*Scientific Reports*

Supplementary Information for

**Upwelling, climate change, and the shifting geography of coral reef development**

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**Supplementary Information included in this file:**

Supplementary Tables S1–S8

Supplementary Methods

Supplementary Figures S1–S5

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**SUPPLEMENTARY INFORMATION**

**Table S1:** Best-fit linear mixed-effect models developed to predict the threshold values of percent coral cover required for reefs in each gulf to maintain a positive rate of net carbonate production, and to maintain accretion rates high enough to keep up with different scenarios of sea-level rise. SE, standard error; df, degrees of freedom.

|  |
| --- |
| **Net carbonate production** |
|  | **Value** | **SE** | **df** | **t-value** | **p** |
| **Intercept** | -9.35 | 0.40 | 28 | -23.65 | <0.001 |
| **Gulf** | -0.71 | 0.39 | 4 | -1.82 | 0.08 |
| **Coral cover** | 0.23 | 0.009 | 28 | 25.17 | <0.001 |
| **Reef accretion potential** |
|  | **Value** | **SE** | **df** | **t-value** | **p** |
| **Intercept** | -5.770 | 0.273 | 28 | -21.104 | <0.0001 |
| **Gulf** | -0.307 | 0.271 | 4 | -1.135 | 0.265 |
| **Coral cover** | 0.155 | 0.007 | 28 | 23.626 | <0.0001 |

**Table S2:** Bioerosion estimates from Eakin’s7 carbonate budget model for Uva Reef, Panama, and the relative contribution of infaunal erosion to total reef bioerosion. All bioerosion estimates are in kg CaCO3 m-2 yr-1.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Reef Zone** | ***Diadema*** | **Fish** | **Infauna** | **Corallivores** | **Total** | **Contribution of infaunal erosion (%)** | **Reference** |
| Back reef | 0.08 | 0.02 | 6.29 | 0.02 | 6.41 | 98% | 1 |
| Reef flat | 0.01 | 1.15 | 3.67 | 0.00 | 4.83 | 76% | 1 |
| Fore reef | 1.04 | 1.28 | 5.95 | 0.02 | 8.29 | 72% | 1 |
| Reef base | 4.38 | 1.25 | 8.01 | 0.00 | 13.64 | 59% | 1 |
| Fore-reef slope (Spring 2016) | 0.02 | 0.18 | 5.69 | 0.09 | 5.98 | 95% | This study |
| Fore-reef slope (Spring 2018) | 0.33 | 0.18 | 6.65 | 0.09 | 7.25 | 92% | This study |

