for details). All data are then summarised in the 'Results' tab, which gives transect and site level data on total carbonate production, production by major coral guilds, life-history strategies (after Darling et al. (2012), derived from Coral Trait Database: https://coraltraits.org/traits/233) and genera. It also provides percent cover data for the same categories.

3.4.1 Site description

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

Site Details

Site	Kisite	Survey Period	January 2012	
Depth	8	Surveyor/s	FJH & CTP	
Latitude	-4.72008	Longitude	39.37481	
Reef Zone (Flat/Fore)	Zone 2			
Notes	North-east side of reef, no swell ~15m visibility			

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

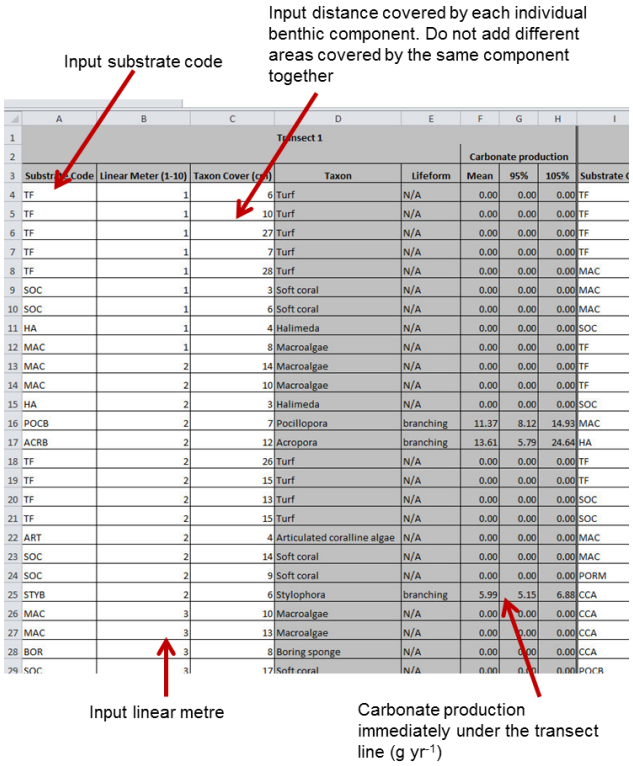
Site Description | Data Entry | Analysis | Macro & Microbioerosion | Results | Calcification Rates

Fig. 4. *Example of the 'Site Description' tab in the 'Caribbean Carbonate Production template v2' spreadsheet*

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

3.4.2 Data entry

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



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

Fig 5. *Example of the 'Data Entry' tab in the 'Caribbean Carbonate Production template v2' spreadsheet*

3.4.3 Analysis

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

3.4.4 Microbioerosion

This tab calculates microbioerosion. The white cell is a published rate of erosion. **Rates can be changed if desired**, and the spreadsheet will automatically calculate the erosion using these new rates.

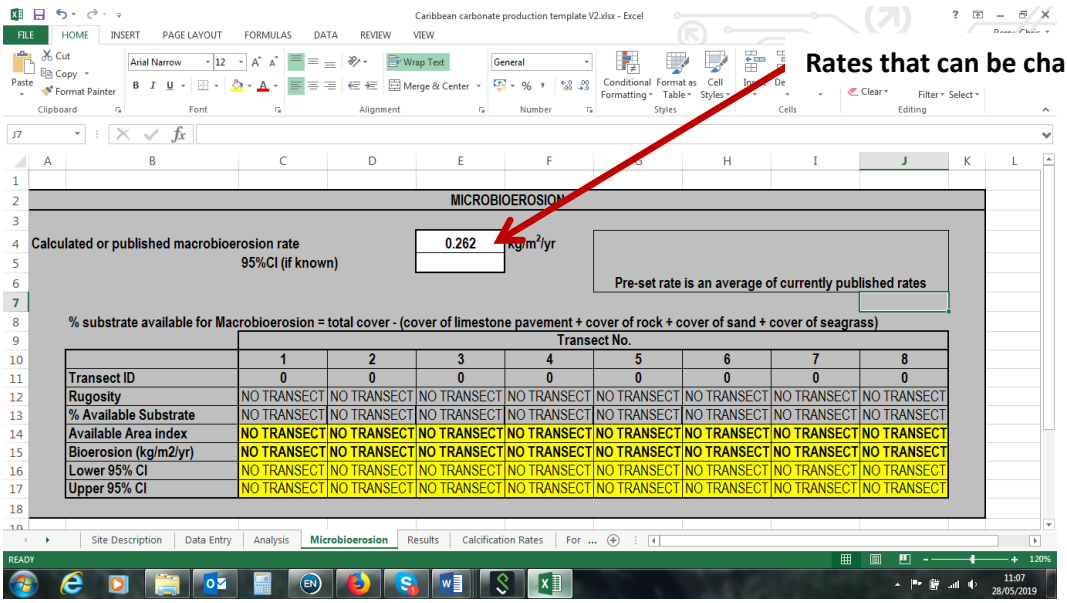


Fig 6 *Example of the 'Microbioerosion' tab in the 'Caribbean Carbonate Production template v2' spreadsheet*

3.4.5 Results

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

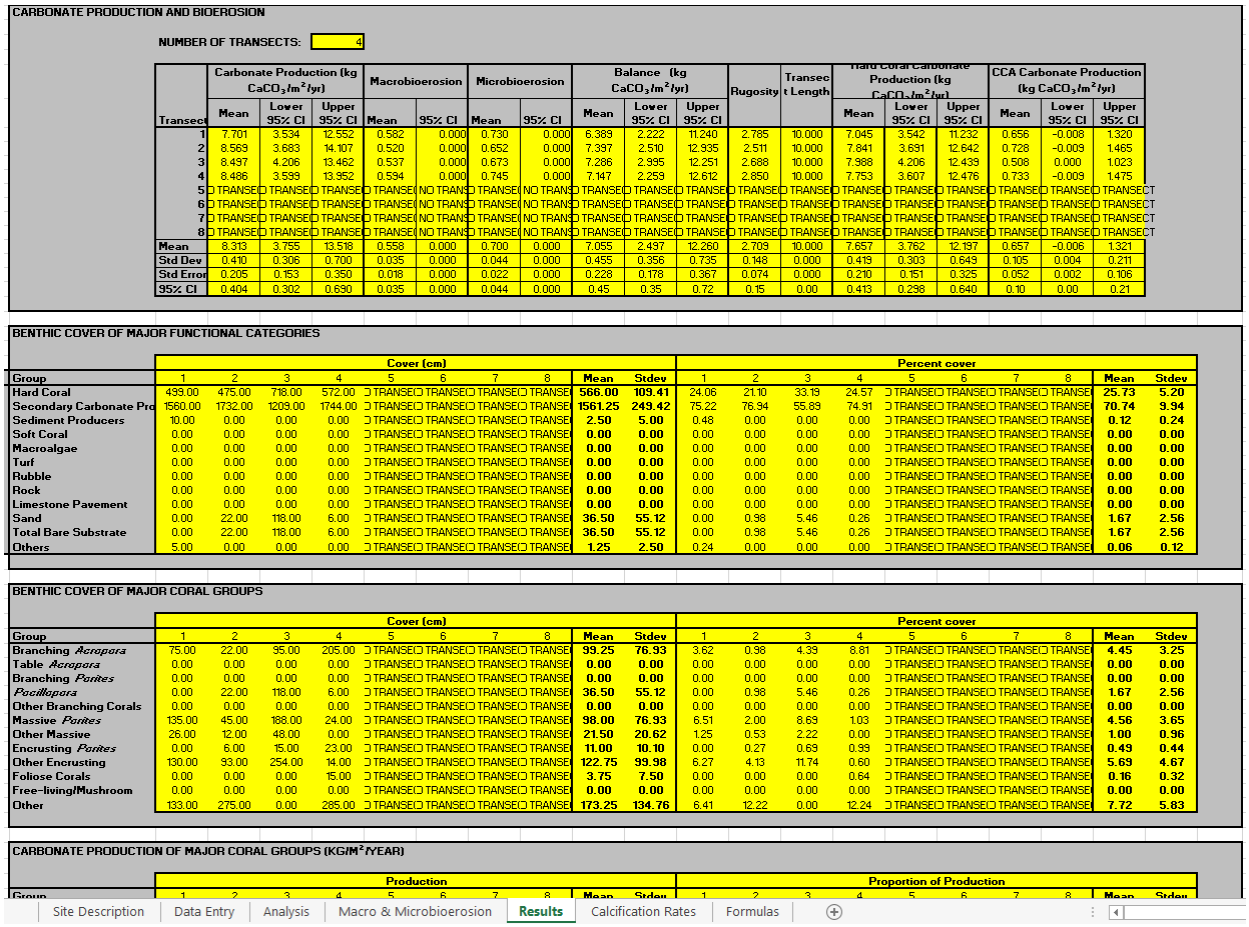
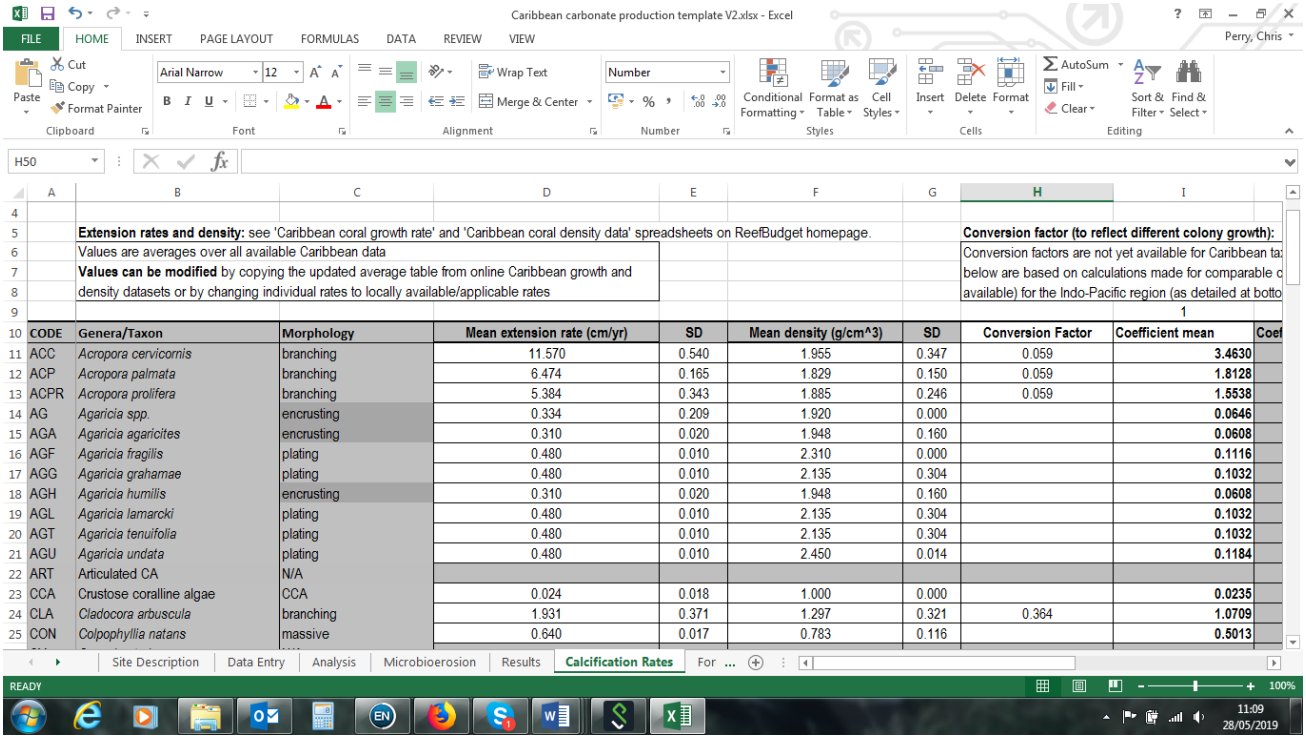


