“Dead-Zones” and Coastal Eutrophication: Case-Study of Chesapeake Bay

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Presentation to *COSEE Trends*

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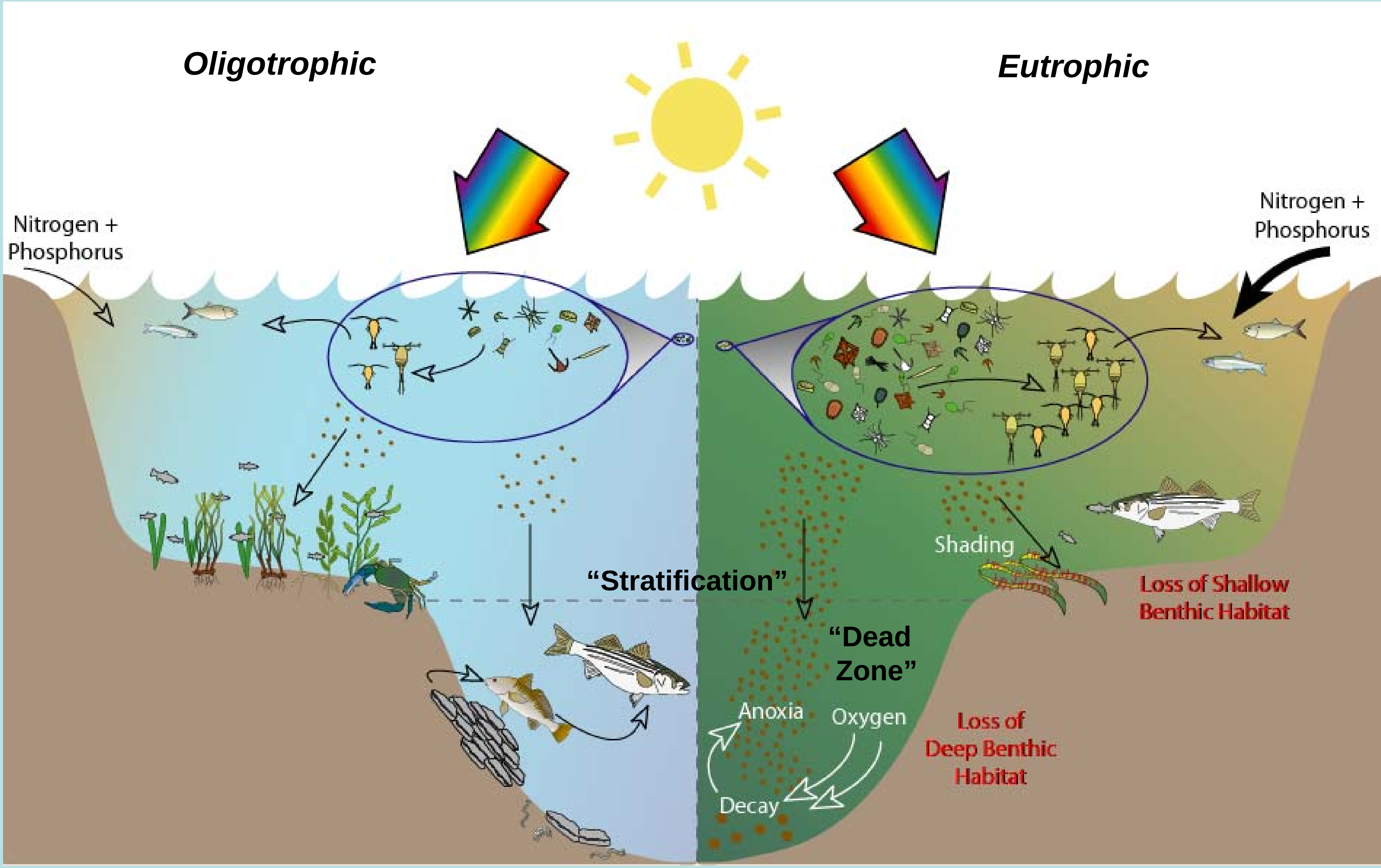
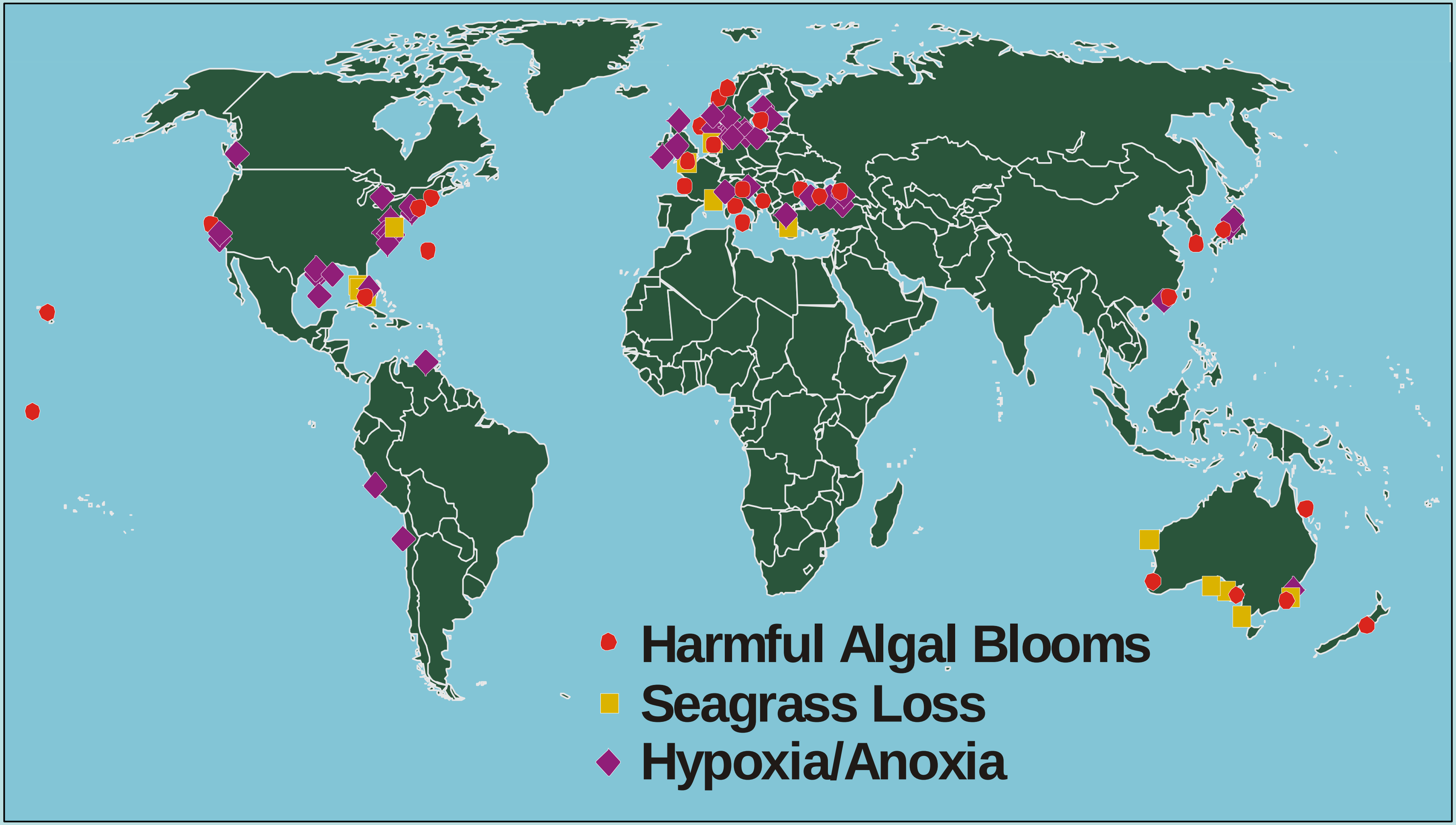
Outline

- **Background Concepts of Eutrophication and "Dead-Zones"**
- **Introduce Features of Chesapeake Bay**
- **Describe Hypoxia Patterns in Bay**
- **Explain Factors Regulating Hypoxia :**
  - **Physical—Flow, Stratification, Mixing**
  - **Biological—Nutrient Loading**
- **Ecological Responses to Hypoxia**
- **Concluding Comments**
- **Epilogue: "Ecosystem Feedbacks" and Restoration of Eutrophic Coastal Systems**

Eutrophication Effects on Coastal Ecosystems



Global Scale of Eutrophication



Background Information

- *Chesapeake Bay*

Key Bay Features

•Large ratio of watershed to estuarine area (= 14:1)

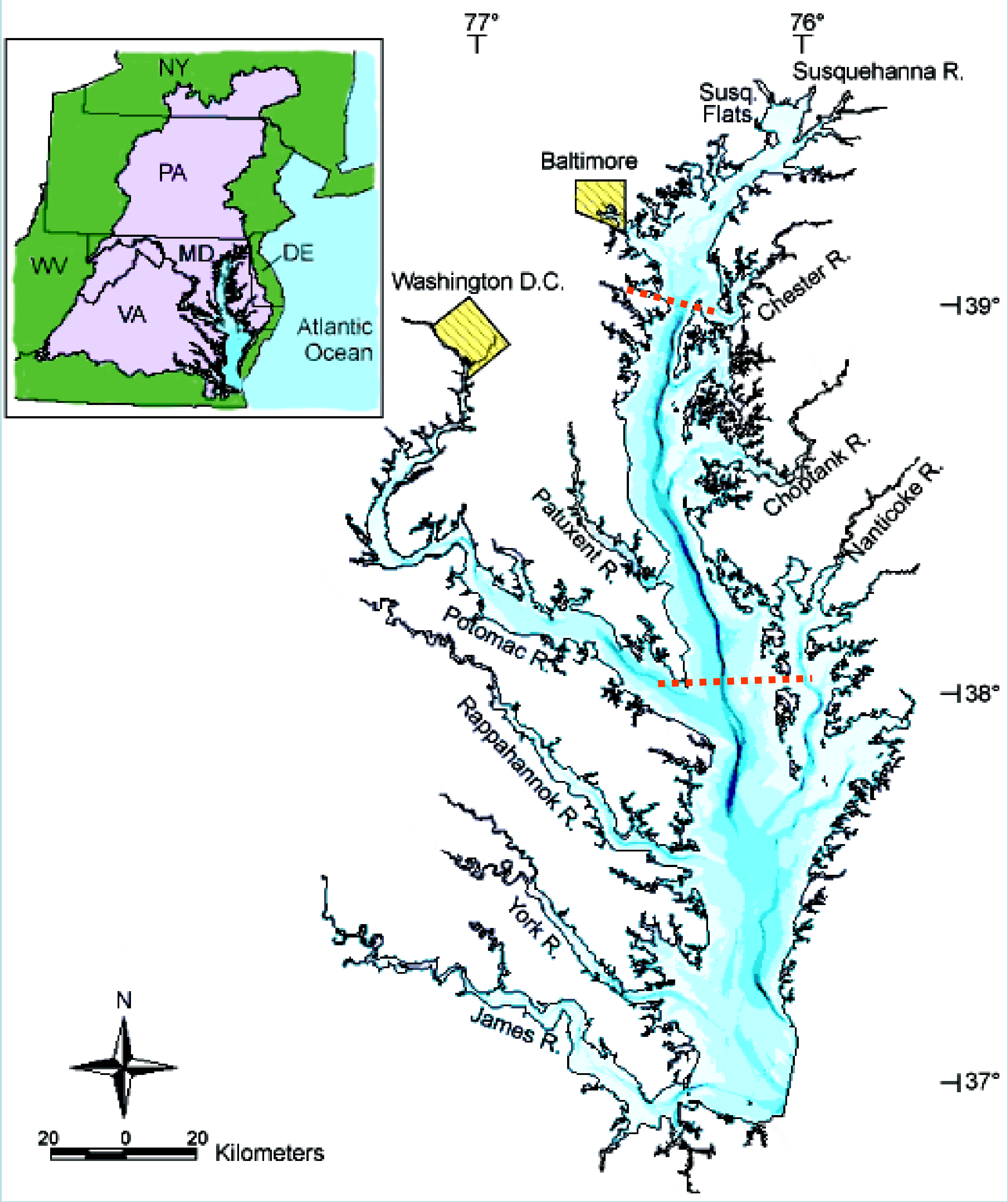
• Deep, narrow channel is seasonally *stratified*

• Broad shallows flank channel (mean z = 6.5m)

• Most of Bay volume is in the mainstem

• Most of its surface area in tributaries & embayments

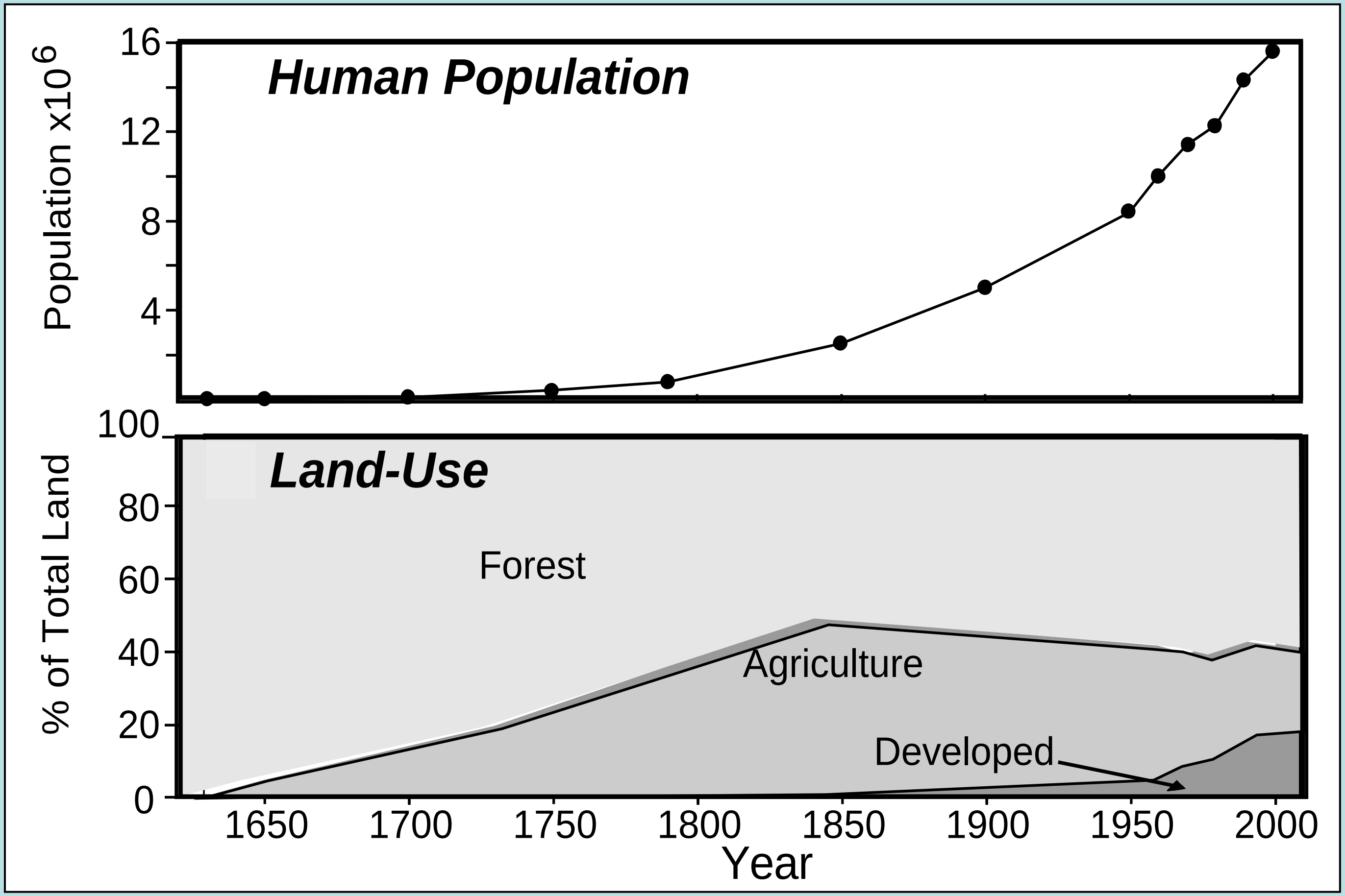
• Relatively long water residence time (~ 6 mo)



