

## RESEARCH ARTICLE

# The role of light in mediating the effects of ocean acidification on coral calcification

Aaron M. Dufault<sup>1,\*</sup>, Aaron Ninokawa<sup>2</sup>, Lorenzo Bramanti<sup>1</sup>, Vivian R. Cumbo<sup>1</sup>, Tung-Yung Fan<sup>3,4</sup> and Peter J. Edmunds<sup>1</sup>

<sup>1</sup>Department of Biology, California State University, 18111 Nordhoff Street, Northridge, CA 91330-8303, USA, <sup>2</sup>Department of Biology, California State University, Fullerton, CA 92834-6850, USA, <sup>3</sup>National Museum of Marine Biology and Aquarium, Taiwan, Republic of China and <sup>4</sup>Institute of Marine Biodiversity and Evolution, National Dong Hwa University, Taiwan, Republic of China

\*Author for correspondence (aaron.dufault@gmail.com)

### SUMMARY

We tested the effect of light and  $P_{\text{CO}_2}$  on the calcification and survival of *Pocillopora damicornis* recruits settled from larvae released in southern Taiwan. In March 2011, recruits were incubated at 31, 41, 70, 122 and 226  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  under ambient (493  $\mu\text{atm}$ ) and high  $P_{\text{CO}_2}$  (878  $\mu\text{atm}$ ). After 5 days, calcification was measured gravimetrically and survivorship estimated as the number of living recruits. Calcification was affected by the interaction of  $P_{\text{CO}_2}$  with light, and at 493  $\mu\text{atm}$   $P_{\text{CO}_2}$  the response to light intensity resembled a positive parabola. At 878  $\mu\text{atm}$   $P_{\text{CO}_2}$ , the effect of light on calcification differed from that observed at 493  $\mu\text{atm}$   $P_{\text{CO}_2}$ , with the result that there were large differences in calcification between 493  $\mu\text{atm}$  and 878  $\mu\text{atm}$   $P_{\text{CO}_2}$  at intermediate light intensities (ca. 70  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ), but similar rates of calcification at the highest and lowest light intensities. Survivorship was affected by light and  $P_{\text{CO}_2}$ , and was highest at 122  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$  in both  $P_{\text{CO}_2}$  treatments, but was unrelated to calcification. In June 2012 the experiment was repeated, and again the results suggested that exposure to high  $P_{\text{CO}_2}$  decreased calcification of *P. damicornis* recruits at intermediate light intensities, but not at lower or higher intensities. Together, our findings demonstrate that the effect of  $P_{\text{CO}_2}$  on coral recruits can be light dependent, with inhibitory effects of high  $P_{\text{CO}_2}$  on calcification at intermediate light intensities that disappear at both higher and lower light intensities.

Supplementary material available online at <http://jeb.biologists.org/cgi/content/full/216/9/1570/DC1>

Key words: Scleractinia, juvenile coral, climate change, bicarbonate, growth, *Pocillopora damicornis*.

Received 23 September 2012; Accepted 15 January 2013

### INTRODUCTION

The effects of light on coral calcification have been studied for decades (Yonge and Nicholls, 1931; Allemand et al., 2011), but interest in this topic waned at the end of the 20th century. Early research recognized that light is not required for coral calcification but rather it accelerates the process in symbiotic corals (Kawaguti and Sakumoto, 1948; Goreau, 1959), with faster rates in the light versus the dark (Allemand et al., 2011) and in shallow versus deep water (Dustan 1975). The relationship between calcification and light in corals was described quantitatively by Chalker (Chalker, 1981), who showed that the shape of this relationship follows a hyperbolic tangent function, as is the case for photosynthesis in many corals (Chalker and Taylor, 1978; Chalker, 1981). In the few cases where the relationship between light and calcification has been measured for tropical corals (all from shallow water <6 m deep), calcification reaches a maximum at  $\sim 400 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$  (Chalker, 1981; Marubini et al., 2001).

Calcification has again become a central topic in coral research as part of the effort to understand the effects of ocean acidification (OA) on coral reefs. Renewed interest has been created by rising atmospheric  $P_{\text{CO}_2}$ , which causes global temperature to rise (IPCC, 2007) and seawater to become less basic as  $\text{CO}_2$  dissolves and liberates protons (Kleypas and Langdon, 2006). OA is expected to reduce oceanic pH by 0.3–0.5 by 2100 (IPCC, 2007), and under these conditions corals generally calcify more slowly (Erez et al., 2011). However, despite the widely publicized negative effects of

OA on coral calcification (Hoegh-Guldberg et al., 2007; Erez et al., 2011), a few corals show signs of resistance to high  $P_{\text{CO}_2}$  (Edmunds, 2011; Comeau et al., 2013a), and some may acclimatize to acidic conditions (Fabricius et al., 2011; Form and Riebesell, 2012; McCulloch et al., 2012). Given the effort to understand the effect of OA on coral calcification, the complex results that are emerging (Erez et al., 2011; Tambutté et al., 2011; Edmunds et al., 2012; Comeau et al., 2012; Comeau et al., 2013a; Comeau et al., 2013b) and the incomplete understanding of the underlying biology (Allemand et al., 2011), it is not surprising that a mechanistic understanding of the effects of OA on coral calcification has proven elusive (Erez et al., 2011; Ries, 2011). However, research on this topic is advancing quickly, and the most recent work is beginning to reveal that the mechanisms involved in the depression of coral calcification by OA conditions are remarkably complex (Comeau et al., 2012; Moya et al., 2012; Kaniewska et al., 2012).

Despite the biological significance of light to symbiotic corals, in the rush to understand how coral calcification is affected by OA the role of light has been overlooked. For instance, calcification of corals under high  $P_{\text{CO}_2}$  has been measured under light intensities that are inconsistent among studies, and mostly low (e.g. Marshall and Clode, 2002; Albright et al., 2008; Edmunds et al., 2012) with limited ecological relevance to the locations from which the corals were collected. To our knowledge, only Marubini and colleagues have investigated the interactive effects of irradiance and OA on coral calcification, and they did so in the laboratory by exposing

*Porites compressa* to  $186 \pm 94$  and  $641 \pm 89 \mu\text{atm } P_{\text{CO}_2}$  at 80, 150 and  $700 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (Marubini et al., 2001). The higher  $P_{\text{CO}_2}$  caused a greater depression of calcification at high than at low irradiances. They augmented their laboratory data with results for *P. compressa* grown at four depths (to contrast light intensities ranging from 2.7 to  $29.5 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) in a large tank filled with seawater manipulated for dissolved inorganic carbon (DIC) chemistry (Langdon et al., 2000); they found that  $P_{\text{CO}_2}$  caused statistically similar reductions in calcification at all irradiances (Marubini et al., 2001). Combining their results, Marubini and colleagues (Marubini et al., 2001) demonstrated that the relationship between calcification and irradiance followed a hyperbolic tangent function (cf. Chalker, 1981), with increased  $P_{\text{CO}_2}$  depressing calcification more at high than at low irradiances, and reducing the sensitivity of calcification to light intensity at low irradiances.

Using the aforementioned studies as a context, we tested for the effect of light on the calcification of *Pocillopora damicornis* exposed to ambient and elevated  $P_{\text{CO}_2}$ , and evaluated survivorship to gain insight into the fitness consequences of calcification. New recruits (i.e. corals ~5 days old) were selected for this analysis because they provide a tractable system in which the effects of  $P_{\text{CO}_2}$  can be studied using calcification (Albright et al., 2010; de Putron et al., 2011) and survivorship (Suwa et al., 2010; Nakamura et al., 2011) as dependent variables.

Further, recruitment is an important event in the life cycle of corals that affects their spatial distribution and population dynamics (Hughes et al., 2000; Bramanti et al., 2005), and while it plays a major role in promoting the recovery of degraded coral reefs (Babcock and Mundy, 1996), recruitment can also function as a bottleneck to population growth (Vermeij and Sandin, 2008; Arnold et al., 2010). The effects of OA on calcification of coral recruits is now being addressed in earnest (Albright, 2011); therefore, we reasoned that it is timely to ask how the results of such studies might be affected by light intensity.

