Are Population-level Effects of Hypoxia on Fish Truly Small or Larger but Elusive?

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Preface

• Basic question: Does hypoxia affect fish at the population level?

• What I am about to say is based on my collaborations with many people

• However, the opinions are mine and not vetted nor endorsed by my collaborators

• My background and training is fisheries and modeling
  – Optimize death
  – Does not bother me to see dead fish
  – But I rarely touch them
  – Contrast with a conservation philosophy
Today

- Preface (done)
- Hypoxia and fish populations
- Why important
- Why field determination is so difficult
- Modeling
- Model-by-model
- View from 10,000 feet
- My conclusions
Hypoxia and Fish

- Hypoxia is increasing in coastal waters (Diaz and Rosenberg 2008)
- Indicates potential eutrophication issues
  - Over-enrichment
  - HABs
  - Ecosystem health
- Conceptual models of more nutrients eventually resulting in reduced demersal then pelagic fish

At first, seems fine
COMPARATIVE EVALUATION OF FISHERY ECOSYSTEMS RESPONSE TO INCREASING NUTRIENT LOADING

- Oligotrophic
- Mesotrophic
- Eutrophic
- Dystrophic

SE. NORTH SEA
N. GULF OF MEXICO
N. ADRIATIC SEA
GREAT LAKES
KATTEGAT
BALTIC SEA
SETO INLAND SEA
YELLOW SEA
N.W. BLACK SEA
CHESAPEAKE BAY

AZOV (55)

NUTRIENT LOADING

Caddy 2000

Diaz 2001, modified and redrawn from Caddy 1993
Hypoxia and Fish

• Cross system comparisons have shown fishery production (catch) increases with increasing nutrient loadings (Caddy 1993; Nixon and Buckley 2002)

• But gets complicated because space for time substitution and no clear link to hypoxia effect (Breitburg et al. 2009)

Starts get murky
Hypoxia and Fish

• Sedentary organisms
  – No doubt they are killed

• Laboratory effects
  – Many experiments
  – Foraging, growth, mortality, avoidance
  – Forced exposure

• Localized effects in nature
  – Habitat compression
  – Displacement

We are still good
Hypoxia and Fish

• Fish kills
  – Visually seems like must have an effect
  – Remember, these are large number populations

• Case studies
  – Baltic, Black, Azov Seas
  – Even these are debated (Daskalov 2003; Oguz, 2005)

• Intuition
  – Maps of massive hypoxia areas must have an effect

Empirical evidence getting weak
Hypoxia and Fish

• Population level effects

• First, definition of population
  – “A group of organisms of one species that interbreed and live in the same place at the same time”
  – Unit stock
  – Management unit

• Hypoxia affects many individuals but not automatic that hypoxia has population impacts

• Conventional wisdom

Houston, we have a problem
“Because hypoxia often occurs in estuaries or near shore areas where the water is poorly mixed, nursery habitat for fish and shellfish is often affected. Without nursery grounds the young animals cannot find the food or habitat they need to reach adulthood. This causes years of weak recruitment to adult populations and can result in an overall reduction or destabilization of important stocks.... The most serious effects of hypoxia on fisheries are probably: longterm weakening of species also stressed by overfishing, habitat loss, longterm changes in ecology, and economic losses.... This situation is detrimental not only for ecosystems but for fishermen who rely on these resources for their livelihood and for consumers who look forward to bountiful fish and shellfish harvests.”
"A 2008 study found more than 400 dead zones around the world, and the Gulf of Mexico's is one of the largest. Snaking along the Louisiana and Texas coasts, the expanding Gulf Dead Zone has drastically reduced seafood stocks and pushed fishers further out to sea."

The Gulf of Mexico's Dead Zone is among the world's largest—and corn is one of the culprits

by Chris Kromm, July 7, 2010, INDYweek.com

"While scientists have yet to measure the impact of the zone on fishing yields, fishermen say they already feel its effects as they are forced to travel ever farther to escape the zone's barren limits. "This is a very serious issue," said Jim Giattina, director of the Gulf of Mexico Program office at the Stennis Space Center in Mississippi. Giattina said the gulf boasts an annual catch of 1.7 billion pounds of fish and shellfish, worth $26 billion. "We've seen what can happen in other places in the world," he said. "We don't want to see a collapse of this fishery."

