



THE  
GEOLOGICAL  
SOCIETY  
OF AMERICA®

# GEOLOGY

ISSN 0091-7613

DECEMBER 2009 ■ VOL. 37 NO. 12 ■ P. 1057-1152



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# Marine calcifiers exhibit mixed responses to CO<sub>2</sub>-induced ocean acidification

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## ABSTRACT

**Anthropogenic elevation of atmospheric carbon dioxide ( $p\text{CO}_2$ ) is making the oceans more acidic, thereby reducing their degree of saturation with respect to calcium carbonate ( $\text{CaCO}_3$ ). There is mounting concern over the impact that future CO<sub>2</sub>-induced reductions in the  $\text{CaCO}_3$  saturation state of seawater will have on marine organisms that construct their shells and skeletons from this mineral. Here, we present the results of 60 d laboratory experiments in which we investigated the effects of CO<sub>2</sub>-induced ocean acidification on calcification in 18 benthic marine organisms. Species were selected to span a broad taxonomic range (crustacea, cnidaria, echinoidea, rhodophyta, chlorophyta, gastropoda, bivalvia, annelida) and included organisms producing aragonite, low-Mg calcite, and high-Mg calcite forms of  $\text{CaCO}_3$ . We show that 10 of the 18 species studied exhibited reduced rates of net calcification and, in some cases, net dissolution under elevated  $p\text{CO}_2$ . However, in seven species, net calcification increased under the intermediate and/or highest levels of  $p\text{CO}_2$ , and one species showed no response at all. These varied responses may reflect differences amongst organisms in their ability to regulate pH at the site of calcification, in the extent to which their outer shell layer is protected by an organic covering, in the solubility of their shell or skeletal mineral, and in the extent to which they utilize photosynthesis. Whatever the specific mechanism(s) involved, our results suggest that the impact of elevated atmospheric  $p\text{CO}_2$  on marine calcification is more varied than previously thought.**

## INTRODUCTION

Surface ocean pH has already decreased by 0.1 units since the industrial revolution, and it is predicted to decline another 0.3–0.4 units by the end of this century (Brewer, 1997). This translates to a nearly 50% reduction in the carbonate ion concentration [ $\text{CO}_3^{2-}$ ] of surface seawater, resulting in aragonite and high-Mg calcite undersaturation in the high-latitude oceans. The effect of CO<sub>2</sub>-induced ocean acidification on marine calcification is currently the subject of intense scientific investigation with regard to both the immediate future (cf. Gattuso et al., 1998; Langdon et al., 2000; Langdon and Atkinson, 2005; Kleypas et al., 2006; see the GSA Data Repository<sup>1</sup>) and the geologic past (Knoll et al., 2007; Zhuravlev and Wood, 2008).

## METHODS

To investigate the impact of ocean acidification on a range of benthic marine calcifiers, we reared 18 calcifying species for 60 d in isothermal (25 °C; see the Data Repository for discussion) experimental seawaters equilibrated with average  $p\text{CO}_2$  values ( $\pm\text{SD}$ ) of 409 ( $\pm 6$ ), 606 ( $\pm 7$ ), 903 ( $\pm 12$ ), and 2856 ( $\pm 54$ ) ppm, corresponding to modern  $p\text{CO}_2$ , and ~2, 3, and 10 times pre-industrial levels (~280 ppm), respectively, and yielding average seawater saturation states ( $\pm\text{SD}$ ) of 2.5 ( $\pm 0.4$ ), 2.0 ( $\pm 0.4$ ),

1.5 ( $\pm 0.3$ ), and 0.7 ( $\pm 0.2$ ) with respect to aragonite (see the Data Repository for detailed methods). These carbonate system parameters were selected to represent the range of values predicted for the coming millennium (Brewer, 1997; Feely et al., 2004) and to span those reported to have occurred since mid-Cretaceous time (ca. 110 Ma; Royer et al., 2004; Tyrrell and Zeebe, 2004). The organisms' net rates of calcification (total calcification minus total dissolution) under the various  $p\text{CO}_2$  treatments were estimated from changes in their buoyant weight and verified with dry weight measurements after harvesting (Fig. 1; see Fig. DR1, Table DR3, and additional methods in the GSA Data Repository).

## RESULTS

In ten of the 18 species (temperate corals, pencil urchins, hard clams, conchs, serpulid worms, periwinkles, bay scallops, oysters, whelks, soft clams; Figs. 1I–1R), net calcification decreased with increasing  $p\text{CO}_2$  (reduced  $\text{CaCO}_3$  saturation state). And in six of the ten negatively impacted species (pencil urchins, hard clams, conchs, periwinkles, whelks, soft clams; Figs. 1J–1L, 1N, and 1Q–1R), we observed net dissolution of the shell in the highest  $p\text{CO}_2$  treatment, for which the experimental seawater was undersaturated with respect to aragonite and high-Mg calcite. However, in four of the 18 species (limpets, purple urchins, coralline red algae, calcareous green algae; Figs. 1D–1G), net calcification increased relative to the control under intermediate  $p\text{CO}_2$  levels (605 and 903 ppm), and then declined at the highest  $p\text{CO}_2$  level (2856 ppm). In three species (crabs, lobsters, and shrimps; Figs. 1A–1C), net calcification was greatest under the highest level of  $p\text{CO}_2$  (2856 ppm). And one species, the blue mussel (Fig. 1H), exhibited no response to elevated  $p\text{CO}_2$ .

Our experiments revealed six general calcification response patterns to elevated  $p\text{CO}_2$  (Fig. 1; Fig. DR3; Table 1): positive (Figs. 1A and 1B); threshold-positive (no change under intermediate  $p\text{CO}_2$ , positive under highest  $p\text{CO}_2$ ; Fig. 1C); parabolic (positive under intermediate  $p\text{CO}_2$ , negative under highest  $p\text{CO}_2$ ; Figs. 1D–1G); neutral (no change; Fig. 1H); threshold-negative (little or no change under intermediate  $p\text{CO}_2$ , negative under highest  $p\text{CO}_2$ ; Figs. 1I–1L); and negative (Figs. 1M–1R). A combination of factors, including the organisms' ability to regulate pH at the site of calcification, the extent of organic-layer coverage of their external shell, their biomineral solubility, and whether they utilize photosynthesis, may contribute to the disparity of these response patterns.

## FACTORS EXPLAINING VARIABLE RESPONSES AMONGST ORGANISMS

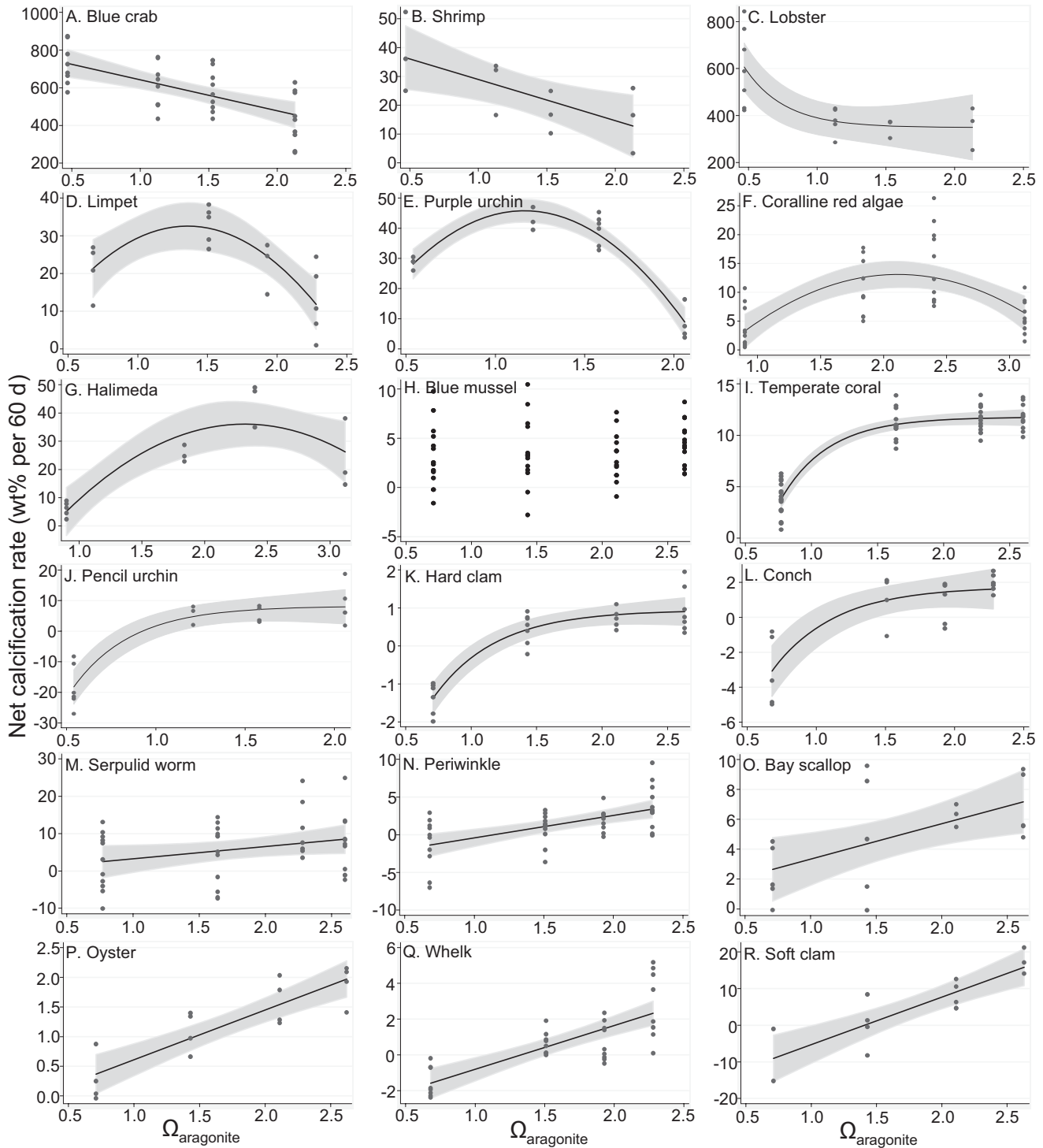
### Regulation of pH at the Site of Calcification Converts $\text{HCO}_3^-$ to $\text{CO}_3^{2-}$

Many calcifying organisms, including scleractinian corals (Al-Horani et al., 2003; Cohen and McConnaughey, 2003), coralline red algae (Borowitzka, 1987; McConnaughey and Whelan, 1997), calcareous green algae (Borowitzka, 1987; McConnaughey and Whelan, 1997; De Beer and Larkum, 2001), foraminifera (Rink et al., 1998), and crabs (Cameron, 1985) are thought to facilitate  $\text{CaCO}_3$  precipitation by elevating pH at the site of calcification. This reduction in  $[\text{H}^+]$  converts  $\text{HCO}_3^-$  to  $\text{CO}_3^{2-}$ , elevating  $[\text{CO}_3^{2-}]$  within calcifying compartments.

Microelectrode data (Rink et al., 1998; De Beer and Larkum, 2001; Al-Horani et al., 2003) show elevated pH—up to 2 units above external seawater—at sites of calcification in several marine calcifiers. These

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<sup>1</sup>GSA Data Repository item 2009279, supplementary information, Table DR1, Figures DR1 and DR2, is available online at [www.geosociety.org/pubs/ft2009.htm](http://www.geosociety.org/pubs/ft2009.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 1.** Calcification response patterns for 18 species of calcifying organisms subjected for 60 d to  $\text{CO}_2$ -induced reductions in  $\text{CaCO}_3$  saturation state of seawater. Net rates of calcification(+)/dissolution(-) were estimated from buoyant weighing (verified with dry weight measured after harvesting) and are expressed as a percentage of the organisms' initial buoyant weight (see GSA Data Repository Fig. DR1 and Tables DR1 and DR3 [see footnote 1]). *Halimeda* growth is in mg/day, since all measured algae emerged under experimental conditions (i.e., initial weight was zero). Linear, quadratic, and exponential regression analyses were used to examine relationship between net calcification rate and aragonite saturation state (Table 1). These regressions were calculated using least squares method and adjusted for clustering within tanks with generalized estimating equations, which employ the Huber-White sandwich estimator of variance in place of the standard estimator of variance to increase the rigor of the test for statistical significance (Rogers, 1993; see GSA Data Repository). The regression analysis (linear, quadratic, or exponential) that yielded the lowest mean squared error for each species is plotted above (see Table 1 and Table DR5). All plotted regressions are statistically significant ( $p \leq 0.05$ ); 95% confidence intervals are shown in gray. Regression analyses are intended to show general trends—the locations of the break-in-slope of the exponential curves (B, I-L) are not precisely constrained by the available data.  $\Omega_{\text{aragonite}} = [\text{Ca}^{2+}][\text{CO}_3^{2-}]/K_{\text{sp}}^*$ , where  $K_{\text{sp}}^*$  is the stoichiometric solubility product of aragonite.  $\Omega_{\text{aragonite}}$  was calculated from measured values of temperature, salinity, alkalinity, and pH (see Table DR2 [see footnote 1]) using Roy et al. (1993) values for carbonic acid constants  $K_1$  and  $K_2$  (see GSA Data Repository [see footnote 1]), the Mucci (1983) value for  $K_{\text{sp}}^*$ , and pressure ( $P$ ) = 1.015 atm.



