Response of Coastal Hypoxia to Nutrient Remediation

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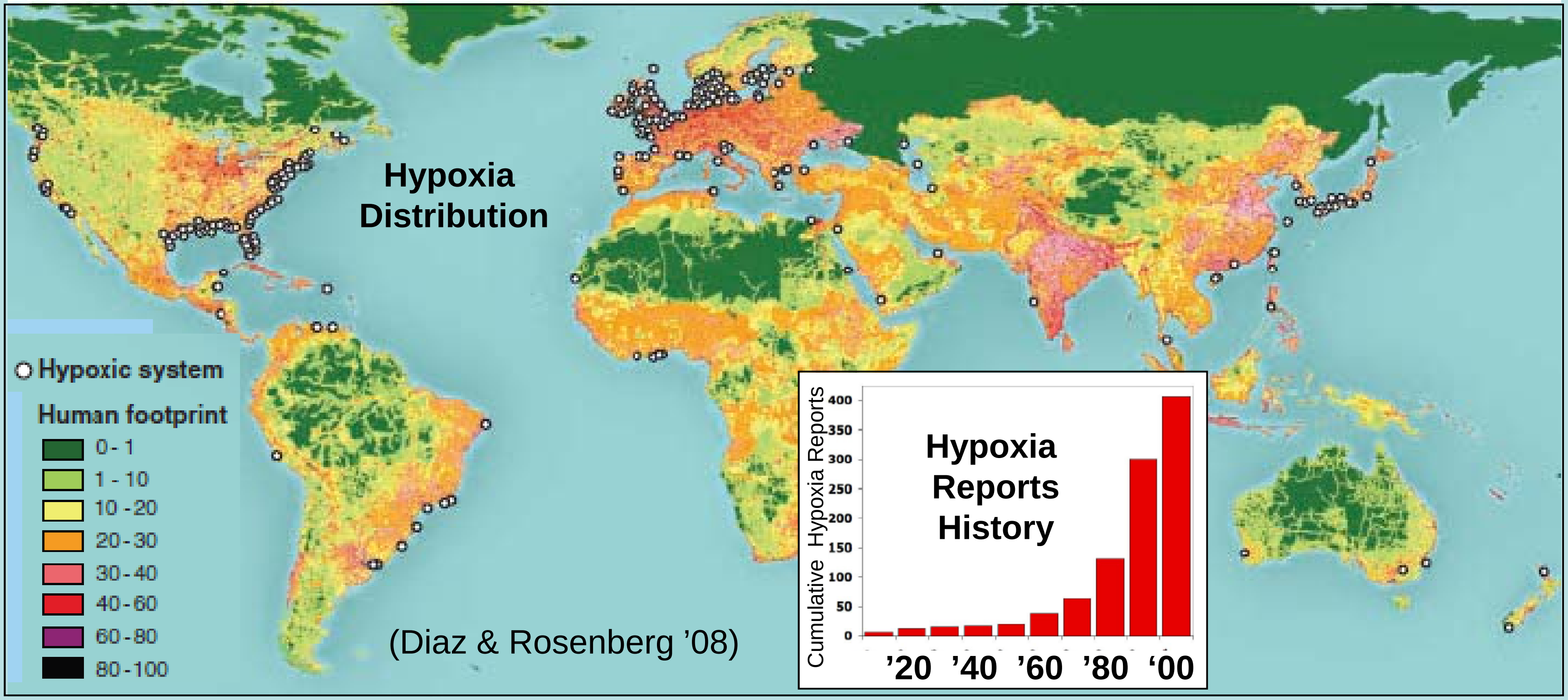
Outline

- **Background & Motivation**
  - -Hypoxia linked to eutrophication
  - -Understand hypoxia response to nutrients
- **Trajectories of Hypoxia Response to Nutrient Inputs**
  - -Theoretical models
  - -Cases Studies
- **Hypoxia-Nutrient “Regime shifts”: Chesapeake Bay**
  - -Response trajectories
  - -Possible explanation
- **Concluding Comments**

Global-Scale Spread of Coastal Hypoxia



- Global distribution of coastal hypoxia
- Hypoxia concentrated near intense human activities
- Global spread of hypoxia related to eutrophication
- Other processes (e.g., climate change) also important

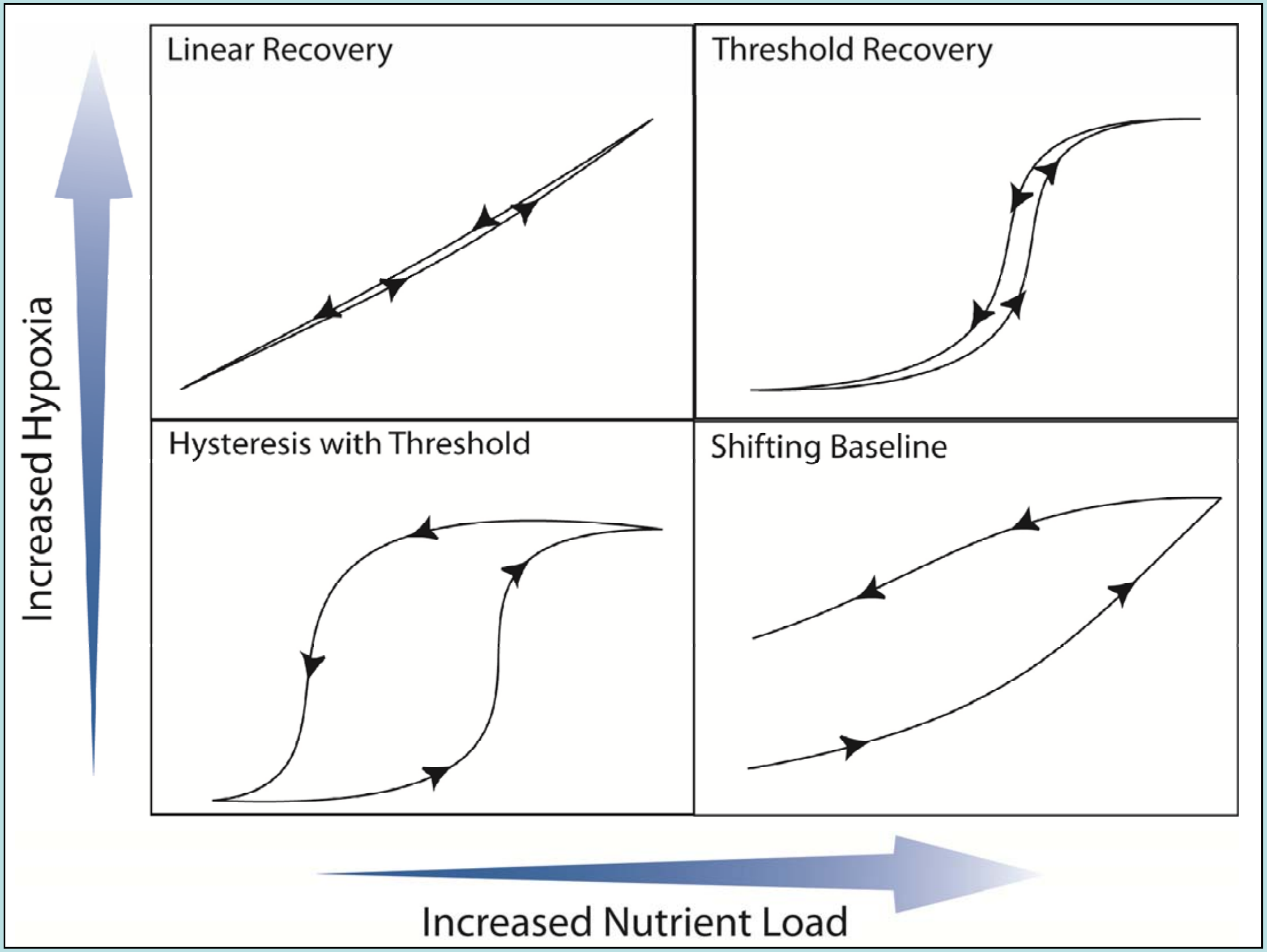
Motivation to Study Hypoxia-Nutrient Relations?

- Expensive societal commitments to reduce nutrient loading to coastal systems worldwide.

- Important to understand how hypoxia will respond to “eutrophication remediation” efforts.