A 'Dead Zone' Grows in the Gulf of Mexico

by Carol Kaesuk Yoon

Copyright 1998 by The New York Times
O'Connor and Whitall (2007) recently stated in their introduction that “hypoxia is now recognized as one of the most significant threats to fisheries production worldwide”.

Chesney and Baltz (2001) concluded that “the exploited nekton are able to tolerate the effects of hypoxia without obvious major consequence for their recruitment, production, or population health”, and that “it is also likely that currently other anthropogenic impacts, such as the direct and indirect effects of fishing, have more significant consequences for the production of nekton populations in the Gulf of Mexico”. 
Why Important?

• Reducing nutrients may be worthwhile
  – Water quality
  – HABs

• No doubt hypoxia has effects
  – On individuals, often many individuals
  – Sessile organisms
  – Lakes and reservoirs
Why Important?

• Presenting the correct reasons and rationale is critical

• Need to know for effective management and planning
  – Determination of remediation actions
  – Effects of fishing and other stressors
  – The public values fish (for better or worse)
Why Field Determination of Effects on Fish is Difficult?

• Complex life cycles mean multiple habitats are used, which prevents comprehensive data collection

• Population affected by multiple factors that vary together and have interactive effects

• Offsetting effects across life stages
Why Field Determination of Effects on Fish is Difficult?

• Separation of hypoxia effects from other factors is difficult

• [Rose’s] Uniqueness principle in ecology
  – Each study, location, and year are special cases

• Thus, we turn to modeling……..
Modeling

• Allows for systematic evaluation of multiple factors in a controlled world

• But, also relies heavily on:
  – Judgment in model building (scaling, processes)
  – Calibration and validation
  – Spatial aspects (e.g., movement)
  – Modelers dilemma: “can never validate a model because if truly did then no need for the model”
<table>
<thead>
<tr>
<th>Scales</th>
<th>Biological</th>
<th>Temporal</th>
<th>Spatial</th>
<th>DO Effects</th>
<th>Hypoxia</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>A One individual</td>
<td>One box</td>
<td>Hourly 6 months</td>
<td>One box</td>
<td>Gonadotropin suppression</td>
<td>Forced 2.7</td>
<td>Yolk production</td>
</tr>
<tr>
<td>B Eggs, larvae 1-5 d cohorts</td>
<td>3 layers</td>
<td>Daily June, July</td>
<td>~2 bottom layer</td>
<td>Move; M and G</td>
<td>~2 bottom layer</td>
<td>Survival</td>
</tr>
<tr>
<td>C Juvenile individuals</td>
<td>2-D grid 100 m²</td>
<td>2 hour summer</td>
<td>M on prey; C, M, move</td>
<td>0.5 to 5 Normoxic perimeter</td>
<td>Survival Biomass</td>
<td></td>
</tr>
<tr>
<td>D Food web Larvae, zoop, cteno</td>
<td>3 layers</td>
<td>12 h (d/n) summer</td>
<td>Move; M and G</td>
<td>1.5 bottom 3 pycnocline</td>
<td>Laval survival</td>
<td></td>
</tr>
<tr>
<td>E 6-species food web</td>
<td>2-D 1 m</td>
<td>Hourly One yr</td>
<td>Move; G, M, and Fec</td>
<td>2-4 lower</td>
<td>Production by species</td>
<td></td>
</tr>
<tr>
<td>F Individual Population</td>
<td>3-D Hydro/WQ</td>
<td>Minutes 10 yrs</td>
<td>M on zoop; Move; M and G</td>
<td>20-40% decrease in volume</td>
<td>YOY survival Pop biomass</td>
<td></td>
</tr>
<tr>
<td>G Individual Population</td>
<td>2-D 1 km</td>
<td>Hourly 140 yrs</td>
<td>Move; Fec, G, and d-d M</td>
<td>Low, medium, severe maps</td>
<td>Size at age Fecundity Abundance</td>
<td></td>
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# Model: Sources

