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# Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming

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## Abstract

Ocean acidification represents a threat to marine species worldwide, and forecasting the ecological impacts of acidification is a high priority for science, management, and policy. As research on the topic expands at an exponential rate, a comprehensive understanding of the variability in organisms' responses and corresponding levels of certainty is necessary to forecast the ecological effects. Here, we perform the most comprehensive meta-analysis to date by synthesizing the results of 228 studies examining biological responses to ocean acidification. The results reveal decreased survival, calcification, growth, development and abundance in response to acidification when the broad range of marine organisms is pooled together. However, the magnitude of these responses varies among taxonomic groups, suggesting there is some predictable trait-based variation in sensitivity, despite the investigation of approximately 100 new species in recent research. The results also reveal an enhanced sensitivity of mollusk larvae, but suggest that an enhanced sensitivity of early life history stages is not universal across all taxonomic groups. In addition, the variability in species' responses is enhanced when they are exposed to acidification in multi-species assemblages, suggesting that it is important to consider indirect effects and exercise caution when forecasting abundance patterns from single-species laboratory experiments. Furthermore, the results suggest that other factors, such as nutritional status or source population, could cause substantial variation in organisms' responses. Last, the results highlight a trend towards enhanced sensitivity to acidification when taxa are concurrently exposed to elevated seawater temperature.

*Keywords:* calcification, carbonate chemistry, climate change, cumulative effects, pH

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## Introduction

Ocean acidification is projected to impact all areas of the ocean, from the deep sea to coastal estuaries (Orr *et al*., 2005; Feely *et al*., 2009, 2010), with potentially wide-ranging impacts on marine life (Doney *et al*., 2009). There is an intense interest in understanding how the projected changes in carbonate chemistry will affect marine species, communities, and ecosystems (Logan, 2010; Gattuso & Hansson, 2011a). The rapidly growing body of experimental research on the biological impacts of acidification spans a broad diversity of marine organisms and reveals an even broader range of species' responses, from reduced calcification rates in oysters (e.g., Gazeau *et al*., 2007; Talmage & Gobler, 2010; Waldbusser *et al*., 2011) to impaired homing ability in reef fishes (Munday *et al*., 2009, 2010) to increased growth rates in macro algae (Hurd *et al*., 2009; Koch *et al*., 2013). Translating the wide range of responses to ecosystem consequences, management actions, and policy decisions requires a synthetic understanding of the sources of variability in species responses to acidification and the corresponding levels of certainty of the impacts.

Meta-analysis is a quantitative technique for summarizing the results of primary research studies. It provides a transparent method to identify key patterns across numerous studies, and can be used to develop hypotheses for future research. Furthermore, it can be a powerful tool for placing individual studies into the context of a broader field of research on a topic. While

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