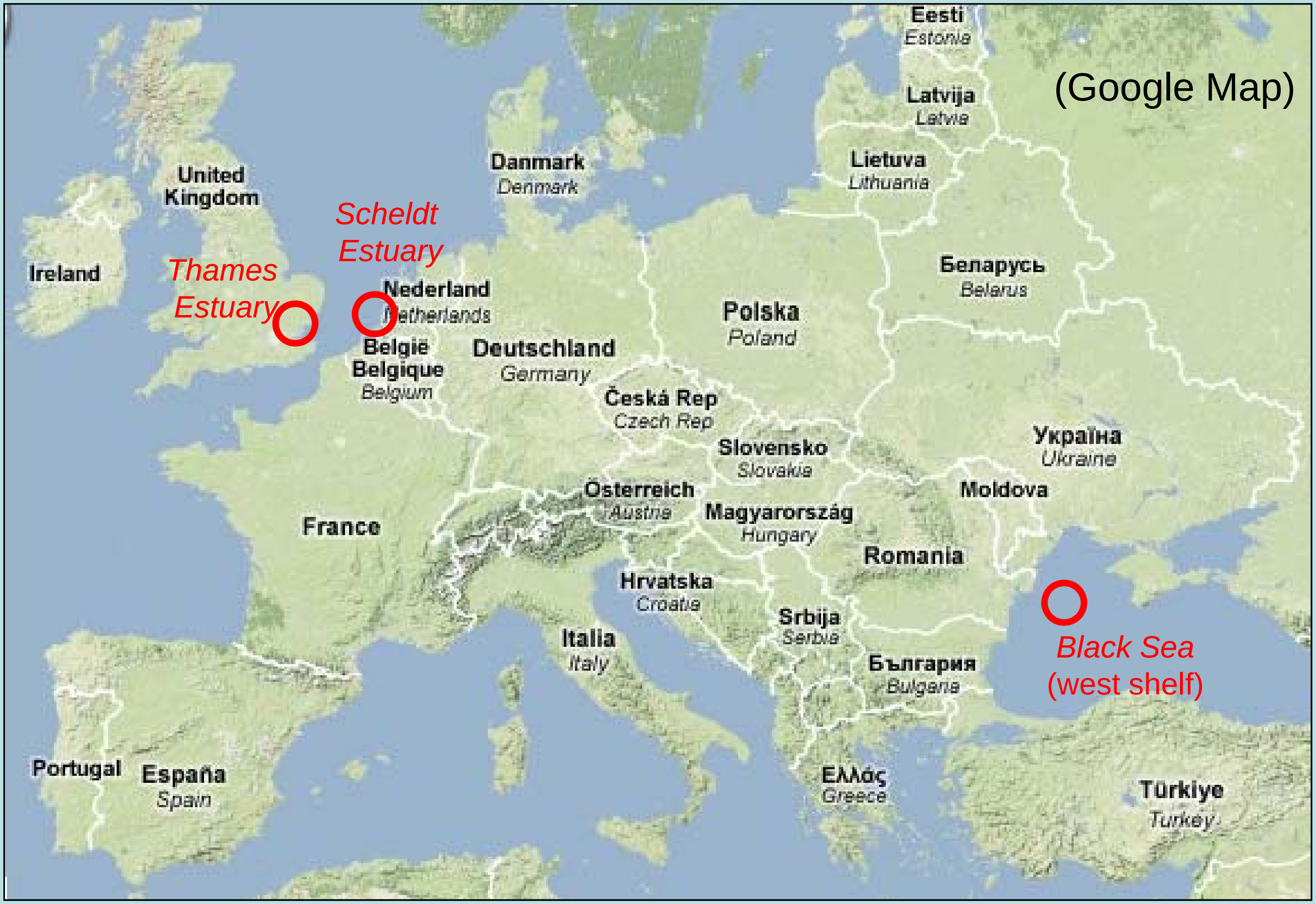
- Theoretical & observed response trajectories?
  - --Positive or negative?
  - --Linear or non-linear?
  - --Immediate or delayed?

Potential Responses of Hypoxia Extent to Nutrient Remediation

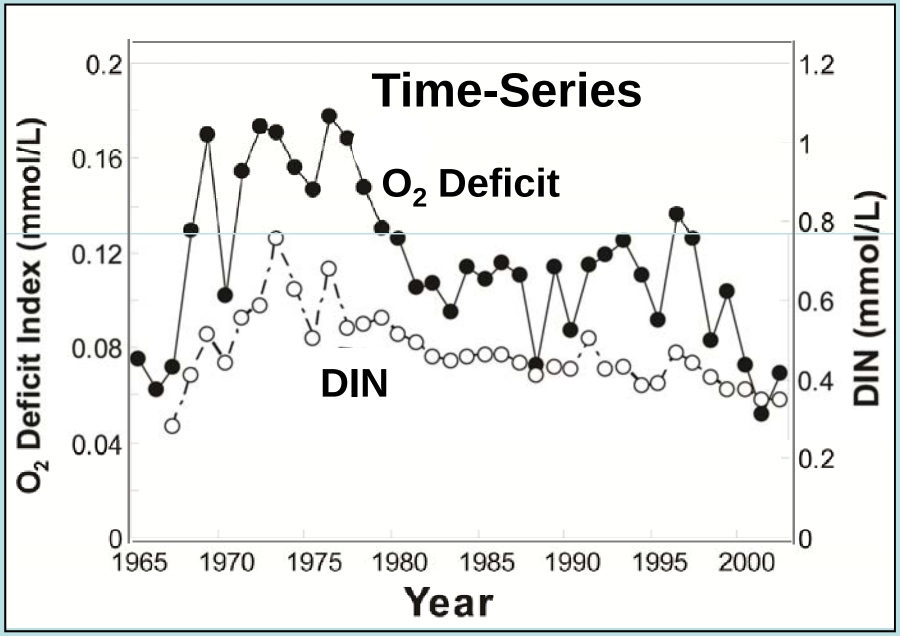


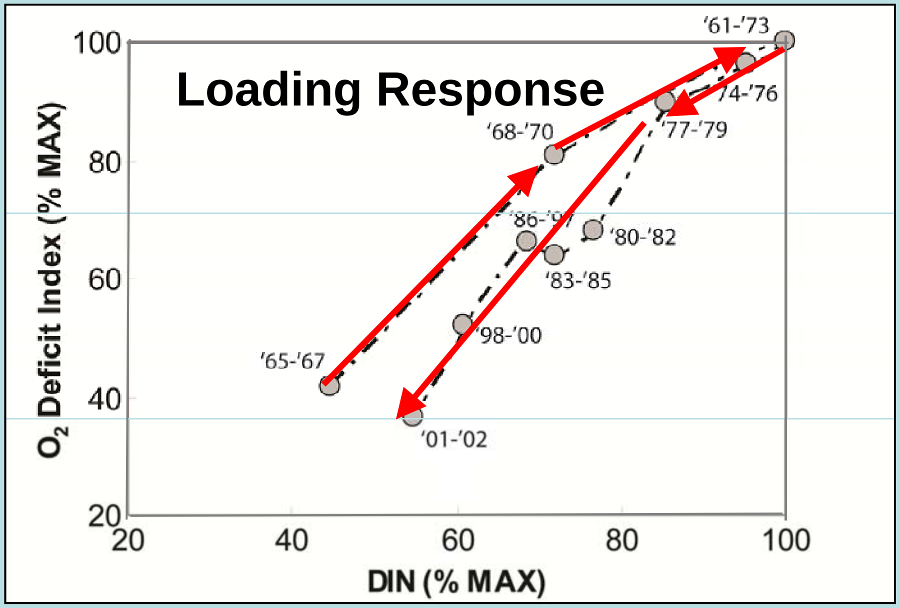
(modified after Duarte et al. 2008)

Example Hypoxia Responses to Nutrient Remediation



Scheldt Estuary Response to Nutrient Remediation

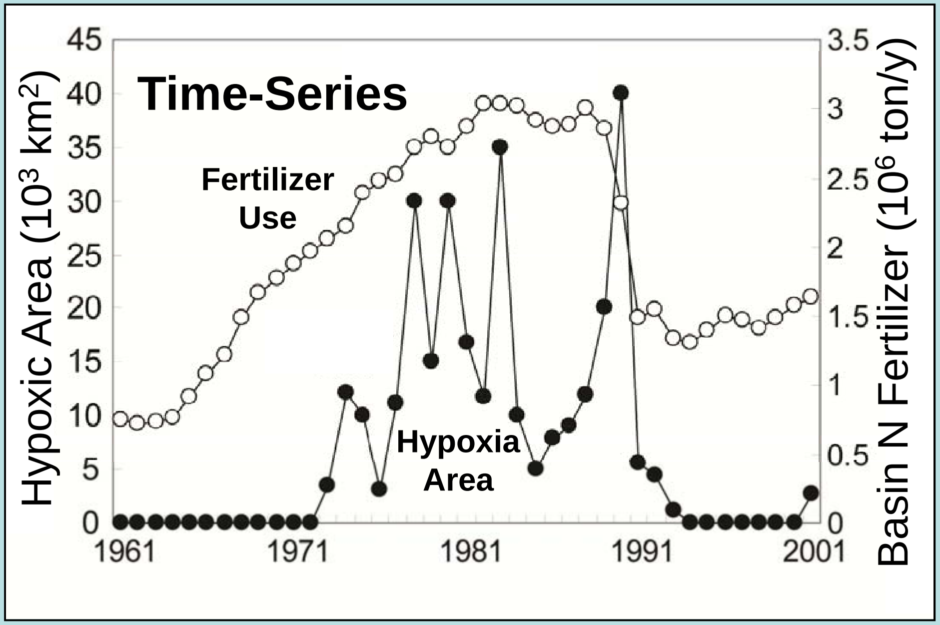


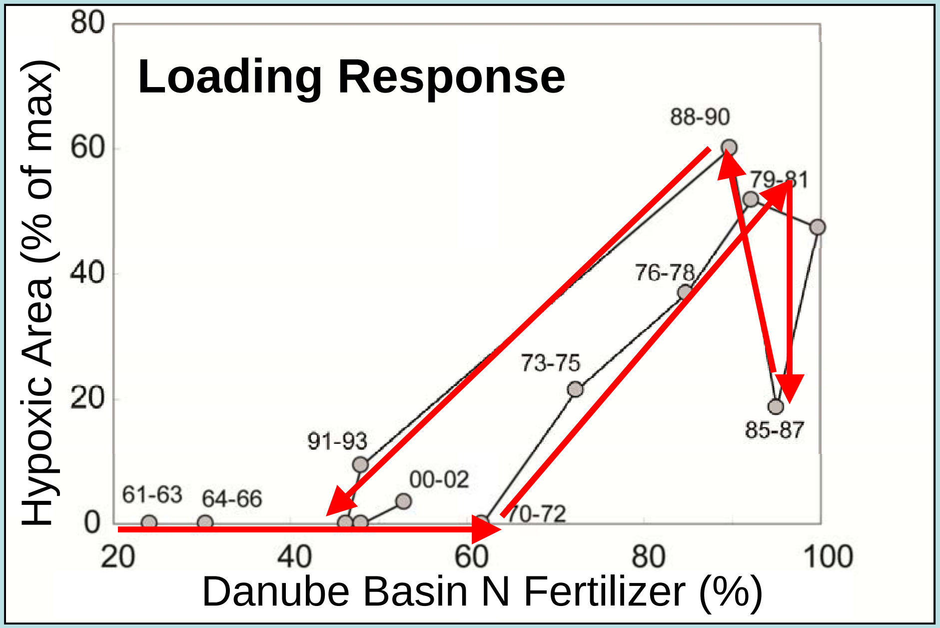


- 40-year record of water quality in Scheldt estuary
- Mean O_2 deficiency (AOU) used as index of hypoxic volume
- DIN used as index of TN loading
- Increase in DIN through 1970s, then decline to 1960s levels through 2000s.
- Hypoxia response to N-Load follows relatively *'Linear'* trajectory.
- *"Baseline Shift"*
(smaller O_2 deficit/N-load).

