1-1-2013

Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming

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10.1002/ece3.516
Harvey, B., Gwynn-Jones, D., & Moore, P. J. (2013). Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecology and Evolution, 3(4), 1016-1030. Availablehere

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Journal:	*Ecology and Evolution*
Manuscript ID:	Draft
Wiley - Manuscript type:	Original Research
Date Submitted by the Author:	n/a
Complete List of Authors:	Harvey, Ben; Aberystwyth University, Institute of Biological, Environmental and Rural Sciences Gwynn-Jones, Dylan; Aberystwyth University, Institute of Biological, Environmental, and Rural Sciences Moore, Pippa; Aberystwyth University, Institute of Biological, Environmental, and Rural Sciences
Search Terms:	Community Ecology, Conservation
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Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming

Running title*:* Interactions of warming and acidification

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Keywords: Meta-analysis, climate change, ocean warming, ocean acidification, additive interactions, synergistic interactions , multiple stressors

Type of paper: Primary Research Article

ABSTRACT

Ocean acidification and warming are considered two of the greatest threats to marine biodiversity, yet the combined effect of these stressors on marine organisms remains largely unclear. Using meta-analytical techniques we assessed the biological responses of marine organisms to the effects of ocean acidification and warming in isolation and combination. We found positive, neutral and negative biological responses that varied across taxonomic groups, life-history stages and trophic levels. Moreover, we found the combined stressors generally exhibited a stronger effect (either positive or negative) than when exposed to the stressors in isolation. Using a subset of fully factorial studies we show that the type of response (e.g. calcification, survival) determines whether multiple stressors interact in a predictable manner, or as an unpredictable 'ecological surprise'. Interactions of the two stressors led to 'ecological surprises' more commonly than predictable outcomes. Additionally, although the analysis of our subset of data showed that 'ecological surprises' were common, meta-analysis of the full data set was not sensitive enough to detect these important interactions. The inherent variability associated with different taxonomic groups, life-history stages and trophic levels may make broad-scale meta-analyses less effective in detecting more specific 'ecological surprises'. Given that the occurrence and importance of 'ecological surprises' are likely to intensify with increasing frequency of stressors interacting in marine systems, there is an urgent need to move towards a more robust, holistic and ecologically realistic approach to climate change experimentation that forewarns of the likely deleterious impacts to marine biodiversity and ecosystem functioning over the next century.

INTRODUCTION

The concentration of atmospheric carbon dioxide (CO_2) has increased from 280ppm in pre-industrial times to a present day level of 387ppm (Feely *et al.* 2009). Over the last 100 years this has led to changes in global sea surface temperatures (+0.74°C) and ocean carbonate chemistry (Orr *et al.* 2005), which have included ocean acidification by 0.1 pH units (Caldeira & Wickett, 2003; Kleypas *et al.* 2006). By the year 2100 sea-surface temperatures are expected to rise by a further 1-4°C while increased CO_2 (aq) will result in the decreased availability of carbonate ions and a further reduction in pH by 0.3-0.5 units (Caldeira & Wickett, 2005; IPCC, 2007; Gooding *et al.* 2009). These changes in temperature and ocean carbonate chemistry are considered two of the greatest threats to marine biodiversity (Kleypas *et al.* 1999; Doney *et al.* 2009), leading to changes in the physiological performance of individual organisms which will in turn alter biotic interactions, community structure and ecosystem functioning.

A range of marine biological responses have already been observed in response to ocean warming including hypoxia (Pörtner & Knust, 2007), coral bleaching (Hoegh-Guldberg *et al.* 2007), species range shifts (Parmesan & Yohe, 2003; Root *et al.* 2003), changes to phenology (Walther *et al.* 2002), and reduced organism body size (Daufresne *et al.* 2009). Experimental manipulations simulating predicted future ocean temperatures have suggested that warming will also lead to increased metabolic costs for plants and animals (O'Connor *et al*. 2009), increased consumption rates (Sanford 1999) and changed food-web structure (Petchey *et al.* 1999). Observed responses of marine organisms to recent ocean acidification are limited (but see Iglesias-Rodriguez *et al.* 2008b; Moy *et al.* 2009), but are expected to become increasingly apparent in the next 50-100 years (Doney *et al.* 2009; Feely *et al.* 2009).

Experimental evidence, however, suggests that responses are likely to be highly varied (Hendriks *et al.* 2010; Kroeker *et al.* 2010) and will include hypercapnic suppression of metabolism (Christensen *et al.* 2011), acid-base balance disturbances (Miles *et al.* 2007), plus both positive and negative effects on skeleton formation (related to a decrease in carbonate saturation; Doney *et al.* 2009; Ries *et al.* 2009).

The vulnerability of marine species and ecosystems to individual climate stressors, particularly temperature, is well established (for reviews; Hoegh-Guldberg & Bruno, 2010; Richardson *et al.* 2012; Wernberg *et al.* 2012), despite this, the cumulative effect of warming and acidification remains unclear (Sala *et al.* 2000; Fabry *et al.* 2008). Recent meta-analyses, across ecological systems, have shown that multiple stressors can lead to 'ecological surprises' (*sensu* Paine *et al.* 1998) with responses dependent on the type of stressor as well as the ecological organisation investigated (e.g. population vs. community, autotroph vs. heterotroph) (Crain *et al.* 2008; Darling & Côté, 2008; Tylianakis *et al.* 2008). Moreover, the mechanism through which the stressor acts upon the organism will affect the response. Multiple stressors acting through a similar pathway may have an additive effect (Crain *et al.* 2008). In contrast, any stress-induced tolerances could lead to antagonisms (Blanck, 2002), while those stressors that act on different, but dependent mechanisms may act synergistically (Kneitel & Chase, 2004).

Organisms vary widely in their individual responses to ocean warming and acidification as a result of differences in their physiological and ecological characteristics (Dupont *et al.* 2008; Fabry, 2008). For example, many marine organisms possessing a calcium carbonate ($CaCO_3$) structure would be considered more susceptible to ocean acidification as this process will impair their capacity to produce calcified skeletons (Doney *et al.* 2009). Conversely, some species, including some calcified species, will have the capacity to buffer against the deleterious effects of acidification by utilising acid-base compensation (eg. fishes; Claiborne & Evans, 1992; Larsen *et al.* 1997), active mobility and metabolism (Widdicombe & Spicer, 2008; Whiteley, 2011) or energy reallocation (Wood *et al.* 2008; McDonald *et al.* 2009). Elevated temperature (up to a limit) may positively enhance metabolism in ectotherms, resulting in faster growth and development (Byrne, 2011). Moreover, it has been speculated that warming could even ameliorate the negative impacts of acidification (McNeil *et al.* 2004; Kleypas & Yates, 2009). Therefore, the concurrent effect of temperature and ocean acidification via elevated CO_2 remains unclear, but is likely to lead to complex biological outcomes.

Species responses to ocean warming and acidification will also vary among life-history stages (Byrne, 2011). Early life-history stages are considered more susceptible to changes in both temperature and ocean acidification (Byrne, 2011). These stressors may, however, have positive and/or negative effects for the successful recruitment of juveniles to the adult population. Trophic level is also likely to determine how species respond due to differences in environmental sensitivity (Petchey *et al.* 2004; Raffaelli, 2004). Previous work has suggested the effects of multiple stressors are likely to act antagonistically in autotrophs, but synergistically in heterotrophs (Crain *et al.* 2008). Furthermore, since higher trophic levels contain less 'biological insurance' (*sensu* Yachi & Loreau, 1999), i.e. less taxonomic, physiological, and genetic diversity, they are predicted to be more susceptible to multiple environmental perturbations (Christensen *et al.* 2006) which could act upon them synergistically (Crain *et al.* 2008).

Studies of the biological effects of elevated temperature and acidification on marine organisms in isolation have provided some insight into the potential tolerance of species to these changing conditions (Gattuso *et al.* 2009). However, given that these stressors are unlikely to operate independently, there is now a need to gain a more ecologically realistic understanding of how the combined effects of temperature and acidification will affect marine biota. This is vital in order to inform future adaptative management strategies. Using a meta-analytical approach of the peer-reviewed literature we assessed the impacts and interactions of ocean acidification and warming on marine biological responses. Given that variability in the strength and direction of responses was expected, we classified data according to taxonomic groups, calcifiers and non-calcifiers, life-history stage and level of trophic organisation (autotroph and heterotroph) in terms of changes in rates of calcification, growth, photosynthesis, reproduction and survival. Specifically, we aimed to address three questions: (i) How do warming and acidification impacts interact? (ii) Do stressors combine in predictable ways or as 'ecological surprises'? (iii) Can inherent biological variability be explained by predetermined categories?

MATERIAL AND METHODS

DATA SELECTION AND SUITABILITY CRITERIA

Searches for peer-reviewed articles in which studies explicitly investigated anthropogenic climate change using either elevated temperature, ocean acidification or elevated temperature and acidification were carried out using ISI Web of Science ©, Google Scholar; the European Project on Ocean Acidification (EPOCA) blog (http://oceanacidification.wordpress.com/), citation searches; analysis of reference lists in comprehensive reviews (Hendriks *et al.* 2010;

Kroeker *et al.* 2010; Wernberg *et al.* 2012), and then cross-referenced with the bibliographies of identified articles.

We limited our review to studies published between 1st January 1990 and 1st January 2012, as the majority of experimental climate change studies that manipulated climate change conditions in line with IPCC AR1 predictions and subsequent updates (IPCC, 1990, 2007) were published after 1990. Only controlled manipulative experiments were used for analysis. In addition, the control treatments of the environmental stressor (eg. pH, CO_2, or temperature) needed to represent current ambient levels and were based on the authors' opinion of 'ambient'. The experimental organisms had to be subjected to elevated temperature alone, acidification alone, or both warming and acidification. When studies included environmental variables in addition to temperature and ocean acidification (such as light availability or nutrients), these responses were only considered at 'ambient' levels of the other environmental variables. To explore predicted future conditions for 2100, the manipulation treatments needed to conform to the IPCC IS92a "business-as-usual" emission scenario for the year 2100 (IPCC, 2007). We omitted studies that manipulated carbonate chemistry using acid addition, because it does not reproduce the changes in HCO_3^- concentration that occur as a result of increased CO_2(aq) (Iglesias-Rodriguez *et al.* 2008a; 2008b; but see; Gattuso & Lavigne, 2009; Schulz *et al.* 2009). Finally, only studies that reported a measureable biological response were included.

As response variables we used calcification (or dissolution) rates, growth, photosynthesis, reproduction and survival (mortality was converted to survival by using 1 - mortality). There were insufficient data on other response variables (eg. feeding rates, metabolism) to enable quantitative analysis. A number of articles included more than one species, response, location, or treatment level. All of the species, responses, locations and treatment levels were included if they met the suitability criteria. This ensured that a broad range of responses could be fully explored, despite lessening the independence of the data from that particular study (Gurevitch *et al.* 1992). To maintain independence of data we included only one response, chosen at random, from studies reporting several responses that could be classified in the same category (eg. growth expressed as changes in length and biomass). Derived metrics from studies that included time-series data were based on the final time point of exposure. To investigate inherent biological variability, records were categorised according to taxonomy, life-history stage, level of trophic organisation (autotroph, heterotroph) and whether the organism possessed a $CaCO_3$ skeletal structure.

To enable a calculation of effect size, studies that met our initial criteria could only be used if they reported a mean response value, some form of variance (standard deviation, standard error or confidence interval), and a sample size. In some instances values were only reported in graphical form, and in these situations data were extracted using the program GraphClick (v. 3.0) (Neuchatel, Switzerland).

DATA ANALYSIS

Biological responses to ocean warming and acidification were measured for each experiment to establish the proportional change between the control and treatment means using response ratios. In their original metric response ratios are weighted towards positive responses, so the response ratios were log transformed to maintain symmetry in the analysis and ease the biological interpretation (Hedges *et al.* 1999). We chose a log response ratio (lnRR), over other methods, to estimate the effect size because of the high capacity to detect true effects and there robustness to small sample sizes (Lajeunesse & Forbes, 2003).

We selected a weighted random-effects model to estimate a summary effect size. Random-effects analysis assumes that the true effect size differs between experiments and the estimated summary effect is the mean of the effects observed across the studies. This means that even if studies have a low weighting, the individual effect sizes from all of the studies will still be incorporated into the summary effect (Borenstein *et al*. 2009). This ensured that the biological variation inherent in the responses was properly accounted for. Both the within-study variance (inverse of the effect size variance) and the between-study variance (σ^2_{pooled}) were used to weight the studies. Therefore studies with higher replication and/or lower variance were considered more precise and weighted accordingly (Hedges & Olkin, 1985).

Statistical significance was attributed to each summary effect size by calculating a bias-corrected 95% confidence interval (CI) and comparing it with zero. If the summary effect size did not overlap zero then it was considered to be significantly different. A total heterogeneity statistic (Q) was used to ascertain that the variation observed was a combination of both true variation (between studies) and random error (within studies) (Borenstein *et al.* 2009). This was tested as the observed weighted sum of squares against a chi square distribution with $n - 1$ degrees of freedom, using the null hypothesis that observations share a common effect size.

Combinations of the treatment effect (CO_2/pH, temperature, temperature and CO_2/pH) and response variables (calcification, growth, photosynthesis, reproduction, and survival) were used as the comparison groups in all analyses. Separate exploratory analyses were also used to test the differences between *a priori* defined groups; it was appreciated that this form of multiple exploratory analyses on the same dataset is prone to Type I error, however, we aimed to use these analyses to identify the underlying patterns of the biological responses. The categorical moderators used were the different taxonomic groups (corals, crustaceans, crustose coralline algae, echinoderms, fishes, non-calcifying algae, molluscs, phytoplankton and seagrasses), calcifying and non-calcifying organisms, developmental stages (embryos, larvae, juveniles and adults), and trophic organisation (autotroph and heterotroph). This process applied a summary effect size and 95% CI to each of the different categories for comparison. To formally test for differences between these categories, a test for heterogeneity (Q_M) was used; this ascertains the total heterogeneity that can be explained by that particular categorical moderator (Gurevitch *et al.* 1992). A significant Q_M indicates that there is a difference between the categories. The taxonomic group of phytoplankton was initially divided into coccolithophores, cyanobacteria, diatoms, dinoflagellates and foraminifera, however, results were pooled again after detecting no difference using a test for heterogeneity (Q_M). Over all of the meta-analytical results, the summary effect sizes were not reported if there were fewer than five studies available for analysis, and categorical moderators were not reported if there were fewer than three studies. This was a pragmatic decision to ensure that a broad range of responses could be assessed, as some categories only had a few studies that met our criteria. Therefore, the categorical analyses did not always include all the observations from the full model.

INTERACTIONS BETWEEN MULTIPLE STRESSORS

Interactions between ocean warming and acidification were ascertained following the methodology of Darling and Côté (2008). The method involved using a weighted fixed-effect model to predict the combined effect of warming and acidification for each response variable. The effects of ocean warming and acidification are unlikely to operate independently, so we used a multiplicative model (± 95% CI) to predict the proportional change of their interaction (Morris *et al.* 2007; Crain *et al.* 2008). Although less conservative than an additive model (Folt *et al.* 1999), we considered a multiplicative model to be more appropriate since the underlying model of the metric lnRR is multiplicative (Hawkes & Sullivan, 2001; Morris *et al.* 2007), and this model is also thought to be more biologically realistic (Sih *et al.* 1998). Results were then compared to the combined warming and acidification observed responses (also calculated using a weighted fixed-effect model ± 95% CI). If the 95% CI of the predicted and observed responses did not overlap then they were considered significantly different. Observed effect sizes that were significantly higher were classed synergistic, significantly lower were antagonistic, and those that were non-significant were multiplicative. To be included, studies had to have carried out a controlled factorial experiment that reported the outcomes of warming and acidification individually and in combination, with a control treatment (Underwood, 1997). Therefore, not all of the observations from the full model could be analysed. Multiple observations from the same study were included if separate factorial results were provided.

SENSITIVITY ANALYSES AND PUBLICATION BIAS

Sensitivity analysis was used to investigate the influence of any experimental study that demonstrated an unusually large effect size. This was achieved in a step-wise manner by ranking each experiment by the magnitude of effect size, removing the largest one, and re-running the analysis. Likewise, if any study contributed five or more observations to a category, the study was omitted and the analyses re-run. If studies were considered to be driving the results, then they were omitted from the analysis of that response variable.