TABLE 1. REGRESSION ANALYSES OF  $\Omega_{\text{ARAGONITE}}$  VS. NET CALCIFICATION RATE AND SUMMARY OF CALCIFICATION-RELEVANT TRAITS

Organism	Scientific name	Panel (Fig. 1)	Best-fit Regression*					Response†	Mineralogy‡	Cover#	Photo**
			Regression	Type	p	R <sup>2</sup>	RMSE				
Crab	<i>Callinectes sapidus</i>	A	$y = -165x + 807$	LIN	0.00	0.41	120.71	positive	HMC	high	no
Shrimp	<i>Penaeus plebejus</i>	B	$y = -14.3x + 43.3$	LIN	0.01	0.47	9.98	positive	HMC	high	no
Lobster	<i>Homarus americanus</i>	C	$y = 1296e^{-0.44x} + 348$	EXP	0.00	0.57	112.11	threshold(+)	HMC	high	no
Limpet	<i>Crepidula fornicata</i>	D	$y = -24.4x^2 + 66.3x - 12.5$	QUAD	0.00	0.59	7.17	parabolic	Arag>LMC	low	no
Purple urchin	<i>Arbacia punctulata</i>	E	$y = -45.7x^2 + 106x - 15.9$	QUAD	0.00	0.91	4.65	parabolic	HMC	high	no
Coralline red alga	<i>Neogoniolithon</i> sp.	F	$y = -6.66x^2 + 28.2x - 16.7$	QUAD	0.03	0.43	4.86	parabolic	HMC	high	yes
Halimeda	<i>Halimeda incrassata</i>	G	$y = -15.4x^2 + 71.2x - 46.6$	QUAD	0.02	0.74	8.73	parabolic	Arag	high	yes
Blue mussel	<i>Mytilus edulis</i>	H	no significant trend ( $p > 0.05$ )	NONE	n/a	n/a	n/a	neutral	LMC>Arag	mod	no
Temperate coral	<i>Oculina arbuscula</i>	I	$y = -67.2e^{-0.277x} + 11.8$	EXP	0.00	0.87	1.43	threshold(-)	Arag	high	yes
Pencil urchin	<i>Eucidaris tribuloides</i>	J	$y = -137e^{-0.40x} + 8.25$	EXP	0.02	0.84	5.68	threshold(-)	HMC	low	no
Hard clam	<i>Mercenaria mercenaria</i>	K	$y = -10.3e^{-0.210x} + 0.94$	EXP	0.00	0.83	0.44	threshold(-)	Arag>HMC	low	no
Conch	<i>Strombus alatus</i>	L	$y = -21.9e^{-0.222x} + 1.75$	EXP	0.00	0.69	1.37	threshold(-)	Arag>LMC	low	no
Serpulid worm	<i>Hydroides crucigera</i>	M	$y = 1.64x - 0.02$	LIN	0.05	0.08	3.93	negative	Arag + HMC	low	no
Periwinkle	<i>Littorina littorea</i>	N	$y = 2.99x - 3.41$	LIN	0.00	0.34	2.55	negative	LMC>Arag	mod	no
Bay scallop	<i>Argopecten irradians</i>	O	$y = 2.37x - 0.97$	LIN	0.00	0.34	2.61	negative	LMC	low	no
Oyster	<i>Crassostrea virginica</i>	P	$y = 0.84x - .23$	LIN	0.00	0.76	0.36	negative	LMC	low	no
Whelk	<i>Urosalpinx cinerea</i>	Q	$y = 2.45x - 3.26$	LIN	0.01	0.58	1.28	negative	Arag>LMC	low	no
Soft clam	<i>Mya arenaria</i>	R	$y = 13.0x - 18.2$	LIN	0.00	0.73	5.31	negative	Arag>HMC	low	no

\*Linear (LIN), quadratic (QUAD), and exponential (EXP) regression analyses were performed for each species using the least squares method (see Table DR5 [see footnote 1]). The regression analysis that yielded the lowest square root of the mean squared error (RMSE) for a given species and that was statistically significant ( $p \leq 0.05$ ) is listed above and plotted in Fig. 1. p—p-value; R<sup>2</sup>—correlation coefficient; y—net calcification rate; x— $\Omega_{\text{ARAGONITE}}$ .

†Response—generalized calcification response pattern exhibited by organisms reared under elevated  $p\text{CO}_2$ ; organisms ranked in increasingly negative order.

‡Mineralogy—polymorph of  $\text{CaCO}_3$  in shell or skeleton (see GSA Data Repository for references), confirmed with X-ray diffraction and scanning electron microscopy; HMC—high-Mg calcite (>4 mol%  $\text{MgCO}_3$ ); LMC—low-Mg calcite (<4 mol%  $\text{MgCO}_3$ ); Arag—aragonite.

#Cover—extent to which shell or skeleton is covered by organic layer.

\*\*Photo—whether organism utilizes  $\text{CO}_2$  via photosynthesis.

localized increases in pH may be achieved in various ways, for example, via conventional proton channeling,  $\text{Ca}^{2+}$ -activated proton-translocating ATPase, light-induced proton-pumping, transcellular symporter and co-transporter proton-solute shuttling, cellular extrusion of hydroxyl ions ( $\text{OH}^-$ ) into the calcifying medium, and  $\text{CO}_2$  utilization via photosynthesis (Borowitzka, 1987; McConnaughey and Whelan, 1997; De Beer and Larkum, 2001; Cohen and McConnaughey, 2003).

The decrease in seawater pH that will accompany the forecasted rise in anthropogenic  $p\text{CO}_2$  will reduce the  $[\text{CO}_3^{2-}]$  of seawater, and, for many organisms, there is experimental evidence that a reduction in seawater  $[\text{CO}_3^{2-}]$  will inhibit calcification, and perhaps cause dissolution of existing shell (cf. Gattuso et al., 1998; Langdon et al., 2000; Langdon and Atkinson, 2005; Kleypas et al., 2006). It is also possible, however, that calcification in some organisms will be enhanced under elevated  $p\text{CO}_2$ . If seawater is the source of the organism's calcifying fluid, then the concentration of dissolved inorganic carbon (DIC) in this fluid will increase as  $p\text{CO}_2$  increases. Organisms able to maintain an elevated pH at their site of calcification, despite reduced external pH, will convert much of this increased DIC, occurring primarily as  $\text{HCO}_3^-$ , to  $\text{CO}_3^{2-}$ . These organisms may experience a final  $[\text{CO}_3^{2-}]$  at their site of calcification that is only slightly less than, and possibly equal to or greater than, that attained under present-day  $p\text{CO}_2$ —depending upon the efficiency of their specific proton-regulating mechanism. Alternatively, organisms such as coccolithophores may utilize  $\text{HCO}_3^-$  directly in calcification (Iglesias-Rodriguez et al., 2008), although mesocosm experiments suggest that reef-building organisms lack this ability (Langdon et al., 2000; Schneider and Erez, 2006). Nonetheless, the ability to convert  $\text{HCO}_3^-$  to  $\text{CO}_3^{2-}$  via proton regulation at the site of calcification, and/or utilize  $\text{HCO}_3^-$  directly in calcification, may explain, in part, why some of the organisms investigated in our experiments exhibited enhanced calcification under conditions of elevated  $p\text{CO}_2$ .

Of the calcifiers that have been investigated in microelectrode studies, those reported to maintain their calcifying fluids at higher pH (corals: 9.3 [Al-Horani et al., 2003; Fig. 1I] and calcareous green algae: 8.8–10.5 [De Beer and Larkum, 2001; Fig. 1G]) were generally less negatively affected

by elevated  $p\text{CO}_2$  in our experiments than those reported to maintain their calcifying fluid at lower pH (bivalve molluscs: pH = 7.33–8.53 [Crenshaw, 1972; Figs. 1K, 1O–1R]). These observations are consistent with the hypothesis that organisms able to maintain an elevated pH and, thus, elevated  $[\text{CO}_3^{2-}]$  at their site of calcification could be less negatively impacted by  $\text{CO}_2$ -induced reductions in the  $\text{CaCO}_3$  saturation state of seawater.

### Protective External Organic Layer

Most calcifying marine organisms produce some type of external organic layer that separates their shell or skeleton from ambient seawater. Crustacea enclose their carapace within a relatively thick epicuticle, urchins cover their tests with an epidermis, algae precipitate  $\text{CaCO}_3$  in spaces bound by cortical tissue, corals nucleate aragonite beneath several layers of epithelial tissue, and molluscs cover their shells with periostracum. The structure and composition of these protective organic layers vary widely amongst organisms. Through visual inspection, we have classified the organisms investigated in this study by their extent of organic-layer coverage (Table 1; high = total coverage; moderate = majority coverage; low = minority coverage). Organisms that accrete shell or skeleton that remains totally covered by an external organic layer, such as the crustacea (Figs. 1A–1C), purple urchins (Fig. 1E), coralline red algae (Fig. 1F), calcareous green algae (Fig. 1G), blue mussel (Fig. 1H), and temperate corals (Fig. 1I), generally exhibited greater resilience to elevated  $p\text{CO}_2$  than those producing shell that is largely exposed to ambient seawater after deposition, such as the conchs (Fig. 1L), serpulid worms (Fig. 1M), periwinkles (Fig. 1N), scallops (Fig. 1O), oysters (Fig. 1P), whelks (Fig. 1Q), and clams (Figs. 1K and 1R).

### $\text{CaCO}_3$ Polymorph Mineralogy

It is also predicted that organisms utilizing the more soluble forms of  $\text{CaCO}_3$ —aragonite and high-Mg calcite—would be more adversely affected by elevated  $p\text{CO}_2$  than those utilizing the less soluble low-Mg calcite form (Morse et al., 2007). Although we did not observe a direct relationship between skeletal mineral solubility and vulnerability to elevated

$p\text{CO}_2$  (Table 1) under the intermediate  $p\text{CO}_2$  levels (606 and 903 ppm), mineralogy did come into play for the highest  $p\text{CO}_2$  level (2856 ppm). Of the six species that exhibited net dissolution under these conditions (pencil urchin, hard clam, conch, periwinkle, whelk, and soft clam; Figs. 1J–1L, 1N, and 1Q–1R), five of these secrete shells that are composed predominantly of the more soluble aragonite (hard clam, conch, whelk, soft clam) and high-Mg calcite (pencil urchin) polymorphs.

### Fertilization of Photosynthesis

The coralline red (Fig. 1F) and calcareous green algae (Fig. 1G) investigated in this study both exhibited increased net calcification under the intermediate  $p\text{CO}_2$  levels (606 and 903 ppm), and the temperate corals (Fig. 1I), which contain photosynthetic symbionts, exhibited no response over this range. This suggests that the direct utilization of  $\text{CO}_2$  via photosynthesis may also influence an organism's calcification response to  $\text{CO}_2$ -induced reductions in saturation state (Table 1). Although the relationship between photosynthesis and calcification is complex, increased  $\text{CO}_2$  in seawater may increase the organism's rate of photosynthesis (Bowes, 1993; Iglesias-Rodriguez et al., 2008), potentially increasing the amount of energy available for converting  $\text{HCO}_3^-$  to  $\text{CO}_3^{2-}$  via pH regulation at the site of calcification. The parabolic calcification response patterns exhibited by the coralline red algae (Fig. 1F) and calcareous green algae (Fig. 1G) in our experiments, which peaked between 600 and 1100 ppm  $p\text{CO}_2$ , are consistent with previous work showing that  $p\text{CO}_2$  is only limiting for photosynthesis in marine algae at partial pressures less than 1000 ppm (Bowes, 1993).

### IDENTIFICATION OF OCEAN ACIDIFICATION EVENTS IN THE GEOLOGIC PAST

Past ocean acidification events, reportedly associated with intervals of intense global volcanism, have been invoked as potential drivers of mass extinctions that have occurred throughout Phanerozoic time (e.g., Knoll et al., 2007). The present study, by identifying both positive and negative responses to elevated  $p\text{CO}_2$  for a wide range of organisms, offers a unique, polyphyletic fingerprint for identifying such  $\text{CO}_2$ -induced extinction events in the fossil record.

### CONCLUSIONS

Our experiments suggest that the response of calcifying marine organisms to elevated atmospheric  $p\text{CO}_2$  will be variable and complex. However, with the data at hand, it is difficult to predict how these changes in calcification will impact organisms' survival, reproductive success, and overall ecosystem health. Even those organisms showing enhanced calcification under elevated  $p\text{CO}_2$  could be negatively impacted by the decline of less  $\text{CO}_2$ -tolerant species within their ecosystems. We have only begun to generate the data needed to assess  $\text{CO}_2$ -driven impacts on organisms and ecosystems in the geologic past, and to anticipate the effects of anthropogenic ocean acidification in the decades and centuries ahead.

### ACKNOWLEDGMENTS

We thank G. Piniak (National Oceanic and Atmospheric Administration), J. Diamond (Marine Biological Laboratory), O. Zmora (University of Maryland, Center of Marine Biotechnology), and R. Crowley (Stonington Lobster Hatchery) for generously providing experimental specimens. M. Holcomb provided critical feedback on the design and implementation of the experiments. This work was supported by funding from the Woods Hole Oceanographic Institution (to Ries and Cohen) and the National Science Foundation (to Cohen and McCorkle).

### REFERENCES CITED

Al-Horani, F.A., Al-Moghrabi, S.M., and De Beer, D., 2003, The mechanism of calcification and its relation to photosynthesis and respiration in the scleractinian coral *Galaxea fascicularis*: *Marine Biology* (Berlin), v. 142, p. 419–426.  
 Borowitzka, M.A., 1987, Calcification in algae—Mechanisms and the role of metabolism: *Critical Reviews in Plant Sciences*, v. 6, no. 1, p. 1–45.  
 Bowes, G., 1993, Facing the inevitable: Plants and increasing atmospheric  $\text{CO}_2$ : *Annual Review of Plant Physiology and Plant Molecular Biology*, v. 44, no. 1, p. 309–332, doi: 10.1146/annurev.pp.44.060193.001521.