## MATERIALS AND METHODS

An orthogonal design was used in which irradiance and  $P_{\text{CO}_2}$  were manipulated to explore individual and combined effects on *P. damicornis* (Linnaeus 1758) recruits. Two experiments were conducted, with a primary experiment in 2011, and a secondary experiment in 2012 that was designed to determine whether crucial aspects of the 2011 experiment could be repeated.

### Primary experiment (March 2011)

In March 2011, eight colonies of *P. damicornis* (~20 cm diameter) were collected from 5–7 m depth on Hobihu Reef, Taiwan. Colonies were returned to the National Museum of Marine Biology and Aquarium (NMMBA, Pingtung, Taiwan) where they were placed individually into 15 l flow-through tanks and exposed to sunlight at  $103 \pm 3 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (mean  $\pm$  s.e.m.,  $N=85$ , measured with a cosine-corrected LI-192 sensor, LI-COR Biosciences, Lincoln, NB, USA). Seawater overflowing from each tank passed through mesh-lined (110  $\mu\text{m}$ ) cups to capture larvae, which were released during the night starting at ~22:00 h (Fan et al., 2002). Larvae released on 14 March 2011 were collected at 08:00 h and pooled among parent colonies in a 1 l beaker. These larvae were collected approximately on the inferred period of peak larval release (Fan et al., 2002).

Pooled larvae were stirred gently to mix them uniformly relative to maternal genotypes and ~2000 were placed at ~11:00 h into each of two plastic containers ( $24 \times 24 \times 12$  cm) used for settlement. Containers were fitted with mesh windows (110  $\mu\text{m}$ ) to allow the passage of seawater, and floated in the tanks containing adult

colonies. Glazed porcelain tiles ( $20 \times 20 \times 8$  mm), which had accumulated natural biofilms after ~1 month incubation in aquaria receiving flowing seawater, were placed into the floating plastic container with the glazed surface upwards. Larvae were allowed to settle on these surfaces for 24 h and, thereafter, swimming larvae were discarded. Recruits on the glazed tiles were removed easily from their settlement surface, which was a crucial step necessary for weighing them individually (described below). Groups of three tiles with recruits (typically with 6–32 recruits per tile) were assigned haphazardly to each of 20 plastic containers ( $15 \times 8 \times 8$  cm), which had two holes ( $6 \times 4$  cm) to allow for the exchange of seawater.

Each of the 20 containers was fitted with a lid of clear plastic film or neutral density (ND) filters (Lee Filters, Andover, Hants, UK) that created five light treatments. A single 0.3 ND filter blocked ~50% of the visible light, and four treatments of 50%, 25%, 12.5% and 6.25% were created by layering filters; a 5th light treatment (100% light) was created using clear plastic film (Glad Products Company, Oakland, CA, USA). ND filters block out a constant proportion of all wavelengths of photosynthetically active radiation (PAR, 400–700 nm), although ultraviolet (UV) radiation (<300 nm wavelength) is blocked completely. The clear plastic film transmitted >80% of the light between 300 and 700 nm. Transmission characteristics of the ND filter and clear plastic film were assessed using a spectrophotometer (Spectronic Genesys 5, Milton Roy, Warminster, PA, USA) (supplementary material Fig. S1).

The containers used to create the light treatments were placed into 120 liter aquaria for 5 days (16–21 March), with two aquaria at ambient  $P_{\text{CO}_2}$  and two at high  $P_{\text{CO}_2}$ . All tanks were maintained at a mean temperature of  $24.0^\circ\text{C}$  (s.e.m.  $<0.1^\circ\text{C}$ ,  $N=40$ ) using independent heaters and chillers regulated by an aquarium controller ( $\pm 0.1^\circ\text{C}$  Aquacontroller Apex Neptune Systems, San Jose, CA, USA). The experimental temperature mimicked ambient seawater temperature at Hobihu Reef 1 week prior to the experiment (mean  $23.6^\circ\text{C}$ , s.e.m.  $<0.1^\circ\text{C}$ ,  $N=1008$ ) (T.-Y.F., unpublished data), and tanks were filled with filtered seawater (1  $\mu\text{m}$ ), which was changed partially (10–15% volume) every day. Tanks were illuminated from 07:00 h to 19:00 h with lamps fitted with a metal halide bulb (Phillips 150 W 10,000 k) and two 39 W fluorescent bulbs (Phillips T5 460 nm) to create a mean irradiance of  $265 \pm 2 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (mean  $\pm$  s.e.m.,  $N=140$ , measured with a spherical quantum sensor LI-193, LI-COR Biosciences).

Light inside each container was measured twice daily using a small (1 mm diameter) cosine-corrected PAR sensor attached to a pulse amplitude-modulated fluorometer (Diving-PAM, Heinz Walz GmbH, Effeltrich, Germany). The small size of the sensor allowed light to be measured ~1 cm above the coral recruits while they were inside the plastic container and beneath the treatment lids. This sensor was calibrated using a separate light meter (LI-1400 Datalogger fitted with a LI-192 sensor, LI-COR Biosciences). To place the experimental light conditions in an ecological context, irradiance at 5 m depth on Hobihu Reef was measured between 5 and 10 March using a  $4\pi$  light sensor (MDS-MkV/L, Alec Electronics, Rockland Oceanographic, Vancouver, Canada) that recorded PAR at 0.002 Hz. The mean ( $\pm$ s.e.m.) light intensity recorded by this sensor from 06:00 h to 18:00 h was  $392 \pm 33 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  ( $N=72$ ) and the maximum daily intensity was  $1151 \pm 205 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  ( $N=6$  days).

The DIC content of seawater was manipulated by bubbling with a premixed gas of a known  $P_{\text{CO}_2}$ , or by bubbling with unmodified air. To mix the gas for the high  $P_{\text{CO}_2}$  treatment, a system employing a variable timed solenoid valve was used, which controlled the flow of air and  $\text{CO}_2$  into a mixing chamber to reach the target  $P_{\text{CO}_2}$  of

900  $\mu\text{atm}$ . The target value was selected to provide a treatment  $P_{\text{CO}_2}$  expected within  $\sim 100$  years under RCP8.5 (van Vurren et al., 2011). The solenoid valve was connected to an infrared gas analyzer (S151, Qubit Systems, Kingston, ON, Canada), which monitored the output gas and provided dynamic control of the duty cycle of the solenoid.

Throughout the experiment, total alkalinity (TA) and pH were measured following standard operating procedure (SOP) 3b and 6b (respectively) (see Dickson et al., 2007). TA was measured using an open cell automatic titrator (Model DS50, Mettler-Toledo, Columbus, OH, USA) filled with certified HCl titrant supplied by Dr A. Dickson (Scripps Institute of Oceanography), and TA was calculated using an Excel spreadsheet (Fangue et al., 2010). The accuracy and precision of the TA measurements were tested against certified reference material (CRM, from Dr A. Dickson) and maintained within 0.7% of certified values. pH was measured on the total scale ( $\pm 0.001$  pH) using *m*-Cresol Purple dye in a spectrophotometric assay (SOP 6b). Salinity was measured with a conductivity meter ( $\pm 0.1$  accuracy, model 340i, WTW GmbH, Weilheim, Germany), and temperature with a certified digital thermometer ( $\pm 0.05^\circ\text{C}$  accuracy, Fisher Scientific Traceable Digital Thermometer, Pittsburgh, PA, USA). TA and pH were used to calculate  $P_{\text{CO}_2}$ ,  $[\text{HCO}_3^-]$ ,  $[\text{CO}_3^{2-}]$  and aragonite saturation state ( $\Omega_{\text{A}}$ ) using CO2SYS (Pierrot et al., 2006).

Upon completion of the experiment, recruits were sampled for calcification, protein and survivorship. First, three recruits per tile were harvested for protein analysis and frozen. Frozen recruits were solubilized in  $0.1 \text{ mol l}^{-1}$  NaOH with sonication (15 s at 10% amplitude) and heating (5 h at  $50^\circ\text{C}$ ), then neutralized with  $1 \text{ mol l}^{-1}$  HCl (to pH 7.0–7.5) and were processed in triplicate. Protein concentration was determined using the BioRad protein assay (BioRad Laboratories, Hercules, CA, USA) scaled to microtiter plates with absorbance at 595 nm read on a 96-well plate spectrophotometer (Synergy H4 Hybrid Reader, Biotek, Winooski, VT, USA; the assay was calibrated using BSA). To measure calcification, recruits were cleaned of tissue in bleach (6% NaOCl for 8 h), removed from the tiles with a razor blade, and weighed individually ( $\pm 100$  ng, UMT2 balance, Mettler-Toledo) after drying (72 h at  $27^\circ\text{C}$ ); calcification was normalized to protein and time ( $\text{mg CaCO}_3 \text{ mg}^{-1} \text{ protein day}^{-1}$ ). Survival was assessed daily throughout the experiment by photographing the tiles with a digital camera (10 megapixel, Canon 40d) fitted with a macro lens. Live coral tissue was readily seen in the images, and presence of the tissue was used to categorize corals as alive or dead.

