SYNTHESIS OF THRESHOLDS OF OCEAN ACIDIFICATION EFFECTS ON PELAGIC MOLLUSKS

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Challenges in Using Ocean Plan for OA

Use biologically relevant endpoints!

Complex process - How to go about this?
Biologically–Relevant Acidification Endpoints: Key Questions

• Which taxa to select? What habitats do they represent?

• What is temporal basis for thresholds? Consider magnitude, duration and frequency of exposure

• How do we deal with multiple stressors?

• How can we translate this information from individual to population level effects?
A Key Graphic that Shows Ranges of Response

- No observed effect (natural variability)
- Resistance Threshold: Initial Point of Decline, Following Region of No Observed Effect
- Sublethal Response (Physiological Response)
- Exhaustion Threshold: Inflection point of decline, after which response is exhausted
- Lethal Response

Population level effects

Decreasing OA conditions
### Selection of Three Focal OA Taxa and Their Habitats

<table>
<thead>
<tr>
<th>Taxa</th>
<th>Habitat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pteropods</td>
<td>Pelagic Calcifying Zooplankton (0-500 m)</td>
</tr>
<tr>
<td>Echinoderms</td>
<td>Shallow to deep-water; pelagic and epibenthic ecological importance</td>
</tr>
<tr>
<td>Crustaceans</td>
<td>Shallow to deep-water pelagic and epibenthic’ commercial importance</td>
</tr>
</tbody>
</table>
Why Pteropod as Focal Taxa?

- Pteropods satisfy all the parameters in the decision criteria
  - Pelagic indicators
  - Extreme sensitivity to OA (shell dissolution)
  - Wide-spread distribution and ecosystem role
We Have This Key Graphic for Pteropods!

6 Thresholds with Magnitude and Duration

How did we arrive at this graphic?
We Are Undertaking a Synthesis of Thresholds
With a 4-step Approach

Sequential steps:
• Data collection and literature review
• Meta-analyses
  – simplification of the responses, exclusion or combination of responses
• Breakpoint analyses
  – Identification of thresholds
• Expert consensus
1st Step: Data Collection and Literature Review

• Global data compilation and synthesis to identify:
  – Which stress response measures are reported?
  – Which OA parameter best described stress response measure?
  – Confounding factors (life history, species)
We Have An Abundance of Data Supporting Derivation of Pteropods Thresholds

Pteropod responses to Ocean Acidification:

• 18 studies and 3k data points

• 22 different response measures!
Aragonite Saturation State Identified as the Best Measure of OA Stress

• Which OA measure to use?
• All of experiments measured responses against $\Omega_{ar}$
  – experts confirmed that this is the best measure of stress response

• The range of experimental conditions represent the existing gradients in the CCS
### Compiled Studies Featured 22 Various Response Measures

<table>
<thead>
<tr>
<th></th>
<th>Type of effect</th>
<th>Response Measure</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exposure</td>
<td>Individuals affected by dissolution</td>
<td>%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Surface Shell Dissolution</td>
<td>%</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Deeper shell dissolution</td>
<td>%</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Transmittance</td>
<td>%</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Opacity</td>
<td>%</td>
</tr>
<tr>
<td>7</td>
<td>Physiological</td>
<td>Calcification as % Glow</td>
<td>%</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Growth: diameter</td>
<td>mm</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Growth: percent</td>
<td>%</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Larval Growth</td>
<td>µm</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Eggs Produced</td>
<td>#·individual⁻¹</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Development Impairment</td>
<td>%</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Egg organogenesis</td>
<td>%</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Shell Length</td>
<td>µm</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>Dry mass</td>
<td>µg</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Diameter</td>
<td>µm</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>Swimming Capacity</td>
<td>cm·s⁻¹</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Calcification</td>
<td>µmol CaCO₃·(g*h)⁻¹</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Respiration</td>
<td>µmol O₂·(mg WW*h)⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>µmol O₂·(g DW*h)⁻¹</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Excretion Rate</td>
<td>µmol N·(g DW*h)⁻¹</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>Gut Clearance</td>
<td>1·h⁻¹</td>
</tr>
<tr>
<td>25</td>
<td>Lethal</td>
<td>Larval Survival</td>
<td>%</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>Survival</td>
<td>%</td>
</tr>
</tbody>
</table>

- Abundance, but...great complexity!
- Different measure for the same category of effects
- Different units
- Reduce down the amount of response measures
  - What to exclude or combine?
Meta-analyses Simplifies the Complexity of Responses

What is it?
• Statistical technique that summarizes the results of primary studies, and identify patterns across the large variable datasets.

We used it for:
• Evaluate robustness and signal:noise ratio of response measure
  — Eliminate some (insignificant) response measure
  — Combine others
• Evaluate the influence of confounding parameters (life stage, duration, species…)
  — Combine or consider separately in threshold analyses?
Meta-analyses: How is It Done?

1) Raw data separated and transformed into a common currency, called ‘effect size’ \((\text{LnRR})\)
2) Assign confidence intervals
Meta-analyses: Interpretation of the Results?