Brewer, P.G., 1997, Ocean chemistry of the fossil fuel  $\text{CO}_2$  signal: The haline signal of "business as usual": *Geophysical Research Letters*, v. 24, p. 1367–1369, doi: 10.1029/97GL01179.  
 Cameron, J.N., 1985, Post-moult calcification in the blue crab (*Callinectes sapidus*): Relationships between apparent net  $\text{H}^+$  excretion, calcium and bicarbonate: *The Journal of Experimental Biology*, v. 119, p. 275–285.  
 Cohen, A.L., and McConnaughey, T.A., 2003, A geochemical perspective on coral mineralization, in Dove, P.M., Weiner S., and De Yoreo, J.J., eds., *Biom mineralization: Reviews in Mineralogy and Geochemistry*, v. 54, p. 151–187.  
 Crenshaw, M.A., 1972, The inorganic composition of molluscan extrapallial fluid: *The Biological Bulletin*, v. 143, p. 506–512.  
 De Beer, D., and Larkum, A.W.D., 2001, Photosynthesis and calcification in the calcifying alga *Halimeda discoidea* studied with microsensors: *Plant, Cell, and Environment*, v. 24, no. 1, p. 1209–1217.  
 Feely, R.A., Sabine, C.S., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J., and Millero, F.J., 2004, Impact of anthropogenic  $\text{CO}_2$  on the  $\text{CaCO}_3$  system in the oceans: *Science*, v. 305, no. 5682, p. 362–366, doi: 10.1126/science.1097329.  
 Gattuso, J.P., Frankignoulle, M., Bourge, I., Romaine, S., and Buddemeier, R.W., 1998, Effect of calcium carbonate saturation of seawater on coral calcification: *Global and Planetary Change*, v. 18, no. 1–2, p. 37–46.  
 Iglesias-Rodriguez, M.D., Halloran, P.R., Rickaby, R.E.M., Hall, I.R., Colmenero-Hidalgo, E., Gittins, J.R., Green, D.R.H., Tyrrell, T., Gibbs, S.J., von Dassow, P., Rehm, E., Armbrust, E.V., and Boessenkool, K.P., 2008, Phytoplankton calcification in a high- $\text{CO}_2$  world: *Science*, v. 320, no. 5874, p. 336–340, doi: 10.1126/science.1154122.  
 Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L., and Robbins, L.L., 2006, Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research: Report of a workshop held 18–20 April 2005, St. Petersburg, Florida, sponsored by the National Science Foundation, National Oceanic and Atmospheric Administration, and the U.S. Geological Survey: <http://www.healthyreefs.org/pdf/communicati.pdf>, 88 p.  
 Knoll, A.H., Bambach, R.K., Payne, J.L., Pruss, S., and Fischer, W.W., 2007, Paleophysiology and end-Permian mass extinction: *Earth and Planetary Science Letters*, v. 256, p. 295–313, doi: 10.1016/j.epsl.2007.02.018.  
 Langdon, C., and Atkinson, M.J., 2005, Effect of elevated  $p\text{CO}_2$  on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment: *Journal of Geophysical Research*, v. 110, p. C09S07, doi: 10.1029/2004JC002576.  
 Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., Barnett, H., and Atkinson, M.J., 2000, Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef: *Global Biogeochemical Cycles*, v. 14, no. 2, p. 639–654, doi: 10.1029/1999GB001195.  
 McConnaughey, T.A., and Whelan, J.F., 1997, Calcification generates protons for nutrient and bicarbonate uptake: *Earth-Science Reviews*, v. 42, no. 1–2, p. 95–117.  
 Morse, J.W., Arvidson, R.S., and Lutge, A., 2007, Calcium carbonate formation and dissolution: *Chemical Reviews*, v. 107, p. 342–381, doi: 10.1021/cr050358j.  
 Mucci, A., 1983, The solubility of calcite and aragonite in seawater at various salinities, temperatures, and one atmosphere total pressure: *American Journal of Science*, v. 283, p. 780–799.  
 Rink, S., Kuhl, M., Bijma, J., and Spero, H.J., 1998, Microsensor studies of photosynthesis and respiration in the symbiotic foraminifer *Orbulina universa*: *Marine Biology* (Berlin), v. 131, p. 583–595, doi: 10.1007/s002270050350.  
 Rogers, W.H., 1993, Regression standard errors in clustered samples: *Stata Technical Bulletin*, v. 13, p. 19–23.  
 Roy, R.N., Roy, L.N., Vogel, K.M., Porter-Moore, C., Pearson, T., Good, C.E., Millero, F.J., and Campbell, D.M., 1993, The dissociation constants of carbonic acid in seawater at salinities 5 to 45 and temperatures 0 to 45°C: *Marine Chemistry*, v. 44, p. 249–267, doi: 10.1016/0304-4203(93)90207-5.  
 Royer, D.L., Berner, R.A., Montañez, I.P., Tabor, N.J., and Beerling, D.J., 2004,  $\text{CO}_2$  as a primary driver of Phanerozoic climate: *GSA Today*, v. 14, no. 3, p. 4–10, doi: 10.1130/1052-5173(2004)014<4:CAAPDO>2.0.CO;2.  
 Schneider, K., and Erez, J., 2006, The effect of carbonate chemistry on calcification and photosynthesis in the hermatypic coral *Acropora eurystoma*: *Limnology and Oceanography*, v. 51, no. 3, p. 1284–1293.  
 Tyrrell, T., and Zeebe, R.E., 2004, History of carbonate ion concentration over the last 100 million years: *Geochimica et Cosmochimica Acta*, v. 68, no. 17, p. 3521–3530, doi: 10.1016/j.gca.2004.02.018.  
 Zhuravlev, A.Y., and Wood, R.A., 2008, Eve of biomineralization: Controls on skeletal mineralogy: *Geology*, v. 36, p. 923–926, doi: 10.1130/G25094A.1.

Manuscript received 7 March 2009

Revised manuscript received 16 July 2009

Manuscript accepted 21 July 2009

Printed in USA

## **GSA-DR material for Ries et al. (2009, *Geology* 37: 1131-1134)**

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### **1. Experimental growth conditions**

Organisms were grown for 60 days in 24 38-Liter glass aquaria filled with 0.2  $\mu\text{m}$ -filtered seawater obtained from Great Harbor in Vineyard Sound off the coast of Cape Cod, Massachusetts. The aquaria were divided into six sets of four, which were continuously equilibrated with air-CO<sub>2</sub> gas mixtures ( $\pm$  SD) of 409 ( $\pm$  6), 606 ( $\pm$  7), 903 ( $\pm$  12), and 2856 ( $\pm$  54) ppm  $p\text{CO}_2$ , yielding average seawater saturation states ( $\pm$  SD) of 2.5 ( $\pm$ 0.4), 2.0 ( $\pm$ 0.4), 1.5 ( $\pm$ 0.3), and 0.7 ( $\pm$ 0.2) with respect to aragonite and 3.8 ( $\pm$ 0.5), 3.1 ( $\pm$ 0.7), 2.3 ( $\pm$ 0.4), and 1.1 ( $\pm$ 0.2) with respect to calcite (Table DR2).

Organisms were grouped in the same sets of aquaria as follows: set 1 - *Callinectes sapidus* (blue crab) and *Homarus americanus* (american lobster); set 2 - *Penaeus plebejus* (edible shrimp), *Littorina littorea* (periwinkle), *Urosalpinx cinerea* (whelk), *Crepidula fornicata* (limpet), and *Strombus alatus* (conch); set 3 - *Halimeda incrassata* (calcareous

green alga) and *Neogoniolithon* sp. (coralline alga); set 4 - *Eucidaris tribuloides* (tropical urchin) and *Arbacia punctulata* (temperate urchin); set 5 - *Hydroides crucigera* (feather duster worm) and *Oculina arbuscula* (temperate coral); set 6 - *Mercenaria mercenaria* (quahog), *Mytilus edulis* (blue mussel), *Mya arenaria* (softshell clam), *Argopecten irradians* (bay scallop), and *Crassostrea virginica* (eastern oyster).

The experimental seawaters were maintained at  $25 \pm 1^\circ\text{C}$  using 50-watt electric heaters. Each tank was continuously filtered with polyester fleece and activated carbon at the rate of 600 L/hour. Aquaria sets 2, 3, and 5 were illuminated with 10 hours/day of 426 Watts per square meter ( $\text{W}/\text{m}^2$ ) irradiance (T8, 8000K aquarium spectrum lamps), aquaria sets 4 and 6 were illuminated with 10 hours/day of 213  $\text{W}/\text{m}^2$  irradiance (T8, 8000K aquarium spectrum lamps), and aquaria set 1 was not illuminated. Each aquarium and attached filtration system was covered with plastic wrap to facilitate equilibration between the gas mixtures and the experimental seawaters and to minimize evaporative water-loss. Seventy-five percent seawater changes (using seawater pre-equilibrated with the experimental air- $\text{CO}_2$  mixtures) were made approximately every 14 days.

Heterotrophic organisms were fed every other day as follows (Table DR4): 900 mg wet weight (mg w-wt) frozen brine shrimp to each *Callinectes sapidus* (blue crab) and *Homarus americanus* (american lobster); 210 mg w-wt edible shrimp to each *Penaeus plebejus* (edible shrimp); 10 mg dry weight (mg d-wt) green algae to each *Littorina littorea* (periwinkle), *Urosalpinx cinerea* (whelk), *Crepidula fornicata* (limpet); 50 mg d-wt green algae to each *Strombus alatus* (conch); 90 mg d-wt green algae to each

*Eucidaris tribuloides* (tropical urchin) and *Arbacia punctulata* (temperate urchin); 90 mg w-wt frozen brine shrimp to each *Hydroides crucigera* (feather duster worm); 330 mg w-wt frozen brine shrimp to each *Oculina arbuscula* (temperate coral); 290 mg w-wt puréed frozen brine shrimp and 10 mg d-wt puréed green algae to each *Mercenaria mercenaria* (quahog), *Mytilus edulis* (blue mussel), *Mya arenaria* (softshell clam), *Argopecten irradians* (bay scallop), and *Crassostrea virginica* (eastern oyster).

## **2. Maintenance of seawater at 25°C**

A seawater temperature of 25°C was employed in these experiments because this value falls within the narrow range of temperatures that is experienced by all of the organisms investigated in this study at some point during the year (Table DR4). Furthermore, a fixed water temperature is necessary to maintain an equivalent range of aragonite saturation states amongst the six sets of aquaria, as temperature plays an important role in determining the effect of  $p\text{CO}_2$  on the aragonite saturation state of seawater (Morse and Mackenzie, 1990). Nevertheless, we recognize that temperature stress could potentially modify an organism's response to  $p\text{CO}_2$ -induced reductions in  $\text{CaCO}_3$  saturation state. However, it is unlikely that the wide range of calcification responses observed in our experiments (Fig. 1) results from differential temperature stress, as both positive and negative calcification response patterns were exhibited by tropical as well as temperate species (Fig. 1; Table DR4).



### 3. Carbonate system manipulation and constraint

The experimental air-CO<sub>2</sub> gases ( $\pm$  SD) of 409 ( $\pm$  6), 606 ( $\pm$  7), 903 ( $\pm$  12), and 2856 ( $\pm$  54) ppm  $p\text{CO}_2$  were formulated using *Cole-Parmer* mass flow controllers (catalog #: K-32907-51; K-32661-16; 00119FB). These air-CO<sub>2</sub> gas mixtures were introduced to the aquaria with 6-inch micro-porous air-stones secured to the base of the aquaria at approximately 30 cm depth. Salinity, temperature, and pH of the experimental seawaters were measured weekly, while alkalinity of the experimental seawaters and  $p\text{CO}_2$  of the mixed gases were measured biweekly. Aragonite saturation state, DIC, and  $p\text{CO}_2$  were calculated from these measured parameters. Average ( $\pm$  standard deviation) values of the measured and calculated carbonate system parameters are presented in Table DR2.

#### *a. Measured parameters (Table DR2)*

Mixed-gas  $p\text{CO}_2$  was measured with a *Qubit S151* infrared  $p\text{CO}_2$  analyzer calibrated with certified air-CO<sub>2</sub> mixed-gas standards (precision =  $\pm$ 2.0%; accuracy =  $\pm$ 1.8%).

Temperature was measured with a partial-immersion mercury-glass thermometer (precision =  $\pm$ 0.3%, accuracy =  $\pm$ 0.4%). Salinity was determined from the measurement of total dissolved solids (TDS) and/or using a refractometer calibrated with simultaneous determinations of TDS (precision =  $\pm$ 0.3%; accuracy =  $\pm$ 0.4%). Alkalinity of seawater in each aquarium was determined biweekly via small (precision =  $\pm$ 0.5%, accuracy =  $\pm$ 0.5%) and/or large volume Gran titrations (precision =  $\pm$ 0.3%, accuracy =  $\pm$ 0.3%) calibrated with certified Dickson alkalinity standards. Seawater pH was determined weekly using an *Orion* pH electrode/meter calibrated with certified NBS pH standards of 4.01, 7.00, and 10.01 (precision =  $\pm$ 0.01; accuracy =  $\pm$ 0.02).

The alkalinity in several sets of tanks was greater for treatments equilibrated with the highest  $p\text{CO}_2$  (2856 ppm) than for tanks equilibrated with lower  $p\text{CO}_2$  (409, 606, 903 ppm; see Table DR2). This was caused by the dissolution of  $\text{CaCO}_3$  occurring in response to the undersaturated conditions ( $\Omega_{\text{arag}} < 1$ ) maintained within the highest  $p\text{CO}_2$  treatments. This should not pose a problem to the interpretation of the results because the calcification response patterns are plotted as a function of the saturation state of seawater with respect to aragonite. Since this parameter is calculated from both the pH and alkalinity of the seawater, it accounts for any effects that the increased alkalinity would have on the aragonite saturation state of the experimental seawaters.

*b. Calculated parameters (Table DR2)*

Aragonite saturation states and DIC of the experimental seawaters, and  $p\text{CO}_2$  of the mixed gases, were calculated from the measured values of temperature, salinity, alkalinity and pH using the program CO2SYS (Pierrot et al, 2006) with Roy et al. (1993) values for carbonic acid constants  $K_1$  and  $K_2$ , Mucci (1983) value for the stoichiometric aragonite solubility product, and pressure = 1.15 atm. Differences amongst  $\Omega_{\text{aragonite}}$  for the experimental seawaters equilibrated with the four  $p\text{CO}_2$  levels are statistically significant ( $p \leq 0.05$ ) for each of the six sets of tanks (Table DR2). Dissolved inorganic carbon (DIC) calculated from simultaneous measurements of pH, alkalinity, temperature, and salinity had an average %-difference of 1.7% relative to DIC values determined at the start of the experiment by large volume Gran Titration (Bradshaw et al., 1981)

calibrated with certified Dickson DIC standards (precision =  $\pm 0.1\%$ , accuracy =  $\pm 0.1\%$ ; Fig. DR2).

#### **4. Selection of dissociation constants for CO2SYS carbonate system calculations**

We recognize that the choice of carbonate dissociation constants will influence the calculated carbonate system parameters, including the two parameters of most relevance to this study - carbonate ion concentration and aragonite saturation state. For example, using carbonate dissociation constants from Roy et al. (1993) in these calculations results in higher carbonate ion concentrations (by  $6.6 \pm 2.5 \mu\text{mol/kg CO}_3^-$ ), and lower aqueous  $\text{CO}_2$  and  $\text{HCO}_3^-$  concentrations (by  $0.2 \pm 0.1$  and  $13.3 \pm 5.1 \mu\text{mol/kg HCO}_3^-$ ), than those calculated using dissociation constants from Dickson and Millero (1987). As a result, using Roy et al (1993) constants with alkalinity and pH as inputs yields a higher estimate of the aragonite saturation state of the 24 aquaria (by  $0.11 \pm 0.04 \mu\text{mol/kg}$ ) than using the Dickson and Millero (1987) constants. However, this difference is small relative to the differences amongst the aragonite saturation states corresponding to the four  $p\text{CO}_2$  levels employed in our experiments. Recalculating our saturation state values with different sets of constants does not visibly alter our figures or the trends they show, nor will it materially alter our discussion of or conclusions from these experiments.

