

# Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*

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Ocean acidification (OA) refers to the ongoing decline in oceanic pH resulting from the uptake of atmospheric CO<sub>2</sub>. Mounting experimental evidence suggests that OA will have negative consequences for a variety of marine organisms. Whereas the effect of OA on the calcification of adult reef corals is increasingly well documented, effects on early life history stages are largely unknown. Coral recruitment, which necessitates successful fertilization, larval settlement, and postsettlement growth and survivorship, is critical to the persistence and resilience of coral reefs. To determine whether OA threatens successful sexual recruitment of reef-building corals, we tested fertilization, settlement, and postsettlement growth of *Acropora palmata* at pCO<sub>2</sub> levels that represent average ambient conditions during coral spawning (~400 μatm) and the range of pCO<sub>2</sub> increases that are expected to occur in this century [~560 μatm (mid-CO<sub>2</sub>) and ~800 μatm (high-CO<sub>2</sub>)]. Fertilization, settlement, and growth were all negatively impacted by increasing pCO<sub>2</sub>, and impairment of fertilization was exacerbated at lower sperm concentrations. The cumulative impact of OA on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO<sub>2</sub> conditions projected for the middle and the end of this century, respectively. Additional declines of 39% (mid-CO<sub>2</sub>) and 50% (high-CO<sub>2</sub>) were observed in postsettlement linear extension rates relative to controls. These results suggest that OA has the potential to impact multiple, sequential early life history stages, thereby severely compromising sexual recruitment and the ability of coral reefs to recover from disturbance.

carbon dioxide | climate change | pH | juvenile | elkhorn coral

The susceptibility of reef-building corals to increasing CO<sub>2</sub> levels has been a central issue in the context of global climate change. Present-day atmospheric CO<sub>2</sub> (pCO<sub>2</sub>) levels are estimated at 387 ppm, 30% higher than the natural range over the last 650,000 y (1). pCO<sub>2</sub> is increasing at an annual rate of 0.5% (2), 200 times faster than any changes that occurred during the last eight glacial cycles (1). Approximately one-third of all CO<sub>2</sub> emissions from the past 200 y has been absorbed by the oceans (3). On dissolution in seawater, CO<sub>2</sub> reacts with H<sub>2</sub>O, triggering a series of chemical reactions that alter the seawater carbonate chemistry; [CO<sub>2</sub>]<sub>aq</sub> and [HCO<sub>3</sub><sup>-</sup>] increase, and [CO<sub>3</sub><sup>2-</sup>], pH, and the carbonate saturation state (Ω) decrease, causing ocean surface waters to become more acidic. Increasing atmospheric CO<sub>2</sub> concentrations have already depleted seawater carbonate concentrations by ~30 μmol kg<sup>-1</sup>, simultaneously reducing the pH of the ocean's surface waters by 0.1 units relative to the pre-industrial era (a 30% increase in [H<sup>+</sup>]) (2). Further reductions of 0.3–0.5 pH units are projected by the end of this century as the oceans continue to absorb anthropogenic CO<sub>2</sub> (2, 3).

Mounting experimental evidence suggests that ocean acidification (OA) will have negative consequences for numerous marine organisms, primarily oceanic calcifiers that rely on the delicate balance of dissolved inorganic carbon species for the formation of their shells and skeletons (4–7). Although recent research efforts have aimed to constrain the mechanisms and effects (both physiological and ecological) of elevated pCO<sub>2</sub> on

adult corals, comparatively little attention has been given to the effect of OA on earlier life history stages.

The majority of reef-building corals rely on external fertilization and the development, survival, and settlement of lecithotrophic (i.e., energy-limited) planula larvae (8). Coral larvae spend hours to days developing in the water column before they are capable of settling on the reef. Larval settlement requires the recognition of water-soluble and substrate-bound chemical cues, physical attachment to the substrate, and subsequent metamorphosis. Recruitment (identification and inclusion in a population) necessitates survival and growth of the newly settled individual. Successful coral recruitment is determined by three sequential life history stages: (i) larval availability (including gamete production and successful fertilization), (ii) settlement ecology (related to larval and substrate condition), and (iii) postsettlement ecology (growth and survival) (9). Environmental factors that disrupt these various processes can result in compromised recruitment or recruitment failure and profoundly affect marine population dynamics (10–12).

