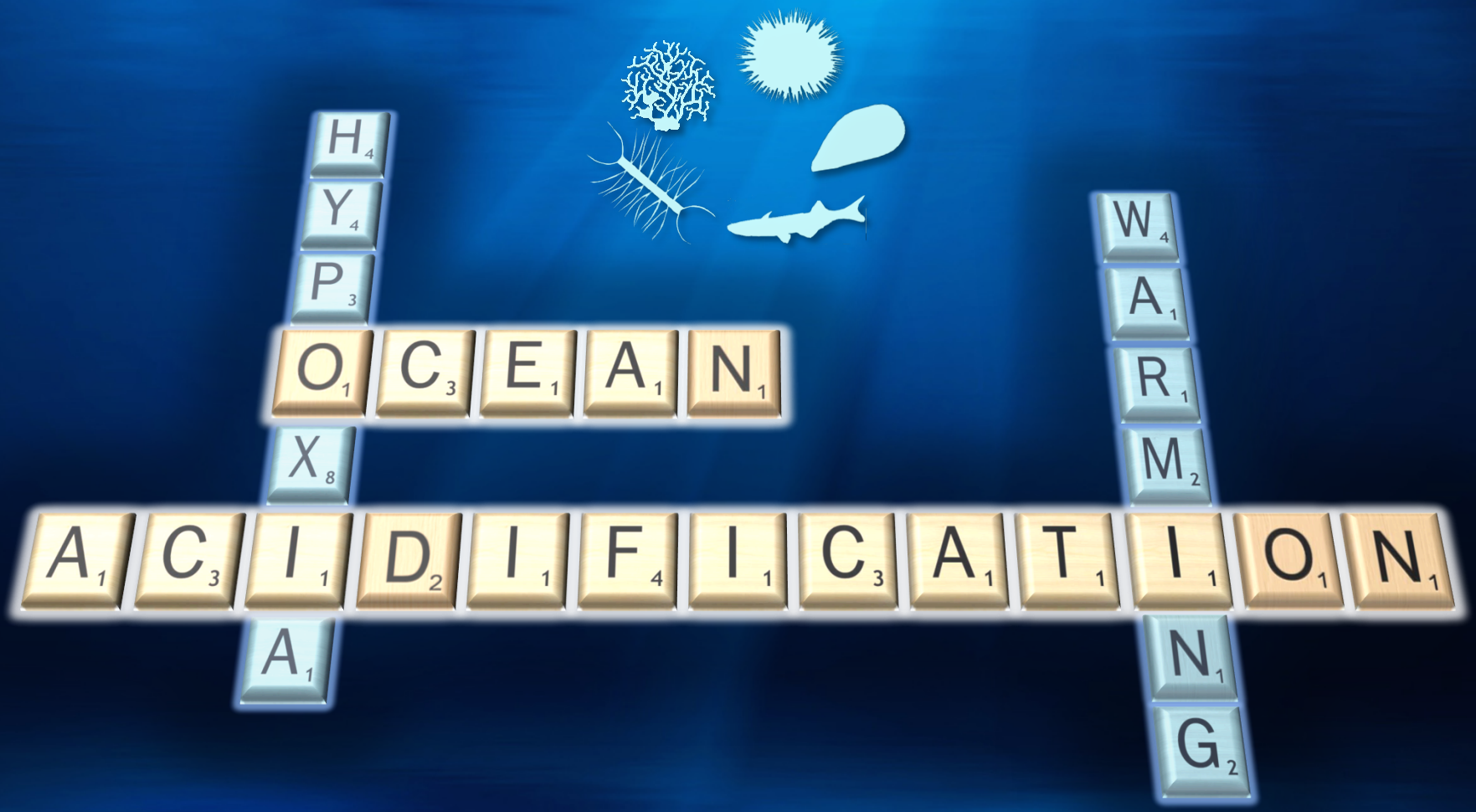
Responses of marine organisms to OA and co-stressors



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University of Connecticut

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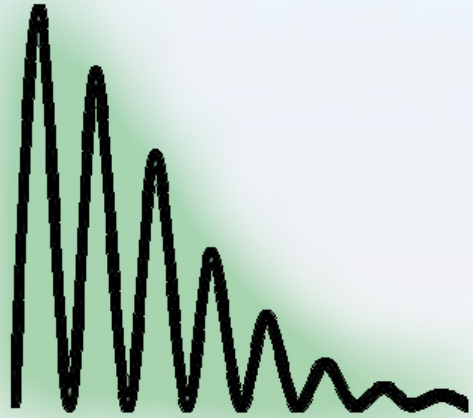
Virginia Institute of Marine Science

Three strawmen

- NOT all is lost.
- There IS reason to worry.
- We HAVE some tools.