Watershed Changes: Land-Use & Population

- **Exponential growth in water-shed population**

- **Land-use shift from forest to farm (thru 1850) to developed (1850 – 2000)**



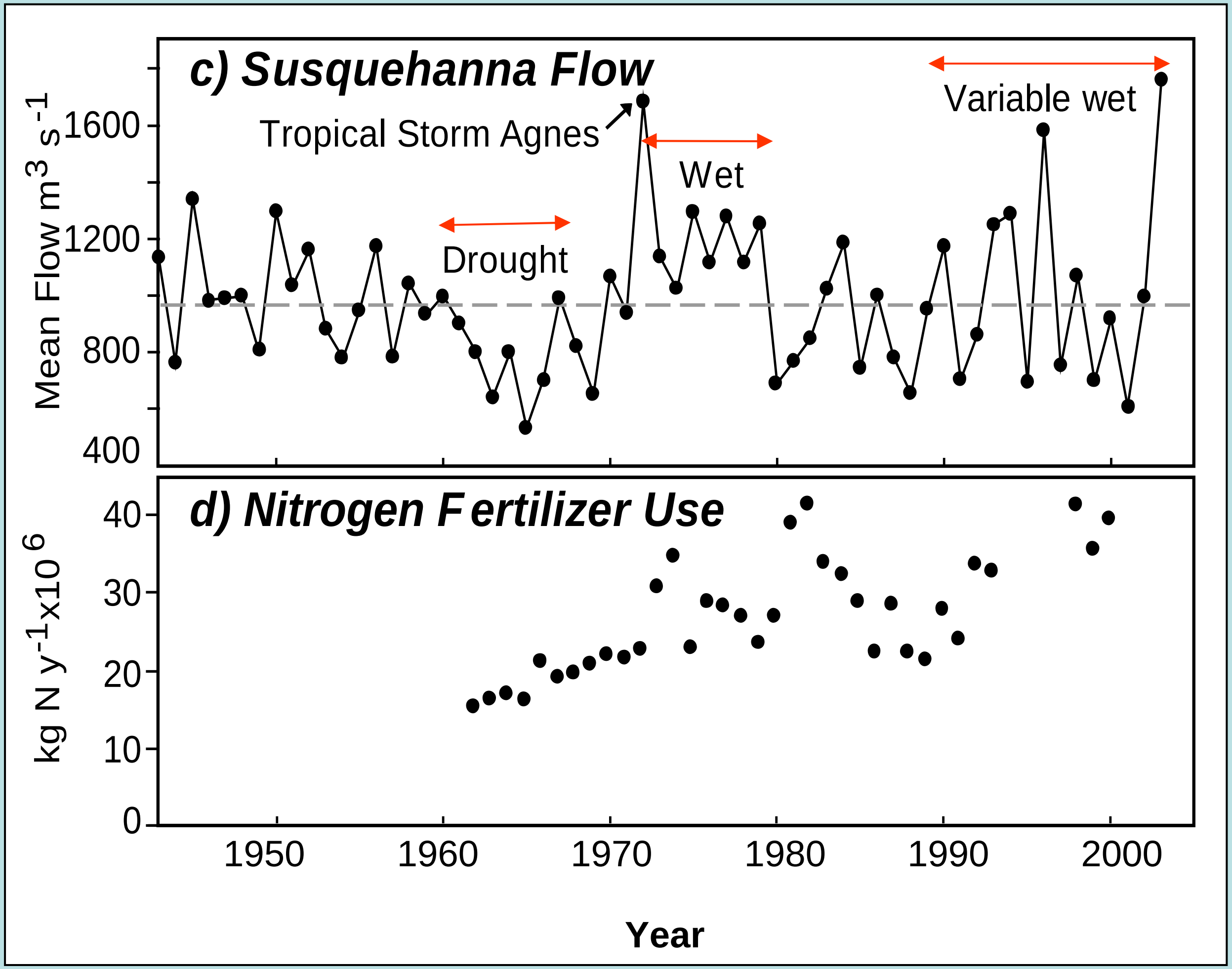
Susquehanna River Flow is Large

(Flood Flow At Conowingo Dam)

Watershed Changes & Variations: Flow & Fertilizer

- **Large variations in river flow (~4X); wet and dry decades but no long-term trends**

- **Fertilizer use in basin has been increasing since 1950, tripling since 1960**

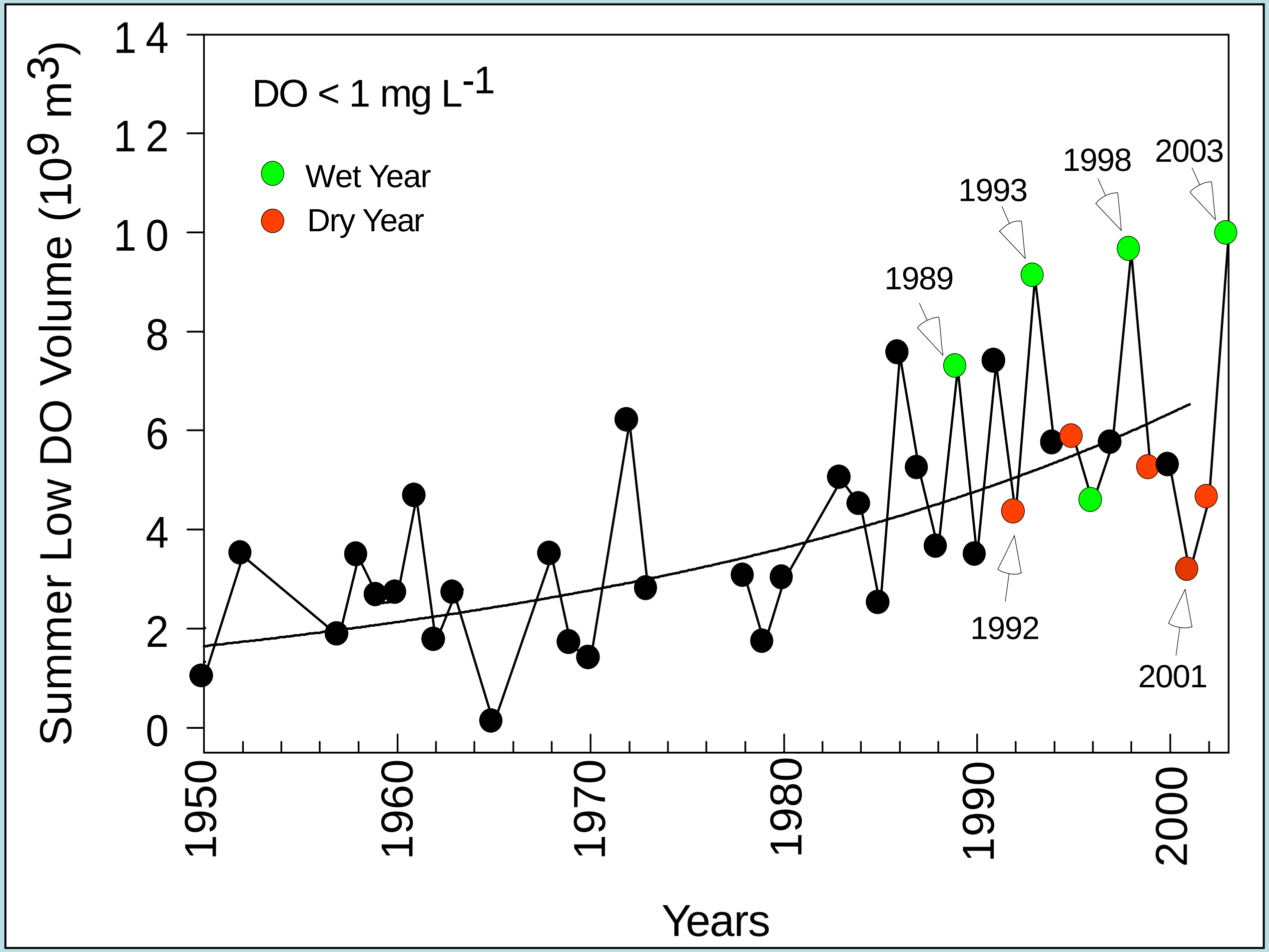


Hypoxia Patterns in Chesapeake Bay

Summer Hypoxic "Dead-Zone": 1950 - 2003

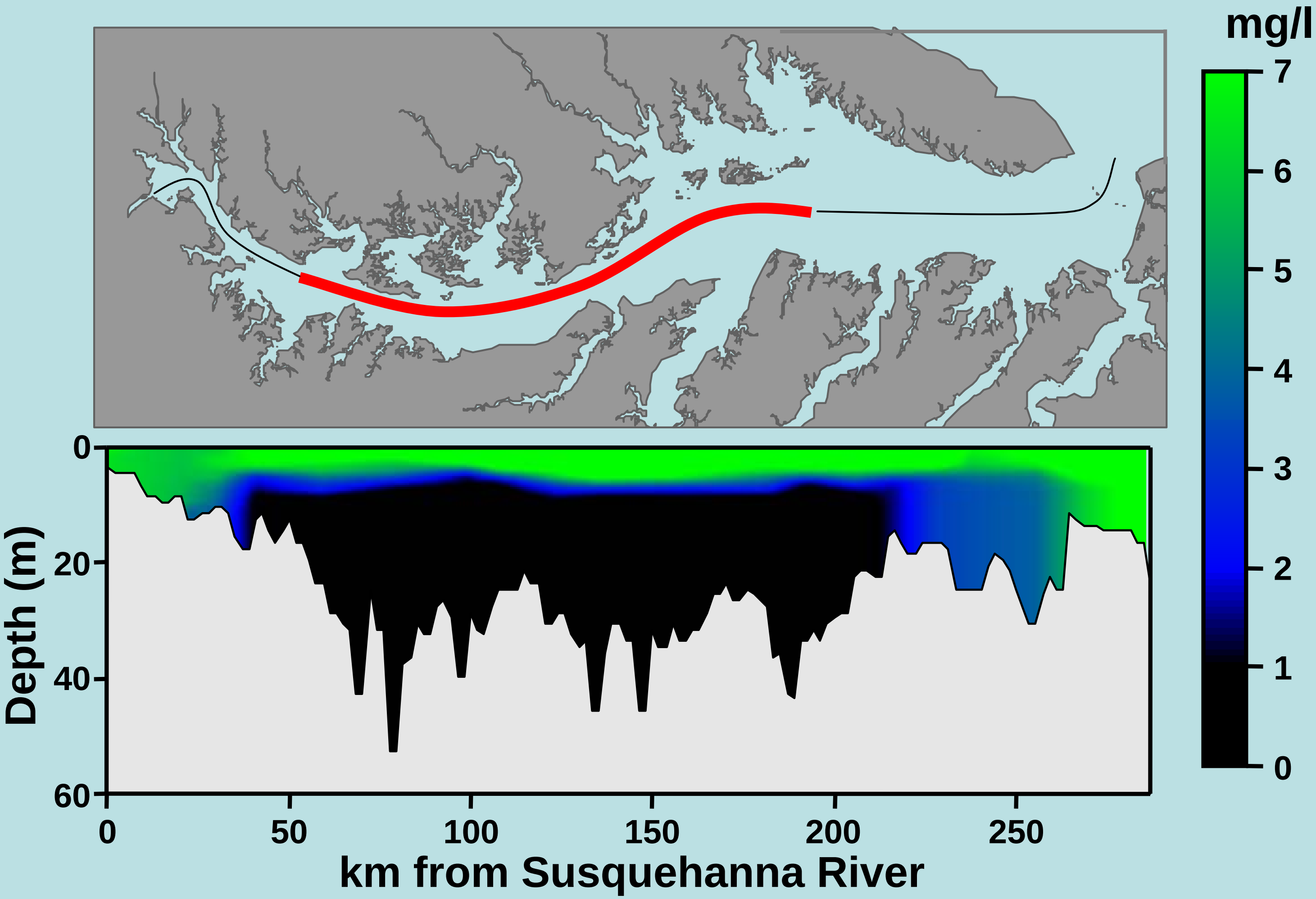
- **Clear increasing trend in volume of severely hypoxic (O_2 < 1 mg/L) from 1950-2003**

- **Within long-term trend, hypoxia is greater in high flow years (wet = green dot) compared to low flow years (dry = red dot)**



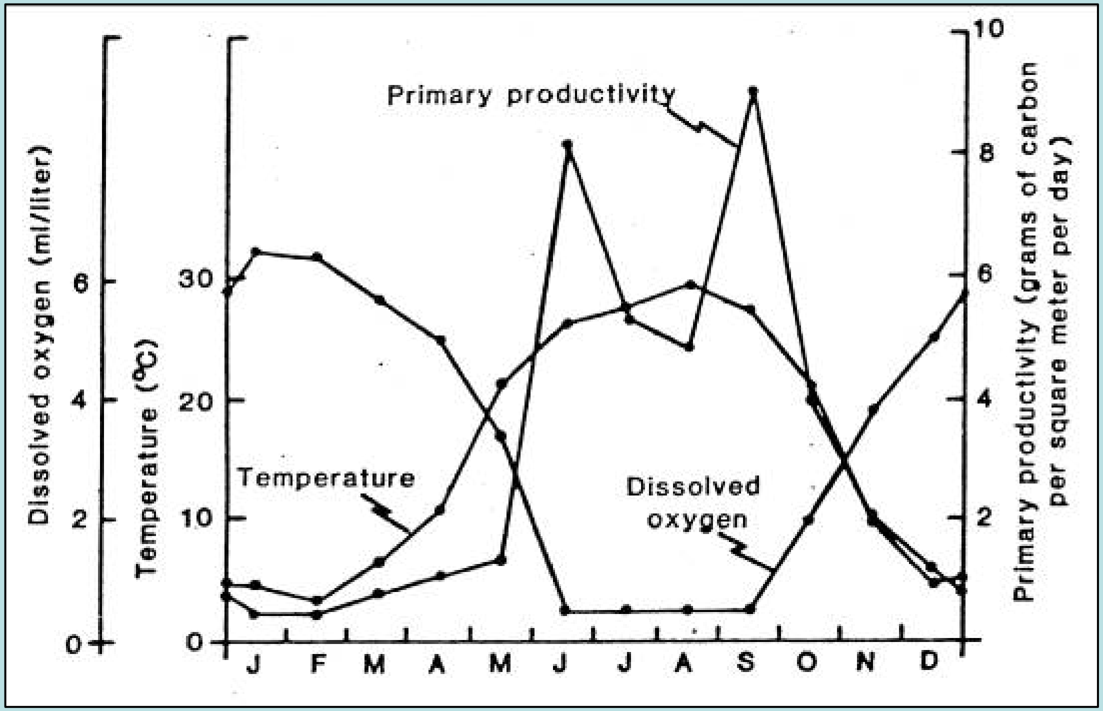
(Hagy et al 2004)

Location of Bay Hypoxic Zone



(Hagy 2002)