The objective of the present study was to investigate the effect of pCO<sub>2</sub> on the three sequential life history stages that are critical to successful sexual recruitment of broadcast-spawning reef corals. The experimental coral chosen for this study was the ecologically significant Caribbean elkhorn coral *Acropora palmata* (Lamarck). This fast-growing, branching species has historically functioned as a primary framework builder on many Caribbean shallow reefs. However, Caribbean acroporid populations have experienced widespread decline over the last several decades due to hurricanes, disease, bleaching, and predation (13, 14). A drastic reduction in population size resulted in the designation of *A. palmata* as a threatened species under the US Endangered Species Act in 2006 (15). Recovery of *A. palmata* populations likely will require high rates of recruitment (13, 16, 17). Although this coral's primary reproductive mode is asexual fragmentation, sexual recruitment is critical for maintaining the genetic diversity of future populations. To determine the effects of OA on the sexual recruitment of this species, we tested fertilization, settlement, and postsettlement growth at three pCO<sub>2</sub> levels, representing average conditions during the spawning season [400 μatm (control)] and the range of pCO<sub>2</sub> increases expected during this century [560 μatm (mid-CO<sub>2</sub>) and 800 μatm (high-CO<sub>2</sub>)], as determined by the Intergovernmental Panel on Climate Change (2).

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**Table 1. Parameter estimates for nonlinear regressions of fertilization data**

	468 $\mu\text{atm}$	673 $\mu\text{atm}$	998 $\mu\text{atm}$
Best-fit values			
Max % Fert	45.93	62.21	53.07
C	1.98	0.40	0.54
SE			
Max % Fert	3.30	17.97	6.02
C	0.46	0.20	0.12
95% confidence interval			
Max % Fert	39.25–52.62	25.39–99.01	40.86–65.28
C	1.06–2.90	–0.0003–0.80	0.30–0.78
Degrees of freedom			
	38	28	37
$R^2$	0.40	0.56	0.84

Max % Fert is the asymptotic average maximum percentage of fertilization, and C is a rate coefficient that determines how quickly the maximum is attained.

urchins (19) and at least one species of coral (21), is one possible explanation for the reductions in fertilization reported herein.

Our data suggest that as sperm concentration declines, the effect of OA on fertilization success intensifies (Fig. 1B). Sperm limitation (i.e., too few sperm to fertilize all eggs) is recognized as one of the key factors limiting the reproductive success of sessile, broadcast-spawning marine invertebrates (22, 23). Thus, it is likely that in situ fertilization occurs at dilute sperm concentrations, with which the effects of OA would be exacerbated. Reproductive failure due to sperm limitation is of increasing concern as hurricanes, disease, and other environmental and anthropogenic stressors continue to reduce coral population densities (i.e., Allee effects) (23, 24). Increasing OA threatens to diminish larval supply, a major determinant of recruit density (25, 26), and depressed recruitment will likely compromise coral reef resilience (the ability of reefs to recover after disturbance). Three-quarters of reef-building coral species spawn gametes and rely on external fertilization and planktonic development (8); thus, if *A. palmata* is representative of spawning species in general, then the fertilization and recruitment success of many spawning corals will likely be impaired as CO<sub>2</sub>-driven OA intensifies.

The results of our fertilization assays underscore the need for caution when designing and interpreting experiments testing the effects of CO<sub>2</sub> on the fertilization of broadcast-spawning marine invertebrates. At our highest sperm concentration (approaching optimal concentrations but unlikely to occur in nature), no treatment effect of CO<sub>2</sub> was observed; however, as sperm concentration decreased, a significant effect of CO<sub>2</sub> emerged (Fig. 1B). In addition, comparison of confidence intervals for slope (Table 1) indicates a significantly higher fertilization rate in the control (468  $\mu\text{atm}$ ) compared with either of the elevated CO<sub>2</sub> treatments. The two elevated CO<sub>2</sub> treatments were not significantly different from one another, however. These results suggest that there may be a threshold response to elevated CO<sub>2</sub> within the range of CO<sub>2</sub> values and sperm concentrations that were tested for this coral species. Future studies should test CO<sub>2</sub> effects across a broad range of OA scenarios and sperm concentrations to accurately assess the presence of a treatment effect.