The number of studies with an effect size of zero that would be required to change the results of the meta analysis from significant to non-significant ('file drawer problem') was determined using Rosenberg's failsafe number (Rosenberg, 2005). It was decided that if five or less studies (of zero effect size) were required to change the effect size, then that categorical analysis was not considered robust.

RESULTS

OVERALL BIOLOGICAL RESPONSES

Out of 196 peer-reviewed articles that investigated the biological responses of marine organisms to ocean warming and/or acidification 107 met our criteria, giving 623 unique observations (Table S1). Observations that did not meet the selection criteria are listed in Table S2, and the results from all the heterogeneity tests for overall within-effects (*Q*) and between categories (Q_M) are reported in Table S3.

Meta-analysis of the whole dataset revealed that calcification was negatively affected by ocean acidification and neutrally affected by ocean warming, although there was some tendency towards a negative response. Combined warming and acidification resulted in a highly significant negative response (Fig. 1). In contrast, the effects of ocean acidification and warming (both independently and combined) had no effect on growth (Fig. 1).

Independently, both ocean acidification and warming resulted in highly variable, but non-significant effects on photosynthesis. Conversely, concurrent acidification and warming revealed a significant positive effect on photosynthesis (Fig. 1).

The independent effects of ocean acidification and warming on reproduction and survival were of similar magnitude and negative. The combined effects of ocean warming and acidification were also negative and of greater magnitude than observed for the stressors in isolation (Fig. 1).

TAXONOMIC GROUPS

The combined effects of ocean warming and acidification on calcification varied between taxonomic groups (Q_M = 7.92, d.f.=2, p=0.019; Fig. 1). For corals and crustaceans there were neutral effects in response to warming and acidification both in isolation and combination. In echinoderms, acidification had a neutral effect on calcification while ocean warming and the two stressors combined resulted in significant negative effects with the concurrent effects tending towards a synergistic interaction.

Responses of crustaceans, echinoderms, molluscs and phytoplankton to the combined effects of warming and acidification varied in terms of growth (Q_M = 14.27, d.f.=3, p=0.003; Fig. 1) . Across all taxa there was no significant effect of warming or acidification in isolation or combination, with the exception of the crustaceans, which displayed a significant negative response to the combined effects of these stressors. For the non-calcifiers (fish, non-calcareous algae and seagrass), there was no significant effect on growth as a result of warming and acidification in isolation, although effects tended towards positive. Unfortunately there were insufficient studies to determine the combined effects of these stressors.

The combined effects of ocean warming and acidification had a significant positive effect on photosynthesis in phytoplankton (Fig. 1). Although, analysis of the combined stressors was not possible for the other primary producers they all showed responses of similar magnitude to ocean acidification and warming in isolation.

For both echinoderms and molluscs, ocean warming (in isolation) had a significant negative effect on reproduction, while for molluscs ocean acidification (in isolation) also had a negative effect. Combined warming and acidification had a significant negative effect on reproduction in both taxa (Fig. 1).

The combined effects of ocean warming and acidification negatively affected survival in crustaceans and molluscs (Fig. 1). Additionally, significant negative responses were also detected in corals and molluscs under warming conditions and for molluscs under high CO_2 conditions.

CALCIFIERS/NON-CALCIFIERS

Due to an insufficient number of studies investigating the concurrent effects of warming and acidification on non-calcifiers, comparisons with calcifiers of the combined impact of these stressors was not possible. Under future ocean chemistry conditions there was, however, significant difference in growth between calcifiers and non-calcifiers (Q_M = 12.22, d.f. =1,

p<0.001; Fig. 2), with growth significantly negatively affected in calcifiers and significantly positively affected in non-calcifiers. Calcifiers exhibited a significantly positive photosynthetic response to the combined effects of warming and acidification (Fig 2), primarily driven by phytoplankton (Fig 1). Where sufficient data existed to enable comparisons, warming and acidification, in isolation and combination, negatively affected survival in both calcifiers and non-calcifiers (Fig 2).

LIFE-HISTORY STAGES

Ocean warming (both independently and in conjunction with acidification) had a significant negative effect on calcification in juveniles, but not in adults. Heterogeneity tests, however, did not reveal significant differences between life history stages for either calcification or growth when exposed to the two stressors in isolation or combination (Table S3). The effects of ocean warming on survival differed significantly between life-history stages with both larvae and juveniles exhibiting more negative responses than adults (Q_M = 23.62, d.f. =2, p<0.001; Fig. 3). Although ocean acidification had a significant negative effect on the survival of larvae and adults, there was no significant difference in responses across life-history stages (Table S3). The combined effects of warming and acidification on survival showed a significant negative response for both larvae and juveniles.

TROPHIC ORGANISATION

Calcification in autotrophs was not significantly affected by either warming or acidification in isolation or combination. The combined effects of warming and acidification had, however, a significant negative effect on calcification in heterotrophs (Fig. 4). Conversely, the effects of warming and acidification did not significantly affect growth in heterotrophs, while in autotrophs ocean warming and acidification had a significant positive effect on growth (Fig. 4). While there were insufficient data to investigate the combined effects of warming and acidification on survival in autotrophs, these stressors in isolation had significant negative effects. In heterotrophs survival was not affected by ocean acidification, but was significantly negatively affected by warming alone and the combined effects of warming and acidification.

INTERACTIONS BETWEEN MULTIPLE STRESSORS

For calcification, growth and survival, combined warming and acidification resulted in negative ‘ecological surprises’ when compared to the multiplicative null expectation model, with a synergistic effect on calcification and an antagonistic effect for both growth and survival (Fig. 5). The observed responses for photosynthesis and reproduction were accurately predicted by the model suggesting that these responses to future warming and acidification may be predictable.

SENSITIVITY ANALYSES AND PUBLICATION BIAS

To test the robustness of our analyses against large effect sizes, we removed each comparison step-wise and re-ran each analysis, omitting experiments if they changed the significance of either heterogeneity or the mean effect size of the response variables. This resulted in twelve experiments being omitted from subsequent analyses across several treatment-response variable scenarios (see Table S2 for more detail). We used Rosenthal’s fail-safe number to assess the importance of potential publication bias and found that our response variables were robust, with the lowest values being 82 and 99 additional studies being required to change the effect size (based on original experiment quantities of 33 and 7 respectively). No individual study contributing more than five experiments changed the significance of either the heterogeneity or mean effect size of the response variables.

DISCUSSION

Meta-analysis of the full dataset revealed that the combined effects of ocean acidification and warming had significant negative effects on calcification, reproduction and survival, and a significant positive effect on photosynthesis. There was, as would be expected, variation amongst taxonomic groups, life-history stages, trophic levels, calcifiers and non-calcifiers. More importantly, our analyses showed that responses to ocean acidification and warming in isolation often differed from the results obtained when these stressors were combined. Our results highlight the need to move away from single-stressor studies towards more ecologically realistic research incorporating multiple stressors, in order to more fully understand how near-future anthropogenic change will affect marine biodiversity.

Analysis of the full dataset did not provide evidence that the combined stressors would result in truly synergistic or antagonistic interactions. However, examination of our subset of fully factorial studies showed that three out of five of our responses generated 'ecological surprises' (sensu Paine *et al.* 1998), where the outcome was not predictable from the sum of the individual stressors (i.e. multiplicative effects; Folt *et al.* 1999). We observed a synergistic effect on calcification and an antagonistic effect on both growth and survival, highlighting that stressor specificity, in addition to other factors, may be involved in driving interaction types (Crain *et al.* 2008). Our findings suggest that the effects of combined warming and acidification may commonly generate unpredictable interactions (i.e. synergies and antagonisms) rather than interacting in a predictable manner, with implications for our ability to predict the future impacts of multiple stressors.

Ecological synergies are anticipated to have important implications for marine systems (Paine *et al.* 1998; Harley *et al.* 2006; Sutherland *et al.* 2006) as they can exacerbate adverse effects and reduce ecosystem resilience (Folke *et al.* 2004). Although antagonistic interactions will reduce the cumulative impact compared to synergies (Didham *et al.* 2007; Brook *et al.* 2008), they will also interact unpredictably. Such unpredictable outcomes are of particular concern because 'ecological surprises' may additionally affect biotic interactions (Tylianakis *et al.* 2008) and trophic complexity (Vinebrooke *et al.* 2004; Darling & Côté, 2008). Multiple stressors are thought to act synergistically when affecting different physiological mechanisms, since this results in ecological trade-offs. This is because synergies are fundamentally a negative functional interaction between traits (Kneitel & Chase, 2004). Alternatively, antagonisms will occur if an individual is exposed to an additional stressor that acts upon the same mechanism as a stressor for which that individual has already adapted or become acclimated to (Blanck, 2002; Christensen *et al.* 2006).

The negative synergistic response detected for calcification in echinoderms, for instance, is consistent with the pattern of ecological synergies and trade-offs (Kneitel & Chase, 2004) in that it may be attributed to an energy re-allocation strategy from somatic or reproductive growth (Melzner *et al.* 2009). For example, an infaunal brittlestar exhibited muscle wastage as an energetic trade-off to maintain calcification under ocean acidification conditions (Wood *et al.* 2008). Our observed antagonistic interaction between ocean warming and acidification for both growth and survival may be consistent with the pattern of developing a stress-tolerance for stressors acting on the same pathway (Christensen *et al.* 2006). For example, acidification may induce a reduced body size, a common stress-tolerance trait (Vinebrooke *et al.* 2004), which makes organisms less susceptible to other stressors, or in this case elevated temperature. In our analyses, the impacts of ocean acidification on survival were more subtle, with neutral or weakly negative effects, while temperature appeared to be the overriding stressor. The only exception to this was in adults in our analysis across life-history stages. This pattern is consistent with previous work (eg. McDonald *et al*. 2009; Findlay *et al*. 2010).

Interestingly, despite establishing robust predictions for near-future changes in carbonate chemistry (Roleda *et al.* 2012), the underlying mechanisms of the biological responses still remain unclear (Gattuso & Hansson 2011; but see Pörtner, 2008). For instance, until recently the effects of ocean acidification on calcification responses were thought to reduce an organism's potential to calcify and enhance the dissolution of their $CaCO_3$ shells (eg. Ries *et al.* 2009). Recent studies have, however, demonstrated that the net calcification loss found in many studies may not demonstrate constraints on calcification, but rather that the dissolving of exposed skeleton (gross dissolution) is greater than the skeletal growth beneath healthy tissue (gross calcification) (Ries, 2011; Rodolfo-Metalpa *et al.* 2011). It is therefore essential to understand the mechanisms through which warming and acidification act, as well as to establish the effect that the stressors have on biological responses.

Early life-history stages are generally considered more susceptible to environmental stressors (Pechenik, 1987), and larval and juvenile stages of marine organisms typically show high mortality rates (Gosselin & Qian, 1997; Hunt & Scheibling, 1997). Our results support the hypothesis that the threshold for deleterious warming may vary between developmental stages (Byrne *et al.* 2009; Byrne *et al.* 2010) with adult survival being significantly higher compared to either larvae or juveniles under predicted warming conditions. However, insufficient studies limited a comparison of the effects of combined warming and acidification on survival across life-history stages. Previous work suggests that for survival the interaction between different types of stressors does not differ between life stages apart from embryos (Darling & Côté, 2008). Our results support these findings, but are perhaps more indicative of differences between life-history stages being less prominent than species-specific sources of heterogeneity (Fabry, 2008; Kurihara, 2008).

In our analyses, the combined effects of warming and acidification positively affected growth in autotrophs, probably due to the effect of temperature on metabolic rate, while CO_2, which is a substrate for photosynthesis, may also have indirectly lead to increased growth at higher CO_2 concentrations. There were no effects on calcification in autotrophs but in heterotrophs calcification was adversely affected, along with survival, by the combined stressors. In heterotrophs growth was unaffected. Collectively, the differences observed are likely attributed to different modes of energy acquisition, and associated indirect effects. For instance, in some autotrophs photosynthesis is expected to increase under near-future climate change (eg. Palacios & Zimmerman, 2007; Fu *et al.* 2008; Hall-Spencer *et al.* 2008), and indirectly, photosynthesis has the potential to stimulate calcification (Ries *et al.* 2009) and increase growth rates (eg. phytoplankton; Loehle, 1995). Moreover, the metabolism complexes of heterotrophs (respiration-limited) are more sensitive to ocean warming than the photosynthesis-limited metabolism of autotrophs (Lopez-Urrutia *et al.* 2006), and thus warming is predicted to lead to stronger consumer-driven control (O'Connor *et al.* 2009). There were insufficient data in our analysis to make comparisons between consumer trophic levels (herbivores, detritivores, consumers and top predators). Given the greater frequency of negative effects in response to single stressors at higher tropic levels (Christensen *et al.* 2006), biological responses and interactions to multiple stressors are also likely to differ between consumer trophic levels (Vinebrooke *et al.* 2004). Therefore, a need clearly exists to incorporate trophic complexity within experimental manipulations (eg. O'Connor, 2009; Ferrari *et al.* 2011) of multiple stressors.

Despite our subset of data, derived from experiments where both temperature and acidification were manipulated in isolation and combination, revealing 'ecological surprises' (Fig 5), analysis of our complete dataset did not reveal either synergistic or antagonistic interactions with combined warming and acidification. Broad-scale meta-analyses may therefore be ineffective in detecting the more specific 'ecological surprises', due to the inherent variability associated with different taxonomic groups, trophic levels and life-history stages. The implications of this are that any inferred additive interaction between acidification and warming may underestimate synergisms, and overestimate antagonisms (although conservatively) (Didham *et al*., 2007). Compared to additive interactions, mitigation measures on synergisms will result in greater than expected returns, however, antagonisms will lead to challenges for management because they will require multiple stressors to be mitigated before considerable recovery can be seen. In contrast to our findings, a previous synthesis of interactions between a broad range of stressors found that the overall interaction effect across all studies in marine systems was synergistic (Crain *et al.* 2008). However, a subsample of their more robust, fully factorial studies, resulted in over half of their studies having predictable additive interactions. Their study included only three examples of the combined impacts of temperature and ocean acidification, but our conflicting results further reinforce the role that stressor identity has in determining multiple stressor interactions. Additionally, since marine systems are subject to multiple interacting stressors (Halpern *et al.* 2007), it is possible that the addition of a third stressor would introduce further adverse consequences (eg. Przeslawski *et al.* 2005).

Although we identified and incorporated the available literature that met our selection criteria, the number of studies was limited across taxonomic groups, trophic levels and life stages leading to restrictions on the analyses we could undertake and highlighting the need for further research effort in this area. Additionally, despite a recognised tradition for effective experimental design in marine ecology (Underwood, 1997), a recent review highlighted that almost half of marine climate change experiments had design weaknesses or deficiencies (Wernberg *et al.* 2012). In that meta-analysis, 91% of studies either lacked treatment replication or carried out a form of pseudo-replication. We found that a third of the studies we investigated were also limited by experimental design, particularly pseudo-replication. This increases the likelihood of Type I errors, i.e. false positives (Hurlbert, 1984). Given the intense scrutiny that climate change science recieves it is essential that climate change ecologists, along with all scientists, design their experiments in order to eliminate potential artifacts as a result of poor experimental design.

Substantial progress has been made in determining the impacts of climate change on marine systems, but several key areas require concerted research effort before marine climate change ecologists can provide the evidence required to inform adaptive management strategies. Studies that investigate the biological responses of individual species to multiple stressors will continue to provide insight into the potential tolerance of species to these changing conditions (Gattuso *et al*. 2009). However, it is likely that over multiple generations phenotypic plasticity and/or genetic evolution will influence the ability of marine organisms to develop a stress-tolerance (Ferrari *et al*. 2011). Therefore, areas of natural variable pH and temperature, such as CO_2 vent systems (eg. Hall-Spencer *et al.* 2008) or areas of upwelling (eg. Bakun, 1990), may provide a method of ecosystem validation to investigate whether prolonged exposure to stressors can promote adaptation. Moreover, physiological studies are needed to investigate the pathways driving the biological responses of marine organisms, in order to better understand the magnitude, direction and interaction of the effects of multiple stressors.

Individual species are responding idiosyncratically to anthropogenic climate change, and it is likely that the temporal and spatial association between species interacting at different trophic levels will also be affected (Harrington *et al*. 1999; Walther *et al*. 2002). Since the complexity of biotic interactions makes it difficult to extrapolate from single-species studies to community or ecosystem levels (Walther *et al*. 2002). Future studies will need to establish the links between climatic impacts at an individual, population, community and ecosystem level (Harley, 2006). This can be achieved by increasing both the trophic complexity and number of stressors, with the aim to scale up to investigations with natural communities and ecosystems. Such large-scale ecosystem level experiments would not only increase our knowledge of the functioning and resilience of marine ecosystems, but provide explicit evidence to policymakers on the effectiveness of conservation and management strategies in response to climate change.

