ReefBudget: Methodology

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1. Census-based approaches to quantifying reef carbonate production

The determination of calcium carbonate budgets on coral reefs, using census-based approaches, provides an opportunity to quantify the relative contributions made by different producer/eroder groups to net biologically-derived reef carbonate production. Using data on organism cover and abundance, alongside annual extension or production rates, and estimates of the rates at which other organisms erode reef framework components, net carbonate production rates (kg $CaCO_3$ m^{-2} yr^{-1}) can be determined. This can be done either for specific habitat zones or depth ranges, or extrapolated to larger spatial scales based on measured/mapped surface areas of different reef environments (kg $CaCO_3$ per habitat yr^{-1}). Delineating reef zones is clearly important because different zones have very different environmental characteristics and biological communities. Thus coral reef surveys for carbonate budgets need to survey each zone independently, or to use a methodology which takes this zonation into account.

The carbonate budget protocol recommended here (termed *ReefBudget*) aims to allow quantification of the carbonate budget status of different habitats or zones within individual coral reef systems. The focus, following the *framework production states* approach of Perry et al. (2008), is on quantifying net rates of biologically-derived reef framework production, encompassing estimates of carbonate production by corals and calcareous encrusters (usually dominated by crustose coralline algae), and framework erosion by internal borers and substrate grazers. These can provide a measure of the functional performance of a reef in terms of the rates of primary framework production. Although clearly important in many systems and a volumetrically important aspect of the accumulating reef structure, sediment production *per se* is not quantified in this methodology. However, additional site specific observations on the abundance of detrital sediments in the areas under study, and on the composition of such sediments can be readily incorporated, providing important data on framework accretionary characteristics and carbonate sediment production regimes.

Key points:

- The recommended methodology arises from field-based testing programmes undertaken during 2010 and 2011 at sites in The Bahamas and in Bonaire, and have been selected based on considerations of accuracy, ease and speed of use, and because of their non-reliance on expensive, high-tech equipment.
- At present the protocol (and supporting on-line database and data entry spreadsheets) has an entirely Caribbean focus, but the approaches recommended here have potential to be extrapolated to Indo-Pacific sites where suitable data exists.
- The methods can be applied to any reef site and depth zone, but considerations of regional variations in calcification rates etc, and of variations with depth need to be made as considered appropriate.
- Data should be collected along transects orientated parallel to the reef or along discrete depth contours within the reef zones that are of interest.

2. Site Selection and transect placement

Within each depth zone both process and ecological data should be collected from along replicate transects, with the following points relevant to ensure consistency in methodologies between sites.

- At each survey depth six fixed 10 m transects should be established – these are used as the ‘master’ survey lines along which all subsequent data (with the exception of fish abundance data) are collected.
- Each transect should ideally be established either along depth contours parallel to the orientation of the reef front (spaced a minimum of 10 m apart) or along discrete (depth consistent) reef structures (e.g., spurs) as deemed most appropriate to the site.
- Transects should be placed approximately 10 m apart.

- Each transect should be marked at the start and end with a fixed marker pin. This not only allows measurements along exactly the same transect line to be made over sequential field days (if needed) but also provides, if permanent markers can be placed, 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.
- The use of 0.5 m long stainless steel or rigid plastic stakes (star picket or Y-shaped pickets) is recommended (Fig. 1A). These should be marked to record transect numbers (the use of engraved acrylic tags is recommended where permanent markers are deployed; see Fig. 1B).
- Each measuring tape used should have a 50 cm length of 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 (Figs. 1C, D).
- The tape should be pulled taut between the two pegs and secured tightly.
- A map of the location and layout of transects relative to the gross reef structure should be produced to facilitate subsequent relocation of the transect points. This should include Global Positioning System co-ordinates of the transects where possible.

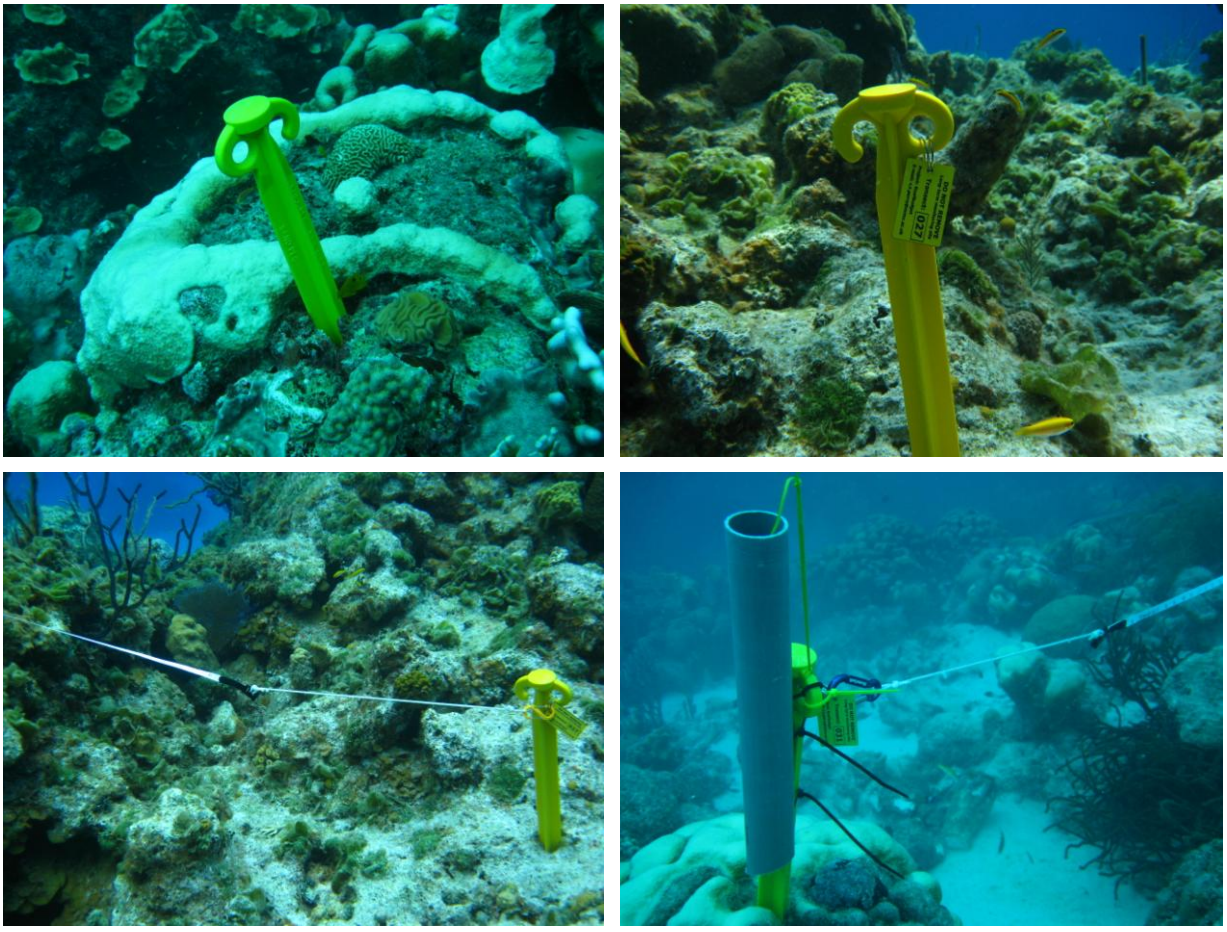


Fig. 1. *(A) Yellow sand peg marker stake in a dead coral head, (B) Marker stake with acrylic identification tag, (C) Survey tape attached to marker stake showing 50 cm long 'leader' cord from clip to main tape, (D) Marker stake with a pvc pipe attached which is acting as a recruitment substrate to determine local rates of calcareous encruster recruitment and carbonate production.*

3. General site characterisation

In order to provide a general characterisation of each study area the following data can usefully be collected in each study area/depth.

1. Data on the **ratio of coral reef framework to sediment** along the depth contour in question. This is most readily achieved by recording the total distance underlain by either sediment or reef framework along the entire depth contour being surveyed.
2. Estimates of **sediment thickness**. This is most readily achieved by probing pockets/veneers of the sediment accumulated on the reef as noted during the above framework:sediment ratio assessments.
3. Gross scale measures of **reef topographic complexity** – measured using a transect tape placed across the reef substrate surface, with water depth measured using a pressure sensor (accurate to +/-0.05 m) at 0.5 m horizontal intervals along the transect. Data can then be plotted to examine topographic features at each reef site, and the total distance of each survey compared to the linear distance between the start and end of the survey lines to estimate gross scale reef rugosity.

4. Determining rates of benthic carbonate production by corals and coralline algae

Quantifying the rates of carbonate production by corals and calcareous encrusters (principally by coralline algae) requires determination of the relative abundance or space occupied by each benthic component on the reefs surface. Such assessments are typically based on data derived from quadrats or transects, or a combination of the two. These methods yield a planar area for each organism or substrate type investigated, which is expressed as percent cover. However, because the surface of most reef's is strongly 3-dimensional (highly rugose), budget survey methodologies must take account of a reef's topographic complexity in order to determine the actual surface area covered by each organism. Most measures or estimates of substrate topographic complexity have been achieved by running a chain of known length (d1) over the substrate, conforming to the topography and measuring the planar distance covered by the chain (d2). Rugosity (topographic complexity) can then be determined as d1/d2 (Hubbard et. al., 1990; Harney and Fletcher 2003; Mallela and Perry 2007). This figure is then applied as a correction factor to individual transects or quadrats to derive a more accurate measure of the true surface area covered by the taxon in question.

4.1 Quantifying benthic cover

The *ReefBudget* method integrates the collection of both benthic cover data and surface rugosity data by using a modified version of the standard **linear intercept methodology**. Whilst the standard linear intercept method records benthic cover underneath a linear transect line, recording data for each 1 cm increment along the line as viewed from above (English et al. 1997; Ohlhorst et al. 1988), the *ReefBudget* methodology records benthic cover by recording information along every 1 cm increment but using a tape laid out to conform to the true surface profile of the reef (Fig. 2). This is most easily achieved by using a 1 m long flexible tape with the cumulative distance of each benthic component (see below) noted within each linear 1 m of the transect. Total surface distance for each linear 1 m of reef can then be calculated and the substrate rugosity is automatically calculated in the data input sheets. Although this methodology is typically more time consuming than the standard method (especially in high rugosity reef zones) it provides far more accurate data on the actual surface area covered by each benthic component on the reef and ensures that the benthic cover on more cryptic surfaces is integrated into the budget measures. The complimentary collection of **swath-type video footage** or **sequential photographs** along each transect is recommended in order to provide a record of substrate characteristics and information on gross transect morphology.

For the purposes of framework budget determinations there is a key requirement to quantify the abundance of corals and calcareous encrusters as framework carbonate producers, but the collection of abundance data on other (non-carbonate producing) groups can be readily incorporated and can provide a context for understanding resultant budgetary data (for example in relation to sites that have undergone transitions to states of high macroalgal abundance). In this context we recommend that data on the following groups be collected from along each transect:

- Coral (to species level where possible[1] or at least to morphological group)
- Crustose coralline algae (CCA) and other calcareous encrusters[2]
- Turf % cover
- Macroalgal % cover[2]
- Calcareous algae (*Halimeda sp.* etc)
- Sediment
- Rubble

NB – Survey codes for groups/species are given on the *ReefBudget* survey sheets (Appendix 1) and can be downloaded from the *ReefBudget* website.

[1] The online coral id programme *Coralpedia* (http://coralpedia.bio.warwick.ac.uk/) is recommended as an excellent image library for Caribbean corals.

[2] Areas of macroalgal cover should be investigated to examine where there is living CCA under the algal canopy. In these cases a mixed classification is recorded so that the most accurate assessments of CCA cover/production or macroalgal cover (if needed) can be obtained.

i.e., MAC – only macroalgae
CCA – only crustose coralline algae
MCCA – macroalgae with living crustose coralline algal crust beneath

Benthic Surveys - Recommended field methodology

(1) Lay out 10 m master transect line – pull taut and fix to a second marker stake at the end of the transect line as described above (Figs. 2 A, B).

(2) Measure the surface distance (cm's) covered by each benthic component beneath the master tape within each linear 1 m of the 10 m survey transect (Figs. 2C-E). Use of a short (0.5–1 m) length of flexible tape that can be laid out to conform to the exact surface profile of the reef is recommended (Fig. 2D, E). Care should be taken to include measures of the surface cover within all cracks and crevices along the linear transect.
NB.1 – Where the transect crosses areas of complex living coral cover (e.g., branching corals) the methodology is most effective if as reliable an estimate as possible is made of the distance covered by living tissue directly beneath the linear transect.
NB. 2 – In contrast to some benthic surveys the distance covered by sand <u>should</u> be included in the measures made.
NB. 3 – Note comments above about checking and recording macroalgal/CCA cover.