(Soetaert et al. 2006)

Black Sea Response to Nutrient Remediation

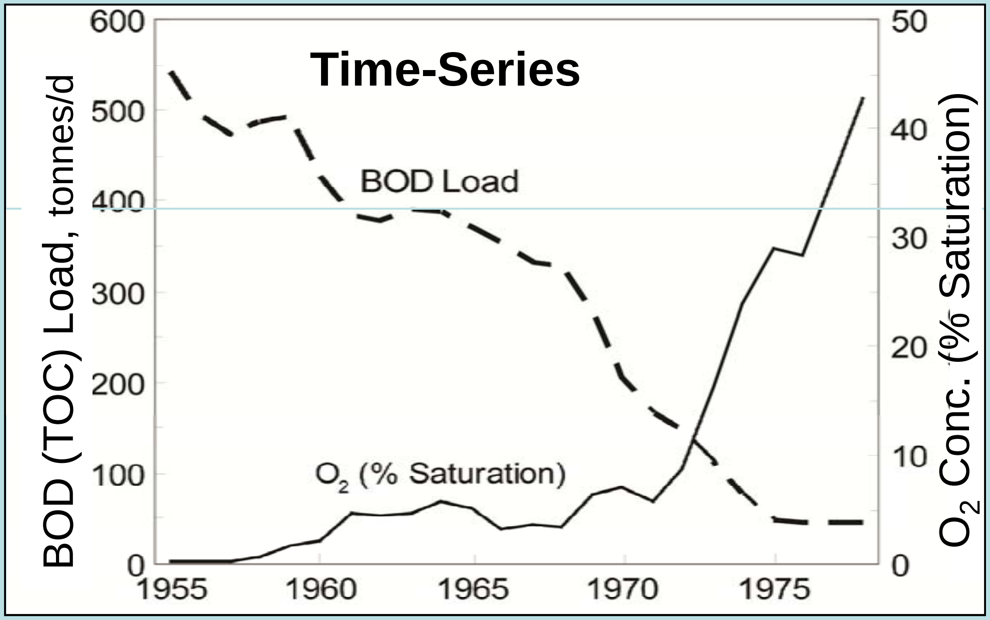


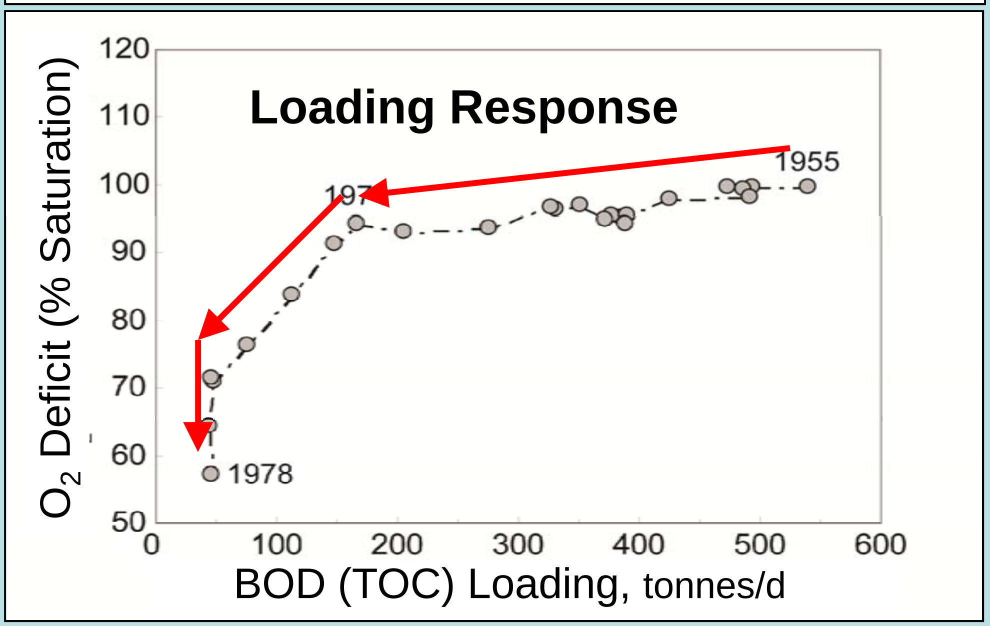


- **Large hypoxic zone appeared with increasing nutrient inputs from Danube River**
- **Many changes in Black Sea ecology (fishery over-harvest, alien species, climate change)**
- **Hypoxia has, however, generally changed in parallel with nutrient loading trends.**
- **Hypoxia began to shrink after a 5-6 year delay from initial reductions in nutrient loading.**
- **Hypoxia response followed *"Hysteretic"* trajectory.**

(Mee 2006, Oguz & Gilbert 2007)

Thames Estuary Response to Remediation of Organic Wastes

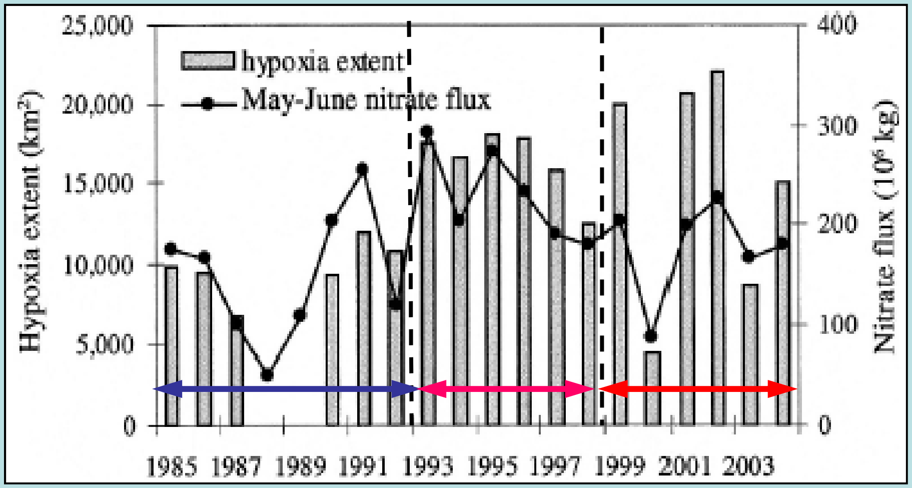


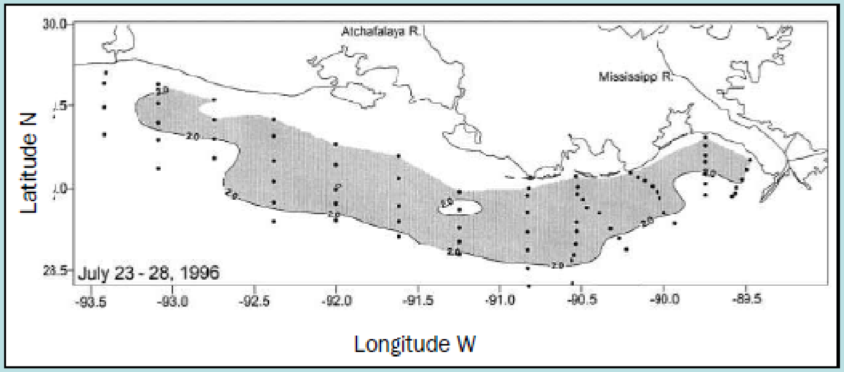


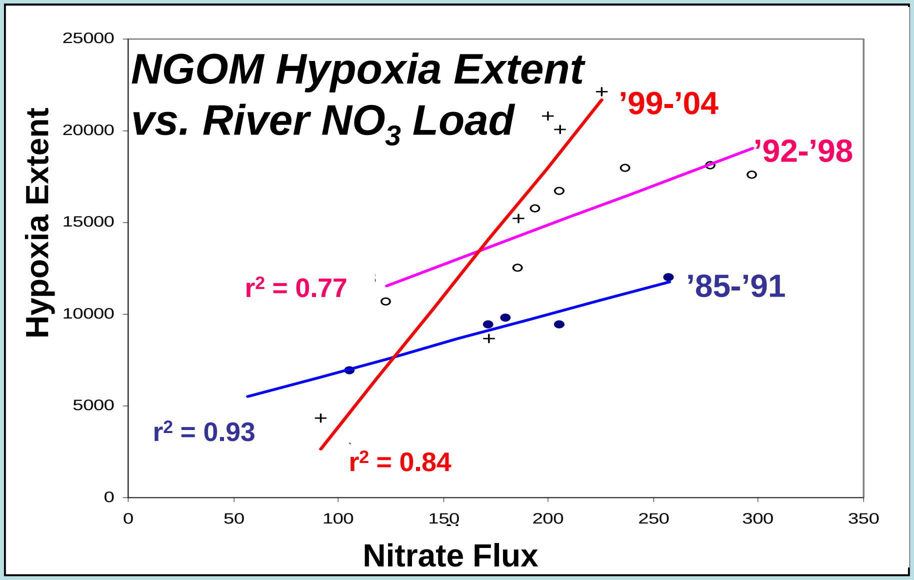
- **Current coastal hypoxia is driven by inorganic nutrient loads, linking algal growth & sinking to O_2 consumption.**
- **Prior to 1975, hypoxia was common in urban estuaries like the Thames R in GB.**
- **This hypoxia was driven by direct loading of labile organic waste from sewage effluents.**
- **Hypoxia response to organic loading (BOD) follows a *"Threshold"* trajectory.**

(Andrews & Rickard 1980)

Northern Gulf of Mexico "Regime-Shift": Hypoxia vs. Mississippi River NO_3 Load







(Rabalais '92; Donner & Scavia '07; Turner et al. '08)

