1. Increased nutrient loading results in increased incidence or size of hypoxia
2. Behavioral and physiological responses to hypoxia by individual organisms
   a) nekton
   b) zooplankton
   c) epibenthos
   d) benthic organisms
3. Benthic community response to hypoxia
4. Commercial fisheries species response to hypoxia
   a) menhaden
   b) shrimp
   c) other large nekton
5. Sea turtle and marine mammal responses to hypoxia
6. Food web responses to hypoxia or to causes of hypoxia
   a) by primary producer community
   b) by secondary producer or higher
   c) jellyfish
7. Officer and Ryther's [1980] prediction supported (regarding Si:N loading ratio)
8. Evidence for rapid decline in resource after period of gain (a catastrophic decline)
9. Societal recognition of the effects of hypoxia on fisheries
   a) recognize possible effects
   b) implemented management to reduce nutrient loading
Evidence of Increased Diatom production, as N ↑
Evidence of Silica Limitation, as Si↓ & Si:N of 1:1

Shifts from Heavily Silicified Diatoms

To Lightly Silicified Diatoms

& Non-Silicified, Flagellates

Si:N
>1 Sinking Diatoms Persistent Hypoxia
+1 Non-sinking Diatoms Seasonal Hypoxia
Non-Diatoms Sporadic Harmful Algal Blooms
Non-Diatoms Frequent Harmful Algal Blooms
<1 Non-sinking Diatoms Algal Blooms

(Turner & Rabalais 1994; Turner et al. 1998; Dortch et al. 2001)
(Qureshi & Rabalais 2001)
Copepods

(Number/Liter)

Month*

Mar Apr May Jun Jul Aug Sep Surf.

Depth*

6m 14m Bott.

Copepod Nauplii

(Number/Liter)

Month*

Mar Apr May Jun Jul Aug Sep Surf.

Depth*

6m 14m Bott.

(Qureshi and Rabalais 2001)
Copepod Nauplii

(Qureshi and Rabalais 2001)
Jellyfish abundance: an indicator of altered food webs

*Aurelia* moon jelly

Source: M. Graham, DISL
Jellyfish abundance:
an indicator of altered food webs

from: Purcell et al. 2001
Copepods

Chrysaora

Mnemiopsis

Bottom Water Dissolved Oxygen (mg/l)

(Purcell et al. 2001)
### TABLE 1. Behavioral and physiological responses of different organisms to hypoxia.

<table>
<thead>
<tr>
<th>Organism</th>
<th>Response to Hypoxia</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shrimp</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Penaeus aztecus</em></td>
<td>detect and avoid</td>
<td>Renaud, 1986</td>
</tr>
<tr>
<td><em>Penaeus setiferus</em></td>
<td>detect and avoid</td>
<td>Renaud, 1986</td>
</tr>
<tr>
<td><em>Penaeus monodon</em></td>
<td>decrease hemocyte phagocytosis</td>
<td>Direkbusararakom &amp; Danayadol, 1998</td>
</tr>
<tr>
<td><em>Penaeus stylirostris</em></td>
<td>decrease total hemocyte count</td>
<td>Le Mouillac et al., 1998</td>
</tr>
<tr>
<td></td>
<td>increased mortality induced by <em>Vibrio alginolyticus</em></td>
<td>Le Mouillac et al., 1998</td>
</tr>
<tr>
<td><strong>Crabs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Callinectes sapidus</em></td>
<td>detect and avoid</td>
<td>Das &amp; Stickle, 1994</td>
</tr>
<tr>
<td></td>
<td>increase oxygen consumption</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td>decrease feeding</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td>reduce growth rate</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td><strong>Acute Hypoxia</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>increase ventilation rate</td>
<td>Batterton &amp; Cameron, 1978</td>
</tr>
<tr>
<td></td>
<td>increase heart rate</td>
<td>deFur &amp; Pease, 1988</td>
</tr>
<tr>
<td></td>
<td>slight increase in cardiac output</td>
<td>deFur &amp; Pease, 1988</td>
</tr>
<tr>
<td></td>
<td><strong>Chronic Hypoxia</strong></td>
<td></td>
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<tr>
<td></td>
<td>decrease oxygen consumption</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td>no change in ventilation</td>
<td>deFur &amp; Pease, 1988</td>
</tr>
<tr>
<td></td>
<td>no change in heart rate</td>
<td>deFur &amp; Pease, 1988</td>
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<tr>
<td></td>
<td>increase hemocyanin O₂ affinity and concentration</td>
<td>deFur et al., 1990</td>
</tr>
<tr>
<td><em>Callinectes similis</em></td>
<td>detect and avoid</td>
<td>Das &amp; Stickle, 1994</td>
</tr>
<tr>
<td></td>
<td>increase oxygen consumption</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td>decrease feeding</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td><strong>Gastropod Molluscs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Stramonita haemastoma</em></td>
<td>reduce growth rate</td>
<td>Das &amp; Stickle, 1993</td>
</tr>
<tr>
<td></td>
<td>large reduction in metabolism</td>
<td>Liu et al., 1990</td>
</tr>
<tr>
<td></td>
<td><strong>Bivalved Molluscs</strong></td>
<td>decrease oxygen consumption</td>
</tr>
<tr>
<td><em>Crassostrea virginica</em></td>
<td>switch to anaerobic metabolism</td>
<td>Stickle et al., 1989</td>
</tr>
<tr>
<td></td>
<td>small reduction in metabolism</td>
<td>Stickle et al., 1989</td>
</tr>
<tr>
<td></td>
<td>decrease production of reactive oxygen species</td>
<td>Boyd &amp; Burnett, 1999</td>
</tr>
</tbody>
</table>