Fig 7 *Example of the 'Results' tab in the 'Caribbean Carbonate Production template v2' spreadsheet*

3.4.6 Calcification Rates

This tab contains the linear extension and density values for each coral genera and morphology combination, which are means calculated from published studies, listed in the '*Caribbean Carbonate Production template v2*' excel file, along with the conversion factor for complex corals where required. **These can all be changed by the user if desired**. There is currently no facility for changing the base equations of the geometric shapes the colony production is calculated from.



CODE	Genera/Taxon	Morphology	Mean extension rate (cm/yr)	SD	Mean density (g/cm^3)	SD	Conversion Factor	Coefficient mean
ACC	*Acropora cervicornis*	branching	11.570	0.540	1.955	0.347	0.059	**3.4630**
ACP	*Acropora palmata*	branching	6.474	0.165	1.829	0.150	0.059	**1.8128**
ACPR	*Acropora prolifera*	branching	5.384	0.343	1.885	0.246	0.059	**1.5538**
AG	*Agaricia spp.*	encrusting	0.334	0.209	1.920	0.000		**0.0646**
AGA	*Agaricia agaricites*	encrusting	0.310	0.020	1.948	0.160		**0.0608**
AGF	*Agaricia fragilis*	plating	0.480	0.010	2.310	0.000		**0.1116**
AGG	*Agaricia grahamae*	plating	0.480	0.010	2.135	0.304		**0.1032**
AGH	*Agaricia humilis*	encrusting	0.310	0.020	1.948	0.160		**0.0608**
AGL	*Agaricia lamarcki*	plating	0.480	0.010	2.135	0.304		**0.1032**
AGT	*Agaricia tenuifolia*	plating	0.480	0.010	2.135	0.304		**0.1032**
AGU	*Agaricia undata*	plating	0.480	0.010	2.450	0.014		**0.1184**
ART	Articulated CA	N/A						
CCA	Crustose coralline algae	CCA	0.024	0.018	1.000	0.000		**0.0235**
CLA	*Cladocora arbuscula*	branching	1.931	0.371	1.297	0.321	0.364	**1.0709**
CON	*Colpophyllia natans*	massive	0.640	0.017	0.783	0.116		**0.5013**

Fig 8. *The 'Calcification Rates' tab in the 'Caribbean Carbonate Production template v2' spreadsheet*

4 Determining rates of reef framework bioerosion

Bioerosion is defined as the corrosion of hard substrates by living agents (Neumann, 1966). A wide variety of organisms contribute to this process including not only specific species of fish and urchins, but also a variety of endolithic organisms (Golubic et al. 1981; Bromley, 1994). The most important of these are certain species of sponges, bivalves, worms, cyanobacteria, chlorophytes, rhodophytes and fungi. However, because many species can be involved and because many of them live cryptically it is a complex and difficult parameter to measure. In the context of carbonate budget studies various experimental approaches have been adopted to investigate the effects of total bioerosion on experimental coral blocks left exposed for long periods of time (e.g., Kiene, 1988; Osorno et al., 2005; Tribollet and Golubic, 2005). These techniques attempt to quantify the bioerosion due to microborers (e.g. cyanobacteria), macroborers (e.g. sponges, bivalves and polychaete worms) and grazers (e.g. urchins). However, such approaches have three major problems: 1) the experiments typically require at least 2-3 years to yield meaningful results; 2) for that bioerosion due to grazing, it is not possible to quantify the extent to which individual species are involved, although much can be inferred from census studies and abundance estimates; and 3) extrapolating results to an entire reef is probably tenuous (Chazottes et al., 1995). A further concern is an ethical one in that the technique has, to-date, required the use of blocks cut from live coral – usually massive *Porites* (Kiene, 1988; Osorno et al., 2005; Tribollet and Golubic, 2005). Consequently, *ReefBudget* recommends a series of alternative methods based on census data and drawing on published rates of erosion by different bioeroder groups as a technologically viable and environmentally acceptable alternative.

4.1 Bioerosion: Urchins

In order to quantify echinoid bioerosion *ReefBudget* uses a census-based approach, involving the collection of data on the numbers and sizes of urchins in the vicinity of each transect. The premise of this is that the rate of erosion by urchins occurs as a function of species and size, with larger individuals causing more erosion (Bak, 1990). Glynn (1996) suggests that the main agents of echinoid bioerosion belong to the genera *Diadema*, *Echinometra*, *Echinostrephus* and *Eucidaris*. A variety of techniques have been used to estimate bioerosion rates in these urchin species; including $CaCO_3$ content of the gut (e.g. Conand et al. 1997) or of their faecal pellets (e.g. Glynn et al. 1979), both with or without estimations of reworked sediment, spine abrasion and gut turnover (e.g. Scoffin et al. 1980; Griffin et al. 2003). It is therefore difficult to compare the urchin erosion rates derived from different studies. However, an evaluation of published data on erosion rates against test size suggests a relatively tightly correlated plot regardless of urchin species. Figure 8A shows aggregated data from 16 studies that consider urchin bioerosion rates (by eight urchin species) relative to test size.

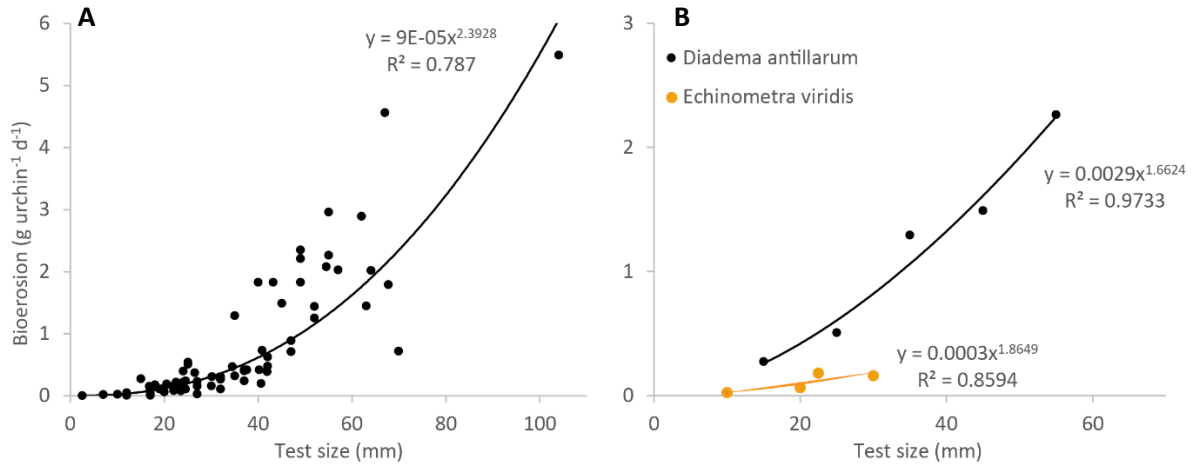


Fig. 8. *(A) Bioerosion rates (g urchin^{-1} d^{-1}) for urchins of various test sizes (includes data from both Caribbean and Indo-Pacific sites). Data aggregated from: Russo (1980); Scoffin et al. (1980); Downing and El-Zahr (1987);*

Glynn (1988); McClanahan and Muthiga (1988); Bak (1990); McClanahan & Kurtis (1991); Mokady et al. (1996); Conand et al. (1997); Teyes-Bonilla & Calderon Aguilera (1999); Mills et al. (2000); Carreiro-Silva and McClanahan (2001); Griffin et al. (2003); Appana and Vuki (2006); Herrera-Escalante et al. (2006); Brown-Saracino et al. (2007). (B) Bioerosion rates (g/urchin/d^{-1}) for Caribbean urchins of various test sizes. Diadema antillarum data is from Scoffin et al. (1980). Echinometra viridis data is from Griffin et al. (2003) and Brown-Saracino et al. (2007).