Seasonal Cycle of Algal Productivity, Temperature and Bottom Dissolved O_2



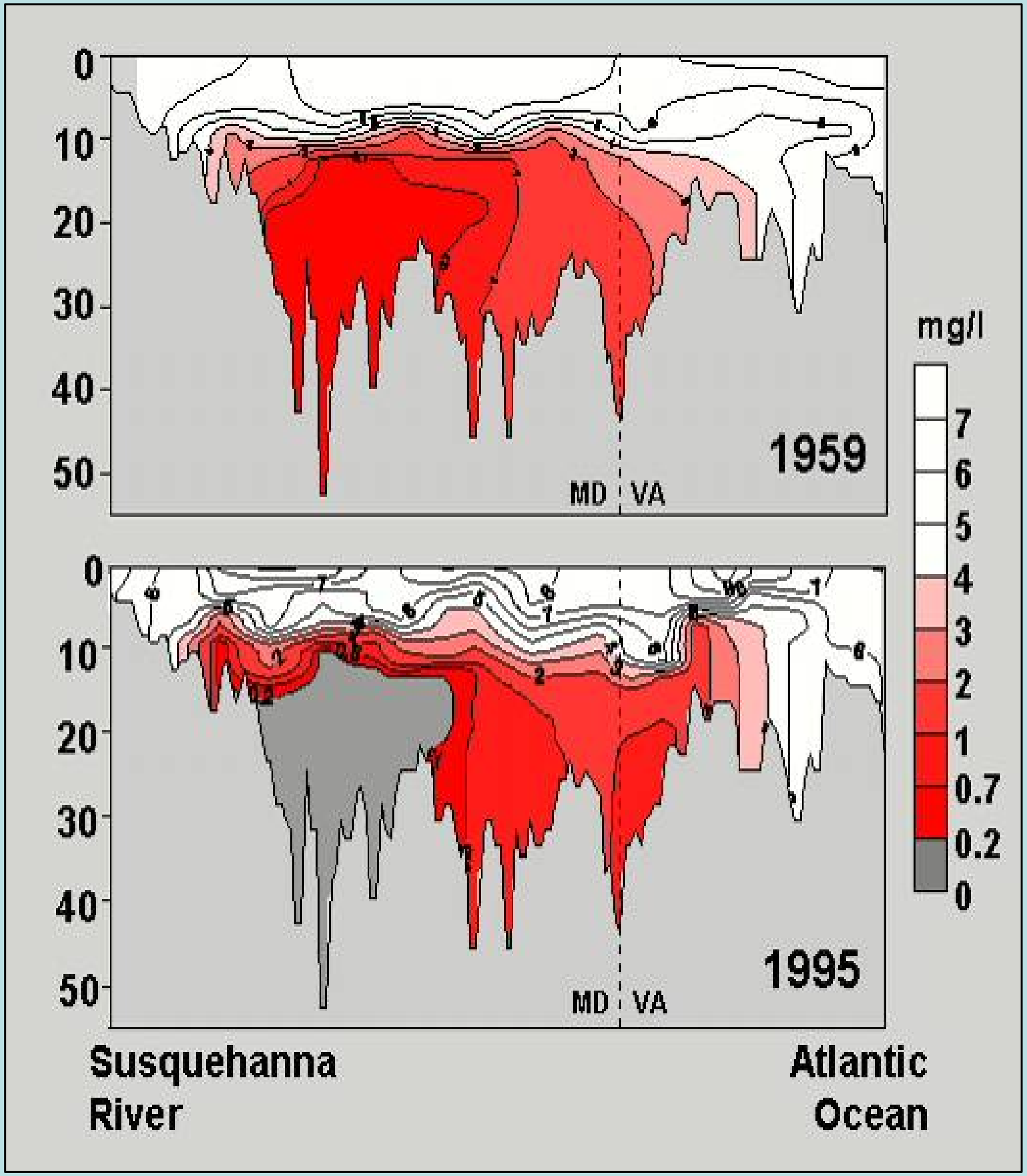
- **Hypoxia confined to summer (June-September)**
- **Hypoxia coincides with peak temperature and productivity**

Spatial Distribution of Bay Hypoxia: 1959 vs. 1995 (low flow)

- **Longitudinal sections of *summer* dissolved oxygen for two years with similar (low flow) freshwater inputs**

- **No anoxic conditions in 1959 but large anoxic (dead) zone in summer of 1995**

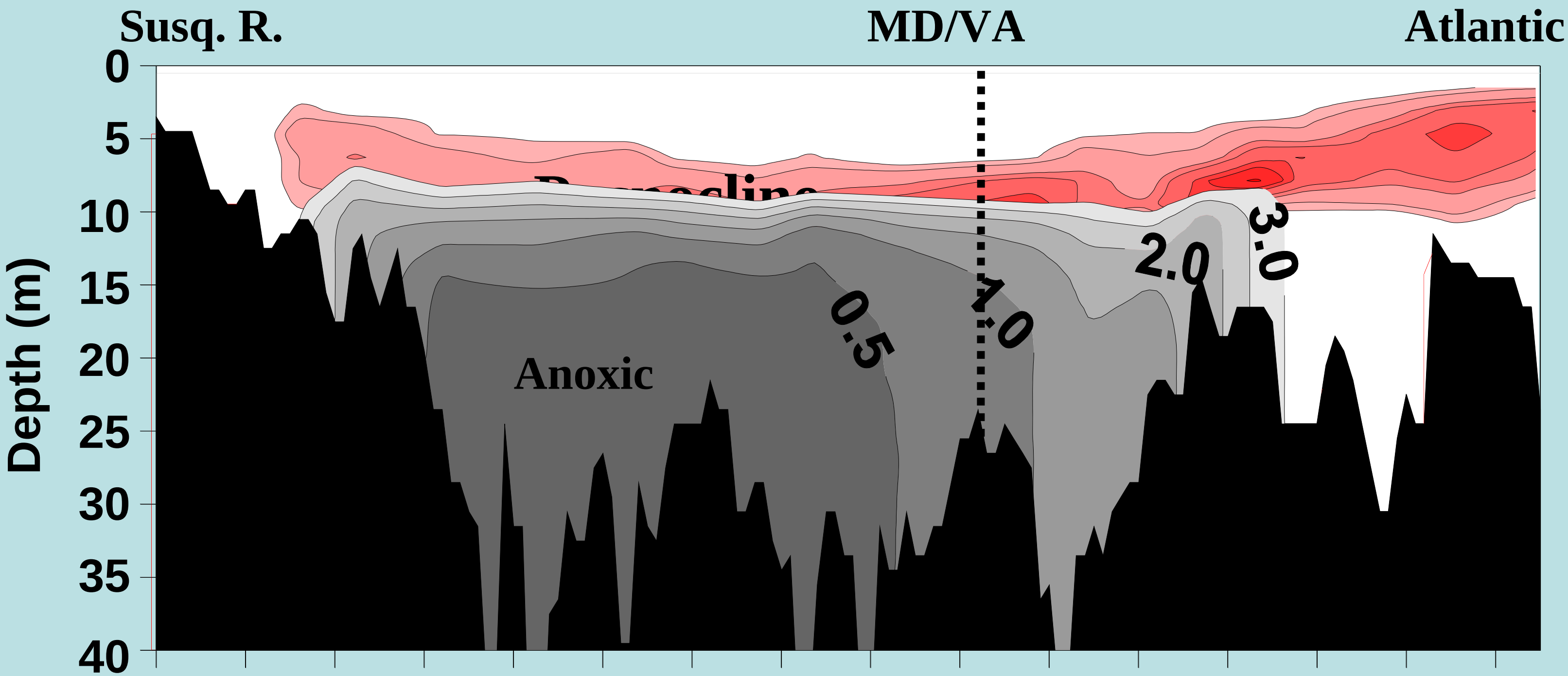
- **Upper oxic layer was much deeper in 1959 (10-12 m) compared to 1995 (5-10 m)**



Factors Regulating Hypoxia

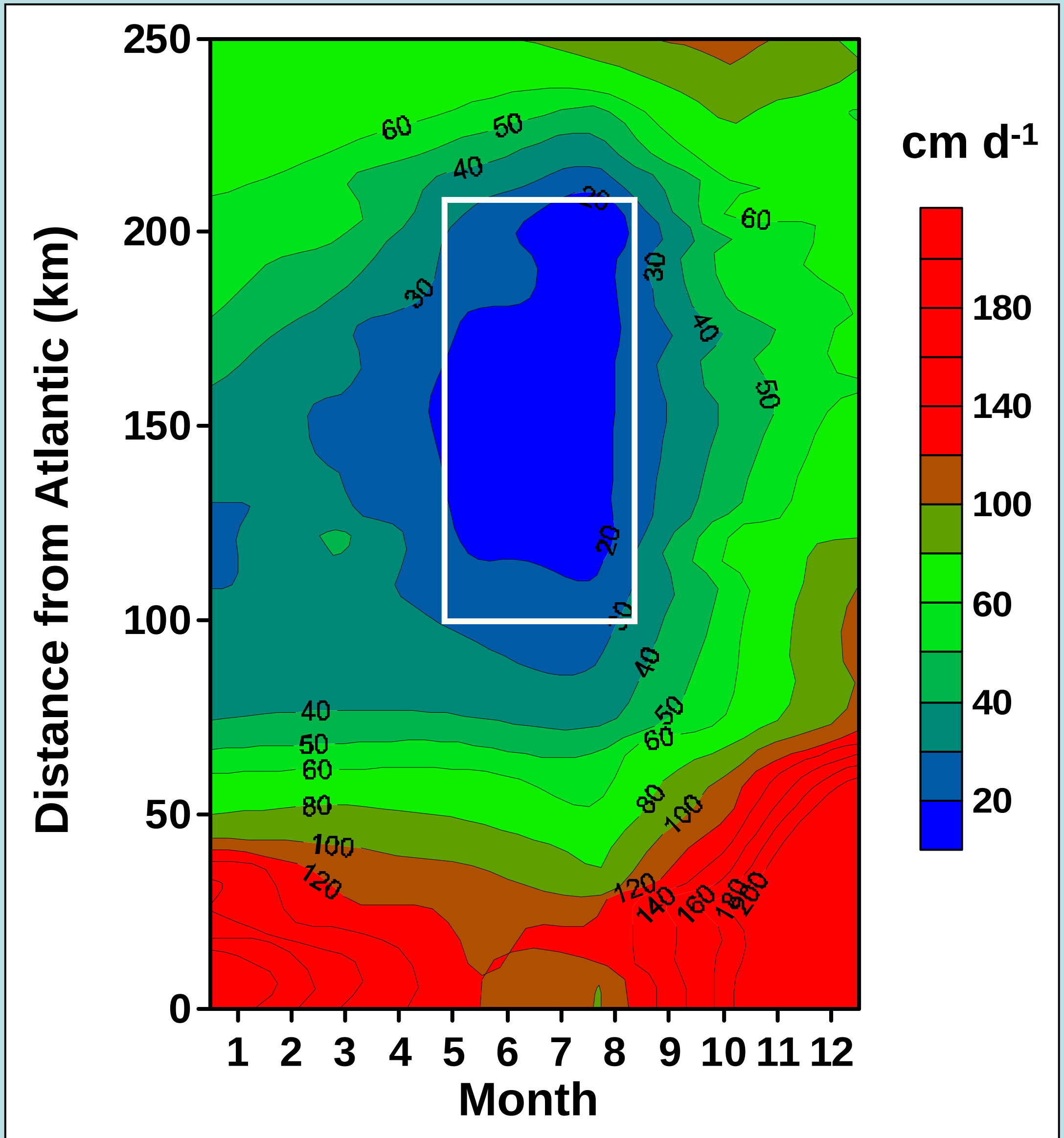
- ***Physical Factors***
- ***Ecological Factors***

Stratification Control of Hypoxia: Position & Intensity of Low O_2 Water



DO declines along landward bottom-layer flow …

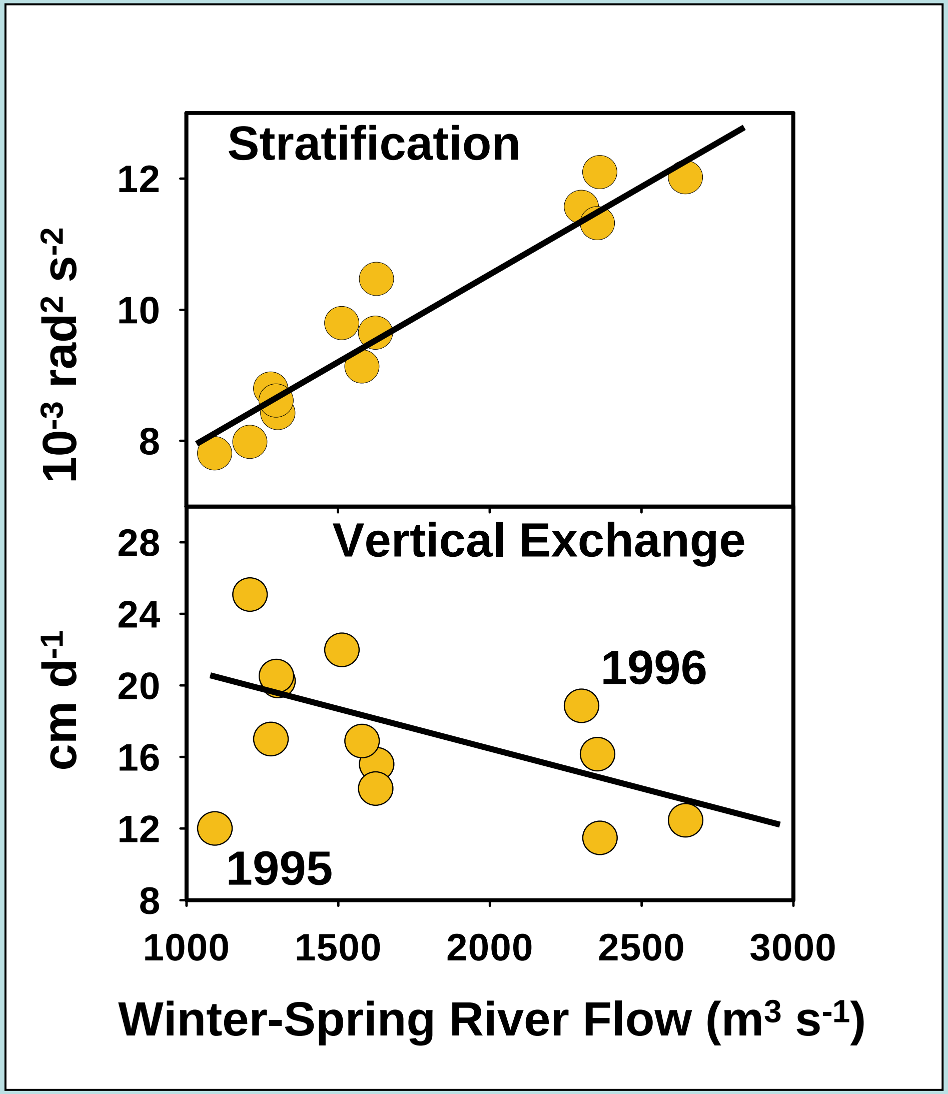
Vertical Exchange between Upper & Lower Layers



- Vertical exchange is minimal in mid-Bay from May-August
- Corresponds to location and duration of hypoxia.
- How does it vary inter-annually?