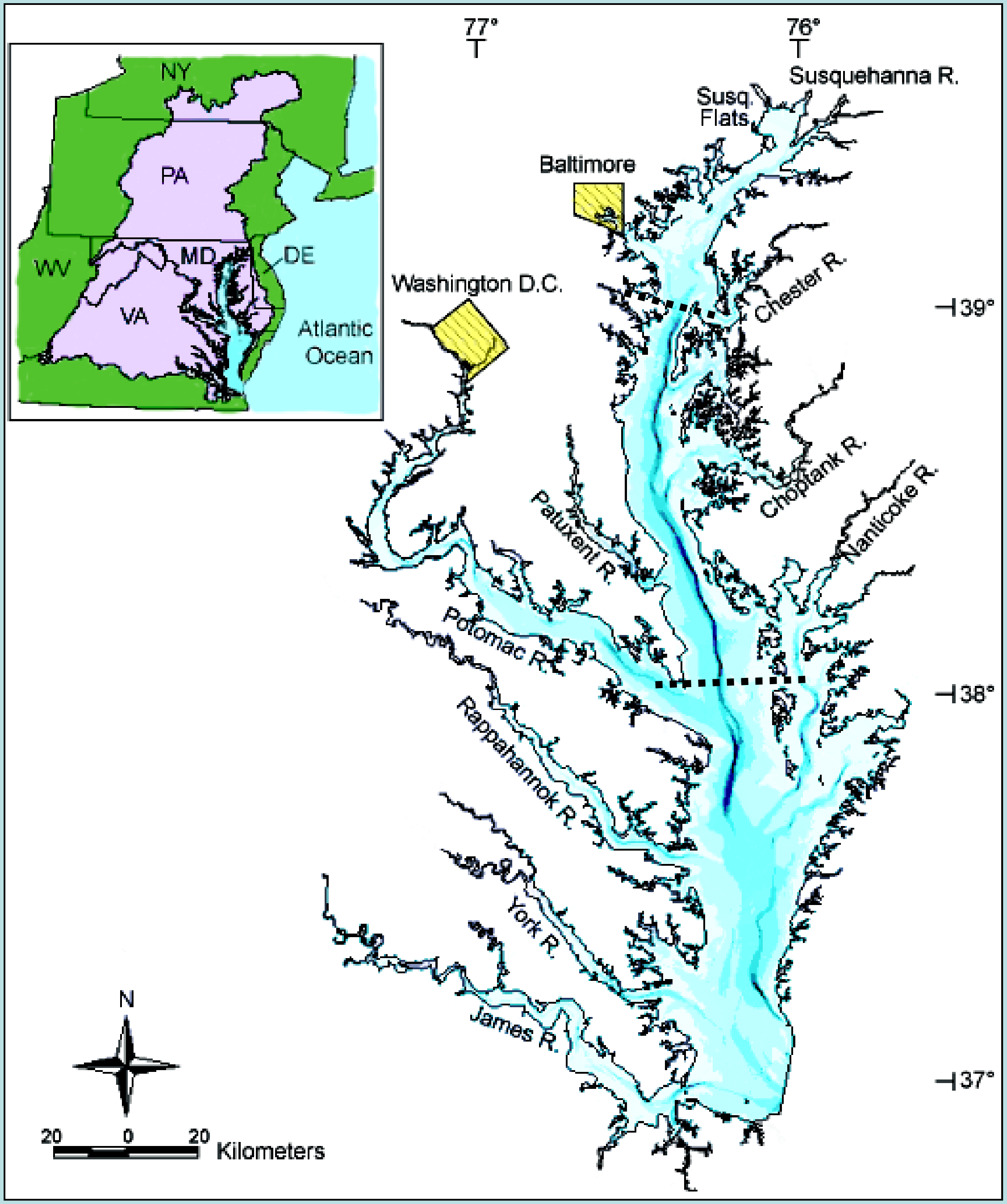
- **Hypoxia in N. Gulf of Mexico is fueled by Miss. River NO_3 load.**
- **Hypoxia varies w/ strong inter-annual changes in flow (~3x)**
- **Two shifts appear in NO_3 vs. Hypoxia relation ('91, '98).**
- **Causes for shift are unclear; POM carry-over hypothesized.**

Understanding “Regime Shifts” in Hypoxia-Nutrient Relation: Chesapeake Bay Example

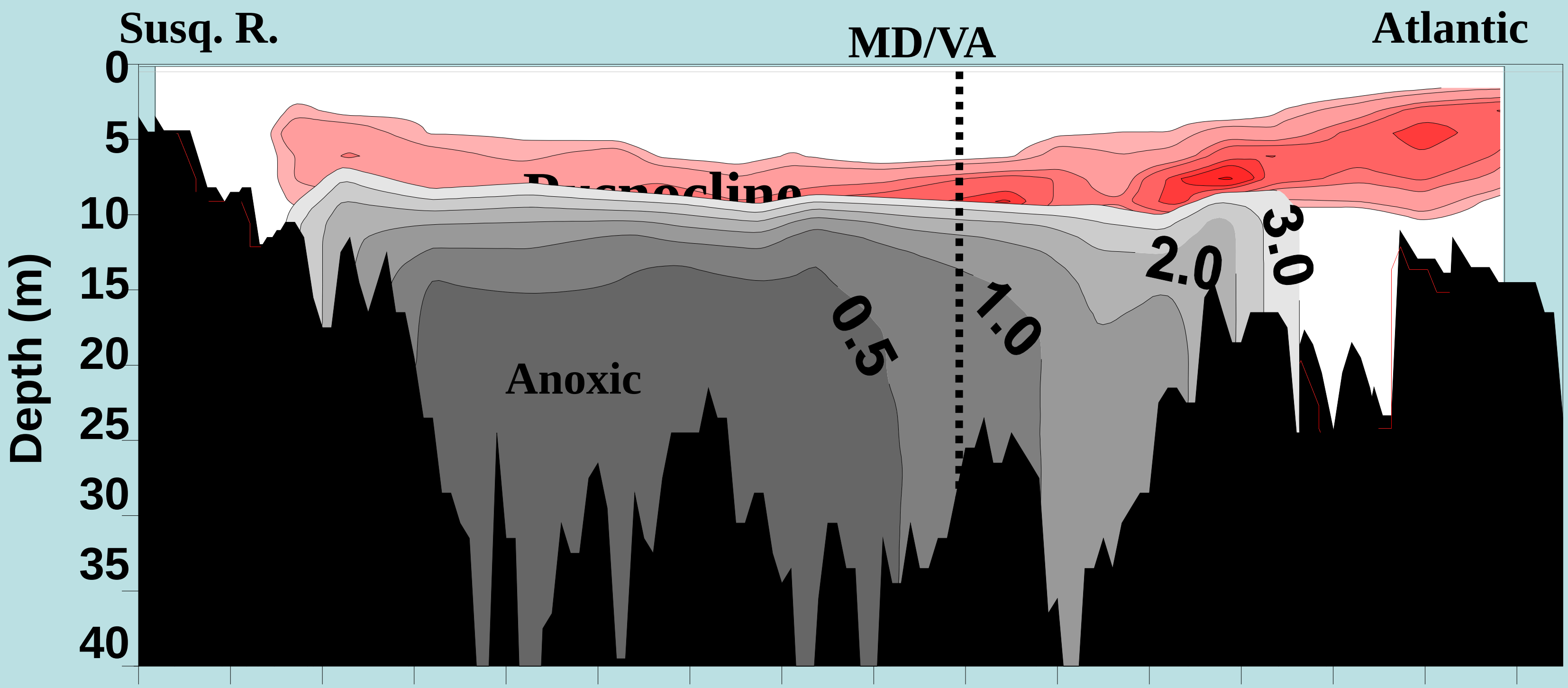
- Background on Chesapeake Bay hypoxia
- Temporal trend of increasing hypoxia extent
- Shifts between Low & High response regimes
- Role of nutrient recycling positive feedback

Chesapeake Bay 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

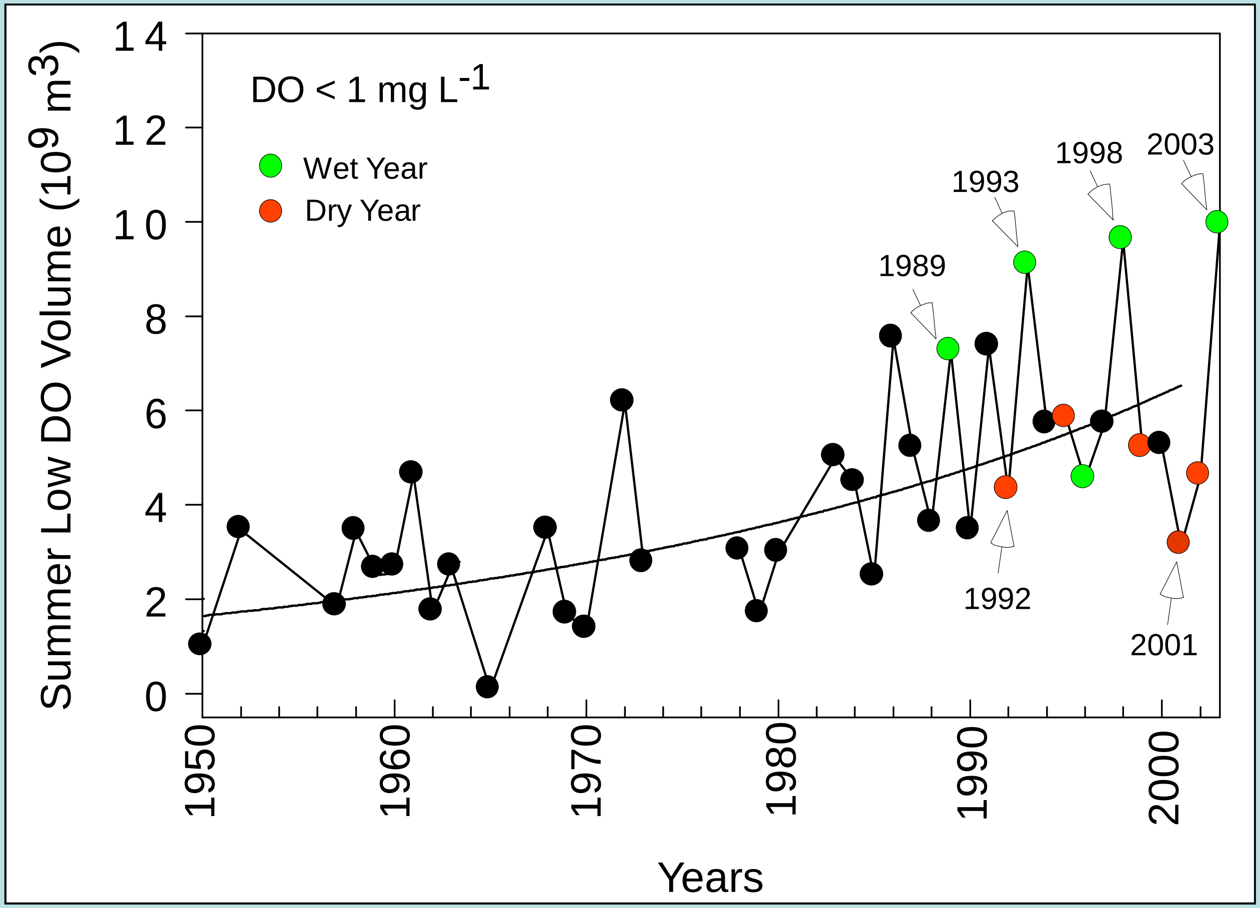


- Pynocline controls position & intensity of low O_2 water.
- Landward transport replenishes deep O_2 pools.