From the perspective of producing estimates of erosion by urchins, a single rate per urchin test size could, based on the above assessment, be applied with a reasonably high degree of confidence. Of note, the regression has an r^2 value of 0.78 and the regression equation is:

Bioerosion rate (g/urchin/day) = $9*10^{-5}.x^{2.3928}$

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

However, a more detailed assessment of the data suggests that there may be a difference in bioerosion rates at the genus level; in general *Echinometra spp*. have lower bioerosion rates than *Diadema spp*. of the same test size. In the Caribbean, published data relating bioerosion rates to urchin test size are relatively limited, but Fig. 8B presents data from three studies dealing with the two dominant species in this region – *Diadema antillarum* and *Echinometra viridis*. From these data, it appears that there are differences in the erosive capabilities of similar sized urchins of the two species. The bioerosion rates for *D antillarum* urchins are about 3 times the rates for *E. viridis* urchins of similar test size. Based on the above, *ReefBudget* recommends that separate equations be utilised to calculate the bioerosion rates for *D. antillarum, Echinometra* urchins and all 'other' urchins:

D. antillarum - Bioerosion rate (g/urchin/day) = $0.0029x^{1.6624}$
Echinometra - Bioerosion rate (g/urchin/day) = $0.0003x^{1.8649}$
Other - Bioerosion rate (g/urchin/day) = $9*10^{-5}.x^{2.3928}$

where x is the test size of an urchin in millimetres

Urchin Surveys - Recommended field methodology

(1) A census of the number and size class of urchins is obtained along each 10 m transect (Fig. 9A).
(2) The census is obtained by examining the substrate 1 m either side of the transect line (a total of 20 sq m).
(3) The number of individuals, identified to species level, in each of the following size classes is identified: 0-20 mm, 21-40 mm, 41-60 mm, 61-80 mm, 81-100 mm etc, (Fig. 9B). A scale bar marked on the side of a dive slate is of use for discriminating categories.

A recommended survey sheet is provided in Appendix 2 and images of the relevant Caribbean bioeroding urchins in Appendix 3.

Fig. 9. *(A) Diver surveying for urchins within an area 1 m either side of the master transect line; (B) Abundance and size class data for each species are recorded on the relevant survey sheet.*

Calculation of the amount of bioerosion

1. For each urchin species and size class the rate of bioerosion per urchin per day (g) can be established using the relevant equations (Figs. 8A, B).
2. The calculated daily rate per species size is multiplied by the number of individuals in each size class to yield the total daily rate of bioerosion per size class for each species.
3. The total daily rate per size class is then multiplied by 365 (no. days in a year) to yield the total bioerosion rate per size class per year (g).
4. Total bioerosion per size class per year is then summed to yield the total bioerosion by each species per year (g) and these can then be summed to yield a rate for all urchins.
5. Total bioerosion is then divided by the transect area (20 m^2) to yield the bioerosion per metre squared ($g/m^2/y$). This value is then converted to $kg/m^2/y$.

The data entry sheets provided (see Fig. 10) can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted should be completed on the 'Site Description' tab. The 'Data Analysis' tabs auto-calculate urchin erosion rates for different species using pre-set species and test size specific relationship data, and give a breakdown of urchin abundance/m^2 and bioerosion rates for each species on each transect and the mean of these. These are shown using both the general urchin erosion rate equation ('Data Analysis GenEQ' tab) and those for individual species ('Data Analysis IndEQ' tab) (Fig. 11). The 'Results' tab provides a mean rate of urchin erosion based on both sets of equations (Fig. 12). The figures used in these calculations can be manually modified in the spreadsheets if more regionally (or depth) specific data are available (or preferred).

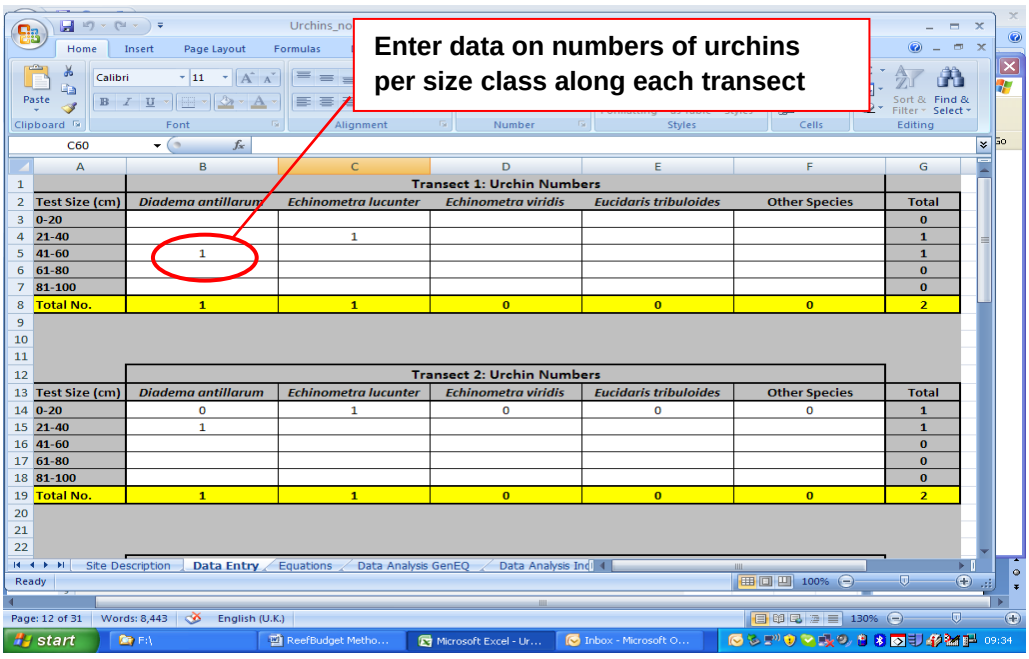


Fig. 10. *Screen grab showing main 'Data Entry' form for urchin data. Data input for each transect is required in the white columns as indicated.*

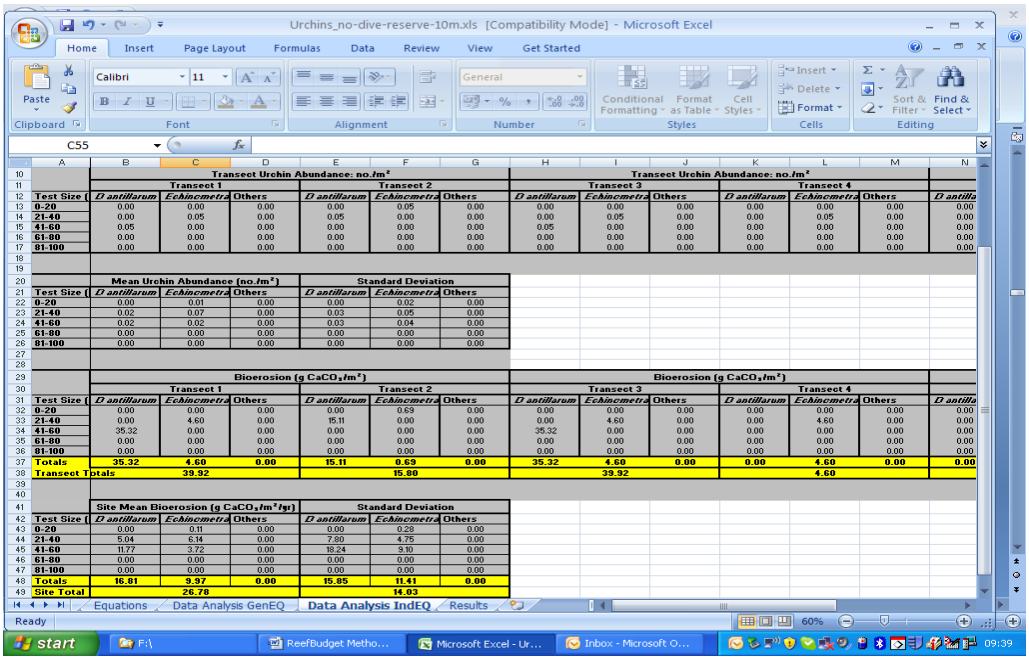


Fig. 11. *Screen grab showing main 'Data Analysis IndEQ' tab, which gives breakdown of urchin abundance and production rates for each transect (in this case using erosion rate equations for individual urchin species)*

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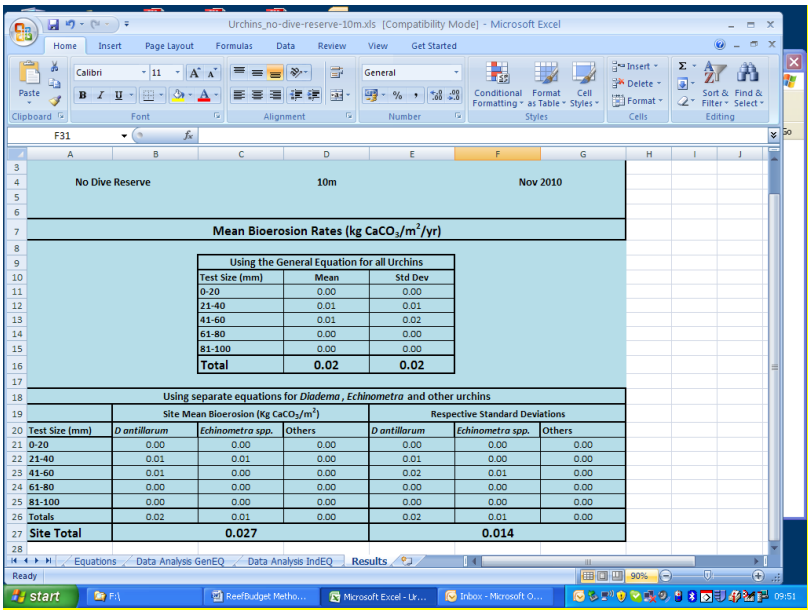


Fig. 12. *Screen grab showing the 'Results' tab for urchin erosion. This provides a summary of mean urchin erosion rates for the depth zone under study based on both general and individual species erosion rate equations.*

4.2 Bioerosion: Fish

There are a number of fish families whose feeding techniques cause the ingestion of $CaCO_3$ e.g., goatfish, parrotfish and surgeonfish. However, there are only a few species which actively erode the reef substratum while feeding. This is because most species ingest unattached or reworked sediment and therefore do not erode reef framework directly. Indeed of six parrotfish species investigated by Frydl and Stearn (1978) only one, *Sparisoma viride*, had a significant erosive impact on the coral reef framework at Bellairs Reef, Barbados. The vast majority of fish bioerosion is caused by parrotfish, although other fish species undoubtedly contribute. *ReefBudget* thus recommends a methodology focused only on quantifying erosion rates by parrotfish as this is the only group for which sufficient erosion rate data exists.