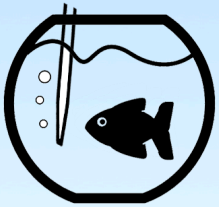
Methods

Multistressors



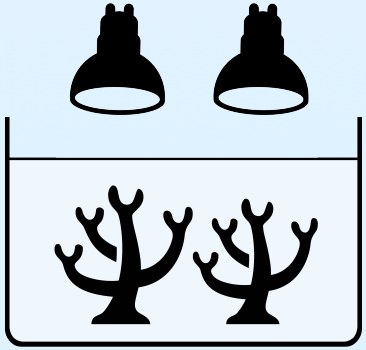
Variability

Mechanisms

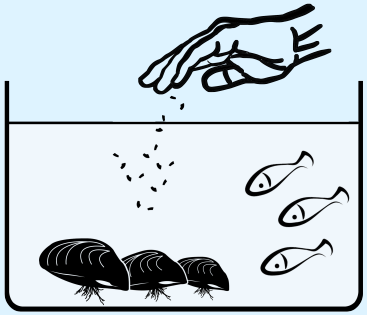


Experiment(er)s got better. Identified co-stressors and confounding effects

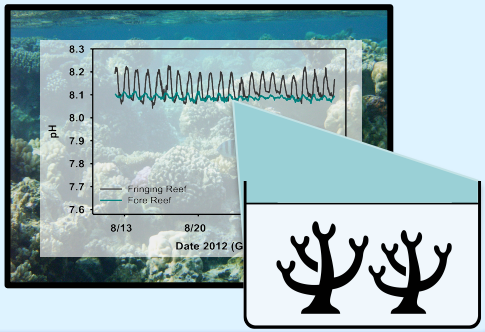
Light alters CO_2 sensitivity in corals



Food levels alter CO_2 sensitivity in mussels and fish



Environmental context is important for experimental design



Key papers

Randall & Tsui Mar Pol Bull 2002

Riebesell et al. Pub Europ Union 2011

Seibel et al. PLOS One 2012

Suggett et al. Coral Reefs 2013

Thomsen et al. Glob Change Biol 2013

Kroeker et al. Glob Change Biol 2013

McElhany & Busch Mar Biol 2013

Cornwall and Hurd ICES J Mar Sci 2015

Ramajo et al. Sci Rep 2016

Murray et al. ICES JMS 2017

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Duarte et al. Est Coasts 2013

Kelly et al. Glob Change Biol 2013

Murray et al. MEPS 2014

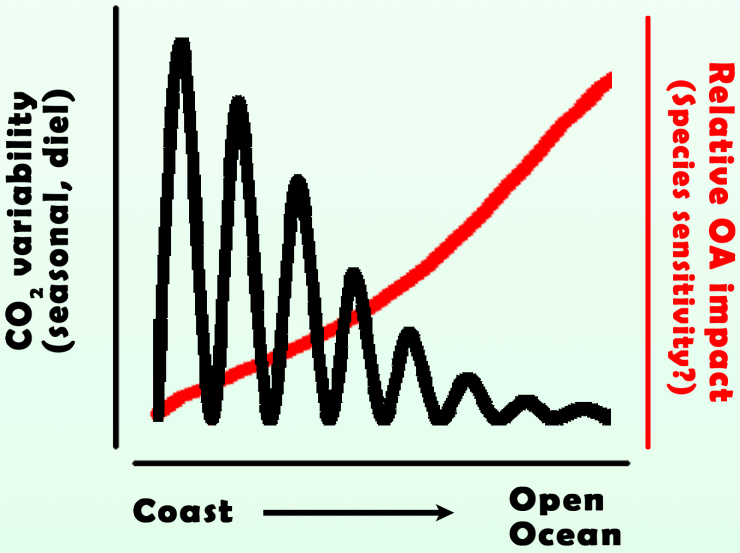
Munday F1000prime Reports 2014

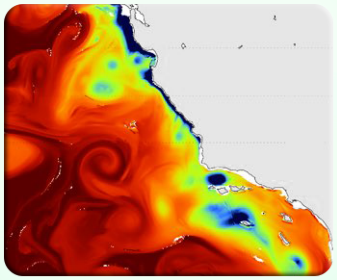
Thor & Dupont Glob Change Biol 2015

Barkley et al. Sci Adv 2015

Rivest et al. Curr Clim Change Rep 2017

Existing CO_2 variability matters. Winners & losers?