#### Secondary experiment (June 2012)

The secondary experiment in June 2012 was conducted in an identical way to the primary experiment, using the same equipment in a slightly different configuration. Notably, logistical problems prevented duplicate tanks being used in each treatment condition, and therefore the effect of  $P_{\text{CO}_2}$  was tested without tank replication. As the lamps were less bright in 2012 than in 2011 because the bulbs were older, and temperature and  $P_{\text{CO}_2}$  were regulated precisely but slightly inaccurately, it was not possible to create identical physical and chemical conditions in the two experiments. Further, it was not possible to conduct both experiments in the same season, and the second experiment was conducted in the summer when ambient seawater temperature was  $\sim 28.0^\circ\text{C}$ .

For the second experiment, eight colonies of *P. damicornis* were collected from 5–7 m depth on Hobihu Reef in early June, which was unusually wet and stormy. Larvae were released from these colonies at NMMBA on 24 June, and at 08:00 h on the day of release

were pooled among parent colonies and settled on tiles as described above. These larvae were released approximately on the inferred peak larval release for June, which typically follows more quickly after the new moon in June than in March (T.-Y.F., unpublished data). Once settled, the containers holding the recruits in the five light treatments were allocated to the  $P_{\text{CO}_2}$  treatments on 26 June, and the recruits were left to grow for 5 days. Experimental tanks were maintained at  $\sim 27.5^\circ\text{C}$ , illuminated at a mean ( $\pm$ s.e.m.) irradiance of  $235 \pm 1 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$  ( $N=40$ ), and exposed to target  $P_{\text{CO}_2}$  values of ambient conditions in the laboratory and  $\sim 940 \mu\text{atm}$ .

At the end of the second experiment, recruits were sampled for calcification as described above with rates normalized to protein and time ( $\text{mg CaCO}_3 \text{ mg}^{-1} \text{ protein day}^{-1}$ ). Logistical constraints prevented protein assays in 2012, and therefore the protein content of each recruit was assumed to be the same as that measured in 2011. Survivorship was measured at the end of the experiment (not daily as in 2011) using a dissecting microscope ( $\times 40$  magnification) to detect the presence of live tissue.

#### Statistical analysis

Calcification was analyzed using two-way nested ANOVA with tank as a random nested factor in light and  $P_{\text{CO}_2}$  treatments; the nested factor was dropped from the analysis when it was not significant (at  $P > 0.25$ ) (Underwood, 1997). This analysis was modified in 2012 because replicate tanks were not employed, and in this case a two-way ANOVA was employed with corals treated as statistical replicates. To test the statistical assumptions of ANOVA, normality was assessed using a Shapiro–Wilks test, and homogeneity of variances was assessed graphically using residuals. To analyze survivorship, a Kaplan–Meier (K–M) product-limit analysis was used (Machin et al., 2006), in which the probability of individual recruits surviving was assumed to be independent among recruits. As K–M analyses cannot accommodate nested experimental designs, replicate corallites were pooled within treatments and log-rank tests (Machin et al., 2006) were used to test for differential survival among light and  $P_{\text{CO}_2}$  treatments. All statistical analyses were conducted using JMP software (version 9.0.2, SAS Institute Inc.).

## RESULTS

### Primary experiment (March 2011)

The clear film and ND filters created light treatments characterized by mean ( $\pm$ s.e.m.) irradiances of  $31 \pm 2$ ,  $41 \pm 2$ ,  $70 \pm 3$ ,  $122 \pm 4$  and  $226 \pm 9 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$  ( $N=10$ ).  $P_{\text{CO}_2}$  treatments were maintained at mean ( $\pm$ s.e.m.) values of  $493 \pm 27 \mu\text{atm}$  (ambient  $P_{\text{CO}_2}$ ) and  $878 \pm 26 \mu\text{atm}$  (high  $P_{\text{CO}_2}$ ) ( $N=5$ ) (Table 1).

*Pocillopora damicornis* larvae settled onto tiles at a density of  $19 \pm 2$  corals per tile (mean  $\pm$  s.e.m.,  $N=61$ ) and grew rapidly, depositing  $104$ – $558 \mu\text{g CaCO}_3$  per recruit over 5 days. Protein content of the recruits was unaffected by light or  $P_{\text{CO}_2}$  (ANOVA light:  $F_{4,25}=1.512$ ,  $P=0.249$ ;  $P_{\text{CO}_2}$ :  $F_{1,25}=0.134$ ,  $P=0.720$ ) and averaged  $0.057 \pm 0.001$  mg per recruit across treatments (mean  $\pm$  s.e.m.,  $N=35$ ). Calcification standardized to overall mean protein content ranged from 1.12 to  $1.57 \text{ mg CaCO}_3 \text{ mg}^{-1} \text{ protein day}^{-1}$ , and was significantly affected by the interactive effect of light and  $P_{\text{CO}_2}$  ( $F_{4,130}=3.57$ ,  $P=0.009$ , Fig. 1A) and the main effect of  $P_{\text{CO}_2}$  ( $F_{1,130}=9.01$ ,  $P=0.003$ ) but not light ( $F_{4,130}=1.221$ ,  $P=0.306$ ).

Calcification as a function of irradiance at ambient  $P_{\text{CO}_2}$  resembled a positive parabola, with calcification maximized at  $70 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$  and decreasing slightly thereafter (Fig. 1A). In contrast, calcification as a function of irradiance at high  $P_{\text{CO}_2}$  resembled a negative parabola. Relative to ambient  $P_{\text{CO}_2}$ , high  $P_{\text{CO}_2}$

Table 1. Physical and chemical features of seawater in the treatment tanks over the primary (March 2011) and secondary (June 2012) experiments

Experiment	Treatment	Temperature (°C)	Salinity	TA (μmol kg <sup>-1</sup> SW)	pH <sub>Total</sub>	P <sub>CO<sub>2</sub></sub> (μatm)	HCO <sub>3</sub> <sup>-</sup> (μmol kg <sup>-1</sup> SW)	CO <sub>3</sub> <sup>2-</sup> (mmol kg <sup>-1</sup> SW)
Primary	Ambient P <sub>CO<sub>2</sub></sub>	24.01±0.14	33.9±0.1	2276±13	7.97±0.02	493±27	1846±30	175±3
	High P <sub>CO<sub>2</sub></sub>	23.98±0.10	33.9±0.1	2274±10	7.75±0.01	878±26	1992±20	115±2
Secondary	Ambient P <sub>CO<sub>2</sub></sub>	27.56±0.02	30.4±0.1	2236±2	7.98±0.01	483±9	1793±6	182±3
	High P <sub>CO<sub>2</sub></sub>	27.49±0.02	30.4±0.1	2222±8	7.73±0.01	938±11	1954±5	111±2

Experiments lasted 5 days. Values are means ± s.e.m. Temperature and salinity were measured twice daily (N=10) with the remaining parameters measured daily (N=5).  
TA, total alkalinity.

had the most conspicuous effects on calcification at intermediate light intensities (41, 70 and 122 μmol photons m<sup>-2</sup> s<sup>-1</sup>), with virtually no effect at the lowest (31 μmol photons m<sup>-2</sup> s<sup>-1</sup>) and highest irradiance (226 μmol photons m<sup>-2</sup> s<sup>-1</sup>). The greatest difference in calcification between ambient and high P<sub>CO<sub>2</sub></sub> occurred at 70 μmol photons m<sup>-2</sup> s<sup>-1</sup>, where calcification was depressed 29% by high P<sub>CO<sub>2</sub></sub>.