In light of this it is pertinent to note that parrotfish size and species are both important factors in controlling bioerosion rates (Bellwood and Choat, 1990). Numerous authors have reported higher bioerosion rates for larger fish (Scoffin et al., 1980; Bellwood, 1995; Bruggemann et al., 1996), but also differences between the eroding capacities of similar sized fish of different species (Bruggemann et al., 1996; Hoey and Bellwood, 2008). Additionally, the life phase of parrotfish is important as feeding rates are higher in the initial phase than in the terminal phase (Bruggemann et al. 1994b; Bruggemann et al. 1994c; Mumby et al. 2006). The key parameters required to assess parrotfish erosion are thus species/life phase abundance and fish size. Typically bioerosion rate is calculated for an individual and then combined with abundance figures to yield rates for a size class/species. Whilst various methods have been used to visually assess parrotfish populations we recommend the use of fish census surveys undertaken along belt transects.

Fish Census: Recommended field methodology

(1) The belt transect approach is advocated. Eight to ten transects should be observed within each of the depth zones used in the study.

(2) Observations should ideally be made between the time periods of 11 am and 5 pm (the periods of maximum feeding activity), although to achieve 10 transects it may be necessary for surveys be made over multiple dives/days.

(3) Each transect should be 30 m in length by 4 m in width. A 30 m line should be run out across the reef zone.

(4) After waiting for a couple of minutes the diver then makes a slow swim back along the line – noting the species, life phase and fork length of each parrotfish (it is recommended that a 1 m calibrated T-bar with attached dive slate be used for this purpose – see Fig. 13).

(5) Parrotfish are recorded in the following size classes 0-9 cm, 10-19 cm, 20-29 cm, 30-39 cm, 40-49 cm and 50-59 cm.

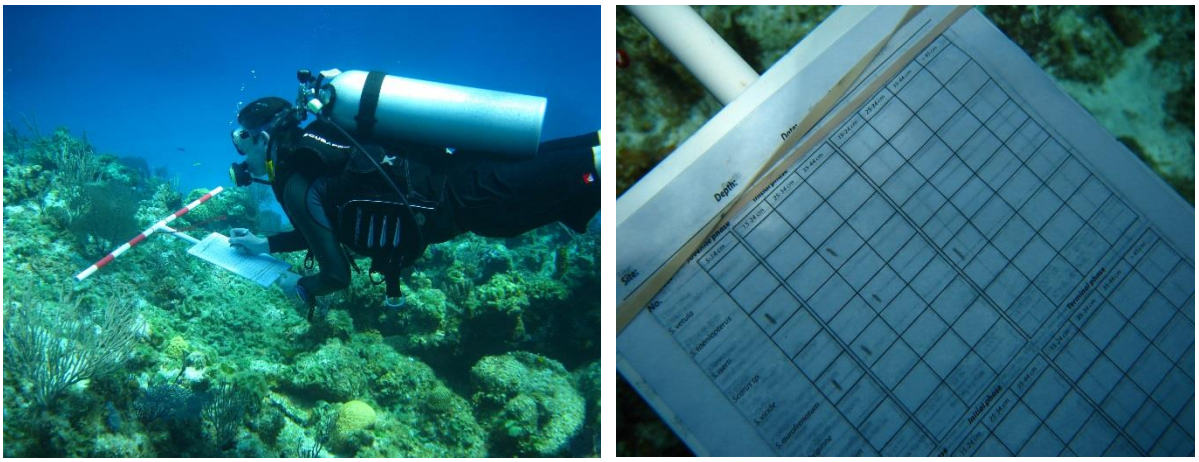


Fig. 13. *(A) Diver surveying for parrotfish with the aid of T-bar for size class classification; (B) Survey sheet on slate attached to T-bar for recording size class-abundance data.*

A copy of the recommended survey sheet is provided in Appendix 4, and of the fish ID sheet in Appendix 5.

Calculation of the amount of bioerosion

The method proposed for calculating bioerosion by fish is based on a model that uses total length and life phase to predict bite rates (bites hr^{-1}), bite volume (cm^3) and proportion of bites leaving scars for each parrotfish species. Currently, this data is patchy and exists for only a subset of species, but

additional data can be added as it becomes available, or if collected as part of the same study. An online resource (see '*Car Parrotfish erosion rates_database'* on the *ReefBudget* website) is provided that summarizes available published data on bite rates, bite volumes and proportion of bites leaving scars for Caribbean parrotfish species.

Daily bite numbers and volume removed per day by each individual fish are calculated from bite rates and volumes by integrating length of day, as defined in the 'Site Description' tab (default 12 h), and diurnal feeding activity (83-88%, Bellwood, 1995). The following equation is then used to calculate species specific erosion rates for the median value within each size class:

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

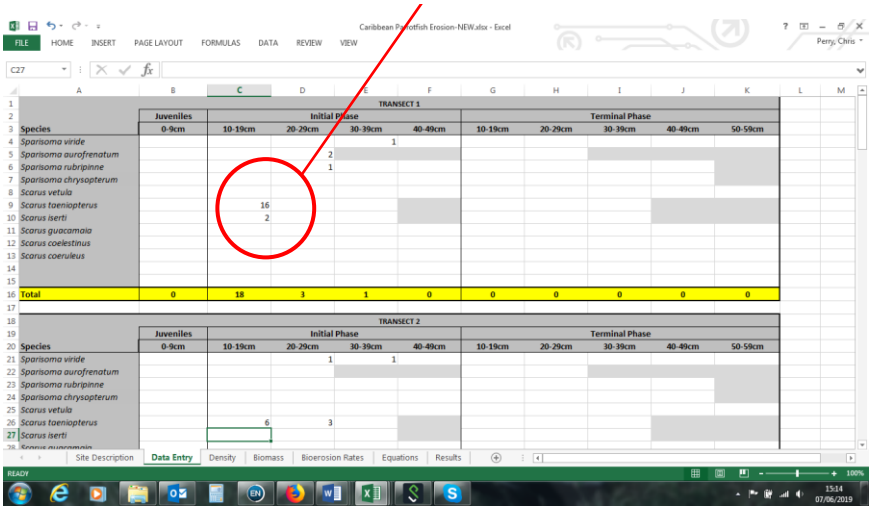
Where v is bite volume (cm^3), s_{prop} is the proportion of bites leaving scars, br is bite rate (bites day^{-1}) and d is substratum density (default 1.72 g cm^{-3}, which is the average over all available coral taxa and growth form density data in the '*Caribbean coral growth and density database'* resource). The substratum density can be adjust for local community compositions as seen fit by the user.
To increase the accuracy of the model predicting bite rates and volumes from parrotfish size it may prove useful to quantify feeding rates and measure bite scars at the survey sites (Box below). Obtained rates can be entered into the spreadsheets in place of the current bite rates.

Recommended field methodology: Bite rate and bite volume

(1) Identify a focal fish, and follow it for a minimum of 2 minutes, or until it has conducted several bite forays (a patch of closely spaced bites, followed by movement to another patch). This ensures it has acclimatised to the presence of the observer and is behaving naturally. Use your discretion – for some individuals more than 2 minutes of acclimatisation may be necessary.
(2) Note total length, life phase and species. Then observe the fish for at least 3 minutes (preferably 5 min), noting how many bites are taken, and how many bites leave visible scars (if possible).
(3) Length, width and, where possible, depth of bites for each species and size class can be measured during additional observations using callipers. As the depth for scrapers and small excavators can be very shallow (<0.1 mm), assumptions of 0.1 mm depth for small excavators and large scraers and 0.05 mm for shallower scrapes can be used if necessary (Yarlett et al. 2018). Grazing scars can occur as 1 mark or 2 marks (made by the upper and lower jaws). In the latter case, both marks should be measured and the volume combined. Bite volume is calculated as length*width*depth.

The data entry sheets calculating parrotfish erosion can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted should be completed on the 'Site Description' tab. Census data on parrotfish species and size class are added on the 'Data Entry' tab (see Fig. 14). The 'Density' and 'Biomass' tabs provide an overview of parrotfish density and biomass for each species and size class per transect and per hectare, and the 'Bioerosion Rate' tab provides bioerosion rates by species in kg m^{-2} yr^{-1} for each transect (Fig. 15). The 'Equations' tab is where alterations can be made to bite rates, percent of bites leaving scars, bite volumes and substrate density. The 'Results' tab provides site average and transect level data on total bioerosion, abundance and biomass (Fig. 16).

Enter data on numbers of individual parrotfish by species, life phase (juvenile, initial, terminal) and size class along each 30 m transect swim.



