Eutrophication in Chesapeake Bay: A Synthesis for Scientific Understanding and Management Applications

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Outline

- Describe Chesapeake Bay features that make it susceptible to effects of nutrient enrichment and eutrophication
- Sketch reconstructed history of eutrophication in Chesapeake Bay
- Describe the major nutrient-induced changes in bottom habitats:
  - Deep—Hypoxia, creation of seasonal “dead zones”
  - Shallow—Loss of submersed aquatic vegetation (SAV)
- Example responses of animal communities to eutrophication
- Describe ecological feedback processes which are influenced by eutrophication, but also exert effects on eutrophication
- Conclude with data and conceptual models to consider how the Bay ecosystem may respond to efforts to restore the estuary through reductions in nutrient loading

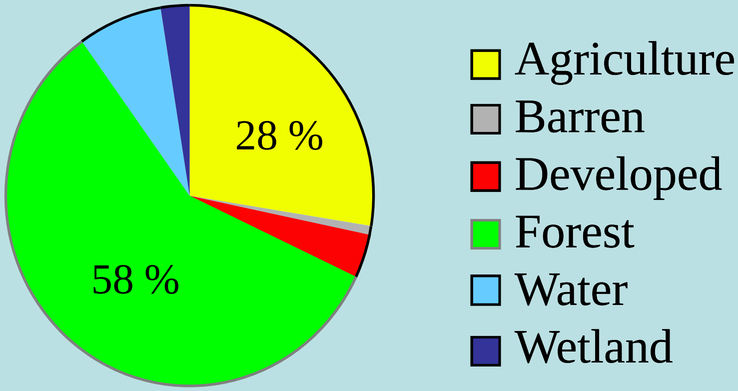
Background and Eutrophication History

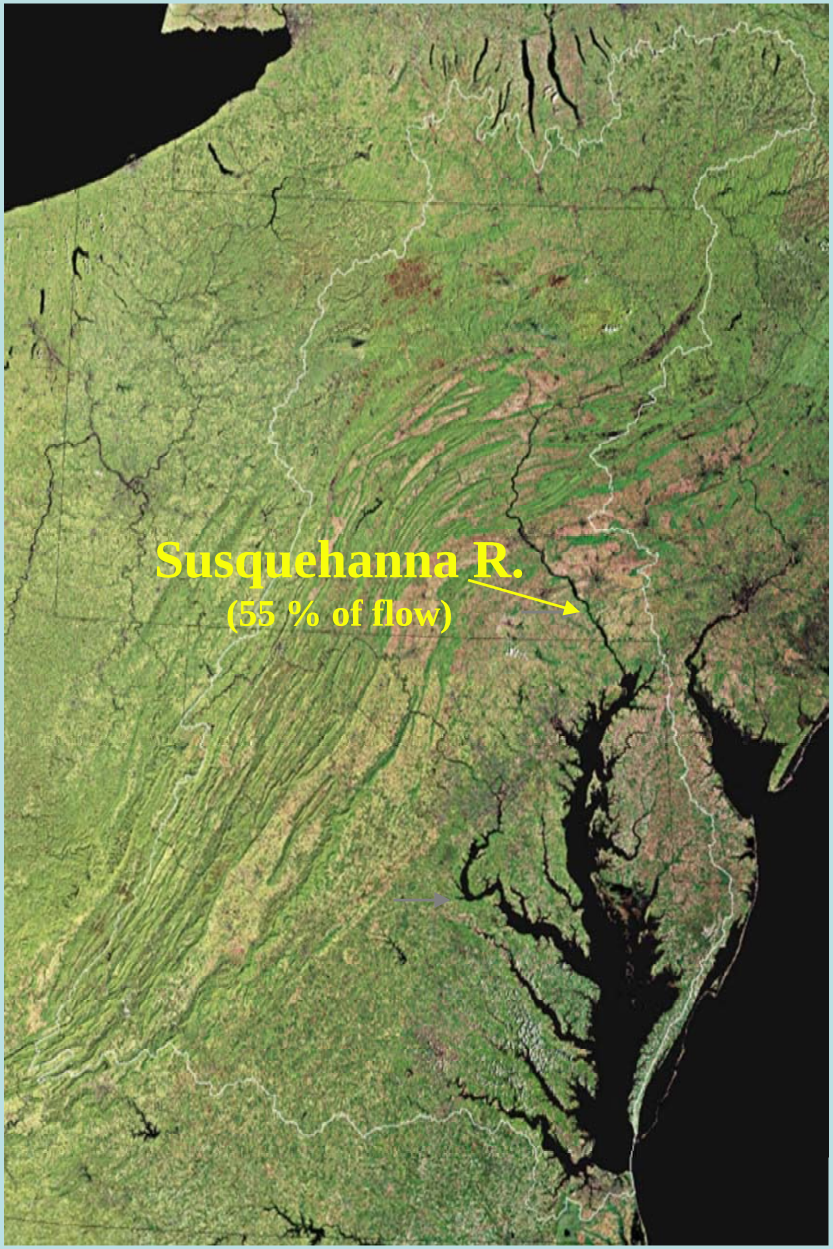
Chesapeake Bay System:

Watershed area
= 116,000 km^2

Water surface area
= 11,500 km^2

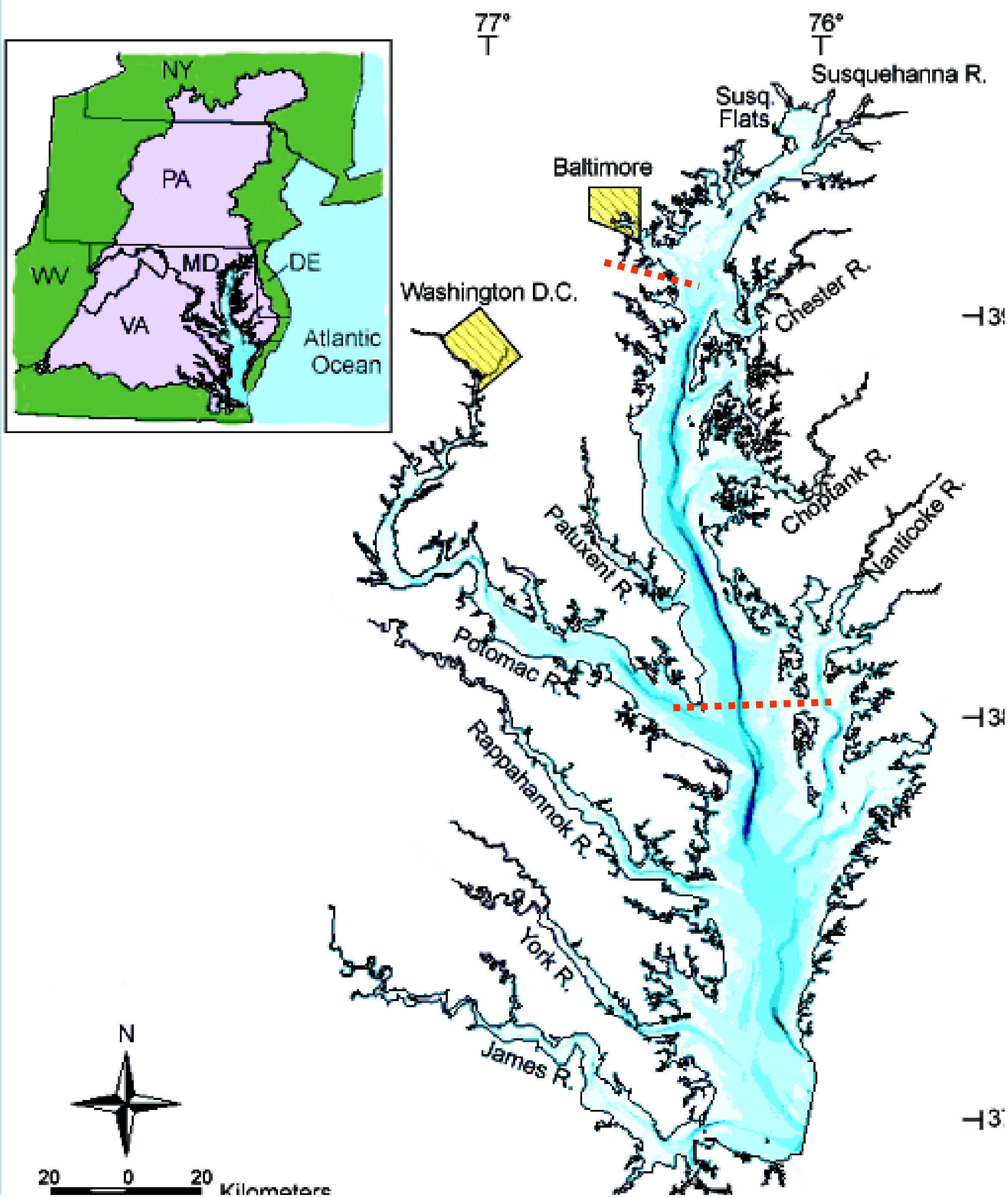
Land-Use in Watershed:





Key Bay Features

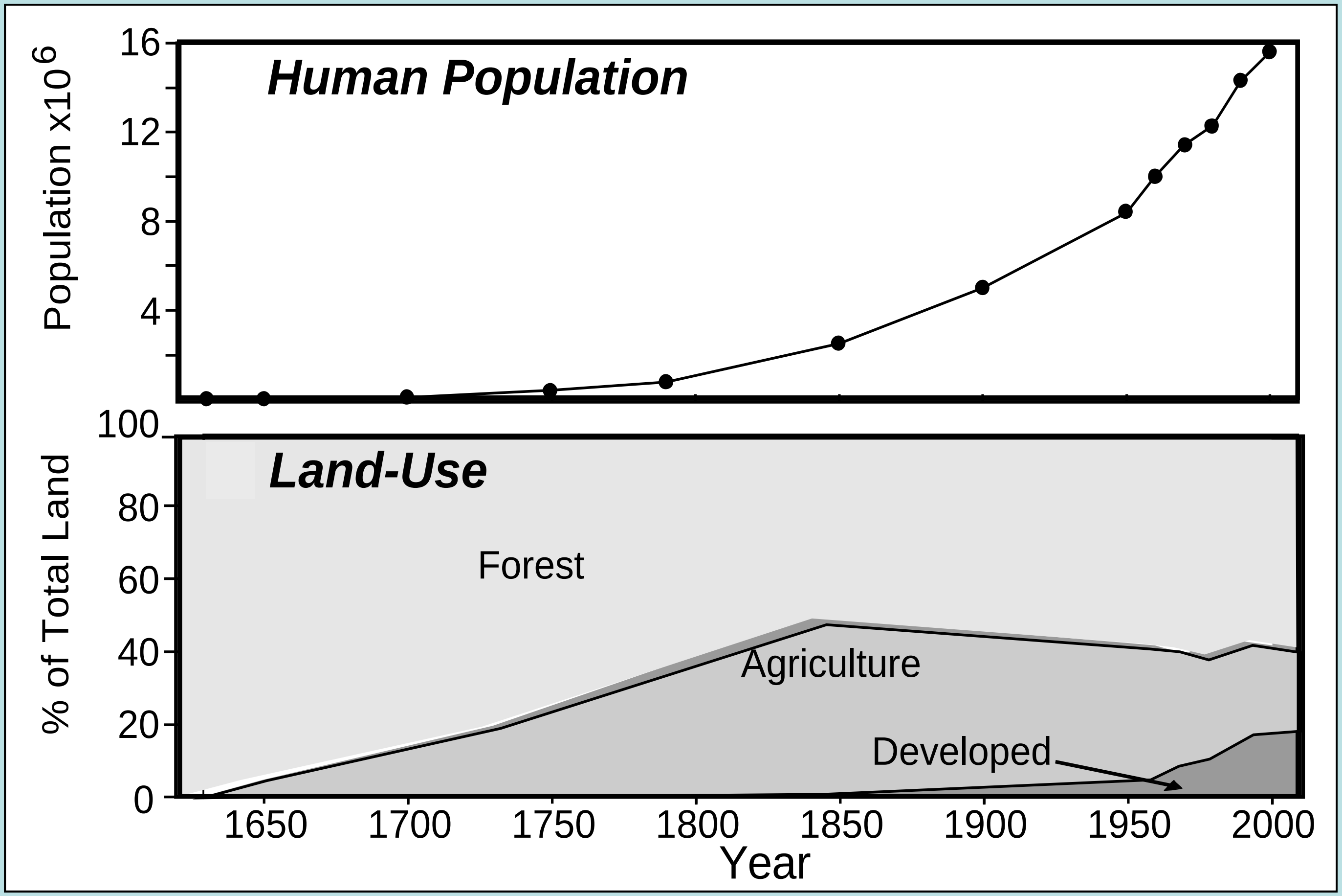
- Large ratio of watershed to estuarine area (14:1); Bay is closely connected to the landscape
- Deep, narrow channel is seasonally stratified, which isolates deep water
- Broad shallows flank channel (mean z = 6.5m)
- Most of Bay volume is in the mainstem
- Most of its surface area in tributaries and sounds
- Relatively long water residence time (~ 6 mo)
- Three regions of main Bay