(Hagy 2002)

Variations & Trends in Chesapeake Bay Hypoxia: 1950 -2003

- **Significant trend in volume of hypoxia, related to nutrient loads**
- **High Inter-annual variation related to river flow hypoxia--greater in wet years (green dot), less in dry years (red dot)**



(Hagy et al 2004)

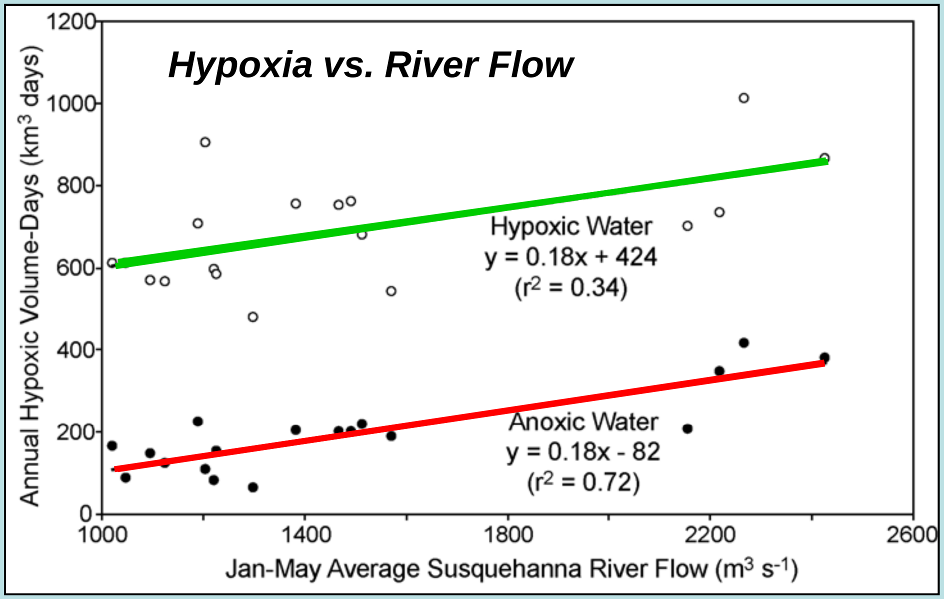
Volume of Summer Hypoxia Related to River Flow and N Loading: Regime Shift in Early 1980s

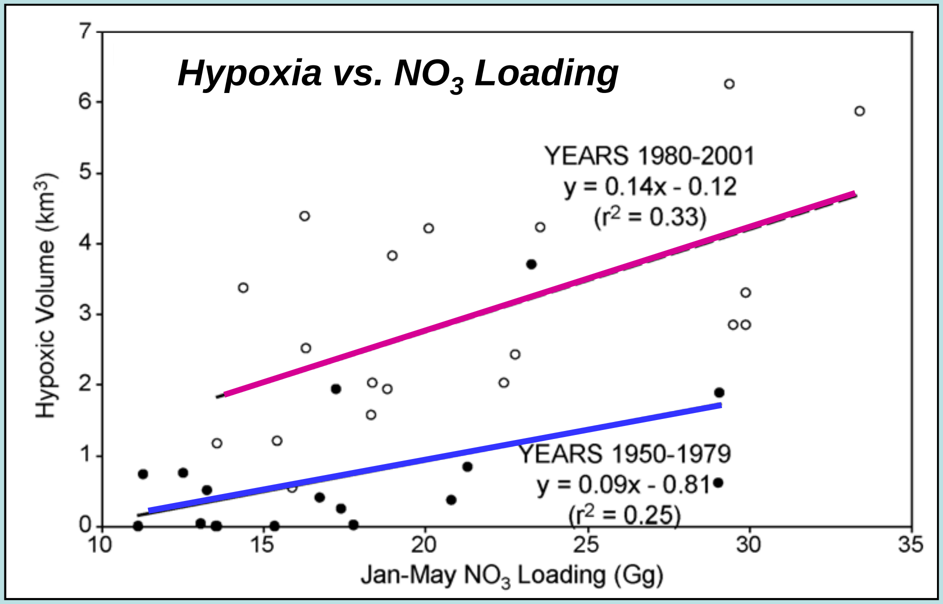
- **Volumes of summer hypoxia (< 1 mg/L) and anoxia (< 0.5 mg/L) related to winter-spring river flow.**

- **Hypoxia also related to NO_3 (& Total N) Loading.**

- **Abrupt increase in slope of hypoxia-nitrate relation for 1950-1980 (blue line) and 1980-2003 (magenta line), shifting amount of hypoxia per unit NO_3 Loading**

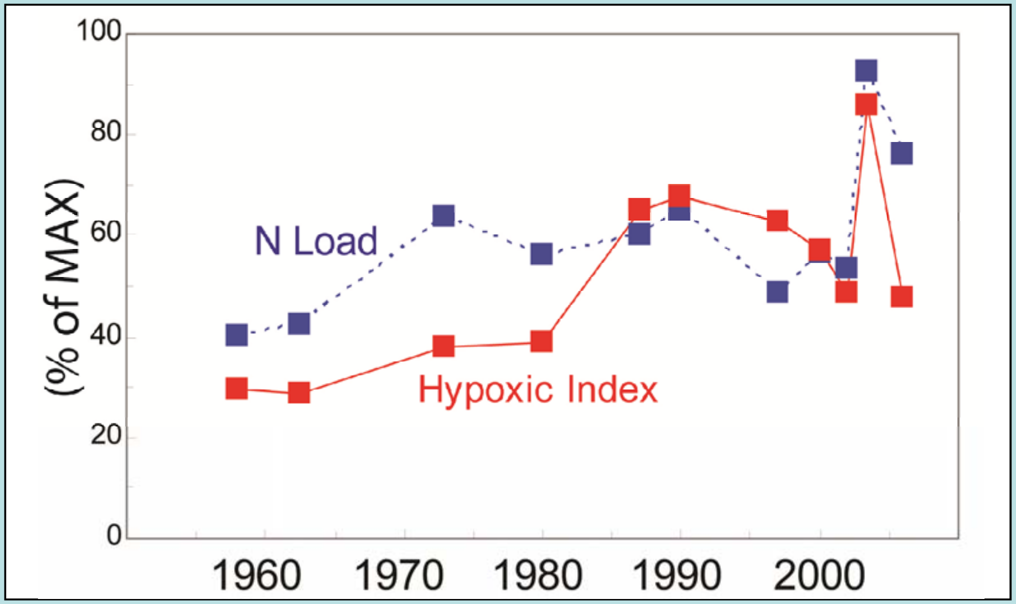
- **What factors drive this abrupt regime shift?**



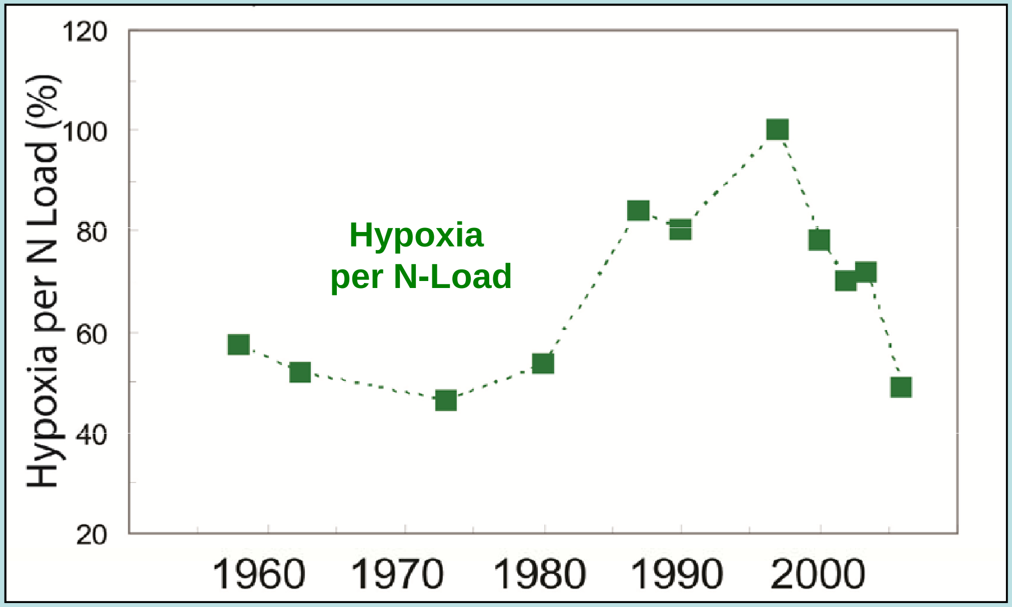


(Hagy et al 2004, Kemp et al 2005)