**Table S3:** Carbonate budget outputs for each site in each time interval.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Time** | **Site** | **Mean (± SE) gross carbonate production (kg m-2 yr-1)** | **Mean (± SE) bioerosion (kg m-2 yr-1)** | **Mean (± SE) net carbonate production (kg m-2 yr-1)** | **Mean (± SE) RAP (mm yr-1)** |
| Spring 2016 | Canales | 6.7 ± 1.2 | -6.4 ± 0.4 | 0.4 ± 1.5 | 0.2 ± 1.0 |
| Spring 2016 | Coiba | 13.0 ± 2.6 | -6.5 ± 0.4 | 6.5 ± 2.9 | 4.2 ± 1.8 |
| Spring 2016 | Uva | 11.6 ± 1.4 | -6.6 ± 0.2 | 5.0 ± 1.6 | 3.3 ± 1.0 |
| Spring 2016 | Contadora | 19.3 ± 0.7 | -5.5 ± 0.2 | 13.9 ± 0.7 | 9.4 ± 0.5 |
| Spring 2016 | Pedro Gonzalez | 17.5 ± 0.9 | -5.2 ± 0.1 | 12.3 ± 1.0 | 8.3 ± 0.6 |
| Spring 2016 | Saboga | 17.6 ± 1.0 | -5.7 ± 0.1 | 11.9 ± 1.0 | 7.5 ± 0.6 |
| Autumn 2016 | Canales | 8.7 ± 0.8 | -6.3 ± 0.2 | 2.3 ± 1.0 | 1.5 ± 0.6 |
| Autumn 2016 | Coiba | 13.0 ± 1.8 | -5.4 ± 0.4 | 7.6 ± 1.6 | 4.9 ± 1.0 |
| Autumn 2016 | Uva | 12.2 ± 1.1 | -6.0 ± 0.4 | 6.1 ± 1.5 | 4.0 ± 0.9 |
| Autumn 2016 | Contadora | 15.9 ± 1.4 | -6.4 ± 0.4 | 9.4 ± 1.6 | 6.6 ± 1.0 |
| Autumn 2016 | Pedro Gonzalez | 18.8 ± 0.5 | -5.2 ± 0.1 | 13.6 ± 0.6 | 9.3 ± 0.4 |
| Autumn 2016 | Saboga | 17.4 ± 0.7 | -6.4 ± 0.4 | 11.0 ± 0.8 | 7.1 ± 0.4 |
| Spring 2017 | Canales | 8.8 ± 1.3 | -7.5 ± 0.3 | 1.4 ± 1.5 | 0.9 ± 1.0 |
| Spring 2017 | Coiba | 11.1 ± 1.0 | -7.5 ± 0.3 | 3.6 ± 1.2 | 2.4 ± 0.7 |
| Spring 2017 | Uva | 11.1 ± 0.8 | -7.1 ± 0.2 | 4.0 ± 0.9 | 2.7 ± 0.6 |
| Spring 2017 | Contadora | 18.3 ± 1.1 | -5.7 ± 0.2 | 12.7 ± 1.1 | 8.6 ± 0.8 |
| Spring 2017 | Pedro Gonzalez | 14.8 ± 0.5 | -6.4 ± 0.1 | 8.3 ± 0.5 | 5.7 ± 0.4 |
| Spring 2017 | Saboga | 17.1 ± 0.5 | -5.9 ± 0.2 | 11.2 ± 0.5 | 7.1 ± 0.3 |
| Autumn 2017 | Canales | 9.8 ± 1.5 | -7.3 ± 0.3 | 2.6 ± 1.8 | 1.7 ± 1.1 |
| Autumn 2017 | Coiba | 11.4 ± 1.3 | -7.5 ± 0.3 | 3.9 ± 1.4 | 2.6 ± 0.9 |
| Autumn 2017 | Uva | 13.1 ± 0.6 | -7.2 ± 0.2 | 5.9 ± 0.7 | 4.0 ± 0.5 |
| Autumn 2017 | Contadora | 19.7 ± 0.7 | -6.0 ± 0.4 | 13.7 ± 0.8 | 9.4 ± 0.5 |
| Autumn 2017 | Pedro Gonzalez | 17.1 ± 0.8 | -6.1 ± 0.2 | 11.0 ± 1.0 | 7.5 ± 0.6 |
| Autumn 2017 | Saboga | 16.0 ± 0.7 | -7.1 ± 0.2 | 8.9 ± 0.9 | 5.9 ± 0.5 |
| Spring 2018 | Canales | 6.6 ± 1.2 | -8.0 ± 0.3 | -1.4 ± 1.5 | -0.9 ± 1.0 |
| Spring 2018 | Coiba | 9.0 ± 0.7 | -8.5 ± 0.5 | 0.5 ± 0.9 | 0.6 ± 0.5 |
| Spring 2018 | Uva | 8.9 ± 1.0 | -8.0 ± 0.3 | 0.9 ± 1.2 | 0.8 ± 0.8 |
| Spring 2018 | Contadora | 18.4 ± 0.3 | -8.9 ± 0.2 | 9.5 ± 0.3 | 6.5 ± 0.2 |
| Spring 2018 | Pedro Gonzalez | 16.8 ± 0.6 | -8.6 ± 0.1 | 8.1 ± 0.6 | 5.5 ± 0.4 |
| Spring 2018 | Saboga | 14.8 ± 0.6 | -9.2 ± 0.1 | 5.6 ± 0.6 | 3.7 ± 0.4 |

**Table S4:** Average gross carbonate production, bioerosion and net carbonate production for the two gulfs surveyed in this study, along with the estimates reported by other studies for reefs from different regions.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Study** | **Site** | **Gross CaCO3 production(kg CaCO3 m-2 yr-1)** | **Bioerosion (kg CaCO3 m-2 yr-1)** | **Net CaCO3 production (kg CaCO3 m-2 yr-1)** |
| This study | Gulf of Panamá, spring 2018 | 16.7 | -8.9 | 7.8 |
| This study | Gulf of Chiriquí, spring 2018 | 8.1 | -8.1 | 0.0 |
| 1 | Uva Reef, 1992 | 4.6 | -8.3 | -3.7 |
| 2 | Maldives Archipelago, Indian Ocean | 8.3 | -3.4 | 4.9 |
| 3 | Palau, western Pacific Ocean | 10.3 | -0.3 | 10.0 |
| 2 | Mexican Caribbean | 3.2 | -3.4 | -0.2 |