Survivorship of *P. damicornis* recruits varied significantly across light and P<sub>CO<sub>2</sub></sub> treatments (Fig. 1A, Fig. 2, Table 2). Survivorship remained >90% in all treatments until day 4, but thereafter treatment effects became apparent. Despite similar calcification at ambient and high P<sub>CO<sub>2</sub></sub> at both the lowest and highest irradiance, survivorship was 34% higher (P=0.012, Table 2) in ambient than in high P<sub>CO<sub>2</sub></sub> at 31 μmol photons m<sup>-2</sup> s<sup>-1</sup>, while at 222 μmol photons m<sup>-2</sup> s<sup>-1</sup> survivorship was 38% greater under high than under low P<sub>CO<sub>2</sub></sub> (P<0.001). In ambient P<sub>CO<sub>2</sub></sub>, only 34% of recruits survived at 70 μmol photons m<sup>-2</sup> s<sup>-1</sup>, the lowest of any irradiance, but in high P<sub>CO<sub>2</sub></sub>, survivorship was lowest (19%) at 41 μmol photons m<sup>-2</sup> s<sup>-1</sup> and highest at 70 μmol photons m<sup>-2</sup> s<sup>-1</sup> (71%). Under both P<sub>CO<sub>2</sub></sub> regimes, survivorship was maximized at 122 μmol photons m<sup>-2</sup> s<sup>-1</sup>. Survivorship was not correlated with calcification at ambient P<sub>CO<sub>2</sub></sub> (r=0.173, d.f.=3, P=0.477) or high P<sub>CO<sub>2</sub></sub> (r=0.424, d.f.=3, P=0.771), or with light intensity at ambient P<sub>CO<sub>2</sub></sub> (r=0.154, d.f.=3, P=0.805) or high P<sub>CO<sub>2</sub></sub> (r=0.733, d.f.=3, P=0.159).

#### Secondary experiment (June 2012)

The physical and chemical conditions in the treatments for the secondary experiment were similar to those created in the primary experiment (Table 1). However, the reef environment from which the parent colonies were collected in June 2012 was different from that encountered in March 2011, notably with higher seawater temperatures and elevated turbidity. A wet and stormy period during June 2012 resulted in heavy rainwater run off, thick clouds and reduced sunlight. The clear film and ND filters created light treatments characterized by mean (±s.e.m.) irradiances of 14±0.6, 27±2, 56±3, 96±3 and 191±4 μmol photons m<sup>-2</sup> s<sup>-1</sup> (N=10). P<sub>CO<sub>2</sub></sub> treatments were maintained at mean (±s.e.m.) values of 483±9 μatm (ambient P<sub>CO<sub>2</sub></sub>) and 938±11 μatm (high P<sub>CO<sub>2</sub></sub>) (N=5; Table 1).

The initial *P. damicornis* larvae released under the adverse conditions of June 2012 were unusual in shape and color, but larvae released subsequently appeared normal in color and size, and were similar to those obtained in March 2011. Only the later released larvae were used in the present analysis. The June larvae settled at a density of 17±1 corals per tile (mean ± s.e.m., N=100) and deposited 17.8–441.3 μg CaCO<sub>3</sub> per recruit in 5 days. Calcification was standardized to the protein concentration of recruits measured in the primary experiment (0.057±0.001 mg per recruit), and this generated calcification rates ranging from 0.06 to 1.55 mg CaCO<sub>3</sub> mg<sup>-1</sup> protein day<sup>-1</sup>. Although calcification was reduced in

June 2012 compared with that in March 2011, it again was affected significantly by the main effect of P<sub>CO<sub>2</sub></sub> (F<sub>1,240</sub>=16.16, P<0.001), but was not affected by light (F<sub>4,240</sub>=0.99, P=0.413) or the interaction

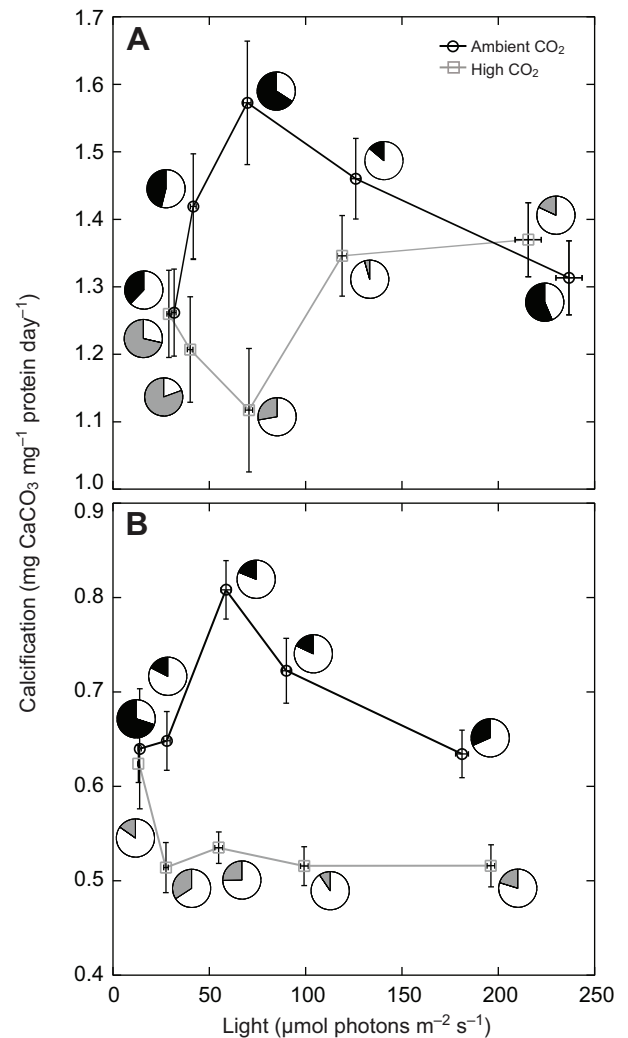


Fig. 1. Calcification of *Pocillopora damicornis* recruits standardized by protein (0.057 mg per recruit) in five light treatments in the primary experiment in March 2011 (A) and the secondary experiment in June 2012 (B). Corals were incubated for 5 days in ambient or high P<sub>CO<sub>2</sub></sub>. Values are means ± s.e.m. (calcification N=6–20 in March 2011, N=7–39 in June 2012; photosynthetically active radiation N=18–20 in March 2011, N=10–20 in June 2012). Pie charts in each plot show the percentage of recruits alive (white) and dead (black, ambient P<sub>CO<sub>2</sub></sub>; gray, high P<sub>CO<sub>2</sub></sub>) as calculated by the Kaplan–Meier analysis at the end of the experiment (N=92–209 in March 2011, N=66–196 in June 2012).

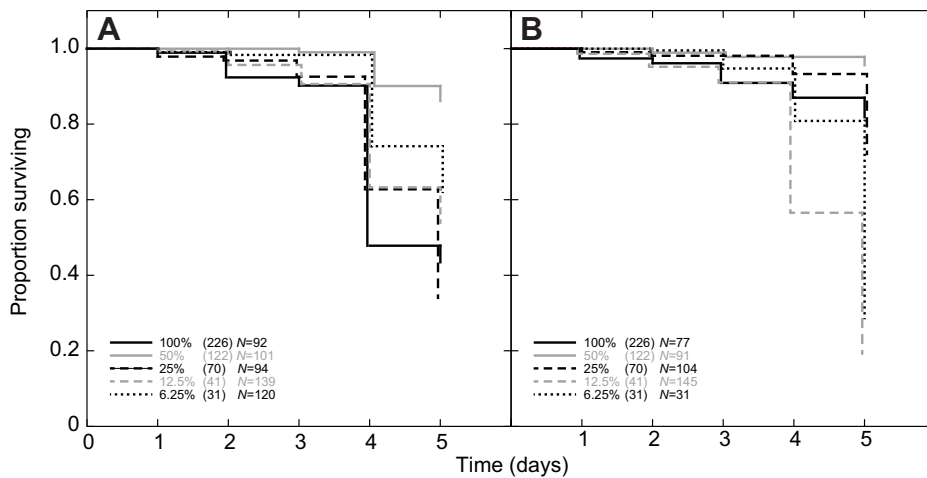


Fig. 2. Survivorship of *P. damicornis* recruits in March 2011 calculated from the Kaplan–Meier analysis in ambient (A) and high (B)  $P_{\text{CO}_2}$  in each of five light treatments.

of light and  $P_{\text{CO}_2}$  ( $F_{4,240}=1.14$ ,  $P=0.339$ , Fig. 1B). Exploratory  $t$ -tests comparing calcification between  $P_{\text{CO}_2}$  treatments revealed no effect of  $P_{\text{CO}_2}$  at  $14 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  ( $t=0.137$ , d.f.=60,  $P=0.892$ ) or  $191 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  ( $t=1.765$ , d.f.=68,  $P=0.082$ ), but a significant difference at the intermediate irradiance of  $56 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  ( $t=3.011$ , d.f.=67,  $P=0.004$ ).