Focusing on Years of Intermediate River Flow

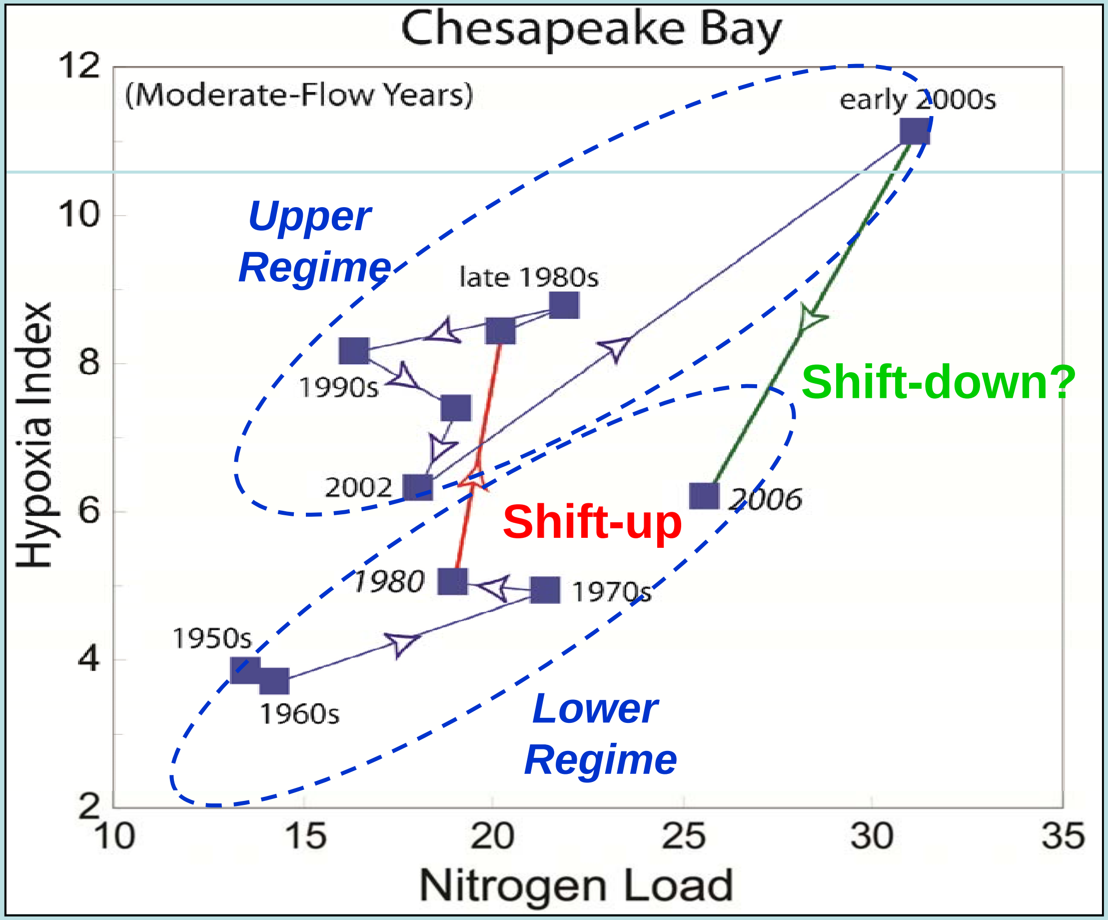


- **To reduce inter-annual variance, we analyzed only years with intermediate flow (mean ± SE).**
- **From 1960–2006, both NO_3-Load and Hypoxia increase steadily**
- **Hypoxia increases more rapidly than NO_3-Loading**



- **Hypoxia volume per NO_3-Load relatively constant until 1980.**
- **Shifts-up through early 2000s & shifts-down later in this decade**
- **By 2006 hypoxia per N-Load returns to pre-1980 levels.**

Bay Hypoxia Response Trajectories for Changes in Nitrogen Loading



- **Visualize response trajectories and regime shifts**
- **Shift-up to new *Upper Regime* in 1980 with more Hypoxia per N-Load**
- **Recent apparent down-shift to *Lower Regime* (initial recovery?)**

Potential Explanations for Observed Shift in Relationship between Hypoxia & N-Loading

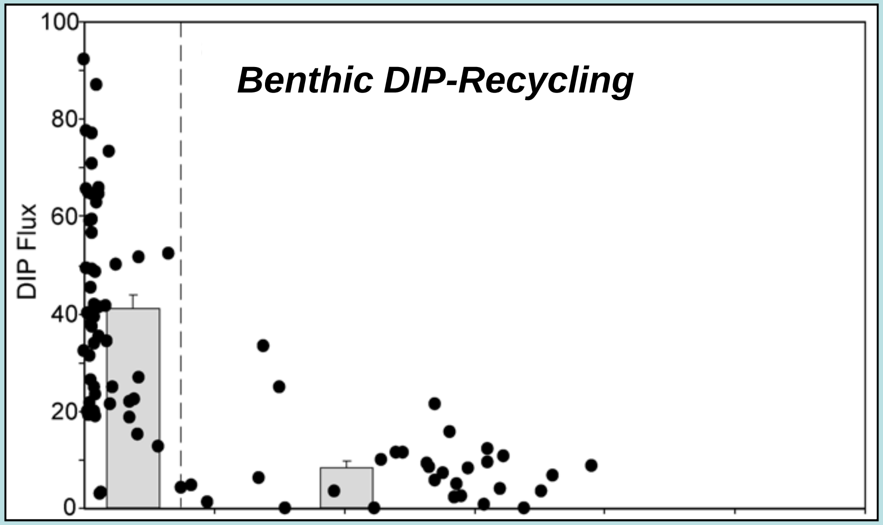
- Decrease in phytoplankton grazing with oyster decline or other food-web changes

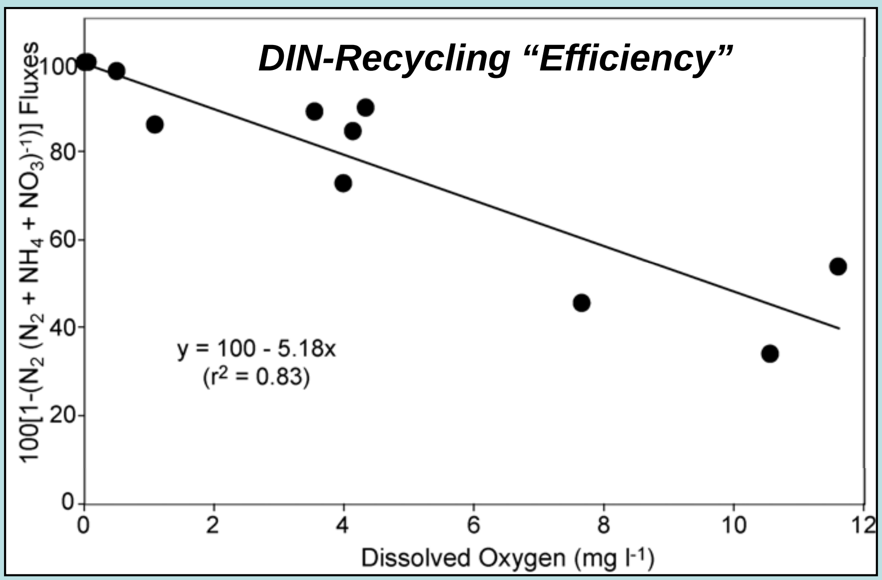
- Loss of nutrient uptake & retention with reductions in seagrass and tidal wetlands

- Climate-induced changes in temperature and/or physical circulation

- Enhanced nutrient recycling efficiency under low O_2 conditions (redox-control, loss of bioturbation).

Hypoxia Enhancement of Benthic Nutrient (N, P) Recycling Efficiency



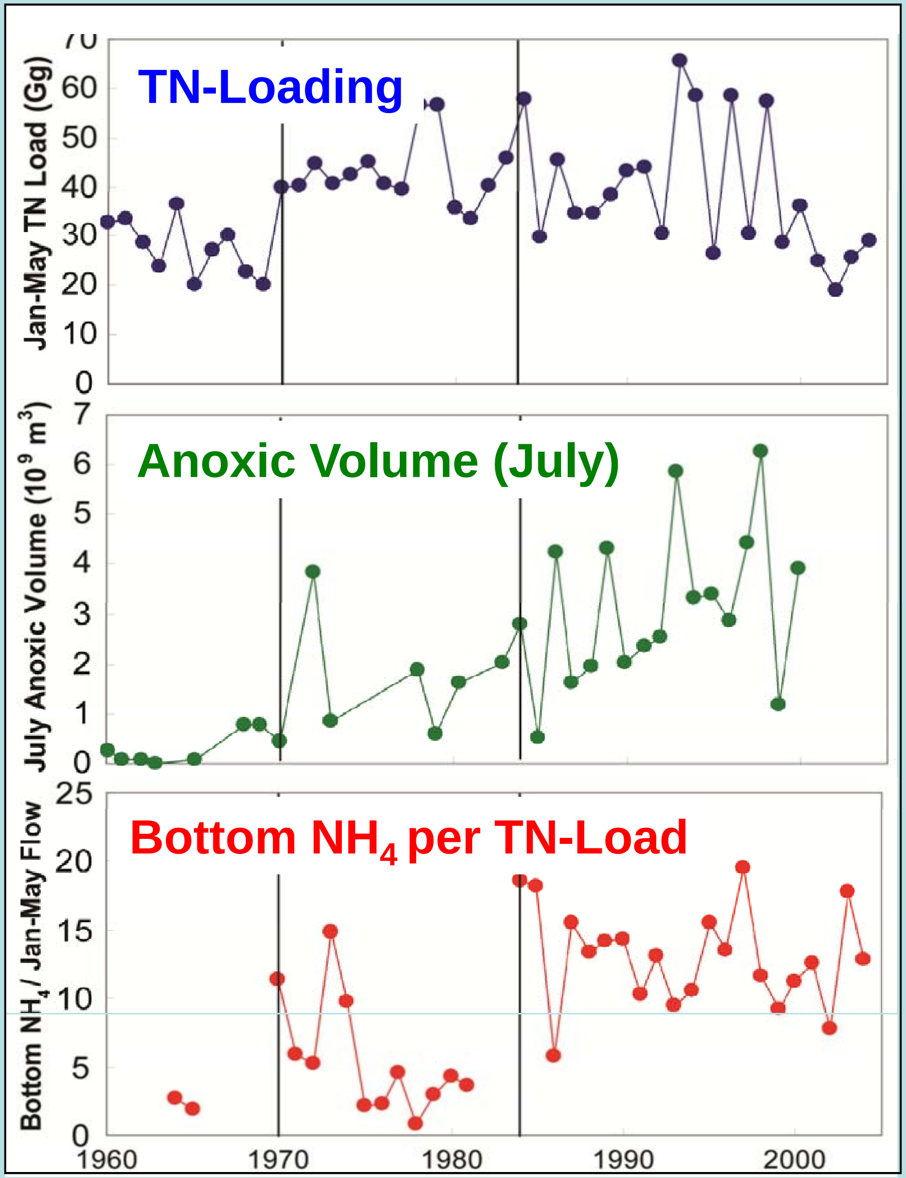


(Kemp et al. 2005)

