Consequences of ocean acidification for North Atlantic larval bivalves

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SoMAS
The success of NY’s fisheries depends on the ability of marine animals to successfully calcify.
Consequences of ocean acidification for North Atlantic larval bivalves

Hard clam (*Mercenaria mercenaria*)
Eastern oyster (*Crassostrea virginica*)
Bay scallop (*Argopecten irradians*)
Acidification effects on bivalve larvae

~ 3 week larval cycle

Veliger
Pediveliger
Metamorphosed
Guide to best practices for ocean acidification research and data reporting
Methods: CO$_2$ treatments and measurements

- CO$_2$ / air mixed in gas proportionator to desired flow rates
- Experiments replicated with pre-mixed gases
- Desired CO$_2$ levels bubbled into replicated treatment vessels
- Constant temperature is maintained via circulating water bath
Methods: CO$_2$ measurements through analyzer

- Seawater was acidified in-line, delivered to a Liqui-Cel$^\text{®}$ and then bubbled with an inert gas (UHP Argon) which allows CO$_2$ to be stripped, and the gas phase (DIC) is read by the PP Systems$^\text{®}$ (EGM), environmental gas analyzer.

- pH measured using traditional electrodes, spectrophotometrically (Dickson et al. 2007), and by ion sensitive field effect transistors (Durafet; Martz et al 2010).

- Full recoveries of DIC and pH certified reference material (A.Dickson, Scripps Institution of Oceanography).

- Daily measurements of pH, dissociation constants (Roy et al. 1993), and DIC were used with CO$_2$ SYS to calculate a full suite of carbonate chemistry including CO$_2$, CO$_3^{2-}$ and $\Omega_{\text{aragonite}}$.
Methods for larvae:

- Larvae were distributed to each treatment beaker <24 hrs after fertilization.
- Larvae were fed daily and seawater was changed 2 - 3x a week.
- Every individual larva was counted on a grid at each water change and development stage was recorded.

Methods

- Broodstock shellfish were obtained from mesotrophic, NY coastal waters.
How does increased CO$_2$ effect the survival of larval bivalves?
The effects of elevated carbon dioxide concentrations on the metamorphosis, size, and survival of larval hard clams (Mercenaria mercenaria), bay scallops (Argopecten irradians), and Eastern oysters (Crassostrea virginica)

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Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish
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Edited by David M. Karl, University of Hawaii, Honolulu, HI, and approved August 31, 2010 (received for review December 3, 2009)

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Effects of Elevated Temperature and Carbon Dioxide on the Growth and Survival of Larvae and Juveniles of Three Species of Northwest Atlantic Bivalves
Stephanie C. Talmage, Christopher J. Gobler*

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Effects of CO₂ and the harmful alga Aureococcus anophagefferens on growth and survival of oyster and scallop larvae
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Elizabeth Depasquale and C.J. Gobler, in prep
Hard clam larvae, two-week survival, 400 – 900 ppm CO₂

- An increase of 100 ppm CO₂ yielded significant declines in Mercenaria larvae survivorship compared to ambient CO₂ conditions.

Talmage and Gobler, 2009
**Mercenaria mercenaria** larvae survival under past, present and future CO$_2$ levels

![Bar chart showing survival rates under different CO$_2$ levels.](chart)

- **Pre-Industrial**: 250 ppm, survival rate 60%
- **Current**: 390 ppm, survival rate 50%
- **Mid-century**: 750 ppm, survival rate 40%
- **Next-century**: 1500 ppm, survival rate 30%

Talmage and Gobler, 2010
Argopecten irradians survival under past, present and future CO₂ levels

The changes in CO₂ which have occurred in the past 200 years are capable of significantly depressing survival of clam and scallop larvae.

Talmage and Gobler, 2010
Elevated CO$_2$ yields higher larval bivalve mortality.