(Hagy 2002)

River Flow, Stratification, & Mixing (1986-'98)

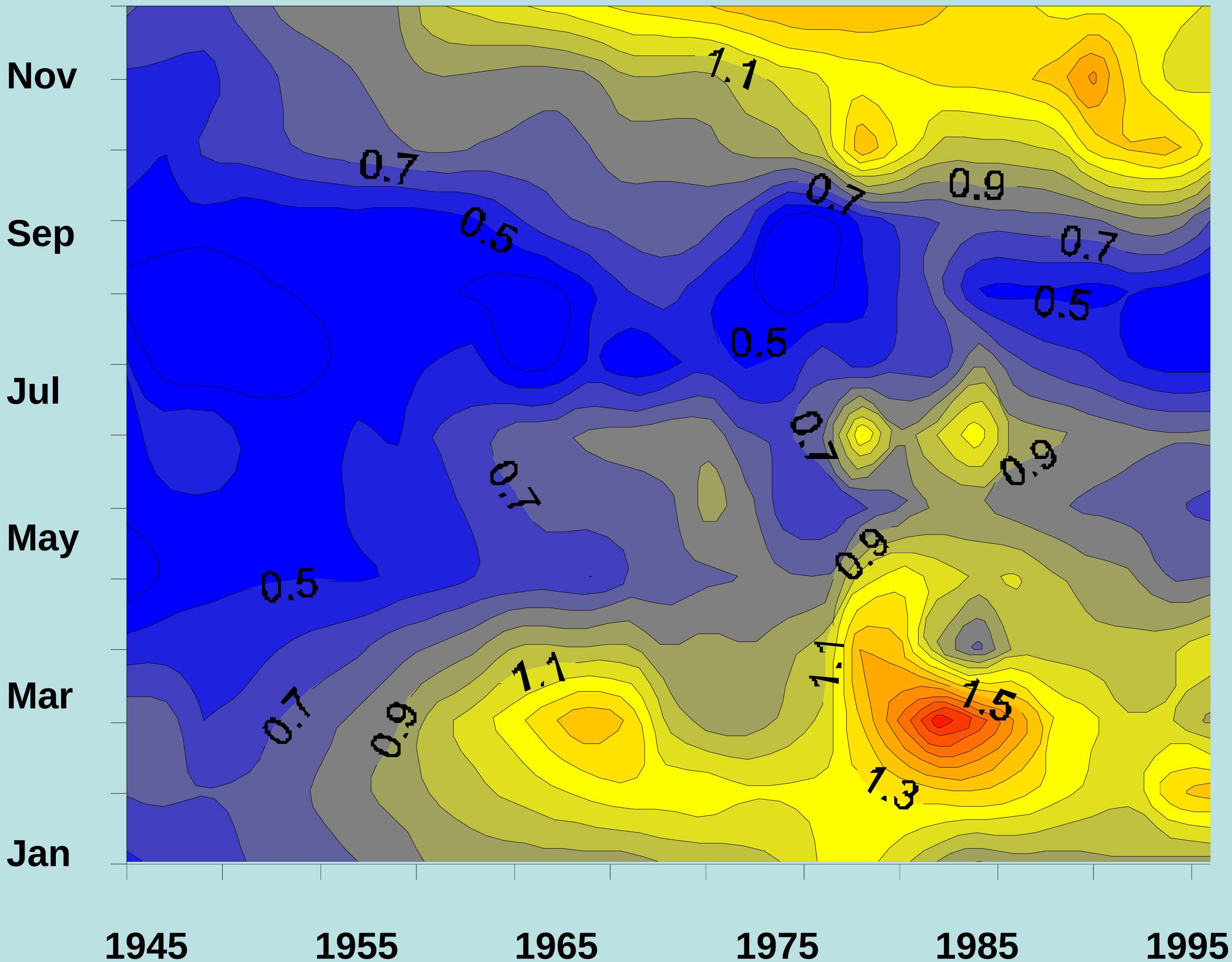


- **Stratification strongly correlated with river flow.**
- **Vertical exchange relation to flow is weaker (buoyancy vs. mixing).**
- **High flow also delivers more nutrients.**

(Hagy 2002)

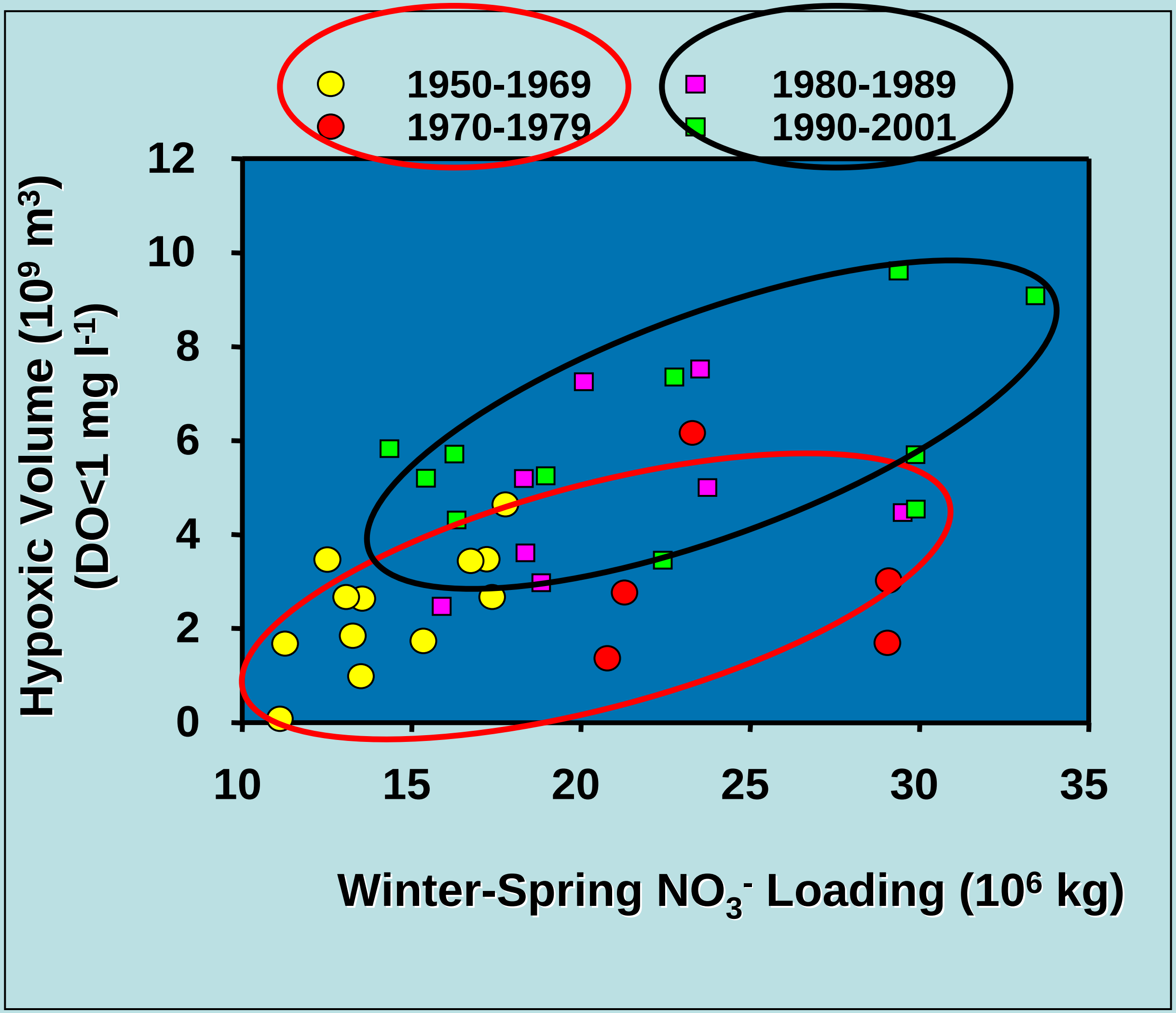
Increasing Nitrogen in Susquehanna River: Seasonal and Long-Term Trends

- **Long-term increases in nitrate levels & changes in seasonality seen over five decades**
- **Highest nitrate levels (yellow, red) occur in cold months**
- **Nitrate trends are closely related to total Nitrogen**
- **N-loads to Bay doubled from 1945 to 1970**



(Hagy et al 2004)

Hypoxia Response to N Loading (1950-2001): Unexpected Shifts in Ecosystem Processes

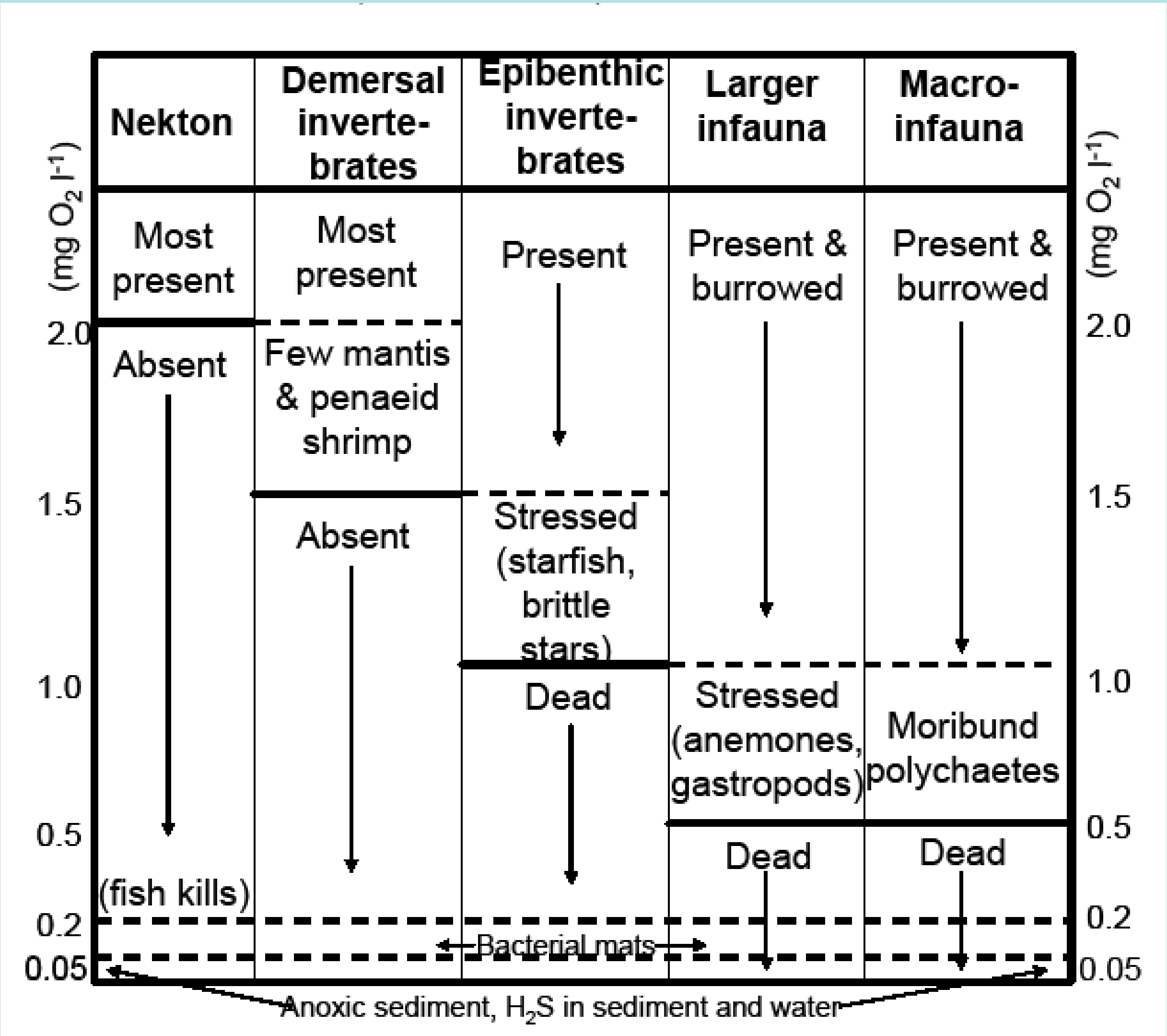


- **Hypoxia increases with N loading.**
- **Equivalent N load since 1980 generates more hypoxia than in past.**
- **Is system less able to assimilate N-load?**
- **No clear explanation for 'regime shift'.**

(Hagy et al. 2004)

Ecological Consequences of Hypoxia & Dead-Zones

Summary of Faunal Responses to Hypoxia in Mississippi River Plume



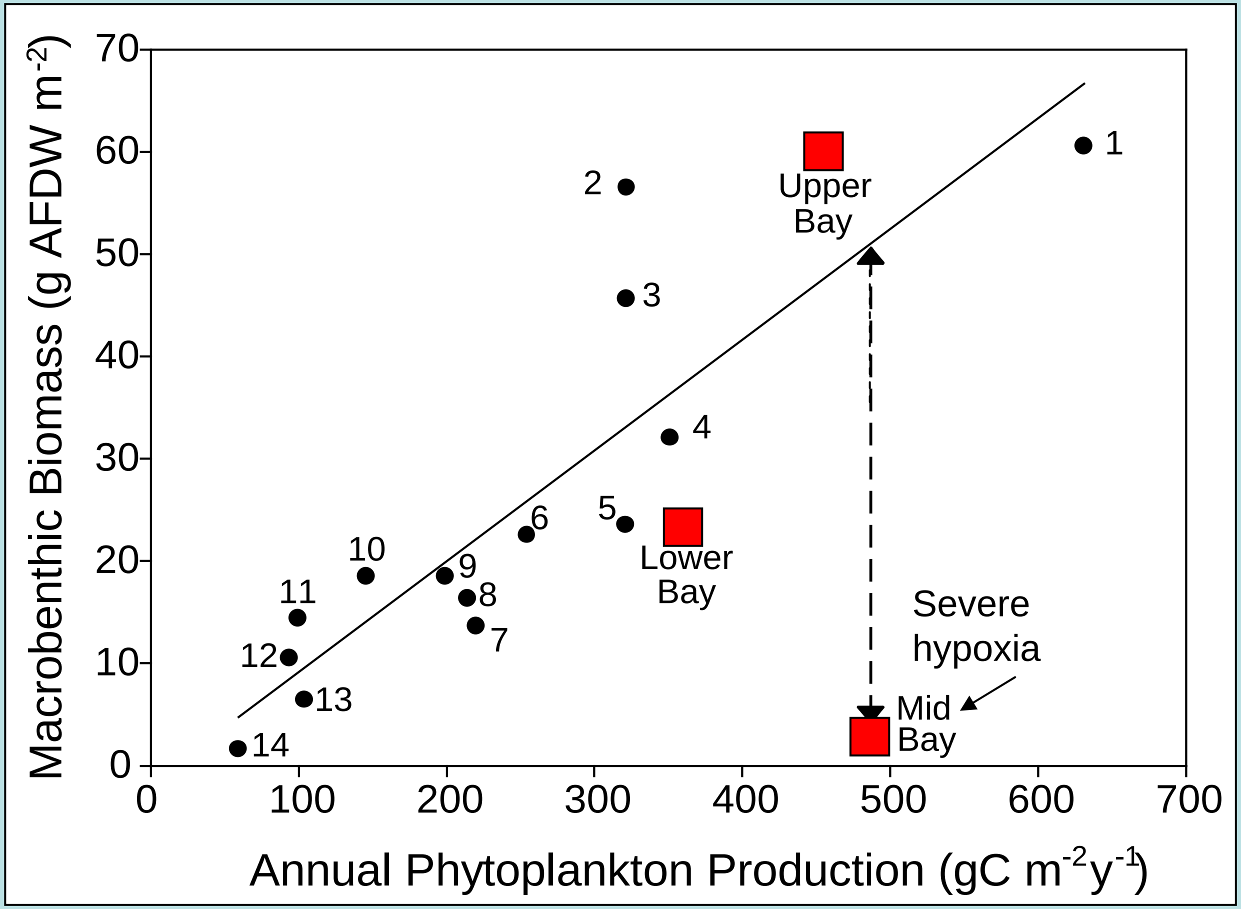
(Rabalais et al. 2001)

Hypoxia Degrades Habitat for Benthic Fauna in Chesapeake Bay

- Comparing estuaries worldwide (#1-14), benthic animal abundance tends to be proportional to algal food produced in water

- Upper and lower Bay generally follow this trend, but hypoxic mid Bay has lower animal biomass than expected

- Loss of bottom habitat causes loss of important fish and invertebrate animals



(Hagy 2002, Herman et al. 1999)