- CO_2 varies naturally in time and space
- Metabolic CO_2 fluctuations important
- Potential for local adaptation, acclimatization - intraspecific differences in CO_2 sensitivity
- Transgenerational plasticity likely, hence the parental environment matters

OA is just one symptom of Marine Climate Change.

- Warming
- Deoxygenation
- Acidification

- Byrne & Przeslawski: Additive negative effects most common (Temp × CO_2)
- Harvey et al. 2013, Przeslawski et al. 2015: Synergistic interactions are most common (Temp × CO_2)
- Early life stages are most susceptible.

Key papers

Pörtner et al J Geophys Res 2005

Darling & Cote Ecol Lett 2008

Harvey et al. Ecol Evol 2013

Byrne & Przeslawski ICB 2013

Kroeker et al. Glob Change Biol 2013

Ban et al. Glob Change Biol 2014

Wallace et al. Est Coast Shelf Sci 2014

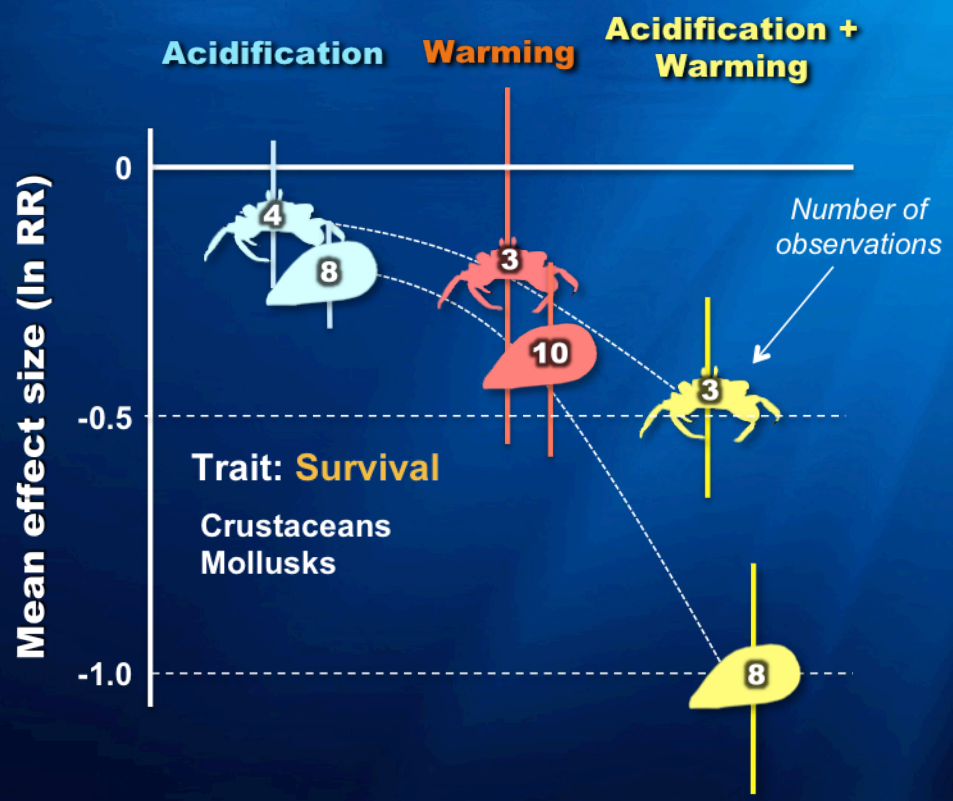
Przeslawski et al. Glob Change Biol 2015