(3) Record data on survey sheets (Fig. 2F) provided (or similar) using recommended taxa specific codes (see copy of survey sheet in Appendix 1). It is important that the <u>correct coding system</u> is followed as these need to be consistent for the accompanying Excel spreadsheets to work effectively. A line should be drawn to delineate the break between each sequential linear 1 m of data recorded.

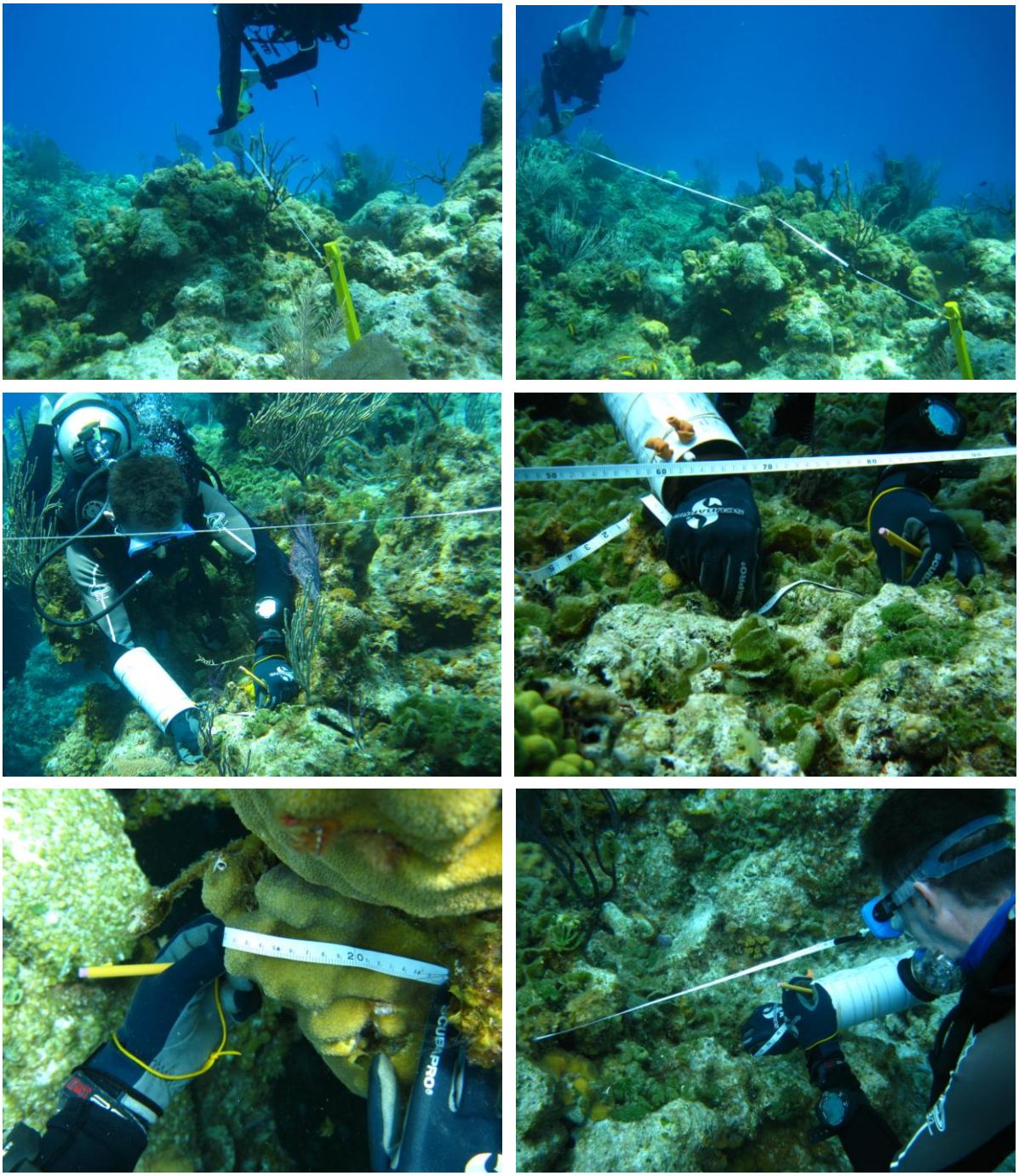


Fig. 2 *(A, B) Master transect line, attached to a fixed marker stake, being laid out; (C) Diver recording the linear distance cover by each benthic component on the substrate immediately beneath the main 10 m transect line; (D, E) Care should be taken to ensure that the flexible substrate measuring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

Calculating carbonate production rates based on benthic cover and rugosity.

In order to derive accurate estimates of carbonate production, the density ($g.cm^{-3}$) of the particular primary (coral) or secondary producer (coralline algae and other calcareous encrusters) in question, needs to be combined with measures of the linear growth rate ($cm.year^{-1}$) and mean percent cover of that organism within the area in question. These data can then be combined with rugosity measures to yield a value for carbonate production relative to the actual

surface area of the reef. The following equation then yields a production rate in kg $CaCO_3$ m^{-2} yr^{-1} for each species. This can then be used to calculate that organism's contribution to the carbonate accretion rate of a given area or zone of a coral reef.

$$\text{Carbonate production rate} = R_z \times ((X_i / 100) \times ((D_i \times Gi \times 10{,}000)/1000))$$

Where,

X_i = mean percent cover of the $_i$th species
D_i = density ($g.cm^{-3}$) of the $_i$th species
G_i = growth rate ($cm.year^{-1}$) of the $_i$th species
Rz = rugosity for the zone (or transect)

The values calculated for each species are then summed to yield a carbonate production value within an individual reef zone. If estimates of carbonate production are required for the wider coral reef system under study, production rates per unit area can, necessarily, be scaled based on knowledge of the area taken up by each zone within the reef for which budget data has been calculated.

4.2.1 Coral growth 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 as it requires significant amounts of new coral sampling and analysis. Undertaking such studies is, in the current era of generally low coral cover, difficult to justify and to resource. Where this is not feasible, a logical alternative is to make use of available published data from sites (and water depths) as proximal and comparable as possible to those under study. To this end an online resource (see *ReefBudget* website) has been developed that includes available coral growth and skeletal density data for the Caribbean. This allows, where possible, same species data (or at the very least same coral morphological group data) to be used from comparable water depths. Analysis of available data on the growth rates of a range of common Caribbean coral species against depth (see Appendix 8) indicate that there is sufficient consistency across the region that the use of regionally averaged growth rate data can be used as a suitable proxy for production rate estimates where more local datasets do not exist.

The data entry sheets 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 within each linear meter of each transect should be input on the 'Data Entry' tab (Fig. 3), from which % cover and production rates for each transect (see Fig. 4), and total carbonate production rate for the site are calculated (see Fig. 5). The spreadsheets have been pre-set to use regional average rates of linear extension and skeletal density for the species in question (or from the nearest morphologically and ecologically similar species where no published measures exist). These figures can be manually modified in the 'Calcification Rates' tab if more regionally (or depth) specific data are available (or preferred) – see *ReefBudget* website for database of available published data.

NB. If you are aware of relevant data that does not appear here please forward such information to Chris Perry (E-mail: c.perry@exeter.ac.uk)

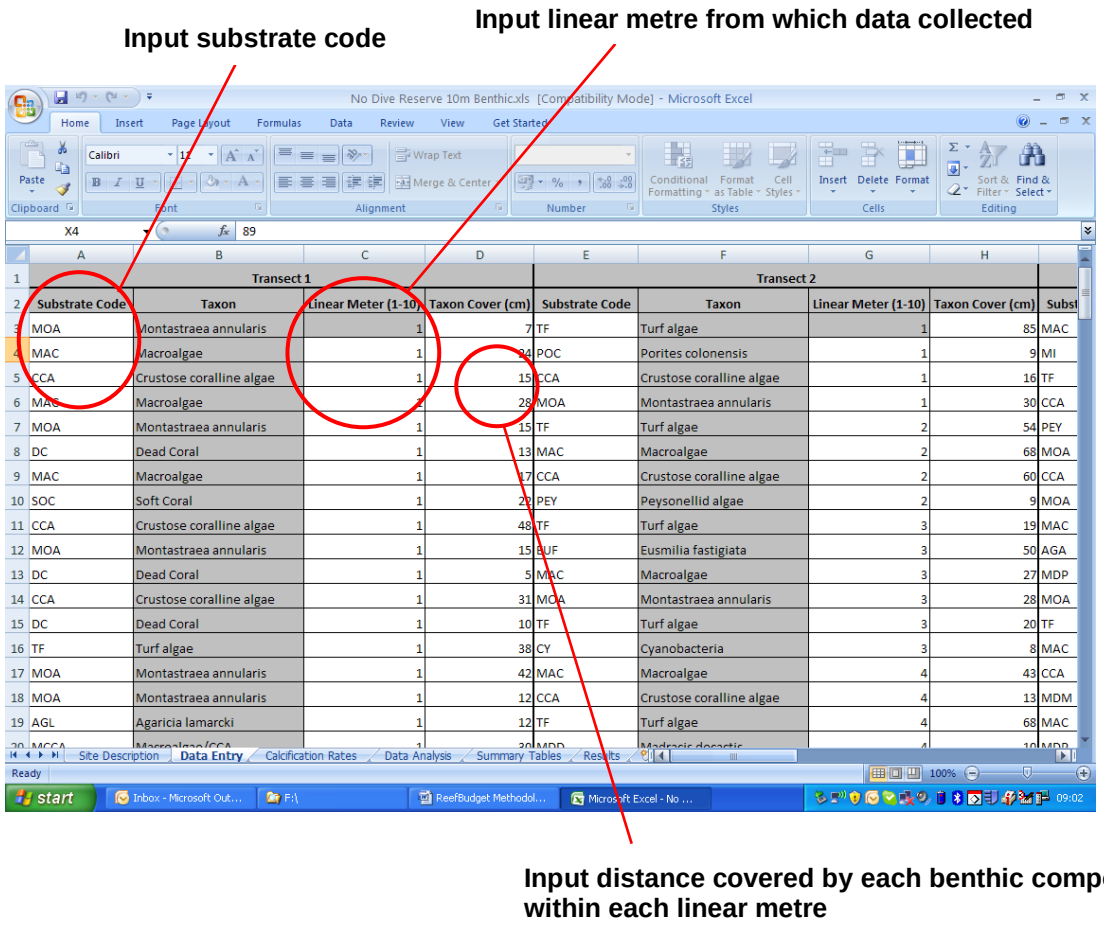


Fig. 3. *Screen grab showing main 'Data Entry' form for benthic community data. Data input for each transect is required in the white columns as indicated.*