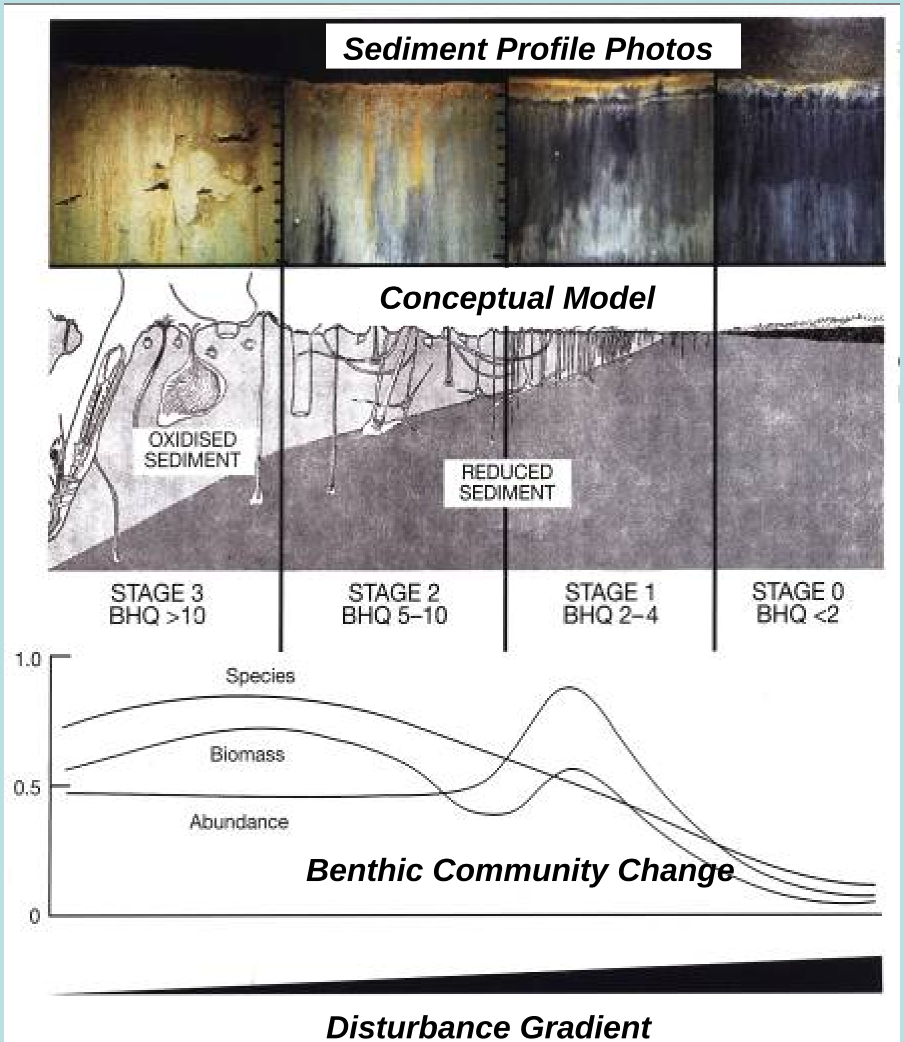
Degraded Bottom Habitats Cause Loss of Benthic Fauna in Hypoxic Regions of Bay

- **With increasing nutrient enrichment and organic production, depth of sediment oxidized zone declines**

- **Fauna shift from diverse large deep-burrowing forms to few small surface-dwellers**

- **Benthic macrofaunal abundance declines markedly**

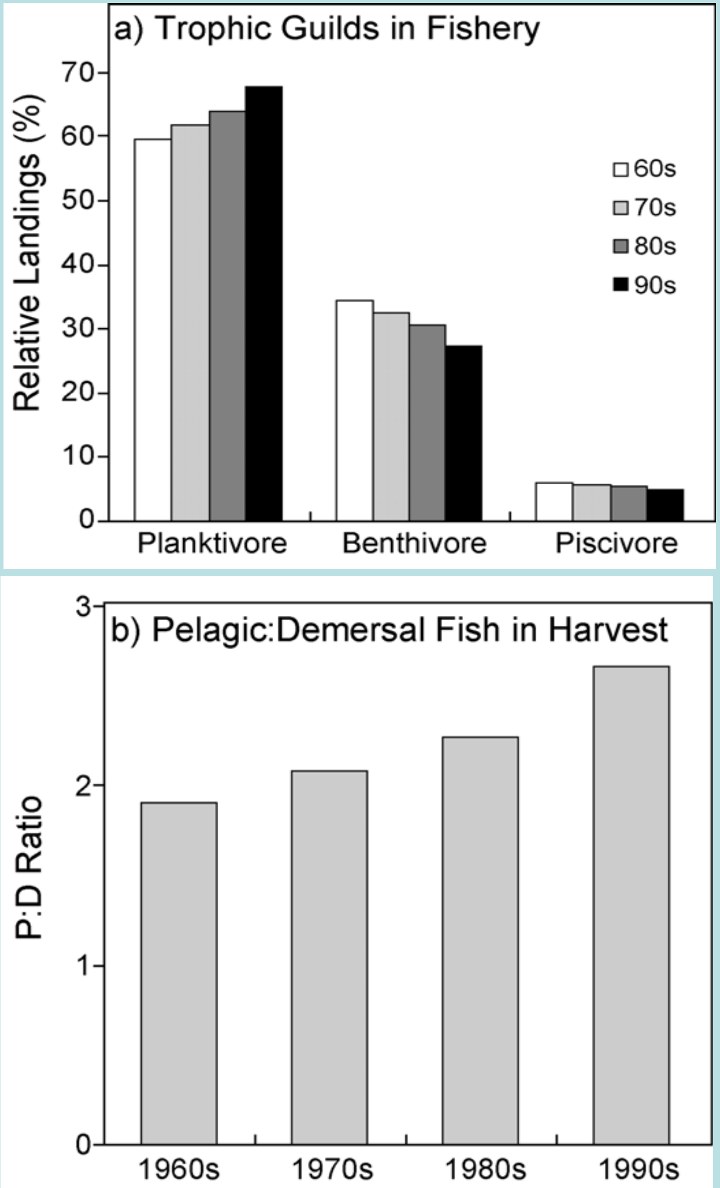
- **Model derived in part from work of by Don Rhoads in LIS**



(Nilsson and Rosenberg 2000)

Degraded Bottom Habitats Alter Fish Community Structure and Harvest

- **Steady decrease in the proportion of fisheries harvest from bottom-dwelling animals**
- **General degradation of bottom habitats in shallow (loss of SAV) and deep (hypoxia) waters**
- **Similar trends are being reported in other systems worldwide**
- **Possible loss of trophic efficiency (fish harvest per unit photosynthesis)**



(Houde in Kemp et al 2005)

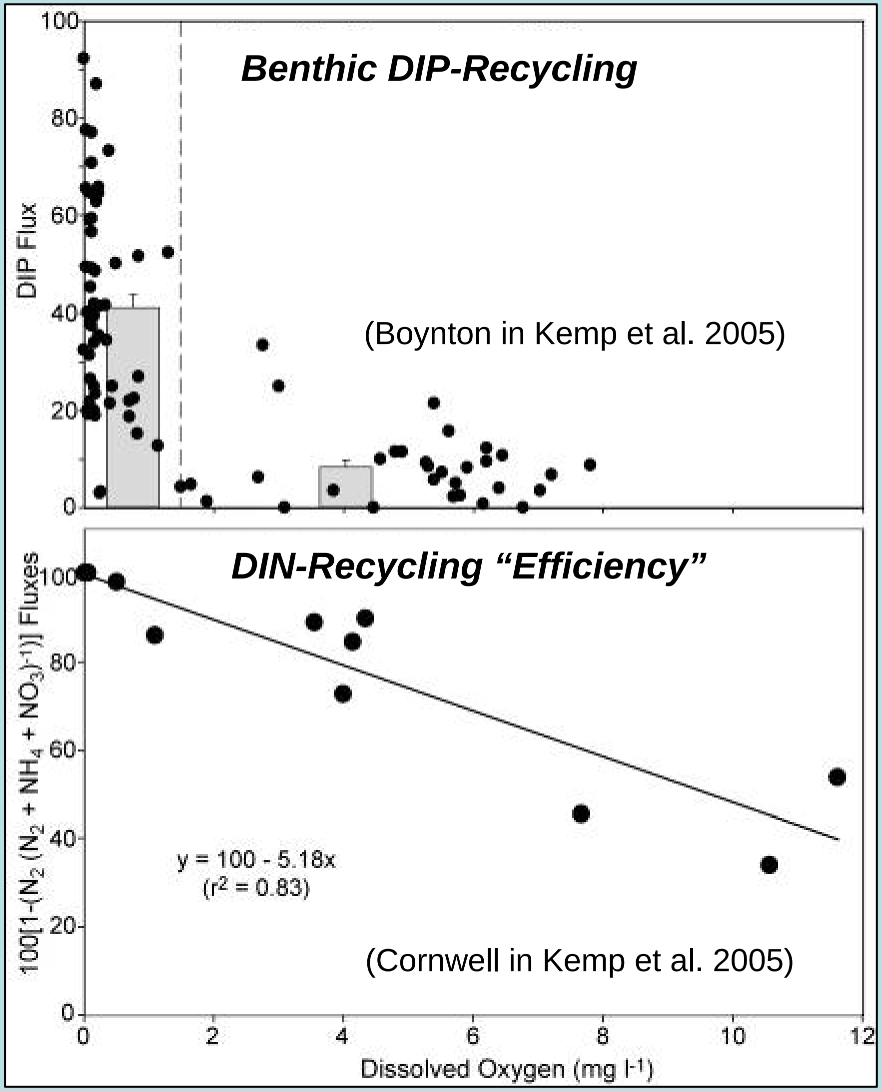
Concluding Comments 1

- **Coastal eutrophication is a global scale phenomenon**
- **Many features of Chesapeake Bay make it susceptible to seasonal development and expansion of hypoxic “dead zones”**
- **Seasonal deep-water hypoxia is generally regulated by stratification and enhanced nutrient loading**
- **A dramatic upward shift in the size and intensity of Bay hypoxia occurred in the early 1980s**
- **Similar hypoxic ‘regime shifts’ have been reported elsewhere**
- **Hypoxic dead zones result in reduced abundance, diversity and production of benthic invertebrates and demersal fish.**

Epilogue: ‘Ecosystem Feedbacks’ and Restoration of Eutrophic Coastal Ecosystems

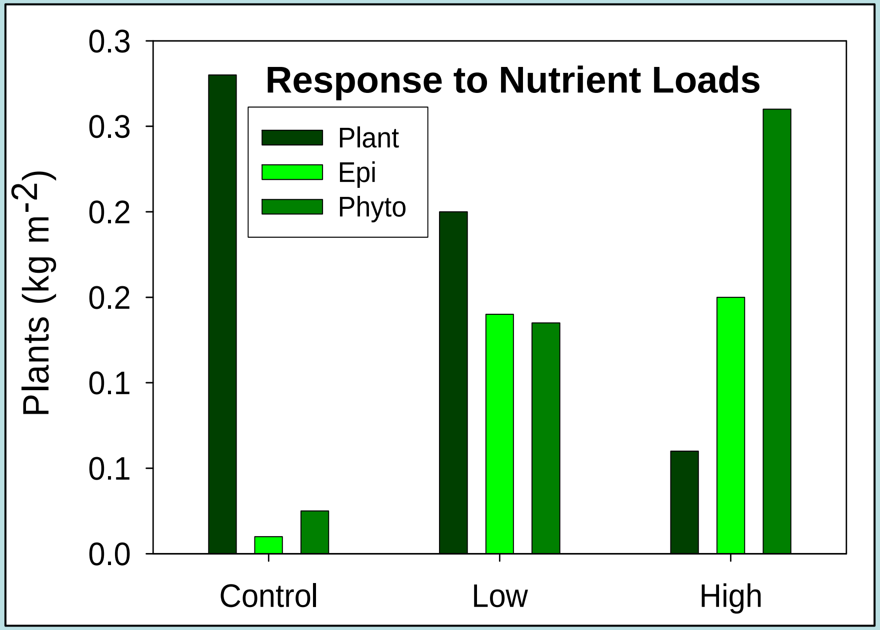
Bottom-Water Hypoxia Enhances Recycling of Benthic Nutrients

- Benthic nutrient (PO_4 & NH_4) recycling sustains algal production and hypoxia thru summer
- Hypoxia causes higher rates nutrient recycling rates
- Thus, hypoxia promotes more algal growth per nutrient input to the Bay
- For N & P recycling, same effect of low O_2 but different mechanisms



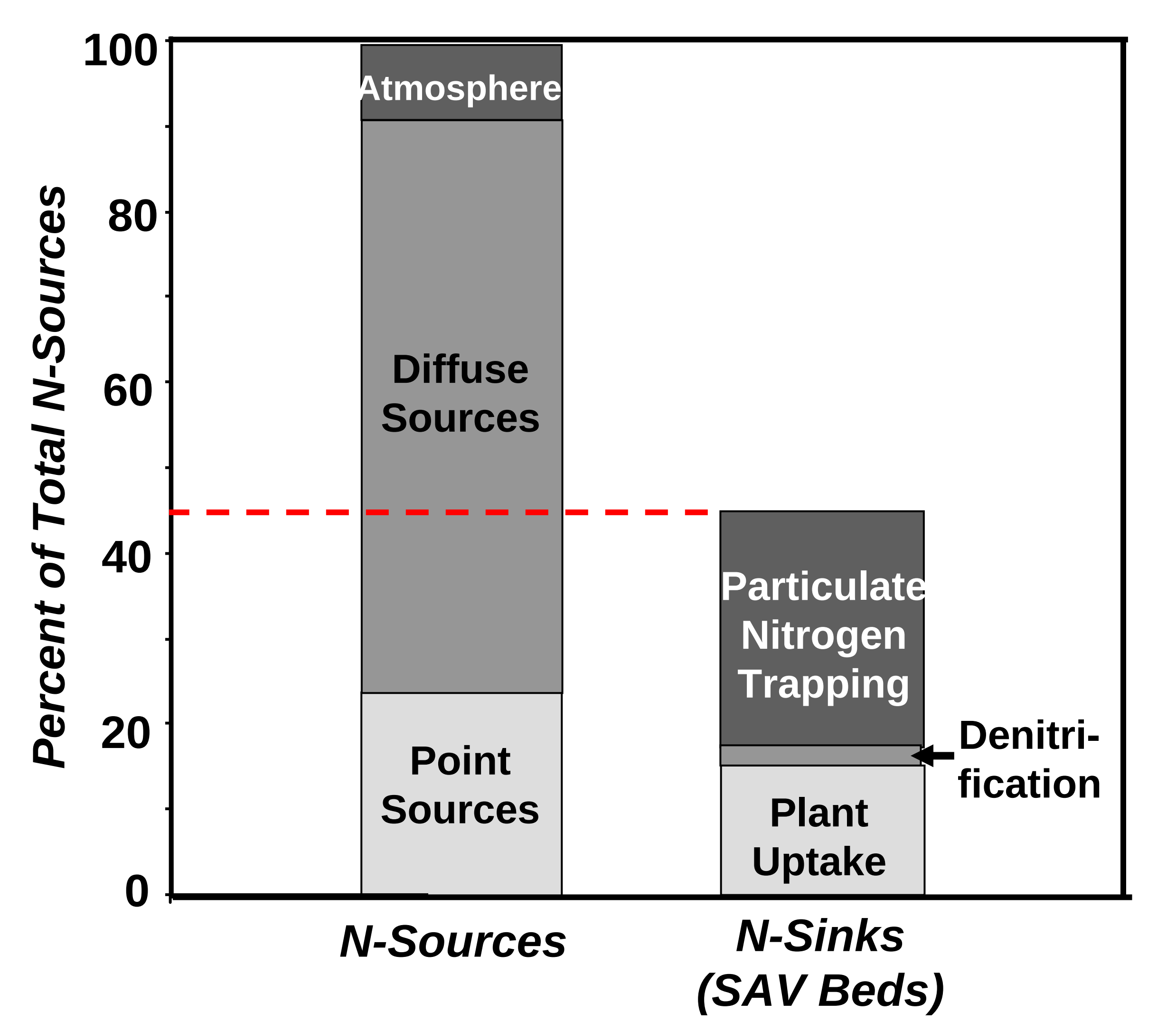
Seagrass (SAV) Decline:
Loss of Particle & Nutrient Trapping

- **Dramatic decline in SAV between 1962 & 1982 throughout the Bay**
- **Many factors contributed to decline, but increased nutrients was primary factor**



