Developing Macrobenthic Indicators of Organic Enrichment and Hypoxia for the Coastal Mississippi Hypoxic Zone

Chet F. Rakocinski and Daneen P. Menke

Department of Coastal Sciences
University of Southern Mississippi
Background
Detrimental consequences of eutrophication threaten ecosystem function and fisheries production in coastal regions around the world (Diaz 2001) and the occurrence and severity of hypoxia has increased exponentially since the 1960’s (Diaz and Rosenberg 2008).
Global Distribution of Eutrophic Dead Zones

Fig. 1. Global distribution of 400-plus systems that have scientifically reported accounts of being eutrophication-associated dead zones. Their distribution matches the global human footprint [the normalized human influence is expressed as a percent (41)] in the Northern Hemisphere. For the Southern Hemisphere, the occurrence of dead zones is only recently being reported. Details on each system are in tables S1 and S2.

This eventual decline reflects the impaired functional capacity of the ecosystem to process potential food resources under oxygen limitation (Xu et al. 1999).

Massive amounts of trophic potential are ultimately redirected into the microbial food web by severe hypoxia and anoxia (Diaz and Rosenberg 2008).

Organic enrichment and hypoxia (or anoxia) are concomitant outcomes of eutrophication in coastal ecosystems, where excessive organic matter is engendered through the stimulatory effects of nutrient loading on primary production (Diaz and Rosenberg 2008).


**Fig. 1.** Distribution of benthic infaunal successional stages along gradient of increasing environmental disturbance (from left to right) (after Pearson & Rosenberg 1978), and associated benthic-habitat quality (BHQ) index (Nilsson & Rosenberg 1997). Sediment-profile images assigned to successional stage are shown above the general model (colours digitally enhanced); oxidised sediment is rust-brown, and reduced sediment grey or black. Bottom graph illustrates generalised changes in species, abundance, and biomass (after Pearson & Rosenberg 1978).
Species-Specific Effects of Low DO

Functional Biodiversity of Benthic Fauna

Table 2. Main functions of species (with codes) used in experiments. B: Baltic; S: Skagerrak

<table>
<thead>
<tr>
<th>Species</th>
<th>Code</th>
<th>Function</th>
<th>Area</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halicryptus spinulosus</td>
<td>Hs</td>
<td>Burrowing, predator, gallery builder</td>
<td>B</td>
<td>Powilleit et al. (1994)</td>
</tr>
<tr>
<td>Macoma balthica</td>
<td>Mb</td>
<td>Burrowing, surface deposit feeder, biodiffuser</td>
<td>B</td>
<td>Karlson et al. (2005)</td>
</tr>
<tr>
<td>Abra nitida</td>
<td>An</td>
<td>Burrowing, surface deposit feeder, biodiffuser</td>
<td>S</td>
<td>Maire et al. (2006)</td>
</tr>
<tr>
<td>Marenzelleria neglecta</td>
<td>Mn</td>
<td>Deep burrowing, sub-surface deposit feeder</td>
<td>B</td>
<td>Karlson et al. (2005)</td>
</tr>
<tr>
<td>Amphiura chiajei</td>
<td>Ac</td>
<td>Burrowing, surface deposit feeder</td>
<td>S</td>
<td>Buchanan (1967)</td>
</tr>
<tr>
<td>Echinocardium cordatum</td>
<td>Ec</td>
<td>Burrowing, sub-surface deposit feeder, biodiffuser</td>
<td>S</td>
<td>Lohrer et al. (2005)</td>
</tr>
<tr>
<td>Calocaris macandreae</td>
<td>Cm</td>
<td>Deep burrowing, sub-surface deposit feeder</td>
<td>S</td>
<td>Nash et al. (1984)</td>
</tr>
</tbody>
</table>

Macrobenthic responses to organic enrichment and hypoxia

- **Top panel** = normoxia
- **Middle panel** = organic enrichment
- **Bottom panel** = severe hypoxia

- Nutrient loading and water column stratification can deprive bottom-dwelling organisms of oxygen

- Resulting shifts in macrobenthic structure and function are reflected by community diversity, stage of succession, and size distributions

- Inset graphs depict corresponding changes in size distributions of macrobenthic communities

(Figure devised using Integration and Application Network (IAN) symbol library; University of Maryland Center for Environmental Science (UMCES))
Coastal macrobenthic communities provide effective indicators of biotic integrity, but discerning anthropogenic from natural stress is tricky.

The ‘Estuarine Quality Paradox’ (Elliott and Quintino 2007) recognizes that the interpretation of macrobenthic indices can be difficult because:

- eurytoulent resident organisms are adapted to dynamic physical conditions and naturally high organic loading
- detection of anthropogenic stress may be further obscured by the use of structural metrics, like taxonomic diversity and the use of indicator taxa

Estuarine indicators should embrace metrics that can:

- be causally linked to specific stressors
- be broadly applied across different habitats and regions
- convey ecosystem function

Linking macrobenthic indicators to ecosystem function

- Organic enrichment attended by hypoxia typically engenders depauperate macrobenthic communities consisting of small-bodied short-lived opportunistic organisms.