Estimation of the
- Significance
- Direction of response
- Magnitude

Step 2: Meta-analyses
Majority of Response Measures Were Negatively Impacted by OA

- Significant negative LnRR response to OA ($\Omega_{ar}$)
- Across exposure, physiological and lethal response
- Measures not significant were excluded from next steps
Life Stage and Regional Differences Contribute to Variability of Responses

- Adults were less sensitive than larvae and juveniles
  - Important for threshold interpretation within the life history context
- Regional differences play a role
  - Experts only combined regional data when justified

Step 2: Meta-analyses
Break-point and Changepoint Analyses
We Need Some Understanding of Thresholds

Increasing OA Stress → Biological Response Measure

- Ideal scenario
- Discernible change in magnitude under stress
- Steep gradient

Increasing OA Stress → Biological Response Measure

- Not easily discriminated
- Statistical analyses
- Endpoint in biological response (Y-axis) corresponding to the acceptable level of stress (X-axis)

Step 3: Breakpoint Analyses

- 50% mortality
- ** Acceptable level of Stressor

change in magnitude
Break-point and Changepoint Analyses Provide Preliminary Thresholds from Lab and in situ Studies

• Identified breakpoint before significant change in data: lowest observed effects (LOE) from experimental studies

• When possible, validate experimentally-derived LOE with the field-derived data to reduce uncertainty
Expert Consensus Was The Final Ingredient in Synthesis

• Seven pteropod experts from across the globe
• Several steps:
  – reviewed the thresholds & meta-analyses
  – Voting on the importance of particular response measure
  – Rating of the thresholds (iterative process)
  – Solidify the Consensus
Expert Consensus Used IPCC Confidence Scale Approach to Assign Rating to Threshold

Based on IPCC methodology (Mastrandea et al., 2010)
Dissolution Measures Had the Greatest Confidence, and Survival the Lowest

Not just thresholds but also confidence score related to threshold. Ranging from very high (dissolution) to very low (egg development and survival).
Thresholds Can Be Applied to Model Output to Visualize Potential Habitat As Risk

- An example of the use of thresholds during an upwelling season

Grid: 60 variable depth levels
Next Steps on Expert Synthesis

• Global review completed for echinoderms and crustaceans
  – Even more data available than for pteropods!
  – Echinoderms: 40 studies, 13k datapoints
  – Crustaceans: 19 studies, 10K datapoints

• Completed threshold analyses for echinoderms

• Currently conducting meta-analyses for echinoderms and crustaceans

• Workshop planned for fall 2018 and spring 2019
Similarity in parameters (life stage and taxa) with pteropods
Difference in OA parameter
Application of Single Stressor Thresholds is Challenging in Our Dynamic Ocean Environment

• So we know we can get to univariate thresholds with a straightforward, consensus-based process…

• But, applying them in the ocean can be more complicated.
  – OA, temperature and DO co-vary, results can be additive, synergistic, or antagonistic
  – How do we account for multiple stressor effects on habitat?

Take home message: We need additional tools to assist with interpretation of thresholds under multiple stressors.
HSIs are statistical models that define relationship between environmental gradients and species abundance or P/A

- Combination of mechanistic or empirical approach
- Can be used to describe nonlinear (interactive) relationship with multiple stressors
- Predict habitat suitability

- We have an example such tool for pteropods now…
What are inputs?

- **Mechanistic model**: Experimental data from multiple-stressor experiments (OA, thermal stress)
- **Empirical model**: Field data
  - time series of pteropods along the US West Coast on abundance and environmental parameters for almost entire decade combined with physical-chemical data
  - One of the largest spatial dataset (NOAA WCOA cruises)
Experimental results directly applied to HSI

- **Mechanistic model**
- We used experiments to provide evidence of OA-T stress
  - Single stressor: partial survival
  - Combined: complete mortality
- Translated these two experimental parameters as drivers of *in situ* mortality
Conceptual Representation of Habitat Compression from Two Interactive Stressors

- Observed P/A in the T-OA space closely follows 50% mortality line
- HSI change when adding an additional stressor
- Transition from one threshold under univariante stressors to a mortality line as indicator of P/A under multiple stressors
Our HSI successfully predicts pteropod distribution

- We found high habitat suitability Index in the north; low in the South (HIS)
- We can start predicting population level effects based on the suitable habitat
HSI Application in the high resolution model output

Most suitable

50% Mortality

Least suitable
Biologically-Based Assessment Endpoints for Pollution Impact on OA in the SCB: Take Home Messages

• We have a **key graphic** of synthesized thresholds for pteropods
  – We went through a 4-step process with experts to get this consensus
  – Work on echinoderms is advancing rapidly
  – These thresholds can be used to interpret monitoring and model output

• We have developed HSI statistical model to consider how multiple stressors impact available habitat
  – We can use the model to **visualize habitat compression**
  – Empirical model helps us translate OA thresholds from **individual to population level effects**

• Numerous applications ongoing—Martha will talk about one of them.
Which Taxa To Use?

We Have Criteria for Selection of Taxa

- Nearshore, far-ranging distribution
- Sensitivity to OA or/and low oxygen impacts
- Representative Habitat, e.g.
  - Pelagic
  - Soft bottom
  - Rocky reef
- Mode of impact
  - E.g. Calcifier versus Non-calcifier
  - Life stage consideration
- Data availability
- Management endpoint: Valuable role in ecosystem or commercially important