**Table S5:** Mean calcification rates used to estimate carbonate production for the non-pocilloporid coral taxa encountered at our study sites. We used local calcification rates for the Gulf of Panamá and the Gulf of Chiriquí when available. We used average calcification rates from other localities of the ETP for taxa for which local calcification rates were not available.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Locality** | **Site** | **Mean Density (g cm-2)** | **Mean extension rate (cm yr-1)** | **Mean Calcification rate (g cm-2 yr-1)** | **Reference** |
| *Gardineroseris planulata* | Panamá | Uva Reef, Gulf of Chiriquí | 1.63 | 0.61 | 0.98 | 4 |
| *Pavona gigantea* | Panamá | Uva Reef, Gulf of Chiriquí | 1.48 | 0.92 | 1.35 | 4 |
| *Pavona gigantea* | Panamá | Saboga Reef, Gulf of Panamá | 1.75 | 0.85 | 1.49 | 5 |
| *Pavona varians* | Panamá | Uva Reef, Gulf of Chiriquí | 1.96 | 0.32 | 0.63 | 4 |
| *Porites lobata* | México | Marieta Islands | 1.19 | 0.56 | 0.67 | 6 |
| *Porites lobata* | México | Zacatoso, Oaxaca | 1.2 | 0.6 | 0.72 | 7 |
| *Porites panamensis* | México | Bahía de Los Angeles | 0.91 | 0.5 | 0.46 | 8 |
| *Porties panamensis* | México | Bahía de La Paz | 0.95 | 1.2 | 1.14 | 8 |
| *Porites panamensis* | México | Cabo Pulmo | 1.35 | 0.91 | 1.23 | 9 |
| *Porites panamensis* | México | Marieta Islands | 1.28 | 0.38 | 0.49 | 9 |
| *Porites panamensis* | México | La Entrega, Oaxaca | 1.12 | 0.31 | 0.35 | 7 |