- Body-size constrains various allometric processes that scale up from the individual to the ecosystem level of organization.

- Thus, macrobenthic indicators based on allometric scaling should also reflect effects of organic enrichment and hypoxia.

- Macrobenthic process indicators are designated as those comprising metrics with some tractable connection to body size.

- Macrobenthic process indicators have not often been used as indicators of organic enrichment and hypoxia.

- An assortment of macrobenthic process indicators is available from the literature, including:
  - Production potential
  - Production: Biomass ratio (P:B; inverse of faunal turnover rate)
  - Normalized biomass-size spectra (NBBS)
NGI Study
Routine NGI sampling line from St. Louis Bay out to CenGOOS buoy site

- Benthic sampling in conjunction with the NOAA-NGI USM monitoring study along an onshore-offshore transect running between Saint Louis Bay and the western-most CenGOOS buoy

- Integrated sampling of macrobenthic process indicators on the Mississippi Bight will afford:
  1. Extended sample space for examining process indicators;
  2. Temporally intensive picture of macrobenthic responses to hypoxia;
  3. Information for ecosystem based management of the MS coastal region

- Extensive area off Mississippi coast experienced severe chronic hypoxia in summer 2008
Objectives

- Elucidate how macrobenthic function may be impaired by hypoxia within the Mississippi Bight area
  - Examine a suite of indicators and functional traits relative to the occurrence of hypoxia on the 10 m and 20 m isobaths
  - Examine the recovery process in terms of indicators and functional traits
  - Compare the benchmark USEPA Benthic Index for the Gulf of Mexico with the macrobenthic process and functional indicators
  - Interpret macrobenthic responses relative to environmental data gathered through efforts of other participating investigators
Measuring Macrobenthic Process Metrics

(1) Volume from area - Squash plate calibration

(2) Wet mass from volume - Conversion factor

(3) Dry mass from wet mass - Conversion factor

(4) Daily production potential - Allometric scaling from per individual dry mass

(5) Aggregate production potential - Accumulated and scaled to per m² area

(6) Turnover rate - Ratio of total dry mass to the daily production potential
Macrobenthic Metrics from Spring 2008 to Summer 2009 at Site 6

**Production Potential at 30° C**
Site 6 - 10 m isobath

<table>
<thead>
<tr>
<th>Month</th>
<th>May 08</th>
<th>Jun 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>mg m⁻² d⁻¹ (mean ± se)</td>
<td>250 ± 10</td>
<td>150 ± 5</td>
</tr>
</tbody>
</table>

**Mean Individual Wet Mass**
Site 6 - 10 m isobath

<table>
<thead>
<tr>
<th>Month</th>
<th>May 08</th>
<th>Jun 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean mg wet mass (mean ± se)</td>
<td>12 ± 2</td>
<td>8 ± 1</td>
</tr>
</tbody>
</table>

**Community Turnover Rate at 30° C**
Site 6 - 10 m isobath

<table>
<thead>
<tr>
<th>Month</th>
<th>May 08</th>
<th>Jun 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>days at 30° C</td>
<td>80 ± 5</td>
<td>60 ± 4</td>
</tr>
</tbody>
</table>

**Total Abundance**
Site 6 - 10 m isobath

<table>
<thead>
<tr>
<th>Month</th>
<th>May 08</th>
<th>Jun 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number m⁻² x 100 (mean ± se)</td>
<td>35 ± 5</td>
<td>15 ± 2</td>
</tr>
</tbody>
</table>
Normalized biomass-size spectra from Spring 2008 to Spring 2009 at site 6.
Benthic Index and Diversity from Spring 2008 to Summer 2009 at site 6

**Benthic Index at 30 ppt**
Site 6 - 10 m isobath

- May 08
- Jul 08
- Nov 08
- May 09
- Jun 09

**Shannon Wiener Diversity**
Site 6 - 10 m isobath

- May 08
- Jul 08
- Nov 08
- May 09
- Jun 09
Numerical Dominants from Spring 2008 to Spring 2009 at site 6

- May 2008: Number = 1,134
- July 2008: Number = 52
- November 2008: Number = 129
- May 2009: Number = 487

- Ampharetidae
- Amphipoda
- Balanoglossus sp.
- Bivalvia
- Cossura delta
- Capitellidae
- Maldanidae
- Paraprionospio pinnata
- Others
Biomass Dominants from Spring 2008 to Spring 2009 at site 6

- **Balanoglossus sp.**
- **Limnopherus ambiguus**
- **Cerianthidae**
- **Diopatra cuprea**
- **Eupolymnia sp.**
- **Maldanidae**
- **Scoletoma verrilli**
- **Speocarcinus lobatus**
- **Paraprionospio pinnata**
- **Sigambra spp.**
- **Others**

May 2008
Wet mass m⁻² = 91.27 g

July 2008
Wet mass m⁻² = 2.46 g

November 2008
Wet mass m⁻² = 6.30 g

May 2009
Wet mass m⁻² = 15.66 g
Preliminary Conclusions about Macrobenthic Indicators