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<td>B</td>
<td>Adamack, Rose, Breitburg, Nice, and Lung (in press) Simulating the effect of hypoxia on bay anchovy egg and larval mortality using coupled watershed, water quality, and individual-based predation models. MEPS.</td>
</tr>
<tr>
<td>C</td>
<td>Craig, Rose, and Rice (in prep.)</td>
</tr>
</tbody>
</table>
Kolesar, Rose, and Breitburg (draft) Hypoxia effects within an intraguild predation food web of *Mnemiopsis leidyi* ctenophores, larval fish, and copepods. |
Sable and Rose (draft) An individual-based model of a tidal marsh community: model description, corroboration, and application for scaling individual-level effects to population-level responses. |
| F | Aaron Adamack (2007) Predicting water quality effects on bay anchovy (*Anchoa Mitchilli*) growth and production in Chesapeake Bay: linking water quality and individual-based fish models. PhD dissertation, LSU. |
| G | Sean Creekmore (2011) Modeling the population effects of hypoxia on Atlantic croaker (*Micropogonias undulatus*) in the Northwestern Gulf of Mexico. MS thesis, LSU. |
Model-by-Model (A)

Gonadotropin (driving)

pituitary

Synthesis T (GtH)

Estradiol (x2)

Testosterone (x1)

ovary

Estradiol (T)

SBP (x3)

SBP (x3)

Estrogen Receptor

Estradiol

Estrogen Receptor (x6)

Vitellogenin (x8)

blood

k1

k-1

k1

k-1

k1

k-1

k1

k-1

k2

k-2

k1

k-1
Model-by-Model (A)

- Lab - 61.8% reduction in fecundity
- Total Estradiol (pg/mL)
- Baseline 2.7 mg/L
- Lab - 59% reduction in Total E2

- Time (months)
- Vitellogenin (mg/mL)
- Lab - 61.8% reduction in fecundity
Model-by-Model (B)

Watershed Model

Water Quality Model

Pycnocline Detection Algorithm

Wet Year

Dry Year

Individual-Based Model

Shading indicates DO
Model-by-Model (B)

**Mortality**

- **Capture rate adjustment**
  - **Sea nettle**: Red bars
  - **Ctenophore**: Blue bars

**Dissolved oxygen (mg liter^{-1})**

**Egg mortality (fraction dying)**

- **0.00**
- **0.25**
- **0.50**
- **0.75**
- **1.00**

**Growth**

- **Growth rate adjustment**
- **Bay anchovy larvae**
- **Bay anchovy eggs**

**Proportional Distribution**

- **Ctenophores**
- **Sea nettles**

**Bottom DO (mg/L)**

- **Surface**
- **Pycnocline**
- **Bottom**

**Bottom DO (mg/L)**
Model-by-Model (B)

1-day egg mortality (%) - Segment 34

Chesapeake Bay boundary condition
- 0.5x
- Baseline
- 1.5x

7-day larval mortality (%) - June date
Model-by-Model (C)

- Initialize environment
- Initialize fish cohort
- Update environment
- Update fish cohort
- Movement
- Growth
- Mortality
- Next fish
- Next 2 hours
- End of Summer

Survival Size Distribution

~5 km ~35 km
upstream downstream

~26 km

“time loop”

“fish loop”
Model-by-Model (C)

- Shimp et al. (2005)

- DO (mg O₂ l⁻¹)

- Growth (%d⁻¹)

- Mortality

- Probability of Survival

- Day of Year

- DO (mg/L)

- McNatt and Rice (2004)

- Growth

- DO (mg O₂ l⁻¹)

- 25°C

- 30°C
Model-by-Model (C)

- Direct Mortality
- Direct Growth
- Direct Mortality and Growth
- Direct and DD Growth
- Direct and Size Mortality
- All