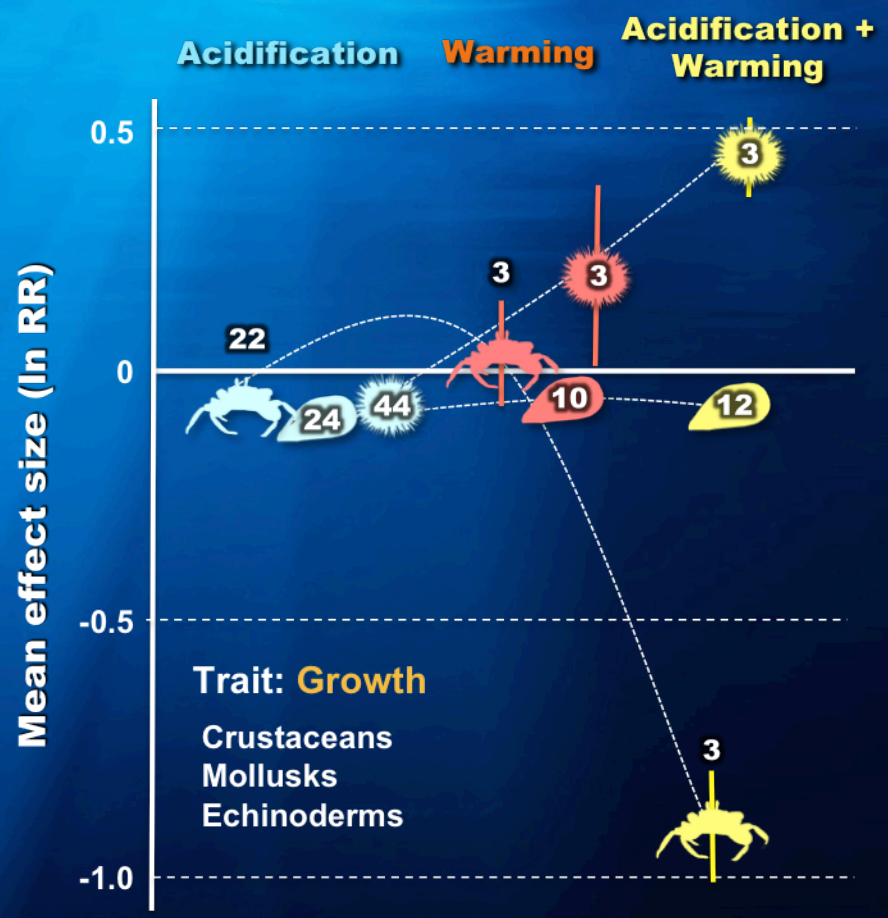
Breitburg et al. Oceanography 2015

Gobler & Baumann Biol Lett 2016

CO_2 × temperature: a meta-analysis

Combining empirical data across studies





- **Biological responses vary across taxa, stages, and trophic levels**
- **Combined stressors generally cause stronger (positive or negative) effects**

doi:10.1002/loe2.10002

OA is just one symptom of Marine Climate Change.

- **Warming**
- **Deoxygenation**
- **Acidification**

- Byrne & Przeslawski: Additive negative effects most common (Temp × CO_2)
- Harvey et al. 2013, Przeslawski et al. 2015: Synergistic interactions are most common (Temp × CO_2)
- Early life stages are most susceptible.
- **OA is more stressful to calcifying than non-calcifying larvae**
- **Gobler & Baumann: CO_2 × O_2 interactions mostly additive, some synergistic effects always found, scarce empirical evidence**

Key papers

Pörtner et al J Geophys Res 2005

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Todgham & Hofmann JEB 2009

Crawley et al. Glob Change Biol 2010

Nilsson et al. Nat Clim Change 2012

Pörtner MEPS 2012

Bignami et al. PNAS 2013

Waldbusser et al. Geophys Res Lett 2013

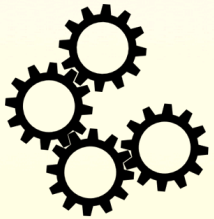
Waldbusser et al. Nat Clim Change 2015

Heuer & Grosell Am J Phys 2014, Sci Rep 2016

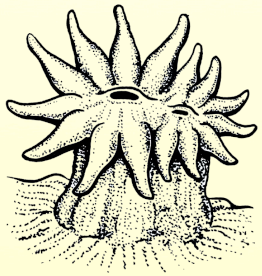
Ern et al. Biol Lett 2017

Esbaugh J Comp Physiol 2017

What does CO_2 actually do to organisms? Many answers.