(Burnett and Stickle 2001)
Nekton

Demersal invertebrates

Epibenthic invertebrates

Larger infauna

Macro-infauna

(mg O₂ l⁻¹)

2.0

1.5

1.0

0.5

0.2

0.05

Most present

Most present

Present

Present & burrowed

Present & burrowed

Absent

Few mantis & penaeid shrimp

Stressed (starfish, brittle stars)

Dead

Dead

(fish kills)

Dead

Stressed (anemones, gastropods)

Moribund polychaetes

Bacterial mats

Anoxic sediment, H₂S in sediment and water

(Rabalais, Harper & Turner, 2001)
Severe Hypoxia 1990, C6A

(Rabalais et al., 2001)
Characteristics of Louisiana Shelf Benthos Subjected to Seasonally Severe Hypoxia

- Reduced species richness
- Severely reduced abundances (but never azoic)
- Low biomass
- Limited taxa (none with direct development)
- Characteristic resistant infauna (e.g., a few polychaetes and sipunculans)
- Limited recovery following abatement of oxygen stress

(Rabalais et al., 2001b)
<table>
<thead>
<tr>
<th>Order/Genus</th>
<th>Severe hypoxia</th>
<th>Normoxic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Settlement Traps</td>
<td>Sediment</td>
</tr>
<tr>
<td><strong>Enoplida</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Dolicholaimus</em></td>
<td>•</td>
<td>—</td>
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<tr>
<td><em>Halalaimus</em></td>
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<td>—</td>
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<td><em>Nemanema</em></td>
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<td>—</td>
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<tr>
<td><em>Oncholaimus</em></td>
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<td>—</td>
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<tr>
<td><em>Viscosia</em></td>
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<td>—</td>
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<tr>
<td><strong>Chromadorida</strong></td>
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<td><em>Cyartonema</em></td>
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<td>—</td>
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<tr>
<td><em>Leptolaimus</em></td>
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<td>—</td>
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<tr>
<td><em>Microlaimus</em></td>
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<td>—</td>
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<tr>
<td><em>Neochromadora</em></td>
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<td>—</td>
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<tr>
<td><em>Paracanthonchus</em></td>
<td>•</td>
<td>—</td>
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<tr>
<td><em>Prochromadorella</em></td>
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<td>—</td>
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<tr>
<td><em>Pselionema</em></td>
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<td><em>Sabatiera</em></td>
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<td><em>Spirinia</em></td>
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<td>—</td>
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<tr>
<td><em>Synonchiella</em></td>
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<td>—</td>
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<tr>
<td><strong>Monhysterida</strong></td>
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<td></td>
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<tr>
<td><em>Ascolaimus</em></td>
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<td>—</td>
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<td><em>Cobbia</em></td>
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<td>—</td>
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<tr>
<td><em>Daptonema</em></td>
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<tr>
<td><em>Metadesmolaimus</em></td>
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<td>—</td>
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<td><em>Odontophora</em></td>
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<td>—</td>
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<tr>
<td><em>Sphaerolaimus</em></td>
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<td>—</td>
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<tr>
<td><em>Terschelingia</em></td>
<td>•</td>
<td>—</td>
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<tr>
<td><em>Parodonchophora</em></td>
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</tbody>
</table>