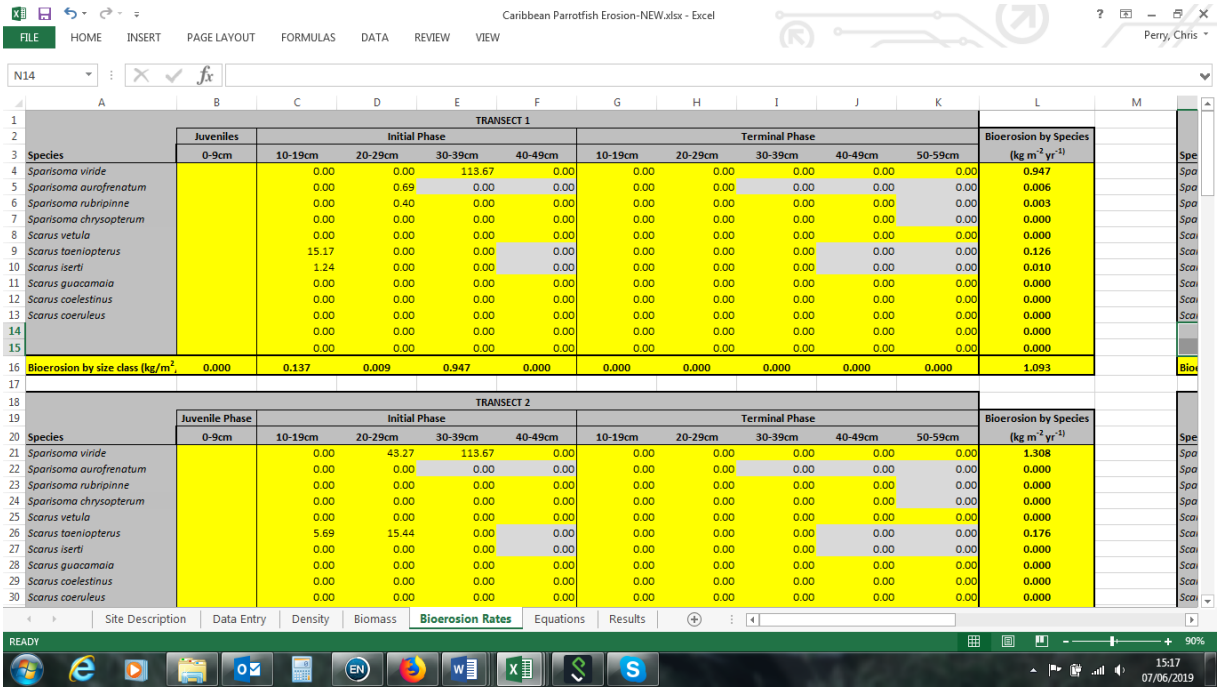
TRANSECT 1

Species	Juveniles 0-9cm	Initial Phase 10-19cm	20-29cm	30-39cm	40-49cm	Terminal Phase 10-19cm	20-29cm	30-39cm	40-49cm	50-59cm
Sparisoma viride				1						
Sparisoma aurofrenatum			2							
Sparisoma rubripinne			1							
Sparisoma chrysopterum										
Scarus vetula										
Scarus taeniopterus		16								
Scarus iserti		2								
Scarus guacamaia										
Scarus coelestinus										
Scarus coeruleus										
Total	0	18	3	1	0	0	0	0	0	0

TRANSECT 2

Species	Juveniles 0-9cm	Initial Phase 10-19cm	20-29cm	30-39cm	40-49cm	Terminal Phase 10-19cm	20-29cm	30-39cm	40-49cm	50-59cm
Sparisoma viride			1		1					
Sparisoma aurofrenatum										
Sparisoma rubripinne										
Sparisoma chrysopterum										
Scarus vetula										
Scarus taeniopterus		6	3							
Scarus iserti										

Fig. 14 *Screen grab showing 'Data entry' tab for parrotfish data. Data input is required in the columns as indicated.*



TRANSECT 1

Species	Juveniles 0-9cm	Initial Phase 10-19cm	20-29cm	30-39cm	40-49cm	Terminal Phase 10-19cm	20-29cm	30-39cm	40-49cm	50-59cm	Bioerosion by Species (kg m^{-2} yr^{-1})
Sparisoma viride		0.00	0.00	113.67	0.00	0.00	0.00	0.00	0.00	0.00	0.947
Sparisoma aurofrenatum		0.00	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.006
Sparisoma rubripinne		0.00	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.003
Sparisoma chrysopterum		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus vetula		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus taeniopterus		15.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.126
Scarus iserti		1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.010
Scarus guacamaia		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus coelestinus		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus coeruleus		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Bioerosion by size class (kg/m^2)	0.000	0.137	0.009	0.947	0.000	0.000	0.000	0.000	0.000	0.000	1.093

TRANSECT 2

Species	Juvenile Phase 0-9cm	Initial Phase 10-19cm	20-29cm	30-39cm	40-49cm	Terminal Phase 10-19cm	20-29cm	30-39cm	40-49cm	50-59cm	Bioerosion by Species (kg m^{-2} yr^{-1})
Sparisoma viride		0.00	43.27	113.67	0.00	0.00	0.00	0.00	0.00	0.00	1.308
Sparisoma aurofrenatum		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Sparisoma rubripinne		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Sparisoma chrysopterum		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus vetula		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus taeniopterus		5.69	15.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.176
Scarus iserti		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus guacamaia		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus coelestinus		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000
Scarus coeruleus		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000

Fig. 15. *Screen grab showing the 'Bioerosion Rates' tab which gives a breakdown of parrotfish abundance, erosion rates per species for each transect and mean bioerosion rates per species.*

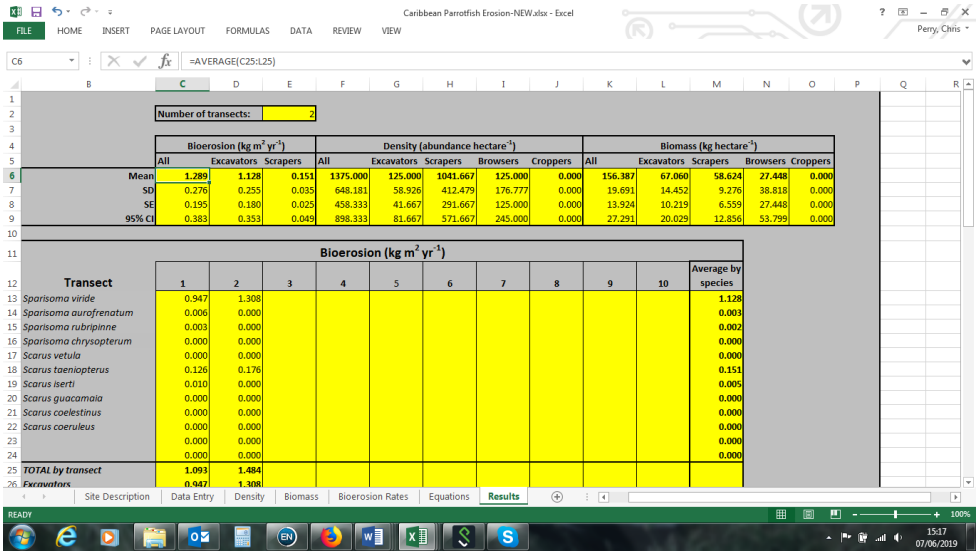


Fig. 16 *Screen grab showing the 'Results' tab for parrotfish erosion.*

4.3 Bioerosion by macroborers (sponges, bivalves, worms)

Macroborers are defined as those eroders which produce boreholes with diameters >1 mm and include endolithic sponges, polychaete and sipunculid worms, bivalves, decapods and cirripeds. Of these groups, sponges have received the greatest attention because, on a reef-wide basis (and especially within the Caribbean), they typically dominate comprising some 75-90% of the macroboring community (in terms of the proportion of substrate infestation; e.g. Goreau and Hartman, 1963; MacGeachy and Stearn, 1976; Highsmith, 1981; Highsmith et al. 1983; Perry, 1998). Approaches to measuring rates of substrate erosion by internal macroborers have primarily relied on two methods: (1) those making use of experimental coral blocks left exposed for long periods (ideally in excess of 24 months) (Kiene, 1988; Osorno et al., 2005); and (2) those that have made estimates of rates of internal bioerosion using cored or slabbed corals from which x-rays have been taken to determine annual growth rates, and against which measures of internal substrate removal can be calibrated per unit of time. A general concern about these methods is an ethical one in that they require either the use of blocks cut from live coral – usually massive *Porites* (Kiene, 1988; Osorno et al., 2005; Tribollet and Golubic, 2005) or widespread coral removal and slabbing. Neither approach is ideal under current regimes of generally low live coral cover. The Caribbean version of *ReefBudget* currently only quantifies sponge bioerosion rates as a conservative estimate of total macrobioerosion within a site. Specifically, in this revised Caribbean version of *ReefBudget*, use is made of recently published data on measured rates of both chemical and mechanical erosion by a number of common Caribbean endolithic sponge species (see de Bakker et al. 2018). These rates are then applied to census-based estimates of the surface tissue cover (cm^2) per unit area reef of each species of endolithic sponge to derive an overall sponge bioerosion rate estimate (kg $CaCO_3$ m^2 yr^{-1}).

Internal (Sponge) Macrobioerosion: Recommended field methodology

(1) Bioeroding sponge surveys should be conducted along each of the fixed transects previously established.
(2) The area covered by individual colonies of bioeroding sponges (cm^2) – to species level (see Appendix 7) - is then quantified within an area encompassing 0.5 m either side of the transect line (total 10 sq m or 100,000 cm^2) – a 0.5 m x 0.5 m transect is useful for delineating this area (Fig. 17A).
(3) The area covered by clionid sponge tissue and the area occupied by visible papillae are then estimated using a transparent sheet with a printed 1 x 1 cm grid (see Fig. 17B).

Fig. 17. *(A) Diver surveying for clionid sponge tissue with the aid of a transect to delineate the survey area; (B) Transparent sheet with printed 1 cm x 1 cm grid to allow quantification of the surface area (cm^2) of the reef covered by boring sponge tissue and papillae – in this case a colony of Cliona delitrix.*

Appendix 6 is a copy of the survey sheet for sponge surveys, and images of the key Caribbean bioeroding sponges are in Appendix 7.