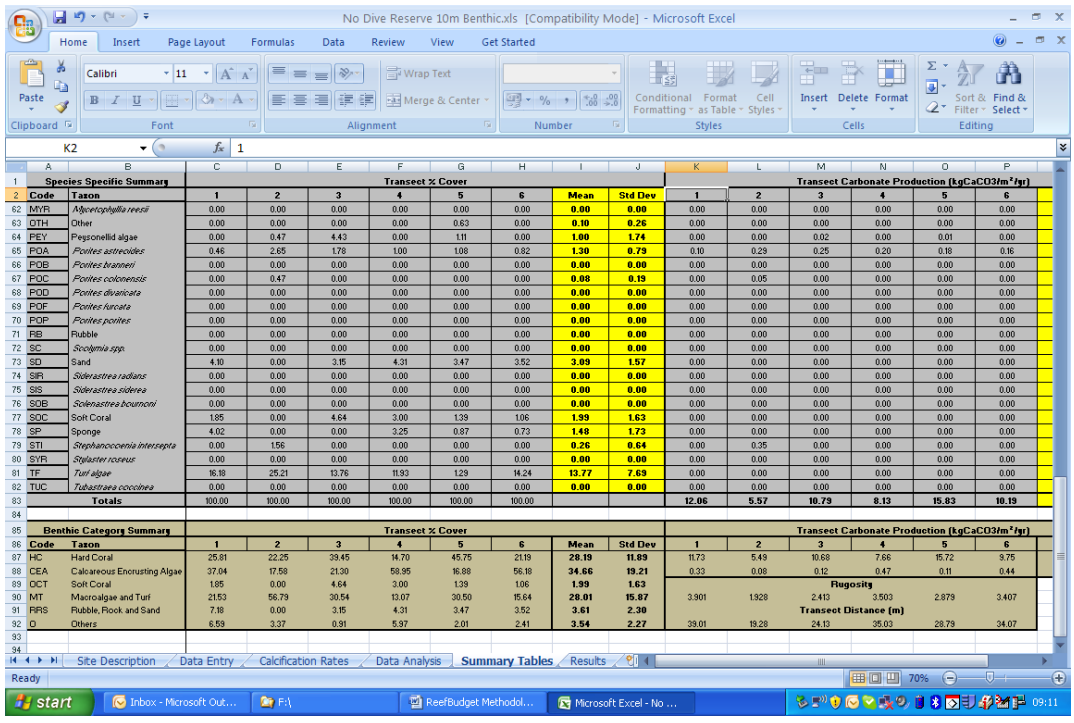
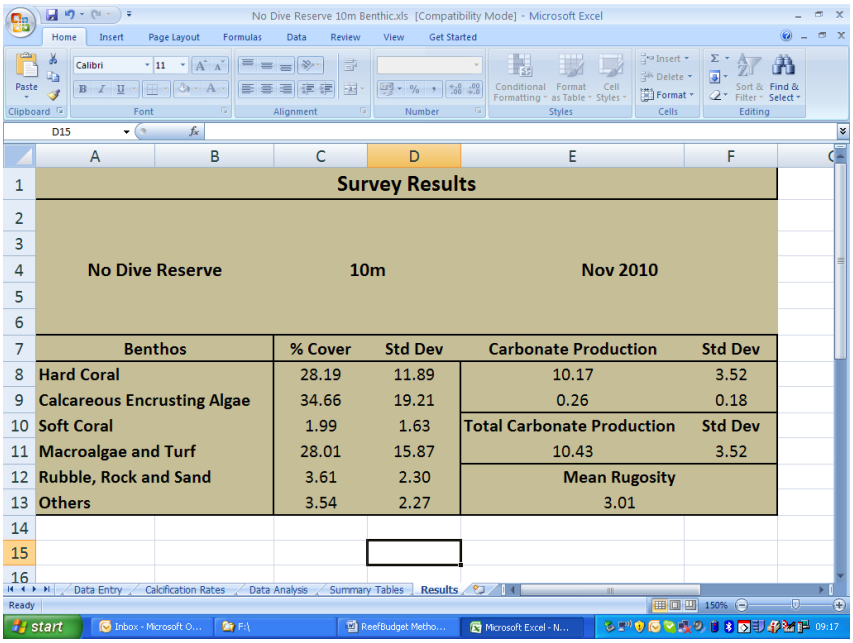


Fig. 4 . *Screen grab showing 'Summary Tables' tab for benthic community data. This provides a summary of % benthic cover and carbonate production along each transect.*



	A	B	C	D	E	F
1			Survey Results			
2						
3						
4		No Dive Reserve		10m	Nov 2010	
5						
6						
7		Benthos	% Cover	Std Dev	Carbonate Production	Std Dev
8		Hard Coral	28.19	11.89	10.17	3.52
9		Calcareous Encrusting Algae	34.66	19.21	0.26	0.18
10		Soft Coral	1.99	1.63	Total Carbonate Production	Std Dev
11		Macroalgae and Turf	28.01	15.87	10.43	3.52
12		Rubble, Rock and Sand	3.61	2.30	Mean Rugosity	
13		Others	3.54	2.27	3.01	
14						
15						
16						

Fig. 5. *Screen grab showing the 'Results' tab for benthic community data. This provides a summary of % cover for the entire depth zone under study and mean carbonate production rates (kg/m^2/yr) by hard corals and calcareous encrusters.*

4.2.2 Crustose coralline algal growth and density measures

Far fewer published data are available on crustose coralline algal (CCA) growth and density rates, making quantitative estimates of rates of CCA production less reliable. Available data are shown on the online resource (see *ReefBudget* website) and can be used to calculate a first order estimate of production rates. However, because of the paucity of existing data we recommend, where possible, the deployment of simple experimental substrates that can be left for 12-24 months in order to quantify rates of calcareous encruster growth per unit area within the study site in question. In such cases, we recommend the placement of sections of plastic pipe (pvc water pipe – approx 5-6 cm diameter) in the proximity of each transect line (n = 6 to 12 pipes per depth) emplaced such that ~20 cm of pipe is exposed above the framework-water interface (Fig. 6). Ideally, these pipes should be monitored to document CCA settlement and growth through being photographed every 3 months, and then retrieved after 12-24 months. Pipes should be retrieved only after a bag has been secured with cable ties over the upper part of the pipe. The upper 10 cm of the pipe is then initially examined for the 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% HCl and dividing by the surface area of the internal and external portions of the 10 cm length of pipe.

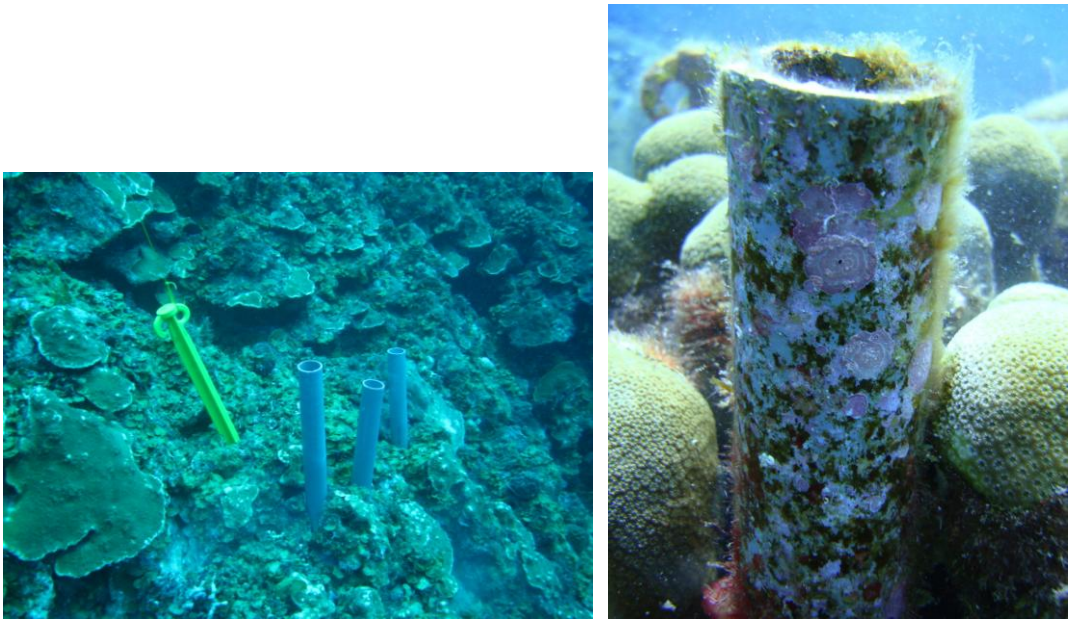


Fig. 6. *(A) An array of PVC settlement pipes placed in the reef framework with an adjacent marker stake. (B) PVC pipe after 3 months deployment in Bonaire – a colony of Titanoderma is visible in the centre.*

5. 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 get 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.

5.1 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 bioerosion rates derived from different studies around the world. However, an evaluation of published data on erosion rates against test size suggests a relatively tightly correlated plot regardless of urchin species. Figure 7A shows the aggregated data from fourteen studies that consider urchin bioerosion rates (by eight urchin species) relative to test size.

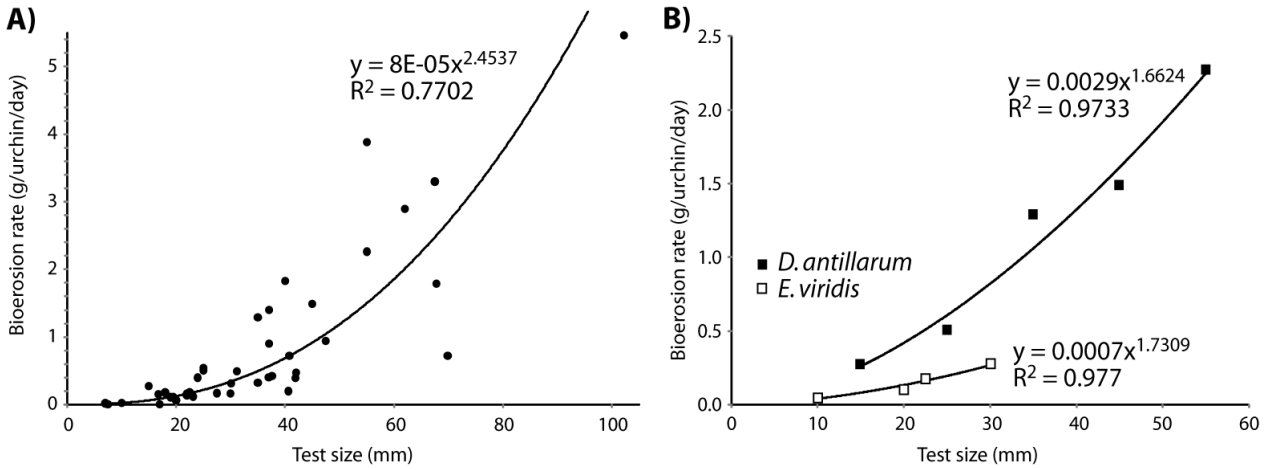


Fig. 7. *(A) Bioerosion rates (g/urchin/d^{-1}) for urchins of various test sizes (includes data from both Caribbean and Indo-Pacific sites). Data aggregated from: Russo (1980); Scoffin et al. (1980); Downing and El-Zahr (1987); McClanahan and Muthiga (1988); Bak (1990); Mokady et al. (1996); Conand et al. (1997); 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 adapted from Brown-Saracino et al. (2007) i.e. $CaCO_3$ gut content equations were used with a gut turnover rate of 14 hrs as recorded for Echinometra mathaei by Carreiro-Silva and McClanahan (2001).*

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 0.77 and the regression equation is:

$$\text{Bioerosion rate (g/urchin/day)} = 8*10^{-5}.x^{2.4537}$$

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. 7B 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. It should be noted that three of the points used for *E. viridis* were calculated from equations in Brown-Saracino et al. (2007) and contribute to the high correlation (r^2 = 0.977). 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, as follows:

D. antillarum - Bioerosion rate (g/urchin/day) = $0.0029x^{1.6624}$

Echinometra - Bioerosion rate (g/urchin/day) = $0.0007x^{1.7309}$

Other - Bioerosion rate (g/urchin/day) = $8*10^{-5}.x^{2.4537}$

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. 8A).
(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. 8B). 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. 8. *(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. 7A, 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. 9) can be downloaded from the *ReefBudget* website (see *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. 10). The 'Results' tab provides a mean rate of urchin erosion based on both sets of equations (Fig. 11). The figures used in these calculations can be manually modified in the spreadsheets if more regionally (or depth) specific data are available (or preferred).

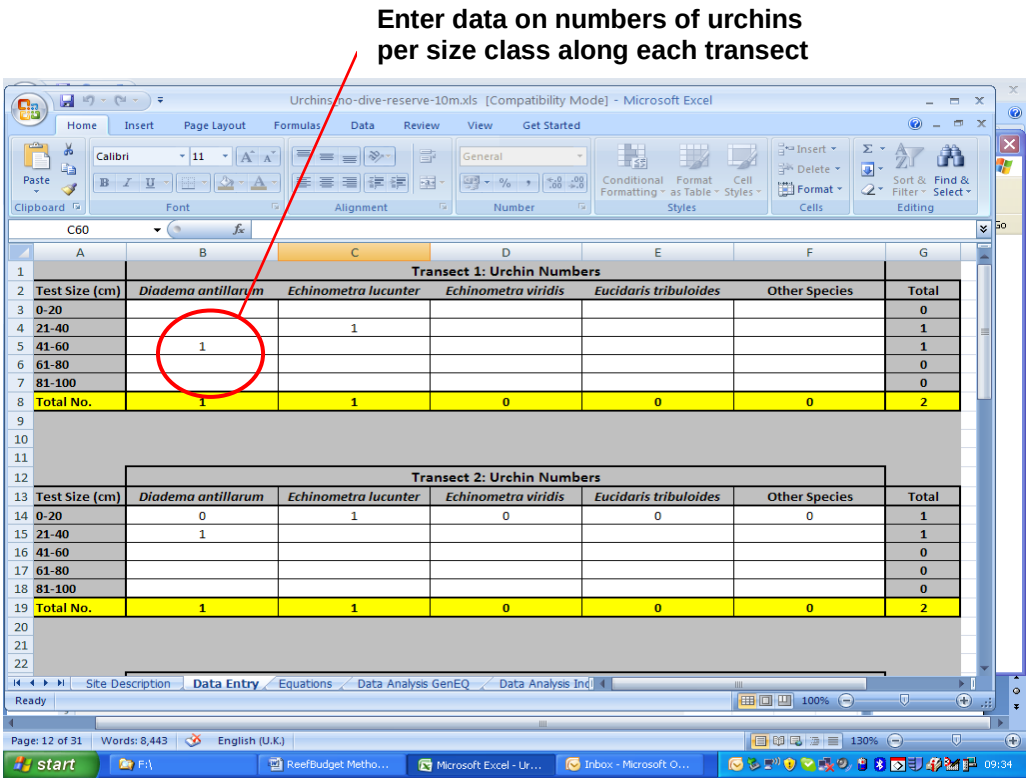


Fig. 9. *Screen grab showing main 'Data Entry' form for urchin data. Data input for each transect is required in the white columns as indicated.*

