Perry et al. Caribbean-wide decline in carbonate production threatens coral reef growth

Supplementary Information

Supplementary Table S1. Site, habitat and gross and net reef carbonate production rates across the Caribbean.
Sites and habitats examined in each country and metrics on live coral cover, rugosity, gross production and erosion, net production and accretion rates. Site abbreviations: CR – Cathedral Rock; HW – Hole-in-the-Wall; SS – ski slopes; CBR – Columbus Reef; SWC – Southwater caye; TBR – Tobacco Reef; CAI – Cai; NDR – No dive reserve; WH – White Hole; BAR – Babylon Reef; DF – Don Fosters; PAL – Pallas Reef; SPR – Spotts Reef. Habitat abbreviations: SEMR – Shelf edge *Montastraea* reef; APZ – *Acropora palmata* zone; FRMZ – Fore-reef *Montastraea* zone; SHG – Shallow hardground; FRS – Fore-reef slope.

Country	Site	Transect	Depth (m)	Habitat	LCC (%)	Gross production (kg $CaCO^3/m^2/yr$)	Gross erosion (kg $CaCO^3/m^2/yr$)	Net production (kg $CaCO^3/m^2/yr$)	Accretion rate (mm yr^{-1})
Bahamas	CR	1	19	SEMR	7.88	2.04	1.49	0.56	0.57
Bahamas	CR	2	19	SEMR	9.61	1.94	1.51	0.43	0.49
Bahamas	CR	3	19	SEMR	5.69	1.25	1.54	-0.29	0.05
Bahamas	HW	1	17	SEMR	5.11	1.10	1.70	-0.60	-0.21
Bahamas	HW	2	17	SEMR	4.09	1.06	1.71	-0.65	-0.23
Bahamas	HW	3	17	SEMR	4.57	1.33	1.64	-0.31	-0.01
Bahamas	SS	1	20	SEMR	12.51	1.80	1.20	0.60	0.57
Bahamas	SS	2	20	SEMR	5.84	1.37	1.17	0.20	0.29
Bahamas	SS	3	20	SEMR	10.81	2.56	1.26	1.30	1.05
Belize	CBR	1	5	APZ	14.23	2.09	1.93	0.16	0.42
Belize	CBR	2	5	APZ	16.26	3.11	2.12	0.99	1.03
Belize	CBR	3	5	APZ	16.25	2.67	2.00	0.67	0.78
Belize	CBR	4	5	APZ	36.65	5.65	2.01	3.64	2.86
Belize	CBR	5	5	APZ	22.58	3.14	2.11	1.03	1.09
Belize	CBR	6	5	APZ	14.37	2.23	2.30	-0.07	0.34
Belize	CBR	1	10	FRMZ	17.16	3.70	0.94	2.76	2.03
Belize	CBR	2	10	FRMZ	26.99	3.76	0.89	2.87	2.11
Belize	CBR	3	10	FRMZ	15.60	1.54	1.02	0.52	0.49
Belize	CBR	4	10	FRMZ	13.24	3.27	1.00	2.27	1.69
Belize	CBR	5	10	FRMZ	9.06	1.22	0.87	0.35	0.36
Belize	CBR	6	10	FRMZ	7.70	1.15	0.98	0.17	0.23
Belize	SWC	1	5	APZ	17.43	3.76	2.39	1.37	1.32
Belize	SWC	2	5	APZ	7.34	0.94	2.27	-1.33	-0.56
Belize	SWC	3	5	APZ	16.99	2.91	2.33	0.58	0.79
Belize	SWC	4	5	APZ	14.26	2.66	2.13	0.53	0.70
Belize	SWC	5	5	APZ	8.52	1.94	2.31	-0.37	0.10
Belize	SWC	6	5	APZ	12.90	1.48	2.23	-0.75	-0.17
Belize	SWC	1	10	FRMZ	31.50	7.26	1.03	6.23	4.44
Belize	SWC	2	10	FRMZ	24.52	11.73	1.05	10.68	7.51
Belize	SWC	3	10	FRMZ	13.44	3.20	0.89	2.31	1.72
Belize	SWC	4	10	FRMZ	10.16	1.96	1.09	0.87	0.71