Watershed Changes: Land-Use & Population Trends

- **Exponential growth in watershed population**

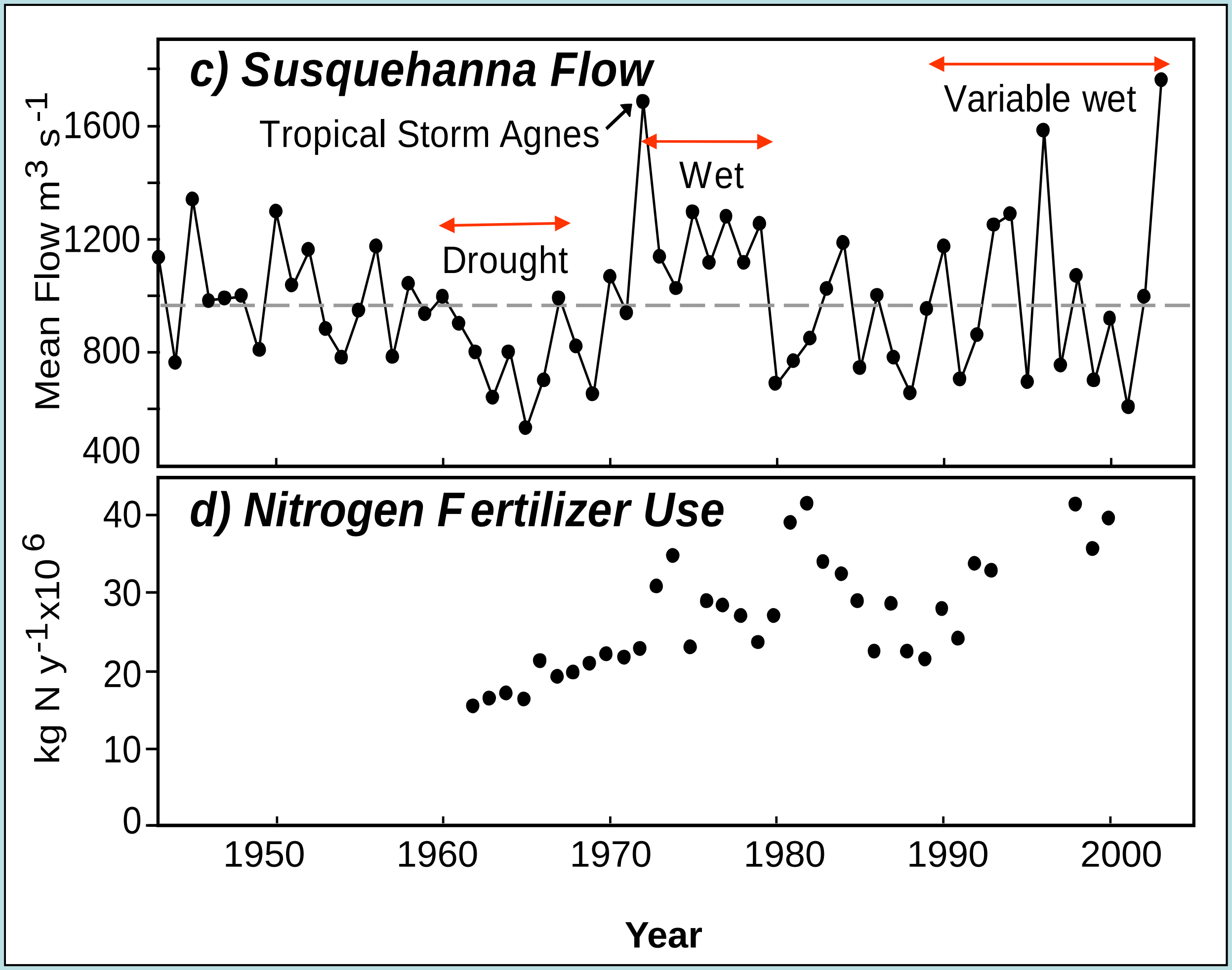
- **Land-use shift from forest to farm (thru 1850) to developed (1850 – 2000)**



Watershed Changes and Variations: Flow & Fertilizer

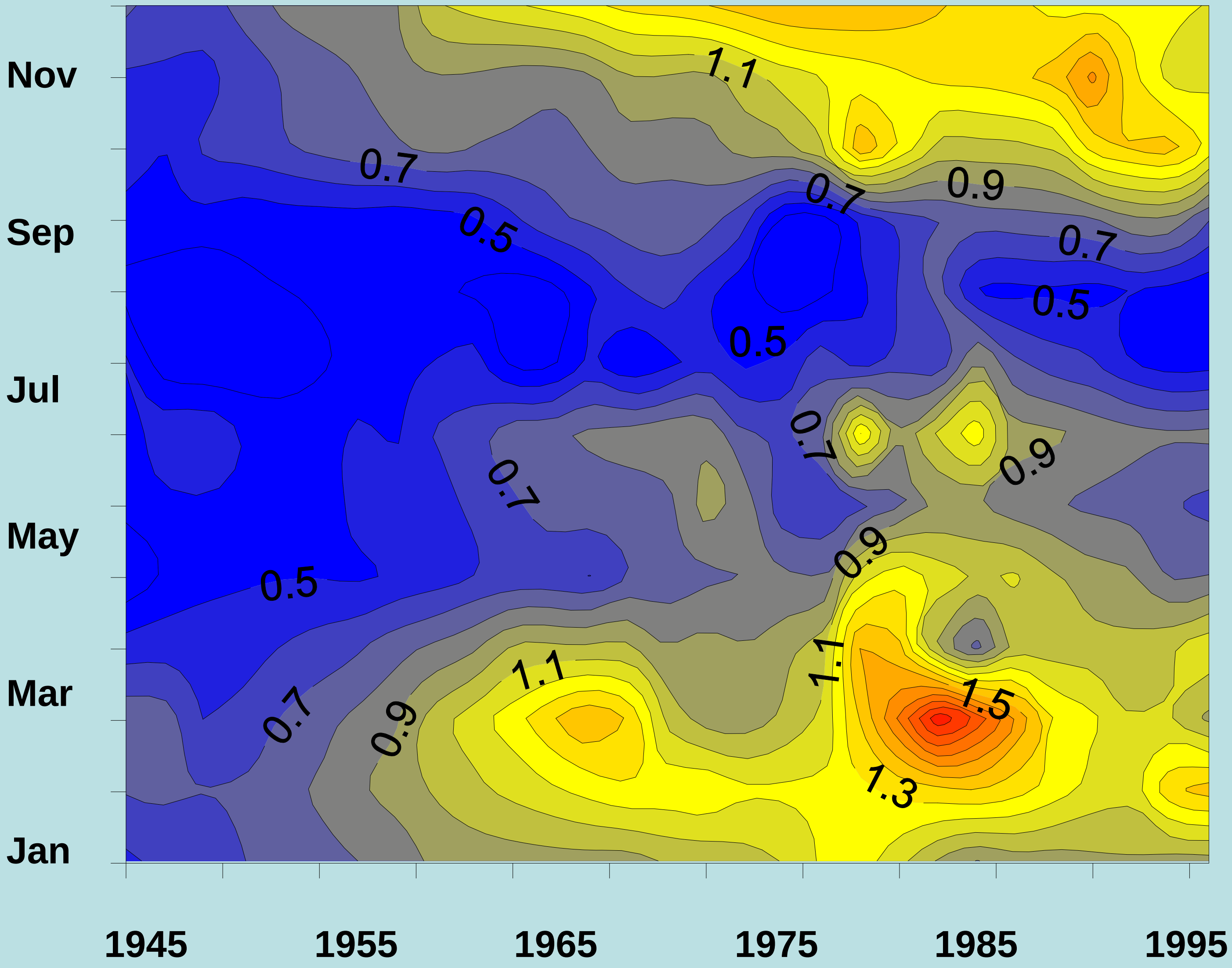
- **Large variations in river flow (~4X); wet and dry decades but no long-term trends**