*Nematodes were often collected (in settlement traps) from the water column above hypoxic or anoxic sediments*

*In normoxic conditions, they were found in the sediments.*

*(Wetzel et al. 2001)*

*represented by a single specimen*
• Most benthic recruitment is via meroplanktonic larvae.

• Amphipods and harpacticoid copepods rely on direct development and are characteristically absent from hypoxic areas.

• Benthic polychaete larvae are distributed throughout the water column regardless of low oxygen conditions.

• *Paraprionospio pinnata*, delayed settlement and remained in the water column until oxygen values returned to a level above 2.0 mg l\(^{-1}\).

• Barnacle cyprid larvae and holoplankton (e.g., chaetognaths) were reduced in densities below the pycnocline when oxygen concentrations were low.

• Species composition and abundance of organisms in the sediment reflected patterns of pelagic larval abundance.

• The supply of meroplanktonic larvae appears to determine the recovery population.

• Recovery of pericarideans, molluscs and echinoderms takes longer.
Farfantepenaeus aztecus
Brown Shrimp

Litopenaeus setiferus
White Shrimp

(spawning
postlarval recruitment
emigration

(source: N. Rabalais, LUMCON)

Figure 7. Trend in annual brown shrimp catch per unit effort (CPUE) from Texas and Louisiana from 1960 through 1998.
Figure 6. July and August brown shrimp catch from Texas and Louisiana versus relative size of the hypoxic zone on the Louisiana shelf during the years from 1985 through 1997.

(Craig et al. 2001)
River discharge $\uparrow$
Salinity in nursery area $\downarrow$
Preferable nursery habitat for brown shrimp $\downarrow$
More hypoxia $\uparrow$
Suitable habitat for brown shrimp offshore $\downarrow$

River discharge $\downarrow$
Salinity in nursery area $\uparrow$
Preferable nursery habitat for brown shrimp $\uparrow$
Less hypoxia $\downarrow$
Suitable habitat for brown shrimp offshore $\uparrow$

Source: N. N. Rabalais, LUMCON

(Downing et al. 1999)
Gulf of Mexico shrimp landings (annual) and the area of wetland in each estuary (Turner, 1977)

Shrimp yield

Trajectory of Wetland Deterioration

Photos: N. N. Rabalais, LUMCON
• Fishery yields have remained strong for the northern Gulf over the last 40 years. But....

• Menhaden production in years with widespread hypoxia were lower (log book analysis). (Smith 2001)

• Effects of hypoxia on distributions of nekton. (Several authors)

• Pattern of pelagic species becoming more abundant and some dominant demersal species declining in prominence within trawl bycatch, particularly between the 1930s and 1989. (Chesney and Baltz 2001)

• Other effects on nekton are probable.

• Other impacts of greater magnitude may have more significant effects than hypoxia on the community structure and secondary production of nekton.

• The effects of hypoxia on the nekton in the northern Gulf may be buffered by characteristics of the basin, the fauna and the ecosystem. These characteristics may partially offset some of the negative impacts of hypoxia seen in other systems by providing spatial and temporal refuges for demersal nekton.
SUMMARY

Coastal Hypoxia
Consequences for Living Resources and Ecosystems

• Many of the behavioral responses of invertebrate and vertebrate prey and predators to hypoxia documented for the Gulf of Mexico shelf are consistent with those in other areas.

• These developments are observed in many other coastal ecosystems, to lesser or greater degrees of detail, but in no substantially or distinctly different ways.

• The species may be different and the degree of hypoxia or duration may vary among regions, but these broadly described patterns are familiar patterns for many stressed ecosystems, including the Baltic, Black Sea and the northern Gulf of Mexico.