Belize	SWC	5	10	FRMZ	22.07	3.06	0.90	2.16	1.61
Belize	SWC	6	10	FRMZ	23.49	3.30	0.85	2.45	1.82
Belize	TBR	1	5	APZ	12.77	5.21	1.72	3.49	2.68
Belize	TBR	2	5	APZ	13.97	1.54	1.78	-0.24	0.12
Belize	TBR	3	5	APZ	19.37	5.41	1.73	3.68	2.80
Belize	TBR	4	5	APZ	15.68	3.92	1.99	1.93	1.64
Belize	TBR	5	5	APZ	8.56	1.60	2.03	-0.43	0.04
Belize	TBR	6	5	APZ	16.75	1.98	2.06	-0.08	0.32
Belize	TBR	1	10	FRMZ	24.04	3.13	1.30	1.83	1.46
Belize	TBR	2	10	FRMZ	18.15	2.90	1.25	1.65	1.31
Belize	TBR	3	10	FRMZ	8.80	1.51	1.26	0.25	0.34
Belize	TBR	4	10	FRMZ	4.06	0.70	1.16	-0.46	-0.16
Belize	TBR	5	10	FRMZ	8.47	1.09	1.16	-0.07	0.11
Belize	TBR	6	10	FRMZ	6.62	1.00	1.23	-0.23	0.00
Bonaire	CAI	1	5	SHG	2.69	0.25	1.20	-0.95	-0.49
Bonaire	CAI	2	5	SHG	5.16	0.43	1.23	-0.80	-0.39
Bonaire	CAI	3	5	SHG	1.87	0.22	1.24	-1.02	-0.54
Bonaire	CAI	4	5	SHG	0.67	0.06	1.23	-1.17	-0.65
Bonaire	CAI	5	5	SHG	1.22	0.18	1.25	-1.07	-0.58
Bonaire	CAI	6	5	SHG	4.56	0.45	1.28	-0.83	-0.41
Bonaire	CAL	1	10	FRS	28.58	4.78	2.38	2.40	2.05
Bonaire	CAL	2	10	FRS	23.38	4.20	2.46	1.74	1.60
Bonaire	CAL	3	10	FRS	23.47	5.07	2.43	2.64	2.22
Bonaire	CAL	4	10	FRS	25.60	4.83	2.34	2.49	2.12
Bonaire	CAL	5	10	FRS	31.02	6.18	2.29	3.89	3.07
Bonaire	CAL	6	10	FRS	18.01	3.14	2.44	0.70	0.90
Bonaire	NDR	1	5	APZ	10.42	2.14	2.99	-0.85	-0.11
Bonaire	NDR	2	5	APZ	48.35	18.56	3.32	15.24	11.03
Bonaire	NDR	3	5	APZ	28.99	8.32	3.16	5.16	4.05
Bonaire	NDR	4	5	APZ	30.22	7.85	3.17	4.68	3.73
Bonaire	NDR	5	5	APZ	13.08	2.29	3.03	-0.74	-0.01
Bonaire	NDR	6	5	APZ	13.71	1.34	3.08	-1.74	-0.69
Bonaire	NDR	1	10	FRMZ	24.66	13.02	2.93	10.09	7.38
Bonaire	NDR	2	10	FRMZ	22.25	6.12	2.61	3.51	2.81
Bonaire	NDR	3	10	FRMZ	39.45	15.85	2.59	13.26	9.57
Bonaire	NDR	4	10	FRMZ	14.70	8.28	2.92	5.36	4.09
Bonaire	NDR	5	10	FRMZ	45.75	19.26	2.58	16.68	11.93
Bonaire	NDR	6	10	FRMZ	21.19	11.11	2.90	8.21	6.07
Bonaire	WH	1	10	FRS	9.47	0.95	1.97	-1.02	-0.40
Bonaire	WH	2	10	FRS	17.46	5.12	2.05	3.07	2.43
Bonaire	WH	3	10	FRS	19.80	3.52	2.06	1.46	1.31
Bonaire	WH	4	10	FRS	18.79	1.86	2.00	-0.14	0.21
Bonaire	WH	5	10	FRS	14.33	2.25	2.15	0.10	0.38
Bonaire	WH	6	10	FRS	20.33	4.49	2.04	2.45	2.00
Gd Cayman	BAR	1	10	FRS	11.67	2.23	1.88	0.35	0.51
Gd Cayman	BAR	2	10	FRS	3.91	1.52	1.90	-0.38	0.01
Gd Cayman	BAR	3	10	FRS	20.03	5.19	1.87	3.32	2.57
Gd Cayman	DF	1	5	SHG	7.63	0.97	2.73	-1.76	-0.75
Gd Cayman	DF	2	5	SHG	10.16	1.33	2.52	-1.19	