4.3.1 Calculation of the amount of bioerosion

Estimating the cover (cm^2) of bioeroding sponges can be achieved with relative ease using the method proposed above. Sponge cover is measured on all surfaces (not just planar view) thus integrating measures of true reef surface area. The surface area of each sponge observed in the study area should be measured as the area inside the perimeter of visible tissue or of the siphons present e.g., see Fig. 18. Bioerosion is then calculated as a function of surface area and erosion rate using the following datasets.

	mg $CaCO_3$ cm^{-2} d^{-1}	kg $CaCO_3$ m^{-2} yr^{-1}	
C. aprica	1.03	3.76	Based on rates in de Bakker et al. 2018
C. caribbaea	1.28	4.67	Based on rates in de Bakker et al. 2018
C. tenuis	1.16	4.23	Average of C. aprica & *C. caribbaea* in de Bakker et al. 2018
C. varians	1.16	4.23	Average of *C. aprica* & *C. caribbaea* in de Bakker et al. 2019
c. deletrix	2.87	10.48	Based on rates in de Bakker et al. 2018
C. amplicavata	2.45	8.94	Based on rates in de Bakker et al. 2018
S. brevitubulatum	1.46	5.33	Based on rates in de Bakker et al. 2018
S. flavolivescens	0.47	1.72	Based on rates in de Bakker et al. 2018

Table 2: Calculated total (mechanical and chemical) rates of erosion by common Caribbean endolithic sponge species

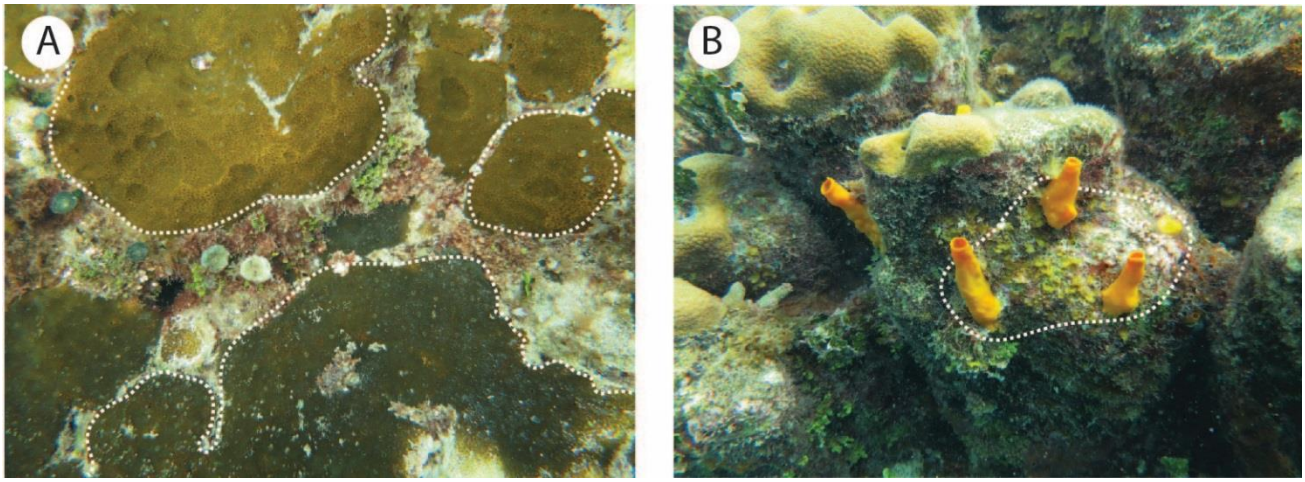


Fig 18. Figures showing how the peripheral areas of sponge tissue should be delineated for A) species with clear surface tissue cover; and B) species with peripheral siphon expression.

To calculate erosion rates by sponges the following information and data then needs to be added for each survey transect into the '*Macrobioerosion*' tab in the '*Caribbean Carbonate Production template v2*' spreadsheet: 1) Transect number (Row 16); 2) Transect length (m) (Row 17); 3) Transect width (m) (Row 18); and 4) Total surface area (cm^2) for each sponge species in the survey area (see Fig. 19). Bioerosion rate by each species and as a total for each transect is then shown in the yellow boxes below. These are summed in the final '*Results*' tab.

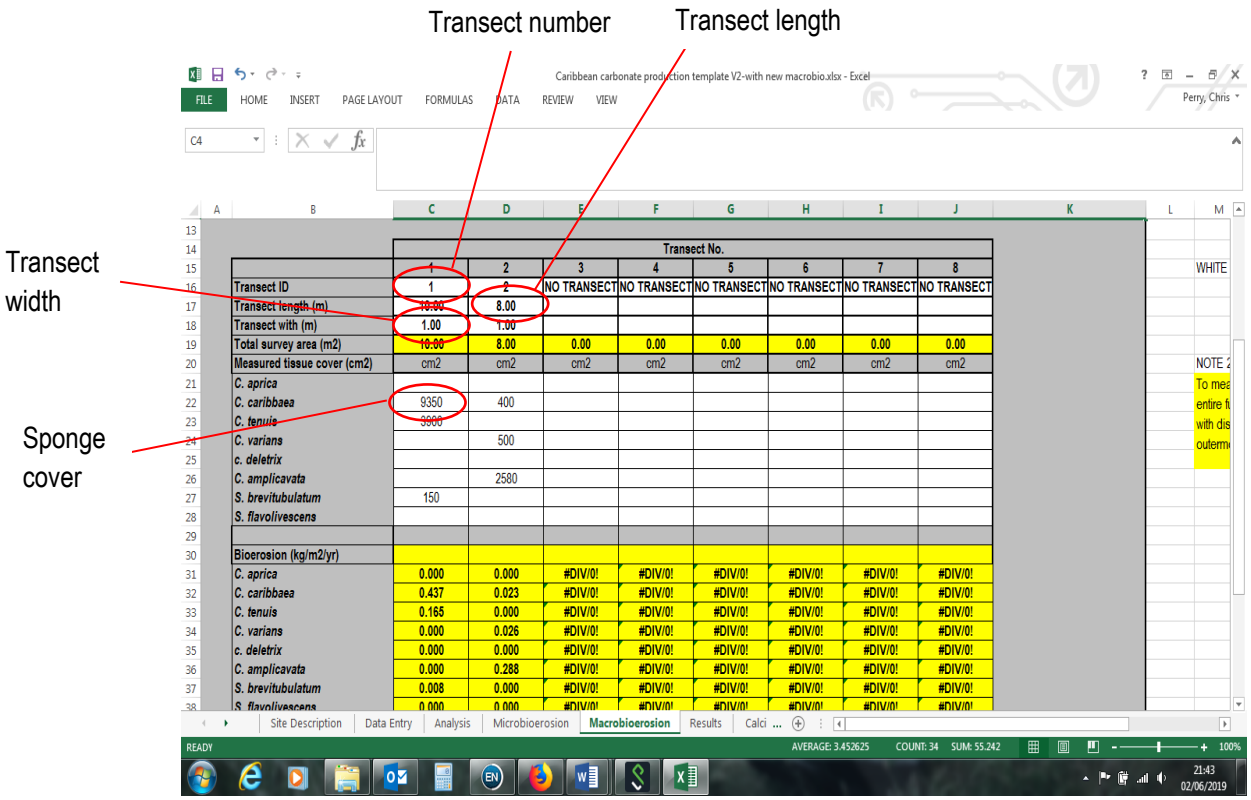


Fig. 19. Sponge bioerosion data entry tab.

4.4 Bioerosion by microborers (cyanobacteria, chlorophytes, fungi)

The carbonate substrate of reefs can also be degraded by the activities of photosynthetic cyanobacteria, chlorophytes and rhodophytes, and heterotrophic fungi and bacteria (Golubic et al. 1981). As with macrobioerosion, assessments of microbioerosion have tended to rely on deploying experimental substrates, predominately dead *Porites* sp. blocks (e.g., Chazottes et al. 1995; Chazottes et al. 2002; Tribollet and Golubic 2005). Most studies have chosen to examine either the bathymetric ranges of individual species, or community composition and succession dynamics of different taxa rather than determining total rates of microboring. Despite data on these processes being sparse, microbioerosion has the potential to contribute to a non-negligible amount of bioerosion on coral reefs, since the published rates are within similar ranges to those of macroborers.

4.4.1 Calculation of the amount of microbioerosion

Estimates of microbioerosion rates are automatically calculated in the '*Caribbean Carbonate Production template v2'* spreadsheet, in the '*Microbioerosion*' tab, based on published rates of microbioerosion (where available, locally derived rates can be manually entered into the spreadsheet) and factored for available surface area of the reef. All substrate not available to bioeroders (sand, non-carbonate rock) is excluded. The spreadsheets are pre-set with an average microbioerosion rate based on all currently available published data (given there is little current Caribbean data).

5. Summing the budget

Once all the data has been collected, the budget for the site can be summed either in the Results tab of the *'Caribbean Carbonate Production template v2*' spreadsheet (see Fig. 20), or in a separate spreadsheet if preferred. Data for each transect needs to be copied and pasted into each column (either from the carbonate production template or from the fish and urchin sheets). If not all the transects could be completed for urchins or sponge surveys then site level means can be added for those transects. Note also that because the parrotfish data is collected as an overall site average and not as discrete transect data the same overall rates of parrotfish erosion (as highly mobile taxa) are added for each transect.