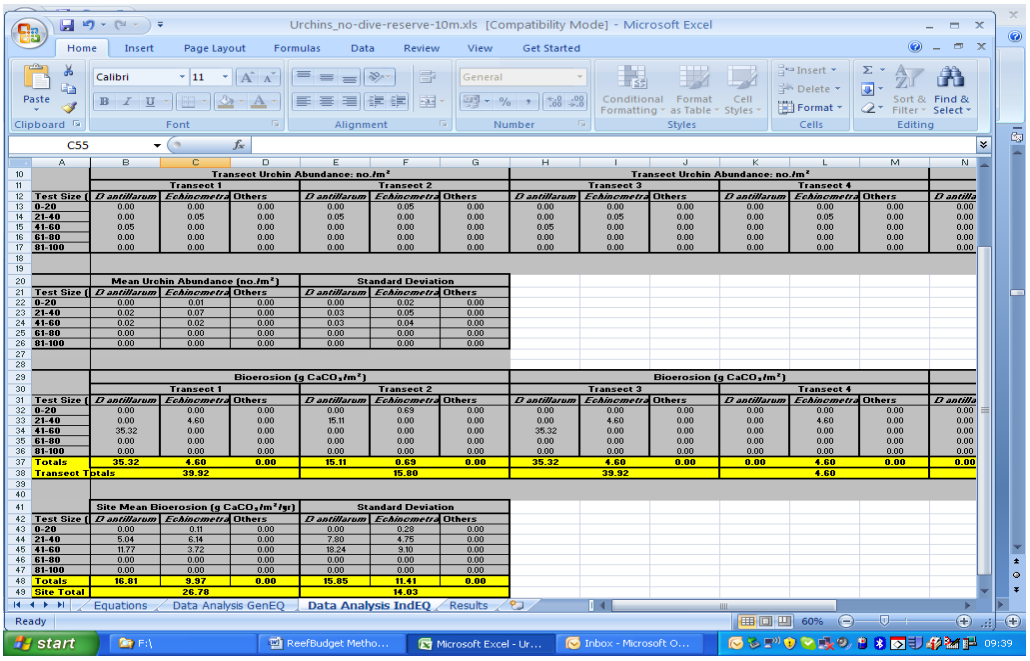


Fig. 10. *Screen grab showing main 'Data Analysis IndEQ' tab, which gives breakdown of urchin abundance and production rates for each transect (in this case using erosion rate equations for individual urchin species)*

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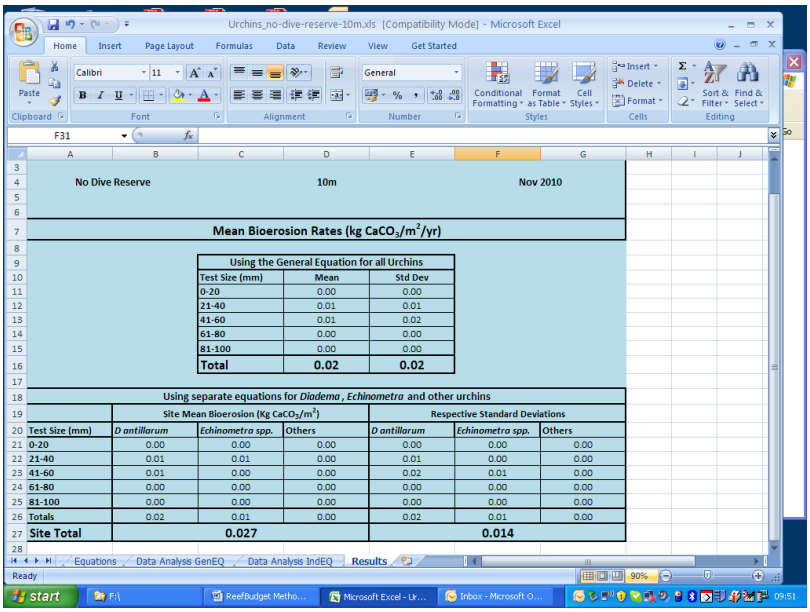


Fig. 11. *Screen grab showing the 'Results' tab for urchin erosion. This provides a summary of mean urchin erosion rates for the depth zone under study based on both general and individual species erosion rate equations.*

5.2 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. 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. 12).

(5) Parrotfish are recorded in the following size classes 5-14 cm, 15-24 cm, 25-34 cm, 35-44 and > 45 cm.

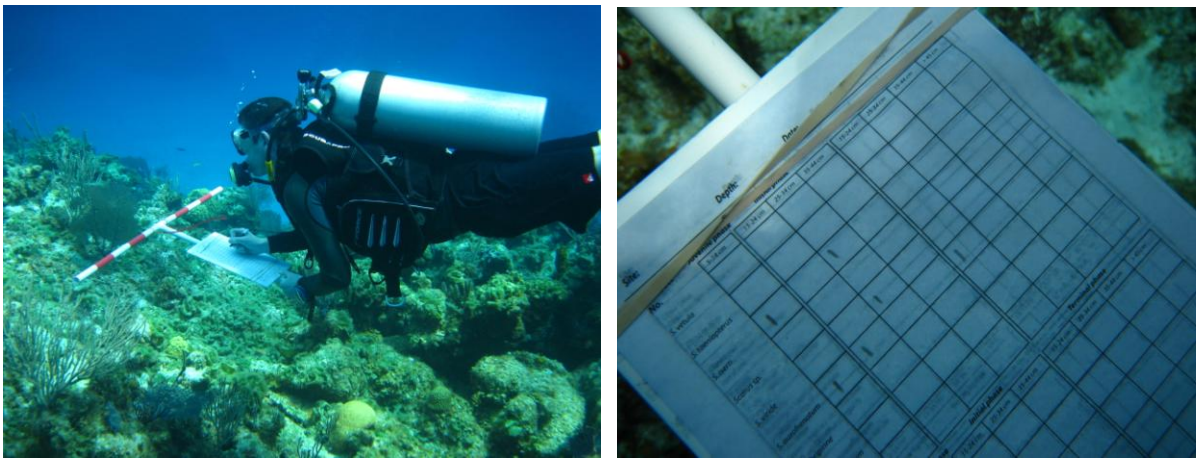


Fig. 12. *(A) Diver surveying for parrotfish with the aid of T-bar for size class classification; (B) Survey sheet on slate attached to T-bar for recording size class-abundance data.*

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 fork length to predict the bite rates (bites/hr) of two parrotfish species (*Sparisoma viride* and *Scarus vetula*) at different life phase stages (following Bruggemann et al. 1994a, b, c; 1996). It is assumed that the relationships between fork length and both bite rate and bite size can be extrapolated within genera (following Mumby et al. 2006). For each parrotfish species, life phase and size class, the rate of bioerosion per parrotfish per day (g) can then be established using the following equation:

Bioerosion Rate = Bite rate x % of bites leaving scars x mass eroded per bite

Details of the calculations, which incorporate a number of factors relating to daylight hours, feeding rates, bite size, life phase and species to bioerosion rates, are provided in Appendix 9. The complexity of the model is such that it may prove useful to investigate feeding rates at desired sites, thereby validating the bite rate equations, which were generated from data collected on coral reefs in Bonaire (Bruggemann et al. 1994b, c) and which have subsequently been tested in Roatan and the Exumas Cays (Mumby et al. 2006). Where this is deemed appropriate the following approach is recommended.

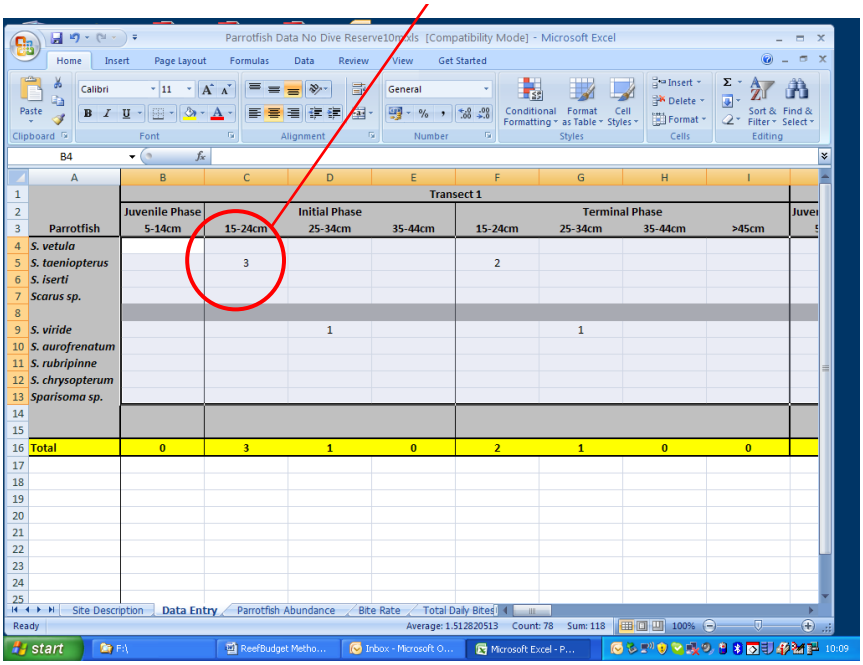
Recommended field methodology: Bite rate verification

In order to verify the accuracy of the model used to predict bite rates using parrotfish size (Mumby et al. 2006), it is necessary to investigate actual bite rates in the field. Individual fish are observed for 5 minute periods, recording their fork length, life phase, species and number of bites. If time is a factor, the most abundant species should be investigated first, prioritising the terminal phases as these will contribute most to bioerosion within the study area. Upon selecting a fish for observation, a period of acclimatisation is allowed (2 min) to ensure natural feeding behaviour. The observer should stay as far away from the fish as is possible whilst still allowing accurate data collection.

Alternative method: Bites rates can also be observed by assessing bites within 1 m^2 quadrats which are placed at random onto the substratum. Once the observer has noted the boundaries of the quadrat, the physical quadrat can be removed so that an unaltered 1 m^2 area of reef can be observed for 5 minutes. The observer waits as far from the area as is possible. Data is recorded after the observer has been away from the survey area for 2 minutes. The number of bites is recorded for each species, life phase and size class. A minimum of 15 quadrats should be observed at each depth.

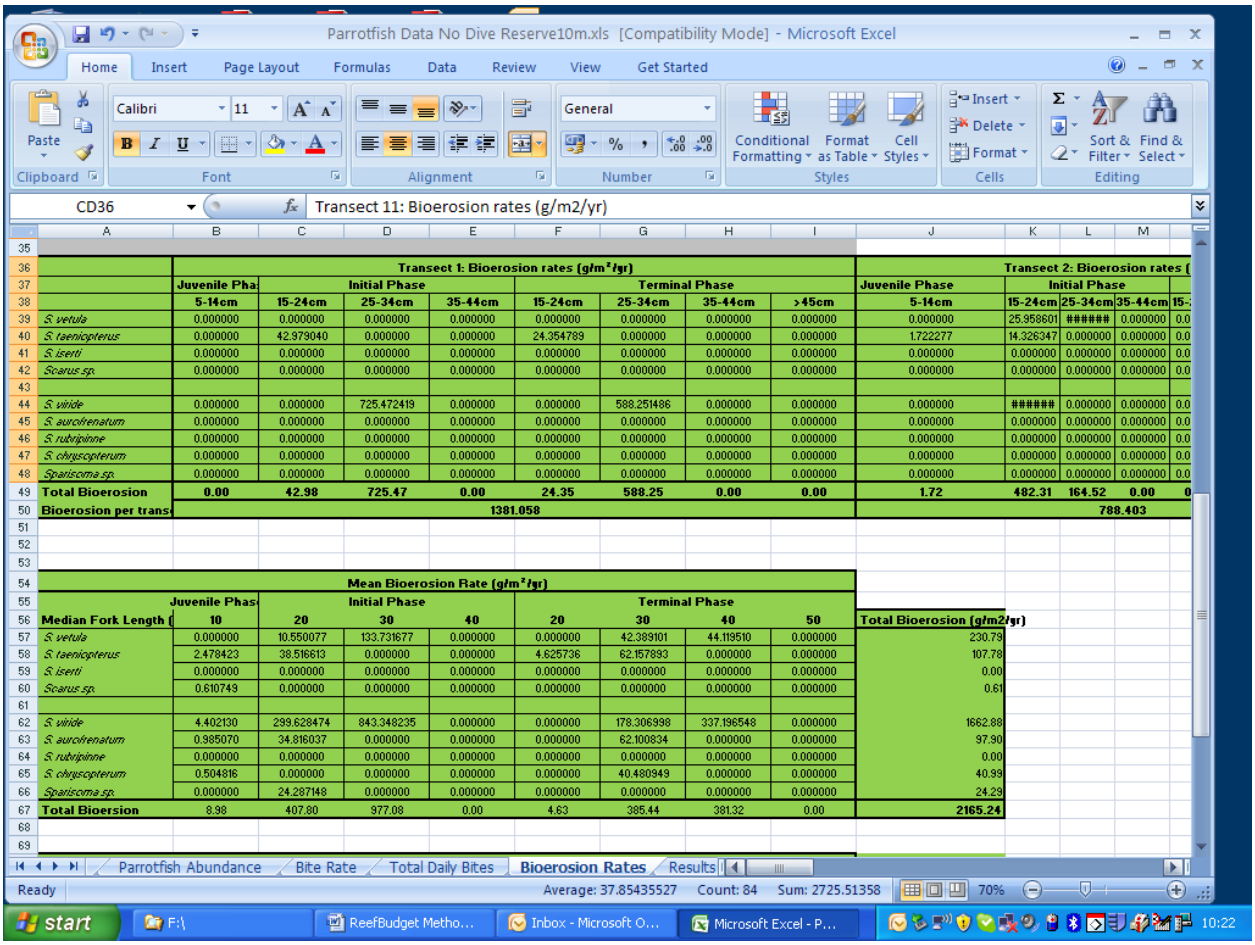
The data entry sheets provided can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted should be completed on the ‘Site Description’ tab. Field data on parrotfish species and size class are added on the ‘Data Entry’ tab (see Fig. 13). The ‘Bioerosion Rates’ tab provides a summary of bioerosion rates/species for each transect and of mean bioerosion rates for each species for the site (Fig. 14). The ‘Results’ tab (Fig. 15) provides a summary of total bioerosion for the site.