#### **5. Specimen collection**

Organisms were collected, pursuant to local, state, and federal regulations, from the following US localities (Table DR4): *Callinectes sapidus* (blue crab) from the Chesapeake Bay, Maryland; *Homarus americanus* (american lobster) from the Gulf of Maine;

*Penaeus plebejus* (edible shrimp), *Eucidaris tribuloides* (tropical urchin), and *Arbacia punctulata* (temperate urchin) from the Atlantic Ocean off the coast of Florida; *Littorina littorea* (periwinkle), *Urosalpinx cinerea* (whelk), *Crepidula fornicata* (limpet), *Mytilus edulis* (blue mussel), and *Crassostrea virginica* (eastern Oyster) from Buzzards Bay, Massachusetts; *Strombus alatus* (conch) from the Gulf of Mexico off the coast of Florida; *Hydroides crucigera* (feather duster worm), *Mercenaria mercenaria* (quahog), *Mya arenaria* (softshell clam), and *Argopecten irradians* (bay scallop) from Nantucket Sound off the coast of Massachusetts; and *Oculina arbuscula* (temperate coral) from the Atlantic Ocean off the coast of North Carolina. After collection, organisms were transported by airplane, boat, or automobile to the Environmental Systems Laboratory at the Woods Hole Oceanographic Institution, where they were immediately placed in holding tanks equilibrated with ambient  $p\text{CO}_2$  (~409 ppm). After approximately 14 days of acclimatization to the laboratory conditions, healthy specimens were transferred to the experimental seawaters for an additional 14 days of acclimatization prior to the official start of the experiment.

## **6. Buoyant weighing technique**

A buoyant weighing method (precision =  $\pm 0.3\%$ ; accuracy varies from  $\pm 0.4\%$  to  $\pm 6.2\%$ , depending on type of organism – see Fig. DR1 and Table DR3) was employed to estimate the organisms' net rates of calcification/dissolution under the experimental conditions (Table DR1). Specimens were suspended at 15 cm depth in an aquarium filled with 0.2  $\mu\text{m}$ -filtered seawater ( $T = 25\text{ }^\circ\text{C}$ ,  $\text{Sal} = 32\text{ ppt}$ ) by a hook or basket attached to an aluminum wire hanging from a *Cole Parmer* bottom-loading scale. Net calcification rates were

calculated as the %-weight difference between the specimens' buoyant weight at the beginning and end of the 60-day experiment. This percentage change in the buoyant weight of these organisms will reflect their total calcification minus their CaCO<sub>3</sub> lost through dissolution, molting, or abrasion. This is referred to in the text as their "net calcification/dissolution rate." Measured changes in buoyant weight were generally on the order of hundreds or thousands of milligrams, well above the milligram precision of the scale. Sixty-day calcification rates were normalized to the specimen's initial size by dividing the specimen's calcification rate by its buoyant weight at the beginning of the experiment (Fig. 1; Table DR1).

The buoyant weighing method for estimating dry CaCO<sub>3</sub> weight was calibrated for each of the organisms investigated in this study by plotting each specimen's final buoyant weight against its final dry CaCO<sub>3</sub> weight (Fig. DR1; Table DR3), which was estimated as the dry weight of the organism's shell or skeleton after tissue, chitin, and vegetative material had been removed via combustion for 6 hours at 550°C (Heiri et al., 2001). Buoyant weight and dry CaCO<sub>3</sub> weight are highly correlated ( $R^2 > 0.96$ ,  $p < 0.0001$ ; Table DR3) and plot on a straight line passing near the origin for each of the species investigated (Fig. DR1). This indicates that a statistically-significant relationship exists between buoyant weight and dry CaCO<sub>3</sub> weight and that this relationship is relatively constant (linear) regardless of the size of the specimen or the  $p\text{CO}_2$  conditions under which it was grown.



We recognize that the buoyant weighing method of estimating net calcification or dissolution is limited by various factors, including (a) the potential for unintended measurement of organic material attached to the shell or skeleton that is of a density unequal to that of seawater and (b) measurement of shell material that changes density throughout the molting cycle (e.g., crustacea). However, since the buoyant weight calibration curves are based upon the specimens actually employed in the experiments, and therefore include the range of molt stages, differences in tissue density, etc. actually measured, any error in the buoyant weight method associated with these factors will be manifest as a deviation from the regressed calibration curve. Thus, the average %-error of the CaCO<sub>3</sub> vs. buoyant wt. regressions quantifies the potential error imparted by these complicating factors for each of the organisms investigated. Critically, these errors range only from 0.4 to 6.2% (Table DR3). Thus, given the excellent correlation between buoyant weight and dry CaCO<sub>3</sub> weight observed for each of the organisms investigated in this study (Fig. DR1, Table DR3), combined with the need to make non-destructive determinations of shell/skeletal mass at the beginning of the experiment, buoyant weight constitutes a viable and justified approach to estimating net rates of calcification or dissolution for the organisms investigated in these experiments.

## **7. Survivorship**

A linear regression of average calcification rate (y; wt-%/60-day) vs. survival rate (x; %) for the species investigated (data obtained from Table DR1) reveals a weak, inverse relationship ( $y = -251.8x + 258.5$ ;  $R^2 = 0.087$ ;  $p=0.01$ ) between these variables, such that calcification rates marginally decline with increasing survival rates. Thus, ancillary tank

stress, as estimated by reduced survivorship, appears not to have resulted in reductions in net rates of calcification.

A linear regression of survival rate (y; %) vs. saturation state (x) for the species investigated (data obtained from Table DR1) reveals that there is no significant relationship between these variables ( $y = 0.017x + 0.746$ ;  $R^2 = 0.004$ ;  $p=0.61$ ). Thus, the reduced survivorship exhibited by organisms under the various  $p\text{CO}_2$  treatments appears not to have resulted directly from increased levels of stress associated with reduced  $\text{CaCO}_3$  saturation states, reduced pH, and/or elevated DIC.

## **8. Previous investigations of closely related species**

Previous investigations of species that are the same or closely related to those investigated in the present study have been conducted by Berge et al. (2006; *Mytilus edulis*), Gazeau et al. (2007; *Mytilus edulis* and *Crassostrea gigas*), and Shirayama and Thornton (2005; *Strombus luhuanus*). While a thorough review of all previous acidification studies is beyond the scope of the present work, we will briefly summarize the findings of these particularly relevant works and discuss how they compare with the results of the present study.

Berge et al. (2006) observed a significant ( $p<0.05$ ) decrease in the rate of shell extension in *Mytilus edulis* when subjected to a range of  $p\text{CO}_2$  levels corresponding to a seawater pH of 6.7, 7.1, 7.4, 7.6, and 8.1. However, over the range of pH levels that we investigated (7.4, 7.6, 8.1), Berge et al (2006) did not identify a statistically significant

( $p < 0.05$ ) change in the rate of shell extension in either large or small specimens. These results are consistent with the results of our study, in which *Mytilus edulis* did not exhibit a statistically significant ( $p < 0.05$ ) change in net calcification rate when subjected to conditions of elevated  $p\text{CO}_2$  spanning a comparable range. However, it is difficult to directly compare the results of Berge et al.'s (2006) work with the present work because Berge et al. measured shell extension rate while we measured net calcification rate (estimated from changes in buoyant weight).

Gazeau et al. (2007) observed a decrease in net rate of calcification (inferred from changes in alkalinity) in *Mytilus edulis* and *Crassostrea gigas* when subjected to a range of  $p\text{CO}_2$  comparable to that investigated in the present work. Their observed negative response by *Mytilus edulis* contrasts with the neutral response that we observed. The negative response that they observed for *Crassostrea gigas* is consistent with the negative response that we observed for *Crassostrea virginica*. However, it is difficult to compare the results of their study with the present study because their study was carried out over a period of two hours, while our study took place over 60 days. The negative responses that they observed may be partly attributable to the mussel's initial shock of being placed in extremely chemically-modified seawater, without any period of acclimatization.

Shirayama and Thornton (2005) observed decreases in both the rate of change in wet weight and shell height of *Strombus luhuanus* when reared in seawaters equilibrated with 560 ppm  $p\text{CO}_2$ . These results are consistent with the results of the present study on *Strombus alatus*. However, direct comparison of the two experiments is complicated by

the fact that Shirayama and Thornton (2005) measured changes in wet weight (which is largely determined by organic tissue mass) and shell height, as opposed to changes in shell mass.

### **9. Huber-White sandwich estimator of variance**

Because specimens of a given species exposed to a given  $p\text{CO}_2$  were all reared in the same aquarium, there exists the possibility that the net calcification rates for these specimens would be more tightly clustered about the mean than if they had each been reared in separate tanks. This would be expected to occur if, for instance, there was something unique about each aquarium, beyond its prescribed carbonate chemistry, that caused the response of the inhabiting specimens to be abnormally similar to each other. This would reduce the variance of the measurements, thereby artificially increasing the likelihood that a regression through the data would pass a test for significance that is based upon a model of normal probability distribution.

We controlled for this so-called “clustering” within tanks by employing Generalized Estimating Equations that employ the Huber-White sandwich estimator of variance, also known as the Robust Covariance Matrix, in place of the standard estimator of variance (Rogers, 1993). Essentially, instead of employing statistical parameters that assume that the data will be normally distributed about the mean (via the standard estimator of variance), the Huber-White estimator of variance uses a Taylor Series Expansion to adjust the statistical parameters so that they are based on the actual distribution of the data in each of the tanks – thus subjecting the data to a more rigorous test for significance

(i.e., one that is *more* difficult to pass). In all cases, the p-value generated using the Huber-White estimator of variance was greater than that generated using the standard estimator of variance, which is indicative of a more rigorous test for significance. This conservative approach minimizes the likelihood of committing a type 1 statistical error.

#### **10. Polymorph mineralogy of investigated organisms presented in Table 1**

Polymorph of CaCO<sub>3</sub> (aragonite, low-Mg calcite, high-Mg calcite) in shell or skeleton of investigated organisms was originally reported in Clarke and Wheeler (1917), Chave (1954), and/or Lowenstam (1954, 1964) and confirmed in the present study by x-ray diffraction and scanning electron microscopy.

#### **11. Captions for supplementary figures**

Figure DR1. Plots of buoyant weight (x-axis) vs. dry CaCO<sub>3</sub> weight (y-axis) of species investigated in the present study. These measurements are highly correlated ( $R^2 > 0.96$ ,  $p < 0.0001$ ) and plot on a straight line passing through the origin, indicating that a statistically significant relationship exists between buoyant weight and dry CaCO<sub>3</sub> weight and that this relationship is relatively constant (pursuant to the statistics presented in Table DR3), regardless of the size of the specimen or the  $p\text{CO}_2$  conditions under which it was grown. Dry CaCO<sub>3</sub> weight is the dry weight of the organism's shell or skeleton after tissue or vegetative material had been removed via combustion for 6 hours at 550°C (Heiri et al., 2001). Regressions were calculated using the least-squares method.



Figure DR2. Plot of dissolved inorganic carbon (DIC) measured from large volume Gran titration (Bradshaw et al., 1981; y-axis) vs. DIC calculated from temperature, salinity, pH, and alkalinity (x-axis) for all 24 experimental seawaters on 8/31/2008. The two methods yielded DIC values that were highly correlated ( $R^2 = 0.9937$ ; average %-difference = 1.7%). Linear regression was calculated using the least-squares method.

Figure DR3. Graphical summary of the calcification response patterns exhibited by organisms grown in experimental seawaters spanning a range of  $\text{CaCO}_3$  saturation states: positive (A); threshold-positive (B); neutral (C); parabolic (D); threshold-negative (E); and negative (F). Aragonite saturation state and  $p\text{CO}_2$  increase in the direction of arrows.

## 12. Headings for supplementary tables

Table DR1. Average aragonite saturation state ( $\Omega_{\text{arag}}$ ), survival rate, number of surviving individuals upon which net calcification rates are based (n), and average net calcification (+)/dissolution (-) rate obtained from buoyant weighing. SD is standard deviation.

Table DR2. Average measured  $p\text{CO}_2$ , salinity (Sal), temperature (Temp), alkalinity (Alk), and pH and average calculated dissolved inorganic carbon (DIC),  $p\text{CO}_2$ , aragonite saturation state ( $\Omega_{\text{arag}}$ ), and student's t-test statistics (t-test, P-value) for differences in  $\Omega_{\text{arag}}$  at given  $p\text{CO}_2$  vs. next lowest  $p\text{CO}_2$  for each aquaria in the 60-day experiment. SD is standard deviation.

Table DR3. Calibration of the buoyant weight method, including the least-squares linear regression through the buoyant weight (x) and dry CaCO<sub>3</sub> weight (y) data, the correlation coefficient of the regression ( $R^2$ ), and the average %-error of the regression (absolute value of the difference between the measured and predicted dry CaCO<sub>3</sub> weight divided by the measured dry CaCO<sub>3</sub> weight).

Table DR4. Collection site, annual water temperature range (National Oceanic and Atmospheric Administration, 2008), food (during experiment), and stage of development of the organisms investigated in the present study.

Table DR5. Linear, quadratic, and exponential regression analyses of  $\Omega_{\text{aragonite}}$  vs. net calcification rate for each of the 18 species investigated in the present study, calculated using the least squares method. The regression analysis (linear, quadratic, or exponential) that yielded the lowest square root of the mean squared error for a given species (i.e., “Best-fit”) is shown in bold and plotted in figure 1 of the text. “p” = p-value; “ $R^2$ ” = correlation coefficient; “RMSE” = square root of the mean squared error.

Table DR6. Detailed weight data for organisms investigated in the experiments. Initial and final buoyant weight refers to buoyant weight at the beginning and end of the experiment, respectively. Initial and final dry weight of CaCO<sub>3</sub> refers to dry weight of CaCO<sub>3</sub> at the beginning and end of the experiment, respectively. Dry weight of CaCO<sub>3</sub> is estimated from the buoyant weights using the empirically derived calibration curves (Fig. DR1, Table DR3).

### References Cited

- Berge, J.A., Bjerkeng, B., Pettersen, O., Schaanning, M.T., and Øxnevad, S., 2006, Effects of increased sea water concentrations of CO<sub>2</sub> on growth of the bivalve *Mytilus edulis*. *Chemosphere*, v. 62, 4 p. 681-687.
- Bradshaw, A.L., Brewer, P.G., Shafer, D.K., and Williams, R.T., 1981, Measurements of total carbon dioxide and alkalinity by potentiometric titration in the GEOSECS program. *Earth and Planetary Science Letters*, v. 55, 1 p. 99-115.
- Chave, K.E., 1954, Aspects of the Biogeochemistry of magnesium, 1. Calcareous marine organisms. *Journal of Geology*, v. 62, p. 266-283.
- Clarke, F.W., and Wheeler, W.C., 1917, The inorganic constituents of marine invertebrates. *United States Geological Survey Professional Paper*, v. 102, p. 1-56.
- Dickson, A.G., and Millero, F.J., 1987, A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep-sea Research*, v. 34, 10 p. 1733-1743.
- Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J.P., Middleburg, J.J., and Heip, C.H.R., 2007, Impact of elevated CO<sub>2</sub> on shellfish calcification. *Geophysical Research Letters*, v. 34, p. L07603.
- Heiri, O.O., Lotter, A.F., and Lemcke, G., 2001, Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, v. 25, 1 p. 101-110.
- Lowenstam, H.A., 1964, Coexisting calcites and aragonites from skeletal carbonates of marine organisms and their strontium and magnesium contents, in Y. Miyake and T.