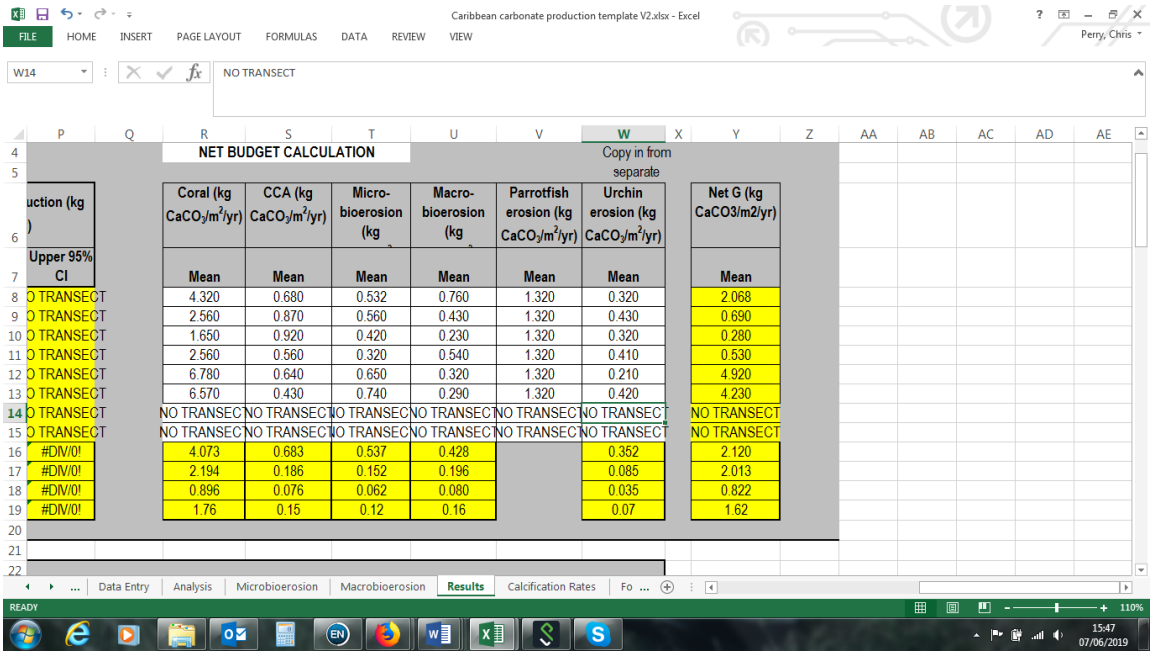


Fig. 20. Budget summary section in 'Results' tab of 'Caribbean Carbonate Production template v2' spreadsheet

6. Confidence ratings for different budget components

Because of the necessary use of available data on parameters such as calcification rates and rates of bioerosion, which derive primarily from the literature, different budget assessments using the *ReefBudget* methodology will inevitably vary in the level of confidence that can be given to different budget components. This confidence rating will thus vary depending not only on the experience of the surveyor (as shown for fish census studies; Bell et al. 1985), but also with the extent to which appropriate local datasets are availability to underpin the budget calculations. Note that the data entry spreadsheet are user changeable in terms of the rate data used, but that they are pre-set with average data derived from all available published literature from the Caribbean. In light of the above, it is recommended that a confidence rating be assigned to each of the budget components calculated in any budget assessment and that these can be shown within any tabulated data from the site under study. Table 3 shows the recommended approach to this and provides a mechanism by which a confidence rating can be assigned to both the methodological component of each study and the data entry component employed in calculating individual production/erosion rates.

Table 3 *Recommended confidence rating scheme for assessing reliability of both the survey methods and supporting data for each component of the budget calculations.*

		Confidence rating – survey methodology		
		High[1]	**Medium**[2]	**Low**[3]
Confidence rating – supporting data	**High**[4]	**H/H** High confidence in survey method and high confidence in supporting datasets	**M/H** Reasonable confidence in survey method but high confidence in supporting datasets	**L/H** Low confidence in survey method but high confidence in supporting datasets
	Medium[5]	**H/M** High confidence in survey method and reasonable confidence in supporting datasets	**M/M** Reasonable confidence in survey method and reasonable confidence in supporting datasets	**L/M** Low confidence in survey method but reasonable confidence in supporting data
	Low[6]	**H/L** High confidence in survey method but low confidence in supporting datasets	**M/L** Reasonable confidence in survey method but low confidence in supporting datasets	**L/L** Low confidence in survey method and low confidence in supporting datasets

[1] High (methodological) – considered to provide an accurate reflection of the abundance of the budgetary component under consideration. This may be the appropriate rating for: i) census studies of benthic coral cover (especially in low topographic complexity systems); or ii) for census studies of readily visible benthic substrate eroders e.g., urchins.

[2] Medium (methodological) – considered to provide a reasonably good estimate of the abundance of the budgetary component under consideration. This may be an appropriate rating for: i) surveys of non-benthic (mobile) faunas (e.g., fish); ii) for census estimates of often cryptic benthic components e.g., CCA or sponge borers; or iii) coral census estimates where there is a high proportion of branched coral cover.

[3] Low (methodological) – considered to provide an approximate estimate of the abundance of the budgetary component under consideration. This would be the appropriate rating for estimates of microbioerosion because the census methods do not employ in-site assessments of species abundance.

[4] High (data) – supporting data considered to be accurate and reliable for the reef under study. This may be the appropriate rating where: i) a high proportion of the supporting data on coral production (especially for the main coral species present) is derived from the country or area under study; or ii) where the use of relatively well constrained size/rate data is employed e.g., for the relationship between urchin size and erosion rate.

[5] Medium (data) – supporting data considered to provide a reasonably good underpinning for the reef under study. This may be the appropriate rating where: i) use is made of the regional average datasets for determining production rates by corals; ii) where some assumptions are required regarding size/rate data relationships e.g., for the relationships between size and erosion rate in different parrotfish species.

[6] Low (data) – supporting data considered to provide an approximate underpinning for the reef under study. This may be the appropriate rating where: i) limited data exists generally for the dominant coral species within the survey area and/or there is a reliance on data from other regions or only from similar morphological groups; ii) where there is at present a general paucity of production/erosion rate data e.g. for CCA or sponge boring; or iii) a reliance on rate data employed independently of in-site surveys e.g., for microbioerosion.

NB. It would be expected that these rating may change over time as new datasets become available.

Appendix 1 – Benthic survey sheet.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website

Site: **Date:**

Depth: **Transect:** **Surveyor:**

Notes:

ACC	Acropora cervicornis
ACP	Acropora palmata
ACPR	Acropora prolifera
AG	Agaricia spp.
AGA	Agaricia agaricites
AGF	Agaricia fragilis
AGG	Agaricia grahamae
AGH	Agaricia humilis
AGL	Agaricia lamarcki
AGT	Agaricia tenuifolia
AGU	Agaricia undata
ART	Articulated CA
CCA	Crustose coralline algae
CLA	Cladocora arbuscula
CON	Colpophyllia natans
CY	Cyanobacteria
DC	Dead coral
DNC	Dendrogyra cylindrus
DCS	Dichocoenia stokesii
DIL	Diploria labyrinthiformis
EUF	Eusmilia fastigiata
FVF	Favia fragum
HA	Halimeda
HCB	Hard coral (branched)
HCE	Hard coral (encrusting)
HCM	Hard coral (massive)
HCP	Hard coral (plate/foliose)
HLC	Helioseris cucullata
ISR	Isophyllia rigida
ISS	Isophyllia sinuosa
LSP	Limestone pavement
MAC	Macroalgae
MCCA	Macroalgae w/CCA
MD	Madracis spp.
MDA	Madracis asperula
MDAU	Madracis auretenra
MDC	Madracis carmabi
MDD	Madracis decactis
MDF	Madracis formosa
MDP	Madracis pharensis
MDS	Madracis senaria
MAE	Manicina areolata
ME	Meandrina spp.
MED	Meandrina danae
MEM	Meandrina meandrites
MIA	Millepora alcicornis
MIC	Millepora complanata
MIS	Millepora striata
MISQ	Millepora squarrosa
MOC	Montastraea cavernosa
MUA	Mussa angulosa
MY	Mycetophyllia spp.
MYA	Mycetophyllia aliciae
MYD	Mycetophyllia danae
MYF	Mycetophyllia ferox
MYL	Mycetophyllia lamarckiana
MYR	Mycetophyllia reesi
OCD	Oculina diffusa
ORA	Orbicella annularis
ORF	Orbicella faveolata
ORFR	Orbicella franksi
OCE	Other calcareous encrusters
OTH	Other
PEY	Peysonellid
POA	Porites astreoides
POB	Porites branneri
POC	Porites colonensis
POD	Porites divaricata
POF	Porites furcata
POP	Porites porites
PSC	Pseudodiploria clivosa
PSS	Pseudodiploria strigosa
RB	Rubble
RCK	Rock
SD	Sand
SCC	Scolymia cubensis
SCL	Scolymia lacera
SIR	Siderastrea radians
SIS	Siderastrea siderea
SOC	Soft coral
SOB	Solenastrea bournoni
SOH	Solenastrea hyades
SP	Sponge
STI	Stephanocoenia intersepta
SYR	Stylaster roseus
TF	Turf
TUC	Tubastraea coccinea

Appendix 2 – Urchin survey sheet.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website

Site: **Depth:** **Date:** **Surveyor:**

Transect No:

Test size

	0-20 mm	21-40 mm	41-60 mm	61-80 mm	81-100 mm
Diadema antillarum					
Echinometra lucunter					
Echinometra viridis					
Eucidaris tribuloides					
Other/notes					

Transect No:

Test size

	0-20 mm	21-40 mm	41-60 mm	61-80 mm	81-100 mm
Diadema antillarum					
Echinometra lucunter					
Echinometra viridis					
Eucidaris tribuloides					
Other/notes					

Transect No:

Test size

	0-20 mm	21-40 mm	41-60 mm	61-80 mm	81-100 mm
Diadema antillarum					
Echinometra lucunter					
Echinometra viridis					
Eucidaris tribuloides					
Other/notes					

Appendix 3 – Caribbean bioeroding urchins

Diadema antillarum

Echinometra viridis

Echinometra lucunter

Eucidaris tribuloides

Appendix 4 – Parrotfish survey sheet.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website