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



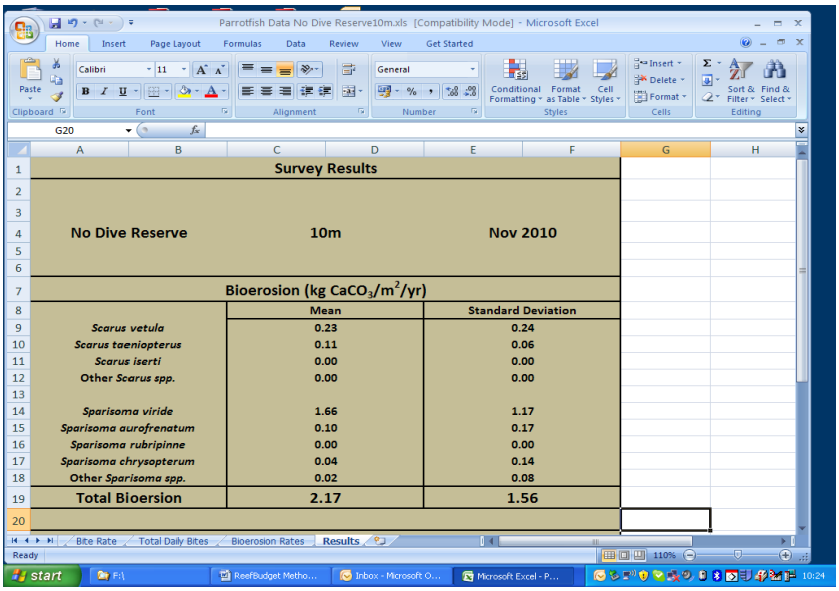
	A	B	C	D	E	F	G	H	I
1		Transect 1							
2		Juvenile Phase	Initial Phase			Terminal Phase			Juve
3	Parrotfish	5-14cm	15-24cm	25-34cm	35-44cm	15-24cm	25-34cm	35-44cm	>45cm
4	*S. vetula*								
5	*S. taeniopterus*		3			2			
6	*S. iserti*								
7	*Scarus sp.*								
8									
9	*S. viride*			1			1		
10	*S. aurofrenatum*								
11	*S. rubripinne*								
12	*S. chrysopterum*								
13	*Sparisoma sp.*								
14									
15									
16	Total	0	3	1	0	2	1	0	0

Fig. 13 *Screen grab showing 'Data entry' tab for parrotfish data. Data input is required in the columns as indicated.*



	A	B	C	D	E	F	G	H	I	J	K	L	M
35													
36		Transect 1: Bioerosion rates (g/m²/yr)								Transect 2: Bioerosion rates (			
37		Juvenile Pha	Initial Phase			Terminal Phase				Juvenile Phase	Initial Phase		
38		5-14cm	15-24cm	25-34cm	35-44cm	15-24cm	25-34cm	35-44cm	>45cm	5-14cm	15-24cm	25-34cm	35-44cm
39	*S. vetula*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	25.958601	######	0.000000
40	*S. taeniopterus*	0.000000	42.979040	0.000000	0.000000	24.354789	0.000000	0.000000	0.000000	1.722277	14.326347	0.000000	0.000000
41	*S. iserti*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
42	*Scarus sp.*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
43													
44	*S. viride*	0.000000	0.000000	725.472419	0.000000	0.000000	588.251486	0.000000	0.000000	0.000000	######	0.000000	0.000000
45	*S. aurofrenatum*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
46	*S. rubripinne*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
47	*S. chrysopterum*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
48	*Sparisoma sp.*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
49	**Total Bioerosion**	**0.00**	**42.98**	**725.47**	**0.00**	**24.35**	**588.25**	**0.00**	**0.00**	**1.72**	**482.31**	**164.52**	**0.00**
50	**Bioerosion per trans**	**1381.058**										**788.403**	
51													
52													
53													
54		Mean Bioerosion Rate (g/m²/yr)											
55		Juvenile Phas	Initial Phase			Terminal Phase							
56	**Median Fork Length (**	**10**	**20**	**30**	**40**	**20**	**30**	**40**	**50**	**Total Bioerosion (g/m2/yr)**			
57	*S. vetula*	0.000000	10.550077	133.731677	0.000000	0.000000	42.389101	44.119510	0.000000	230.79			
58	*S. taeniopterus*	2.478423	38.516613	0.000000	0.000000	4.625736	62.157893	0.000000	0.000000	107.78			
59	*S. iserti*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.00			
60	*Scarus sp.*	0.610749	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.61			
61													
62	*S. viride*	4.402130	299.628474	843.348235	0.000000	0.000000	178.306998	337.196548	0.000000	1662.88			
63	*S. aurofrenatum*	0.985070	34.816037	0.000000	0.000000	0.000000	62.100834	0.000000	0.000000	97.90			
64	*S. rubripinne*	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.00			
65	*S. chrysopterum*	0.504816	0.000000	0.000000	0.000000	0.000000	40.480949	0.000000	0.000000	40.99			
66	*Sparisoma sp.*	0.000000	24.287148	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	24.29			
67	**Total Bioersion**	8.98	407.80	977.08	0.00	4.63	385.44	381.32	0.00	**2165.24**			
68													
69													

Fig. 14. *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.*



Survey Results

No Dive Reserve	10m	Nov 2010

Bioerosion (kg $CaCO_3/m^2/yr$)

	Mean	Standard Deviation
Scarus vetula	0.23	0.24
Scarus taeniopterus	0.11	0.06
Scarus iserti	0.00	0.00
Other *Scarus spp.*	0.00	0.00
Sparisoma viride	1.66	1.17
Sparisoma aurofrenatum	0.10	0.17
Sparisoma rubripinne	0.00	0.00
Sparisoma chrysopterum	0.04	0.14
Other *Sparisoma spp.*	0.02	0.08
Total Bioersion	2.17	1.56

Fig. 15 *Screen grab showing the 'Results' tab for parrotfish erosion.*

5.3 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, 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.

ReefBudget currently only quantifies sponge bioerosion rates as a conservative estimate of total macrobioerosion within a site. To this end, the use of a new rapid in-situ assessment method, that directly builds upon the non-destructive sponge cover census methods of Ward-Paige et al. (2005), is recommended. To estimate rates of endolithic sponges bioerosion from this census data *ReefBudget* utilizes published datasets to derive a relationship between sponge tissue cover and bioerosion rate, an approach also discussed theoretically by Rose & Risk (1985) and Schönberg (2001), and recently employed to assess sponge bioerosion rates in the Adriatic (Calcinai et al. 2011). Specifically, published data is used to establish: i) the relationship between % surface area of sponge tissue/papillae cover, and the % volume of substrate removed by endolithic sponges (data in Rose & Risk (1985); Fig. 16A); and ii) the relationship between % volume of substrate removed by macroborers and bioerosion rate in kg $CaCO_3/m^2/yr$ (data in Scoffin et al. 1980; Tribollet and Golubic 2005; Chazotte et al. 1995; Fig. 16B). Using these data it is then possible to derive a relationships between % surface area of sponge papillae (as a function of volume removed) and bioerosion rate data (Scoffin et al. 1980; Tribollet and Golubic 2005; Chazotte et al. 1995), whereby bioerosion rate = % surface area of sponge tissue/papillae x 0.0231(Fig. 17).

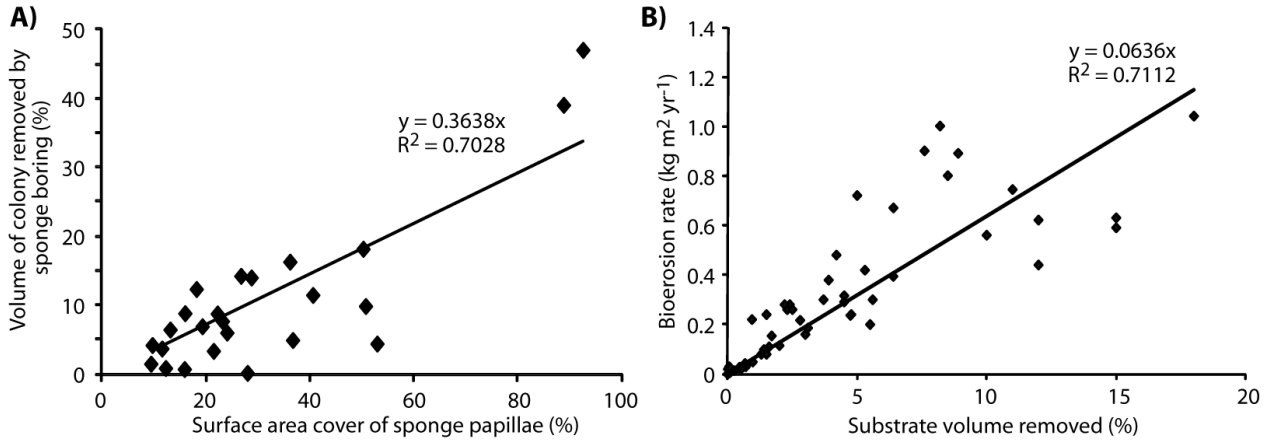


Fig. 16 *(A) Data from Rose & Risk (1985) showing the relationship between % surface area of sponge tissue/papillae and the % volume of coral colony removed by sponge boring. (B) Relationship between the % colony volume removed by borers and the rate of bioerosion (data from Scoffin et al. 1980, Chazottes et al. 1995, Tribollet and Golubic, 2005). Note: Additional data to expand the datasets that underpin this methodology are being collected on an on-going basis through ReefBudget and will be integrated within the online data entry sheets as they become available.*

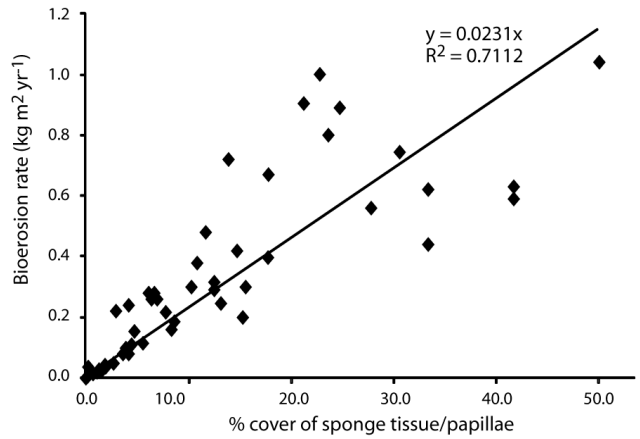


Fig. 17 *Plot showing the resultant relationship between % cover of sponge papillae/tissue and the rate of bioerosion.*

Thus it is possible to use census-based measures of sponge tissue cover to estimate rates of internal bioerosion. Estimates of worm and bivalve bioerosion are excluded in this analysis. However, given this is one of the less certain areas of the budget we advocate this approach as a suitably conservative measure of estimating endolithic macrobioerosion.