The effect of  $p\text{CO}_2$  on larval settlement may indicate either a direct effect (physiological disruption of settlement and/or metamorphosis) or an indirect effect (interference with benthic habitat cues or behavior). Although these two mechanisms are not mutually exclusive, previous settlement experiments conducted with *Porites astreoides* larvae indicated that elevated  $p\text{CO}_2$  does not significantly affect the ability of larvae to successfully settle and metamorphose (6). It is important to note, however, that this previous study tested only the direct effect of  $p\text{CO}_2$  on

larval settlement and did not address the potential for indirect effects. The presence of an effect in the present study suggests that an indirect mechanism is primarily responsible for the trends reported herein, whereby  $p\text{CO}_2$  alters the community composition of the substrata during the conditioning phase, thereby altering the biological and chemical cues responsible for settlement. Both positive settlement cues from crustose coralline algae (CCA) and settlement interference by turf algae have been documented (27–31). Visual inspection of the settlement substrata used in the present study confirms that the higher CO<sub>2</sub> treatments resulted in greater colonization by filamentous algae. Visible differences in colonization by CCA that were apparent approximately 3 wk after settlement experiments are consistent with previously documented reductions in CCA colonization as a result of OA (32) and suggest that nonvisible differences were present at the time of settlement. Both the increase in filamentous algae and the decrease in CCA colonization may explain the depressed settlement observed on high-CO<sub>2</sub>-conditioned tiles.

The observed reductions in linear extension of *A. palmata* juveniles are consistent with the hypothesis that calcification and, ultimately, growth decline as  $p\text{CO}_2$  increases and saturation state decreases (4–7). Slowed juvenile growth likely will translate into increased juvenile mortality, given that the risk of mortality is inversely proportional to juvenile growth rate and colony size (26, 33, 34). In addition, for corals and other species that exhibit direct relationships among colony size, onset of sexual maturity (35), and fecundity (34), reduced growth will substantially diminish reproductive potential. Slowed growth will result in a longer time spent in juvenile, nonreproductive life stages, which, in combination with adult loss, would shift population structures toward dominance by smaller size classes, ultimately reducing effective population sizes, population fecundity, and the resilience of reef-building corals (36).

Sessile, broadcast-spawning organisms face several population bottlenecks during early life, including fertilization, settlement, and early postsettlement survivorship and growth (26). As a result, natural larval and early juvenile mortality of many marine invertebrates often exceeds 99% (37, 38). Stochastic events or chronic stressors that further reduce survivorship during these critical stages have the potential to significantly alter future population sizes (26, 37). Although OA is now recognized as a substantial threat to marine calcifiers and their ability to secrete calcium carbonate shells and/or skeletons, our findings demonstrate that increasing  $p\text{CO}_2$  has the potential to impact multiple life history stages of corals, including critical processes independent of calcification. The compounding nature of these impacts on successive life history stages suggests that the consequences of OA on coral populations and reef communities might be more severe than originally perceived.

## Materials and Methods

The fertilization experiments described in this report were conducted in field laboratories in Key Largo, FL. Settlement and growth experiments were conducted at the Climate Change Laboratory at the Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL.

**Spawn Collection.** Two stands of previously genotyped *Acropora palmata* in the Upper Florida Keys were monitored for spawning during August 2009. Gamete bundles were collected from two distinct genets at Elbow Reef and one at Sand Island. Corals spawned at  $\approx 2200$  hours. Gamete bundles disintegrated  $\approx 30$  min after release, whereupon eggs and sperm from each colony were separated via pipet. Eggs were washed between five and seven times with filtered seawater to remove residual sperm. Equal volumes of eggs from each genet were combined to create a “stock” egg batch for use in fertilization experiments. The same was done with the sperm.