Percent of Baseline Biomass

Low Recruitment
High Recruitment
Zooplankton

Acartia tonsa

LC$_{50} = 0.95 – 1.4$ mg / L

Fish Larvae

LC$_{50} = 1 – 2$ mg / L

Ctenophores

100% survival

DO $\geq 0.5$ mg / L

72 h

Surface 6 mg/L

Pycnocline 3

Bottom 1.5
Model-by-Model (D)

Intraguild Predation

Relaxed Competition

Relaxed Predation
Model-by-Model (D)

Baseline IGP

Relaxed Predation

Relaxed Competition

Larval Fish

Ctenophores

Adult Copepods

Ordinal Day

Number / m$^3$

0 2 4 6 8 10 12

0 2000 4000 6000 8000 10000 12000

High DO

Low DO

0 1 2 3 4 5 6

0 160 180 200 220 240
Model-by-Model (D)

The graph shows the number of larvae surviving to 15 mm under different conditions. The x-axis represents the days to 15 mm, and the y-axis represents the number of larvae surviving to 15 mm.

- **High DO** and **Low DO** conditions are compared for each scenario.
- **Baseline** scenario shows a lower number of larvae surviving compared to the other scenarios.
- **Relaxed Predation** and **Relaxed Competition** scenarios show higher survival rates compared to the Baseline.

The graph indicates that under relaxed conditions (predation or competition), larvae have a higher chance of surviving to 15 mm compared to baseline conditions.
Model-by-Model (E)

- Channel
  - Baseline DO Cycles
  - DO Stress Cycles
  - Rising and High Tide
  - Falling and Low Tide

- Tidal Creeks and Marsh Edge
  - Rising and High Tide
  - Falling and Low Tide

- Marsh Interior and Pools
  - High Tide
  - Rising and Falling Tide
  - Low Tide

Dissolved Oxygen (mg/L)
Model-by-Model (E)

Growth rates of all species
Fecundity of resident species

Bay Anchovy
Zooplankton (2 groups)
Silversides

Sheepshead Minnow
Benthos (3 groups)

Shrimp
Killifish

Blue Crab

Conditions
Dissolved O₂
Temperature
Tidal stage
Prey density
Predator density
Individual size

Individual Processes
Growth
Movement
Mortality
Spawning
Model-by-Model (E)

Total Abundance (x10^4)

- Inland Silverside
- Bay Anchovy
- Sheepshead Minnow
- Gulf Killifish
- Blue Crab

Days: 0 50 100 150 200 250 300 350

Total Abundance (x10^5)

- Grass Shrimp

Dissolved Oxygen

- Baseline Low
- Degraded Habitat

Total Annual Production (grams wet weight y^-1 x10^3)

- Grass Shrimp
- Sheepshead Minnow
- Silverside
- Gulf Killifish
- Blue Crab

- Baseline Habitat
- Degrade Habitat

- Dissolved Oxygen
- Baseline Low
- Dissolved Oxygen
- Baseline Low

- Baseline Low
- Dissolved Oxygen
- Baseline Low
- Dissolved Oxygen

- Baseline
- Low

- Baseline
- Low

- Baseline
- Low

- Baseline
- Low

- Baseline
- Low
3D hydrodynamic model (CH3D), eutrophication model (CE-QUAL-ICM), and sediment diagenesis model

Simulates 24 constituents
- Forms of N, P, and Si
- Algae and zooplankton
- DO and temperature

Bay is divided into 4073 cells
- 729 surface cells
- Minimum 2 layers thick
- Maximum 15 layers thick
Model-by-Model (F)
Zooplankton
(Normal Year, July, high recruitment)
Model-by-Model (F)

**Decreased nutrient loading**

- **Biomass (1000's metric tonnes)**
- **Survival to October (percent)**

- **Direct effects**
- **No direct effects**

**Increased nutrient loading**

- **Biomass (1000's metric tonnes)**
- **Survival to October (percent)**

- **Dry**
- **Normal**
- **Wet**
Model-by-Model (G)