Internal 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) 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. 18A).
(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. 18B).

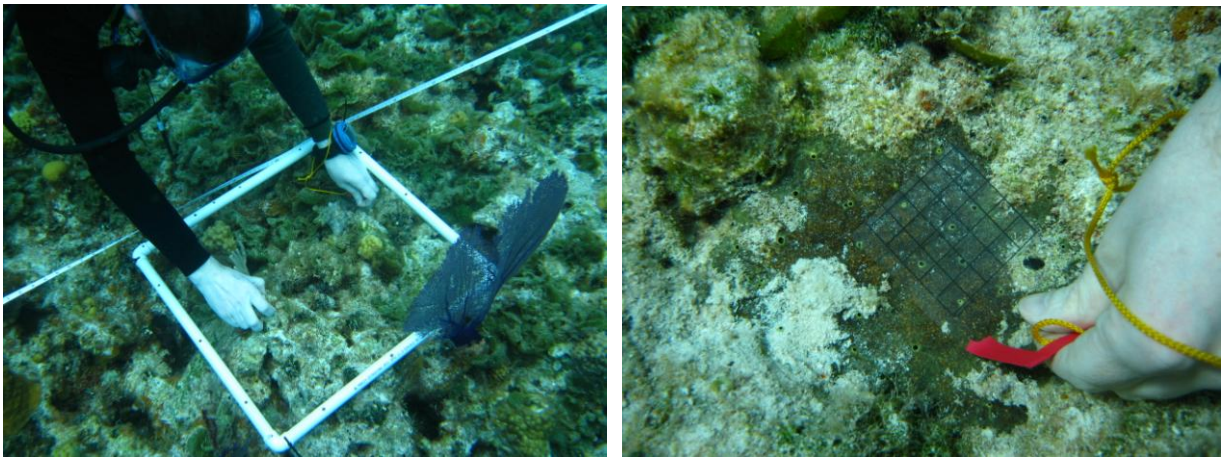


Fig. 18. *(A) Diver surveying for clionid sponge tissue with the aid of a transect to delineate the survey area; (B) Transparent sheet with printed 1 cm x 1 cm grid to allow quantification of the surface area (cm^2) of the reef covered by boring sponge tissue and papillae – in this case a colony of Cliona 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.

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 covered by sponge tissue then needs to be calculated as:

$$a/b \times 100$$

Where: a = surface area of sponge tissue (cm^2)
b = surface area of the belt transect (cm^2)

Based on the relationships previously established between the % surface area of sponge tissue cover and bioerosion rate, it is then possible to estimate the rate of endolithic sponge bioerosion based on % surface area of the reef covered by endolithic sponge tissue and papillae. This provides a non-destructive means of estimating sponge bioerosion rates.

The data entry sheets provided can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted should be completed on the 'Site Description' tab. Data on the area covered by each sponge species (cm^2) should be input using the 'Data Entry' tab (Fig. 20). The % sponge cover and the calculated rates of sponge bioerosion for each

transect are shown on the 'Data Analysis' tab (Fig. 21). The 'Results' tab (Fig. 22) shows the mean % sponge cover and mean bioerosion rate for the site.

Enter data on area (cm^2) occupied by each individual colony of each bioeroding sponge species along each transect line.

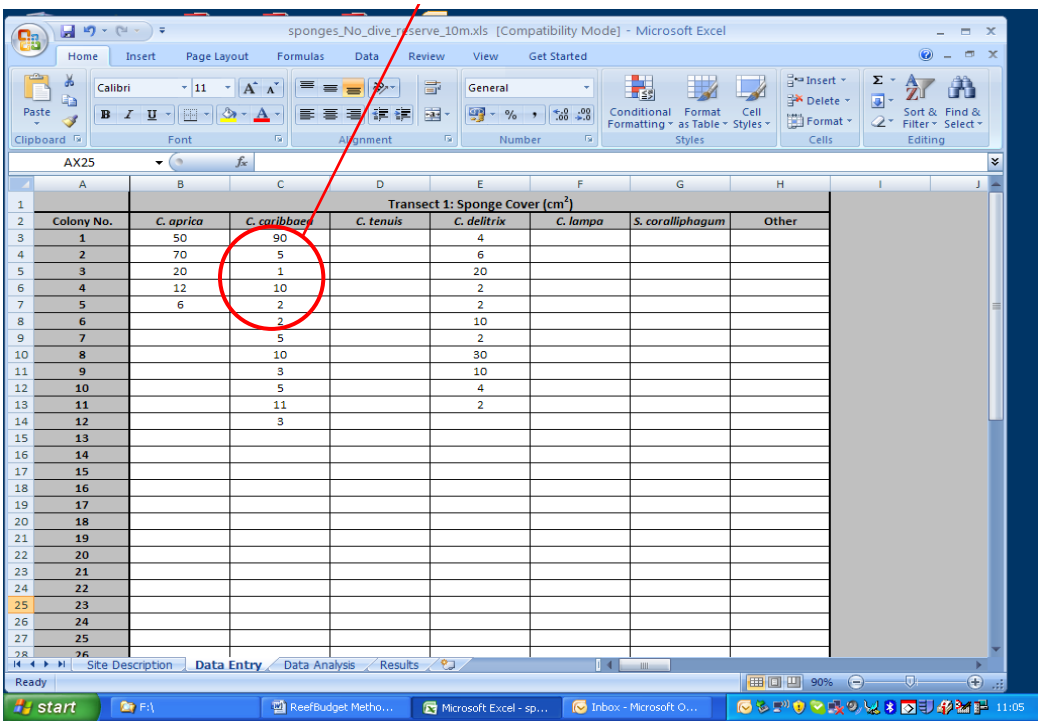


Fig. 19 *Screen grab showing the 'Data Entry' tab for the input of sponge tissue cover data.*

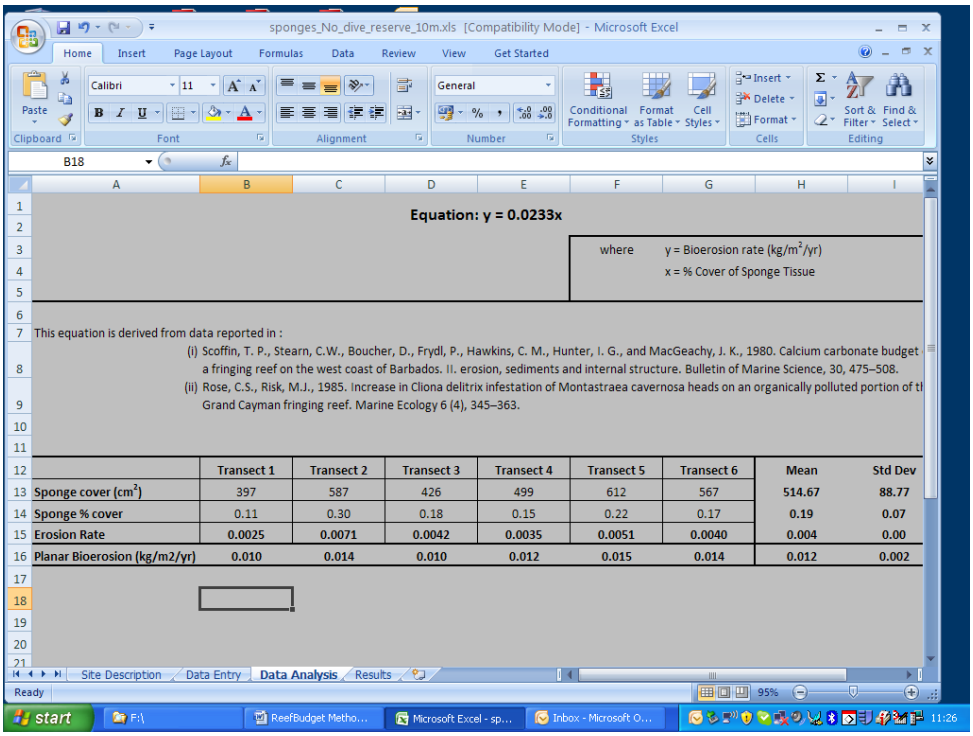


Fig. 20 *Screen grab showing the 'Data Analysis' tab which provides a breakdown of % sponge cover and bioerosion rates for each transect.*

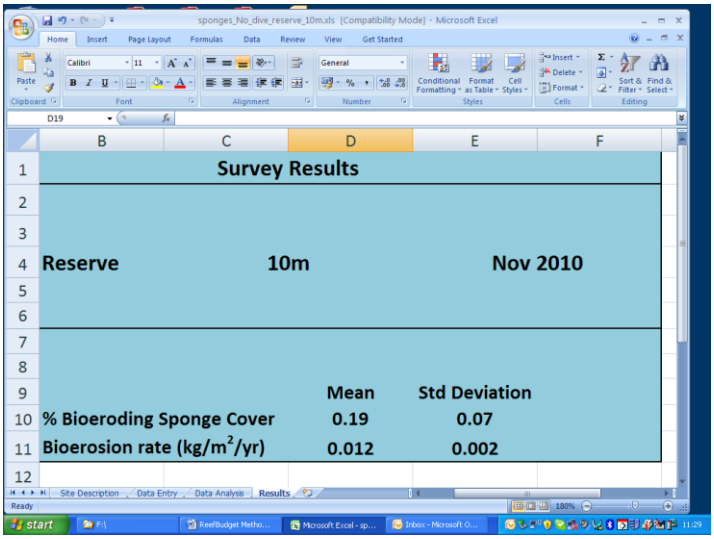


Fig. 21 *Screen garb showing 'Results' tab with mean % sponge cover and mean bioerosion for the site.*

5.4 Bioerosion by microborers (cyanobacteria, chlorophytes, fungi)

Carbonate substrate degradation by euendolithic microorganisms is associated with the activities of a range of photosynthetic cyanobacteria, chlorophytes and rhodophytes, and hetrotrophic fungi and bacteria (Golubic et al. 1975). Assessments of microbioerosion have relied heavily on the deployment of experimental substrates. Most studies have, however, simply used these to examine the bathymetric ranges of individual species, only a very few have used them to determine rates of microboring. Those rates that have been published are shown in Appendix 10. Although available data on this process is not extensive, it is questionable whether reef carbonate budgets can ignore the process entirely, since the published rates are often within the ranges calculated for macroborers.

Internal microbioerosion: Recommended field methodology

Due to the inherent difficulties in establishing microborer rates and until more extensive experimental data becomes available (especially for the Caribbean) we recommend that the following rates be applied:

Reef crest sites - 0.1 kg $CaCO_3/m^2/yr$ (based on data collected after 12 and 24 months deployment by Chazottes et al. 1995; 2002).
Fore-reef sites – 0.3 kg $CaCO_3/m^2/yr$ (derived from data collected after 36 months deployment as an average of data from various sites across the Great Barrier Reef determined by Tribollet & Golubic (2005).

These rates should be applied to all areas of reef substrate within each reef zone (excluding sand and rubble).

The data entry sheets provided can be downloaded from the *ReefBudget* website. General site data and details of the transects conducted should be completed on the 'Site Description' tab. Data on the calculated rates of microbioerosion, as a function of the surface area of available substrate on each transect, are shown for either 'shallow' or 'deeper' fore reef sites on the respective spreadsheet tabs (Fig. 22). These provide both an estimate of microbioerosion for each transect and the mean for the study site.