**Seawater Chemistry.** Seawater chemistry was manipulated via direct bubbling with CO<sub>2</sub>-enriched air to create three target conditions: 400  $\mu\text{atm}$  (control), 560  $\mu\text{atm}$  (mid-CO<sub>2</sub>), and 800  $\mu\text{atm}$  (high-CO<sub>2</sub>). Actual chemical and physical

Table 2. Physical and chemical conditions during the experimental periods (mean  $\pm$  1 SD)

	Salinity	T °C	TA $\mu\text{mol kg}^{-1}$	pH <sub>T</sub>	pCO <sub>2</sub> $\mu\text{atm}$	HCO <sub>3</sub> <sup>-</sup> $\mu\text{mol kg}^{-1}$	CO <sub>3</sub> <sup>2-</sup> $\mu\text{mol kg}^{-1}$	CO <sub>2</sub> $\mu\text{mol kg}^{-1}$	TCO <sub>2</sub> $\mu\text{mol kg}^{-1}$	<sup>b</sup> Ca <sup>2+</sup> mmol kg <sup>-1</sup>	Ω <sub>arag</sub>
Ambient seawater (n = 4 hourly samples)											
Ambient seawater	36.5 $\pm$ 0.1	30.054 $\pm$ 0.001	2,385 $\pm$ 3	8.00 $\pm$ 0.01	454 $\pm$ 12	1,793 $\pm$ 8	242 $\pm$ 4	11.0 $\pm$ 0.3	2,046 $\pm$ 4	10.7 $\pm$ 0.3	3.89 $\pm$ 0.07
Fertilization (n = 1 initial)											
Control	35.1 $\pm$ 0.1	28.0 $\pm$ 0.1	2,310 $\pm$ 2	7.986 $\pm$ 0.004	468 $\pm$ 5	1,794 $\pm$ 3	210 $\pm$ 2	12.3 $\pm$ 0.1	2,016.7 $\pm$ 0.9	10.3 $\pm$ 0.3	3.38 $\pm$ 0.03
Mid-CO <sub>2</sub>	34.4 $\pm$ 0.1	28.0 $\pm$ 0.1	2,293 $\pm$ 1	7.8538 $\pm$ 0.0008	673 $\pm$ 1	1,899.0 $\pm$ 0.4	161.3 $\pm$ 0.3	17.76 $\pm$ 0.03	2,078.0 $\pm$ 0.7	10.1 $\pm$ 0.3	2.608 $\pm$ 0.0005
High-CO <sub>2</sub>	34.5 $\pm$ 0.1	28.0 $\pm$ 0.1	2,352.4 $\pm$ 0.5	7.715 $\pm$ 0.0003	998 $\pm$ 7	2,045 $\pm$ 1	126.4 $\pm$ 0.7	26.3 $\pm$ 0.2	2,197.6 $\pm$ 0.8	10.1 $\pm$ 0.3	2.04 $\pm$ 0.01
Settlement (n = 1 initial)											
Control	34.5 $\pm$ 0.1	28.0 $\pm$ 0.1	2,339 $\pm$ 2	7.966 $\pm$ 0.002	491 $\pm$ 3	1,834.3 $\pm$ 0.4	207 $\pm$ 1	12.93 $\pm$ 0.07	2,054.2 $\pm$ 0.6	10.1 $\pm$ 0.3	3.34 $\pm$ 0.12
Mid-CO <sub>2</sub>	34.8 $\pm$ 0.1	28.0 $\pm$ 0.1	2,388 $\pm$ 3	7.87 $\pm$ 0.01	654 $\pm$ 19	1,956 $\pm$ 6	178 $\pm$ 4	17.2 $\pm$ 0.5	2,151 $\pm$ 3	10.2 $\pm$ 0.3	2.87 $\pm$ 0.06
High-CO <sub>2</sub>	34.9 $\pm$ 0.1	28.0 $\pm$ 0.1	2,336.2 $\pm$ 0.9	7.751 $\pm$ 0.0003	876 $\pm$ 7	1,998 $\pm$ 1	139.6 $\pm$ 0.9	23.1 $\pm$ 0.2	2,159.7 $\pm$ 0.5	10.3 $\pm$ 0.3	2.23 $\pm$ 0.01
Growth (n = 5 weekly samples)											
Control	34 $\pm$ 1	28.2 $\pm$ 0.1	2,482 $\pm$ 42	8.04 $\pm$ 0.03	436 $\pm$ 41	1,886 $\pm$ 53	247 $\pm$ 15	11 $\pm$ 1	2,144 $\pm$ 46	10.0 $\pm$ 0.3	4.0 $\pm$ 0.2
Mid-CO <sub>2</sub>	34.2 $\pm$ 0.7	28.2 $\pm$ 0.1	2,471 $\pm$ 32	7.93 $\pm$ 0.04	599 $\pm$ 69	1,987 $\pm$ 55	200 $\pm$ 13	16 $\pm$ 2	2,203 $\pm$ 46	10.0 $\pm$ 0.3	3.3 $\pm$ 0.2
High-CO <sub>2</sub>	35 $\pm$ 1	28.12 $\pm$ 0.09	2,479 $\pm$ 37	7.79 $\pm$ 0.05	882 $\pm$ 111	2,109 $\pm$ 52	154 $\pm$ 14	23 $\pm$ 3	2,286 $\pm$ 46	10.1 $\pm$ 0.3	2.5 $\pm$ 0.2