As observed in 2011, calcification in recruits as a function of irradiance resembled a positive parabola at ambient  $P_{\text{CO}_2}$  (Fig. 1B), while at high  $P_{\text{CO}_2}$  the relationship between calcification and light differed slightly from that recorded in 2011. In 2012 and at elevated  $P_{\text{CO}_2}$ , calcification was highest at  $14 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  but thereafter declined with increasing irradiance and remained similar between 27 and  $191 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (Fig. 1B). Nevertheless, the shape of the calcification–light relationships at ambient and elevated  $P_{\text{CO}_2}$  demonstrated that the relative effect of  $P_{\text{CO}_2}$  differed as a function of light intensity, with no effect at the lowest light intensity, the strongest effect (a 34% reduction) at  $56 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  and an intermediate effect at the highest light intensity.

Survivorship of *P. damicornis* recruits from 2012 varied across light and  $P_{\text{CO}_2}$  treatments (Fig. 1B). Despite similar calcification at ambient and elevated  $P_{\text{CO}_2}$  at the lowest irradiance, survivorship was 55% higher in ambient than in elevated  $P_{\text{CO}_2}$ . The lowest survivorship in ambient  $P_{\text{CO}_2}$  was recorded at  $14 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (30%), but at elevated  $P_{\text{CO}_2}$  the lowest survivorship was recorded at  $27 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (66%); the highest survivorship in ambient  $P_{\text{CO}_2}$  occurred at  $27 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (83%), and in elevated  $P_{\text{CO}_2}$  it occurred at  $96 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (91%). As was observed in 2011, survivorship was not correlated with either calcification or light intensity at either  $P_{\text{CO}_2}$  ( $r \leq 0.486$ , d.f.=3,  $P \geq 0.407$ ).

## DISCUSSION

Similar results from two experiments repeated in different years strengthen the conclusion that the effects of  $P_{\text{CO}_2}$  on calcification of *P. damicornis* recruits are influenced by light intensity. In the only previous study that has addressed the interactive effect of  $P_{\text{CO}_2}$  ( $186$  versus  $641 \mu\text{atm } P_{\text{CO}_2}$  achieved through HCl addition) and light on coral calcification, a calcification–irradiance response describing a hyperbolic tangent was reported, with calcification depressed by irradiances  $>81 \mu\text{mol photons m}^{-2} \text{s}^{-1}$  (Marubini et al., 2001). In contrast, our experiments conducted in 2011 demonstrated that the effect of light on calcification resembled a positive parabola at ambient  $P_{\text{CO}_2}$ , but at high  $P_{\text{CO}_2}$  the shape of the relationship changed

to resemble an inverse parabola. Although the effects of light were less clear in the replicate experiment in 2012, nevertheless the qualitative shape of the calcification–light response differed between  $P_{\text{CO}_2}$  treatments, and  $P_{\text{CO}_2}$  effects were most strongly developed at intermediate light intensities. In both experiments, therefore, the relative effect of high  $P_{\text{CO}_2}$  on calcification was absent at the lowest light intensity, absent-to-weak at the highest light intensities, and strongly developed at intermediate light intensities ( $25$ – $75 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ ).

A comparison of calcification rates of coral recruits in the present analysis with those reported elsewhere (reviewed in Albright, 2011) reveals a high degree of variability in the response to  $P_{\text{CO}_2}$ . Based on the interactive effects of light and  $P_{\text{CO}_2}$  reported here, we hypothesize that this variability can be attributed to different experimental light intensities. For instance, Albright and colleagues (Albright et al., 2008) measured the planar area of *Porites astreoides* recruits exposed to acidified seawater (pH 7.8,  $P_{\text{CO}_2}$  720 ppm and  $25.4$ – $26.6^\circ\text{C}$ ) under artificial lights delivering on average  $<10 \mu\text{mol photons m}^{-2} \text{s}^{-1}$ , and reported 72–84% reductions by high  $P_{\text{CO}_2}$ . Subsequently, Albright and Langdon tested the effects of high  $P_{\text{CO}_2}$  (obtained with gas bubbling) on *P. astreoides* recruits under natural light (intensities not provided), and found that growth (by area) was

Table 2. Results from log rank tests of the survivorship of *Pocillopora damicornis* recruits calculated by Kaplan–Meier analysis in the primary and the secondary experiment

Experiment	Comparisons	Level	$\chi^2$	d.f.	$P$ -value
Primary	$P_{\text{CO}_2}$ treatment	Ambient	60.5	4	<0.001
		High	209.9	4	<0.001
	Light treatment	226	22.8	1	<0.001
		122	4.9	1	0.027
		70	34.0	1	<0.001
Secondary	$P_{\text{CO}_2}$ treatment	Ambient	67.9	4	<0.001
		High	36.1	4	<0.001
	Light treatment	191	1.95	1	0.162
		96	3.5	1	0.062
		56	1.2	1	0.270
	27	7.6	1	0.006	
	14	73.2	1	<0.001	

Comparisons between all light treatments (in  $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ) in ambient and high  $P_{\text{CO}_2}$  treatments as well as individual tests of light treatments between  $P_{\text{CO}_2}$  treatments are shown.

reduced by 35% at 775  $\mu\text{atm}$  versus 330  $\mu\text{atm}$  (Albright and Langdon, 2011). de Putron and colleagues grew recruits of *P. astreoides* and *Favia fragum* under 61  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$ , and found that calcification (by mass) at 29.4°C was reduced by 41% and 38% (respectively) at 1441  $\mu\text{atm } P_{\text{CO}_2}$  delivered with gas bubbling (de Putron et al., 2011); Cohen and colleagues grew recruits of *F. fragum* at 61  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$  and 25°C and found that calcification (by mass) was reduced by 26% at saturation state of aragonite  $\Omega_{\text{arag}}=2.40$  versus  $\Omega_{\text{arag}}=3.7$  (Cohen et al., 2009); and Anlauf and colleagues grew recruits of *P. panamensis* at 134  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$  and reported that calcification (by mass) was reduced by 40% at 950  $\mu\text{atm } P_{\text{CO}_2}$  (at 29.4°C and created by gas bubbling) compared with controls at 486  $\mu\text{atm } P_{\text{CO}_2}$  and 28.4°C (Anlauf et al., 2011). Recently, we grew recruits of *Seriatopora caliendrum* at 305  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$  and 25.1–25.4°C, and found that calcification (by mass) was unaffected by 623 versus 456  $\mu\text{atm } P_{\text{CO}_2}$ , but was elevated 50% by 830 versus 464  $\mu\text{atm } P_{\text{CO}_2}$ , in both cases with  $P_{\text{CO}_2}$  manipulated by gas bubbling (Dufault et al., 2012). Together, the aforementioned studies support a trend for the negative effect of elevated  $P_{\text{CO}_2}$  on calcification of coral recruits to be related inversely to light intensity, at least above a threshold value (here  $\sim 50 \mu\text{mol photons m}^{-2}\text{s}^{-1}$ ). Indeed, if the results of Albright and Langdon (Albright and Langdon, 2011) are excluded from our data compilation (as they did not record light intensity), the inverse association between the effect size of  $P_{\text{CO}_2}$  on calcification and light is significant ( $r=-0.882$ ,  $\text{d.f.}=6$ ,  $P<0.05$ ). Studies of the effects of high  $P_{\text{CO}_2}$  on the calcification of coral recruits appear more likely to reveal inhibitory effects at intermediate light intensities than at high light intensities.