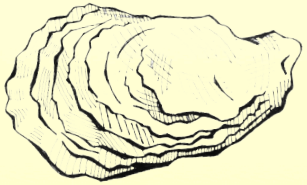


Physiological frameworks



Coral pH up-regulation may counter OA effects

CO_2? pH? Saturation state? What is the actual stressor for calcifiers?



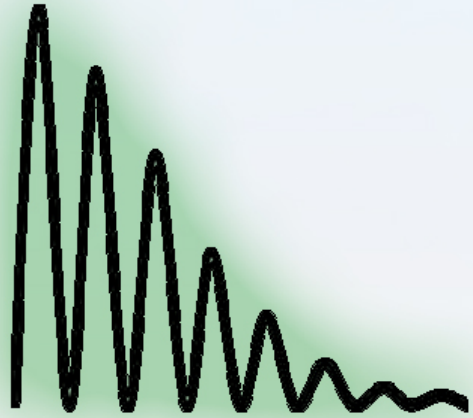
Insights into acid/ base regulation in fish and other marine organisms

Inhibition of a neurotransmitter causes behavioral effects in fish

$CO_2 \rightarrow$ GABA

Methods

Multistressors



Variability

Mechanisms

References

Ban SS, Graham NA, Connolly SR (2014) Evidence for multiple stressor interactions and effects on coral reefs. Glob Change Biol 20: 681-697.

Barkley HC, Cohen AL, Golbuu Y, Starczak VR, DeCarlo TM, Shamberger KE (2015) Changes in coral reef communities across a natural gradient in seawater pH. Science Advances 1: e1500328.

Bignami S, Enochs IC, Manzello DP, Sponaugle S, Cowen RK (2013) Ocean acidification alters the otoliths of a pantropical fish species with implications for sensory function. P Natl Acad Sci USA 110: 7366-7370.

Breitburg DL, Salisbury J, Bernhard JM, Cai W-J, Dupont S, Doney SC, Kroeker KJ, Levin L, Long WC, Milke LM, Miller SH, Phelan B, Passow U, Seibel BA, Todgham AE, Tarrant AM (2015) And on top of all that… Coping with ocean acidification in the midst of many stressors. Oceanography 28: 48-61.

Byrne M, Przeslawski R (2013) Multistressor impacts of warming and acidification of the ocean on marine invertebrates' life histories. Integrative and Comparative Biology 53: 582-596.

Crawley A, Kline DI, Dunn S, Anthony K, Dove S (2010) The effect of ocean acidification on symbiont photorespiration and productivity in *Acropora formosa*. Glob Change Biol 16: 851-863

Cornwall CE, Hurd CL (2016) Experimental design in ocean acidification research: problems and solutions. ICES J Mar Sci 73: 572-581.

Darling ES, Côté IM (2008) Quantifying the evidence for ecological synergies. Ecol Lett 11: 1278-1286.

Duarte CM, Hendriks IE, Moore TS, Olsen YS, Steckbauer A, Ramajo L, Carstensen J, Trotter JA, McCulloch M (2013) Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. Est Coast 36: 221-236.

Ern R, Johansen JL, Rummer JL, Esbaugh AJ (2017) Effects of hypoxia and ocean acidification on the upper thermal niche boundaries of coral reef fishes. Biol Letters 13: 20170135.

Esbaugh AJ (2017) Physiological implications of ocean acidification for marine fish: emerging patterns and new insights. J Comp Physiol B: 1-13.

Gobler CJ, Baumann H (2016) Hypoxia and acidification in marine ecosystems: Coupled dynamics and effects on ocean life. Biol Letters 12: 20150976.

Harvey BP, Gwynn-Jones D, Moore PJ (2013) Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecology and Evolution 3: 1016-1030.

Heuer RM, Grosell M (2014) Physiological impacts of elevated carbon dioxide and ocean acidification on fish. American Journal of Physiology-Regulatory, Integrative and Comparative Physiology 307: 1061-1084.

Heuer RM, Grosell M (2016) Elevated CO_2 increases energetic cost and ion movement in the marine fish intestine. Sci Rep 6: 34480.

Hofmann GE, Smith JE, Johnson, KS, Send U, Levin LA, Micheli F, Price NN, Peterson B, Takeshita Y, Matson PG, Crook ED, Kroeker KJ, Gambi MC, Rivest EB, Frieder CA, Yu PC, Martz TR (2011) High-frequency dynamics of ocean pH: a multi-ecosystem comparison. PLOS One 6: e28983.