-0.43

Gd Cayman	DF	3	5	SHG	4.98	0.86	2.75	-1.89	-0.85
Gd Cayman	DF	4	5	SHG	1.28	0.32	2.64	-2.32	-1.17
Gd Cayman	DF	5	5	SHG	7.68	1.47	2.60	-1.13	-0.37
Gd Cayman	DF	6	5	SHG	2.22	0.36	2.65	-2.29	-1.16
Gd Cayman	DF	1	10	FRMZ	16.36	7.86	3.71	4.15	3.43
Gd Cayman	DF	2	10	FRMZ	15.14	3.9	3.61	0.29	0.75
Gd Cayman	DF	3	10	FRMZ	13.05	3.45	3.63	-0.18	0.43
Gd Cayman	DF	4	10	FRMZ	13.52	5.71	3.57	2.14	2.03
Gd Cayman	DF	5	10	FRMZ	17.34	4.46	3.76	0.70	1.10
Gd Cayman	DF	6	10	FRMZ	17.01	4.14	3.79	0.35	0.87
Gd Cayman	PAL	1	5	APZ	10.25	2.68	2.05	0.63	0.78
Gd Cayman	PAL	2	5	APZ	5.79	1.14	2.13	-0.99	-0.35
Gd Cayman	PAL	3	5	APZ	12.45	1.69	1.97	-0.28	0.10
Gd Cayman	PAL	4	5	APZ	13.05	3.69	2.16	1.53	1.41
Gd Cayman	PAL	5	5	APZ	2.37	0.47	2.01	-1.54	-0.76
Gd Cayman	SPR	1	10	FRMZ	16.1	4.04	2.56	1.48	1.40
Gd Cayman	SPR	2	10	FRMZ	25.97	5.36	2.57	2.79	2.31
Gd Cayman	SPR	3	10	FRMZ	18.78	3.91	2.60	1.31	1.29
Gd Cayman	SPR	4	10	FRMZ	14.13	2.09	2.56	-0.47	0.06
Gd Cayman	SPR	5	10	FRMZ	21.19	4.90	2.61	2.29	1.97
Gd Cayman	SPR	6	10	FRMZ	14.54	3.11	2.57	0.54	0.75

Supplementary Table S2. Type III Tests of Fixed Effects

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	38.599	55.540	.000
LCC	1	94.939	159.102	.000
Habitat	4	15.961	3.170	.043

a. Dependent Variable: NPtrans.

Supplementary Table S3. Estimates of Covariance Parameters

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.012383	.001935	6.400	.000	.009117	.016820
Intercept + Habitat [subject = Country * Reef]	Variance	.003212	.001638	1.961	.050	.001182	.008727

Supplementary Methods: Linear Mixed Effects Modelling

Linear mixed effects models were chosen to examine relationships between G and potential controls including the percentage cover of hard corals and macroalgae (Pinheiro and Bates 2000, Zuur et al. 2009). The spatial nature of the data meant that transects within reefs were likely to be more similar to each other than to transects on other reefs. The data were also unbalanced as the number of transects surveyed at each reef was not constant. Consequently, linear mixed effects models were chosen to examine the relationships between net carbonate production (G) and potential controls including the percentage cover of hard corals and macroalgae. All modelling was performed in SPSS 19. Initially a saturated model was chosen, such that all sensible fixed and random effects of interest were included. The data was nested within reef and country and restricted maximum likelihood estimation was used to run the model. Thereafter, Akaike Information Criterion (AIC) was used to select a suitable covariance structure and subsequently the best combination of random effects (see Supplementary Tables S2 and S3). This model was assessed graphically by examining a histogram of the standardised residuals to check for normality and by plotting the residuals versus the predicted values. Heterogeneity of variance was clear at this stage and the dependent variable (net carbonate production) was transformed: log (y + 3). The model was run again with the transformed data as the dependent variable and the assumptions of normality and homogeneity of variance were confirmed. The fixed effects were then assessed by examining the significance of regression parameters (Pinheiro and Bates 2000, Zuur et al. 2009). The final model is described below using the SPSS syntax and important outputs:

```
MIXED NPtrans BY Country Habitat WITH LCC
  /CRITERIA=CIN(95) MXITER(1000) MXSTEP(1000) SCORING(1) SINGULAR(0.000000000001) HCONVERGE(0,
ABSOLUTE) LCONVERGE(0, ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
  /FIXED=LCC Habitat | SSTYPE(3)
  /METHOD=REML
  /PRINT=SOLUTION TESTCOV
  /RANDOM=INTERCEPT Habitat | SUBJECT(Country*Reef) COVTYPE(ID).
```


- Pinheiro, J.C & Bates, D.M. Mixed-Effects Models in S and S-Plus. Springer 528 p. (2000)
- Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A. & Smith, G.M. Mixed Effects Models and Extensions in Ecology with R. Springer 574 p. (2009).