**Table S6:** *In situ* measurements of the reef framework taken during push-coring operations at each site. Aluminum tubes, which were 7.6 cm in diameter, were forced by hand vertically into the uncemented frameworks10. Penetration was calculated by measuring the outer length of the core tube standing partially inserted into the reef, and subtracting that measurement from its total length. Recovery was measured by dropping a weighted measuring tape into the core barrel until it landed on the material collected and stopped descending. The inner length was subtracted from the total length of the tube to calculate recovery. Recovery as a proportion of penetration yielded compaction, and porosity was estimated as 1 minus compaction.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Gulf** | **Site** | **Core** | **Total Length****(cm)** | **Outer Length****(cm)** | **Inner Length****(cm)** | **Interval Penetration** | **Interval Recovery** | **Interval Compaction** | **Porosity** |
| Panamá | Contadora | EP08-24 | 474 | 328 | 397 | 146 | 77 | 0.53 | 0.47 |
| Panamá | Contadora | EP08-24 | 474 | 254 | 343 | 74 | 54 | 0.73 | 0.27 |
| Panamá | Contadora | EP08-24 | 474 | 169 | 298 | 85 | 45 | 0.53 | 0.47 |
| Panamá | Contadora | EP08-24 | 474 | 91 | 243 | 78 | 55 | 0.71 | 0.29 |
| Panamá | Contadora | EP08-25 | 494 | 397 | 459 | 97 | 35 | 0.36 | 0.64 |
| Panamá | Contadora | EP08-25 | 494 | 315 | 413 | 82 | 46 | 0.56 | 0.44 |
| Panamá | Contadora | EP08-25 | 494 | 250 | 365 | 65 | 48 | 0.74 | 0.26 |
| Panamá | Contadora | EP08-25 | 494 | 154 | 301 | 96 | 64 | 0.67 | 0.33 |
| Panamá | Contadora | EP08-25 | 494 | 79 | 251 | 75 | 50 | 0.67 | 0.33 |
| Panamá | Contadora | EP08-26 | 488 | 386 | 448 | 102 | 40 | 0.39 | 0.61 |
| Panamá | Contadora | EP08-26 | 488 | 333 | 422 | 53 | 26 | 0.49 | 0.51 |
| Panamá | Contadora | EP08-26 | 488 | 295 | 410 | 38 | 12 | 0.32 | 0.68 |
| Panamá | Contadora | EP08-26 | 488 | 209 | 375 | 86 | 35 | 0.41 | 0.59 |
| Panamá | Contadora | EP08-26 | 488 | 199 | 335 | 90 | 40 | 0.44 | 0.56 |
| Panamá | Contadora | EP09-27 | 476 | 380 | 423 | 96 | 53 | 0.55 | 0.45 |
| Panamá | Contadora | EP09-27 | 476 | 297 | 367 | 83 | 56 | 0.67 | 0.33 |
| Panamá | Contadora | EP09-27 | 476 | 249 | 336 | 48 | 31 | 0.65 | 0.35 |
| Panamá | Contadora | EP09-27 | 476 | 192 | 313 | 57 | 23 | 0.40 | 0.60 |
| Panamá | Contadora | EP09-27 | 476 | 91 | 253 | 101 | 60 | 0.59 | 0.41 |
| Panamá | Contadora | EP08-28 | 613 | 428 | 505 | 185 | 108 | 0.58 | 0.42 |
| Panamá | Contadora | EP08-28 | 613 | 372 | 471 | 56 | 34 | 0.61 | 0.39 |
| Panamá | Contadora | EP08-28 | 613 | 269 | 402 | 103 | 69 | 0.67 | 0.33 |
| Panamá | Contadora | EP08-28 | 613 | 201 | 345 | 68 | 57 | 0.84 | 0.16 |
| Panamá | Contadora | EP08-28 | 613 | 171 | 329 | 30 | 16 | 0.53 | 0.47 |
| Chiriquí | Canales | EP10-35 | 613 | 527 | 580 | 86 | 33 | 0.38 | 0.62 |
| Chiriquí | Canales | EP10-35 | 613 | 339 | 470 | 188 | 110 | 0.59 | 0.41 |
| Chiriquí | Canales | EP10-35 | 613 | 282 | 433 | 57 | 37 | 0.65 | 0.35 |
| Chiriquí | Canales | EP10-35 | 613 | 183 | 373 | 99 | 60 | 0.61 | 0.39 |
| Chiriquí | Canales | EP10-35 | 613 | 108 | 303 | 75 | 70 | 0.93 | 0.07 |
| Chiriquí | Canales | EP07-41 | 613 | 529 | 534 | 84 | 79 | 0.94 | 0.06 |
| Chiriquí | Canales | EP07-41 | 613 | 402 | 503 | 127 | 31 | 0.24 | 0.76 |
| Chiriquí | Canales | EP07-41 | 613 | 267 | 407 | 135 | 96 | 0.71 | 0.29 |
| Chiriquí | Canales | EP07-41 | 613 | 190 | 354 | 77 | 53 | 0.69 | 0.31 |
| Chiriquí | Canales | EP07-41 | 613 | 109 | 294 | 81 | 60 | 0.74 | 0.26 |
| Chiriquí | Canales | EP07-42 | 613 | 308 | 390 | 305 | 223 | 0.73 | 0.27 |
| Chiriquí | Canales | EP07-42 | 613 | 203 | 312 | 105 | 78 | 0.74 | 0.26 |
| Chiriquí | Canales | EP07-42 | 613 | 93 | 233 | 110 | 79 | 0.72 | 0.28 |
| Chiriquí | Canales | EP07-420 | 609 | 377 | 457 | 232 | 152 | 0.66 | 0.34 |
| Chiriquí | Canales | EP07-420 | 609 | 303 | 403 | 74 | 54 | 0.73 | 0.27 |
| Chiriquí | Canales | EP07-420 | 609 | 105 | 268 | 198 | 135 | 0.68 | 0.32 |
| Panamá | Pedro Gonzalez | EP17-101 | 605 | 383 | 580 | 222 | 25 | 0.11 | 0.89 |
