Thresholds in Degradation and Recovery of Hypoxic Coastal Ecosystems

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Before investing in efforts to remediate hypoxia by reducing inputs of nutrient and organic wastes, we need a clear sense of expected responses over time.

Many potential alternatives include:
- Linear dose-response
- Threshold response
- Hysteresis parallel tracks
- Baseline shift

Unfortunately, few clear documented case studies have been published.

More exist, but data are hard to obtain.
Chesapeake Bay Hypoxia Case:

Key Physical Features

- Large ratio of watershed to estuarine area (~ 14:1)
- Deep channel is seasonally **stratified**
- Broad shallows flank channel (mean Z = 6.5m)
- Relatively long water residence time (~ 6 mo)
Stratification Control of Hypoxia

- Pynocline strength (red) controls position & intensity of hypoxia (gray)
- Vertical mixing & landward transport replenish deep $O_2$ pools in summer.

(Hagy 2002 Univ. of MD Thesis)
Trend in Bay Summer Hypoxia Volume (1950-2004)

- Exponential increase, w/ strongest change since 1980
- Interannual variability driven by high and low river flow

(Hagy 2002 Thesis)
Volume of Summer Hypoxia Related to River Flow and N Loading: Regime Shift in Early 1980s

- Volumes of summer hypoxia (< 1 mg/L) and anoxia (< 0.5 mg/L) related to winter-spring river flow.

- Abrupt increase in slope of hypoxia-nitrate relation for 1950-1980 and 1980-2003 (hypoxia per NO₃ Load)

- What factors drive this abrupt regime shift?

Is Chesapeake Hypoxia Regime Shift Unique?

- Examples (there are others) of abrupt shifts in hypoxia per N-Load
- Change-point analysis used to detect shifts.
- Explanations differ but unexpected increases deter efforts to remediate hypoxia

(Kemp et al. 2009. BG)
Significant Shift in Bottom Water NH$_4$ Pools Since Early 1980s

- Bottom-water NH$_4$ pools generally increase with TN loading.
- In early 1980s the size of the bottom NH$_4$ pools increased (>2x) abruptly
- Biogeochemical change (hypoxia $\rightarrow$ benthic fauna loss $\rightarrow$ denitrification loss $\rightarrow$ more NH$_4$ recycling $\rightarrow$ more algae $\rightarrow$ more hypoxia)
Hypoxia Enhancement of Benthic Nutrient (NH$_4^+$) Recycling Efficiency

- NH$_4$ ‘Recycling Efficiency’ (NRE) is flux ratio (NH$_4$ / (NH$_4$ + N$_2$))
- $NRE$ increases w/ decreasing O$_2$ as nitrification-denitrification is inhibited (NH$_4$ shunted & lost to N$_2$)
- Increased $NRE$ with hypoxia further driven by loss of benthic animals
- Thus, NH$_4$ recycling is higher under hypoxic conditions.
  - Higher NH$_4$ recycling $\rightarrow$ More algae $\rightarrow$ More hypoxia $\rightarrow$ More recycling
- Is increased $NRE$ a result or a cause of hypoxia intensification? Or both?

(J. Cornwell data in Kemp et al. ’05 MEPS)
Potential Explanations for ‘Regime Shift’ in Hypoxia vs. N-Loading

- We considered other explanations
- Increased water temperature tends to decrease respiration and O₂ solubility
- Decadal-scale climate shifts might affect river flow or wind
- Decline of reef-forming shellfish filter feeders would decrease control on plankton algal growth
- Other changes (not shown) include loss of nutrient trapping with degradation of tidal marshes and submersed plant beds
Coherence Between NAO & Hypoxia

- Strong correlation and coherence between NAO & hypoxia over time.
- NAO indexed to weaker Bermuda High & loss of S winds that cause vertical mixing; also indexed to Gulf Stream position, higher salinity & stratification.
- Less mixing during positive phase of NAO promotes more hypoxia per N.
• Longer term trends in Winter NAO index shows variations and periodic (~10-30 yr) shifts between positive and negative phases.
• Last major shift coincides with Bay “regime shift” in hypoxia per N-loading
• Index in recent years suggests a shift back down to negative phase (& possible increase in vertical mixing and weakening of stratification).
Hypoxia Response to Changes in N-Load

- To minimize effects of interannual variations in flow on relation, use mean data from years with intermediate flow.

- Between 1980 - 1985, relation of hypoxia to N-Loading shifted up to higher regime.

- This caused more hypoxia per unit N-loading, frustrating efforts to remediate.

- Recent years show down-shift back to pre-1980 conditions, giving hope for hypoxia controls.
Concluding Comments

• Cost-effective strategies for hypoxia remediation require understanding of expected responses to interventions (e.g., reductions in nutrient load).

• Many physical and biogeochemical processes control hypoxia, and these must be clearly understood before choosing remediation strategy.

• Chesapeake hypoxia has grown with increasing nutrient loading, and an abrupt increase in hypoxia/N-load occurred in early 1980s.

• It appears that hypoxia-enhanced N-recycling has contributed to this “Regime Shift” and/or Bay recalcitrance to restoration.

• However, abrupt changes in climatic conditions (indexed to winter NAO) coincide with this hypoxia “regime shift,” driving physical controls on hypoxia.

• There may be reason for “cautious optimism” for Bay hypoxia recovery; possibly, a “shift-down” to lower regime with less hypoxia per N-load.