- Koyama, eds., Recent researches in the fields of hydrosphere, atmosphere and nuclear geochemistry: Tokyo, p. 373-404.
- Lowenstam, H.A., 1954, Factors affecting the aragonite:calcite ratios in carbonate-secreting marine organisms. *Journal of Geology*, v. 62, p. 284-322.
- Morse, J.W., and Mackenzie, F.T., 1990, *Geochemistry of Sedimentary Carbonates* v. 48: Amsterdam, Elsevier, 707 p.
- Mucci, A., 1983, The solubility of calcite and aragonite in seawater at various salinities, temperatures, and one atmosphere total pressure. *American Journal of Science*, v. 283, p. 780-799.
- National Oceanic and Atmospheric Administration. National Oceanic and Atmospheric Administration Integrated Ocean Observing System 2008  
<http://ioos.noaa.gov/program/products.html>.
- Pierrot, D., Lewis, E., and Wallace, D. W. R., 2006, *MS Excel Program Developed for CO<sub>2</sub> System Calculations*. ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- Roy, R.N., Roy, L.N., Vogel, K.M., Porter-Moore, C., Pearson, T., Good, C.E., Millero, F.J., and Campbell, D.M., 1993, The dissociation constants of carbonic acid in seawater at salinities 5 to 45 and temperatures 0 to 45°C. *Marine Chemistry*, v. 44, p. 249-267.
- Shirayama, Y., and Thornton, H., 2005, Effect of increased atmospheric CO<sub>2</sub> on shallow water marine benthos. *Journal of Geophysical Research*, v. 10, p. C09S08.

Figure DR1

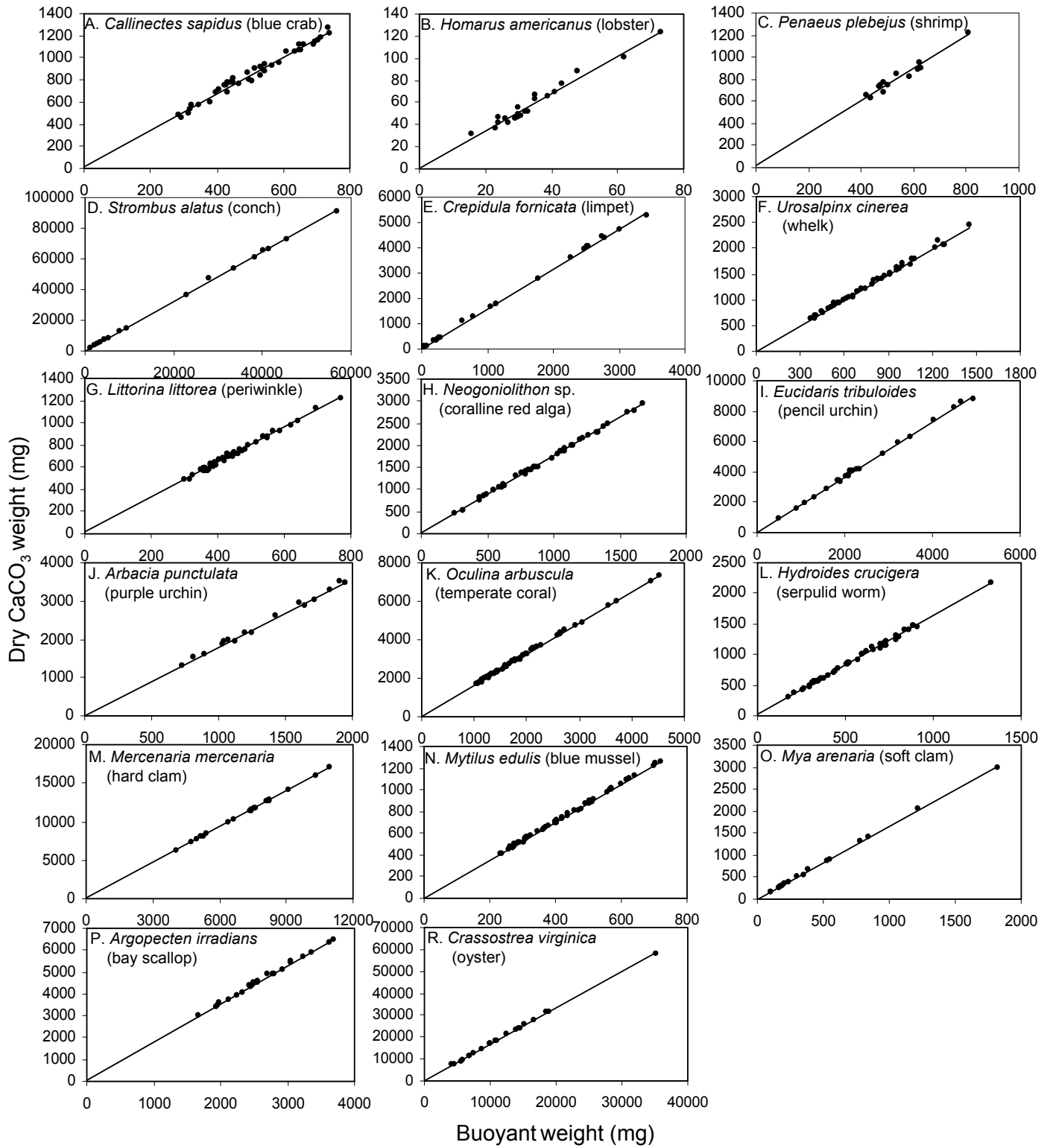




Figure DR2

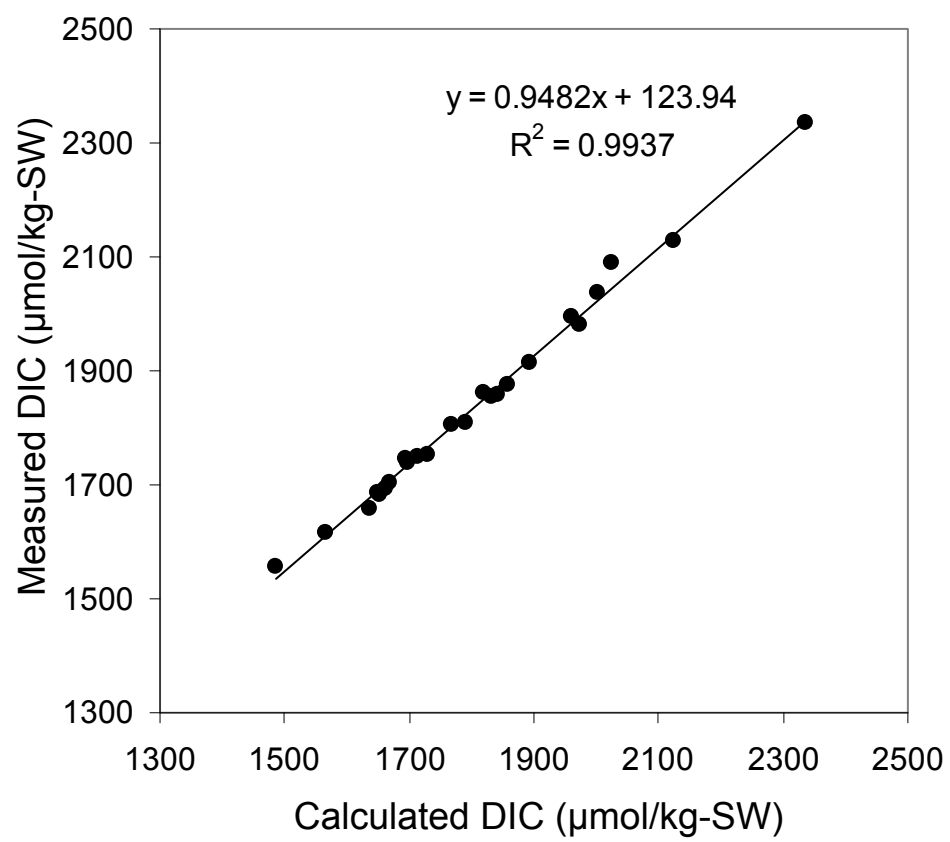


Figure DR3

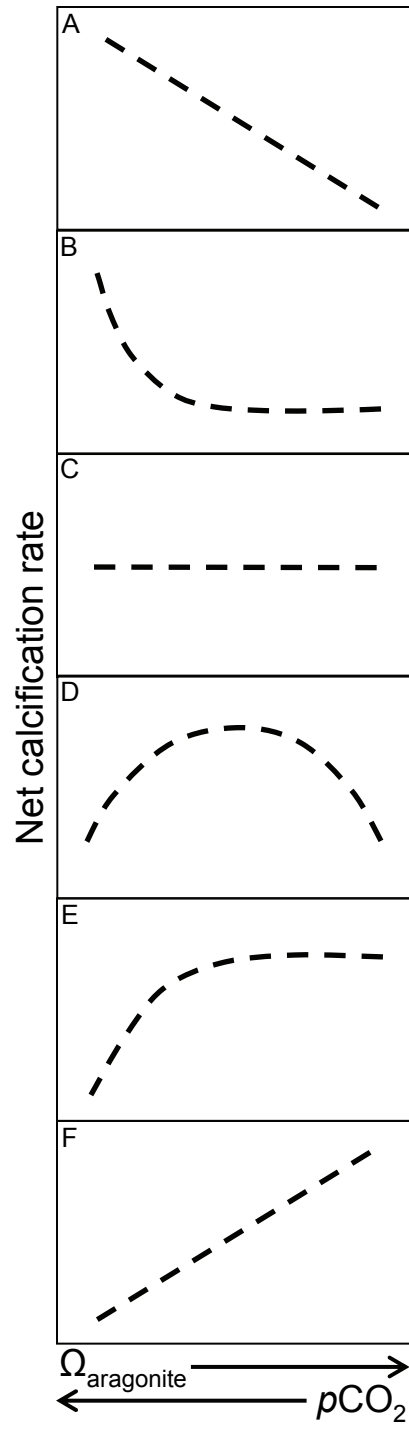


Table DR1

Organism	Scientific name	Qarag	SD	Survival rate	n	Net calcification (AVG) (wt-%/60-day)	SD (wt-%/60-day)
Lobster	<i>Homarus americanus</i>	2.13	0.38	25%	3	353.0	91.0
Lobster	<i>Homarus americanus</i>	1.53	0.39	25%	3	349.5	39.6
Lobster	<i>Homarus americanus</i>	1.13	0.25	42%	5	376.3	58.6
Lobster	<i>Homarus americanus</i>	0.47	0.07	58%	7	606.1	164.6
Crab	<i>Callinectes sapidus</i>	2.13	0.38	75%	9	433.8	138.0
Crab	<i>Callinectes sapidus</i>	1.53	0.39	83%	10	598.2	116.7
Crab	<i>Callinectes sapidus</i>	1.13	0.25	75%	9	600.9	117.3
Crab	<i>Callinectes sapidus</i>	0.47	0.07	67%	8	724.0	109.2
Shrimp	<i>Penaeus plebejus</i>	2.13	0.38	100%	3	15.3	11.4
Shrimp	<i>Penaeus plebejus</i>	1.53	0.39	100%	3	17.3	7.4
Shrimp	<i>Penaeus plebejus</i>	1.13	0.25	100%	3	27.5	9.4
Shrimp	<i>Penaeus plebejus</i>	0.47	0.07	100%	3	37.8	13.7
Conch	<i>Strombus alatus</i>	2.28	0.19	100%	6	2.0	0.5
Conch	<i>Strombus alatus</i>	1.93	0.26	83%	5	0.8	1.2
Conch	<i>Strombus alatus</i>	1.51	0.20	83%	5	1.2	1.4
Conch	<i>Strombus alatus</i>	0.68	0.12	83%	5	-3.1	2.0
Limpet	<i>Crepidula fornicata</i>	2.28	0.19	71%	5	12.4	9.5
Limpet	<i>Crepidula fornicata</i>	1.93	0.26	43%	3	22.2	6.8
Limpet	<i>Crepidula fornicata</i>	1.51	0.20	71%	5	33.0	5.0
Limpet	<i>Crepidula fornicata</i>	0.68	0.12	57%	4	21.2	7.0
Whelk	<i>Urosalpinx cinerea</i>	2.28	0.19	67%	8	2.9	1.9
Whelk	<i>Urosalpinx cinerea</i>	1.93	0.26	75%	9	0.7	1.1
Whelk	<i>Urosalpinx cinerea</i>	1.51	0.20	67%	8	0.7	0.6
Whelk	<i>Urosalpinx cinerea</i>	0.68	0.12	67%	8	-1.5	0.9
Periwinkle	<i>Littorina littorea</i>	2.28	0.19	100%	12	3.8	2.9
Periwinkle	<i>Littorina littorea</i>	1.93	0.26	75%	9	1.9	1.6
Periwinkle	<i>Littorina littorea</i>	1.51	0.20	92%	11	0.9	2.1
Periwinkle	<i>Littorina littorea</i>	0.68	0.12	83%	10	-1.2	3.4
Coralline red alga	<i>Neogoniolithon sp.</i>	3.12	0.22	83%	10	5.7	2.9
Coralline red alga	<i>Neogoniolithon sp.</i>	2.40	0.42	92%	11	14.5	6.6
Coralline red alga	<i>Neogoniolithon sp.</i>	1.84	0.13	83%	10	10.7	4.7
Coralline red alga	<i>Neogoniolithon sp.</i>	0.90	0.05	92%	11	3.6	3.5
Halimeda	<i>Halimeda incrassata</i>	3.12	0.22	100%	3	23.9	12.5
Halimeda	<i>Halimeda incrassata</i>	2.40	0.42	100%	3	43.9	7.8
Halimeda	<i>Halimeda incrassata</i>	1.84	0.13	100%	3	25.4	3.0
Halimeda	<i>Halimeda incrassata</i>	0.90	0.05	100%	5	6.0	2.6
Pencil urchin	<i>Eucidaris tribuloides</i>	2.06	0.35	83%	5	8.7	6.4
Pencil urchin	<i>Eucidaris tribuloides</i>	1.58	0.30	67%	4	5.6	2.7
Pencil urchin	<i>Eucidaris tribuloides</i>	1.21	0.14	50%	3	5.6	3.1
Pencil urchin	<i>Eucidaris tribuloides</i>	0.54	0.06	100%	6	-18.3	7.3
Purple urchin	<i>Arbacia punctulata</i>	2.06	0.35	67%	4	8.2	5.7
Purple urchin	<i>Arbacia punctulata</i>	1.58	0.30	100%	6	39.4	5.0
Purple urchin	<i>Arbacia punctulata</i>	1.21	0.14	50%	3	42.8	3.8
Purple urchin	<i>Arbacia punctulata</i>	0.54	0.06	67%	4	28.5	1.9
Coral	<i>Oculina arbuscula</i>	2.60	0.26	58%	11	11.8	1.2
Coral	<i>Oculina arbuscula</i>	2.28	0.18	79%	15	11.6	1.2
Coral	<i>Oculina arbuscula</i>	1.64	0.18	63%	12	11.1	1.5
Coral	<i>Oculina arbuscula</i>	0.77	0.07	89%	17	3.8	1.7
Serpulid worm	<i>Hydroides crucigera</i>	2.60	0.26	92%	11	3.5	4.1
Serpulid worm	<i>Hydroides crucigera</i>	2.28	0.18	78%	7	5.5	3.8
Serpulid worm	<i>Hydroides crucigera</i>	1.64	0.18	100%	12	2.3	4.0
Serpulid worm	<i>Hydroides crucigera</i>	0.77	0.07	92%	11	1.3	3.8
Hard clam	<i>Mercenaria mercenaria</i>	2.63	0.30	100%	7	1.0	0.6
Hard clam	<i>Mercenaria mercenaria</i>	2.11	0.41	71%	5	0.7	0.3
Hard clam	<i>Mercenaria mercenaria</i>	1.43	0.15	100%	7	0.5	0.4
Hard clam	<i>Mercenaria mercenaria</i>	0.71	0.05	86%	6	-1.4	0.4
Blue mussel	<i>Mytilus edulis</i>	2.63	0.30	100%	15	4.4	2.2
Blue mussel	<i>Mytilus edulis</i>	2.11	0.41	87%	13	3.1	2.5
Blue mussel	<i>Mytilus edulis</i>	1.43	0.15	93%	14	3.6	3.4
Blue mussel	<i>Mytilus edulis</i>	0.71	0.05	93%	14	3.1	3.2
Soft clam	<i>Mya arenaria</i>	2.63	0.30	50%	3	17.5	3.5
Soft clam	<i>Mya arenaria</i>	2.11	0.41	83%	5	7.7	3.6
Soft clam	<i>Mya arenaria</i>	1.43	0.15	67%	4	0.2	6.9
Soft clam	<i>Mya arenaria</i>	0.71	0.05	33%	2	-8.1	6.9
Bay scallop	<i>Argopecten irradians</i>	2.63	0.30	67%	5	6.9	2.1
Bay scallop	<i>Argopecten irradians</i>	2.11	0.41	50%	3	6.3	0.8
Bay scallop	<i>Argopecten irradians</i>	1.43	0.15	83%	5	4.8	4.2
Bay scallop	<i>Argopecten irradians</i>	0.71	0.05	83%	5	2.3	1.9
Oyster	<i>Crassostrea virginica</i>	2.63	0.30	67%	4	1.9	0.3
Oyster	<i>Crassostrea virginica</i>	2.11	0.41	67%	4	1.6	0.4
Oyster	<i>Crassostrea virginica</i>	1.43	0.15	67%	4	1.1	0.3
Oyster	<i>Crassostrea virginica</i>	0.71	0.05	67%	4	0.3	0.4