What are the secondary effects?
Mercenaria mercenaria, 36 day old juvenile scanning electron microscopy images
Mercenaria mercenaria, 36 day old juvenile scanning electron microscopy images

Pre-Industrial

~250 ppm, CO₂

~390 ppm, CO₂

~750 ppm, CO₂

~1500 ppm, CO₂

Present

~250 ppm, CO₂

~390 ppm, CO₂

~750 ppm, CO₂

~1500 ppm, CO₂

Mid Century

~250 ppm, CO₂

~390 ppm, CO₂

~750 ppm, CO₂

~1500 ppm, CO₂

Next Century

~250 ppm, CO₂

~390 ppm, CO₂

~750 ppm, CO₂

~1500 ppm, CO₂
<table>
<thead>
<tr>
<th>Mercenaria mercenaria, 36 day old juvenile scanning electron microscopy images</th>
</tr>
</thead>
</table>
| Pre-Industrial  
| ~250 ppm, CO₂  
| ![Image](a)  
| ![Image](b)  
| ![Image](c)  |
| Present  
| ~390 ppm, CO₂  
| ![Image](a)  
| ![Image](b)  
| ![Image](c)  |
| Mid Century  
| ~750 ppm, CO₂  
| ![Image](a)  
| ![Image](b)  
| ![Image](c)  |
| Next Century  
| ~1500 ppm, CO₂  
| ![Image](a)  
| ![Image](b)  
| ![Image](c)  |
Mercenaria mercenaria, 36 day old juvenile scanning electron microscopy images
Secondary effects of elevated CO₂ on larval bivalves include significant \( (p<0.05) \) reductions in (Talmage and Gobler 2009, 2010, 2011, 2012, in prep):

1) Size,
2) Thickness,
3) Shell integrity,
4) Shell morphology,
5) Rate of metamorphosis,
6) Lipid content,
7) RNA:DNA,
8) Calcification rate.

What are the longer term implications of larval exposure to high or low CO₂ for juvenile bivalve growth?

Larval stage CO₂ exposure $\rightarrow$ Juvenile stage grow-out, ‘normal conditions’

$\sim 250, 390, \& 750 \text{ ppm}$

Ambient, in-situ

Growth of juveniles bay scallops monitored for 10-months.
Long term growth of *Argopecten irradians*

- The legacy of three week larval exposure is evident 10 months later

Talmage and Gobler, in prep
Shallow coastal ecosystems: multiple stressors

Pristine conditions • Anthropogenically impacted

Estuaries already experience:
• Acidification
• Hypoxia
• Thermally stressful conditions
• Suboptimal food, harmful algae
Temperature and CO$_2$ with *Mercenaria mercenaria*

![Graph showing survival rates at different CO$_2$ levels and temperatures.](image)

- High levels of CO$_2$ coupled with high temperature additively reduce larval survival.

Talmage and Gobler, 2011
Coastal waters are acidifying; harmful algal blooms are becoming more common.

What are the combined effects of these stressors on bivalve larvae?
Harmful algae and CO₂ with *Argopecten irradians*

- Harmful algae coupled with elevated CO₂ can synergistically suppress larval bivalve survival beyond elevated CO₂ alone.

Talmage and Gobler, 2012
- Hypereutrophic estuaries (e.g. Jamaica Bay, NY, USA) are already **acidic and hypoxic**.

- Surface waters (0.5m), mid-day, October 2011.
How does acidification and hypoxia impact the metamorphosis and survival of larval bivalves?
Differential effects of acidification and hypoxia on the survival and metamorphosis of larval bay scallops, *Argopecten irradians*.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH</th>
<th>Dissolved oxygen (mg L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>8.07 ± 0.05</td>
<td>8.17 ± 1.14</td>
</tr>
<tr>
<td>Hypoxic</td>
<td>8.12 ± 0.02</td>
<td>1.04 ± 0.35</td>
</tr>
<tr>
<td>Acidic</td>
<td>7.62 ± 0.05</td>
<td>8.22 ± 0.99</td>
</tr>
<tr>
<td>Hypoxic &amp; acidic</td>
<td>7.64 ± 0.04</td>
<td>1.29 ± 0.38</td>
</tr>
</tbody>
</table>