In conclusion, our findings highlight a complex set of outcomes when the combined effects of ocean warming and acidification on marine organisms are considered. Specifically, we established that the magnitude, direction and interaction of the effects of multiple stressors varies between response type probably as a result of the pathways driving the biological response. Responses also differ between taxonomic groups, trophic levels and life stages. Most importantly, in our subset of data we identified 'ecological surprises' that were not found in our broad-scale dataset, reinforcing the need for more robust assessments in this field. However, two of our responses (photosynthesis and reproduction) did interact in a predictable manner. Understanding the variation of these additive responses will enable more accurate assessment of the likely outcomes of mitigation measures. Importantly, we must also consider further abiotic and biotic stressors in the marine environment that are likely to also interact with warming and acidification (Halpern *et al.* 2007). Understanding how multiple stressors will impact and interact on different trophic levels also represents a major challenge in the marine biosciences. Experimental manipulation of multiple stressors will provide a sound scientific basis to inform climate change adaptive management strategies, but more generally will also enhance our understanding of the functioning and resilience of marine ecosystems.

ACKNOWLEDGEMENTS

We thank members of the Aquatic, Behavioural and Evolutionary Biology and Ecology Research Groups who provided valuable input into discussions surrounding this manuscript and Sonia Consuegra, Peter Dennis and John Gee for providing suggestions for improving the manuscript. The vector graphics used in Figure 2 are from the Integration and Application Network (http://ian.umces.edu/symbols/), University of Maryland Center for Environmental Science. Funding for BH was provided by an Institute of Biological, Environmental and Rural Sciences PhD Studentship. Funding for PM was provided through a Marie Curie Career Integration Grant PCIG10-GA-2011-303685.

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SUPPORTING INFORMATION

Table S1 Experiments included in meta-analysis

Table S2 Selection criteria for exclusion from meta-analysis

Table S3 Heterogeneity tests – within groups (Q) and between groups (Q_M)

FIGURE CAPTIONS

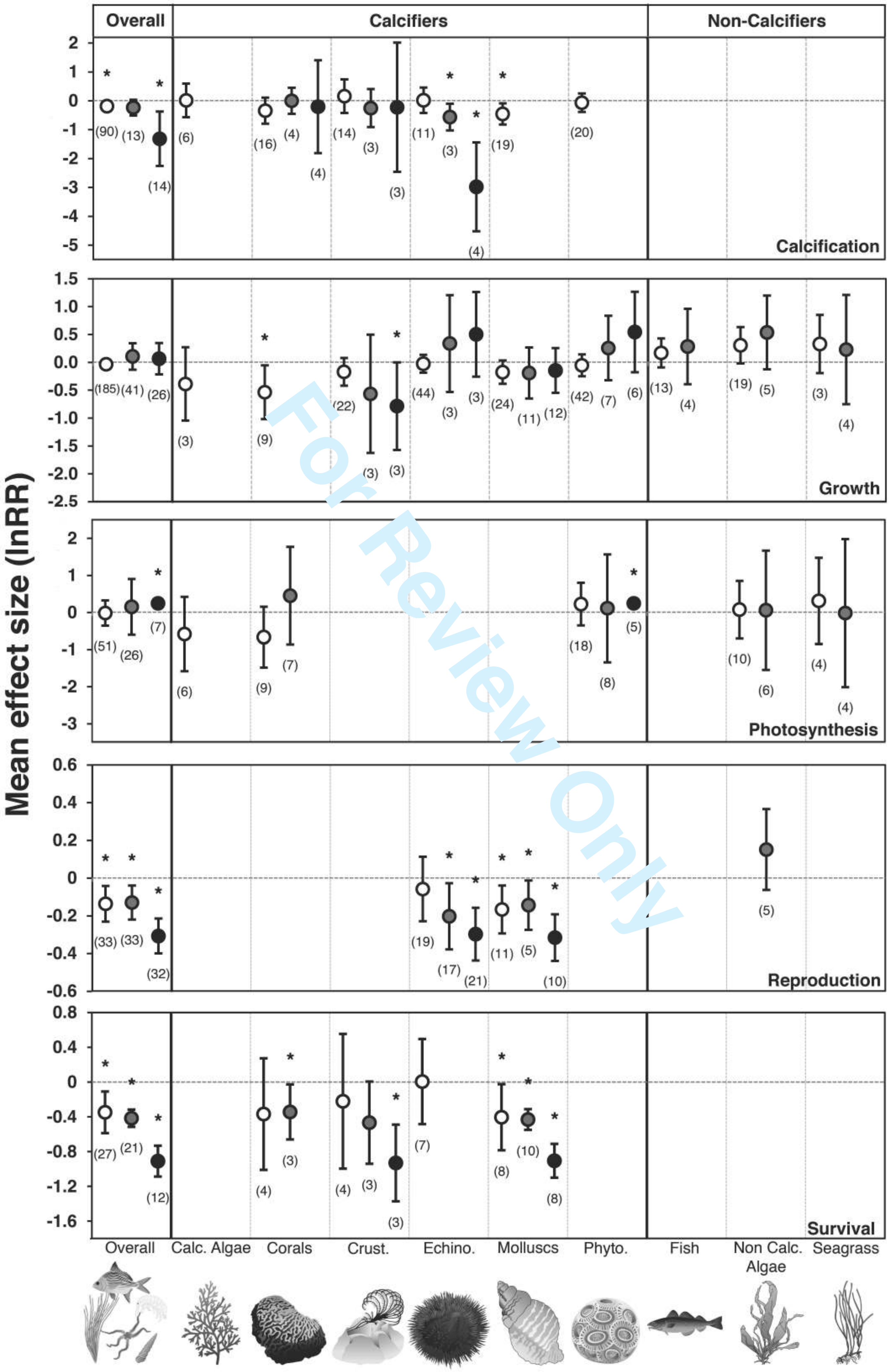
Figure 1 The mean effect of ocean acidification (clear circles), ocean warming (grey circles), and combined ocean acidification and warming (black circles) on calcification, growth, photosynthesis, reproduction and survival for different taxonomic groups. The mean log response ratio and ±95% confidence intervals are shown for overall (combined results), calcifiers (calcifying algae, corals, crustaceans, echinoderms, molluscs and phytoplankton) and non-calcifiers (fishes, non-calcified algae, seagrass). The number of observations in each analysis is shown in parentheses. The zero line indicates no effect, and significance (*) of mean effects is determined when the ±95% confidence interval does not overlap zero.

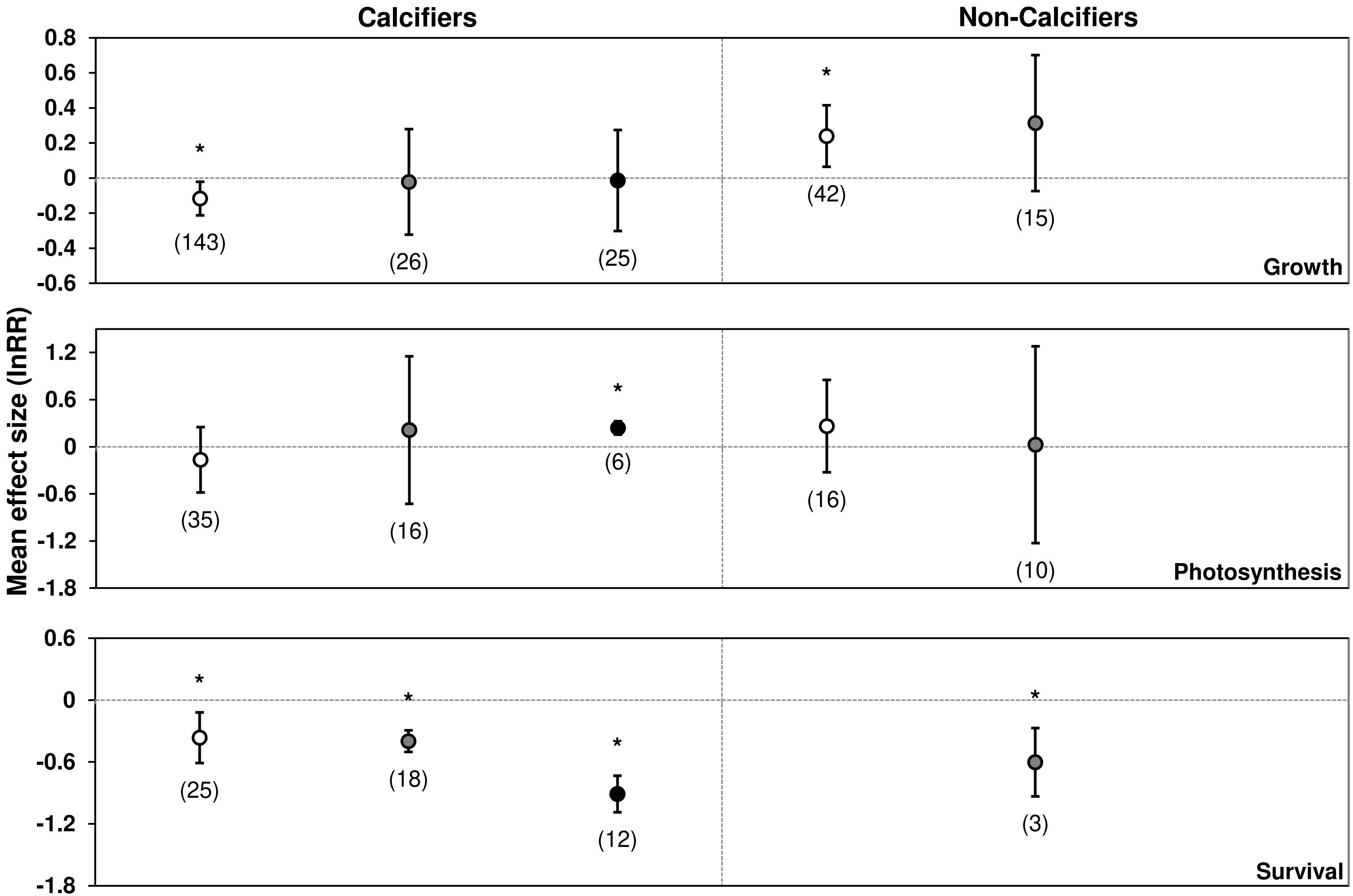
Figure 2 The mean effect of ocean acidification (clear circles), ocean warming (grey circles), and combined ocean acidification and warming (black circles) on growth, photosynthesis and survival for calcifying and non-calcifying organisms. The mean log response ratio and ±95% confidence intervals are shown for calcifiers and non-calcifiers. The number of observations in each analysis is shown in parentheses. The zero line indicates no effect, and significance (*) of mean effects is determined when the ±95% confidence interval does not overlap zero.

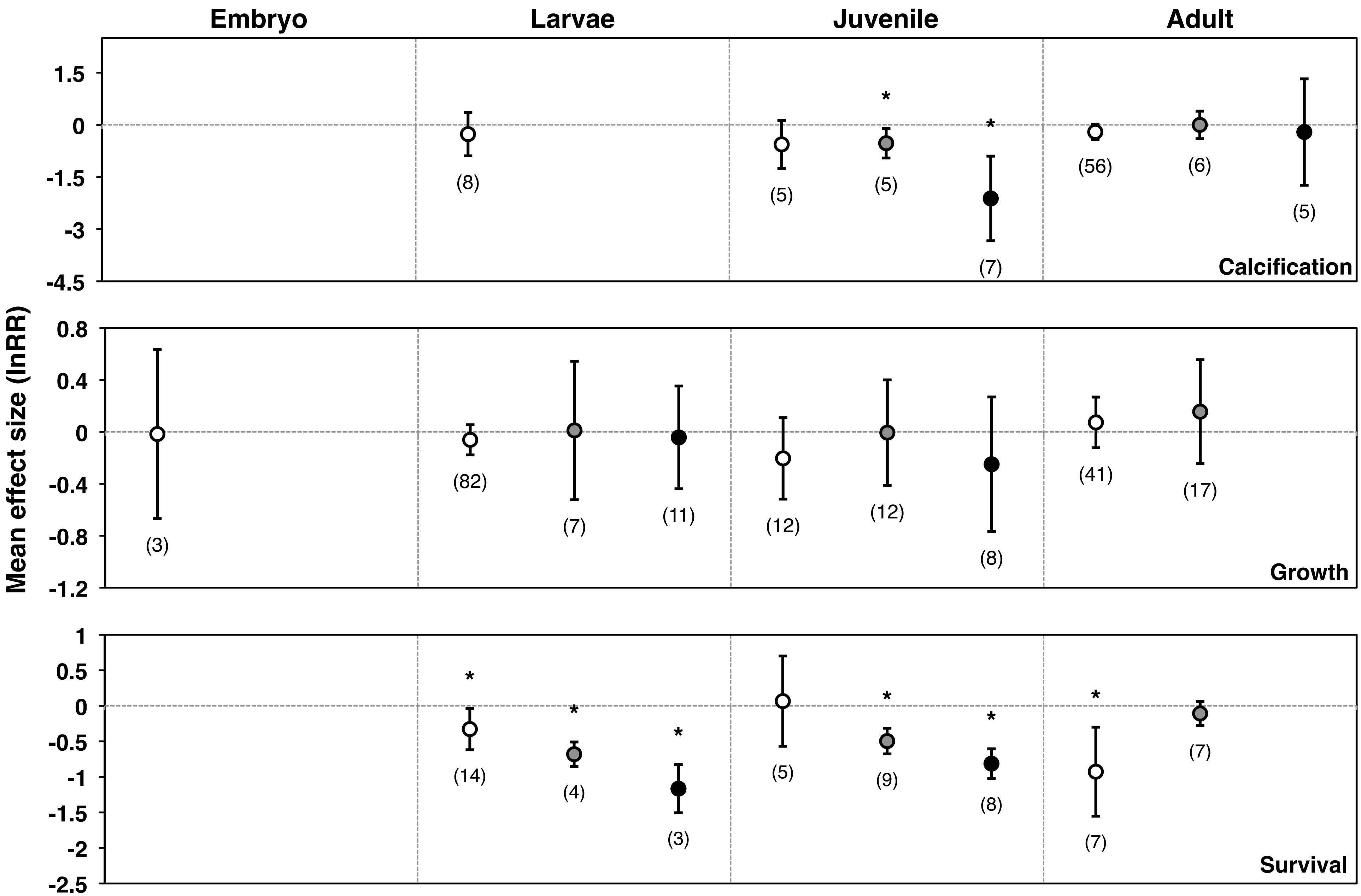
Figure 3 The mean effect of ocean acidification (clear circles), ocean warming (grey circles), and combined ocean acidification and warming (black circles) on calcification, growth and survival in different life-stages. The mean log response ratio and ±95% confidence intervals are shown for embryos, larvae, juveniles and adults. The number of observations in each analysis is shown in parentheses. The zero line indicates no effect, and significance (*) of mean effects is determined when the ±95% confidence interval does not overlap zero.