Table DR2

Tank	MEASURED										CALCULATED									
	pCO2	SD	Sal	SD	Temp	SD	Aik	SD	pH	SD	DIC	SD	pCO2	SD	Qarag	SD	t-test	P-value		
Lobster/Crab/Shrimp (I)	409	5.66	32.0	0.169	24.9	0.179	1860	156.7	8.03	0.0562	1678	139.64	526	63	2.13	0.380	n/a	n/a		
Lobster/Crab/Shrimp (II)	606	7.26	31.8	0.148	25.0	0.141	1849	131.0	7.85	0.0962	1732	119.26	839	171	1.53	0.388	2.49	0.0188		
Lobster/Crab/Shrimp (III)	903	11.74	32.1	0.969	25.0	0.152	1817	161.9	7.72	0.0575	1744	154.98	1146	124	1.13	0.247	1.92	0.0484		
Lobster/Crab/Shrimp (IV)	2856	53.73	31.9	0.187	25.1	0.114	1817	171.2	7.31	0.0348	1860	169.23	3103	217	0.47	0.074	5.76	0.0011		
Conch/Limpet/Whelk/Periwinkle (I)	409	5.66	31.8	0.088	25.1	0.110	1770	107.5	8.09	0.0304	1568	100.95	420	46	2.28	0.187	n/a	n/a		
Conch/Limpet/Whelk/Periwinkle (II)	606	7.26	31.8	0.228	24.9	0.152	1798	141.8	8.00	0.0719	1634	147.12	561	137	1.93	0.263	2.42	0.0231		
Conch/Limpet/Whelk/Periwinkle (III)	903	11.74	31.9	0.191	24.9	0.148	1849	62.8	7.86	0.0734	1733	77.91	831	168	1.51	0.199	2.81	0.0130		
Conch/Limpet/Whelk/Periwinkle (IV)	2856	53.73	31.7	0.110	24.9	0.134	2079	124.2	7.42	0.0659	2097	111.49	2758	316	0.68	0.123	8.02	0.0000		
Coralline red alga/Halimeda (I)	409	5.66	31.8	0.207	25.0	0.055	2008	56.5	8.19	0.0317	1738	50.35	359	32	3.12	0.221	n/a	n/a		
Coralline red alga/Halimeda (II)	606	7.26	31.7	0.118	25.0	0.152	1987	127.3	8.05	0.0604	1786	100.71	526	68	2.40	0.420	3.41	0.0071		
Coralline red alga/Halimeda (III)	903	11.74	31.5	0.155	25.1	0.164	2044	53.2	7.91	0.0286	1903	45.91	802	48	1.84	0.129	2.81	0.0187		
Coralline red alga/Halimeda (IV)	2856	53.73	31.8	0.258	24.9	0.130	2354	37.0	7.49	0.0216	2350	33.21	2593	106	0.90	0.050	15.33	0.0000		
Pencil urchin/Purple urchin (I)	409	5.66	31.9	0.269	25.1	0.122	1744	146.8	8.04	0.0574	1563	126.86	473	67	2.06	0.347	n/a	n/a		
Pencil urchin/Purple urchin (II)	606	7.26	31.8	0.099	25.0	0.152	1751	168.3	7.90	0.0510	1623	144.58	686	35	1.58	0.302	2.37	0.0228		
Pencil urchin/Purple urchin (III)	903	11.74	31.7	0.286	24.9	0.114	1792	116.6	7.77	0.0241	1707	107.63	999	44	1.21	0.136	2.46	0.0244		
Pencil urchin/Purple urchin (IV)	2856	53.73	31.7	0.218	25.0	0.148	1891	78.2	7.36	0.0328	1921	73.47	2854	159	0.54	0.060	10.01	0.0000		
Coral/Serpulid worm (I)	409	5.66	31.7	0.208	25.0	0.191	1960	29.7	8.11	0.0628	1738	46.83	450	83	2.60	0.263	n/a	n/a		
Coral/Serpulid worm (II)	606	7.26	31.6	0.353	24.9	0.129	2012	36.7	8.03	0.0376	1824	31.62	573	52	2.28	0.175	2.00	0.0509		
Coral/Serpulid worm (III)	903	11.74	31.7	0.426	24.9	0.141	2027	29.9	7.85	0.0519	1907	29.70	915	110	1.64	0.183	5.04	0.0012		
Coral/Serpulid worm (IV)	2856	53.73	31.5	0.633	25.2	0.058	2071	48.3	7.48	0.0332	2070	40.33	2377	128	0.77	0.067	9.00	0.0004		
Clams/Mussel/Scallop/Oyster (I)	409	5.66	32.1	0.288	25.1	0.148	1833	125.3	8.15	0.0404	1598	112.11	370	46	2.63	0.299	n/a	n/a		
Clams/Mussel/Scallop/Oyster (II)	606	7.26	31.7	0.199	25.1	0.110	1862	141.3	8.02	0.0803	1684	126.47	547	119	2.11	0.408	2.31	0.0272		
Clams/Mussel/Scallop/Oyster (III)	903	11.74	31.9	0.251	25.0	0.158	1856	91.7	7.83	0.0452	1749	87.20	892	108	1.43	0.151	3.51	0.0085		
Clams/Mussel/Scallop/Oyster (IV)	2856	53.73	31.9	0.240	25.0	0.084	2063	42.6	7.45	0.0370	2071	50.88	2551	256	0.71	0.050	10.11	0.0001		

Table DR3

Organism	Scientific name	Buoyant (x) vs. CaCO <sub>3</sub> wt (y) (mg)	R <sup>2</sup>	AVG %-err
Lobster	<i>Homarus americanus</i>	$y = 1.687x + 0.5583$	0.9684	6.202%
Crab	<i>Callinectes sapidus</i>	$y = 1.649x + 13.83$	0.9782	3.558%
Shrimp	<i>Penaeus plebejus</i>	$y = 1.468x + 13.20$	0.9521	3.745%
Conch	<i>Strombus alatus</i>	$y = 1.608x - 38.29$	0.9993	1.323%
Limpet	<i>Crepidula fornicata</i>	$y = 1.578x + 12.76$	0.9994	5.339%
Whelk	<i>Urosalpinx cinerea</i>	$y = 1.653x + 5.449$	0.9951	1.986%
Periwinkle	<i>Littorina littorea</i>	$y = 1.576x + 10.13$	0.9909	1.925%
Coralline red alga	<i>Neogoniolithon</i> sp.	$y = 1.745x + 8.957$	0.9985	1.815%
Pencil urchin	<i>Eucidaris tribuloides</i>	$y = 1.830x - 27.03$	0.9986	1.465%
Purple urchin	<i>Arbacia punctulata</i>	$y = 1.787x + 17.37$	0.9933	2.144%
Coral	<i>Oculina arbuscula</i>	$y = 1.612x + 33.78$	0.9991	1.131%
Serpulid worm	<i>Hydroides crucigera</i>	$y = 1.614x + 14.95$	0.9967	2.150%
Hard clam	<i>Mercenaria mercenaria</i>	$y = 1.551x - 7.818$	0.9997	0.408%
Blue mussel	<i>Mytilus edulis</i>	$y = 1.750x + 2.759$	0.9985	1.121%
Soft clam	<i>Mya arenaria</i>	$y = 1.661x - 6.619$	0.9994	3.107%
Bay scallop	<i>Argopecten irradians</i>	$y = 1.744x + 62.49$	0.9958	1.108%
Oyster	<i>Crassostrea virginica</i>	$y = 1.654x + 249.0$	0.9989	1.997%



Table DR4

<b>Organism</b>	<b>Scientific name</b>	<b>Collection site</b>	<b>Ann temp range (°C)</b>	<b>Food</b>	<b>Age</b>
Lobster	<i>Homarus americanus</i>	Gulf of Maine, ME	1 - 26	<i>Artemia</i> sp.	juvenile
Crab	<i>Callinectes sapidus</i>	Chesapeake Bay, MD	3 - 32	<i>Artemia</i> sp.	juvenile
Shrimp	<i>Penaeus plebejus</i>	Atlantic Ocean, FL	20 - 32	<i>Artemia</i> sp.	adult
Conch	<i>Strombus alatus</i>	Gulf of Mexico, FL	20 - 30	green algae	adult
Limpet	<i>Crepidula fornicata</i>	Buzzards Bay, MA	3 - 28	green algae	adult
Whelk	<i>Urosalpinx cinerea</i>	Buzzards Bay, MA	3 - 28	green algae	adult
Periwinkle	<i>Littorina littorea</i>	Buzzards Bay, MA	3 - 28	green algae	adult
Coralline red alga	<i>Neogoniolithon</i> sp.	Atlantic Ocean, FL	20 - 32	autotrophic	adult
Halimeda	<i>Halimeda incrassata</i>	Atlantic Ocean, FL	20 - 32	autotrophic	adult
Pencil urchin	<i>Eucidaris tribuloides</i>	Atlantic Ocean, FL	20 - 32	green algae	adult
Purple urchin	<i>Arbacia punctulata</i>	Nantucket Sound, MA	1 - 27	green algae	adult
Coral	<i>Oculina arbuscula</i>	Atlantic Ocean, NC	15 - 30	<i>Artemia</i> sp.	adult
Serpulid worm	<i>Hydroides crucigera</i>	Nantucket Sound, MA	1 - 27	<i>Artemia</i> sp.	adult
Hard clam	<i>Mercenaria mercenaria</i>	Nantucket Sound, MA	1 - 27	<i>Artemia</i> +algae	adult
Blue mussel	<i>Mytilus edulis</i>	Buzzards Bay, MA	3 - 28	<i>Artemia</i> +algae	adult
Soft clam	<i>Mya arenaria</i>	Nantucket Sound, MA	1 - 27	<i>Artemia</i> +algae	adult
Bay scallop	<i>Argopecten irradians</i>	Nantucket Sound, MA	1 - 27	<i>Artemia</i> +algae	adult
Oyster	<i>Crassostrea virginica</i>	Buzzards Bay, MA	3 - 28	<i>Artemia</i> +algae	adult