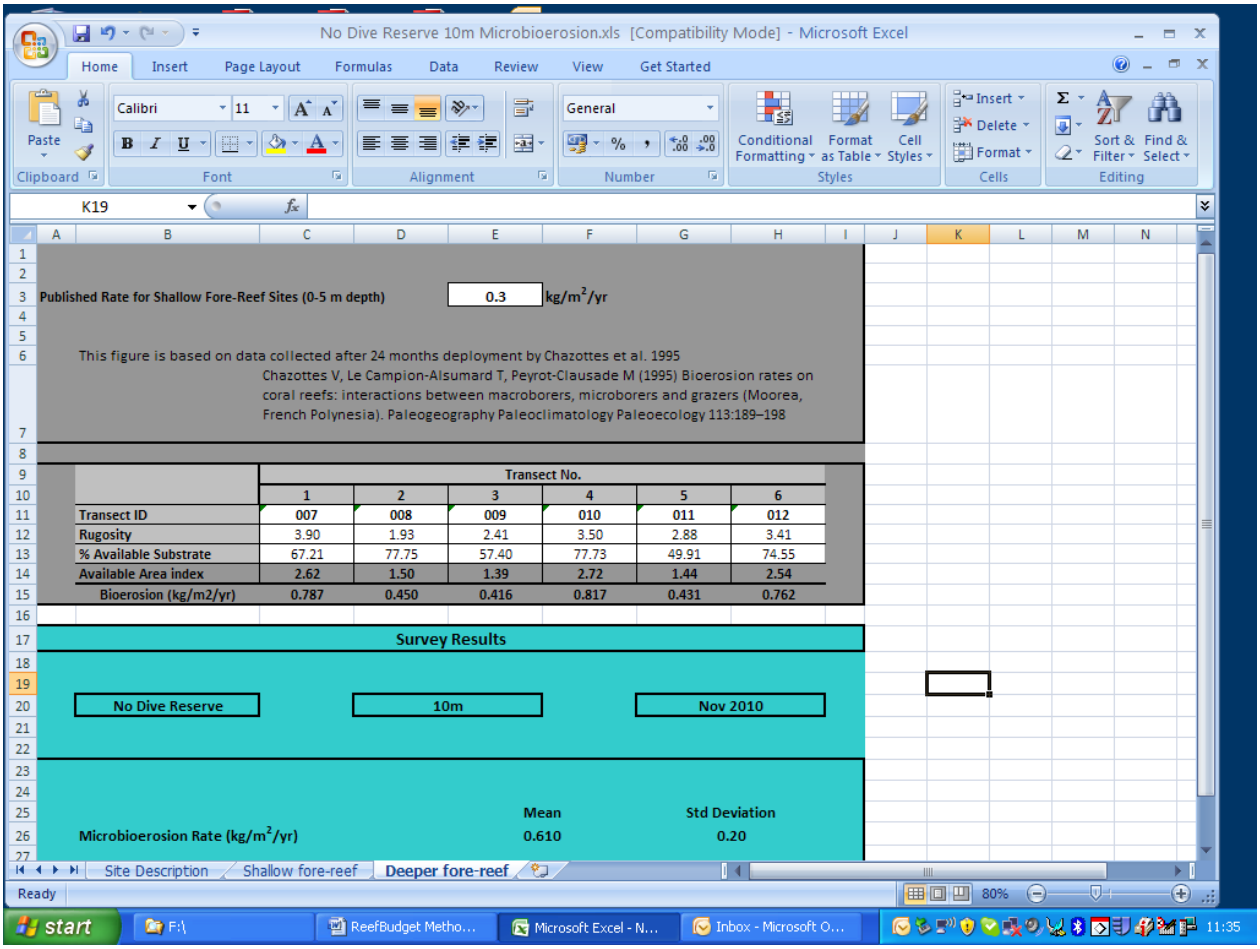


Fig. 22 *Screen grab showing the results summary for 'Deeper fore-reef' sites and both individual transect and mean microbioersion estimates.*

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 1 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 1 *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 datasets
	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:**

Code	Taxon cover (cm)	Code	Taxon cover (cm)	Code	Taxon cover (cm)

Notes:

CCA	Crustose coralline algae
PEY	Peysonellid
OCE	Other calcareous encrusters
HA	Halimeda
ART	Articulated coralline algae
CY	Cyanobacteria
MAC	Macroalgae
MCCA	Macroalgae/CCA
TF	Turf algae
OTH	Other/unknown
RB	Rubble
SD	Sand
SOC	Soft coral
SP	Sponge
DC	Dead coral
HCB	Hard coral (branched)
HCE	Hard coral (encrusting)
HCP	Hard coral (platey/foliose)
HCM	Hard coral (massive)
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
Con	Colpophyllia natans
Dcs	Dichoenia stokesii
Di	Diploria spp.
Dic	Diploria clivosa
Dil	Diploria labyrinthiformis
Dis	Diploria strigosa
Dnc	Dendrogyra cylindrus
Euf	Eusmilia fastigiata
Fvf	Favia fragum
Isr	Isophyllastrea rigida
Iss	Isophyllia sinuosa
Lec	Leptoceris cucullata
Mae	Manicina areolata
Md	Madracis spp.
Mdc	Madracis carmabi
Mdd	Madracis decactis
Mdf	Madracis formosa
Mdm	Madracis mirabilis
Mdp	Madracis pharensis
Mds	Madracis senaria
Me	Meandrina sp.
Med	Meandrina danae
Mem	Meandrina meandrites
Mi	Millepora spp.
Mo	Montastrea spp.
Moa	Montastrea annularis
Moc	Montastrea cavernosa
Mof	Montastrea faveolata
Mofr	Montastrea franksi
Mua	Mussa angulosa
My	Mycetophyllia spp.
Mya	Mycetophyllia aliciae
Myd	Mycetophyllia danaana
Myf	Mycetophyllia ferox
Myl	Mycetophyllia lamarckiana
Myr	Mycetophyllia reesii
Poa	Porites astreoides
Pob	Porites branneri
Poc	Porites colonensis
Pod	Porites divaricata
Pof	Porites furcata
Pop	Porites porites
Sc	Scolymia sp.
Sir	Siderastrea radians
Sis	Siderastrea siderea
Sob	Solenastrea bournoni
Sti	Stephanocoenia intersepta
Syr	Stylaster roseus
Tuc	Tubastrea 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

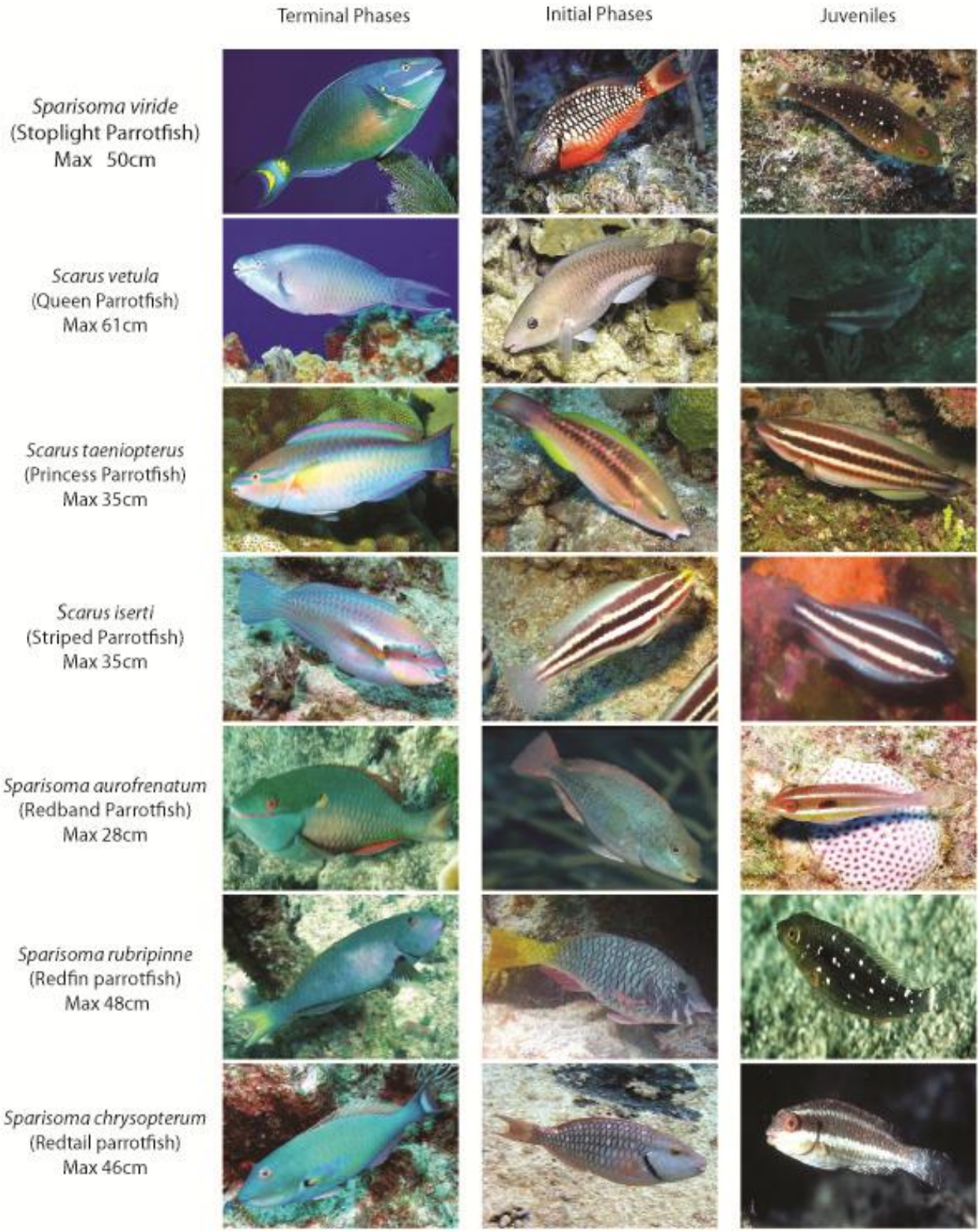
Site: **Depth:** **Date:** **Surveyor:**

Transect No.	**Initial phase**				**Terminal phase**			
	5-14 cm	15-24 cm	25-34 cm	35-44 cm	15-24 cm	25-34 cm	35-44 cm	> 45 cm
S. vetula								
S. taeniopterus								
S. iserti								
Scarus sp.								
S. viride								
S. aurofrenatum								
S. rubripinne								
S. chrysopterum								
Sparisoma sp.								

Transect No.	**Initial phase**				**Terminal phase**			
	5-14 cm	15-24 cm	25-34 cm	35-44 cm	15-24 cm	25-34 cm	35-44 cm	> 45 cm
S. vetula								
S. taeniopterus								
S. iserti								
Scarus sp.								
S. viride								
S. aurofrenatum								
S. rubripinne								
S. chrysopterum								
Sparisoma sp.								

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:

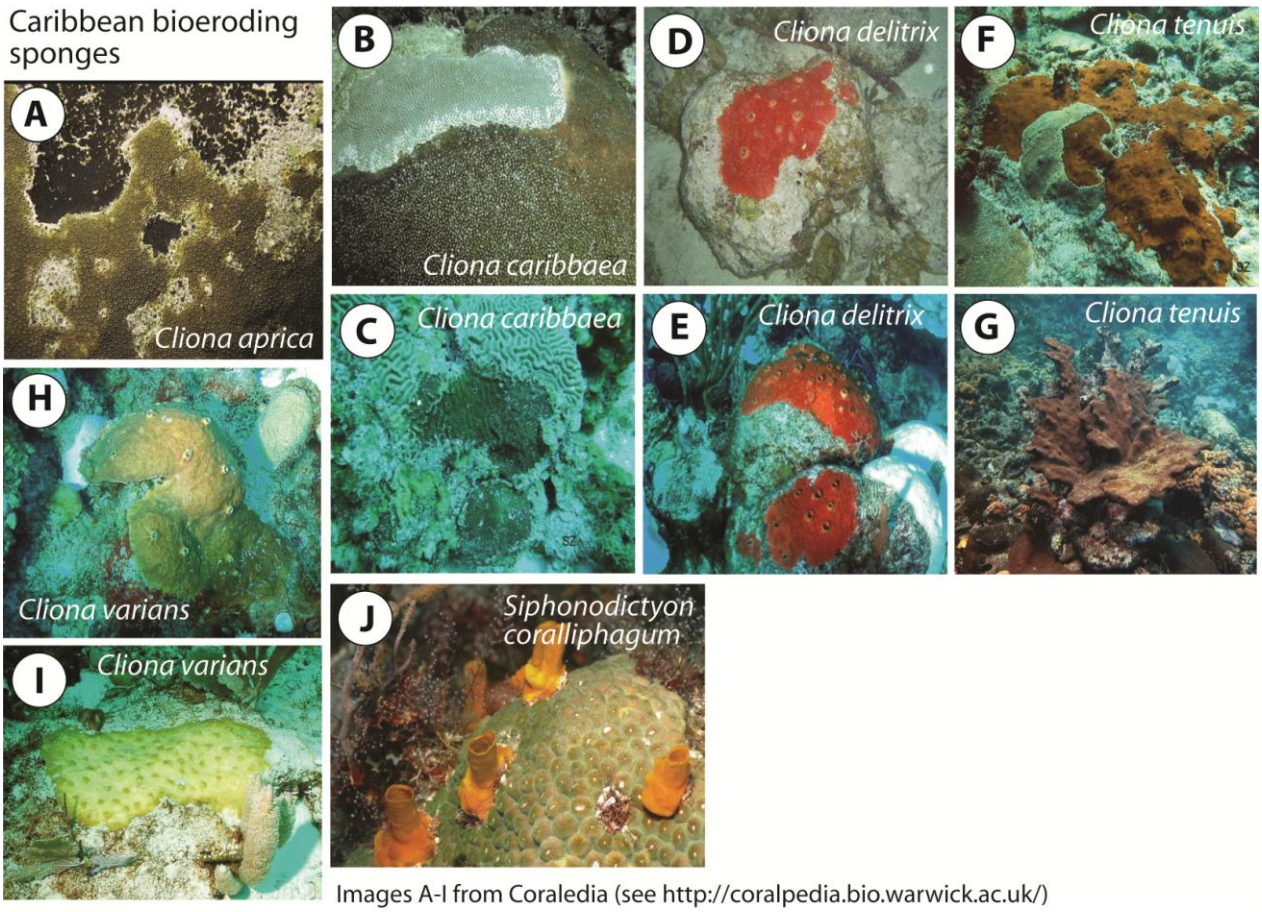
Species	***Area cover (cm^2)***	*Total*
Cliona aprica *Dark brown - fields of papillae, merging*		
Cliona caribbaea *Brown - continuous tissue*		
Cliona tenuis *Brown - very thin, almost transparent layer of continuous tissue*		
Cliona varians *Brown, osculae light yellow - thick continuous tissue or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