Averages for ambient seawater are based on hourly water sampling at 0–4 h postspawning (2200–0200 hours) on Elbow Reef (site of gamete collection), 11 d after *A. palmata* spawning in August 2009. All measurements are based on duplicate or triplicate analyses for each sampling period. pH<sub>T</sub>, pCO<sub>2</sub>, HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>2-</sup>, CO<sub>2</sub>, and Ω<sub>arag</sub> were calculated using CO2SYS with an input temperature of 25 °C and an output temperature according to the tank or ambient seawater as noted in the table. Calcium concentration was calculated based on 10.28 mmol kg<sup>-1</sup> of Ca<sup>2+</sup> at a salinity of 35.

conditions that persisted during each experiment are outlined in Table 2. The control was bubbled only with air and approximates the average ambient seawater chemistry that was observed at 0–4 h postspawning (2200–0200 hours, hours of maximum sperm activity and highest potential for fertilization) on Elbow Reef, Key Largo, FL (the site of gamete collection) as determined by hourly water sampling at 11 d postspawning (n = 4 hourly samples) (Table 2). Treatment water was filtered (0.2 μm) before use in experiments, to limit respiratory alterations of desired CO<sub>2</sub> levels. Water samples were obtained and analyzed at the start of fertilization and settlement experiments to verify distinct treatments; samples were obtained weekly for growth experiments. Water samples were analyzed for TA and pH. TA was determined in duplicate using automated, open-cell Gran titration (SOP3b; ref. 39), and accuracy was checked against certified seawater reference material (from A. Dickson, Scripps Institute of Oceanography). pH on the total scale was determined using an Orion ROSS combination pH electrode (Thermo Scientific) calibrated at 25 °C against a seawater Tris buffer (SOP6a; ref. 39). Concentrations of CO<sub>3</sub><sup>2-</sup>, Ca<sup>2+</sup>, and Ω<sub>arag</sub> were computed from TA, pH, temperature, and salinity using the CO2SYS program (from E. Lewis, Brookhaven National Laboratory), dissociation constants for carbonate determined by Mehrbach et al. (40) as refit by Dickson and Millero (41), and the dissociation constant for boric acid determined by Dickson (42). pH is reported on the total scale, the scale on which K1 and K2 were determined in the Gran functions.

**Fertilization Assays.** Concentrated sperm (3.21  $\times$  10<sup>8</sup> sperm mL<sup>-1</sup>), representing equal contributions from three parental genotypes, were diluted to 3.21  $\times$  10<sup>6</sup>, 1.61  $\times$  10<sup>6</sup>, 6.41  $\times$  10<sup>5</sup>, and 3.20  $\times$  10<sup>5</sup> sperm mL<sup>-1</sup> in filtered treatment water. Optimal sperm concentrations for other species of broadcast-spawning corals have been reported to range between 10<sup>5</sup> and 10<sup>6</sup> sperm mL<sup>-1</sup> (43). After 1-mL subsamples of each dilution were fixed in 10% formalin for verification of sperm concentrations (eight replicate counts by hemocytometer), 10 mL of each sperm dilution–treatment combination was transferred via pipet into each of 10 replicate 15-mL glass vials. A 10-mL volume of sperm-free seawater was transferred into an extra vial as a negative (no-sperm) control. Then 100 μL of eggs (~200–250 eggs) was immediately added to each vial, and the mixture was swirled. Fertilization experiments were initiated within 3 h of spawning and conducted at 28  $\pm$  0.1 °C. Embryos were subsampled at 4 h and fixed in 10% formaldehyde. Subsequently, 100–200 undamaged eggs from each subsample were examined using a dissecting microscope and classified as either fertilized (showing normal cleavage patterns of cell division) or unfertilized (showing no signs of cleavage).