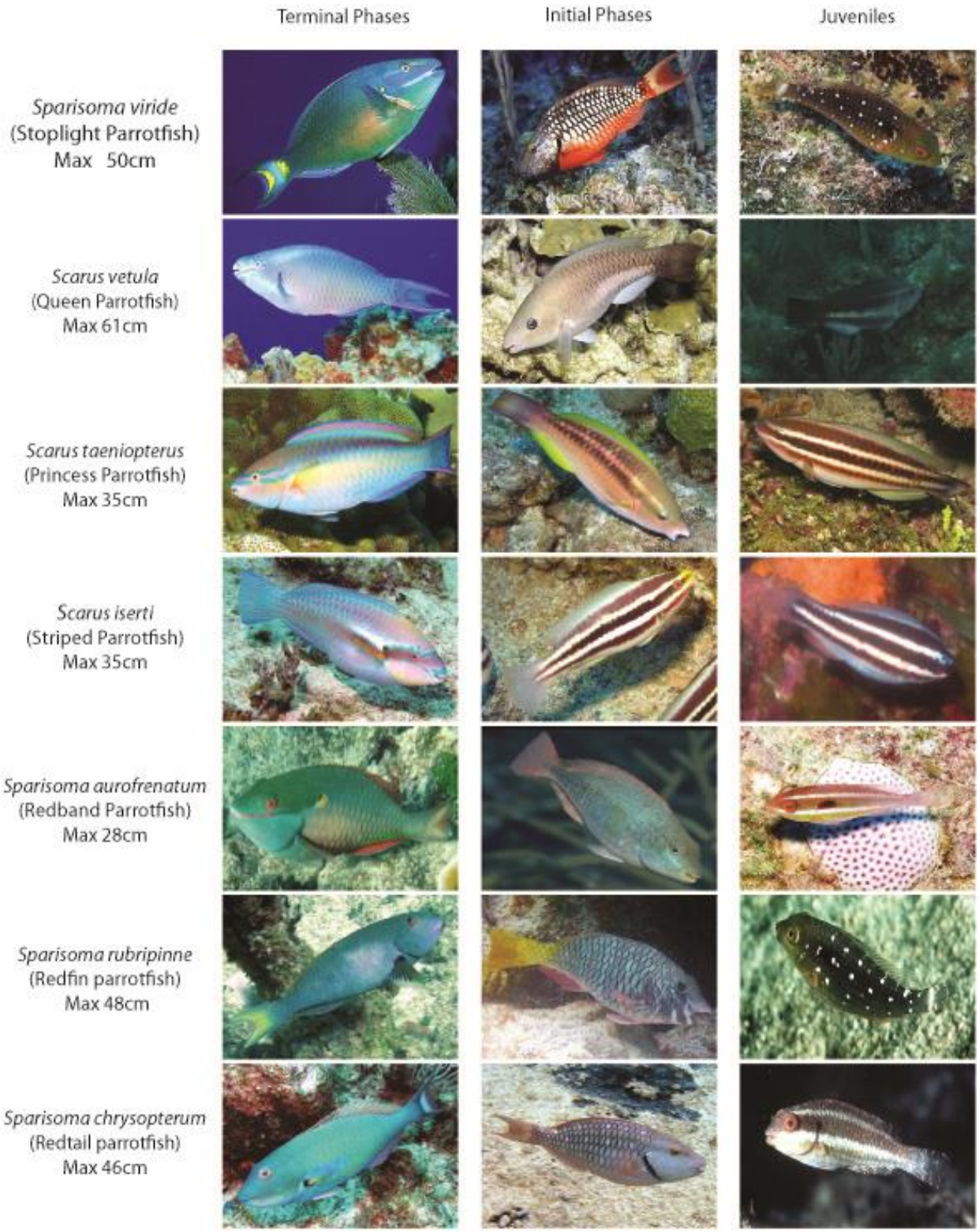
Site: ***Depth:*** ***Date:*** ***Surveyor:***

Transect No.	Juveniles	Initial Phase				Terminal Phase				
	0-9cm	10-19cm	20-29cm	30-39cm	40-49cm	10-19cm	20-29cm	30-39cm	40-49cm	50-59cm
Sp viride										
Sp aurofrenatum										
Sp rubripinne										
Sp chrysopterum										
Sc vetula										
Sc taeniopterus										
Sc iserti										
Sc guacamaia										
Sc coelestinus										
Sc coeruleus										

Transect No.	Juveniles	Initial Phase				Terminal Phase				
	0-9cm	10-19cm	20-29cm	30-39cm	40-49cm	10-19cm	20-29cm	30-39cm	40-49cm	50-59cm
Sp viride										
Sp aurofrenatum										
Sp rubripinne										
Sp chrysopterum										
Sc vetula										
Sc taeniopterus										
Sc iserti										
Sc guacamaia										
Sc coelestinus										
Sc coeruleus										

Appendix 5 – Parrotfish identification chart.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website



Appendix 6 – Boring sponge survey sheet.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website

Site: **Depth:** **Date:** **Surveyor:**

Transect No:

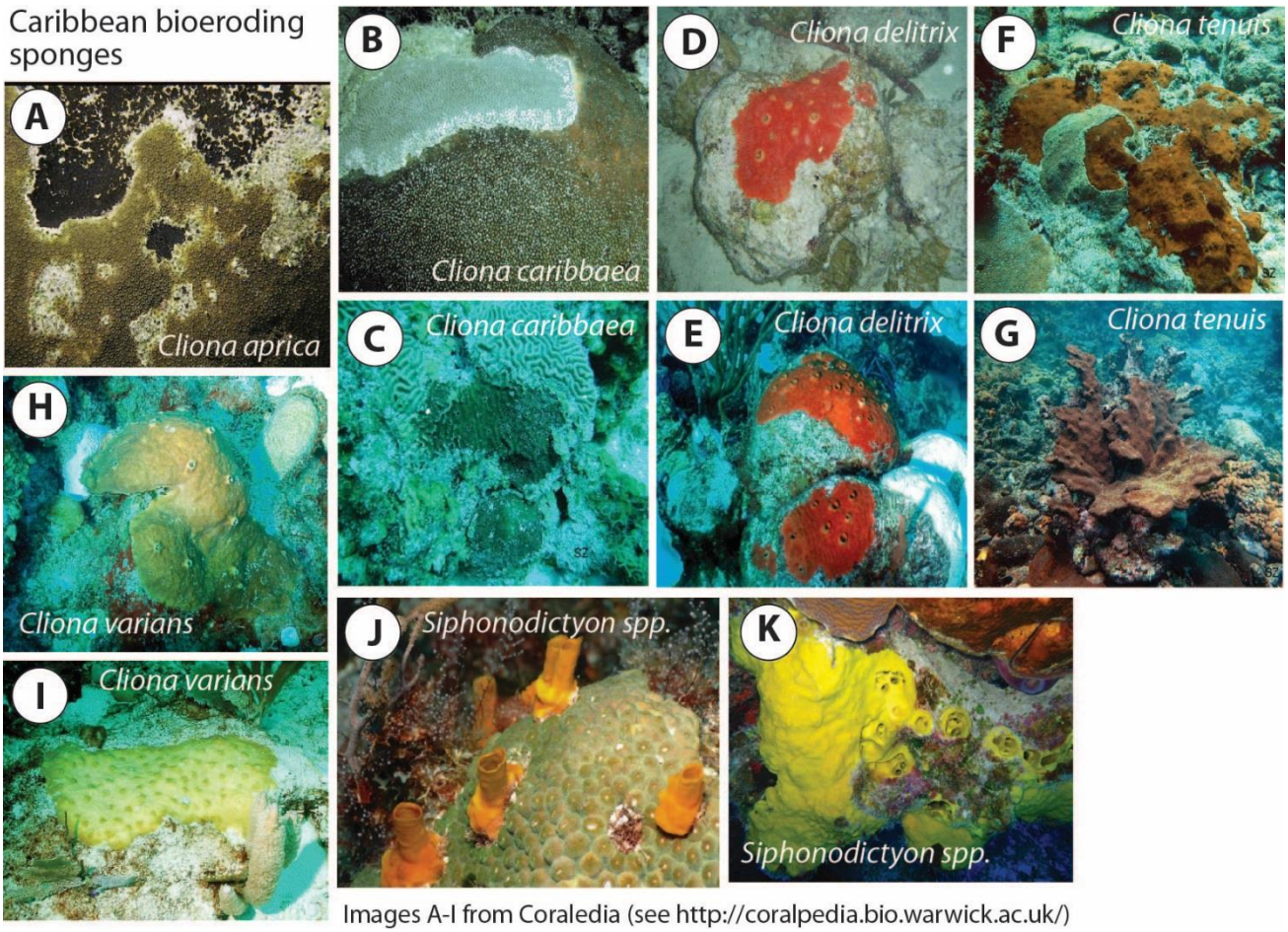
Species	Area cover (cm^2)	Total
Cliona aprica *Dark brown - fields of papillae, merging*		
Cliona caribbaea *Brown - continuous tissue*		
Cliona tenuis *Brown - very thin, almost transparent layer of continuous tissue*		
Cliona varians *Brown, osculae light yellow - thick continuous tissue or free-living sponge*		
Cliona delitrix *Dark orange to bright red - continuous, knobbly tissue, large fleshy exhalents*		
Siphonodictyon spp. *Yellow - fleshy chimneys, often from live coral*		
Other		

Transect No:

Species	Area cover (cm^2)	Total
Cliona aprica *Dark brown - fields of papillae, merging*		
Cliona caribbaea *Brown - continuous tissue*		
Cliona tenuis *Brown - very thin, almost transparent layer of continuous tissue*		
Cliona varians *Brown, osculae light yellow - thick continuous tissue or free-living sponge*		
Cliona delitrix *Dark orange to bright red - continuous, knobbly tissue, large fleshy exhalents*		
Siphonodictyon spp. *Yellow - fleshy chimneys, often from live coral*		
Other		

Appendix 7 – Boring sponge identification chart.

NB. Copies can be downloaded in .jpg format from the *ReefBudget* website



Images A-I from Coraledia (see http://coralpedia.bio.warwick.ac.uk/)