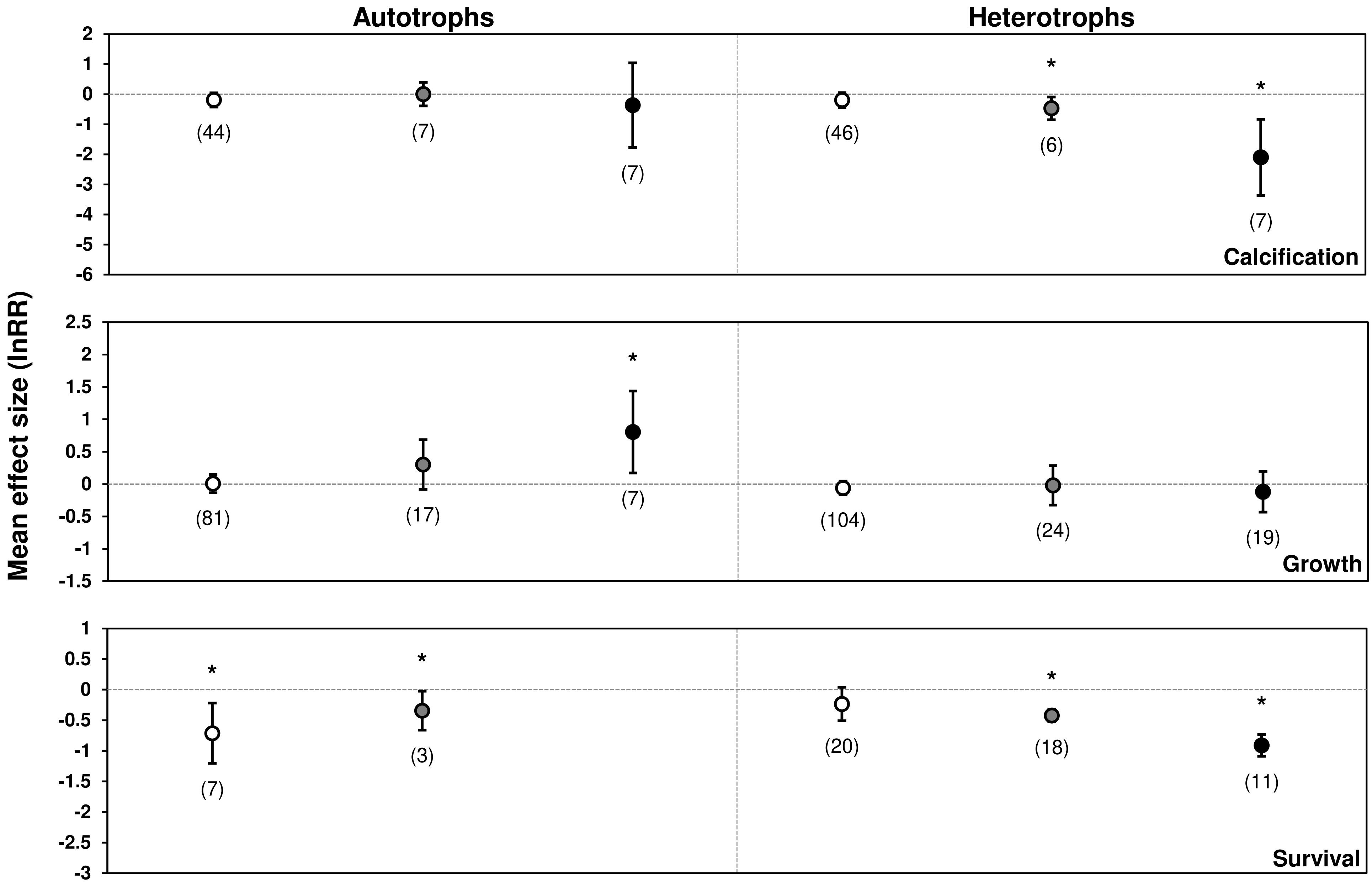
Figure 4 The mean effect of ocean acidification (clear circles), ocean warming (grey circles), and combined ocean acidification and warming (black circles) on calcification, growth, photosynthesis, reproduction and survival for different levels of trophic organisation. The mean log response ratio and ±95% confidence intervals are shown for autotrophs and heterotrophs. The number of observations in each analysis is shown in parentheses. The zero line indicates no effect, and significance (*) of mean effects is determined when the ±95% confidence interval does not overlap zero.

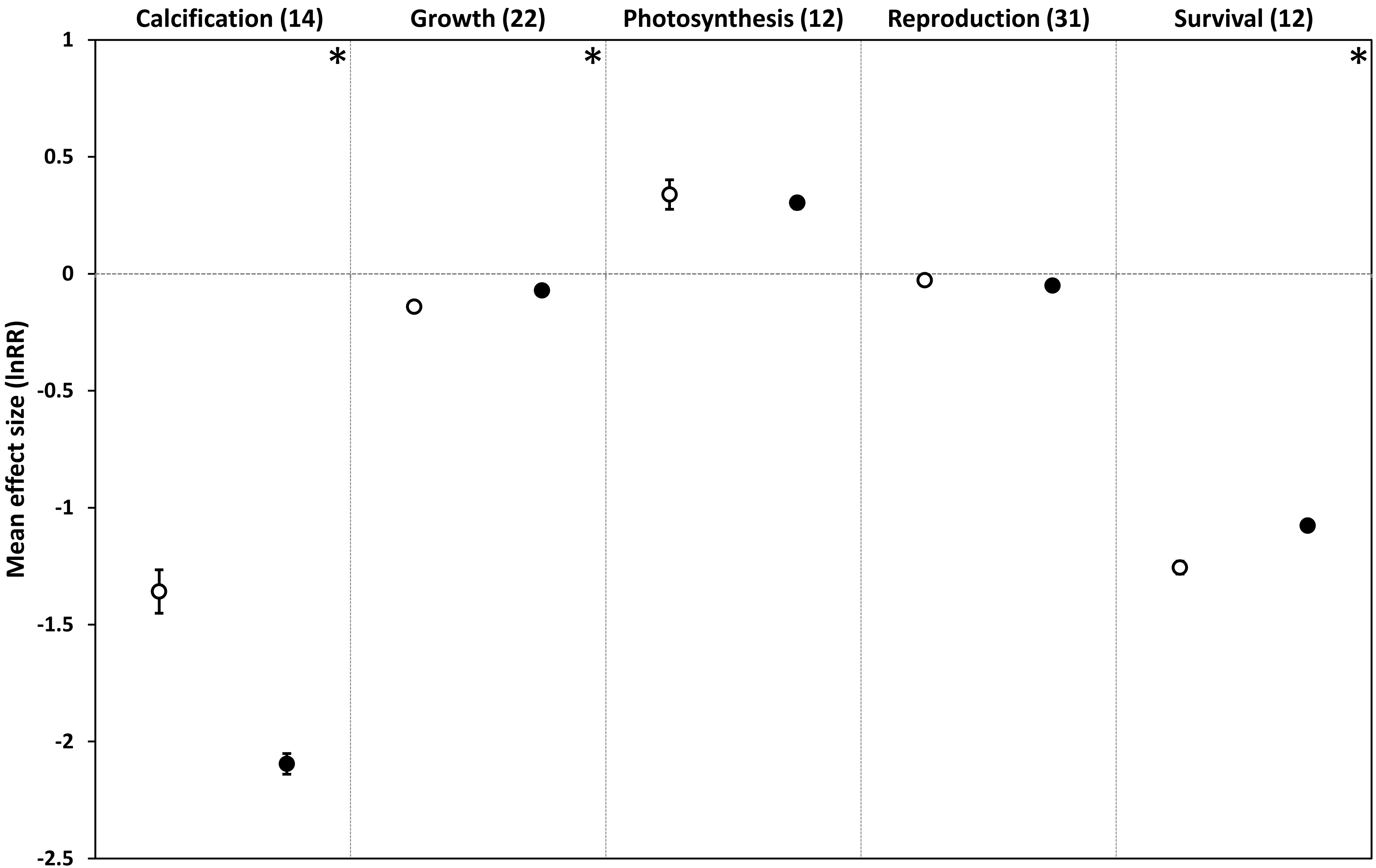
Figure 5 The mean effect of combined ocean warming and acidification as a predicted multiplicative null expectation model (clear circles), and observed responses (filled circles) for different response variables. The mean log response ratio and ±95% confidence intervals are shown for calcification, growth, photosynthesis, reproduction and survival. The number of observations in each analysis is shown in parentheses by the associated response variable. The zero line indicates no effect, significance of mean effects is determined when the ±95% confidence interval does not overlap each other, and each significant response variables is denoted *.


Overall
Calcifiers
Non-Calcifiers
Calcification
Growth
Photosynthesis
Reproduction
Survival
Mean effect size (lnRR)
Overall
Calc. Algae
Corals
Crust.
Echino.
Molluscs
Phyto.
Fish
Non Calc. Algae
Seagrass


Calcifiers
Non-Calcifiers
Mean effect size (lnRR)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
*
*
(143)
(26)
(25)
(42)
(15)
Growth
1.2
0.6
0
-0.6
-1.2
-1.8
*
(35)
(16)
(6)
(16)
(10)
Photosynthesis
0.6
0
-0.6
-1.2
-1.8
*
*
*
*
(25)
(18)
(12)
(3)
Survival


Embryo
Larvae
Juvenile
Adult
Mean effect size (lnRR)
1.5
0
-1.5
-3
-4.5
*
*
(8)
(5)
(5)
(7)
(56)
(6)
(5)
Calcification
0.8
0.4
0
-0.4
-0.8
-1.2
(3)
(82)
(7)
(11)
(12)
(12)
(8)
(41)
(17)
Growth
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
*
*
*
*
*
*
(14)
(4)
(3)
(5)
(9)
(8)
(7)
(7)
Survival


Autotrophs
Heterotrophs
Mean effect size (lnRR)
Calcification
Growth
Survival
2
1
0
-1
-2
-3
-4
-5
-6
2.5
1.5
0.5
-0.5
-1.5
-2.5
*
(44)
(7)
(7)
(46)
(6)
(7)
(81)
(17)
(7)
(104)
(24)
(19)
(3)
(20)
(18)
(11)


Calcification (14)
Growth (22)
Photosynthesis (12)
Reproduction (31)
Survival (12)
*
*
*
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Mean effect size (lnRR)

ST1 - Experiments included in meta-analysis

Each row represents an individual experiment that was included for meta-analysis. Columns 'B - F' describes the experiment as: the manipulated stressor, taxonomic group, species, trophic level and life-stage. Columns 'G - K' describe the number of times each response (Calcification, growth, photosynthesis, reproduction and survival) was tested.

Source	Manipulation Group	Taxonomic Group
Aline et al., 2006	CO2	Corals
Anestis et al., 2007	Temperature	Molluscs
Anlauf et al., 2011	CO2	Corals
Anlauf et al., 2011	CO2	Corals
Anlauf et al., 2011	Temperature	Corals
Anlauf et al., 2011	Temperature	Corals
Anlauf et al., 2011	Temperature and CO2	Corals
Anthony et al., 2008	CO2	Corals
Anthony et al., 2008	CO2	Corals
Anthony et al., 2008	CO2	Crustose Coralline Algae
Anthony et al., 2008	Temperature	Corals
Anthony et al., 2008	Temperature	Corals
Anthony et al., 2008	Temperature	Crustose Coralline Algae
Anthony et al., 2008	Temperature and CO2	Corals
Anthony et al., 2008	Temperature and CO2	Corals
Anthony et al., 2008	Temperature and CO2	Crustose Coralline Algae
Arnold et al., 2009	CO2	Crustaceans
Barcelos e Ramos et al., 2010	CO2	Phytoplankton
Borchard et al., 2011	CO2	Phytoplankton
Borchard et al., 2011	Temperature and CO2	Phytoplankton
Brennand et al., 2010	CO2	Echinoderms
Brennand et al., 2010	Temperature	Echinoderms
Brennand et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2009	CO2	Echinoderms
Byrne et al., 2009	CO2	Echinoderms
Byrne et al., 2009	Temperature	Echinoderms
Byrne et al., 2009	Temperature	Echinoderms
Byrne et al., 2009	Temperature and CO2	Echinoderms
Byrne et al., 2009	Temperature and CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Echinoderms
Byrne et al., 2010	CO2	Molluscs
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms
Byrne et al., 2010	Temperature	Echinoderms

Byrne et al., 2010	Temperature	Molluscs
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Echinoderms
Byrne et al., 2010	Temperature and CO2	Molluscs
Catarino et al., 2011	CO2	Echinoderms
Chan et al., 2011	CO2	Echinoderms
Chen and Gao, 2011	CO2	Phytoplankton
Christensen et al., 2011	Temperature	Echinoderms
Clarke et al., 2009	CO2	Echinoderms
Clarke et al., 2009	CO2	Echinoderms
Clarke et al., 2009	CO2	Echinoderms
Clarke et al., 2009	CO2	Echinoderms
Comeau et al., 2009	CO2	Molluscs
Comeau et al., 2010	CO2	Molluscs
Connell and Russell, 2010	CO2	Macroalgae
Connell and Russell, 2010	Temperature	Macroalgae
Connell and Russell, 2010	Temperature and CO2	Macroalgae
Crawley et al., 2010	CO2	Corals
Crim et al., 2011	CO2	Molluscs
Cullen and Sherrell, 2005	CO2	Phytoplankton
de Kluijver et al., 2010	CO2	Phytoplankton
Diaz Pulido et al., 2011	CO2	Corals
Diaz Pulido et al., 2011	CO2	Macroalgae
Donelson et al., 2010	Temperature	Fishes
Doo et al., 2011	CO2	Echinoderms
Dupont et al., 2008	CO2	Echinoderms
Dupont et al., 2010	CO2	Echinoderms
Dupont et al., 2010	CO2	Echinoderms
Edmunds et al., 2001	Temperature	Corals
Edmunds, 2011	CO2	Corals
Engel et al., 2005	CO2	Phytoplankton
Epelbaum et al., 2009	Temperature	Tunicates
Epelbaum et al., 2009	Temperature	Tunicates
Epelbaum et al., 2009	Temperature	Tunicates
Feng et al., 2008	CO2	Phytoplankton
Feng et al., 2008	Temperature	Phytoplankton
Feng et al., 2008	Temperature and CO2	Phytoplankton
Fernandez et al., 2011	CO2	Molluscs
Findlay et al., 2008	CO2	Molluscs
Findlay et al., 2008	Temperature	Molluscs
Findlay et al., 2008	Temperature and CO2	Molluscs
Findlay et al., 2009	CO2	Crustaceans
Findlay et al., 2009	CO2	Crustaceans
Findlay et al., 2010	CO2	Crustaceans
Findlay et al., 2010	CO2	Crustaceans

Findlay et al., 2010	CO2	Crustaceans
Findlay et al., 2010	Temperature	Crustaceans
Findlay et al., 2010	Temperature	Crustaceans
Findlay et al., 2010	Temperature	Crustaceans
Findlay et al., 2010	Temperature and CO2	Crustaceans
Findlay et al., 2010	Temperature and CO2	Crustaceans
Findlay et al., 2010	Temperature and CO2	Crustaceans
Franke and Clemmesen, 2011	CO2	Fishes
Franke and Clemmesen, 2011	CO2	Fishes
Fredersdorf et al., 2009	Temperature	Macroalgae
Fredersdorf et al., 2009	Temperature	Macroalgae
Fu et al., 2007	CO2	Phytoplankton
Fu et al., 2007	CO2	Phytoplankton
Fu et al., 2007	Temperature	Phytoplankton
Fu et al., 2007	Temperature	Phytoplankton
Fu et al., 2007	Temperature and CO2	Phytoplankton
Fu et al., 2007	Temperature and CO2	Phytoplankton
Fu et al., 2008	CO2	Phytoplankton
Fu et al., 2008	CO2	Phytoplankton
Fu et al., 2008	Temperature	Phytoplankton
Fu et al., 2008	Temperature	Phytoplankton
Fu et al., 2008	Temperature and CO2	Phytoplankton
Fu et al., 2008	Temperature and CO2	Phytoplankton
Gao and Zheng, 2010	CO2	Crustose Coralline Algae
Garcia et al., 2011	CO2	Cyanobacteria
Gattuso et al., 1998	CO2	Corals
Gaylord et al., 2011	CO2	Molluscs
Gazeau et al., 2011	CO2	Molluscs
Gazeau et al., 2011	CO2	Molluscs
Gooding et al., 2009	CO2	Echinoderms
Gooding et al., 2009	Temperature	Echinoderms
Gooding et al., 2009	Temperature and CO2	Echinoderms
Grossart et al., 2006	CO2	Bacteria
Gutow and Franke, 2001	Temperature	Crustaceans
Hauton et al., 2009	CO2	Crustaceans
Havenhand and Schlegel, 2009	CO2	Molluscs
Havenhand and Schlegel, 2009	CO2	Molluscs
Havenhand et al., 2008	CO2	Echinoderms
Havenhand et al., 2008	CO2	Echinoderms
Hoffman et al., 2003	Temperature	Macroalgae
Hoffman et al., 2003	Temperature	Macroalgae
Holcomb et al., 2010	CO2	Corals
Hutchins et al., 2007	CO2	Bacteria
Iglesias Rodriguez et al., 2008	CO2	Phytoplankton
Imsland et al., 2007	Temperature	Fishes
Imsland et al., 2007	Temperature	Fishes
Isla et al., 2008	Temperature	Crustaceans
Israel and Hophy, 2002	CO2	Macroalgae
Israel and Hophy, 2002	CO2	Macroalgae
Israel and Hophy, 2002	CO2	Macroalgae