Excess Nutrients Inhibit SAV Survival But Healthy Beds are Nutrient Sinks

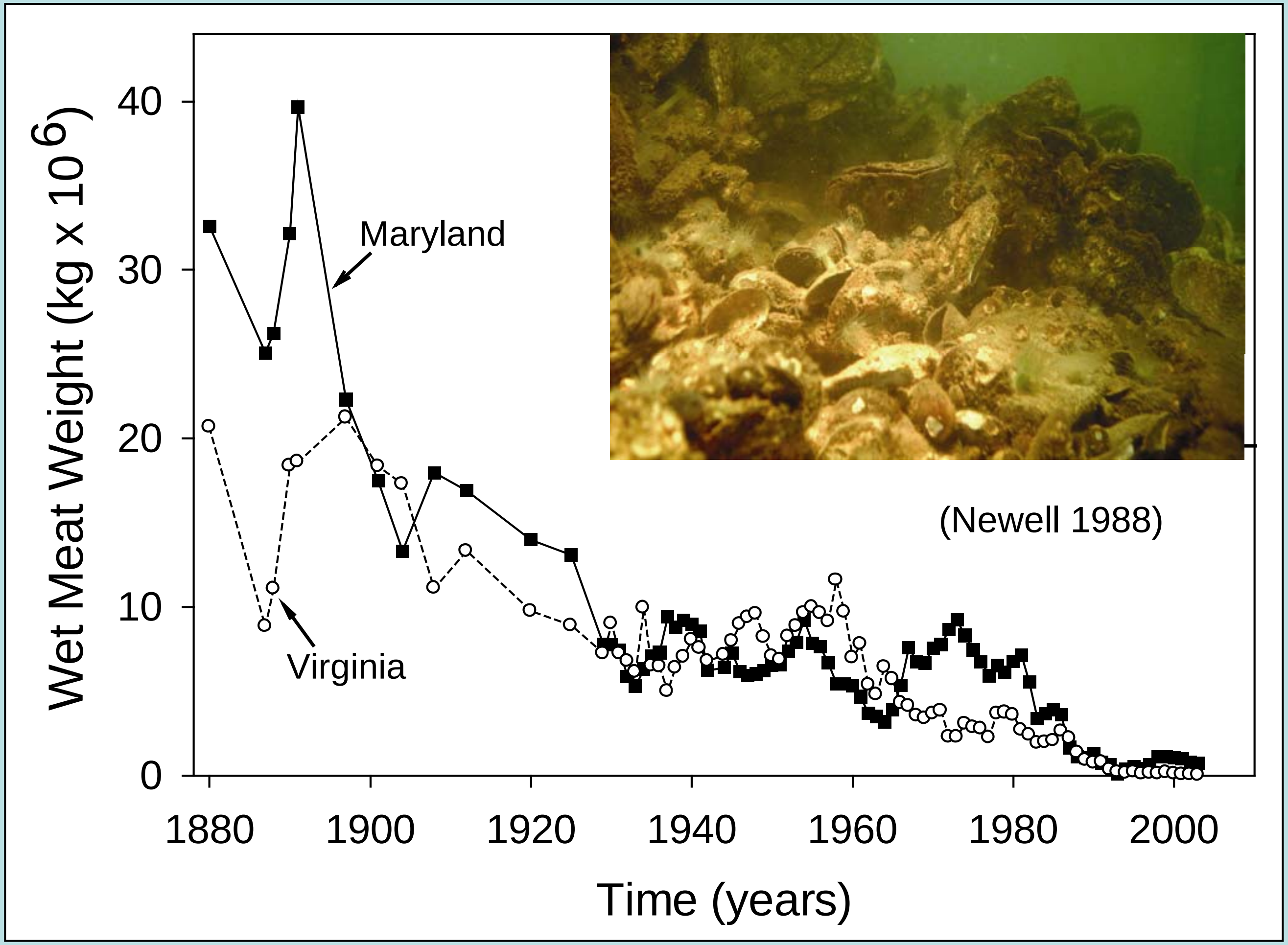
- Historical Bay SAV beds were capable of 'removing' ~45% of current N Loading
- Primary pathways of N removal would be trapping particulate N & direct assimilation
- Calculation only considers mainstem upper (MD) Bay
- N removal rates would be larger if whole Bay were considered



(Kemp et al 2005)

Oyster Decline: Loss of Particle Filtration

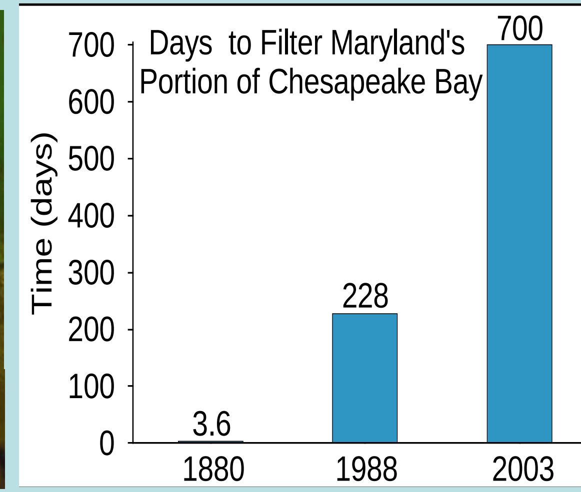
- Decline in oyster abundance has caused loss of nutrient filtration capacity
- Oyster declines due primarily to over-fishing and disease
- Historic oyster populations were able to filter Bay water volume in days
- Current oyster populations filter Bay water in months-years
- Oyster restoration would help mitigate eutrophication effects

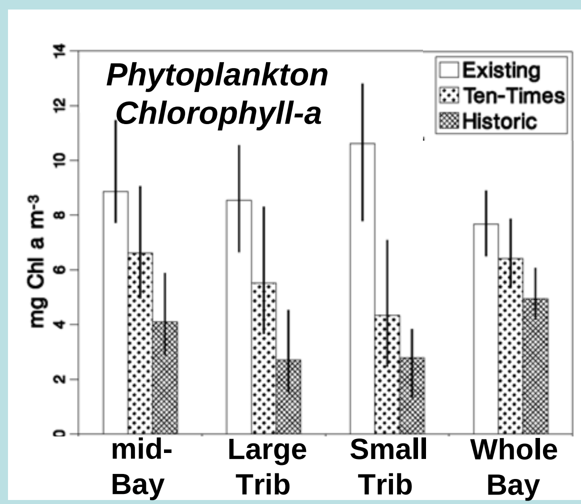


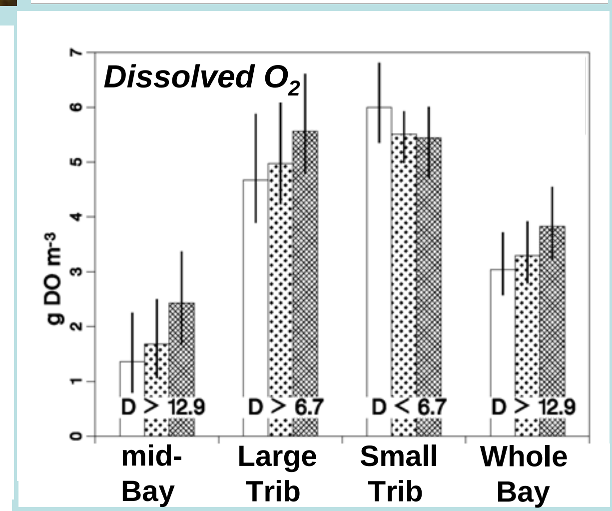
(Kemp et al 2005)

Oyster Filtration Effects on Bottom Hypoxia

- Oyster restoration to meet management mandate (10x), and to estimated pre-colonial conditions (100x)
- Dramatic declines in phytoplankton with restoration throughout Bay
- Small improvements in bottom O_2 with oyster restoration (~ effects of reduced nutrient loading)
- Restoration improves water clarity (& SAV cover)
- 10x restoration ~ 50% effect of 100x restoration



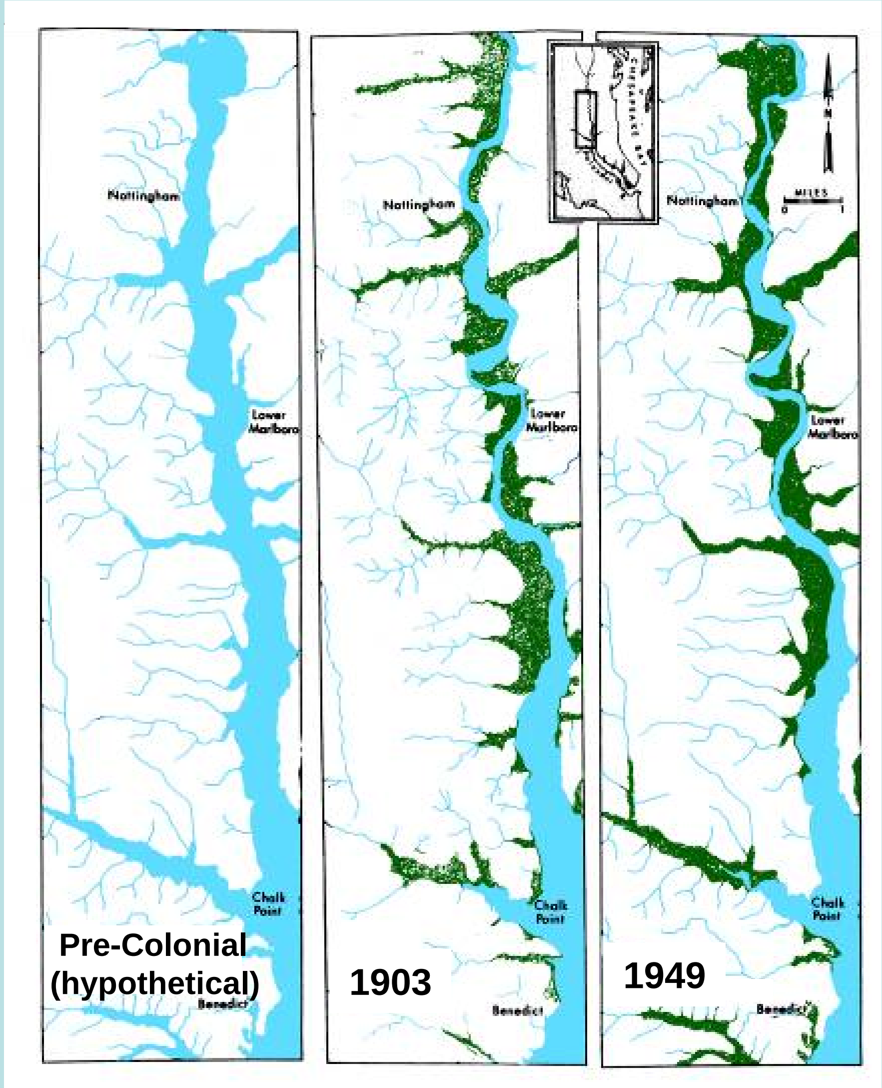




(Cerco and Noel 2007)

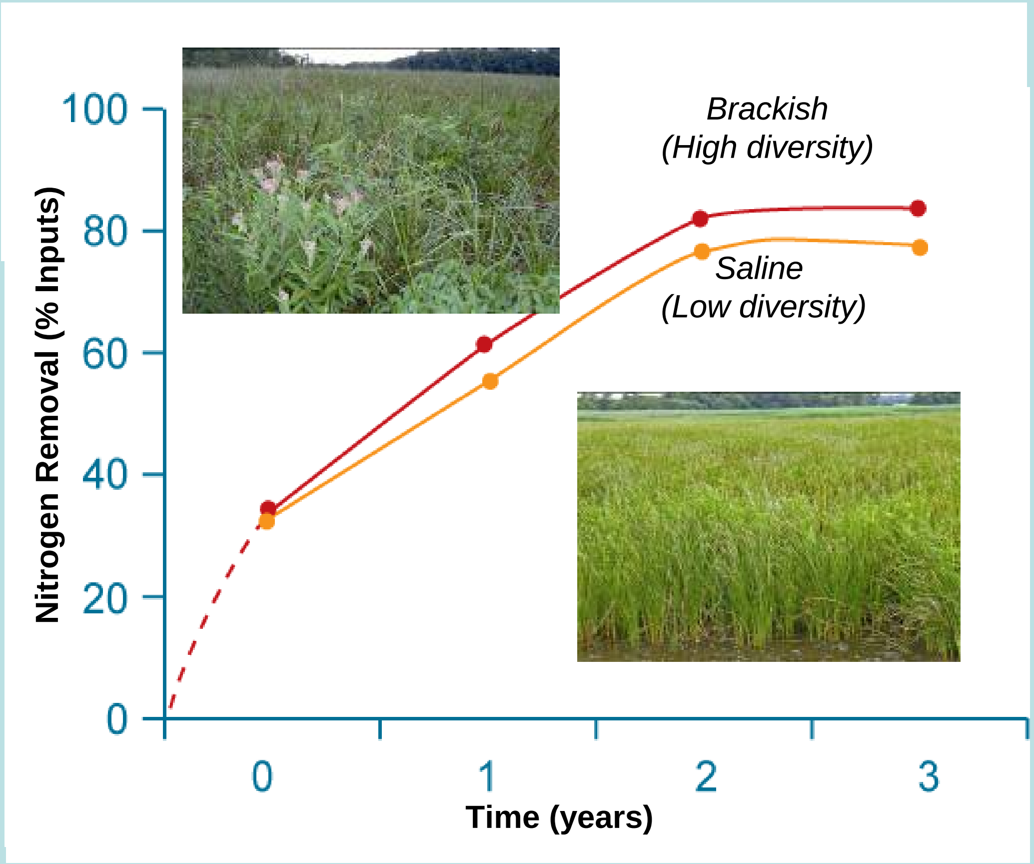
Tidal Marshes Expanding with Soil Erosion, But Contracting with Sea-Level Rise

- **Tidal marshes are important features of Bay watershed**
- **Marsh area expanded since colonial times due to increased soil erosion from watershed**
- **Marshes have served as buffers filtering nutrient inputs from watershed**
- **Marsh area is declining due to sea level rise and reduced soil erosion**