| Panamá | Pedro Gonzalez | EP17-101 | 605 | 325 | 545 | 58 | 35 | 0.60 | 0.40 |
| Panamá | Pedro Gonzalez | EP17-101 | 605 | 286 | 531 | 39 | 14 | 0.36 | 0.64 |
| Panamá | Pedro Gonzalez | EP17-102 | 486 | 323 | 457 | 163 | 29 | 0.18 | 0.82 |
| Panamá | Pedro Gonzalez | EP17-102 | 486 | 259 | 411 | 64 | 46 | 0.72 | 0.28 |
| Panamá | Pedro Gonzalez | EP17-102 | 486 | 197 | 359 | 62 | 52 | 0.84 | 0.16 |
| Panamá | Pedro Gonzalez | EP17-102 | 486 | 149 | 343 | 48 | 16 | 0.33 | 0.67 |
| Panamá | Pedro Gonzalez | EP17-102 | 486 | 138 | 333 | 11 | 10 | 0.91 | 0.09 |
| Panamá | Pedro Gonzalez | EP17-103 | 604 | 305 | 487 | 299 | 117 | 0.39 | 0.61 |
| Panamá | Pedro Gonzalez | EP17-103 | 604 | 254 | 445 | 51 | 42 | 0.82 | 0.18 |
| Panamá | Pedro Gonzalez | EP17-104 | 477 | 350 | 407 | 127 | 70 | 0.55 | 0.45 |
| Panamá | Pedro Gonzalez | EP17-104 | 477 | 215 | 322 | 135 | 85 | 0.63 | 0.37 |
| Panamá | Pedro Gonzalez | EP17-104 | 477 | 201 | 319 | 14 | 3 | 0.21 | 0.79 |
| Panamá | Pedro Gonzalez | EP17-104 | 477 | 188 | 317 | 13 | 2 | 0.15 | 0.85 |
| Panamá | Saboga | EP09-30 | 497 | 325 | 420 | 172 | 77 | 0.45 | 0.55 |
| Panamá | Saboga | EP09-30 | 497 | 249 | 363 | 76 | 57 | 0.75 | 0.25 |
| Panamá | Saboga | EP09-31 | 489 | 394 | 450 | 95 | 39 | 0.41 | 0.59 |
| Panamá | Saboga | EP09-31 | 489 | 319 | 396 | 75 | 54 | 0.72 | 0.28 |
| Panamá | Saboga | EP09-31 | 489 | 229 | 329 | 90 | 67 | 0.74 | 0.26 |
| Panamá | Saboga | EP09-31 | 489 | 155 | 275 | 74 | 54 | 0.73 | 0.27 |
| Panamá | Saboga | EP09-31 | 489 | 122 | 249 | 33 | 26 | 0.79 | 0.21 |
| Panamá | Saboga | EP09-31 | 489 | 104 | 235 | 18 | 14 | 0.78 | 0.22 |
| Panamá | Saboga | EP09-32 | 493 | 403 | 464 | 90 | 29 | 0.32 | 0.68 |
| Panamá | Saboga | EP09-32 | 493 | 310 | 408 | 93 | 56 | 0.60 | 0.40 |
| Panamá | Saboga | EP09-32 | 493 | 224 | 344 | 86 | 64 | 0.74 | 0.26 |
| Panamá | Saboga | EP09-32 | 493 | 130 | 273 | 94 | 71 | 0.76 | 0.24 |
| Panamá | Saboga | EP09-33 | 468 | 382 | 439 | 86 | 29 | 0.34 | 0.66 |
| Panamá | Saboga | EP09-33 | 468 | 289 | 383 | 93 | 56 | 0.60 | 0.40 |
| Panamá | Saboga | EP09-33 | 468 | 215 | 327 | 74 | 56 | 0.76 | 0.24 |
| Panamá | Saboga | EP09-33 | 468 | 106 | 249 | 109 | 78 | 0.72 | 0.28 |
| Chiriquí | Coiba | EP13-53 | 604 | 434 | 460 | 170 | 144 | 0.85 | 0.15 |
| Chiriquí | Coiba | EP14-56 | 477 | 244 | 448 | 233 | 29 | 0.12 | 0.88 |
| Chiriquí | Coiba | EP14-56 | 477 | 212 | 423 | 32 | 25 | 0.78 | 0.22 |
| Chiriquí | Coiba | EP14-56 | 477 | 132 | 375 | 80 | 48 | 0.60 | 0.40 |
| Chiriquí | Coiba | EP14-56 | 477 | 57 | 310 | 75 | 65 | 0.87 | 0.13 |
| Chiriquí | Coiba | EP14-57 | 604 | 435 | 520 | 169 | 84 | 0.50 | 0.50 |
| Chiriquí | Uva | EP10-36 | 613 | 254 | 570 | 359 | 43 | 0.12 | 0.88 |
| Chiriquí | Uva | EP10-37 | 613 | 385 | 570 | 228 | 43 | 0.19 | 0.81 |
| Chiriquí | Uva | EP10-37 | 613 | 338 | 565 | 47 | 5 | 0.11 | 0.89 |
| Chiriquí | Uva | EP10-37 | 613 | 260 | 550 | 78 | 15 | 0.19 | 0.81 |
| Chiriquí | Uva | EP10-37 | 613 | 175 | 462 | 85 | 88 | 1.04 | -0.04 |
| Chiriquí | Uva | EP10-37 | 613 | 85 | 390 | 90 | 72 | 0.80 | 0.20 |
| Chiriquí | Uva | EP10-38 | 613 | 457 | 520 | 156 | 93 | 0.60 | 0.40 |
| Chiriquí | Uva | EP10-38 | 613 | 329 | 425 | 128 | 95 | 0.74 | 0.26 |
| Chiriquí | Uva | EP10-38 | 613 | 237 | 354 | 92 | 71 | 0.77 | 0.23 |
| Chiriquí | Uva | EP10-38 | 613 | 163 | 278 | 74 | 76 | 1.03 | -0.03 |
| Chiriquí | Uva | EP10-38 | 613 | 127 | 270 | 36 | 8 | 0.22 | 0.78 |
| Chiriquí | Uva | EP10-38 | 613 | 120 | 260 | 7 | 10 | 1.43 | -0.43 |
| Chiriquí | Uva | EP11-44 | 613 | 500 | 580 | 113 | 33 | 0.29 | 0.71 |
| Chiriquí | Uva | EP11-44 | 613 | 350 | 489 | 150 | 91 | 0.61 | 0.39 |
| Chiriquí | Uva | EP11-44 | 613 | 290 | 453 | 60 | 36 | 0.60 | 0.40 |
| Chiriquí | Uva | EP11-44 | 613 | 195 | 400 | 95 | 53 | 0.56 | 0.44 |
| Chiriquí | Uva | EP11-44 | 613 | 135 | 372 | 60 | 28 | 0.47 | 0.53 |
| Chiriquí | Uva | EP11-45 | 613 | 475 | 590 | 138 | 23 | 0.17 | 0.83 |
| Chiriquí | Uva | EP11-45 | 613 | 294 | 483 | 181 | 107 | 0.59 | 0.41 |
| Chiriquí | Uva | EP11-45 | 613 | 122 | 370 | 172 | 113 | 0.66 | 0.34 |