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



Watershed Changes have Caused Increased Nitrogen in Susquehanna River Inputs to Bay

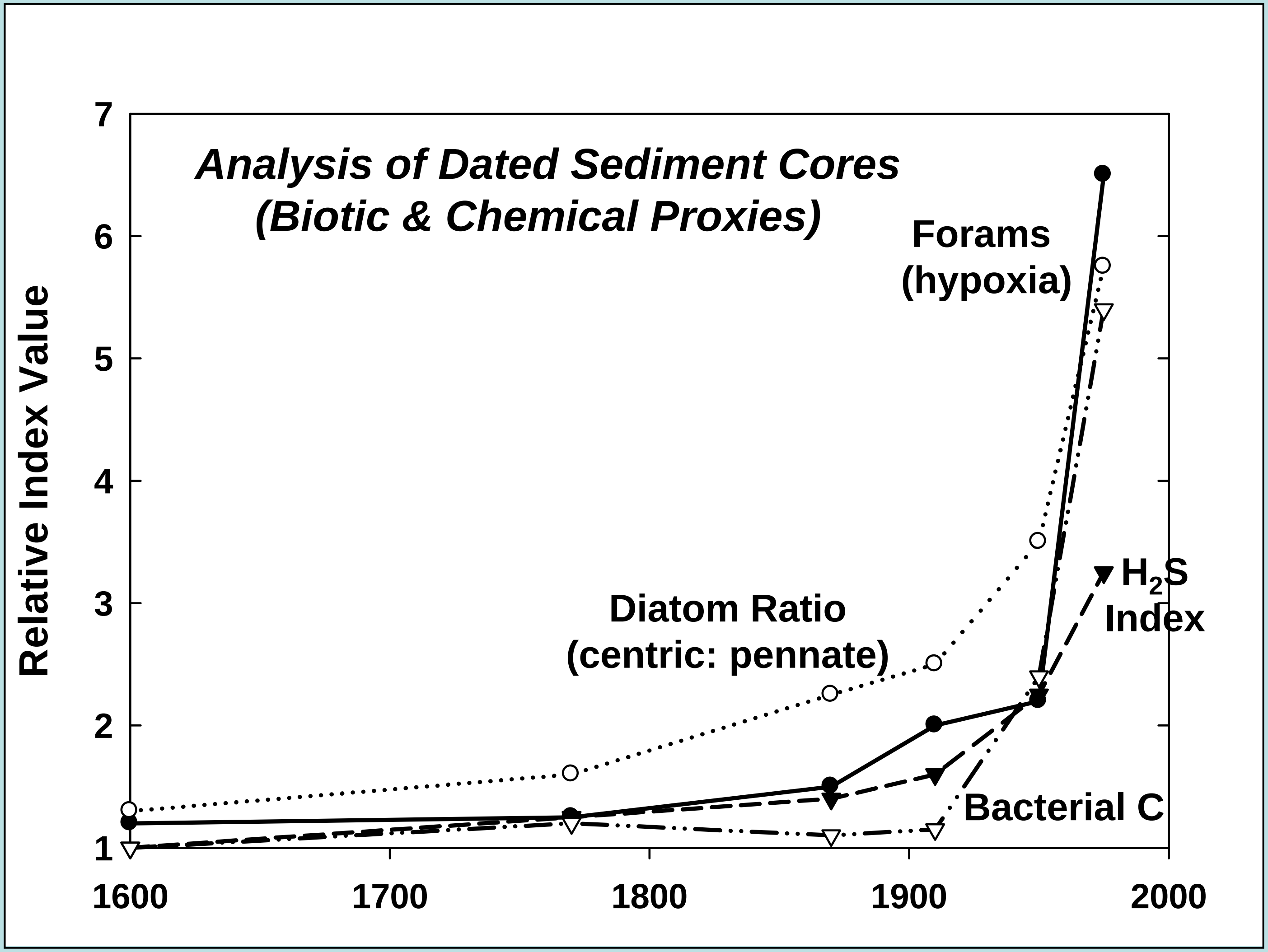
- **Long-term increases in nitrate levels & changes in seasonality seen over five decades**
- **Highest nitrate levels (yellow, red) occur in cold months**
- **Nitrate trends are closely related to total Nitrogen**
- **N-loads to Bay doubled from 1945 to 1970**