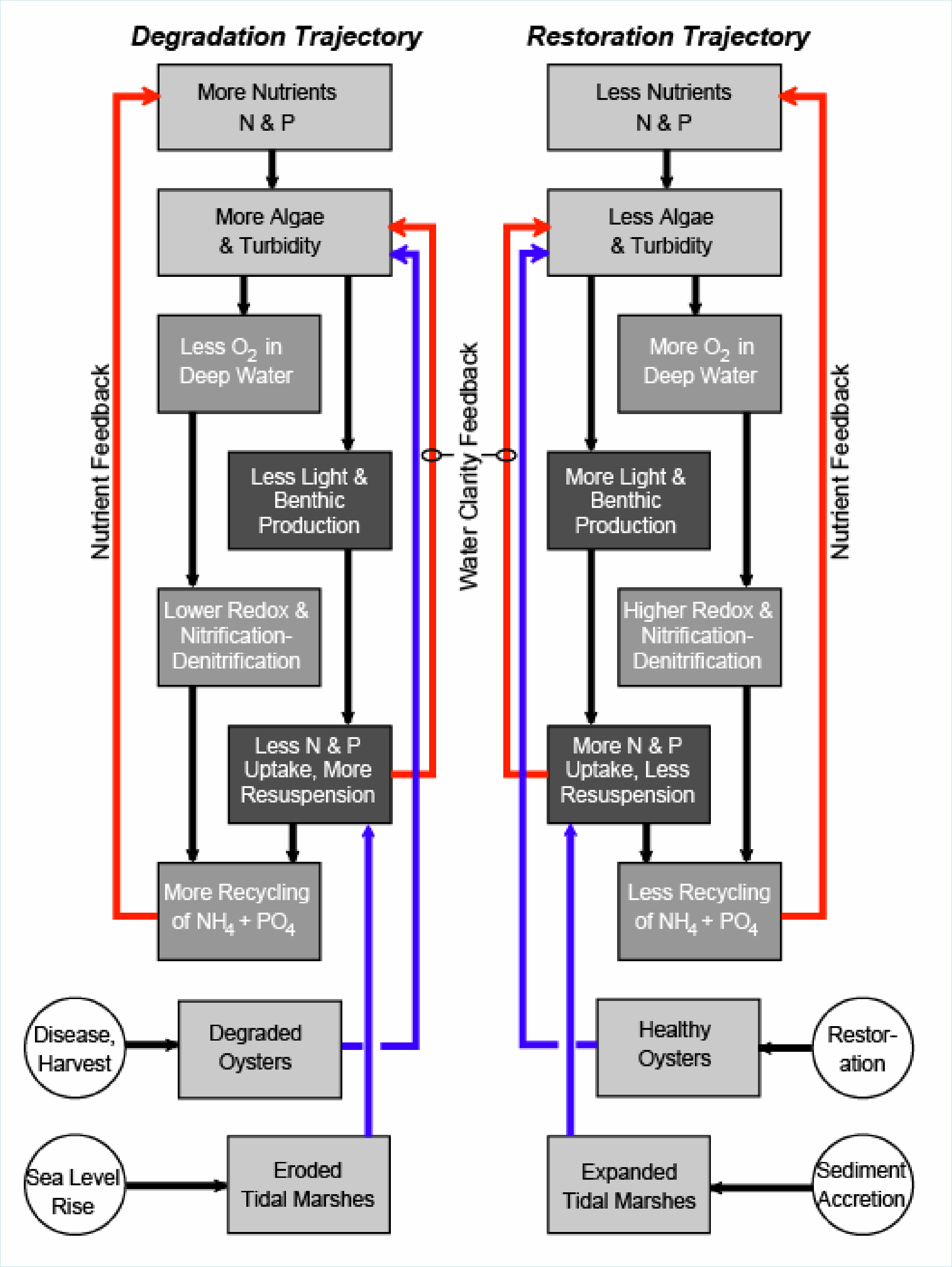
Tidal Marshes Serve as Nutrient Filters at Watershed-Estuary Margins

- **Tidal marshes have enormous capacity to filter sediments & nutrients**
- **Nitrogen removal capacity measured in experimental marsh ecosystems**
- **80% of N-inputs from land and estuary removed in three year-old marshes**
- **Similar effects on N-loading for diverse (brackish) and mono-specific (salt) marshes**
- **Marsh restoration would help re-establish lost filtration capacity**



Ecosystem Feedbacks affect Bay Response to Nutrient Management

- **Positive & negative feedbacks control paths of ecosystem change with Bay degradation**
- **Among other mechanisms, N & P inputs affect hypoxia & light**
- **Hypoxia leads to more nutrients, more algae, & more hypoxia**
- **Turbidity leads to less SAV causing more turbidity, less SAV**
- **Oysters & marshes tend to reinforce these feedbacks**
- **Processes reverse w/ restoration, thus reinforcing trends**

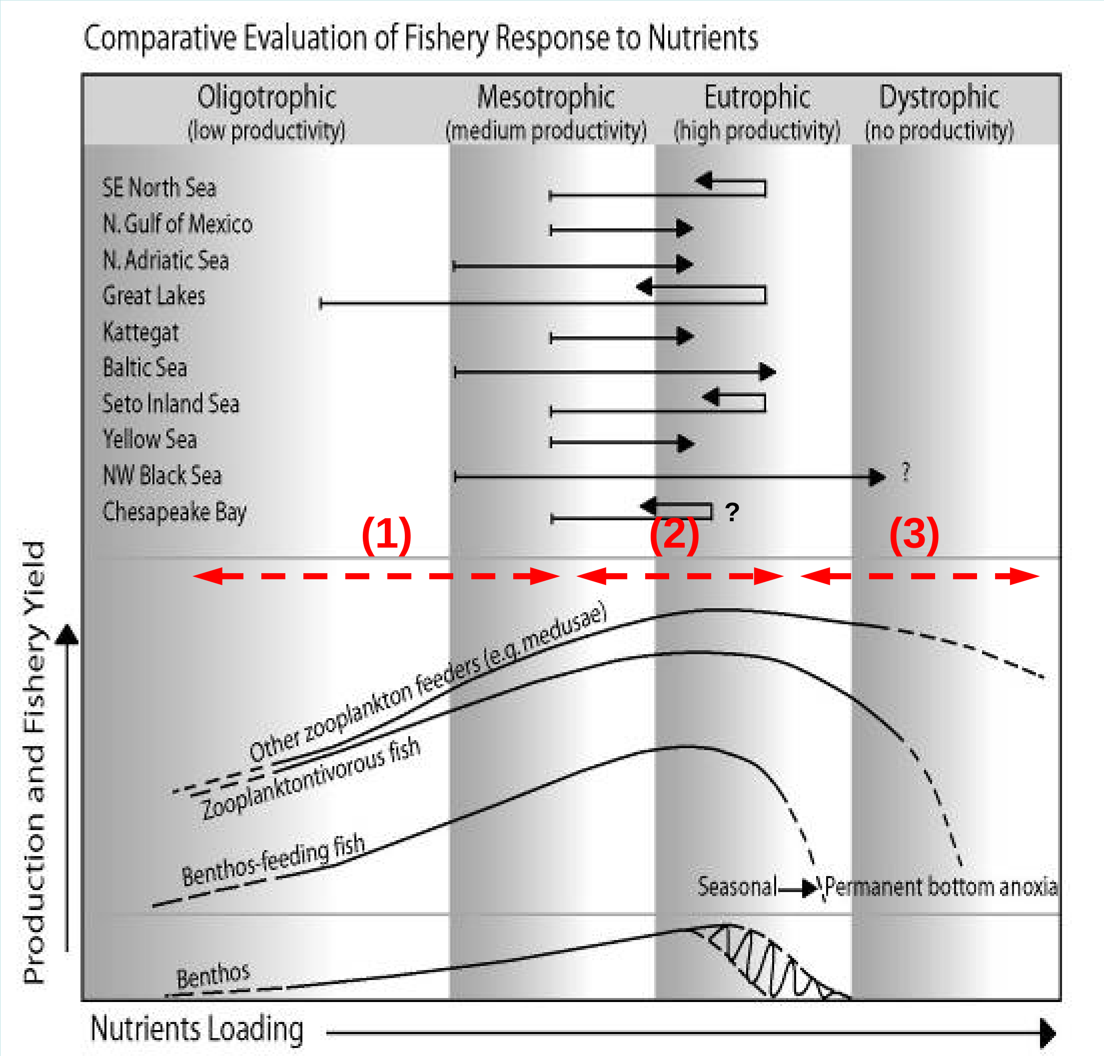


(Kemp et al. 2005)

Concluding Comments 2

- "Dead-zones" are an expanding problem that is linked to coastal eutrophication at global scales
- Although some systems are more susceptible to hypoxia due to inherent physics, anthropogenic nutrient loading is a key driving factor
- Restoration of Bays and estuaries worldwide requires reduction in nutrient loading to coastal systems
- Diverse ecological feedback processes complicate Bay restoration
- Hypoxia stimulates more algal growth thru enhanced nutrient recycling
- Loss of SAV, tidal marshes and oyster beds causes reduced natural filtration of nutrients from coastal waters
- Ecological positive feedbacks reinforce both coastal ecosystem degradation and restoration
- Thresholds and delayed responses may be expected with loading,

Fishery Responses to Eutrophication



- **Stages of Fish respond to nutrient enrichment**
- **First: Fishery production increases with nutrients**
- **Second: Fishery does not respond to nutrients**
- **Third: Fishery production declines with nutrients**

(Caddy 1993)

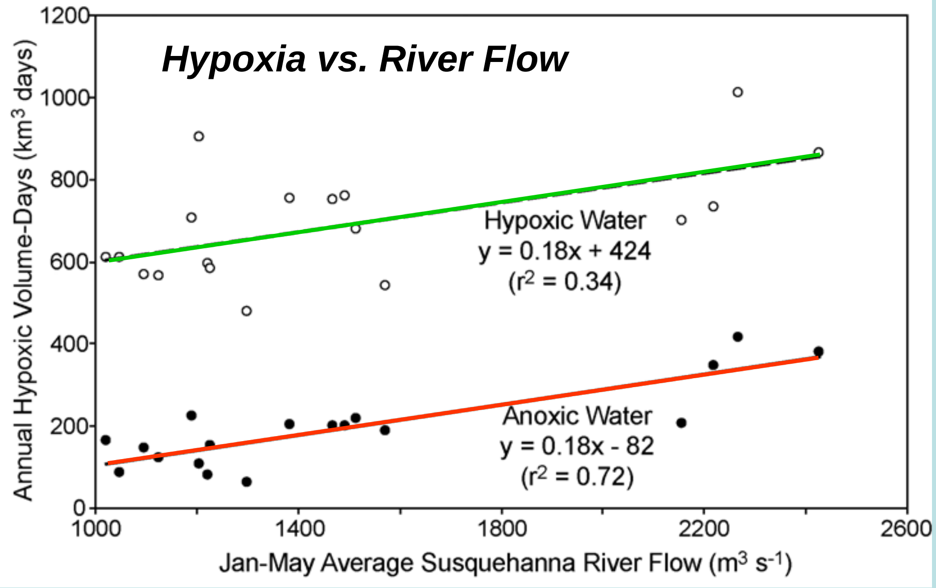
Volume of Summer Hypoxic Water is Related to River flow and Nitrate Loading, with Regime Shift in Early 1980s

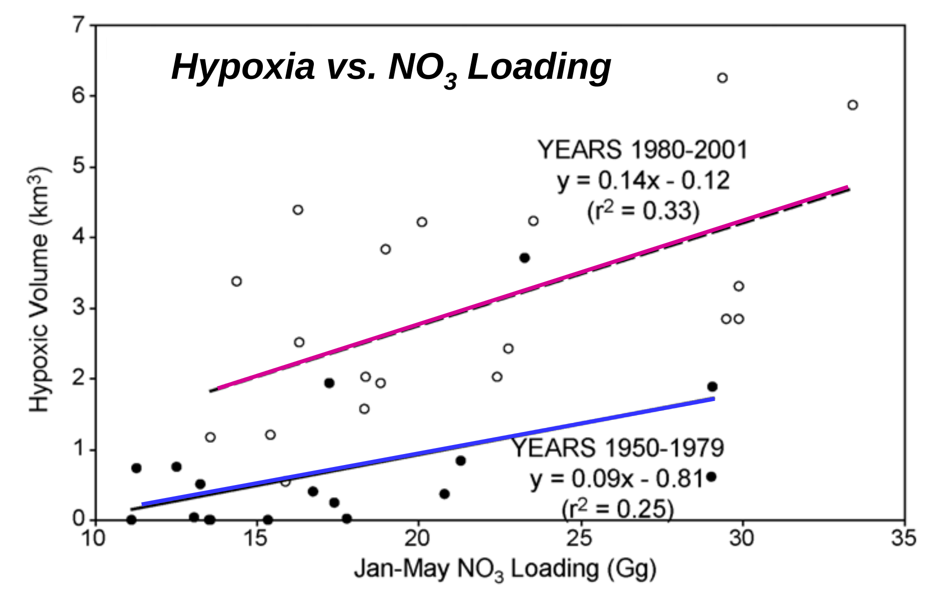
- **Volumes of summer hypoxic (O_2 < 1 mg/L) and anoxic (O_2 < 0.5 mg/L) clearly related to winter-spring river flow**

- **Abrupt increase in slope of time trend from 1950-1980 (blue line) to 1980-2003 (magenta line). Currently, there is more hypoxia per unit NO_3 Loading**

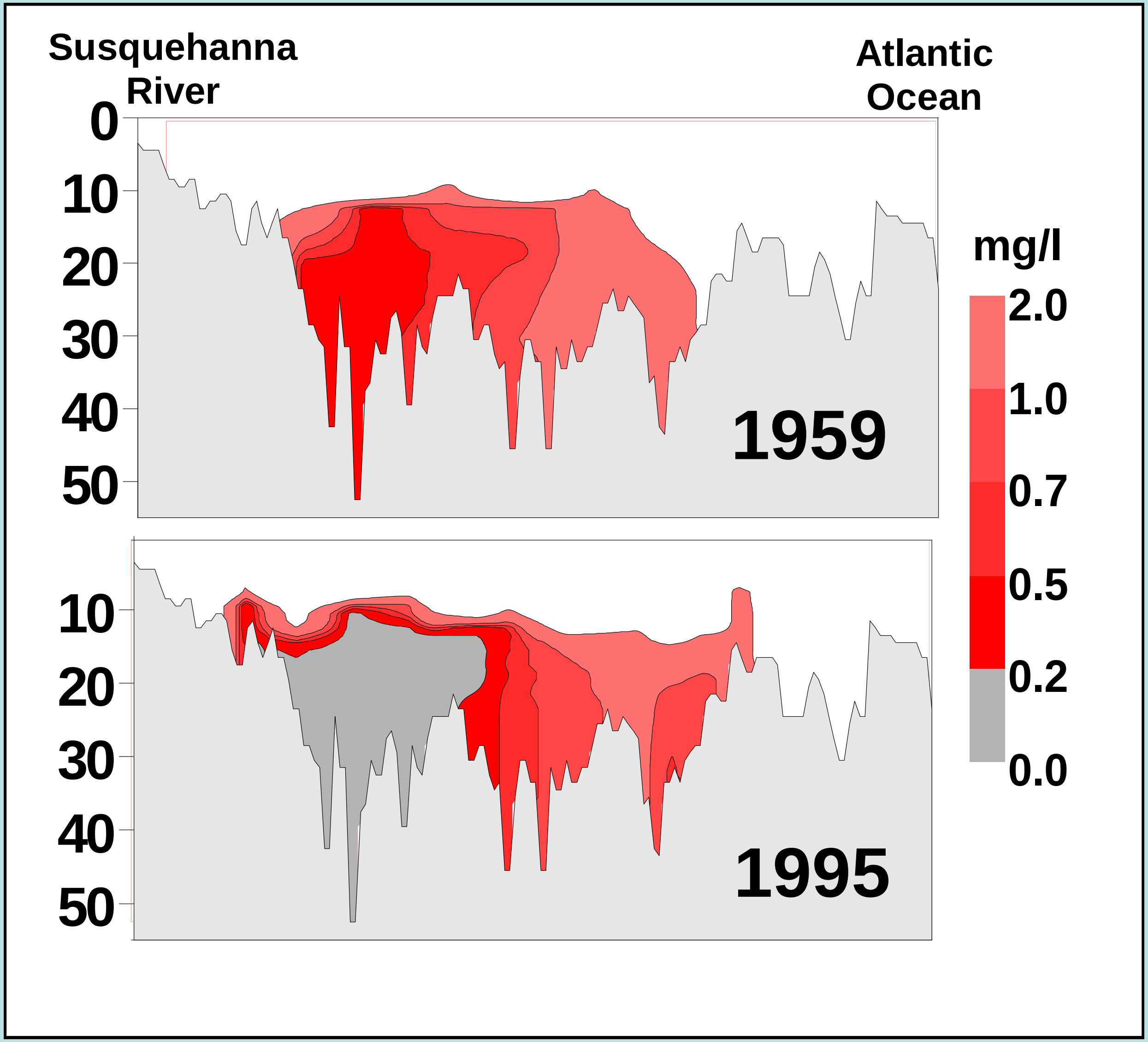
- **What factors have contributed to this abrupt regime shift leading to more hypoxia per loading? Positive feedback mechanisms at work?**

(Hagy et al 2004, Kemp et al 2005)