**Supplementary Methods**

**Benthic Rugosity**

Previous studies have measured the rugosity of the reef framework by draping a chain of known length over the framework and calculating the ratio between the known chain length and the linear distance covered by the draped chain11. Other studies that have not directly measured rugosity have used the published average rugosities of individual coral colonies to correct the calculated rates of carbonate production12,13. A comparison of framework-scale rugosity, measured over tens of meters at Uva (fore-reef rugosity index = 1.51), with centimeter-scale rugosity estimated for individual *Pocillopora* colonies across the Mexican Pacific (rugosity index = 2.95–3.75) showed that framework-scale rugosity is much lower than colony-level rugosity as a result of the tightly-packed structure of *Pocillopora* framework14,15. Indeed, the dense *Pocillopora* framework at our sites created an almost-flat surface, which made it particularly challenging to accurately measure rugosity using traditional chain methodologies. The rugosity of the framework would be drastically overestimated if we were to use estimates of colonly-level rugosity. Furthermore, branching colonies actively calcify at their branch-tips, unlike massive species, which actively calcify across their entire surfaces16. Because of these complications, and because rugosity was not measured *in situ* at our sites, that variable was not incorporated into our carbonate budget model.

**Infaunal Bioerosion**

The carbonate budget developed by Eakin1 for Uva Reef (1988–1994) indicated that cryptofaunal bioerosion was the main bioerosive pressure on the reef at that time (Table S2). Infaunal bioerosion at Uva accounted for >50% of total bioerosion in every reef zone. Eakin used the bioerosion rates estimated by Glynn17 for the infaunal bioerosion of *Pocillopora* skeletons, which are the same rates we incorporated into our model. Therefore, different estimates of infaunal bioerosion rates between Eakin’s model and ours are caused by differences in benthic cover.

**Sea-Urchin Densities and Bioerosion**

At each site, six 25 x 1 m video belt transects were deployed haphazardly by SCUBA divers and captured with a GoPro camera, which were pointed down 1 m from the reef surface as they travelled along the transect at a constant speed. The total abundance of *Diadema mexicanum*, the only species that was present, was estimated for each video transect by visually counting each individual seen within the transect area. Since sea urchins are predominantly nocturnal, our density estimates are likely underestimates of the actual population at each site (Fig. S1; ref. 18). Sea-urchin bioerosion estimates for each site were then calculated using the rates reported by Glynn17 for live, dead, and algal-dominated *Pocillopora* framework and multiplied by the sea-urchin densities from the video transects. Our sea-urchin bioerosion estimates are lower than those estimated by Eakin1 (Table S2), which is a result of the difference in sea-urchin densities (Fig. S2). The high sea-urchin densities reported by Eakin1 are a consequence of the 1982–1983 El Niño event, which caused extensive coral mortality and an increase in algal cover. This increase in resource availability led to a spike in sea-urchin densities that persisted through the 1980s and the early 1990s. In contrast, when our density estimates are compared with pre-1983 and more recent surveys, they fall within the range of these values.



**Figure S1:** Mean (± standard error) density of *D. mexicanum* (ind. m-2) for each gulf across the five surveys from 2016–2018.