Light intensities used in the present experiments ( $\sim 14$ – $226 \mu\text{mol photons m}^{-2}\text{s}^{-1}$ ) were lower than those recorded at the depth from which the parent colonies were collected (5–7 m), but nonetheless are ecologically relevant for *P. damicornis* at Hobihu Reef where this species occurs from at least 2 to 10 m depth. The mean light intensity on exposed surfaces at 5 m depth at Hobihu Reef just prior to the March 2011 experiment was 392  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$ , but intensities lower than this would be found in the sheltered microenvironments favored for coral settlement (Nozawa, 2008). Interestingly, *P. damicornis* larvae from Hobihu Reef tended not to settle on exposed surfaces at high light intensities ( $>120 \mu\text{mol photons m}^{-2}\text{s}^{-1}$ ) in the laboratory, and instead favored cracks and crevices; at lower light intensities ( $\sim 50$ – $75 \mu\text{mol photons m}^{-2}\text{s}^{-1}$ ) they settled on exposed surfaces (A.M.D., unpublished data). These observations of the settlement behavior of *P. damicornis* larvae contextualize the present analysis, and suggest that coral recruits may normally settle *in situ* at light intensities under which they are most susceptible to high  $P_{\text{CO}_2}$ . Conversely, coral larvae that settle in the ‘wrong’ conditions under ambient  $P_{\text{CO}_2}$  (i.e. in high light intensities) might be better able to resist the effects of elevated  $P_{\text{CO}_2}$ . The possibility that high  $P_{\text{CO}_2}$  could act as a selective force on coral larvae to affect the beneficial consequences of settlement location deserves further attention.

The analysis of the survivorship of *P. damicornis* recruits reveals two interesting trends. First, given the relationship between rapid growth and survival in small corals (Jackson, 1977), it is surprising that survival and calcification were unrelated. As calcification creates the skeleton upon which coral tissue is located, and is a primary means by which size increases through asexual division and coloniality, we expected that survival would increase with calcification-driven increases in size. This was not the case, however, and at ambient  $P_{\text{CO}_2}$  in 2011 the lowest survival (34%) coincided approximately with the highest calcification at 70  $\mu\text{mol}$

$\text{photons m}^{-2}\text{s}^{-1}$ . At ambient  $P_{\text{CO}_2}$  in 2012, the highest survival remained  $>80\%$  at intermediate light treatments (27–96  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$ ), while calcification varied by up to 25%. These results suggest that the survival of small corals is determined by more than rapid growth (and increased size), and perhaps in an aquarium (as in the present study) that is safe from the risks of extrinsic mortality, mortality due to intrinsic effects (*sensu* Kirkwood and Austad, 2000) is elevated.

Second, even though calcification in coral recruits generally was depressed at low light intensities (especially in the 2011 experiment), and elevated  $P_{\text{CO}_2}$  has negative fitness consequences for at least one invertebrate (Wood et al., 2008), our results reveal that survivorship of *P. damicornis* recruits was elevated at high  $P_{\text{CO}_2}$  (878–938  $\mu\text{atm}$ ) compared with that at ambient  $P_{\text{CO}_2}$  (483–493  $\mu\text{atm}$ ) in three out of five irradiances tested in both 2011 and 2012. Although these results must be interpreted with caution as they were obtained in an aquarium, where sources of extrinsic mortality like competition and predation were absent, nevertheless it is intriguing to speculate they reflect the role of tissue quality in determining resistance to intrinsic sources of mortality. If this speculation is correct, then it is reasonable to hypothesize that tissue quality is modulated indirectly by elevated  $P_{\text{CO}_2}$  accelerating photosynthesis by *Symbiodinium* (Anthony et al., 2008; Crawley et al., 2010), particularly at high light intensities. *Symbiodinium* utilize  $\text{HCO}_3^-$  as a carbon source in photosynthesis, converting it to  $\text{CO}_2$  with a carbon-concentrating mechanism prior to fixation in the Calvin cycle (Furla et al., 2000). As rising  $P_{\text{CO}_2}$  increases seawater  $[\text{HCO}_3^-]$ , high  $P_{\text{CO}_2}$  has the potential to accelerate photosynthesis (Erez et al., 2011), although experimental evidence in support of this trend is equivocal (e.g. Schneider and Erez, 2006; Crawley et al., 2010; Brading et al., 2011). Nevertheless, it might be valuable to further explore the role of high  $P_{\text{CO}_2}$  (and hence elevated  $\text{HCO}_3^-$ ) in accelerating photosynthesis in *Symbiodinium*, hence affecting the translocation of photosynthetically fixed carbon to the animal host (Muscatine, 1990), and its role in augmenting holobiont biomass (Rodrigues and Grottoli, 2007) and (as in the present case) perhaps modulating survival.

Finally, the most intriguing aspect of the current analysis is the contrasting shape of the calcification–irradiance responses at ambient and high  $P_{\text{CO}_2}$ . Following our 2011 research, it was clear that the  $P_{\text{CO}_2}$ –light interaction relied heavily on the two calcification rates recorded at 70  $\mu\text{mol photons m}^{-2}\text{s}^{-1}$  (Fig. 1), and therefore the experiment was repeated in order to evaluate the possibility that the results could be attributed to chance alone. Although calcification rates were lower in June 2012 than in March 2011 – most likely reflecting seasonality in coral performance (Fitt et al., 2000; Thornhill et al., 2011) – the results of the two experiments were similar for ambient  $P_{\text{CO}_2}$  and deviated under high  $P_{\text{CO}_2}$  when light was  $>56 \mu\text{mol photons m}^{-2}\text{s}^{-1}$ . The altered response of corals at high irradiances under high  $P_{\text{CO}_2}$  in the second experiment may be the result of seasonal changes to holobiont physiology caused by increased temperature during the second experiment (27.5 versus 24.0°C), or by changes to seawater quality caused by heavy rainfall just prior to the start of the second experiment.

While it was beyond the scope of the present study to experimentally test for a mechanistic basis to the common response recorded in 2 years, it is intriguing to speculate that our results reflect light-dependent use of  $\text{HCO}_3^-$  for coral calcification (Comeau et al., 2013b). According to Comeau and colleagues (Comeau et al., 2013b), tropical corals calcify by utilizing  $\text{CO}_3^{2-}$  in the day and night – and therefore calcification is depressed at high  $P_{\text{CO}_2}$  (which reduces  $[\text{CO}_3^{2-}]$ ) (Erez et al., 2011) – but additionally corals use

[HCO<sub>3</sub><sup>-</sup>] in a light-dependent manner during the day. The research by Comeau and colleagues (Comeau et al., 2013b) can be used to reconcile aspects of the variation in response of coral recruits to high P<sub>CO<sub>2</sub></sub> that have been reported previously (cited above) and in the present study. In the case of the present study, it is possible, therefore, that high P<sub>CO<sub>2</sub></sub> depresses calcification at intermediate light intensities because of lowered CO<sub>3</sub><sup>2-</sup>, but as light intensities increase, light-dependent use of HCO<sub>3</sub><sup>-</sup> causes calcification to again increase. At ambient P<sub>CO<sub>2</sub></sub>, HCO<sub>3</sub><sup>-</sup> limitation may then cause calcification to decline at high light intensities (see Comeau et al., 2013b).

#### ACKNOWLEDGEMENTS

This work was submitted in partial fulfillment of the MS degree for A.M.D. We thank S. Zamudio and C. Wall for field assistance and maintaining treatment conditions, and an anonymous reviewer whose comments improved an earlier draft of this paper. This is contribution number 192 of the CSUN Marine Biology Program.

#### AUTHOR CONTRIBUTIONS

All authors contributed to lab work and field collections. A.M.D., V.R.C. and P.J.E. designed the study. Data analysis was carried out by A.M.D., A.N., L.B., V.R.C. and P.J.E. The manuscript was written by A.M.D., A.N., L.B., V.R.C. and P.J.E. All authors commented on the manuscript and contributed to revisions.

#### COMPETING INTERESTS

No competing interests declared.

#### FUNDING

This research was funded by the US National Science Foundation [grant no. OCE 08-44785], a Graduate Thesis Support grant from California State University, Northridge (CSUN) (to A.M.D.), and a National Science Foundation Research Experiences for Undergraduates (REU) award (to A.N.).