Dissolved O_2 in Low-Flow Years



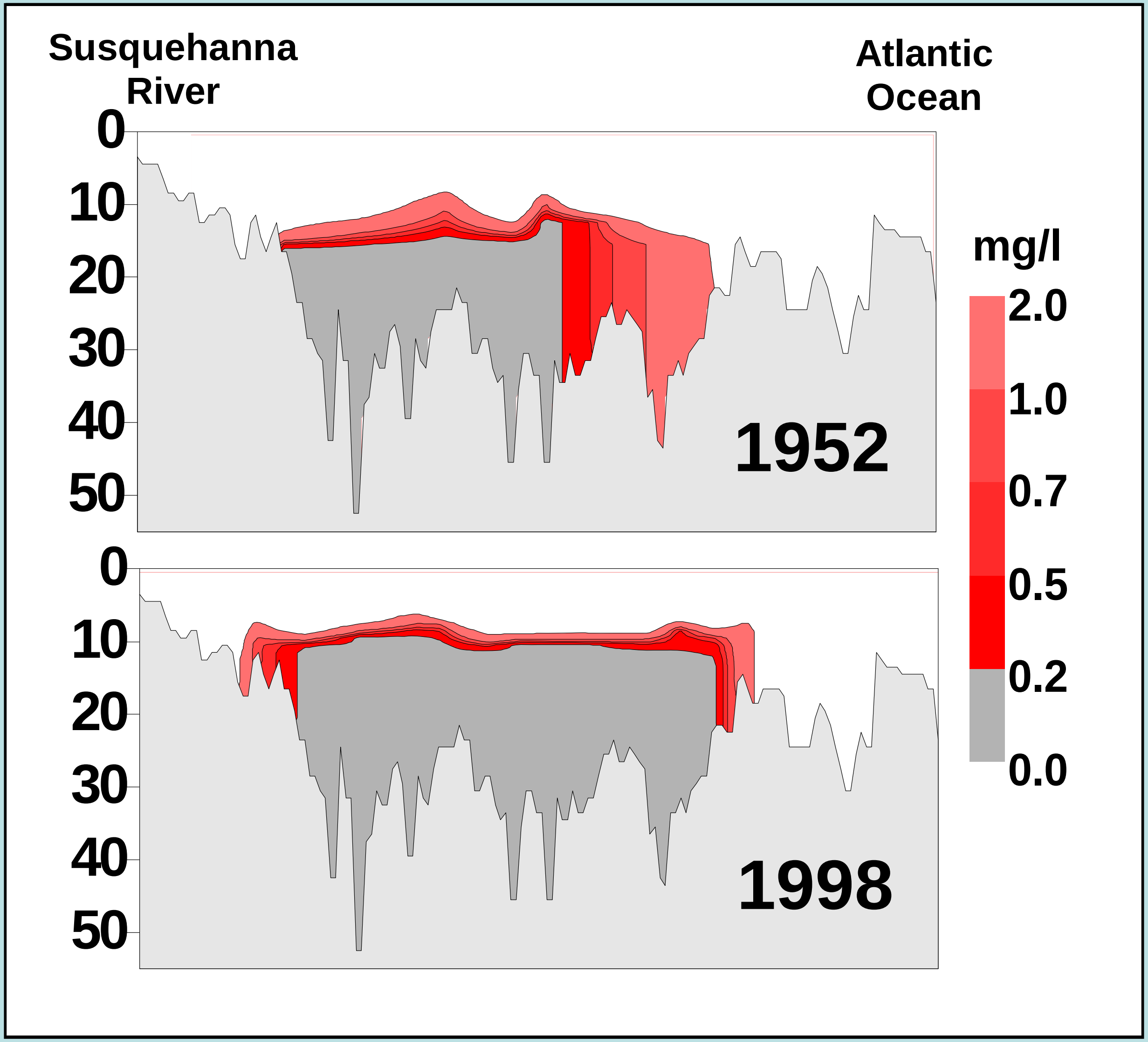
Major differences between conditions in 1950s and present are

-- increased intensity

-- seaward expansion.

(Hagy 2002)

Dissolved O_2 in High-Flow Years



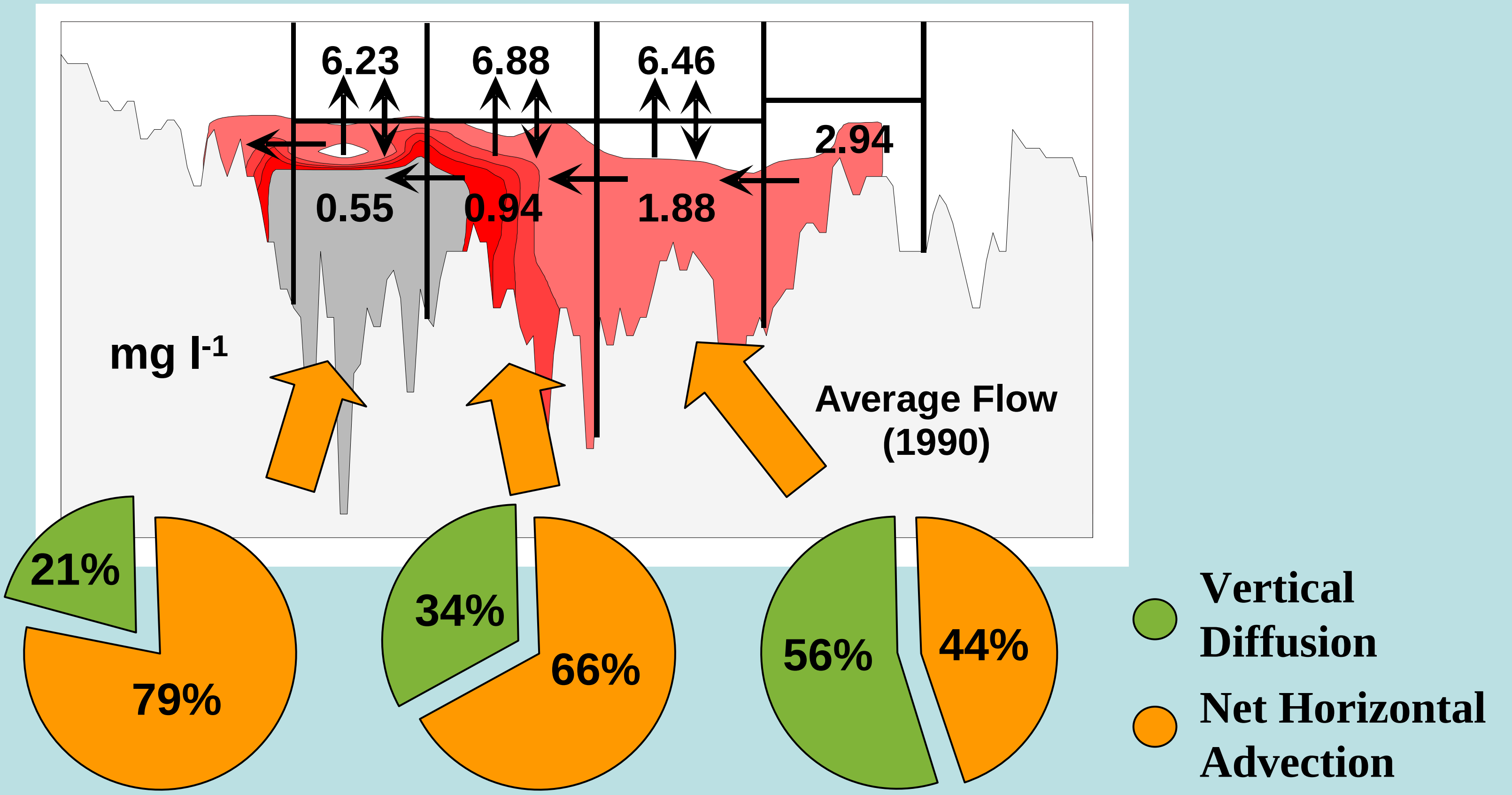
Major difference between earlier years and present years is

-- seaward expansion

-- deeper hypoxic area

(Hagy 2002)

Oxygen Budget for Mid Bay

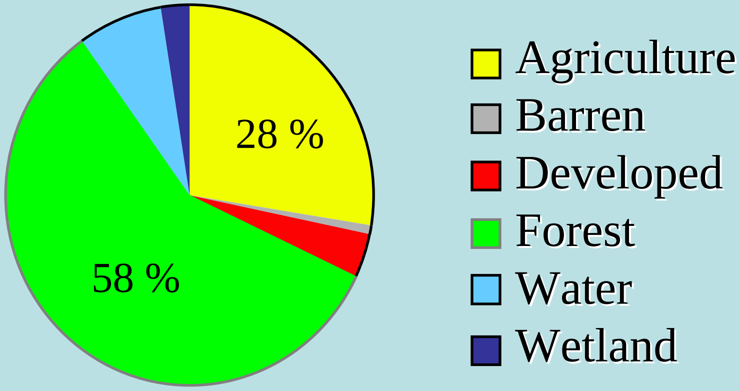


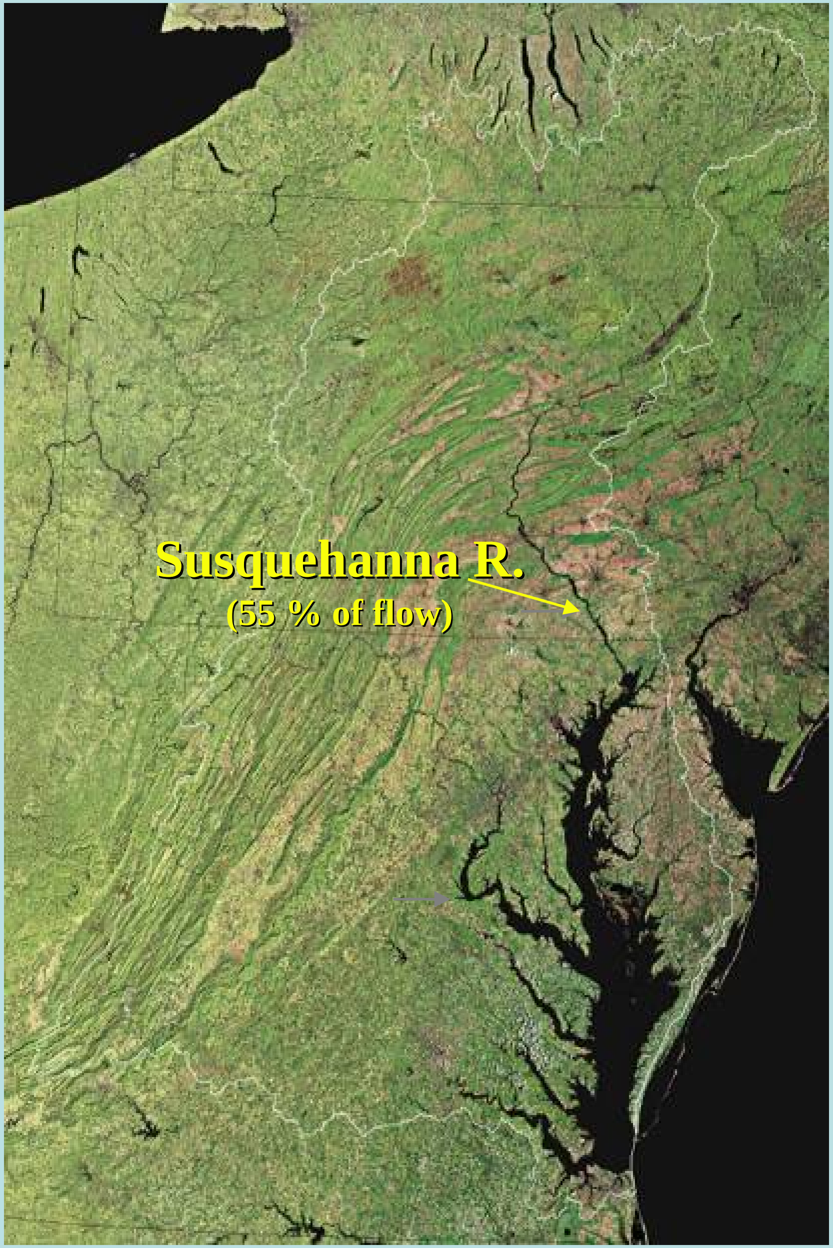
Chesapeake Bay System:

Watershed area
= 116,000 km²

Water surface area
= 11,500 km²

Land-Use in Watershed:

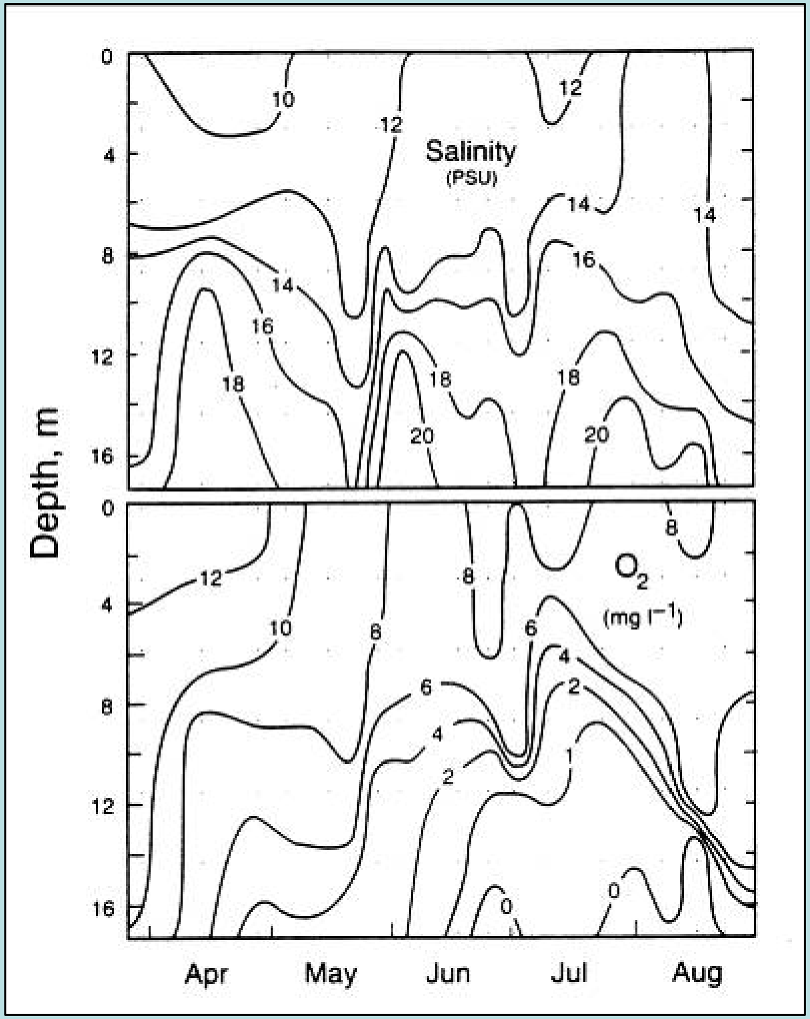




Concluding Thoughts

- Restoration
- Implications

Salinity and O_2 Seasonal and Vertical Distributions



(Kemp et al. 1992)

Concluding Comments

- **Coastal eutrophication is a global scale problem, and Chesapeake Bay is a system that is inherently susceptible to effects of nutrient enrichment**
- **Eutrophication effects first evident 200 years ago, with intense hypoxia and dramatic SAV loss first occurring in the 1950s and 1960s**
- **A dramatic upward shift in the hypoxic zone size occurred around 1980, with more hypoxia generated per nutrient loading now compared to past**
- **Increased turbidity with eutrophication has caused large reductions in benthic primary production (algal & SAV)**
- **Changes in abundance and community composition of demersal fish and benthic invertebrates have occurred in response to bottom habitat losses**
- **Human-induced changes of oyster and marshes habitats further stimulate Bay ecosystem response to nutrient enrichment and nutrient abatement**
- **Ecological positive feedbacks reinforce both Bay degradation response to nutrient enrichment, and Bay restoration response to nutrient reductions**
- **Thresholds and delayed responses may be expected with reduced nutrient loading, but habitat restoration may tend stimulate recovery**