- **High rates of DIP release to overlying water at O_2 < 1.5 mg l^{-1}**
- **Results from reduced solubility of reduced iron compounds.**

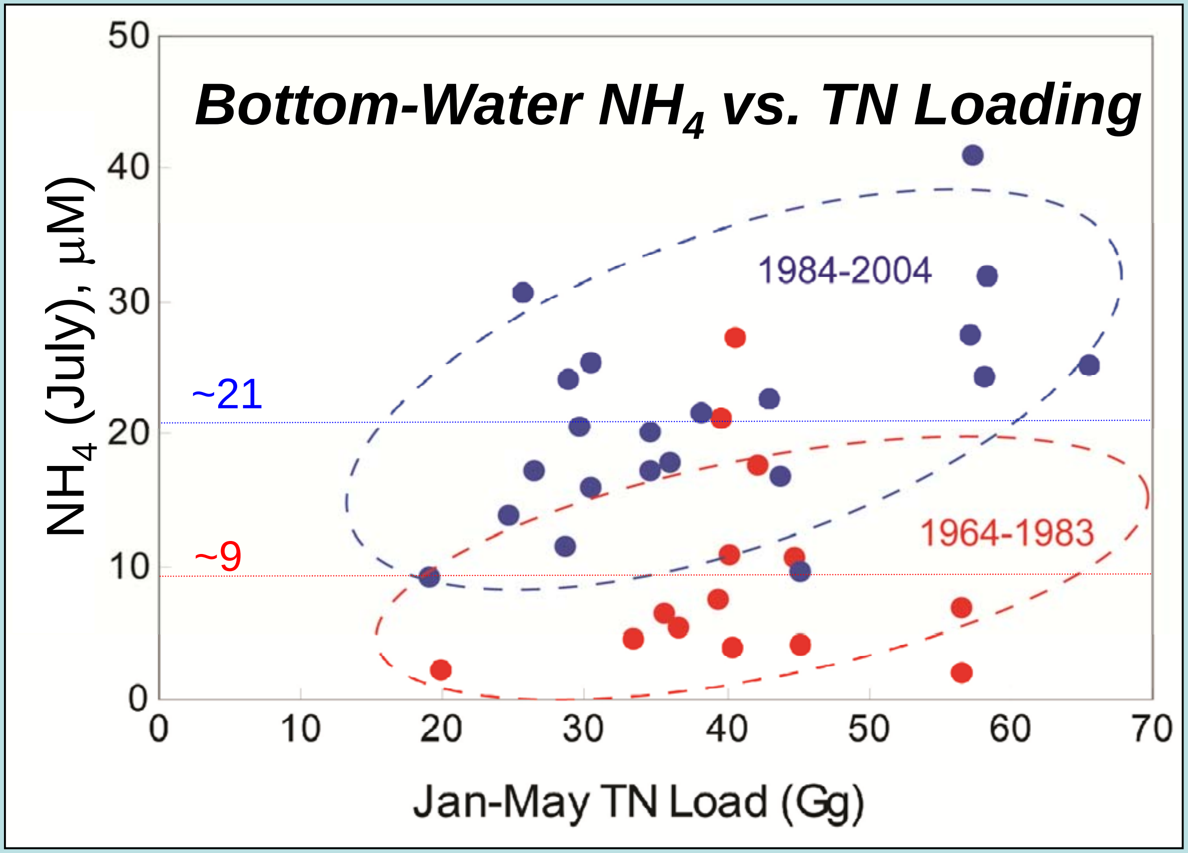
- **DIN 'Recycling Efficiency' (NRE) is flux ratio (DIN/(DIN + N_2)**
- **NRE increases w/ decreasing O_2, because of nitrification inhibition**
- **Thus, DIN recycling higher under hypoxic conditions.**

Changes in Bay's Bottom Water NH_4 with Nutrient Loading and Hypoxia



- TN-loading increases to 1992 with abrupt jump in 1970, then fluctuates and declines.
- Anoxia volume fluctuates, but increases rather steadily into 2000s.
- Bottom-water NH_4 pool appears to jump up in 1970 & again in 1985

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 (by >2x) abruptly & unexpectedly.**
- **Apparently there was a biogeochemical change maybe related to hypoxia & benthic macrofauna.**

Concluding Comments

- Limited reports on hypoxia responses to reduced nutrient loading, but several are consistent with trajectories predicted from theory.

- Sequence of processes linking nutrient loading to hypoxia production is susceptible to influence from other factors (e.g., climate, food-webs).

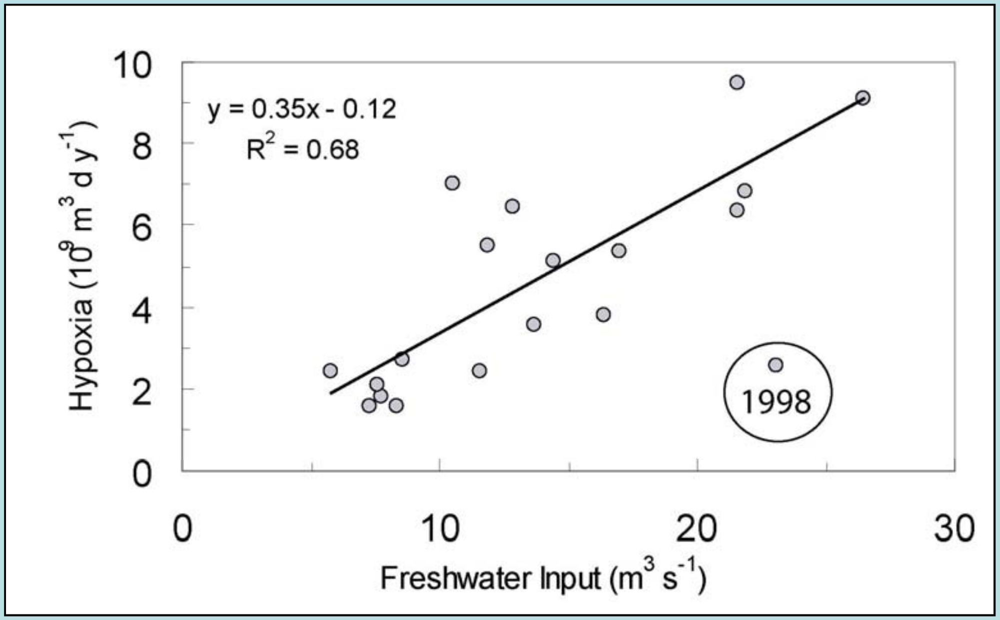
- Some stratified coastal systems (NGOM, CB) exhibit abrupt shifts in relation between Nutrients & Hypoxia; “regime-shifts” difficult to explain.

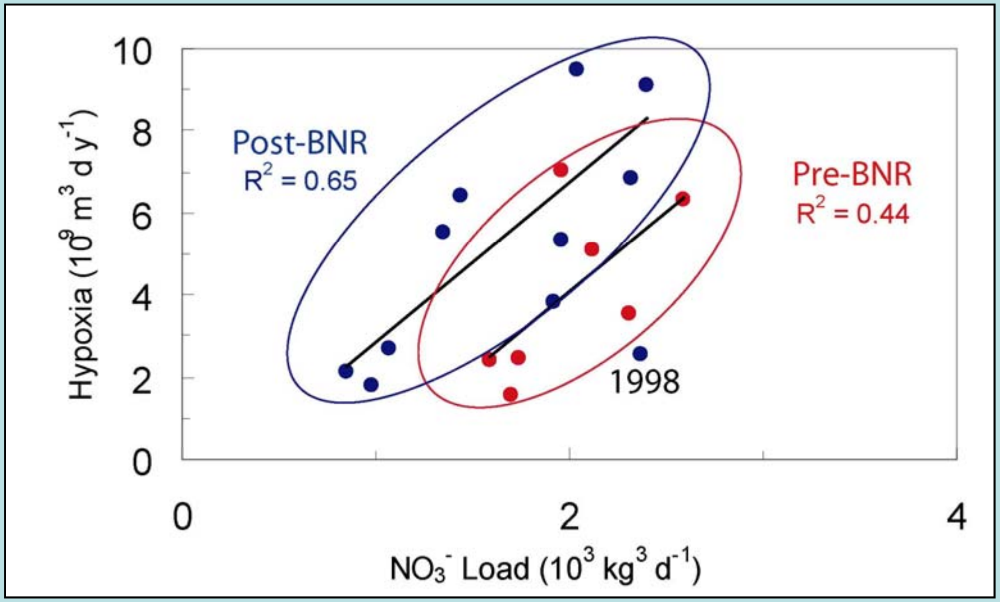
- One plausible explanation involves hypoxia-enhanced nutrient recycling; positive-feedback that may increase O_2 consumption per nutrient loading.

- Improved understanding (& modeling) of expected hypoxia response is crucial given the large economic investment needed for nutrient reduction.