Hagy et al 2004

Evidence of Chesapeake Bay Eutrophication Effects in Sediment Strata

- **Early signs of enrichment ~ 200 years ago**
- **Declines in water clarity and benthic diatoms ~100 years ago**
- **Persistent Hypoxia/Anoxia ~ 50 years ago**



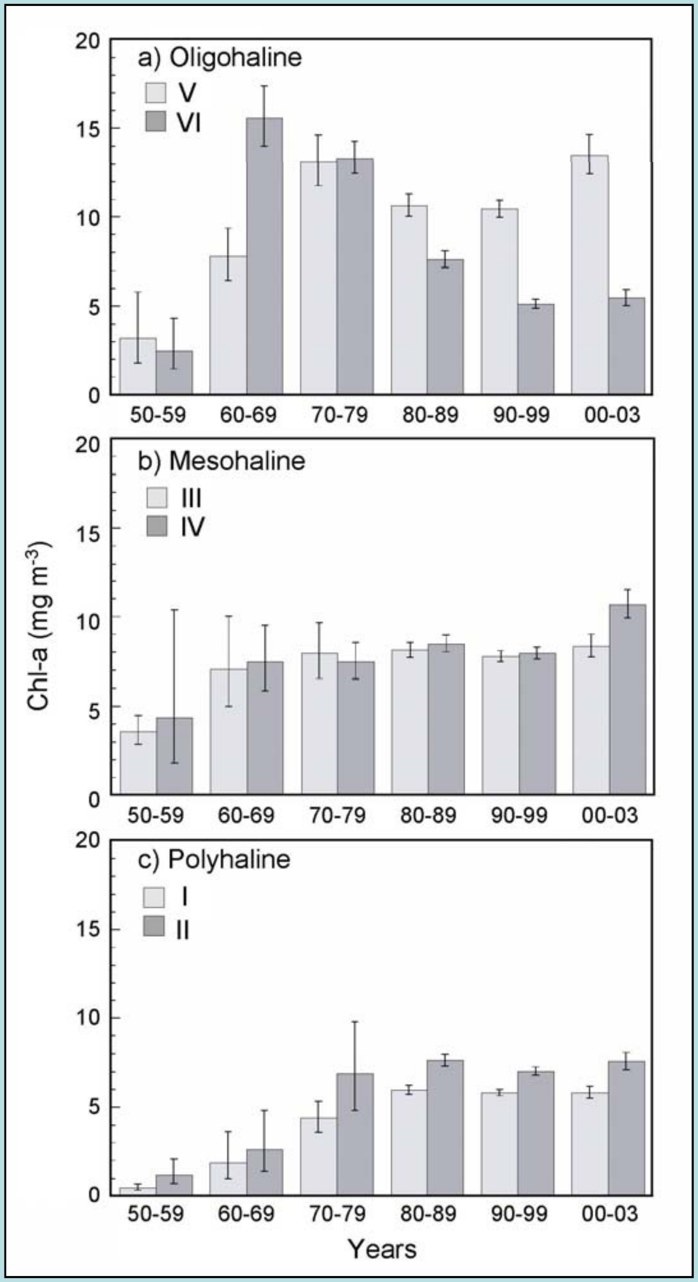
(Adapted from Kemp et al 2005)

Algal Biomass Responses to Nutrient Enrichment: 1950-2003

- **Phytoplankton biomass has increased from 1950s – 1970s in in all salinity zones of the Bay**

- **Spatial progression in temporal trends from oligohaline to polyhaline zones**

- **Response largest in the polyhaline region—where nutrient levels are lowest and most limiting for algal growth**



(Harding in Kemp et al. 2005)