Kelly MW, Padilla-Gamiño JL, Hofmann GE (2013) Natural variation and the capacity to adapt to ocean acidification in the keystone sea urchin *Strongylocentrotus purpuratus*. Glob Change Biol 19: 2536-2546.

Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM, Gattuso JP (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Change Biol 19: 1884-1896.

McElhany P, Busch DS (2012) Appropriate pCO_2 treatments in ocean acidification experiments. Mar Biol 160: 1807-1812.

Miller GM, Watson S-A, Donelson JM, McCormick MI, Munday PL (2012) Parental environment mediates impacts of increased carbon dioxide on a coral reef fish. Nature Clim Change 2: 858-861.

Munday PL (2014) Transgenerational acclimation of fishes to climate change and ocean acidification. F1000Prime Rep 6.

Murray CS, Fuiman L, Baumann H (2017) Consequences of elevated CO_2 exposure across multiple life stages in a coastal forage fish. ICES J Mar Sci 74: 1051-1061.

Murray CS, Malvezzi AJ, Gobler CJ, Baumann H (2014) Offspring sensitivity to ocean acidification changes seasonally in a coastal marine fish. Mar Ecol Prog Ser 504: 1-11.

Nilsson GE, Dixson DL, Domenici P, McCormick MI, Sorensen C, Watson S-A, Munday PL (2012) Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function. Nature Clim Change 2: 201-204.

Parker LM, Ross PM, O'Connor WA, Borysko L, Raftos DA, Pörtner H-O (2012) Adult exposure influences offspring response to ocean acidification in oysters. Glob Change Biol 18: 82-92.

Pörtner HO (2012) Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. Mar Ecol Prog Ser 470: 273-290.

Pörtner HO, Langenbuch M, Michaelidis B (2005) Synergistic effects of temperature extremes, hypoxia, and increases in CO_2 on marine animals: From Earth history to global change. J Geophys Res: Oceans 110: C09S10.

Przeslawski R, Byrne M, Mellin C (2015) A review and meta-analysis of the effects of multiple abiotic stressors on marine embryos and larvae. Glob Change Biol 21: 2122-2140.

Ramajo L, Pérez-León E, Hendriks IE, Marbà N, Krause-Jensen D, Sejr MK, Blicher ME, Lagos NA, Olsen YS, Duarte CM (2016) Food supply confers calcifiers resistance to ocean acidification. Sci Rep 6: 19374.

Randall D, Tsui T (2002) Ammonia toxicity in fish. Mar Pol Bull 45: 17-23.

Riebesell U, Fabry VJ, Hansson L, Gattuso JP (2011) Guide to best practices for ocean acidification research and data reporting. Publications Office of the European Union: 260.

Rivest EB, Comeau S, Cornwall, CE (2017) The role of natural variability in shaping the response of coral reef organisms to climate change. Curr Clim Change Rep 3: 271-281.

Seibel BA, Maas AE, Dierssen HM (2012) Energetic plasticity underlies a variable response to ocean acidification in the pteropod, *Limacina helicina antarctica*. PLoS ONE 7: e30464.

Suggett DJ, Dong LF, Lawson T, Lawrenz E, Torres L, Smith DJ (2013) Light availability determines susceptibility of reef building corals to ocean acidification. Coral Reefs 32: 327-337.

Thomsen J, Casties I, Pansch C, Körtzinger A, Melzner F (2013) Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. Glob Change Biol 19: 1017-1027.

Thor P, Dupont S (2015) Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. Glob Change Biol 21: 2261-2271.

Todgham AE, Hofmann GE (2009) Transcriptomic response of sea urchin larvae *Strongylocentrotus purpuratus* to CO_2-driven seawater acidification. J Exp Biol 212: 2579-2594.

Waldbusser GG, Brunner EL, Haley BA, Hales B, Langdon CJ, Prahl FG (2013) A developmental and energetic basis linking larval oyster shell formation to acidification sensitivity. Geophys Res Lett 40: 2171-2176.

Waldbusser GG, Hales B, Langdon CJ, Haley BA, Schrader P, Brunner EL, Gray MW, Miller CA, Gimenez I (2015) Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nature Clim Change 5: 273.

Wallace RB, Baumann H, Grear JS, Aller RC, Gobler CJ (2014) Coastal ocean acidification: The other eutrophication problem. Estuar Coast Shelf S 148: 1-13.