Table DR5

Organism	Linear			Quadratic			Exponential			Best-fit	Calcification response			
	Regression	p	R <sup>2</sup> RMSE	Regression	p	R <sup>2</sup> RMSE	Regression	p	R <sup>2</sup> RMSE					
Crab	<b>y = -165x + 807</b>	<b>0.00</b>	<b>0.41</b> <b>120.71</b>	<b>y = 41.0x<sup>2</sup> - 57.9x + 752</b>	0.00	0.41	121.74	<b>y = -119e<sup>60.6x</sup> + 871</b>	0.33	0.41	121.58	linear	positive	
Shrimp	<b>y = -14.3x + 43.3</b>	<b>0.01</b>	<b>0.47</b> <b>9.98</b>	<b>y = 5.61x<sup>2</sup> - 28.8x + 50.6</b>	0.00	0.49	10.30	<b>y = 48.0e<sup>-70.7x</sup> + 3.71</b>	0.27	0.49	10.33	linear	positive	
Lobster	<b>y = 173x + 649</b>	0.05	0.43	126.40	<b>y = 181x<sup>2</sup> - 620x + 856</b>	0.00	0.56	114.79	<b>y = 1296e<sup>-344x</sup> + 348</b>	<b>0.00</b>	<b>0.57</b> <b>112.11</b>	exponential	threshold(+)	
Limpet	<b>y = -5.67x + 31.4</b>	0.43	0.11	10.22	<b>y = -24.4x<sup>2</sup> + 66.3x - 12.5</b>	<b>0.00</b>	<b>0.59</b> <b>7.17</b>	<b>y = -0.001e<sup>5718x</sup> + 27.1</b>	0.53	0.41	8.64	quadratic	parabolic	
Purple urchin	<b>y = -9.93x + 43.9</b>	0.50	0.15	13.42	<b>y = -45.7x<sup>2</sup> + 106x - 15.9</b>	<b>0.00</b>	<b>0.91</b> <b>4.65</b>	<b>y = 639e<sup>-1.56x</sup> - 595</b>	0.51	0.15	13.44	quadratic	parabolic	
Coralline red alga	<b>y = 1.82x + 4.94</b>	0.57	0.06	6.17	<b>y = -6.66x<sup>2</sup> + 28.2x + -16.7</b>	<b>0.03</b>	<b>0.43</b> <b>4.86</b>	<b>y = -750e<sup>-523x</sup> + 10.5</b>	0.00	0.23	5.57	quadratic	parabolic	
Halimeda	<b>y = 11.6x + 0.04</b>	0.18	0.43	12.42	<b>y = -15.4x<sup>2</sup> + 71.2x - 46.6</b>	<b>0.02</b>	<b>0.74</b> <b>8.73</b>	<b>y = -23340e<sup>-242x</sup> + 3228</b>	0.62	0.63	1039.75	quadratic	parabolic	
Blue mussel	<b>y = 0.53x + 2.67</b>	0.12	0.02	2.84	<b>y = 0.51x<sup>2</sup> - 1.18x + 3.82</b>	0.09	0.02	2.86	<b>y = -1806e<sup>-0.03x</sup> + 1809</b>	0.12	0.02	2.84	none	neutral
Temperate coral	<b>y = 4.56x + 1.19</b>	0.01	0.74	1.97	<b>y = -3.93x<sup>2</sup> + 17.4x - 7.22</b>	0.00	0.86	1.46	<b>y = -67.2e<sup>-277x</sup> + 11.8</b>	<b>0.00</b>	<b>0.87</b> <b>1.43</b>	exponential	threshold(-)	
Pencil urchin	<b>y = 18.1x - 25.1</b>	0.01	0.73	7.21	<b>y = -16.2x<sup>2</sup> + 59.4x - 45.3</b>	0.00	0.83	5.89	<b>y = -137e<sup>-304x</sup> + 8.25</b>	<b>0.02</b>	<b>0.84</b> <b>5.68</b>	exponential	threshold(-)	
Hard clam	<b>y = 1.12x - 1.73</b>	0.04	0.67	0.60	<b>y = -0.94x<sup>2</sup> + 4.28x - 3.89</b>	0.00	0.81	0.46	<b>y = -10.3e<sup>-210x</sup> + 0.94</b>	<b>0.00</b>	<b>0.83</b> <b>0.44</b>	exponential	threshold(-)	
Conch	<b>y = 3.01x - 4.60</b>	0.01	0.62	1.48	<b>y = -2.00x<sup>2</sup> + 8.87x - 8.11</b>	0.00	0.68	1.40	<b>y = -21.9e<sup>-222x</sup> + 1.75</b>	<b>0.00</b>	<b>0.69</b> <b>1.37</b>	exponential	threshold(-)	
Serpulid worm	<b>y = 1.64x - 0.02</b>	<b>0.05</b>	<b>0.08</b> <b>3.93</b>	<b>y = -0.35x<sup>2</sup> + 2.80x - 0.81</b>	0.08	0.09	3.99	<b>y = -9.27e<sup>-28.1x</sup> + 8.64</b>	0.82	0.08	3.99	linear	negative	
Bay scallop	<b>y = 2.37x - 0.97</b>	<b>0.00</b>	<b>0.34</b> <b>2.61</b>	<b>y = -0.94x<sup>2</sup> + 5.52x - 1.14</b>	0.00	0.36	2.66	<b>y = -10.3e<sup>-80.3x</sup> + 8.13</b>	0.00	0.36	2.66	linear	negative	
Periwinkle	<b>y = 2.99x - 3.41</b>	<b>0.00</b>	<b>0.34</b> <b>2.55</b>	<b>y = 1.00x<sup>2</sup> - 0.01x - 1.65</b>	0.00	0.35	2.57	<b>y = 1.49e<sup>69.3x</sup> - 3.52</b>	0.03	0.35	2.57	linear	negative	
Oyster	<b>y = 0.84x - 23</b>	<b>0.00</b>	<b>0.76</b> <b>0.36</b>	<b>y = -0.21x<sup>2</sup> + 1.55x - 0.71</b>	0.00	0.78	0.36	<b>y = -3.67e<sup>-53.2x</sup> + 2.80</b>	0.00	0.78	0.36	linear	negative	
Whelk	<b>y = 2.45x - 3.26</b>	<b>0.01</b>	<b>0.58</b> <b>1.28</b>	<b>y = 0.69x<sup>2</sup> + 0.47x - 2.09</b>	0.01	0.59	1.28	<b>y = -168.6e<sup>-1.485x</sup> + 165.3</b>	0.01	0.58	1.28	linear	negative	
Soft clam	<b>y = 13.0x - 18.2</b>	<b>0.00</b>	<b>0.73</b> <b>5.31</b>	<b>y = 2.46x<sup>2</sup> + 4.57x - 12.1</b>	0.00	0.73	5.31	<b>y = 14.6e<sup>42.3x</sup> - 27.2</b>	0.06	0.74	5.43	linear	negative	

Table DR6

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Lobster	2.13	34	120	58	203
Lobster	2.13	34	162	58	274
Lobster	2.13	32	170	55	287
Lobster	1.53	37	149	63	253
Lobster	1.53	34	161	58	272
Lobster	1.53	35	165	60	279
Lobster	1.13	34	131	58	221
Lobster	1.13	36	191	61	322
Lobster	1.13	34	178	58	302
Lobster	1.13	33	153	56	258
Lobster	1.13	32	153	55	259
Lobster	0.47	37	225	63	380
Lobster	0.47	35	330	60	558
Lobster	0.47	37	193	63	326
Lobster	0.47	34	295	58	499
Lobster	0.47	35	241	60	407
Lobster	0.47	34	181	58	306
Lobster	0.47	37	289	63	488
Crab	2.13	145	518	253	868
Crab	2.13	144	522	251	875
Crab	2.13	142	958	248	1593
Crab	2.13	144	672	251	1123
Crab	2.13	145	1056	253	1755
Crab	2.13	142	780	248	1301
Crab	2.13	143	644	250	1075
Crab	2.13	146	774	255	1290
Crab	2.13	143	978	250	1627
Crab	1.53	145	830	253	1383
Crab	1.53	147	1215	256	2017
Crab	1.53	144	1031	251	1715
Crab	1.53	145	907	253	1510
Crab	1.53	145	965	253	1604
Crab	1.53	143	765	250	1275
Crab	1.53	142	847	248	1411
Crab	1.53	147	1244	256	2064
Crab	1.53	143	1077	250	1790
Crab	1.53	142	1200	248	1993
Crab	1.13	144	875	251	1456
Crab	1.13	139	1036	243	1722
Crab	1.13	145	887	253	1476
Crab	1.13	146	1253	255	2080
Crab	1.13	142	1225	248	2034
Crab	1.13	145	1117	253	1855
Crab	1.13	144	879	251	1463
Crab	1.13	144	1019	251	1694
Crab	1.13	139	744	243	1241
Crab	0.47	145	1107	253	1839
Crab	0.47	144	974	251	1620
Crab	0.47	142	1030	248	1713
Crab	0.47	141	1366	246	2267
Crab	0.47	145	1130	253	1877
Crab	0.47	147	1213	256	2014
Crab	0.47	143	1257	250	2086
Crab	0.47	149	1451	260	2406
Shrimp	2.13	406	420	610	630
Shrimp	2.13	345	435	520	652
Shrimp	2.13	537	625	801	931
Shrimp	1.53	483	533	723	796
Shrimp	1.53	380	475	571	711
Shrimp	1.53	401	468	602	700
Shrimp	1.13	429	500	643	747
Shrimp	1.13	476	629	712	937
Shrimp	1.13	366	489	551	731
Shrimp	0.47	595	810	887	1202
Shrimp	0.47	288	439	436	658
Shrimp	0.47	495	619	740	922
Conch	2.28	2292	2330	3648	3708
Conch	2.28	3585	3631	5727	5800
Conch	2.28	9277	9524	14879	15276
Conch	2.28	33906	34531	54482	55487
Conch	2.28	37959	38872	61000	62468
Conch	2.28	45328	46222	72849	74286
Conch	1.93	1322	1317	2087	2079

Table DR6 (continued)

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Conch	1.93	4594	4565	7349	7303
Conch	1.93	8123	8229	13023	13194
Conch	1.93	41103	41888	66055	67317
Conch	1.93	33973	34591	54590	55585
Conch	1.51	2862	2831	4563	4514
Conch	1.51	5430	5484	8693	8780
Conch	1.51	22612	23083	36321	37079
Conch	1.51	45020	45978	72354	73895
Conch	1.51	56354	57481	90580	92391
Conch	0.68	3174	3138	5065	5007
Conch	0.68	4862	4822	7779	7715
Conch	0.68	30137	28672	48422	46066
Conch	0.68	42249	40718	67897	65436
Conch	0.68	43183	41029	69401	65936
Crepidula	2.28	2580	2752	4084	4355
Crepidula	2.28	1896	2260	3004	3579
Crepidula	2.28	909	1131	1447	1797
Crepidula	2.28	264	293	430	474
Crepidula	2.28	50	51	92	93
Crepidula	1.93	902	1124	1436	1786
Crepidula	1.93	1968	2510	3119	3973
Crepidula	1.93	168	193	279	317
Crepidula	1.51	2177	3010	3448	4762
Crepidula	1.51	1869	2546	2962	4030
Crepidula	1.51	464	626	745	1001
Crepidula	1.51	194	245	318	399
Crepidula	1.51	166	214	275	351
Crepidula	0.68	2720	3413	4305	5398
Crepidula	0.68	833	1057	1328	1681
Crepidula	0.68	248	277	404	449
Crepidula	0.68	643	777	1027	1238
Whelk	2.28	693	727	1151	1207
Whelk	2.28	1011	1057	1677	1752
Whelk	2.28	1128	1141	1870	1891
Whelk	2.28	788	816	1307	1355
Whelk	2.28	1320	1341	2188	2221
Whelk	2.28	1255	1256	2080	2082
Whelk	2.28	1313	1337	2176	2216
Whelk	2.28	873	918	1449	1523
Whelk	1.93	1016	1013	1684	1680
Whelk	1.93	526	525	875	874
Whelk	1.93	656	666	1091	1106
Whelk	1.93	1130	1151	1873	1909
Whelk	1.93	581	581	966	966
Whelk	1.93	592	589	983	978
Whelk	1.93	416	422	693	703
Whelk	1.93	1029	1032	1706	1711
Whelk	1.93	585	599	973	996
Whelk	1.51	1275	1281	2113	2123
Whelk	1.51	1530	1532	2535	2538
Whelk	1.51	1005	1014	1667	1682
Whelk	1.51	1023	1035	1696	1716
Whelk	1.51	484	485	806	807
Whelk	1.51	880	880	1460	1460
Whelk	1.51	1311	1321	2172	2189
Whelk	1.51	765	780	1271	1295
Whelk	0.68	689	676	1144	1123
Whelk	0.68	591	578	982	961
Whelk	0.68	1157	1154	1917	1914
Whelk	0.68	713	697	1184	1157
Whelk	0.68	1014	1007	1681	1670
Whelk	0.68	711	706	1181	1173
Whelk	0.68	625	610	1039	1015
Whelk	0.68	661	648	1098	1076
Periwinkle	2.28	522	538	832	858
Periwinkle	2.28	364	386	583	619
Periwinkle	2.28	764	772	1215	1227
Periwinkle	2.28	413	428	662	685
Periwinkle	2.28	549	567	875	903
Periwinkle	2.28	592	621	943	989
Periwinkle	2.28	428	441	685	705
Periwinkle	2.28	432	432	691	690
Periwinkle	2.28	421	461	674	737
Periwinkle	2.28	694	695	1104	1105
Periwinkle	2.28	451	484	721	773

Table DR6 (continued)

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Periwinkle	2.28	571	587	910	936
Periwinkle	1.93	455	467	727	747
Periwinkle	1.93	362	361	580	579
Periwinkle	1.93	381	384	610	616
Periwinkle	1.93	409	415	655	664
Periwinkle	1.93	445	446	712	713
Periwinkle	1.93	383	393	613	629
Periwinkle	1.93	419	431	670	689
Periwinkle	1.93	358	375	574	601
Periwinkle	1.93	311	318	500	511
Periwinkle	1.51	369	378	592	606
Periwinkle	1.51	390	403	625	645
Periwinkle	1.51	485	492	775	786
Periwinkle	1.51	429	434	686	693
Periwinkle	1.51	526	516	839	823
Periwinkle	1.51	541	548	863	874
Periwinkle	1.51	380	391	609	626
Periwinkle	1.51	539	548	859	874
Periwinkle	1.51	475	476	759	760
Periwinkle	1.51	451	454	720	726
Periwinkle	1.51	666	642	1059	1021
Periwinkle	0.68	376	380	602	609
Periwinkle	0.68	423	432	677	690
Periwinkle	0.68	363	363	582	582
Periwinkle	0.68	353	363	566	582
Periwinkle	0.68	351	326	563	524
Periwinkle	0.68	348	351	558	563
Periwinkle	0.68	446	438	714	700
Periwinkle	0.68	453	451	724	721
Periwinkle	0.68	367	357	589	572
Periwinkle	0.68	572	536	912	855
Coralline red alga	3.12	727	763	1278	1340
Coralline red alga	3.12	1498	1554	2623	2721
Coralline red alga	3.12	1545	1618	2706	2832
Coralline red alga	3.12	1199	1216	2100	2131
Coralline red alga	3.12	738	778	1296	1367
Coralline red alga	3.12	572	588	1008	1035
Coralline red alga	3.12	926	1005	1625	1763
Coralline red alga	3.12	779	843	1368	1480
Coralline red alga	3.12	898	995	1576	1745
Coralline red alga	3.12	1123	1198	1969	2099
Coralline red alga	2.4	1207	1307	2115	2290
Coralline red alga	2.4	907	1087	1592	1906
Coralline red alga	2.4	926	1040	1625	1824
Coralline red alga	2.4	1032	1135	1810	1990
Coralline red alga	2.4	1085	1293	1902	2265
Coralline red alga	2.4	1124	1209	1970	2119
Coralline red alga	2.4	982	1067	1722	1871
Coralline red alga	2.4	1344	1562	2354	2735
Coralline red alga	2.4	548	670	965	1178
Coralline red alga	2.4	402	508	711	895
Coralline red alga	2.4	315	342	558	606
Coralline red alga	1.84	735	772	1292	1356
Coralline red alga	1.84	1056	1117	1851	1958
Coralline red alga	1.84	763	858	1341	1506
Coralline red alga	1.84	482	567	849	998
Coralline red alga	1.84	598	690	1052	1213
Coralline red alga	1.84	770	814	1353	1429
Coralline red alga	1.84	562	613	990	1079
Coralline red alga	1.84	869	1016	1525	1782
Coralline red alga	1.84	1238	1353	2169	2370
Coralline red alga	1.84	727	794	1278	1394
Coralline red alga	0.9	550	553	969	974
Coralline red alga	0.9	237	239	423	426
Coralline red alga	0.9	468	508	826	895
Coralline red alga	0.9	1303	1320	2282	2312
Coralline red alga	0.9	1110	1137	1946	1993
Coralline red alga	0.9	424	455	749	803
Coralline red alga	0.9	1030	1061	1806	1860
Coralline red alga	0.9	834	862	1464	1513
Coralline red alga	0.9	461	465	813	820
Coralline red alga	0.9	330	365	584	646
Coralline red alga	0.9	621	629	1093	1107
Halimeda	3.12	n/a	n/a	n/a	n/a
Halimeda	3.12	n/a	n/a	n/a	n/a