Loss of Benthic Habitats

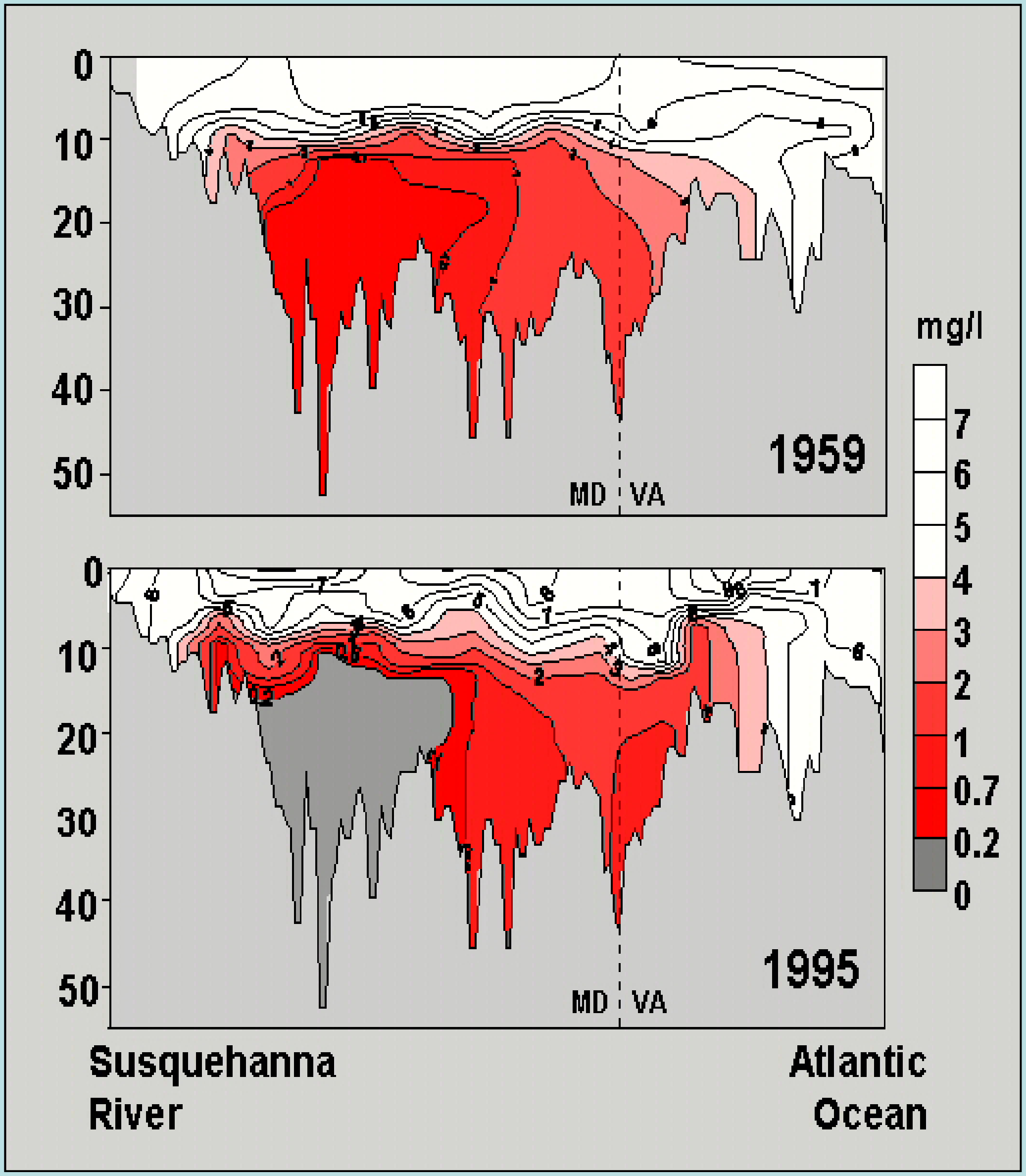
- *Deep Water: Hypoxia*

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)**

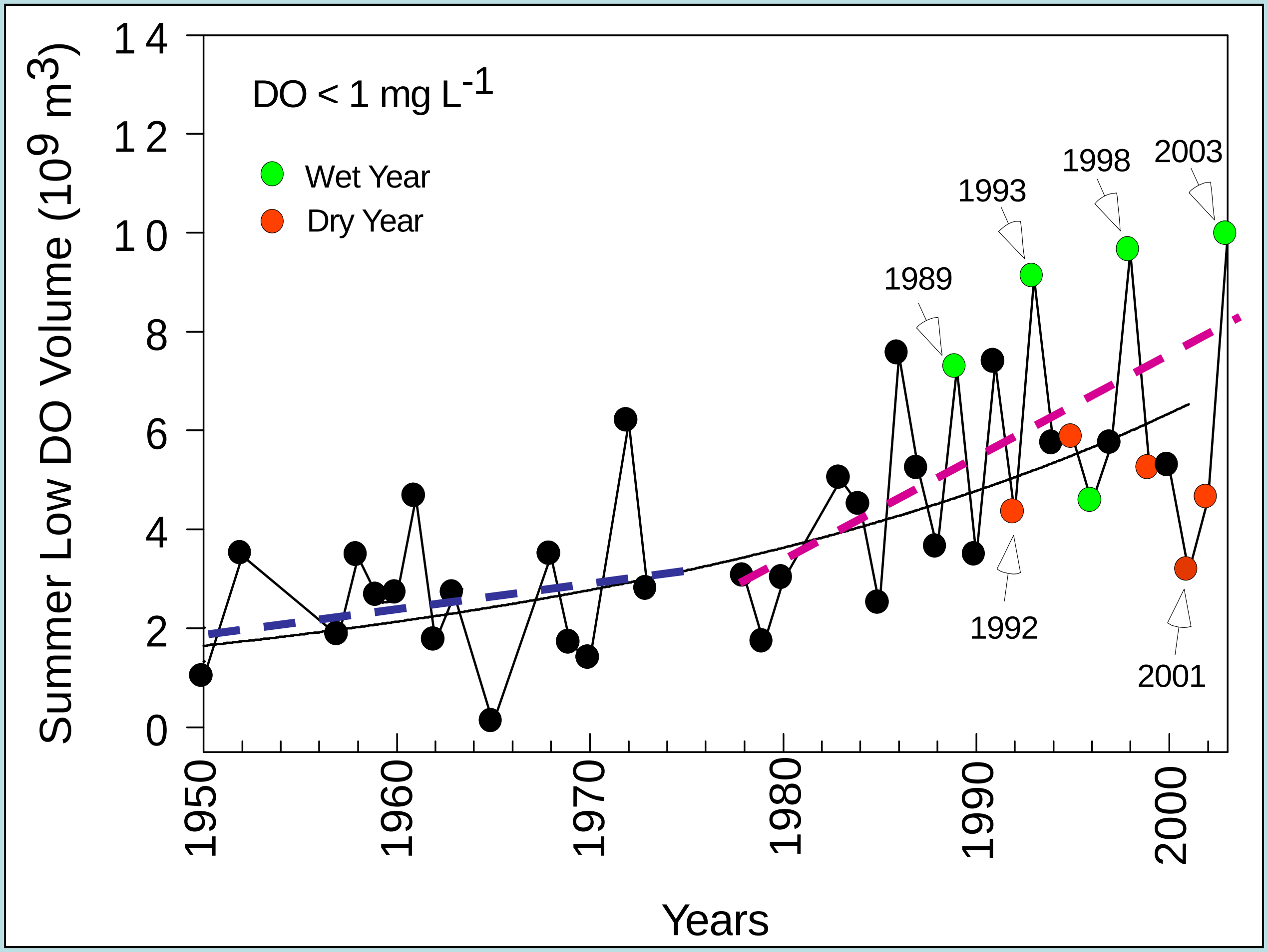


Increasing Volume of Summer Hypoxic Water in Response to Elevated Nutrients and Phytoplankton: 1950 - 2003

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