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 coralliphagum *Yellow - fleshy chimneys, often from live coral*		
Other/notes		

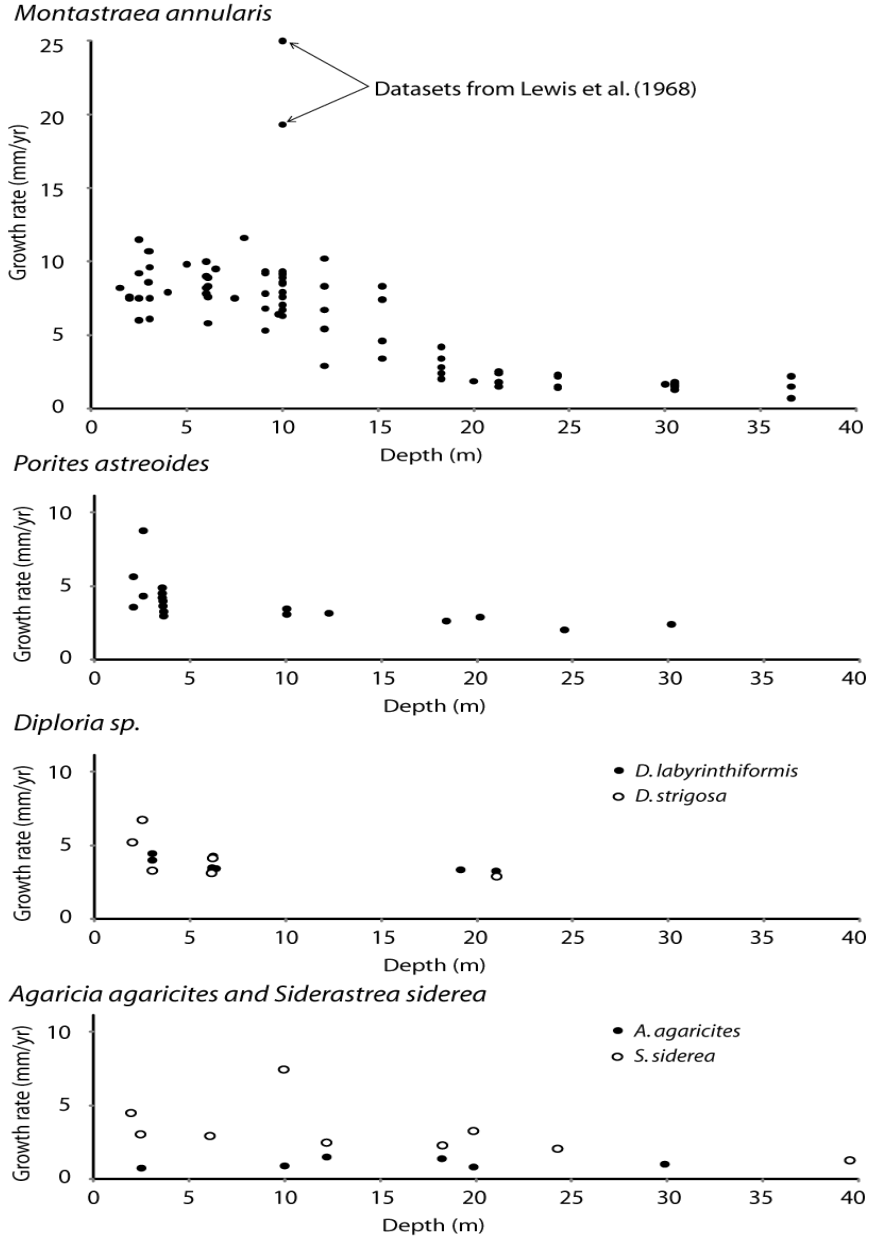
Appendix 7 – Boring sponge identification chart.

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



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

Appendix 8 – Regional patterns of coral growth rates versus water depth



Comparisons of growth rates versus water depth for a number of common framework contributing scleractinian coral species from sites in the Caribbean, the Gulf of Mexico and the Western Atlantic. Data is from the following published sources: *Montastrea annularis* – Barbados, 10m, Lewis et al. (1968), Tomascik and Sander (1985); Belize, 10m, Graus and Macintyre (1982); Curacao, 10m, Bak (1976); Florida, 0-12m, Hoffmeister and Muller (1964), Hudson (1981), Leder et al. (1991), Vaughan (1915); Jamaica, 0-30m, Aller and Dodge (1974), Dustan (1975), Huston (1985), Lewis et al. (1968); Mexico, 1-10m, Carricart-Ganivet (2004), Carricart-Ganivet and Merino (2001), Carricart-Ganivet et al. (2000); Panama, 1-3m, Guzman et al. (1991); St. Croix, 2-37m, Baker and Weber (1975), Dodge and Brass (1984), Gladfelter et al. (1978), Hubbard and Scaturo (1985). *Porites astreoides* – Cuba, 3.5m, Elizalde-Rendon et al. (2010); Florida, 2.5m, Vaughan (1915); Jamaica, 2.5-30m, Chornesky and Peters (1987), Huston (1985); Mexico, 3.5m, Elizalde-Rendon et al. (2010); Panama, 2m, Guzman et al. (1991); St Croix, 2-24m, Gladfelter et al (1978), Hubbard and Scaturo (1985). *Diploria labyrinthiformis* – Bermuda, 3-32m, Logan et al. (1994); St Croix, 6-30m, Hubbard and Scaturo (1985). *Diploria strigosa* – Bermuda, 2.5-32m, Logan et al. (1994); Florida, 2.5m, Vaughan (1915); Panama, 2m, Guzman et al. (1991). *Agaricia agaricites* – Jamaica, 2.5-30m, Huston (1985); St Croix, 12-18m, Hubbard and Scaturo (1985). *Siderastrea siderea* – Florida, 2.5m, Vaughan (1915); Jamaica, 10-20m, Huston (1985); Panama, 2m, Guzman et al. (1991); St Croix, 6-40m, Hubbard and Scaturo (1985).

Appendix 9 – Calculations of parrotfish erosion rates

1. For each parrotfish species, life phase and size class, the rate of bioerosion per parrotfish per day (g) can be established using the median value within the size class and the following equation:

   Bioerosion Rate (g/individual/day) = Bite rate* x (% of bites leaving scars)** x mass eroded per bite**

   * Using data in Mumby et al. 2006

   ** Using data in Bruggemann et al. 1996

2. The equations for bite rate are specific for species and life phase and are described below.

   Bite rate (h^{-1}) of *Sparisoma* spp. = CSp ((1088.84 – (17.12 x FL)) – Species offset)

   Bite rate (h^{-1}) of *Scarus* spp. = CSc ((3329 – (33.00 x FL)) – Species offset)

   Where, FL = fork length (cm)
   CSp = weighting factor for *Sparisoma* life phases; 0.80 for TP, 1 for IP and 0.84 for juveniles
   CSc = weighting factor for *Scarus* life phases; 0.85 for TP and 1 for IP and juveniles

   Species offset = 0 for *Scarus vetula*
   1196 for *Scarus taeniopterus*
   1714 for *Scarus iserti*
   260 for *Sparisoma aurofrenatum*
   142 for *Sparisoma rubripinne*
   264 for *Sparisoma chrysopterum*
   56 for *Sparisoma viride*

3. Once the relevant bite rates for each parrotfish species within life phase and size class groups have been calculated, a figure for the number of bites per day can be worked out. For the *Scarus* genus, bite rate is multiplied by 9.33. For the *Sparisoma* genus, the following equation must be used:

   TDB = 284.8 + 0.84(bite rate x (DLP – 0.62))

   Where, TDB = total daily bites

   DLP = Daylight Period

   Note: The equations for *Scarus vetula* bite rates averaged the bites/hr between 12 and 5 pm and a separate factor is required to establish the total daily bites. Grazing, for *S. vetula*, begins 57 mins after sunrise increasing until 12 pm and then decreases after 5 pm finishing 18 min after sunset. So the foraging period at Karpata, in Bonaire, equals the length of the daylight period (DLP) minus 0.65 hrs. Bruggemann et al. (1994c) use a factor of 9.33 to establish a figure for total daily bites for *S. vetula*.

   For *Sparisoma viride* (Bruggemann et al. 1994b) the foraging period is the length of the daylight period (DLP) minus 0.62 hrs. DLP can be calculated for different latitudes using the equations of Dring (1984). The bite rate equation is based on observations between 9 am and 5 pm and a weighting factor (C) which is unique to both life phase and depth. The above bite rate equations ignore depth, so we may have to substitute in new weighting factors for depths below 3.5m i.e outside territories. To calculate the total daily bites (TDB) the following equation is used:

   TDB = 284.8 + 0.84(bite rate x (DLP – 0.62))

4. The percentage of bites which leave a scar varies with fork length and species. Once again the available data (Bruggemann et al 1996) only describes this factor for *Scarus vetula* and *Sparisoma viride* and so it must be assumed that these relationships can be extrapolated within genera. The scar rate (scar producing bites/day) is calculated by multiplying the total no. of daily bites by the proportion of bites which leave a scar.

Size Class	*Sparisoma*	*Scarus*
5-14cm	12%	11%
15-24cm	58%	14%
25-34cm	74%	30%
≥ 35cm	80%	45%

5. The mass of framework removed per scar for *Scarus vetula* can be calculated using the equation:

$$\text{Carbonate mass removed (g/scar)} = 0.306 \times 10^{-6} \times FL^3$$

Again the lack of available data for other *Scarus* species requires that we assume that this relationship can be extrapolated within the genus. Bruggemann et al (1996) found no difference in the quantity of carbonate removed between different dead coral substrates or between different food types, so it is also assumed that this equation is ubiquitous. This figure is then multiplied by the number of scar producing bites per day to yield the mass of calcium carbonate eroded per individual per day.

Note: The mass of framework removed per scar for *Sparisoma viride* is dependent on the food type being eaten and therefore any relationship will vary from place to place depending on the availability of food and also on the food preferences of the parrotfish.

Bruggemann et al (1994a) found the following relationship between scar volume and FL:

$$VOL = 1.362 \times 10^{-6} \times FL^3$$

Appendix 10 – Rates of microbioerosion of coral substrate.

Assessments of microbioerosion have relied heavily on the deployment of experimental substrates. Most studies have simply used these to examine the bathymetric ranges of individual species, only a very few have used them to determine rates of microboring. Those rates that have been published are shown below. Although available data on this process is not extensive, it is questionable whether reef carbonate budgets should ignore the process entirely, since the published rates are within the ranges calculated for macroborers.

MICROBORING RATES
Internal bioerosion studies (using coral experimental blocks).

Pacific

Site	Months	Environment	Rate (kg m^2 yr^{-1})	Reference
French Polynesia – Moorea	24	Reef flat - Porites blocks	0.20	Chazottes et al. 1995
GBR inner-shelf – Low Isles	36	Porites blocks (7-10 m depth)	0.08	Tribollet & Golubic 2005
GBR inner-shelf – Snapper Island	36	Porites blocks (7-10 m depth)	0.18	Tribollet & Golubic 2005
GBR mid-shelf – Lizard Island	36	Porites blocks (7-10 m depth)	0.30	Tribollet & Golubic 2005
GBR outer-shelf – Ribbon Reef	36	Porites blocks (7-10 m depth)	0.47	Tribollet & Golubic 2005
GBR outer-shelf – Harrier Reef	36	Porites blocks (7-10 m depth)	0.32	Tribollet & Golubic 2005
Coral Sea – Osprey Reef	36	Porites blocks (7-10 m depth)	0.43	Tribollet & Golubic 2005
Indian Ocean				
Reunion (Transect 1)	12	Porites blocks (Lagoon < 2m depth)	0.05	Chazottes et al. 2002
Reunion (Transect 2)	12	Porites blocks (Lagoon < 2m depth)	0.07	Chazottes et al. 2002
Reunion (Transect 3)	12	Porites blocks (Lagoon < 2m depth)	0.04	Chazottes et al. 2002