Israel and Hophy, 2002	CO2	Macroalgae
Israel and Hophy, 2002	CO2	Macroalgae
Israel and Hophy, 2002	CO2	Macroalgae
Jury et al., 2010	CO2	Corals
Kim et al., 2006	CO2	Phytoplankton
Kim et al., 2006	CO2	Phytoplankton
Koch et al., 2007	Temperature	Seagrass
Koch et al., 2007	Temperature	Seagrass
Kranz et al., 2009	CO2	Bacteria
Kubler et al., 1999	CO2	Macroalgae
Kurihara et al., 2004	CO2	Echinoderms
Kurihara et al., 2004	CO2	Echinoderms
Kurihara et al., 2004	CO2	Echinoderms
Kurihara et al., 2004	CO2	Echinoderms
Kurihara et al., 2008	CO2	Crustaceans
Langer et al., 2006	CO2	Phytoplankton
Leclercq et al., 2000	CO2	Corals
Lischka et al., 2011	CO2	Molluscs
Lischka et al., 2011	Temperature	Molluscs
Lischka et al., 2011	Temperature and CO2	Molluscs
Liu et al., 2008	Temperature	Cnidarians
Melzner et al., 2011	CO2	Molluscs
Munday et al., 2009	CO2	Fishes
O'Connor, 2009	Temperature	Macroalgae
Parker et al., 2010	CO2	Molluscs
Parker et al., 2010	CO2	Molluscs
Parker et al., 2010	CO2	Molluscs
Parker et al., 2010	CO2	Molluscs
Parker et al., 2010	Temperature	Molluscs
Parker et al., 2010	Temperature	Molluscs
Parker et al., 2010	Temperature	Molluscs
Parker et al., 2010	Temperature	Molluscs
Parker et al., 2010	Temperature and CO2	Molluscs
Parker et al., 2010	Temperature and CO2	Molluscs
Parker et al., 2010	Temperature and CO2	Molluscs
Parker et al., 2010	Temperature and CO2	Molluscs
Pistevos et al., 2011	CO2	Bryozoans
Pistevos et al., 2011	CO2	Bryozoans
Pistevos et al., 2011	Temperature	Bryozoans
Pistevos et al., 2011	Temperature	Bryozoans
Pistevos et al., 2011	Temperature and CO2	Bryozoans
Pistevos et al., 2011	Temperature and CO2	Bryozoans
Price et al., 2011	CO2	Macroalgae
Price et al., 2011	CO2	Macroalgae
Przeslawski et al., 2005	Temperature	Molluscs
Putnam et al., 2008	Temperature	Corals
Putnam et al., 2008	Temperature	Corals
Riebesell et al., 2000	CO2	Phytoplankton
Riebesell et al., 2000	CO2	Phytoplankton
Ries et al., 2009	CO2	Annelids

Ries et al., 2009	CO2	Corals
Ries et al., 2009	CO2	Crustaceans
Ries et al., 2009	CO2	Crustaceans
Ries et al., 2009	CO2	Crustaceans
Ries et al., 2009	CO2	Crustose Coralline Algae
Ries et al., 2009	CO2	Crustose Coralline Algae
Ries et al., 2009	CO2	Echinoderms
Ries et al., 2009	CO2	Echinoderms
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2009	CO2	Molluscs
Ries et al., 2010	CO2	Corals
Rodolfo Metalpa et al., 2010	CO2	Corals
Rodolfo Metalpa et al., 2010	Temperature	Corals
Rodolfo Metalpa et al., 2010	Temperature and CO2	Corals
Roleda et al., 2011	CO2	Macroalgae
Russell et al., 2009	CO2	Crustose Coralline Algae
Russell et al., 2009	CO2	Macroalgae
Russell et al., 2011	CO2	Crustose Coralline Algae
Russell et al., 2011	CO2	Macroalgae
Schmidt et al., 2011	Temperature	Phytoplankton
Schmidt et al., 2011	Temperature	Phytoplankton
Schmidt et al., 2011	Temperature	Phytoplankton
Schram et al., 2011	CO2	Echinoderms
Sciandra et al., 2003	CO2	Phytoplankton
Shirayama and Thornton, 2005	CO2	Echinoderms
Shirayama and Thornton, 2005	CO2	Echinoderms
Shirayama and Thornton, 2005	CO2	Molluscs
Spielmeyer and Pohnert, 2011	CO2	Phytoplankton
Spielmeyer and Pohnert, 2011	CO2	Phytoplankton
Spielmeyer and Pohnert, 2011	CO2	Phytoplankton
Stumpp et al., 2011	CO2	Echinoderms
Stumpp et al., 2011	CO2	Echinoderms
Suffrian et al., 2008	CO2	Cyanobacteria
Suffrian et al., 2008	CO2	Phytoplankton
Suffrian et al., 2008	CO2	Phytoplankton
Suffrian et al., 2008	CO2	Phytoplankton
Suwa et al., 2010	CO2	Corals
Suwa et al., 2010	CO2	Corals
Talmage and Gobler, 2009	CO2	Molluscs
Talmage and Gobler, 2009	CO2	Molluscs
Talmage and Gobler, 2009	CO2	Molluscs
Talmage and Gobler, 2011	CO2	Molluscs
Talmage and Gobler, 2011	CO2	Molluscs

Talmage and Gobler, 2011	Temperature	Molluscs
Talmage and Gobler, 2011	Temperature	Molluscs
Talmage and Gobler, 2011	Temperature	Molluscs
Talmage and Gobler, 2011	Temperature	Molluscs
Talmage and Gobler, 2011	Temperature	Molluscs
Talmage and Gobler, 2011	Temperature and CO2	Molluscs
Talmage and Gobler, 2011	Temperature and CO2	Molluscs
Talmage and Gobler, 2011	Temperature and CO2	Molluscs
Thom, 1996	CO2	Seagrass
Thom, 1996	CO2	Seagrass
Thomsen and Melzner, 2010	CO2	Molluscs
Tortell et al., 2008	CO2	Phytoplankton
Vilchis et al., 2005	Temperature	Molluscs
Vilchis et al., 2005	Temperature	Molluscs
Walther et al., 2010	CO2	Crustaceans
Walther et al., 2011	CO2	Crustaceans
Wood et al., 2008	CO2	Echinoderms
Wood et al., 2009	CO2	Echinoderms
Wood et al., 2011	Temperature	Echinoderms
Zou, 2005	CO2	Macroalgae

Organism	Trophic Level	Life Stage	Calcification	Growth	Photosynthesis	Reproduction
Porites lobata	Autotroph	Adult			1	
Mytilus galloprovincialis	Heterotroph	Adult				
Porites panamensis	Autotroph	Adult				
Porites panamensis	Autotroph	Larvae		1		
Porites panamensis	Autotroph	Adult				
Porites panamensis	Autotroph	Larvae		1		
Porites panamensis	Autotroph	Larvae				
Acropora intermedia	Autotroph	Adult	1		1	
Porites lobata	Autotroph	Adult	1		1	
Porolithon onkodes	Autotroph	Adult	1		1	
Acropora intermedia	Autotroph	Adult	1		1	
Porites lobata	Autotroph	Adult	1		1	
Porolithon onkodes	Autotroph	Adult	1		1	
Acropora intermedia	Autotroph	Adult	1		1	
Porites lobata	Autotroph	Adult	1		1	
Porolithon onkodes	Autotroph	Adult	1		1	
Homarus gammarus	Heterotroph	Larvae		12		
Emiliania huxleyi	Autotroph	Culture	2			
Emiliania huxleyi	Autotroph	Culture		2		
Emiliania huxleyi	Autotroph	Culture		1		
Tripneustes gratilla	Heterotroph	Larvae		2		
Tripneustes gratilla	Heterotroph	Larvae		1		
Tripneustes gratilla	Heterotroph	Larvae		2		
Heliocidaris erythrogramma	Heterotroph	Adult				2
Heliocidaris erythrogramma	Heterotroph	Embryos				2
Heliocidaris erythrogramma	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Embryos				1
Heliocidaris erythrogramma	Heterotroph	Adult				2
Heliocidaris erythrogramma	Heterotroph	Embryos				2
Centrostephanus rodgersii	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Adult				4
Heliocidaris erythrogramma	Heterotroph	Juvenile	2			
Heliocidaris tuberculata	Heterotroph	Adult				2
Patiriella regularis	Heterotroph	Adult				1
Tripneustes gratilla	Heterotroph	Adult				2
Haliotis coccoradiata	Heterotroph	Adult				2
Centrostephanus rodgersii	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Adult				2
Heliocidaris erythrogramma	Heterotroph	Adult				8
Heliocidaris erythrogramma	Heterotroph	Juvenile	2			
Heliocidaris tuberculata	Heterotroph	Adult				1
Patiriella regularis	Heterotroph	Adult				2
Tripneustes gratilla	Heterotroph	Adult				1

Haliotis coccoradiata	Heterotroph	Adult				2
Centrostephanus rodgersii	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Adult				2
Heliocidaris erythrogramma	Heterotroph	Adult				8
Heliocidaris erythrogramma	Heterotroph	Juvenile	4			
Heliocidaris tuberculata	Heterotroph	Adult				2
Patiriella regularis	Heterotroph	Adult				2
Tripneustes gratilla	Heterotroph	Adult				2
Haliotis coccoradiata	Heterotroph	Adult				4
Arbacia dufresnei	Heterotroph	Larvae		1		
Dendraster excentricus	Heterotroph	Larvae		12		
Phaeocystis globosa	Autotroph	Culture		1	1	
Ophionereis schayeri	Heterotroph	Adult				
Evechinus chloroticus	Heterotroph	Larvae	1	1		
Pseudechinus huttoni	Heterotroph	Larvae	1	1		
Sterechinus neumayeri	Heterotroph	Larvae	1	1		
Tripneustes gratilla	Heterotroph	Larvae	1	1		
Limacina helicina	Heterotroph	Adult	1			
Cavolinia inflexa	Heterotroph	Larvae		1		
Turf Algae	Autotroph	Adult		1	1	
Turf Algae	Autotroph	Adult		1	1	
Turf Algae	Autotroph	Adult		1	1	
Acropora formosa	Autotroph	Adult			2	
Haliotis kamtschatkana	Heterotroph	Larvae		1		
Natural Assemblage Phytoplankton	Autotroph	-		8		
Total phytoplankton	Autotroph	Culture		2		
Acropora intermedia	Autotroph	Adult		6		
Lobophora papenfussii	Autotroph	Adult		6		
Acanthochromis polyacanthus	Heterotroph	Adult		2		2
Centrostephanus rodgersii	Heterotroph	Larvae		2		
Ophiothrix fragilis	Heterotroph	Larvae		12		
Crossaster papposus	Heterotroph	Juvenile		1		
Crossaster papposus	Heterotroph	Larvae		1		
Porites astreoides	Autotroph	Larvae			1	
Porites spp.	Autotroph	Adult	1	1		
Emiliania huxleyi	Autotroph	-		2		
Botryllis schlosseri	Heterotroph	Adult				1
Botryllis schlosseri	Heterotroph	Juvenile		1		
Botrylloides violaceus	Heterotroph	Juvenile		1		
Emiliania huxleyi	Autotroph	Culture		1	1	
Emiliania huxleyi	Autotroph	Culture		1	1	
Emiliania huxleyi	Autotroph	Culture		1	1	
Ruditapes decussatus	Heterotroph	Juvenile		2		
Patella vulgata	Heterotroph	Adult				
Patella vulgata	Heterotroph	Adult				
Patella vulgata	Heterotroph	Adult				
Semibalanus balanoides	Heterotroph	Adult				
Semibalanus balanoides	Heterotroph	Embryos	1			
Elminius modestus	Heterotroph	Juvenile	1	1		
Semibalanus balanoides	Heterotroph	Juvenile	1	1		

Semibalanus balanoides	Heterotroph	Juvenile	1	1		
Elminius modestus	Heterotroph	Juvenile	1	1		
Semibalanus balanoides	Heterotroph	Juvenile	1	1		
Semibalanus balanoides	Heterotroph	Juvenile	1	1		
Elminius modestus	Heterotroph	Juvenile	1	1		
Semibalanus balanoides	Heterotroph	Juvenile	1	1		
Semibalanus balanoides	Heterotroph	Juvenile	1	1		
Clupea harengus	Heterotroph	Adult				1
Clupea harengus	Heterotroph	Embryos		1		
Alaria esculenta	Autotroph	Adult				3
Alaria esculenta	Autotroph	Juvenile			4	
Prochlorococcus	Autotroph	Culture		1	1	
Synechococcus	Autotroph	Culture		1	1	
Prochlorococcus	Autotroph	Culture		1	1	
Synechococcus	Autotroph	Culture		1	1	
Prochlorococcus	Autotroph	Culture		1	1	
Synechococcus	Autotroph	Culture		1	1	
Heterosigma akashiwo	Autotroph	Culture			1	
Prorocentrum minimum	Autotroph	Culture			1	
Heterosigma akashiwo	Autotroph	Culture		1	1	
Prorocentrum minimum	Autotroph	Culture		1	1	
Heterosigma akashiwo	Autotroph	Culture		1	1	
Prorocentrum minimum	Autotroph	Culture		1	1	
Corallina sessilis	Autotroph	Adult	1	1	3	
Trichodesmium erythraeum	Autotroph	Culture		1		
Stylophora pistillata	Autotroph	Adult	4			
Mytilus californianus	Heterotroph	Larvae		2		
Crassostrea gigas	Heterotroph	Adult				1
Crassostrea gigas	Heterotroph	Embryos		1		
Pisaster ochraceus	Heterotroph	Juvenile		1		
Pisaster ochraceus	Heterotroph	Juvenile		1		
Pisaster ochraceus	Heterotroph	Juvenile		1		
Community	Heterotroph	Culture		1		
Idotea metallica	Heterotroph	Adult				2
Gammarus locusta	Heterotroph	Adult		2		
Crassostrea gigas	Heterotroph	Adult				1
Crassostrea gigas	Heterotroph	Larvae				1
Heliocidaris erythrogramma	Heterotroph	Adult				1
Heliocidaris erythrogramma	Heterotroph	Larvae				1
Alaria marginata	Autotroph	Adult				1
Fucus gardneri	Autotroph	Adult				1
Astrangia poculata	Autotroph	Adult		1		
Trichodesmium spp	Heterotroph	Culture		3	3	
Emiliania huxleyi	Autotroph	Culture	3	3	3	
Gadus Morhua	Heterotroph	Adult		1		
Gadus Morhua	Heterotroph	Juvenile		1		
Pseudocalanus sp.	Heterotroph	Adult				2
Cystoseira sp	Autotroph	Adult		1		
Enteromorpha linza	Autotroph	Adult		1		
Pterocladia capillaceae	Autotroph	Adult		1		

Soliieria sp.	Autotroph	Adult		2		
Spatoglossum sp.	Autotroph	Adult		1		
Ulva sp.	Autotroph	Adult		2		
Madracis auretenra	Autotroph	Adult	1			
Nitzschia spp.	Autotroph	Community		1		
Skeletonoma costatum	Autotroph	Community		1		
Halodule wrightii	Autotroph	Adult			2	
Thalassia testudinum	Autotroph	Adult		4	2	
Trichodesmium spp	Heterotroph	Culture		1	1	
Lomentaria articulata	Autotroph	Adult		1		
Echinometra mathaei	Heterotroph	Adult				1
Echinometra mathaei	Heterotroph	Larvae		1		
Hemicentrotus pulcherrimus	Heterotroph	Adult				1
Hemicentrotus pulcherrimus	Heterotroph	Larvae		1		
Palaemon pacificus	Heterotroph	Adult		2		
Emiliania huxleyi	Autotroph	Culture	8	8	8	
Community	Autotroph	Mixed			2	
Limacina helicina	Heterotroph	Juvenile		2		
Limacina helicina	Heterotroph	Juvenile		2		
Limacina helicina	Heterotroph	Juvenile		4		
Aurelia aurita	Heterotroph	Juvenile				
Mytilis edulis	Heterotroph	Adult		1		
Amphiprion percula	Heterotroph	Larvae		12		
Sargassum filipendula	Autotroph	Adult		4	1	
Crassostrea gigas	Heterotroph	Adult				3
Crassostrea gigas	Heterotroph	Larvae		3		
Saccostrea glomerata	Heterotroph	Adult				3
Saccostrea glomerata	Heterotroph	Larvae		3		
Crassostrea gigas	Heterotroph	Adult				1
Crassostrea gigas	Heterotroph	Larvae		1		
Saccostrea glomerata	Heterotroph	Adult				1
Saccostrea glomerata	Heterotroph	Larvae		1		
Crassostrea gigas	Heterotroph	Adult				3
Crassostrea gigas	Heterotroph	Larvae		3		
Saccostrea glomerata	Heterotroph	Adult				3
Saccostrea glomerata	Heterotroph	Larvae		3		
Celleporella hyalina	Heterotroph	Adult				1
Celleporella hyalina	Heterotroph	Larvae		1		
Celleporella hyalina	Heterotroph	Adult				1
Celleporella hyalina	Heterotroph	Larvae		1		
Celleporella hyalina	Heterotroph	Adult				1
Celleporella hyalina	Heterotroph	Larvae		1		
Halimeda opuntia	Autotroph	Adult	1		1	
Halimeda taenicola	Autotroph	Adult	1		1	
Bembicium nanum	Heterotroph	Embryos				
Stylophora pistillata	Autotroph	Adult			1	
Stylophora pistillata	Autotroph	Larvae			1	
Emiliania huxleyi	Autotroph	Culture	2			
Gephyrocapsa oceanica	Autotroph	Culture	2			
Hydroides crucigera	Heterotroph	Adult	2			