Table DR6 (continued)

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Pencil urchin	2.06	1669	1701	3028	3086
Pencil urchin	2.06	1215	1443	2196	2614
Pencil urchin	2.06	2637	2800	4799	5096
Pencil urchin	2.06	2436	2586	4430	4705
Pencil urchin	2.06	4016	4445	7322	8107
Pencil urchin	1.58	1844	1899	3347	3448
Pencil urchin	1.58	1379	1494	2497	2707
Pencil urchin	1.58	1555	1672	2819	3032
Pencil urchin	1.58	3503	3629	6383	6614
Pencil urchin	1.21	1740	1880	3157	3413
Pencil urchin	1.21	2704	2885	4921	5252
Pencil urchin	1.21	5723	5842	10446	10664
Pencil urchin	0.54	1119	816	2020	1466
Pencil urchin	0.54	893	702	1607	1258
Pencil urchin	0.54	1518	1356	2751	2455
Pencil urchin	0.54	2809	2579	5114	4692
Pencil urchin	0.54	5058	3942	9229	7187
Pencil urchin	0.54	5395	4308	9846	7856
Purple urchin	2.06	618	720	1123	1304
Purple urchin	2.06	1260	1308	2269	2355
Purple urchin	2.06	1324	1391	2383	2502
Purple urchin	2.06	884	951	1597	1716
Purple urchin	1.58	486	707	886	1280
Purple urchin	1.58	539	762	980	1379
Purple urchin	1.58	963	1278	1738	2302
Purple urchin	1.58	987	1324	1781	2383
Purple urchin	1.58	1089	1555	1963	2797
Purple urchin	1.58	1203	1683	2168	3025
Purple urchin	1.21	589	822	1070	1486
Purple urchin	1.21	778	1144	1409	2062
Purple urchin	1.21	826	1174	1494	2116
Purple urchin	0.54	742	968	1344	1748
Purple urchin	0.54	774	974	1400	1759
Purple urchin	0.54	1352	1743	2433	3132
Purple urchin	0.54	1398	1801	2515	3237
Coral	2.60	1463	1620	2393	2645
Coral	2.60	1790	1966	2920	3203
Coral	2.60	1446	1618	2364	2642
Coral	2.60	1999	2225	3256	3620
Coral	2.60	1294	1468	2119	2400
Coral	2.60	2961	3318	4807	5382
Coral	2.60	2644	2917	4296	4736
Coral	2.60	2505	2830	4072	4596
Coral	2.60	2402	2686	3906	4364
Coral	2.60	2007	2282	3269	3712
Coral	2.60	3403	3793	5520	6148
Coral	2.28	1668	1863	2722	3036
Coral	2.28	1424	1579	2330	2580
Coral	2.28	1884	2106	3071	3428
Coral	2.28	2394	2647	3893	4300
Coral	2.28	3964	4340	6424	7030
Coral	2.28	1370	1545	2243	2525
Coral	2.28	1763	1965	2876	3201
Coral	2.28	3192	3548	5179	5752
Coral	2.28	1906	2131	3106	3469
Coral	2.28	2284	2518	3716	4092
Coral	2.28	1623	1831	2650	2985
Coral	2.28	1958	2212	3190	3600
Coral	2.28	2644	3012	4296	4889
Coral	2.28	3269	3670	5303	5950
Coral	2.28	1302	1436	2133	2348
Coral	1.64	1989	2180	3240	3548
Coral	1.64	1727	1916	2818	3122
Coral	1.64	2346	2604	3815	4231
Coral	1.64	1180	1329	1935	2176
Coral	1.64	2174	2377	3538	3866
Coral	1.64	1704	1885	2780	3072
Coral	1.64	1571	1742	2566	2842
Coral	1.64	1677	1857	2737	3027
Coral	1.64	1802	2034	2939	3313
Coral	1.64	2145	2443	3492	3972
Coral	1.64	2617	2919	4252	4739
Coral	1.64	1912	2078	3116	3384
Coral	0.77	2082	2177	3391	3543
Coral	0.77	1661	1765	2711	2879

Table DR6 (continued)

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO <sub>3</sub>	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Coral	0.77	1851	1902	3018	3100
Coral	0.77	2200	2231	3580	3630
Coral	0.77	1822	1837	2971	2995
Coral	0.77	2368	2430	3850	3951
Coral	0.77	1815	1895	2960	3089
Coral	0.77	1717	1787	2802	2914
Coral	0.77	2170	2250	3532	3661
Coral	0.77	1833	1884	2989	3071
Coral	0.77	2354	2495	3828	4056
Coral	0.77	2651	2803	4308	4552
Coral	0.77	2096	2170	3412	3532
Coral	0.77	1329	1349	2176	2208
Coral	0.77	1872	1977	3052	3221
Coral	0.77	1977	2080	3220	3387
Serpulid worm	2.60	750	800	1226	1306
Serpulid worm	2.60	499	516	821	848
Serpulid worm	2.60	339	337	562	559
Serpulid worm	2.60	458	475	755	782
Serpulid worm	2.60	584	623	957	1020
Serpulid worm	2.60	1379	1362	2240	2213
Serpulid worm	2.60	555	579	911	949
Serpulid worm	2.60	834	836	1361	1364
Serpulid worm	2.60	744	775	1216	1266
Serpulid worm	2.60	917	912	1495	1487
Serpulid worm	2.60	323	363	536	601
Serpulid worm	2.28	449	462	739	761
Serpulid worm	2.28	876	892	1430	1455
Serpulid worm	2.28	538	569	883	933
Serpulid worm	2.28	711	738	1163	1206
Serpulid worm	2.28	932	957	1520	1560
Serpulid worm	2.28	325	364	539	602
Serpulid worm	2.28	358	391	593	646
Serpulid worm	1.64	822	840	1342	1371
Serpulid worm	1.64	668	701	1093	1146
Serpulid worm	1.64	331	346	548	573
Serpulid worm	1.64	371	361	614	598
Serpulid worm	1.64	402	431	664	711
Serpulid worm	1.64	788	760	1287	1242
Serpulid worm	1.64	367	391	608	646
Serpulid worm	1.64	403	422	666	696
Serpulid worm	1.64	618	653	1012	1069
Serpulid worm	1.64	765	785	1250	1282
Serpulid worm	1.64	504	500	829	822
Serpulid worm	1.64	559	538	917	883
Serpulid worm	0.77	730	710	1193	1161
Serpulid worm	0.77	411	403	679	665
Serpulid worm	0.77	229	228	385	383
Serpulid worm	0.77	706	735	1155	1201
Serpulid worm	0.77	832	863	1358	1408
Serpulid worm	0.77	427	447	705	736
Serpulid worm	0.77	812	824	1325	1345
Serpulid worm	0.77	390	370	644	612
Serpulid worm	0.77	299	319	498	530
Serpulid worm	0.77	918	966	1497	1574
Serpulid worm	0.77	598	590	981	967
Hard clam	2.63	1787	1815	2764	2807
Hard clam	2.63	5104	5128	7908	7945
Hard clam	2.63	5501	5608	8523	8690
Hard clam	2.63	7625	7699	11819	11933
Hard clam	2.63	7548	7595	11698	11772
Hard clam	2.63	10537	10617	16335	16459
Hard clam	2.63	8263	8292	12808	12852
Hard clam	2.11	5426	5472	8409	8479
Hard clam	2.11	6814	6862	10560	10636
Hard clam	2.11	6610	6647	10245	10302
Hard clam	2.11	8316	8407	12890	13032
Hard clam	2.11	11378	11425	17639	17712
Hard clam	1.43	842	849	1298	1308
Hard clam	1.43	3006	2999	4654	4644
Hard clam	1.43	5381	5402	8338	8370
Hard clam	1.43	4901	4946	7594	7664
Hard clam	1.43	7792	7848	12077	12164
Hard clam	1.43	9432	9484	14621	14702
Hard clam	1.43	8570	8577	13285	13295
Hard clam	0.71	4415	4355	6840	6747

Table DR6 (continued)

Organism	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Hard clam	0.71	3851	3775	5966	5847
Hard clam	0.71	4908	4820	7605	7468
Hard clam	0.71	8632	8547	13381	13249
Hard clam	0.71	8485	8390	13152	13005
Hard clam	0.71	9439	9340	14632	14479
Blue mussel	2.63	308	314	542	552
Blue mussel	2.63	221	237	390	418
Blue mussel	2.63	290	302	511	532
Blue mussel	2.63	253	263	446	462
Blue mussel	2.63	260	273	458	481
Blue mussel	2.63	311	318	547	560
Blue mussel	2.63	397	419	697	736
Blue mussel	2.63	445	470	781	826
Blue mussel	2.63	460	492	808	865
Blue mussel	2.63	593	617	1041	1083
Blue mussel	2.63	476	518	836	909
Blue mussel	2.63	558	566	980	993
Blue mussel	2.63	418	437	734	767
Blue mussel	2.63	590	599	1036	1050
Blue mussel	2.63	676	705	1186	1236
Blue mussel	2.11	281	285	495	501
Blue mussel	2.11	355	369	625	648
Blue mussel	2.11	256	275	450	484
Blue mussel	2.11	254	257	447	453
Blue mussel	2.11	318	315	559	554
Blue mussel	2.11	353	369	620	648
Blue mussel	2.11	395	404	695	710
Blue mussel	2.11	550	570	965	1001
Blue mussel	2.11	360	370	633	650
Blue mussel	2.11	612	644	1074	1129
Blue mussel	2.11	473	505	831	887
Blue mussel	2.11	705	720	1237	1263
Blue mussel	2.11	568	571	997	1002
Blue mussel	1.43	263	291	464	512
Blue mussel	1.43	229	234	404	413
Blue mussel	1.43	319	323	560	569
Blue mussel	1.43	368	399	647	701
Blue mussel	1.43	260	269	458	473
Blue mussel	1.43	382	405	671	712
Blue mussel	1.43	368	380	647	668
Blue mussel	1.43	440	438	773	769
Blue mussel	1.43	320	311	562	547
Blue mussel	1.43	429	457	753	802
Blue mussel	1.43	406	420	714	738
Blue mussel	1.43	498	507	875	890
Blue mussel	1.43	606	627	1063	1100
Blue mussel	1.43	490	505	861	887
Blue mussel	0.71	344	363	604	639
Blue mussel	0.71	315	310	554	545
Blue mussel	0.71	290	318	510	560
Blue mussel	0.71	281	286	495	503
Blue mussel	0.71	291	307	513	539
Blue mussel	0.71	401	400	704	703
Blue mussel	0.71	334	348	588	611
Blue mussel	0.71	410	420	721	738
Blue mussel	0.71	443	478	778	839
Blue mussel	0.71	551	557	967	977
Blue mussel	0.71	488	501	857	879
Blue mussel	0.71	395	402	694	707
Blue mussel	0.71	493	513	865	901
Blue mussel	0.71	703	701	1233	1230
Soft clam	2.63	248	301	405	493
Soft clam	2.63	687	784	1135	1296
Soft clam	2.63	1559	1825	2582	3025
Soft clam	2.11	174	185	283	301
Soft clam	2.11	147	165	237	267
Soft clam	2.11	373	390	612	641
Soft clam	2.11	477	527	785	868
Soft clam	2.11	1161	1215	1921	2011
Soft clam	1.43	169	168	274	273
Soft clam	1.43	214	197	349	320
Soft clam	1.43	544	551	897	909
Soft clam	1.43	782	848	1292	1401
Soft clam	0.71	121	103	195	164



Table DR6 (continued)

Organi	Qarag	Buoyant Weight		Dry Weight of CaCO3	
		Initial (mg)	Final (mg)	Initial (mg)	Final (mg)
Soft clam	0.71	354	350	581	575
Bay scallop	2.62	2011	2124	3570	3766
Bay scallop	2.62	1842	1930	3275	3429
Bay scallop	2.62	2565	2708	4537	4786
Bay scallop	2.62	2794	3056	4935	5391
Bay scallop	2.62	2566	2797	4538	4940
Bay scallop	2.11	1866	1969	3318	3496
Bay scallop	2.11	2314	2476	4098	4381
Bay scallop	2.11	2627	2793	4643	4934
Bay scallop	1.43	2258	2451	4001	4338
Bay scallop	1.43	2391	2503	4233	4428
Bay scallop	1.43	2567	2565	4539	4535
Bay scallop	1.43	3016	3061	5322	5400
Bay scallop	1.43	3372	3695	5944	6507
Bay scallop	0.71	2301	2338	4075	4140
Bay scallop	0.71	1887	1972	3353	3501
Bay scallop	0.71	2151	2238	3813	3966
Bay scallop	0.71	3636	3634	6404	6400
Bay scallop	0.71	3198	3242	5640	5716
Oyster	2.62	6761	6902	11431	11665
Oyster	2.62	12210	12472	20444	20878
Oyster	2.62	13709	13972	22923	23359
Oyster	2.62	14318	14519	23930	24264
Oyster	2.11	4100	4152	7030	7117
Oyster	2.11	9833	10009	16512	16803
Oyster	2.11	16417	16751	27403	27954
Oyster	2.11	18634	18863	31069	31449
Oyster	1.43	4476	4506	7652	7701
Oyster	1.43	5513	5566	9367	9456
Oyster	1.43	10980	11127	18410	18653
Oyster	1.43	14999	15208	25057	25404
Oyster	0.71	5896	5898	10001	10005
Oyster	0.71	7532	7598	12707	12816
Oyster	0.71	8798	8820	14800	14837
Oyster	0.71	9930	9926	16673	16666