#### REFERENCES

- Albright, R. (2011). Reviewing the effects of ocean acidification on sexual reproduction and early life history stages of reef-building corals. *J. Mar. Biol.* **2011**, ID 473615.
- Albright, R. and Langdon, C. (2011). Ocean acidification impacts multiple early life history processes of the Caribbean coral *Porites astreoides*. *Glob. Change Biol.* **17**, 2478-2487.
- Albright, R., Mason, B. and Langdon, C. (2008). Effect of aragonite saturation state on settlement and post-settlement growth of *Porites astreoides* larvae. *Coral Reefs* **27**, 485-490.
- Albright, R., Mason, B., Miller, M. and Langdon, C. (2010). Ocean acidification compromises recruitment success of the threatened Caribbean coral *Acropora palmata*. *Proc. Natl. Acad. Sci. USA* **107**, 20400-20404.
- Allemand, D., Tambutté, É., Zoccola, D. and Tambutté, S. (2011). Coral calcification, cells to reefs. In *Coral Reefs: an Ecosystem in Transition* (ed. Z. Dubinsky and N. Stambler), pp.119-150. New York; Springer.
- Anlauf, H., D'Croz, L. and O'Dea, A. (2011). A corrosive concoction: The combined effects of ocean warming and acidification on the early growth of a stony coral are multiplicative. *J. Exp. Mar. Biol. Ecol.* **397**, 13-20.
- Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S. and Hoegh-Guldberg, O. (2008). Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proc. Natl. Acad. Sci. USA* **105**, 17442-17446.
- Arnold, S. N., Steneck, R. S. and Mumby, P. J. (2010). Running the gauntlet: inhibitory effects of algal turfs on the processes of coral recruitment. *Mar. Ecol. Prog. Ser.* **414**, 91-105.
- Babcock, R. and Mundy, C. (1996). Coral recruitment: consequences of settlement choice for early growth and survivorship in two scleractinians. *J. Exp. Mar. Biol. Ecol.* **206**, 179-201.
- Brading, P., Warner, M. E., Davey, P., Smith, D. J., Achterberg, E. P. and Suggett, D. J. (2011). Differential effects of ocean acidification on growth and photosynthesis among phylotypes of Symbiodinium (Dinophyceae). *Limnol. Oceanogr.* **56**, 927-938.
- Bramanti, L., Magagnoli, G., DeMaio, L. and Santangelo, G. (2005). Recruitment, early survival and growth of the Mediterranean red coral *Corallium rubrum* (L. 1758), a four-year study. *J. Exp. Mar. Biol. Ecol.* **314**, 69-78.
- Chalker, B. E. (1981). Simulating light-saturation curves for photosynthesis and calcification by reef-building corals. *Mar. Biol.* **63**, 135-141.
- Chalker, B. E. and Taylor, D. L. (1978). Rhythmic variation in calcification and photosynthesis associated with the coral, *Acropora cervicornis* (Lamarck). *Proc. R. Soc. B* **201**, 179-189.
- Cohen, A. L., McCorkle, D. C., de Putron, S., Gaetani, G. A. and Rose, K. A. (2009). Morphological and compositional changes in the skeletons of new coral recruits reared in acidified seawater: insights into the biomineralization response to ocean acidification. *Geochem. Geophys. Geosyst.* **10**, Q07005.
- Comeau, S., Edmunds, P. J., Spindel, N. B. and Carpenter, R. C. (2013a). The response of eight coral reef calcifiers to increasing partial pressure of CO<sub>2</sub> do not exhibit a tipping point. *Limnol. Oceanogr.* **58**, 388-398.
- Comeau, S., Carpenter, R. C. and Edmunds, P. J. (2013b). Coral reef calcifiers buffer their response to ocean acidification using both bicarbonate and carbonate. *Proc. Biol. Sci.* **280**, 20122374.
- Crawley, A., Kline, D., Dunn, S., Anthony, K. and Dove, S. (2010). The effects of ocean acidification on symbiotic photosynthesis and productivity in *Acropora formosa*. *Glob. Change Biol.* **16**, 851-863.
- de Putron, S. J., McCorkle, D. C., Cohen, A. L. and Dillon, A. B. (2011). The impact of seawater saturation state and bicarbonate ion concentration on calcification by new recruits of two Atlantic corals. *Coral Reefs* **30**, 321-328.
- Dickson, A. G., Sabine, C. L. and Christian, J. R. (ed.) (2007). *Guide to Best Practices for Ocean CO<sub>2</sub> Measurements: PICES Special Publication 3*. Sidney, BC: North Pacific Marine Science Organization.
- Dufault, A. M., Cumbo, V. R., Fan, T.-Y. and Edmunds, P. J. (2012). Effects of diurnally oscillating P<sub>CO<sub>2</sub></sub> on the calcification and survival of coral recruits. *Proc. Biol. Sci.* **279**, 2951-2958.
- Dustan, P. (1975). Growth and form in the reef-building coral *Montastrea annularis*. *Mar. Biol.* **33**, 101-107.
- Edmunds, P. J. (2011). Zooplanktivory ameliorates the effects of ocean acidification on the reef coral *Porites* spp. *Limnol. Oceanogr.* **56**, 2402-2410.
- Edmunds, P. J., Brown, D. and Moriarty, V. (2012). Interactive effects of ocean acidification and temperature on two scleractinian corals from Moorea, French Polynesia. *Glob. Change Biol.* **18**, 2173-2183.
- Erez, J., Reynaud, S., Silverman, J., Schneider, K. and Allemand, D. (2011). Coral calcification under ocean acidification and global change. In *Coral Reefs: an Ecosystem in Transition* (ed. Z. Dubinsky and N. Stambler), pp.151-176. New York: Springer.
- Fabricius, K. E., Langdon, C., Uthicke, S., Humphrey, C., Noonan, S., De'ath, G., Okazaki, R., Muehlechner, N., Glas, M. and Lough, J. M. (2011). Losers and winners in coral reefs acclimated to elevated carbon dioxide concentrations. *Nat. Clim. Chang.* **1**, 165-169.
- Fan, T.-Y., Li, J.-J., Le, S.-X. and Fang, L.-S. (2002). Lunar periodicity of larval release by pocilloporid corals in southern Taiwan. *Zool. Stud.* **41**, 288-294.
- Fangue, N., O'Donnell, M. J., Sewell, M. A., Matson, P. G., MacPherson, A. C. and Hofmann, G. E. (2010). A laboratory-based, experimental system for the study of ocean acidification effects on marine invertebrate larvae. *Limnol. Oceanogr. Methods* **8**, 441-452.
- Fitt, W. K., McFarland, F. K., Warner, M. E. and Chilcoat, G. C. (2000). Seasonal patterns of tissue biomass and densities of symbiotic dinoflagellates in reef corals and relation to coral bleaching. *Limnol. Oceanogr.* **45**, 677-685.
- Form, A. U. and Riebesell, U. (2012). Acclimation to ocean acidification during long-term CO<sub>2</sub> exposure in the cold-water coral *Lophelia pertusa*. *Glob. Change Biol.* **18**, 843-853.
- Furla, P., Galgani, I., Durand, I. and Allemand, D. (2000). Sources and mechanisms of inorganic carbon transport for coral calcification and photosynthesis. *J. Exp. Biol.* **203**, 3445-3457.
- Goreau, T. F. (1959). The physiology of skeleton formation in corals. I. A method for measuring the rate of calcium deposition by corals under different conditions. *Biol. Bull.* **116**, 59-75.
- Hoegh-Guldberg, O., Mumby, P. J., Hooten, A. J., Steneck, R. S., Greenfield, P., Gomez, E., Harvell, C. D., Sale, P. F., Edwards, A. J., Caldeira, K. et al. (2007). Coral reefs under rapid climate change and ocean acidification. *Science* **318**, 1737-1742.
- Hughes, T. P., Baird, A. H., Dinsdale, E. A., Moltschaniwskiy, N. A., Pratchett, M. S., Tanner, J. E. and Willis, B. L. (2000). Supply-side ecology works both ways: the link between benthic adults, fecundity, and larval recruits. *Ecology* **81**, 2241-2249.
- IPCC (2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.
- Jackson, J. B. C. (1977). Competition on marine hard substrata: the adaptive significance of solitary and colonial strategies. *Am. Nat.* **111**, 743-767.
- Kaniewska, P., Campbell, P. R., Kline, D. I., Rodriguez-Lanetty, M., Miller, D. J., Dove, S. and Hoegh-Guldberg, O. (2012). Major cellular and physiological impacts of ocean acidification on a reef building coral. *PLoS ONE* **7**, e34659.
- Kawaguti, S. and Sakumoto, D. (1948). The effect of light on the calcium deposition of corals. *Bull. Oceanogr. Inst. Taiwan* **4**, 65-70.
- Kirkwood, T. B. L. and Austad, S. N. (2000). Why do we age? *Nature* **408**, 233-238.
- Kleypas, J. A. and Langdon, C. (2006). Coral reefs and changing seawater chemistry. In *Coral Reefs and Climate Change: Science and Management*. AGU Monograph Series, Coastal and Estuarine Studies, Vol. 61 (ed. J. T. Phinney, O. Hoegh-Guldberg, J. Kleypas, W. Skirving and A. Strong), pp.73-110. Washington, DC: American Geophysical Union.
- Langdon, C., Takahashi, T., Sweeney, C., Chipman, D., Goddard, J., Marubini, F., Aceves, H., Barnett, H. and Atkinson, M. (2000). Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochem. Cycles* **14**, 639-654.
- Machin, D., Cheung, Y. B. and Parmar, M. K. B. (2006). *Survival Analysis, a Practical Approach*, 2nd edn. Chichester, UK: John Wiley and Sons Ltd.
- Marshall, A. T. and Clode, P. L. (2002). Effect of increased calcium concentration in sea water on calcification and photosynthesis in the scleractinian coral *Galaxea fascicularis*. *J. Exp. Biol.* **205**, 2107-2113.
- Marubini, F., Barnett, H., Langdon, C. and Atkinson, M. J. (2001). Dependence of calcification on light and carbonate ion concentration for the hermatypic coral *Porites compressa*. *Mar. Ecol. Prog. Ser.* **220**, 153-162.
- McCulloch, M., Falter, J., Trotter, J. and Montagna, P. (2012). Coral resilience to ocean acidification and global warming through pH upregulation. *Nature Climate Change* **2**, 623-627.
- Moya, A., Huisman, L., Ball, E. E., Hayward, D. C., Grasso, L. C., Chua, C. M., Woo, H. N., Gatuso, J.-P., Forêt, S. and Miller, D. J. (2012). Whole transcriptome analysis of the coral *Acropora millepora* reveals complex responses to CO<sub>2</sub>-driven acidification during the initiation of calcification. *Mol. Ecol.* **21**, 2440-2454.