Oculina arbuscula	Autotroph	Adult	2			
Callinectes sapidus	Heterotroph	Adult	2			
Homarus americanus	Heterotroph	Adult	2			
Penaeus plebejus	Heterotroph	Adult	2			
Halimeda incrassata	Autotroph	Adult	2			
Neogoniolithon sp.	Autotroph	Adult	2			
Arbacia punctulata	Heterotroph	Adult	2			
Eucidaris tribuloides	Heterotroph	Adult	2			
Argopecten irradians	Heterotroph	Adult	2			
Crassostrea virginica	Heterotroph	Adult	2			
Crepidula fornicata	Heterotroph	Adult	2			
Littorina littorea	Heterotroph	Adult	2			
Mercenaria mercenaria	Heterotroph	Adult	2			
Mya arenaria	Heterotroph	Adult	2			
Mytilus edulis	Heterotroph	Adult	2			
Strombus alatus	Heterotroph	Adult	2			
Urosalpinx cinerea	Heterotroph	Adult	2			
Oculina arbuscula	Autotroph	Adult	4			
Cladocora caespitosa	Autotroph	Adult	2		2	
Cladocora caespitosa	Autotroph	Adult	2		2	
Cladocora caespitosa	Autotroph	Adult			2	
Macrocystus pyrifera	Autotroph	Adult				1
Lithphyllum sp.	Autotroph	Adult		1	1	
Feldmannia spp.	Autotroph	Adult		1	1	
Lithphyllum sp.	Autotroph	Adult		1	1	
Feldmannia spp.	Autotroph	Adult		1	1	
Amphistegina radiata	Autotroph	Adult		2	1	
Calcarina hispida	Autotroph	Adult			1	
Heterostegina depressa	Autotroph	Adult			1	
Luidia clathrata	Heterotroph	Adult		1		
Emiliania huxleyi	Autotroph	Culture	1		1	
Echinometra mathaei	Heterotroph	Juvenile		1		
Hemicentrotus pulcherrimus	Heterotroph	Juvenile		1		
Strombus luhuanus	Heterotroph	Juvenile		1		
Emiliania huxleyi	Autotroph	Culture		2		
Phaeodactylum tricornutum	Autotroph	Culture		1		
Thalassiosira pseudonana	Autotroph	Culture		1		
Strongylocentrotus purpuratus	Heterotroph	Embryos		1		
Strongylocentrotus purpuratus	Heterotroph	Larvae		1		
Cyanobacteria	Autotroph	Culture		2		
Diatoms	Autotroph	Culture		2		
Dinoflagellates	Autotroph	Culture		2		
Prymnesiophytes	Autotroph	Culture		2		
Acropora digitifera	Autotroph	Larvae		1		
Acropora tenuis	Autotroph	Larvae				
Argopecten irradians	Heterotroph	Larvae		1		
Crassostrea virginica	Heterotroph	Larvae		1		
Mercenaria mercenaria	Heterotroph	Larvae		1		
Argopecten irradians	Heterotroph	Larvae		1		
Mercenaria mercenaria	Heterotroph	Larvae		1		

Argopecten irradians	Heterotroph	Juvenile		1		
Argopecten irradians	Heterotroph	Larvae		1		
Crassostrea virginica	Heterotroph	Juvenile		1		
Mercenaria mercenaria	Heterotroph	Juvenile		1		
Mercenaria mercenaria	Heterotroph	Larvae		1		
Argopecten irradians	Heterotroph	Juvenile				
Argopecten irradians	Heterotroph	Larvae		1		
Mercenaria mercenaria	Heterotroph	Larvae		1		
Nereocystis luetkeana	Autotroph	Adult			4	
Zostera marina	Autotroph	Adult		3	4	
Mytilus edulis	Heterotroph	Adult		2		
Phytoplankton Assemblage	Autotroph	Culture		1		
Haliotis fulgens	Heterotroph	Adult		1		1
Haliotis rufescens	Heterotroph	Adult		1		1
Hyas araneus	Heterotroph	Larvae		3		
Hyas araneus	Heterotroph	Larvae	4			
Amphiura filiformis	Heterotroph	Adult	1	1		
Amphiura filiformis	Heterotroph	Adult				
Ophiocten sericeum	Heterotroph	Adult	1	1		
Hizikia fusiforme	Autotroph	Adult		1	1	

Survival

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ST2 - Selection criteria for exclusion in meta-analysis

Each row represents an individual observation that was omitted from subsequent analysis. Therefore, some studies may include a number of observations, in which some are included (and listed within ST1) and some are omitted. Columns 'B - F' describes the experiment as: the manipulated stressor, response, taxonomic group, species and life-stage. Columns 'G - L' describe the reason that particular experiment did not meet the criteria. Stressor Level describes when either the CO2/pH or temperature manipulation was greater than the IPCC 2100 predictions (i.e. >0.5 pH reduction, >1300ppm CO2, or >5 °C increase). Response indicates that the particular response variable of that experiment did not have a sufficient number to be quantatively assessed. Fieldwork indicates that the experiment was carried out in the field and therefore omitted because of possible confounding factors. No Variance highlights that either the study did not provide a form of uncertainty (either standard deviation, standard error or confidence interval) or that the study only had 1 replicate. Carbonate Chemistry indicates that the carbonate chemistry of the experiment was manipulated using an HCL Addition rather than manipulating the DIC. Other reason

Source	Manipulation Group
Albright et al., 2008, Coral Reefs, 27:485–490	CO2
Albright et al., 2008, Coral Reefs, 27:485–490	CO2
Anestis et al., 2007, Am. J. Physiol-Reg. I., 293:R911-21	Temperature
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
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Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
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Anthony et al., 2008, Proc. Nat. Acad. Sci., 105:17442-6	Temperature and CO2
Barcelos e Ramos et al., 2010, Biogeosciences, 7:177-86	CO2
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Batten and Bamber, 1996, Mar. Pollut. Bull., 32:283-287	CO2
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Batten and Bamber, 1996, Mar. Pollut. Bull., 32:283-287	CO2
Batten and Bamber, 1996, Mar. Pollut. Bull., 32:283-287	CO2
Batten and Bamber, 1996, Mar. Pollut. Bull., 32:283-287	CO2
Batten and Bamber, 1996, Mar. Pollut. Bull., 32:283-287	CO2
Beniash et al., 2010, Mar. Ecol. Prog. Ser., 419:95–108	CO2
Beniash et al., 2010, Mar. Ecol. Prog. Ser., 419:95–108	CO2
Beniash et al., 2010, Mar. Ecol. Prog. Ser., 419:95–108	CO2
Berge et al., 2006, Chemosphere, 62:681-687	CO2
Bibby et al., 2007, Biol. Lett., 3:699-701	CO2
Bibby et al., 2007, Biol. Lett., 3:699-701	CO2
Bibby et al., 2007, Biol. Lett., 3:699-701	CO2
Brennand et al., 2010, Plos One, 5:e11372	Temperature
Brennand et al., 2010, Plos One, 5:e11372	Temperature and CO2

Burkhardt et al., 2001, Limnol. Oceanogr., 46:1378-1391	CO_2
Burkhardt et al., 2001, Limnol. Oceanogr., 46:1378-1391	CO_2
Byrne et al., 2009, Proc. Roy. Soc. Lond. B, 276:1883-1888	CO_2
Byrne et al., 2009, Proc. Roy. Soc. Lond. B, 276:1883-1888	Temperature
Byrne et al., 2009, Proc. Roy. Soc. Lond. B, 276:1883-1888	Temperature
Byrne et al., 2009, Proc. Roy. Soc. Lond. B, 276:1883-1888	Temperature and CO_2
Byrne et al., 2009, Proc. Roy. Soc. Lond. B, 276:1883-1888	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Biol., 157:2061-9	Temperature and CO_2
Byrne et al., 2010, Mar. Env. Res., 69:234-9	CO_2
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Campbell et al., 2011, Global Change. Biol., 17:2958-2970	Temperature
Catarino et al., 2011, Polar Biol., 35:455-461	CO_2
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Chan et al., 2011, J. Exp. Biol., 214:3857-3867	CO_2
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Christensen et al., 2011, J. Exp. Mar. Biol. Ecol., 403:31-8	Temperature and CO_2
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Clarke et al., 2009, Mar. Biol., 156:1125-37	CO_2
Clarke et al., 2009, Mar. Biol., 156:1125-37	CO_2
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Doo et al., 2011, Ices. J. Mar. Sci., doi:10.1093/icesjms/fsr123	CO2
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Ellis et al., 2009, Aquat. Biol., 5:41–8	CO2
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Epelbaum et al., 2009, J. Exp. Mar. Biol. Ecol., 369:43-52	Temperature
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Findlay et al., 2008, Aquat. Biol., 3:51-62	CO2
Findlay et al., 2008, Aquat. Biol., 3:51-62	CO2
Findlay et al., 2008, Aquat. Biol., 3:51-62	CO2
Findlay et al., 2008, Aquat. Biol., 3:51-62	Temperature
Findlay et al., 2008, Aquat. Biol., 3:51-62	Temperature
Findlay et al., 2008, Aquat. Biol., 3:51-62	Temperature and CO2
Findlay et al., 2008, Aquat. Biol., 3:51-62	Temperature and CO2
Findlay et al., 2009, Mar. Ecol. Prog. Ser., 389:193-202	CO2
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Findlay et al., 2010, Estuar. Coast. Shelf. S., 86:675–82	CO2
Findlay et al., 2010, Estuar. Coast. Shelf. S., 86:675–82	Temperature and CO2
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Fredersdorf et al., 2009, Oecologia, 160:483-492	Temperature
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Gazeau et al., 2011, Plos One, 6:e23010	CO2
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Gooding et al., 2009, Proc. Nat. Acad. Sci., 106:9316-21	CO2
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Grossart et al., 2006, Limnol. Oceanogr., 51:1–11	CO2
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Hale et al., 2010, Oikos, 120:661–74	CO2
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Hale et al., 2010, Oikos, 120:661–74	CO2
Hale et al., 2010, Oikos, 120:661–74	CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
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Hale et al., 2010, Oikos, 120:661–74	Temperature and CO2
Hall Spencer et al., 2008, Nature, 454:96-9	CO2
Hammer et al., 2011, Mar. Env. Res., 72:135-42	CO2
Hare et al., 2007, Mar. Ecol. Prog. Ser., 352:9-16	CO2
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Hare et al., 2007, Mar. Ecol. Prog. Ser., 352:9-16	Temperature
Hare et al., 2007, Mar. Ecol. Prog. Ser., 352:9-16	Temperature
Hare et al., 2007, Mar. Ecol. Prog. Ser., 352:9-16	Temperature and CO2
Hare et al., 2007, Mar. Ecol. Prog. Ser., 352:9-16	Temperature and CO2
Harris et al., 1999, J. Shellfish Res., 18:611-9	CO2
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Harris et al., 1999, J. Shellfish Res., 18:611-9	CO2
Hauton et al., 2009, Biogeosciences, 6:1479-89	CO2
Hoffman et al., 2003, J. Phycol., 39:268-272	Temperature
Hoffman et al., 2003, J. Phycol., 39:268-272	Temperature
Hueerkamp et al., 2001, B. Mar. Sci., 69:215-236	Temperature
Hueerkamp et al., 2001, B. Mar. Sci., 69:215-236	Temperature
Hueerkamp et al., 2001, B. Mar. Sci., 69:215-236	Temperature
Hueerkamp et al., 2001, B. Mar. Sci., 69:215-236	Temperature
Hueerkamp et al., 2001, B. Mar. Sci., 69:215-236	Temperature
Iglesias-Rodriguez et al., 2008, 320, 336-40	CO2
Iglesias-Rodriguez et al., 2008, 320, 336-40	CO2
Iglesias-Rodriguez et al., 2008, 320, 336-40	CO2
Imsland et al., 2007, J. Fish Biol., 71:1371-1382	Temperature
Imsland et al., 2007, J. Fish Biol., 71:1371-1382	Temperature
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Isla et al., 2008, Global Change. Biol., 14:895-906	Temperature
Isla et al., 2008, Global Change. Biol., 14:895-906	Temperature
Israel and Hophy, 2002, Global Change. Biol., 8:831-40	CO2
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Israel and Hophy, 2002, Global Change. Biol., 8:831-40	CO2
Israel and Hophy, 2002, Global Change. Biol., 8:831-40	CO2
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Israel and Hophy, 2002, Global Change. Biol., 8:831-40	CO2
Jacobson et al., 2008, Aquat. Biol., 1:269-276	Temperature
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Jokial et al., 2008, Coral Reefs, 27:473–83	CO2
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Koch et al., 2007, J. Exp. Mar. Biol. Ecol., 341:91-101	Temperature
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Response	Taxonomic Group
Growth	Corals
Survival	Corals
Survival	Molluscs
Photosynthesis	Corals
Photosynthesis	Corals
Photosynthesis	Crustose Coralline Algae
Bleaching	Corals
Bleaching	Corals
Bleaching	Crustose Coralline Algae
Calcification	Corals
Calcification	Corals
Calcification	Crustose Coralline Algae
Photosynthesis	Corals
Photosynthesis	Corals
Photosynthesis	Crustose Coralline Algae
Bleaching	Corals
Bleaching	Corals
Bleaching	Crustose Coralline Algae
Bleaching	Corals
Bleaching	Corals
Bleaching	Crustose Coralline Algae
Calcification	Corals
Calcification	Corals
Calcification	Crustose Coralline Algae
Photosynthesis	Corals
Photosynthesis	Corals
Photosynthesis	Crustose Coralline Algae
Growth	Phytoplankton
Photosynthesis	Phytoplankton
Fitness	Annelids
Fitness	Annelids
Growth	Annelids
Growth	Annelids
Survival	Annelids
Survival	Annelids
Fitness	Molluscs
Fitness	Molluscs
Growth	Molluscs
Growth	Molluscs
Fitness	Molluscs
Growth	Molluscs
Survival	Molluscs
Survival	Echinoderms
Survival	Echinoderms

Photosynthesis	Phytoplankton
Photosynthesis	Phytoplankton
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Molluscs
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Echinoderms
Reproduction	Molluscs
Reproduction	Echinoderms
Reproduction	Echinoderms
Bleaching	Macroalgae
Development	Echinoderms
Growth	Echinoderms
Fitness	Echinoderms
Photosynthesis	Corals
Fitness	Echinoderms
Fitness	Echinoderms
Fitness	Echinoderms
Survival	Echinoderms
Survival	Echinoderms
Survival	Echinoderms
Survival	Echinoderms
Growth	Corals
Fitness	Microalgae
Growth	Molluscs
Abundance	Macroalgae
Abundance	Macroalgae
Abundance	Macroalgae
Fitness	Molluscs
Survival	Molluscs
Feeding	Fishes
Fitness	Fishes
Interaction Strength	Fishes
Abundance	Nematodes
Biodiversity	Nematodes
Fitness	Crustaceans