Percent metamorphosis, one month:
- pH: p<0.1
- DO: p<0.0001
- pH x DO: p<0.005

Percent survival, one month:
- pH: p<0.001
- DO: p<0.05
- pH x DO: p=0.86

Gobler et al, in prep
Inter-species comparison of bivalve larval susceptibility to acidification
Meta-analysis: Declines in survival under high CO$_2$ ($\sim$1,500 ppm) for Eastern oysters, hard clams, and bay scallops

<table>
<thead>
<tr>
<th>Species</th>
<th>% Decline in Survival under high CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. virginica Eastern oyster</td>
<td>10</td>
</tr>
<tr>
<td>M. mercenaria Hard clam</td>
<td>25</td>
</tr>
<tr>
<td>A. irradians Bay scallop</td>
<td>50</td>
</tr>
</tbody>
</table>

Gobler et al, in prep
Inter-stage comparison of bivalve susceptibility to acidification
Larval bivalves are more sensitive to high CO$_2$ than juveniles

Gobler et al, in prep
Negative impacts of elevated CO₂ on mollusk larvae:

21+ studies; 15+ species as of early 2012

- Bechmann et al. (2011), *Mytilus edulis* (mussel)
- Gaylord et al. (2011), *Mytilus californianus* (mussel)
- Gazeau et al. (2010), *Mytilus edulis* (mussel)
- Gazeau et al. (2011), *Crassostrea gigas* (oyster)
- Kurihara et al. (2007), *Crassostrea gigas* (oyster)
- Kurihara et al. (2008), *Mytilus galloprovincialis* (mussel)
- Miller et al. (2009), *Crassostrea virginica* (oyster)
- Parker et al. (2009, 2011, 2012), *Saccostrea glomerata* (oyster)
- Parker et al. (2010), *Crassostrea gigas* (oyster)
- Watson et al. (2009), *Saccostrea glomerata* (oyster)
- Byrne et al. (2011), *Haliotis coarctata* (abalone)
- Ellis et al. (2009), *Littorina obtusata* (snail)
- Kimura et al. (2011), *Haliotis discus hannai* (abalone)
- Zippay and Hofmann (2010), *Haliotis rufescens* (abalone)
Larval bivalve shells are made of highly soluble amorphous calcium carbonate, $\Omega_{\text{ACC}}$ is lower and more important than $\Omega_{\text{aragonite}}$ for larval shellfish (Weiss et al 2002).
Reduced early life growth and survival in a fish as a direct response to elevated CO$_2$ levels. Bauman, Talmage and Gobler, 2012.

![Graph showing the relationship between CO$_2$ concentration and survival percentage, with a correlation coefficient $r^2 = 0.56$.]

![Graph showing the relationship between CO$_2$ concentration and standard length, with a correlation coefficient $r^2 = 0.95$.]

Inland silversides, *Menidia beryllina*
Conclusions:

- The changes in CO₂ which have occurred in the past 200 years are capable of significantly depressing survival of some bivalve larvae.

- Secondary effects of elevated CO₂ on larval bivalves include reductions in size, shell thickness, shell integrity, rates of metamorphosis, lipid content, RNA:DNA ratios, and calcification rates.

- The legacy effect of larval CO₂ exposure on juvenile growth is detectable 10 months post-metamorphosis.

- Estuarine stressors such as hypoxia, elevated temperatures, and harmful algal blooms combine with acidification to worsen outcomes for larval bivalves.

- The sensitivity of bivalve larvae to elevated CO₂ varies by species.

- Larval bivalves are more sensitive to high CO₂ than juvenile stages.
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