A regional assessment of sea-urchin populations was recently conducted across the eastern tropical Pacific (ETP)19. According to the survey, the average urchin density for the ETP was 0.5 ind m-2, and the average bioerosive pressure from sea urchins was 0.16 kg CaCO3 m-2 yr-1 (ref.19). During 2009–2010, the average sea-urchin density was 0.7 ind m-2 (±0.35) for the Gulf of Panamá, and 0.3 ind m-2 (±0.43) for the Gulf of Chiriquí19. We estimated the average sea-urchin density for the Gulf of Chiriquí to be 2 ind m-2 (±1.64), and 1.9 (±0.86) for the Gulf of Panamá for the period 2016–2018. These values are higher than the estimates from Alvarado et al.19 and fall within the range of pre-1983 estimates (2.7 ind m-2 ±0.65; Fig. S2).



**Figure S2:** Historical estimates *of* *Diadema mexicaum* densities (mean±95% CI) for the Gulf of Chiriquí. Data were compiled from Glynn17, Eakin14, Alvarado et al.19, and this study to visualize the historical trends in urchin densities at this site.

**Parrotfish Grazing**

The parrotfish species at our sites were *Scarus ghobban* and *S. rubroviolaceus*, the dominant herbivorous fishes on reefs of the ETP20. Both of these species scrape the coral substrate while foraging, which is a much less destructive process than excavating. Furthermore, *S. ghobban* does not consistently produce scars while foraging21. In other regions, large, excavating parrotfish are the main contributors to the majority of parrotfish-driven bioerosion22,23. In the Mexican Caribbean, for example, a decrease in bioerosion rates wasdriven primarily by a decrease in abundance and a shift towards smaller size classes of the excavating species *Sparisoma viride*. Parrotfish bioerosion decreased from 1.7 kg CaCO3 m-2 yr-1 in 2004 to 0.7 kg CaCO3 m-2 yr-1 in 201823. In the Indian Ocean, large excavators accounted for >60% of total parrotfish bioerosion, with average parrotfish bioerosion being 3.6 kg CaCO3 m-2 yr-1 for the Chagos Archipelago and 3.1 kg CaCO3 m-2 yr-1 for the Maldives22. Parrotfish bioerosion estimates of 1.3–1.6 kg CaCO3 m-2 yr-1 have been recorded at the shallow the *Pocillopora* reefs of Gorgona Island, Colombia20; however, this was the result of a parrotfish density of 1544 ind. ha-1. The parrotfish density at Gorgona Island is almost four times greater than that of the Gulf of Chiriquí, and 50% greater than that of the Gulf of Panamá (Table S7).

**Table S7:** Comparison of parrotfish densities and bioerosion rates estimated for different localities within the eastern Pacific.

|  |  |  |  |
| --- | --- | --- | --- |
| **Site** | **Parrotfish density (ind. ha-1)** | **Bioerosion (kg CaCO3 m-2 yr-1)** | **Reference** |
| Gulf of Chiriquí | 422 | 0.20 | This study |
| Gulf of Panamá | 970 | 0.46 | This study |
| Gulf of Panamá (upwelling) | 970 | 0.22 | This study |
| Gorgona Island | 1544 | 1.59 | 20 |

Although our density estimates for the parrotfish assemblage are lower than the ones reported for the Gorgona Island, our population-density estimates for *S. rubroviolaceous* fall within the range of estimates reported for Uva Island reef between 1980 and 201024 (Fig. S3). On the other hand, our estimates for *S. ghobban* are higher than historical ones24 (Fig. S4). Almost all of the individuals recorded at our sites were juveniles, and although juveniles tend to have higher bite rates than adults, a smaller proportion of their bites are significant enough to scar the substrate. The absence of large excavating parrotfish species at our sites explains why parrotfish bioerosion is not the dominant bioeroding agent.



**Figure S3:** Historical (1980–2010) and recent (2018–2019) population-density estimates (ind m-2; mean ±95% CI) for *Scarus rubroviolaceous* at Uva Island reef, Gulf of Chiriquí. Historical data were retrieved and modified from Glynn et al.24.



**Figure S4:** Historical (1980–2010) and recent (2018–2019) population-density estimates (ind m-2; mean ±95% CI) for *Scarus ghobban* at Uva Island reef, Gulf of Chiriquí. Historical data were retrieved and modified from Glynn et al.24.

**Corallivory by *Arothron meleagris***

Multiple studies have assessed the population density and bioerosion rates of the pufferfish *Arothron meleagris* (Tetraodontidae)to determine its contribution to carbonate budgets25–27. The population density of *A. meleagris* varies across regions of the eastern Pacific from 0.3 ind ha-1 on Contadora Island, Gulf of Chiriquí to 231 ind ha-1 recorded at Azufrada Reef, Colombia27,28. The average population density of *A. meleagris* across the eastern Pacific is 46.5 ind ha-1 (Table S8). In 2018, we estimated an average population density of 0 and 33 ind. ha-1 for the Gulf of Panamá and the Gulf of Chiriquí, respectively. In 2019, we estimated an average population density of 0 and 23 ind ha-1 for the Gulf of Panamá and the Gulf of Chiriquí, respectively. When compared with historical data24, our population-density estimates for *A. meleagris* fall within the range of historical densities for Pacific Panamá (Fig. S5).