Survival	Crustaceans
Biodiversity	Phytoplankton
Survival	Corals
Growth	Corals
Calcification	Phytoplankton
Calcification	Phytoplankton
Calcification	Phytoplankton
Fitness	Echinoderms
Fitness	Echinoderms
Abundance	Echinoderms
Development	Crustaceans
Reproduction	Crustaceans
Abundance	Seagrass
Development	Molluscs
Reproduction	Molluscs
Growth	Tunicates
Growth	Tunicates
Survival	Tunicates
Survival	Tunicates
Photosynthesis	Corals
Survival	Corals
Feeding	Molluscs
Fitness	Molluscs
Feeding	Fishes
Interaction Strength	Fishes
Survival	Fishes
Survival	Fishes
Survival	Fishes
Survival	Fishes
Survival	Crustaceans
Survival	Crustaceans
Survival	Crustaceans
Survival	Crustaceans
Survival	Crustaceans
Survival	Crustaceans
Survival	Crustaceans
Development	Crustaceans
Calcification	Crustaceans
Growth	Crustaceans
Survival	Crustaceans
Calcification	Crustaceans
Growth	Crustaceans
Survival	Crustaceans
Calcification	Corals
Growth	Fishes
Reproduction	Fishes
Survival	Fishes
Photosynthesis	Macroalgae
Reproduction	Macroalgae
Reproduction	Fishes

Growth	Phytoplankton
Growth	Phytoplankton
Calcification	Corals
Calcification	Molluscs
Calcification	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Feeding	Echinoderms
Feeding	Echinoderms
Feeding	Echinoderms
Abundance	Bacteria
Development	Crustaceans
Reproduction	Crustaceans
Abundance	Annelids
Abundance	Arthropods
Abundance	Community
Abundance	Echinoderms
Abundance	Molluscs
Biodiversity	Annelids
Biodiversity	Arthropods
Biodiversity	Community
Biodiversity	Molluscs
Abundance	Annelids
Abundance	Arthropods
Abundance	Community
Abundance	Echinoderms
Abundance	Molluscs
Biodiversity	Annelids
Biodiversity	Arthropods
Biodiversity	Community
Biodiversity	Molluscs
Abundance	Annelids
Abundance	Arthropods
Abundance	Community
Abundance	Echinoderms
Abundance	Molluscs
Biodiversity	Annelids
Biodiversity	Arthropods
Biodiversity	Community
Biodiversity	Molluscs
Abundance	Community
Fitness	Molluscs
Abundance	Phytoplankton
Photosynthesis	Phytoplankton
Abundance	Phytoplankton
Photosynthesis	Phytoplankton
Abundance	Phytoplankton
Photosynthesis	Phytoplankton
Feeding	Molluscs
Feeding	Molluscs

Fitness	Molluscs
Growth	Molluscs
Growth	Molluscs
Survival	Molluscs
Survival	Molluscs
Survival	Crustaceans
Reproduction	Macroalgae
Survival	Macroalgae
Symbionts	Corals
Symbionts	Corals
Symbionts	Corals
Symbionts	Corals
Symbionts	Corals
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Fishes
Growth	Fishes
Reproduction	Crustaceans
Reproduction	Crustaceans
Fitness	Crustaceans
Reproduction	Crustaceans
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Growth	Macroalgae
Reproduction	Crustaceans
Survival	Crustaceans
Abundance	Crustose Coralline Algae
Abundance	Macroalgae
Abundance	Molluscs
Abundance	Molluscs
Calcification	Corals
Growth	Corals
Growth	Corals
Growth	Crustaceans
Growth	Crustose Coralline Algae
Reproduction	Corals
Reproduction	Corals
Abundance	Seagrass
Abundance	Seagrass
Growth	Seagrass
Photosynthesis	Seagrass
Photosynthesis	Seagrass
Abundance	Annelids
Abundance	Crustaceans

Abundance	Crustaceans
Abundance	Crustaceans
Abundance	Crustaceans
Abundance	Molluscs
Abundance	Molluscs
Growth	Macroalgae
Growth	Crustose Coralline Algae
Growth	Macroalgae
Reproduction	Crustose Coralline Algae
Reproduction	Echinoderms
Reproduction	Echinoderms
Calcification	Molluscs
Growth	Molluscs
Growth	Molluscs
Feeding	Crustaceans
Growth	Crustaceans
Growth	Phytoplankton
Calcification	Corals
Photosynthesis	Corals
Calcification	Phytoplankton
Calcification	Phytoplankton
Photosynthesis	Phytoplankton
Photosynthesis	Phytoplankton
Fitness	Molluscs
Fitness	Molluscs
Fitness	Molluscs
Reproduction	Cnidarians
Survival	Cnidarians
Calcification	Corals
Calcification	Crustose Coralline Algae
Survival	Crustose Coralline Algae
Calcification	Crustose Coralline Algae
Survival	Crustose Coralline Algae
Calcification	Crustose Coralline Algae
Survival	Crustose Coralline Algae
Calcification	Corals
Calcification	Corals
Calcification	Corals
Calcification	Corals
Calcification	Corals
Calcification	Corals
Growth	Crustaceans
Growth	Crustaceans
Reproduction	Crustaceans
Growth	Molluscs
Growth	Molluscs
Fitness	Fishes
Fitness	Fishes
Fitness	Fishes
Fitness	Fishes

Fitness	Fishes
Fitness	Fishes
Fitness	Crustaceans
Interaction Strength	Crustaceans
Growth	Molluscs
Reproduction	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Growth	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Reproduction	Molluscs
Growth	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Reproduction	Molluscs
Growth	Molluscs
Growth	Molluscs
Reproduction	Molluscs
Reproduction	Molluscs
Growth	Bryozoans
Reproduction	Bryozoans
Growth	Bryozoans
Reproduction	Bryozoans
Growth	Bryozoans
Reproduction	Bryozoans
-	Macroalgae
Fitness	Molluscs
Fitness	Molluscs
Fitness	Molluscs
Survival	Molluscs
Survival	Molluscs
Survival	Molluscs
Growth	Corals
Calcification	Corals
Photosynthesis	Corals
Calcification	Corals
Photosynthesis	Corals
Calcification	Corals
Photosynthesis	Corals
Calcification	Annelids
Calcification	Corals
Calcification	Crustaceans
Calcification	Crustaceans
Calcification	Crustaceans
Calcification	Crustose Coralline Algae
Calcification	Crustose Coralline Algae
Calcification	Echinoderms

Calcification	Echinoderms
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Molluscs
Calcification	Corals
Calcification	Corals
Calcification	Bryozoans
Calcification	Corals
Calcification	Corals
Calcification	Molluscs
Growth	Corals
Calcification	Corals
Calcification	Corals
Photosynthesis	Corals
Growth	Phytoplankton
Reproduction	Macroalgae
Feeding	Echinoderms
Growth	Molluscs
Abundance	-
Biodiversity	-
Fitness	Phytoplankton
Fitness	Phytoplankton
Photosynthesis	Phytoplankton
Photosynthesis	Phytoplankton
Photosynthesis	Phytoplankton
Calcification	Corals
Photosynthesis	Corals
Fitness	-
Calcification	Phytoplankton
Growth	Phytoplankton
Photosynthesis	Phytoplankton
Survival	Echinoderms
Survival	Echinoderms
Survival	Molluscs
Abundance	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Growth	Phytoplankton
Fitness	-
Abundance	Echinoderms
Growth	Corals

Survival	Corals
Survival	Corals
Growth	Macroalgae
Growth	Macroalgae
Survival	Molluscs
Growth	Molluscs
Growth	Molluscs
Growth	Molluscs
Survival	Molluscs
Survival	Molluscs
Survival	Molluscs
Growth	Molluscs
Growth	Molluscs
Growth	Molluscs
Survival	Molluscs
Growth	Molluscs
Growth	Molluscs
Growth	Molluscs
Fitness	0
Photosynthesis	Seagrass
Photosynthesis	Seagrass
Growth	Molluscs
Calcification	Corals
Reproduction	Molluscs
Calcification	Molluscs
Development	Crustaceans
Growth	Crustaceans
Development	Crustaceans
Growth	Crustaceans
Development	Crustaceans
Growth	Crustaceans
Calcification	Crustaceans
Calcification	Crustaceans
Calcification	Crustaceans
Survival	Cnidarians
Survival	Cnidarians
Survival	Cnidarians
Calcification	Echinoderms
Growth	Echinoderms
Survival	Echinoderms
Fitness	Echinoderms
Growth	Echinoderms
Fitness	Echinoderms
Fitness	Echinoderms
Growth	Echinoderms
Calcification	Corals
Abundance	-
Calcification	Phytoplankton
Calcification	Phytoplankton
Growth	Phytoplankton

Growth	Phytoplankton
Growth	Seagrass
Photosynthesis	Seagrass
Calcification	Phytoplankton
Growth	Phytoplankton

Organism	Life Stage	Stressor Level	Other Response
Porites astreoides	Larvae		
Porites astreoides	Larvae		
Mytilus galloprovincialis	Adult	*	
Acropora intermedia	Adult		
Porites lobata	Adult		
Porolithon onkodes	Adult		
Acropora intermedia	Adult	*	*
Porites lobata	Adult	*	*
Porolithon onkodes	Adult	*	*
Acropora intermedia	Adult	*	
Porites lobata	Adult	*	
Porolithon onkodes	Adult	*	
Acropora intermedia	Adult	*	
Porites lobata	Adult	*	
Porolithon onkodes	Adult	*	
Acropora intermedia	Adult		*
Porites lobata	Adult		*
Porolithon onkodes	Adult		*
Acropora intermedia	Adult	*	*
Porites lobata	Adult	*	*
Porolithon onkodes	Adult	*	*
Acropora intermedia	Adult	*	
Porites lobata	Adult	*	
Porolithon onkodes	Adult	*	
Acropora intermedia	Adult	*	
Porites lobata	Adult	*	
Porolithon onkodes	Adult	*	
Emiliania huxleyi	Culture		
Emiliania huxleyi	Culture		
Nereis virens	Adult	*	
Nereis virens	Juvenile	*	
Nereis virens	Adult	*	
Nereis virens	Juvenile	*	
Nereis virens	Adult	*	
Nereis virens	Juvenile	*	
Crassostrea gigas	Adult	*	
Crassostrea gigas	Juvenile	*	
Crassostrea gigas	Juvenile	*	
Mytilus edulis	Adult	*	
Littorina littorea	Adult	*	
Littorina littorea	Adult	*	
Littorina littorea	Adult	*	
Tripneustes gratilla	Larvae	*	
Tripneustes gratilla	Larvae	*	

Phaeodactylum tricornutum	Culture	*	
Thalassiosira weissflogii	Culture	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris erythrogramma	Embryos	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris erythrogramma	Embryos	*	
Centrostephanus rodgersii	Adult	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris tuberculata	Adult	*	
Patiriella regularis	Adult	*	
Tripneustes gratilla	Adult	*	
Haliotis coccoradiata	Adult	*	
Centrostephanus rodgersii	Adult	*	
Heliocidaris tuberculata	Adult	*	
Tripneustes gratilla	Adult	*	
Centrostephanus rodgersii	Adult	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris tuberculata	Adult	*	
Patiriella regularis	Adult	*	
Tripneustes gratilla	Adult	*	
Haliotis coccoradiata	Adult	*	
Heliocidaris erythrogramma	Adult	*	
Heliocidaris erythrogramma	Adult	*	
Delisea pulchra	Adult		
Arbacia dufresnei	Larvae		*
Arbacia dufresnei	Larvae	*	
Dendraster excentricus	Larvae		*
Acropora muricata	Adult		
Ophionereis schayeri	Adult		*
Ophionereis schayeri	Adult	*	*
Ophionereis schayeri	Adult		*
Evechinus chloroticus	Larvae	*	
Pseudechinus huttoni	Larvae	*	
Sterechinus neumayeri	Larvae	*	
Tripneustes gratilla	Larvae	*	
Favia fragum	Juvenile		
Chlamydomonas reinhardtii	-		*
Cavolinia inflexa	Larvae	*	
Turf Algae	Adult		*
Turf Algae	Adult		*
Turf Algae	Adult		*
Haliotis kamtschatkana	Larvae		*
Haliotis kamtschatkana	Larvae	*	
Pseudochromis fuscus	Adult		*
Pseudochromis fuscus	Adult		*
Pseudochromis fuscus	Adult		*
Nematode community	Adult		*
Nematode community	Adult		*
Pagurus bernhardus	Adult	*	

Pagurus bernhardus	Adult	*	
Community	Community		
Acropora intermedia	Adult		
Acropora intermedia	Adult		
Ammonia tepida	Culture	*	
Ammonia tepida	Culture		
Ammonia tepida	Culture	*	
Centrostephanus rodgersii	Larvae		*
Centrostephanus rodgersii	Larvae		*
Crossaster papposus	Larvae		*
Echinogammarus marinus	Embryos	*	*
Echinogammarus marinus	Adult	*	
Zostera marina	Adult		*
Littorina obtusata	Embryos		*
Littorina obtusata	Adult		
Botryllis schlosseri	Juvenile	*	
Botrylloides violaceus	Juvenile	*	
Botryllis schlosseri	Juvenile	*	
Botrylloides violaceus	Juvenile	*	
Turbinaria mesenterina	Adult	*	
Turbinaria mesenterina	Adult	*	
Ruditapes decussatus	Juvenile		*
Ruditapes decussatus	Juvenile		*
Pseudochromis fuscus	Adult		*
Pseudochromis fuscus	Adult		*
Pomacentrus amboinensis	Juvenile		
Pomacentrus chrysurus	Juvenile		
Pomacentrus moluccensis	Juvenile		
Pomacentrus nagasakiensis	Juvenile		
Elminius modestus	Adult		
Semibalanus balanoides	Adult		
Semibalanus balanoides	Juvenile		
Elminius modestus	Adult		
Semibalanus balanoides	Juvenile		
Elminius modestus	Adult		
Semibalanus balanoides	Juvenile		
Semibalanus balanoides	Embryos		*
Semibalanus balanoides	Juvenile	*	
Semibalanus balanoides	Juvenile	*	
Semibalanus balanoides	Juvenile	*	
Semibalanus balanoides	Juvenile	*	
Semibalanus balanoides	Juvenile	*	
Semibalanus balanoides	Juvenile	*	
Oculina patagonica	Adult	*	
Clupea harengus	Embryos	*	
Clupea harengus	Adult	*	
Clupea harengus	Embryos	*	
Alaria esculenta	Juvenile	*	
Alaria esculenta	Adult	*	
Gadus Morhua	Adult	*	

Heterosigma akashiwo	Culture		
Prorocentrum minimum	Culture		
Acropora sp	Adult		
Crassostrea gigas	Adult		
Mytilus edulis	Adult		
Crassostrea gigas	Embryos	*	
Crassostrea gigas	Adult	*	
Pisaster ochraceus	Juvenile		*
Pisaster ochraceus	Juvenile		*
Pisaster ochraceus	Juvenile		*
Community	Culture		*
Idotea metallica	Adult		*
Idotea metallica	Adult	*	
Community	Community	*	*
Community	Community	*	*
Community	Community	*	*
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Community	Community	*	*
Community	Community		*
Community	Community		*
Community	Mixed		
Acesta excavata	Adult	*	
Phytoplankton Assemblage	-		*
Phytoplankton Assemblage	-		
Phytoplankton Assemblage	-		*
Phytoplankton Assemblage	-		
Phytoplankton Assemblage	-		*
Phytoplankton Assemblage	-		
Haliotis laevigata	Juvenile	*	
Haliotis rubra	Juvenile	*	

Haliotis laevigata	Juvenile	*	
Haliotis laevigata	Juvenile	*	
Haliotis rubra	Juvenile	*	
Haliotis laevigata	Juvenile	*	
Haliotis rubra	Juvenile	*	
Gammarus locusta	Adult		
Fucus gardneri	Adult	*	
Fucus gardneri	Adult	*	
Pavona clavus	Adult		*
Pavona gigantea	Adult		*
Pocillopora damicornis	Adult		*
Pocillopora elegans	Adult		*
Porites lobata	Adult		*
Emiliania huxleyi	Culture		
Emiliania huxleyi	Culture		
Emiliania huxleyi	Culture		
Gadus Morhua	Adult	*	
Gadus Morhua	Juvenile	*	
Pseudocalanus sp.	Adult		
Pseudocalanus sp.	Adult		
Pseudocalanus sp.	Adult		*
Pseudocalanus sp.	Adult	*	
Enteromorpha linza	Adult	*	
Hypnea cornuta	Adult	*	
Hypnea musciformis	Adult	*	
Padina pavonia	Adult	*	
Porphyra sp.	Adult	*	
Pterocladia cappillacea	Adult	*	
Sargassum vulgare	Adult	*	
Ulva sp.	Adult	*	
Monoporeia affinis	Adult	*	
Monoporeia affinis	Adult	*	
Lithophyllum, pallescens, Hydrolithon sp., Porolithon sp.	Community		
Turf Algae	Community		
Dendrostrea sandwichensis	Community		
Serpulorbis sp.	Community		
Montipora capitata	Community		
Montipora capitata	Community		
Pocillopora damicornis	Juvenile		
Balanus sp.	Community		
Lithophyllum, pallescens, Hydrolithon sp., Porolithon sp.	Community		
Montipora capitata	Community		
Pocillopora damicornis	Adult		
Halodule wrightii	Adult		*
Thalassia testudinum	Adult		*
Thalassia testudinum	Adult	*	
Halodule wrightii	Adult	*	
Thalassia testudinum	Adult	*	
Polychaetes	Community	*	
Amphipods	Community		