- Full life cycle
- Hourly processes
  - Growth
  - Mortality
  - Reproduction
  - Movement
- Daily temperature, chlorophyll-a, DO
Model-by-Model (G)

Data from Stierhoff et al. (2006)
Model-by-Model (G)

*scenario: 1 = mild, 2 = intermediate, and 3 = severe

- Average age 2+ abundance for model years 61-100 ranged from 87-89% of baseline abundance
Model-by-Model (G)

• A 31% reduction in average long-term abundance

• Many exposed a little
  – 23% of age-1 and 60% of age-2 individuals on Sept 1 were ever exposed to DO < 4.0 mg/L for at least one hour

• Very few exposed a lot
  – On any hour, a maximum of 5% exposed, and usually <1%

• Small effects on processes
  – <3% of incoming age-1 and age-2 died from hypoxia
  – Eggs per gram and per individual decreased by <5%
  – No detectable change (<2%) in weight-at-age
View from 10,000 Feet

• Responses larger in simpler models
  – Forced exposure on one fish (A)
  – 1-day egg and 7-day larval cohorts (B)
  – Once add avoidance, responses smaller
  – “flexibility” results in small responses

• More feedbacks and indirect pathways, the smaller the main effects but larger the interaction and indirect effects
View from 10,000 Feet

• Indirect and interaction effects

• Offsetting effects across life stages (egg vs larva in B)

• Form of growth and mortality (DD and size in C)

• Hypoxia effects amplified by other conditions (recruitment in C), but not always (competition and predation in D)

• Multi-species food web (winners and losers in E)
View from 10,000 Feet

• Masked by other factors
  – Higher production with worse hypoxia (hidden foregone production in F)

• Accumulation of subtle effects
  – Widespread low exposure but very low percent high exposure and small changes in growth and fecundity (G)
  – Required decades to accumulate (G)
Other Models

- My look at other modeling analyses either supports or does not contradict these conclusions

- For example, growth rate potential (Brandt and Mason 2003; Constaninini et al 2008; Ludsin et al 2009)

- NOAA’s CHRP and NGOMEX
My Conclusions

• Exposure is critical
  – Behavior
  – Avoidance
  – Fluctuating DO
  – Many individuals exposed a little (precision)

• Consequences of being forced to move to less optimal habitat
  – Community ecology has failed us
My Conclusions

• On a typical year, hypoxia generally has small effects on coastal fish populations
  – Notable exceptions but they are exceptions

• Population effects can be moderate to large under certain conditions

• Arise from indirect accumulated effects
My Conclusions

• Often, effects are masked by variation in other factors (detectability versus presence)

• Wrong to infer hypoxia effects can be ignored

• Indeed, very important to quantify the effects
  – “hidden costs”
  – Lost year-classes
  – Distort population responses, especially when large episodic effects
Where do we go from here?

• We (Thomas, Creekmore, Rahman, Craig) are continuing the modeling and data collection for (G)

• Diurnal DO effects in Chesapeake Bay (Breitburg et al. CHRP)

• Others (e.g., Roman et al. NGOMEX)
Where do we go from here?

- Modeling Summit
  - First, the modelers – devil in the details
  - Then everyone
  - Previous workshops focused on other topics

- Time for a synthesis paper on population level effects of hypoxia on coastal species
Preparation documents sent to review panel members for the Gulf of Mexico Red Snapper stock assessment
“Mr. Osborne, may I be excused? My brain is full.”

“You should check your e-mails more often. I fired you over three weeks ago.”
Kid Scoop Puzzler

How many of these see-through fish can you find?

24

Standards Links: Reading Comprehension: Follow simple written directions.

Overcoming The FIVE DYSFUNCTIONS of a TEAM

A FIELD GUIDE

FOR LEADERS, MANAGERS, AND FACILITATORS

PATRICK LENCIONI

AUTHOR OF DEATH BY MEETING

Based on the New York Times best-seller The Five Dysfunctions of a Team
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