Extra Slides—Not Used

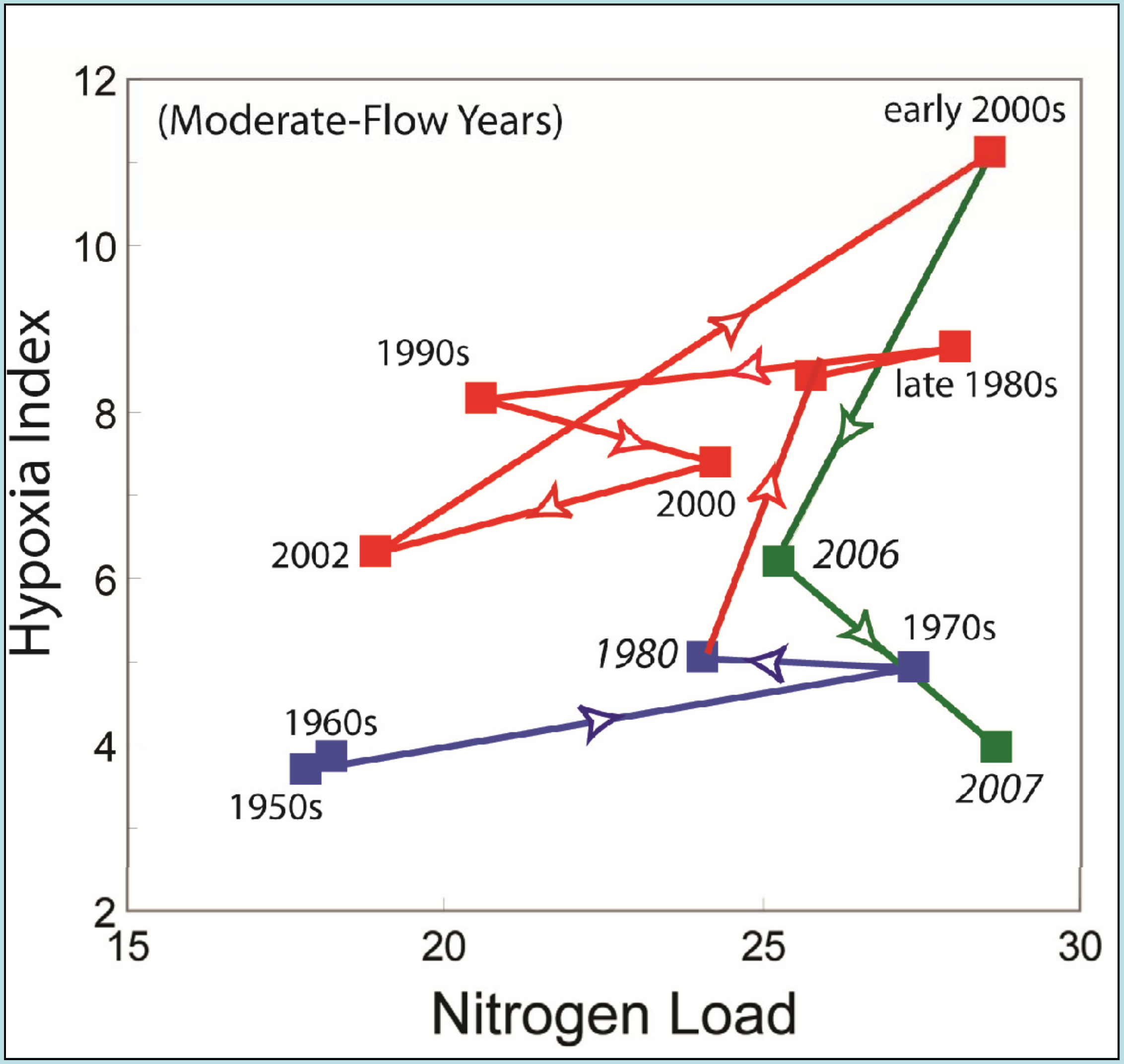
Patuxent River Estuary Hypoxia Regime-Shift





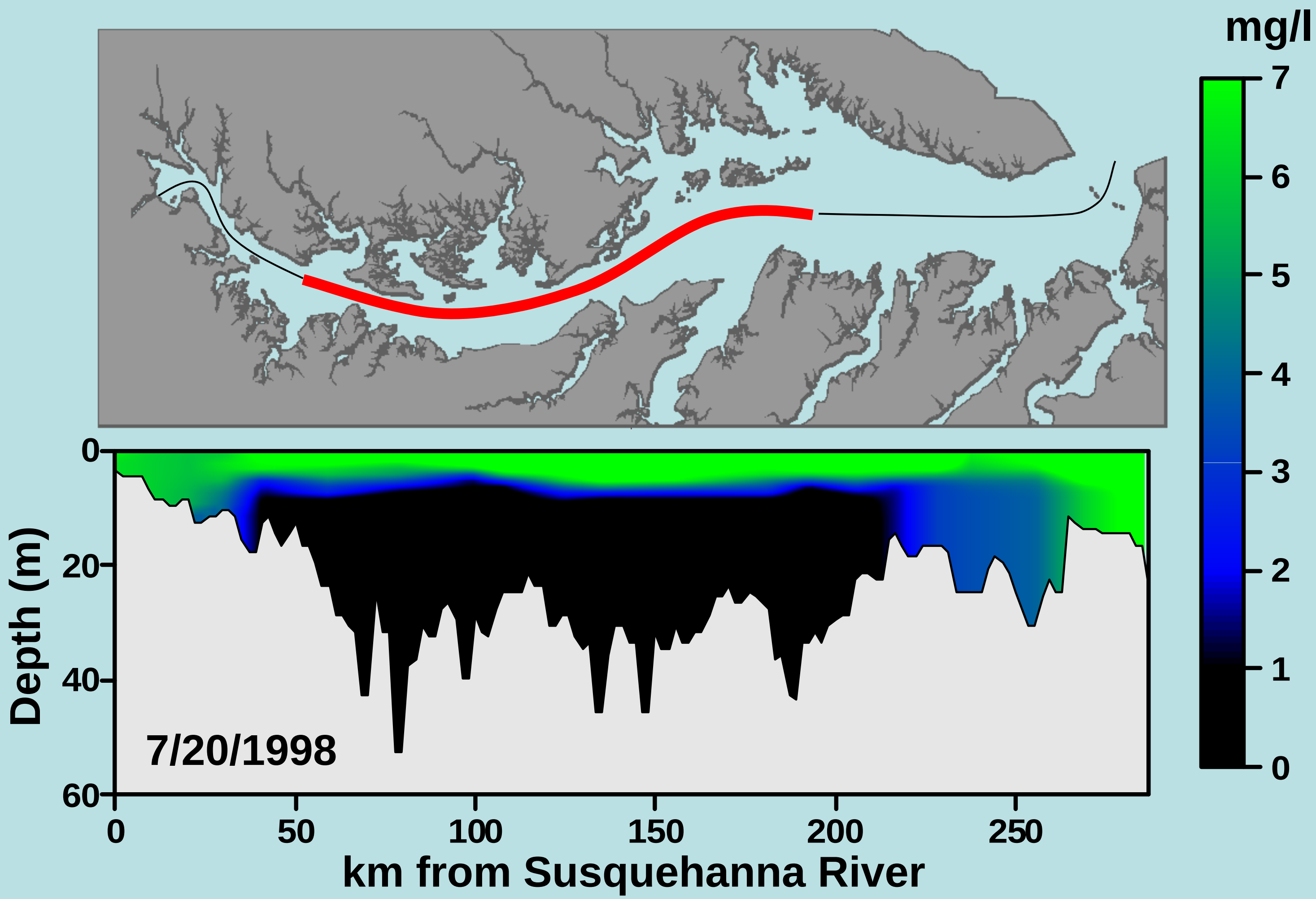
- Hypoxic volume in Patuxent is also related to river flow
- Outlier in 1998 likely due to summer mixing events
- Different relationships between Nitrate loading and hypoxia for years before and those after initiating BNR (note: 1998 still an outlier)
- Why more Hypoxia per unit N loading post BNR? Other sources of N?

(Testa 2006)



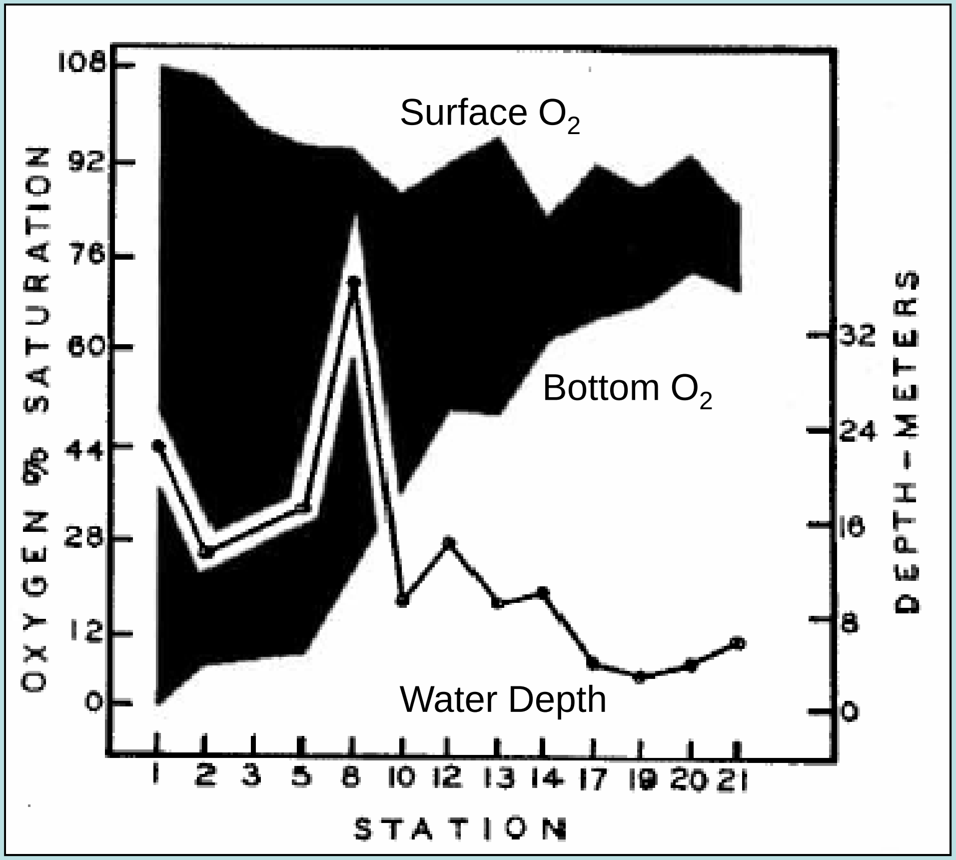
- Same data as we gave Bosch, but with 2007 included
- Note that 2007 falls even lower than 2006. Given the less than expected hypoxia from the first slide, it looks like it will fall back to the lower regime as well if it is moderate flow
- Damn…I guess this is good news
- Bad news is we don't know why

Chesapeake Bay Hypoxia Distribution



(Hagy 2002)

Summer Chesapeake Hypoxia Reported from 1930s



(Newcombe & Horne 1938 Science)

Chesapeake Bay's Interannual Variations in River-Borne Nutrient Loading