Decapods	Community		
Isopods	Community	*	
Tanaids	Community		
Bivalves	Community	*	
Gastropods	Community		
Lomentaria articulata	Adult	*	
Porolithon gardineri	Community		
Non-calcifying algae	Community		
Porolithon gardineri	Community		
Echinometra mathaei	Adult		
Hemicentrotus pulcherrimus	Adult		
Crassostrea gigas	Adult	*	
Crassostrea gigas	Adult	*	
Mytilus galloprovencialis	Embryos	*	
Palaemon pacificus	Adult	*	
Palaemon pacificus	Adult	*	
Marginopora kudakajimensis	Culture		
Porites compressa, Montipora verucosa	Adult		
Porites compressa, Montipora verucosa	Adult		
Calcidiscus leptoporus	Culture		
Coccolithus pelagicus	Culture		
Calcidiscus leptoporus	Culture		
Coccolithus pelagicus	Culture		
Limacina helicina	Juvenile		*
Limacina helicina	Juvenile		*
Limacina helicina	Juvenile		*
Aurelia aurita	Adult	*	
Aurelia aurita	Juvenile	*	
Lophelia pertusa	Adult		
Lithophyllum cabiochae	Adult		
Lithophyllum cabiochae	Adult		
Lithophyllum cabiochae	Adult		
Lithophyllum cabiochae	Adult		
Lithophyllum cabiochae	Adult		
Lithophyllum cabiochae	Adult		
Porites compressa	Adult	*	
Porites compressa	Adult		
Acropora verweyi	Adult		
Galaxea fascicularia	Adult		
Pavona cactus	Adult		
Turbinaria reniformis	Adult		
Amphibalanus amphitrite	Juvenile	*	
Amphibalanus amphitrite	Larvae	*	
Amphibalanus amphitrite	Adult	*	
Mytilis edulis	Adult	*	
Mytilus galloprovincialis	Juvenile	*	
Ostorhinchus cyanosoma	Adult		*
Ostorhinchus doederleini	Adult		*
Ostorhinchus cyanosoma	Adult		*
Ostorhinchus doederleini	Adult		*

Ostorhinchus cyanosoma	Adult		0
Ostorhinchus doederleini	Adult		*
Ampithoe longimana	Adult		*
Ampithoe longimana	Adult		*
Saccostrea glomerata	Larvae		
Saccostrea glomerata	Adult		
Saccostrea glomerata	Larvae	*	
Saccostrea glomerata	Adult	*	
Saccostrea glomerata	Larvae	*	
Saccostrea glomerata	Adult	*	
Crassostrea gigas	Larvae	*	
Saccostrea glomerata	Larvae	*	
Crassostrea gigas	Adult	*	
Saccostrea glomerata	Adult	*	
Crassostrea gigas	Larvae	*	
Saccostrea glomerata	Larvae	*	
Crassostrea gigas	Adult	*	
Saccostrea glomerata	Adult	*	
Mytilus galloprovincialis	Adult		
Perna canaliculus	Adult		
Mytilus galloprovincialis	Adult		
Perna canaliculus	Adult		
Celleporella hyalina	Larvae	*	
Celleporella hyalina	Adult	*	
Celleporella hyalina	Larvae	*	
Celleporella hyalina	Adult	*	
Celleporella hyalina	Larvae	*	
Celleporella hyalina	Adult	*	
Community	Community		
Bembicium nanum	Embryos		*
Dolabrifera brazieri	Embryos		*
Siphonaria denticulata	Embryos		*
Bembicium nanum	Embryos	*	
Dolabrifera brazieri	Embryos		
Siphonaria denticulata	Embryos		
Acropora cervicornis	Adult		
Stylophora pistillata	Adult		
Stylophora pistillata	Adult		
Stylophora pistillata	Adult		
Stylophora pistillata	Adult		
Stylophora pistillata	Adult		
Stylophora pistillata	Adult		
Hydroides crucigera	Adult	*	
Oculina arbuscula	Adult	*	
Callinectes sapidus	Adult	*	
Homarus americanus	Adult	*	
Penaeus plebejus	Adult	*	
Halimeda incrassata	Adult	*	
Neogoniolithon sp.	Adult	*	
Arbacia punctulata	Adult	*	

Eucidaris tribuloides	Adult	*	
Argopecten irradians	Adult	*	
Crassostrea virginica	Adult	*	
Crepidula fornicata	Adult	*	
Littorina littorea	Adult	*	
Mercenaria mercenaria	Adult	*	
Mya arenaria	Adult	*	
Mytilus edulis	Adult	*	
Strombus alatus	Adult	*	
Urosalpinx cinerea	Adult	*	
Oculina arbuscula	Adult	*	
Cladocora caespitosa	Adult	*	
Myriapora truncata	Adult		
Balanophyllia europaea	Adult		
Cladocora caespitosa	Adult	*	
Patella caerulea	Adult	*	
Cladocora caespitosa	Adult		
Balanophyllia europaea	Adult		
Balanophyllia europaea	Adult		
Cladocora caespitosa	Adult		
Emiliania huxleyi	Culture		
Macrocystus pyrifera	Adult	*	
Pisaster ochraceus			
Nucella canaliculata			
-			
-			
Amphistegina radiata	Adult	*	*
Heterostegina depressa	Adult	*	*
Amphistegina radiata	Adult	*	
Calcarina hispida	Adult	*	
Heterostegina depressa	Adult	*	
Acropora eurystoma	Adult		
Acropora eurystoma	Adult		
-			*
Emiliania huxleyi	Culture		
Emiliania huxleyi	Culture		
Emiliania huxleyi	Culture		
Echinometra mathaei	Juvenile		
Hemicentrotus pulcherrimus	Juvenile		
Strombus luhuanus	Juvenile		
Community	Culture		*
Emiliania huxleyi	Culture	*	
Phaeodactylum tricornutum	Culture	*	
Thalassiosira pseudonana	Culture	*	
Emiliania huxleyi	Culture	*	
Phaeodactylum tricornutum	Culture	*	
Thalassiosira pseudonana	Culture	*	
-			*
Strongylocentrotus purpuratus	Larvae		*
Acropora digitifera	Larvae	*	

Acropora digitifera	Larvae	*	
Acropora tenuis	Larvae	*	
Nereocystis luetkeana	Juvenile	*	
Saccharina latissima	Juvenile	*	
Argopecten irradians	Larvae		
Argopecten irradians	Larvae	*	
Crassostrea virginica	Larvae	*	
Mercenaria mercenaria	Larvae	*	
Argopecten irradians	Larvae	*	
Crassostrea virginica	Larvae	*	
Mercenaria mercenaria	Larvae	*	
Argopecten irradians	Juvenile	*	
Crassostrea virginica	Juvenile	*	
Mercenaria mercenaria	Juvenile	*	
Argopecten irradians	Juvenile	*	
Argopecten irradians	Juvenile	*	
Crassostrea virginica	Juvenile	*	
Mercenaria mercenaria	Juvenile	*	
0			
Nereocystis luetkeana	Adult	*	
Zostera marina	Adult	*	
Mytilus edulis	Adult	*	
Corallium rubrum	Adult	*	
Haliotis rufescens	Adult		
Crassostrea gigas	Larvae	*	
Hyas araneus	Larvae		*
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	*
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	
Hyas araneus	Larvae	*	
Aurelia labiata	Juvenile		
Aurelia labiata	Juvenile	*	
Aurelia labiata	Juvenile	*	
Amphiura filiformis	Adult	*	
Amphiura filiformis	Adult	*	
Amphiura filiformis	Adult	*	
Ophiocten sericeum	Adult	*	*
Ophiocten sericeum	Adult	*	
Ophiocten sericeum	Adult		*
Ophiocten sericeum	Adult	*	*
Ophiocten sericeum	Adult	*	
-			
-			*
Emiliania huxleyi	Culture		
Gephyrocapsa oceanica	Culture		
Emiliania huxleyi	Culture		

Gephyrocapsa oceanica	Culture	
Zostera marina	Adult	*
Zostera marina	Adult	*
Emiliania huxleyi	Culture	
Emiliania huxleyi	Culture	

Fieldwork	No Variance	Carbonate Chemistry: HCL addition	Other Reason
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Predation Cues

Predation Cues

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Upper Thermal Limit

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Repeat of Ries et al., 2009
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ST3 - Heterogeneity Tests - Within Groups (Q) and Between Groups (Qm)

Heterogeneity statistics for each model in the different response variables. Separate analyses were conducted to compare similarity in effect size between each group

Statistical Model			d.f	Q	P
Full model:	CO2	Calcification	89	66.38891	0.965091
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	-	-	-
Taxonomic Groups					
		Between groups	6	10.11529	0.11988
		Within groups	81	56.15998	0.983939
Life Stages					
		Between groups	2	0.98711	0.610453
		Within groups	67	57.27249	0.795732
Autotroph / Heterotroph					
		Between groups	1	0.000917	0.975848
		Within groups	88	66.388	0.958555

Statistical Model			d.f	Q	P
Full model:	Temperature	Calcification	12	6.706097	0.876409
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	-	-	-
Taxonomic Groups					
		Between groups	2	3.673571	0.159329
		Within groups	10	2.99407	0.981563
Life Stages					
		Between groups	1	3.373508	0.066253
		Within groups	9	3.294133	0.951484
Autotroph / Heterotroph					
		Between groups	1	2.856914	0.090982
		Within groups	11	3.849183	0.974123

Statistical Model			d.f	Q	P
Full model:	Temperature and CO2	Calcification	13	10.30223	0.669053
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	-	-	-
Taxonomic Groups					
		Between groups	2	7.282403	0.026221
		Within groups	11	2.93331	0.991578
Life Stages					
		Between groups	1	3.325488	0.068214
		Within groups	10	6.890225	0.735766
Autotroph / Heterotroph					
		Between groups	1	3.21096	0.073147
		Within groups	12	7.09127	0.851524

Statistical Model			**d.f**	**Q**	**P**
Full model:	CO_2	Growth	184	79.50974	1
Calcifiers / Non-Calcifiers					
		Between groups	1	12.22165	0.000472
		Within groups	183	67.28809	1
Taxonomic Groups					
		Between groups	8	16.57577	0.034843
		Within groups	170	61.44674	1
Life Stages					
		Between groups	3	2.465172	0.481618
		Within groups	134	56.87432	1
Autotroph / Heterotroph					
		Between groups	1	0.581635	0.445672
		Within groups	183	78.9281	1

Statistical Model			**d.f**	**Q**	**P**
Full model:	Temperature	Growth	40	22.86788	0.986448
Calcifiers / Non-Calcifiers					
		Between groups	1	1.795096	0.180306
		Within groups	39	21.07279	0.991504
Taxonomic Groups					
		Between groups	6	5.951578	0.428636
		Within groups	31	16.74605	0.982598
Life Stages					
		Between groups	2	0.351527	0.838816
		Within groups	33	21.11176	0.945629
Autotroph / Heterotroph					
		Between groups	1	1.674628	0.19564
		Within groups	39	21.19326	0.991013

Statistical Model			**d.f**	**Q**	**P**
Full model:	Temperature and CO_2	Growth	25	16.04101	0.913602
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	25	10.01303	0.996617
Taxonomic Groups					
		Between groups	3	14.26619	0.002564
		Within groups	21	1.712536	1
Life Stages					
		Between groups	1	7.130137	0.00758
		Within groups	18	6.308307	0.994778
Autotroph / Heterotroph					
		Between groups	1	6.543602	0.010526
		Within groups	24	9.497408	0.996327

Statistical Model			d.f	Q	P
Full model:	CO_2	Photosynthesis	50	24.34661	0.999166
Calcifiers / Non-Calcifiers					
		Between groups	1	1.355637	0.244295
		Within groups	49	22.99097	0.999435
Taxonomic Groups					
		Between groups	4	4.600559	0.33079
		Within groups	42	18.75501	0.999267
Life Stages					
		Between groups	-	-	-
		Within groups	26	18.8692	0.841904
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	50	24.34661	0.999166

Statistical Model			d.f	Q	P
Full model:	Temperature	Photosynthesis	25	4.014843	0.999999
Calcifiers / Non-Calcifiers					
		Between groups	1	0.054102	0.816073
		Within groups	24	3.96074	0.999999
Taxonomic Groups					
		Between groups	3	0.541265	0.909737
		Within groups	22	3.473578	0.999998
Life Stages					
		Between groups	2	0.235583	0.888881
		Within groups	18	3.769427	0.999846
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	25	4.014843	0.999999

Statistical Model			d.f	Q	P
Full model:	Temperature and CO_2	Photosynthesis	6	4.125859	0.659649
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	6	4.125859	0.659649
Taxonomic Groups					
		Between groups	-	-	-
		Within groups	6	4.088998	0.664634
Life Stages					
		Between groups	-	-	-
		Within groups	1	2.78E-17	1
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	6	4.125859	0.659649

Statistical Model			d.f	Q	P
Full model:	CO2	Reproduction	32	15.00094	0.995389
Calcifiers / Non-Calcifiers					
		Between groups	1	3.170592	0.074975
		Within groups	31	11.83035	0.999263
Taxonomic Groups					
		Between groups	1	3.483788	0.061973
		Within groups	30	3.979337	1
Life Stages					
		Between groups	2	0.059077	0.970894
		Within groups	30	14.94187	0.990064
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	32	14.73757	0.996086

Statistical Model			d.f	Q	P
Full model:	Temperature	Reproduction	32	26.74311	0.729845
Calcifiers / Non-Calcifiers					
		Between groups	1	1.414748	0.23427
		Within groups	31	25.32836	0.75284
Taxonomic Groups					
		Between groups	4	11.58831	0.02069
		Within groups	26	15.07243	0.955995
Life Stages					
		Between groups	-	-	-
		Within groups	32	14.81015	0.995903
Autotroph / Heterotroph					
		Between groups	1	8.004761	0.004665
		Within groups	31	18.73835	0.959136

Statistical Model			d.f	Q	P
Full model:	Temperature and CO2	Reproduction	31	41.92531	0.091087
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	31	41.92531	0.091087
Taxonomic Groups					
		Between groups	1	0.037652	0.846143
		Within groups	29	41.8552	0.057864
Life Stages					
		Between groups	1	17.88687	2.34E-05
		Within groups	30	24.03844	0.770282
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	31	41.92531	0.091087

Statistical Model			d.f	Q	P
Full model:	CO2	Survival	26	21.07494	0.738085
Calcifiers / Non-Calcifiers					
		Between groups	1	0.344861	0.557037
		Within groups	25	20.73008	0.70756
Taxonomic Groups					
		Between groups	4	9.11735	0.058232
		Within groups	22	11.95759	0.958249
Life Stages					
		Between groups	2	5.229557	0.073184
		Within groups	24	15.84539	0.893576
Autotroph / Heterotroph					
		Between groups	1	2.737702	0.098006
		Within groups	25	18.33724	0.827744

Statistical Model			d.f	Q	P
Full model:	Temperature	Survival	20	29.24892	0.082972
Calcifiers / Non-Calcifiers					
		Between groups	1	1.324548	0.249778
		Within groups	19	27.92437	0.084895
Taxonomic Groups					
		Between groups	3	2.643547	0.449906
		Within groups	14	25.28083	0.031894
Life Stages					
		Between groups	2	23.62438	7.41E-06
		Within groups	18	5.624542	0.997496
Autotroph / Heterotroph					
		Between groups	1	0.221652	0.637784
		Within groups	19	29.02727	0.065557

Statistical Model			d.f	Q	P
Full model:	Temperature and CO2	Survival	11	14.67871	0.197683
Calcifiers / Non-Calcifiers					
		Between groups	-	-	-
		Within groups	11	14.67871	0.197683
Taxonomic Groups					
		Between groups	1	0.013307	0.908162
		Within groups	10	14.6654	0.144745
Life Stages					
		Between groups	1	3.006553	0.082928
		Within groups	10	11.67216	0.307597
Autotroph / Heterotroph					
		Between groups	-	-	-
		Within groups	11	14.67569	0.197831