- Macrobenthic process indicators convey different perspectives on changes in the trophic status of the benthic subsystem relative to the effects of and the recovery from severe hypoxia on the Mississippi Bight;

- The conventional Benthic Index is less consistent than the process and functional indicators for conveying the condition of the macrobenthic community relative to the effects of and the recovery from severe hypoxia on the Mississippi Bight;

- Considerations of functional traits of dominant macrobenthic constituents relative to the effects of and the recovery from severe hypoxia lends insights into the mediating role played by tolerant organisms, as characterized by apparent adaptations to hypoxic conditions.
Linking Macrobenthic Process Indicators to Hypoxia
Peters Mass Balance Simulation Model

Simulation model: “to predict the movement of material through the ecosystem as a function of time and ecosystem size structure”

- Size of each $W_i$ box represents the biomass of size class $i$
- Allometric terms for $I$, ingestion, $R$, respiration, $D$, egestion, $M$, mortality, and $G$, production
- Eventually, an equilibrium biomass-size distribution is reached
- Mediating environmental factors include organic enrichment, dissolved oxygen (DO), temperature, food quantity, and food quality

Adapted from Peters 1983
The Ecological Implications of Body Size

Mediating Factors
Organic Enrichment
Dissolved Oxygen
Temperature
Food Quantity
Food Quality

- $R_i$: Respiration
- $D_i$: Decomposition
- $G_i$: Growth
- $M_i$: Mortality
- $I_i$: Ingestion
- $W_i$: Biomass of size class $i$
Body-size is a fundamental ecological attribute because it underpins vital rates that can be scaled up to the ecosystem level through allometric rules.

A basic tenet of 'metabolic ecology'.

Allometric scaling of vital rates in the Peters mass balance model (PMBM) is based on the “\( \frac{3}{4} \) scaling rule.”

Coefficients used from the Greisbach, Peters, and Youakim 1982 version of the model.

Vital rates expressed in g mass g\(^{-1}\) d\(^{-1}\).

---

**The Peters Mass Balance Model Terms**

\( W_i \) = average individual body mass in g

\( B_i \) = standing biomass for organisms of size \( W_i \)

\( I_i \) = Ingestion; \( 0.033 \ W_i^{-0.25} \)

\( R_i \) = Respiration; \( 0.010 \ W_i^{-0.25} \)

\( G_i \) = Production; \( 0.010 \ W_i^{-0.25} \)

\( D_i \) = Defecation; \( 0.013 \ W_i^{-0.25} \)

\( M_i \) = Mortality; \( (\frac{B_i^F}{\sum B_i^F}) \sum I_i \)

\( \sum I_i \) = food requirements for the animal community
Hypothesis:

- Owing to design considerations related to high surface:volume (i.e., uptake) and less branching of transport networks, small aquatic organisms can attain much higher mass-specific OCR than large organisms.

- But ironically, large organisms might have greater ability than small ones to regulate OCR under declining DO, because it is difficult for small organisms to sustain high weight-specific OCR.

- The ratio of the OCR curve parameters, b/a, conveys the capacity for metabolic regulation.

- For this simulation, b/a is scaled internally and symmetrically, from 0.5 to 2, across the 8 size classes.

---

Incorporating DO Limitation:

- For the simulation, two 32d scenarios were composed from continuous DO and temperature conditions in summer 2005 at two sites in East Bay, Florida.

- Missing data in the 32d series were patched with cloned data to obtain complete representative series.

- Fifteen minute intervals were aggregated into hourly observations for model calculations.

- Although the PB5 scenario exhibits wide daily DO fluctuations and frequent low DO values, it seldom dips into hypoxia.

- However, conditions are hypoxic most of the time for the PB1 scenario.

- Macrofaunal data used in the simulation came from PB1 in late spring 2004, before the onset of seasonal hypoxia.
The upper graph depicts biomass-size distribution outputs from two PMBM runs. The constrained biomass-size distribution experienced the 32 d PB5 scenario at the end of the 732 d period. The reference biomass-size distribution represents the same point in time without any DO limitation (i.e., 732 d with 100% Ingestion).

Overall, biomass is reduced and large size classes are relatively better represented under DO Limitation. The lower graph shows the difference between constrained and reference outputs in terms of normalized biomass size spectra (NBSS).

Note that the largest size class shifts up slightly, while the other size classes shift downward to a greater extent with size.
Biomass-Size Distribution after 32 d of DO Limitation – PB1 scenario

The upper graph depicts biomass-size distribution outputs for reference and PB1 scenarios within the PMBM.

The effects of ingestion deficits are even greater when the community is subjected to the 32d PB1 scenario.

Total biomass is reduced to a greater extent than in the PB5 scenario, and differences are accentuated progressively with decreasing body size.

The lower graph shows the difference in terms of NBSS between PB1 and reference scenarios.

Note that the size classes progressively shift downward with decreasing size more than in the PB5 scenario.
Thank You!