- Muscatine, L.** (1990). The role of symbiotic algae in carbon and energy flux in reef corals. In *Ecosystems of the World*, Vol. 25, *Coral Reefs* (ed. Z. Dubinsky), pp 75-87. New York: Elsevier.
- Nakamura, M., Ohki, S., Suzuki, A. and Sakai, K.** (2011). Coral larvae under ocean acidification: survival, metabolism, and metamorphosis. *PLoS ONE* **6**, e14521.
- Nozawa, Y.** (2008). Micro-crevice structure enhances coral spat survivorship. *J. Exp. Mar. Biol. Ecol.* **367**, 127-130.
- 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, TN: US Department of Energy.
- Ries, J.** (2011). A physicochemical framework for interpreting the biological calcification response to CO<sub>2</sub>-induced ocean acidification. *Geoch. Cosmo. Acta* **75**, 4053-4064.
- Rodrigues, L. J. and Grottoli, A. G.** (2007). Energy reserves and metabolism as indicators of coral recovery from bleaching. *Limnol. Oceanogr.* **52**, 1874-1882.
- Schneider, K. and Erez, J.** (2006). The effect of carbonate chemistry on calcification and photosynthesis in the hermatypic coral *Acropora eurystoma*. *Limnol. Oceanogr.* **51**, 1284-1293.
- Suwa, R., Nakamura, M., Morita, M., Shimada, K., Iguchi, A., Sakai, K. and Suzuki, A.** (2010). Effects of acidified seawater on early life stages of scleractinian corals (Genus *Acropora*). *Fish. Sci.* **76**, 93-99.
- Tambutté, S., Holcomb, M., Ferrier-Pages, C., Reynaud, S., Tambutte, E., Zoccola, D. and Allemand, D.** (2011). Coral biomineralization: from the gene to the environment. *J. Exp. Mar. Biol. Ecol.* **408**, 58-78.
- Thornhill, D. J., Rotjan, R. D., Todd, B. D., Chilcoat, G. C., Iglesias-Prieto, R., Kemp, D. W., Lajeunesse, T. C., Reynolds, J. M., Schmidt, G. W., Shannon, T. et al.** (2011). A connection between colony biomass and death in Caribbean reef-building corals. *PLoS ONE* **6**, e29535.
- Underwood, A. J.** (1997). *Experiments in Ecology: Their Logical Design and Interpretation Using Analysis of Variance*. Cambridge: Cambridge University Press.
- van Vurren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F. et al.** (2011). The representative concentration pathways: an overview. *Clim. Change* **109**, 5-31.
- Vermeij, M. J. A. and Sandin, S. A.** (2008). Density-dependent settlement and mortality structure the earliest life phases of a coral population. *Ecology* **89**, 1994-2004.
- Wood, H. L., Spicer, J. I. and Widdicombe, S.** (2008). Ocean acidification may increase calcification rates, but at a cost. *Proc. Biol. Sci.* **275**, 1767-1773.
- Yonge, C. M. and Nicholls, A. G.** (1931). Studies on the physiology of corals. V. The effect of starvation in light and darkness on the relationship between corals and zooxanthellae. *Sci. Rept. Barrier Reef Exp.* **1**, 177-211.



## SUPPLEMENTAL FILE

### The role of light in mediating the effects of ocean acidification on coral calcification

Aaron M Dufault<sup>1</sup>, Aaron Ninokawa<sup>2</sup>, Lorenzo Bramanti<sup>1</sup>, Vivian R Cumbo<sup>1</sup>, Tung-Yung Fan<sup>3,4</sup> and Peter J Edmunds<sup>1</sup>

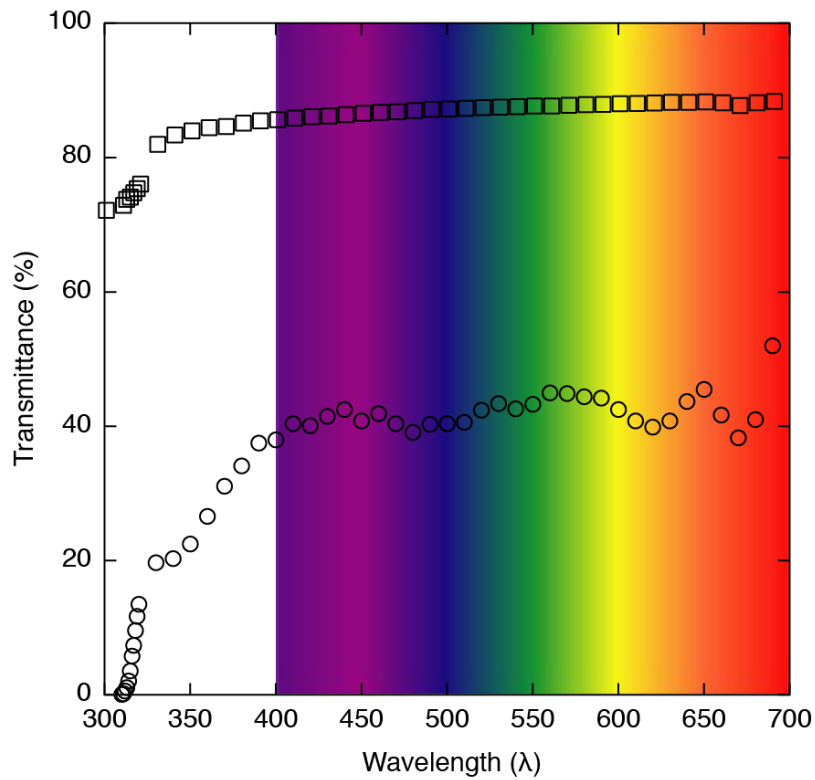


Fig. S1. Transmission characteristics of the ND filter (open squares) and clear plastic film (open circles) that were used to create light treatments in the experiment testing the effects of pCO<sub>2</sub> on the growth and survival of recruits of *Pocillopora damicornis*.