Nonlinear regressions (exponential rise to maximum, two parameter) were fit to percent fertilization at sperm concentration data. Regressions were fit separately for each CO<sub>2</sub> concentration using least squares residuals. The data were fit to the following model:

$$\% \text{ Fert} = \max \% \text{ Fert} (1 - e^{-C * SC}),$$

where %Fert is the percent fertilization at sperm concentration (SC), max% Fert is the asymptotic average maximum percent fertilization, and C is a rate coefficient that determines how quickly (or slowly) the maximum is attained (i.e., the slope). Justification for the use of this model is provided in *SI Text*. A comparison-of-fit test was conducted on arcsine-transformed data to test the null hypothesis (H0) that one curve best fits all data sets.

Data from the 0.32  $\times$  10<sup>5</sup> sperm mL<sup>-1</sup> · 673 μatm treatment were omitted from the regression (“x” in Fig. S2B), resulting in 30 df at 673 μatm. Reliable data were not available for this cell due to sperm contamination. This notion is supported by the model results, which indicate an expected value much lower than what was found for that cell. In addition, one outlier was removed from the 998-μatm treatment, resulting in 39 df (“+” in Fig. S2C); this outlier was >2.5 SD away from the mean. It is important to note that omitting these points did not change the statistical outcome of the regression analyses, but did provide a better fit for the model.

**Settlement Assays.** Gametes not used for fertilization experiments were fertilized, reared to competency in ambient seawater, and used in assays to test the effects of pCO<sub>2</sub> on settlement success. Five-day-old larvae [5 days after spawning (dAS)] were introduced to settlement assays, where they were offered limestone settlement tiles that had been preconditioned for 40 d in recirculating aquaria corresponding to the three CO<sub>2</sub> treatments. A single source of live rock was divided equally among the three treatment aquaria to provide a consistent source of crustose coralline algae and microfauna during the conditioning phase of the experiment. Settlement assays were conducted in six-well nontreated polystyrene tissue culture

plates (BD Biosciences) using the same treatment water as used for substrate conditioning. One settlement tile, 10 mL of treatment water, and 10 larvae were randomly added to each well. Four 24-well plates were used per treatment. The plates were securely covered and submerged in treatment tanks to ensure temperature control (28 °C) and to prevent gas exchange (i.e., equilibration of mid- and high-CO<sub>2</sub> levels with atmosphere). Water was exchanged by syringe every 48 h, with care taken to not disturb larvae.

Tiles were examined at 6, 8, and 11 dAS. Previous studies have shown that the first permanent larval settlement (i.e., metamorphosed and permanently settled juvenile polyps) of two acroporid species occurred at 5–6 dAS, and most larval settlement (85–97% of total) occurred within 9–10 dAS (44). The number of settled larvae on the top and bottom of each tile was counted using a dissecting microscope. Larvae were classified as “settled” when they had fully metamorphosed (i.e., a flat/disk-shaped appearance rather than pear-shaped), with little or no possibility of active detachment and further migration (11). Percentage data were arcsine-transformed and analyzed using regression analysis.

**Linear Extension.** After settlement, juveniles from the settlement experiments were reared in recirculating treatment aquaria over the course of 50 d. Linear

extension was routinely measured using an optical micrometer, capable of measuring linear extension rates to a precision of 0.5 μm. During each measurement period, juveniles were briefly removed from the treatment aquaria, fitted onto the stage of the micrometer, and advanced through the path of the optical micrometer. Each measurement was conducted in less than 3 min, thereby minimizing the time that spat were out of the water. Linear extension was calculated as the change in elevation over time. Individuals exhibiting partial or full mortality were excluded from the analysis. Data were analyzed by regression analysis.

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