Limnol. Oceanogr., 57(3), 2012, 698–710

doi:10.4319/lo.2012.57.3.0698

The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects

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Abstract
We report results from an oyster hatchery on the Oregon coast, where intake waters experienced variable carbonate chemistry (aragonite saturation state , 0.8 to . 3.2; pH , 7.6 to . 8.2) in the early summer of 2009. Both larval production and midstage growth (, 120 to , 150 mm) of the oyster Crassostrea gigas were significantly negatively correlated with the aragonite saturation state of waters in which larval oysters were spawned and reared for the first 48 h of life. The effects of the initial spawning conditions did not have a significant effect on early-stage growth (growth from D-hinge stage to , 120 mm), suggesting a delayed effect of water chemistry on larval development

Oceanography

Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. Oceanography 28(2):146–159

Barton, A., G.G. Waldbusser, R.A. Feely, S.B. Weisberg, J.A. Newton, B. Hales, S. Cudd, B. Eudeline, C.J. Langdon, I. Jefferds, T. King, A. Suhrbier, and K. McLaughlin. 2015.
http://dx.doi.org/10.5670/oceanog.2015.38.

Abstract
In 2007, the US west coast shellfish industry began to feel the effects of unprecedented levels of larval mortality in commercial hatcheries producing the Pacific oyster Crassostrea gigas. Subsequently, researchers at Whiskey Creek Shellfish Hatchery, working with academic and government scientists, showed a high correlation between aragonite saturation state (Ωarag) of inflowing seawater and survival of larval groups, clearly linking increased CO2 to hatchery failures. This work led the Pacific Coast Shellfish Growers Association (PCSGA) to instrument shellfish hatcheries and coastal waters, establishing a monitoring network in collaboration with university researchers and the US Integrated Ocean Observing System. Analytical developments, such as the ability to monitor Ωarag in real time, have greatly improved the industry's understanding of carbonate chemistry and its variability and informed the development of commercial-scale water treatment systems. These treatment systems have generally proven effective, resulting in billions of additional oyster larvae supplied to Pacific Northwest oyster growers. However, significant challenges remain, and a multifaceted approach, including selective breeding of oyster stocks, expansion of hatchery capacity, continued monitoring of coastal water chemistry, and improved understanding of biological responses will all be essential to the survival of the US west coast shellfish industry.

Annu. Rev. Mar. Sci. 2014. 6:221–47

Ocean Acidification in the Coastal Zone from an Organism's Perspective: Multiple System Parameters, Frequency Domains, and Habitats

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Abstract
Multiple natural and anthropogenic processes alter the carbonate chemistry of the coastal zone in ways that either exacerbate or mitigate ocean acidification effects. Freshwater inputs and multiple acid-base reactions change carbonate chemistry conditions, sometimes synergistically. The shallow nature of these systems results in strong benthic-pelagic coupling, and marine invertebrates at different life history stages rely on both benthic and pelagic habitats. Carbonate chemistry in coastal systems can be highly variable, responding to processes with temporal modes ranging from seconds to centuries. Identifying scales of variability relevant to levels of biological organization requires a fuller characterization of both the frequency and magnitude domains of processes contributing to or reducing acidification in pelagic and benthic habitats. We review the processes that contribute to coastal acidification with attention to timescales of variability and habitats relevant to marine bivalves.

PLOS ONE | DOI:10.1371/journal.pone.0128376 June 10, 2015

Ocean Acidification Has Multiple Modes of Action on Bivalve Larvae

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Abstract
Ocean acidification (OA) is altering the chemistry of the world's oceans at rates unparalleled in the past roughly 1 million years. Understanding the impacts of this rapid change in baseline carbonate chemistry on marine organisms needs a precise, mechanistic understanding of physiological responses to carbonate chemistry. Recent experimental work has shown shell development and growth in some bivalve larvae, have direct sensitivities to calcium carbonate saturation state that is not modulated through organismal acid-base chemistry. To understand different modes of action of OA on bivalve larvae, we experimentally tested how pH, PCO2, and saturation state independently affect shell growth and development, respiration

rate, and initiation of feeding in Mytilus californianus embryos and larvae. We found, as documented in other bivalve larvae, that shell development and growth were affected by aragonite saturation state, and not by pH or PCO2. Respiration rate was elevated under very low pH (~7.4) with no change between pH of ~ 8.3 to ~7.8. Initiation of feeding appeared to be most sensitive to PCO2, and possibly minor response to pH under elevated PCO2. Although different components of physiology responded to different carbonate system variables, the inability to normally develop a shell due to lower saturation state precludes pH or PCO2 effects later in the life history. However, saturation state effects during early shell development will carry-over to later stages, where pH or PCO2 effects can compound OA effects on bivalve larvae. Our findings suggest OA may be a multi-stressor unto itself. Shell development and growth of the native mussel, M. californianus, was indistinguishable from the Mediterranean mussel, Mytilus galloprovincialis, collected from the southern U.S. Pacific coast, an area not subjected to seasonal upwelling. The concordance in responses suggests a fundamental OA bottleneck during development of the first shell material affected only by saturation state.

Nature Climate Change – Articles **PUBLISHED ONLINE: 15 DECEMBER 2014 | DOI: 10.1038/NCLIMATE2479**

Saturation-state sensitivity of marine bivalve larvae to ocean acidification

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Abstract
Ocean acidification results in co-varying inorganic carbon system variables. Of these, an explicit focus on pH and organismal acid–base regulation has failed to distinguish the mechanism of failure in highly sensitive bivalve larvae. With unique chemical manipulations of seawater we show definitively that larval shell development and growth are dependent on seawater saturation state, and not on carbon dioxide partial pressure or pH. Although other physiological processes are a_ected by pH, mineral saturation state thresholds will be crossed decades to centuries ahead of pH thresholds owing to nonlinear changes in the carbonate system variables as carbon dioxide is added. Our findings were repeatable for two species of bivalve larvae could resolve discrepancies in experimental results, are consistent with a previous model of ocean acidification impacts due to rapid calcification in bivalve larvae, and suggest a fundamental ocean acidification bottleneck at early life-history for some marine keystone species.