**Table S8:** Compilation of studies that have assessed the population density of *Arothron meleagris* on eastern Pacific reefs.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Country** | **Locality** | **Site** | **Date** | **Density (ind/ha)** | **Habitat** | **Reference** |
| Costa Rica | Caño Island | Caño Island | 1985 | 5 | *Porites* reef | 28 |
| Costa Rica | Caño Island | Caño Island | 1986/87 | 11 | *Porites* reef | 28 |
| Costa Rica | Caño Island | Caño Island | 1987 | 8 | *Porites* reef | 28 |
| Panama | Gulf of Chiriqui | Uva Island | 1981 | 50 | *Pocillopora* reef | 28 |
| Panama | Gulf of Chiriqui | Uva Island | 1981/84 | 55 | *Pocillopora* reef | 29 |
| Panama | Gulf of Chiriqui | Uva Island | 1986/89 | 55 | *Pocillopora* reef | 28 |
| Panama | Gulf of Chiriqui | Secas Island | 1986/88 | 27 | *Pocillopora* reef | 28 |
| Panama | Gulf of Panama | Señora Islet | 1971 | 40 | *Pocillopora* reef | 25 |
| Panama | Gulf of Panama | Señora Islet | 1987 | 0 | *Pocillopora* reef | 28 |
| Panama | Gulf of Panama | Saboga | 1987 | 0 | *Pocillopora* reef | 28 |
| Panama | Gulf of Panama | Contadora | 1987 | 0.3 | *Pocillopora* reef | 28 |
| Colombia | Gorgona Island | Azufrada reef | 1979 | 12 | *Pocillopora* reef | 30 |
| Colombia | Gorgona Island | Azufrada Reef | 1987/88 | 34 | *Pocillopora* reef | 28 |
| Colombia | Gorgona Island | Azufrada Reef | 1989 | 25.8 | *Pocillopora* reef | 31 |
| Colombia | Gorgona Island | Azufrada Reef | 1993 | 80 | *Pocillopora* reef | 32 |
| Colombia | Gorgona Island | Azufrada Reef | 2012 | 231 | Reef crest | 27 |
| Colombia | Gorgona Island | Azufrada Reef | 2012 | 192 | Reef flat | 27 |
| Colombia | Gorgona Island | Playa Blanca | 1989 | 21.9 | *Pocillopora* reef | 31 |
| Mexico | Gulf of California | Cabo Pulmo | 1991/92 | 39 | *Pocillopora* reef | 26 |
| Mexico | Tenacatita Bay | Playa Mora | 2002/04 | 43.7 | *Pocillopora* reef | 33 |

 For the bioerosion rates of *Arothron* *meleagris*, we used the estimates from Palacios et al.27. They estimated bioerosion by recording bite-rates and feeding activity in the wild, which yielded estimates that were eight times higher than those from previous studies in aquaria25,26.

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**Figure S5:** Historical (1980–2010) and recent (2018–2019) population-density estimates (ind m-2; mean ±95% CI) for *Arothron meleagris* at Uva Island reef, Gulf of Chiriquí. Historical data were retrieved and modified from Glynn et al.24.

**Sedimentation rates**

Sediments that fill the void spaces of the reef framework provide a significant contribution to reef accretion34. To estimate the amount of sediments that were incorporated into the reef framework, we used cores that were previously taken at the same reefs we surveyed to estimate the proportion of the reef framework that was composed of sediment. The relationship between the linear depth of the core samples and the radiocarbon ages, calibrated using the Marine 20 calibration curve35, was used to get an estimate of sediment accretion for each gulf in mm yr-1. The average sediment-accretion rates for the GoP and the GoC were 0.4 mm yr-1 and 0.3 mm yr-1, respectively. Since we are using bulk sediment volumes, these estimates include the influence of autochthonous and allochthonous sediments. If we assume that the average density of the sedimentary matrix is 1.1 g cm-3, based on estimates from Caribbean reef cores13, we get rates of sediment production of 0.4 and 0.3 kg CaCO3 m-2 yr-1 for the GoP and GoC, respectively. These rates of sediment production closely resemble those estimated by Hubbard34 for Caribbean reefs.

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