- **Abrupt increase in slope of time trend from 1950-1980 (blue line) to 1980-2003 (magenta line)**

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



Adapted from Hagy et al 2004

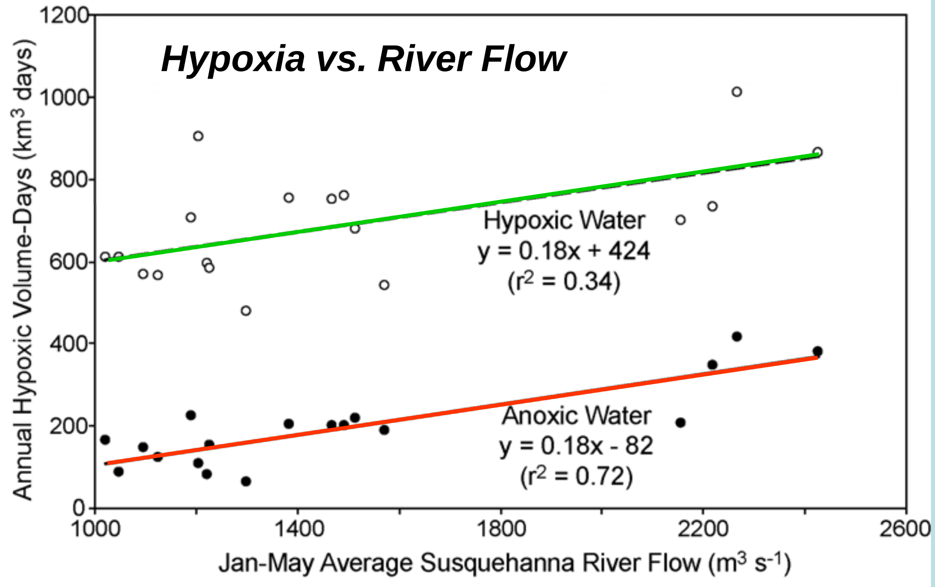
Volume of Summer Hypoxic Water is Related to River flow and Nitrate Loading, with Regime Shift in Early 1980s

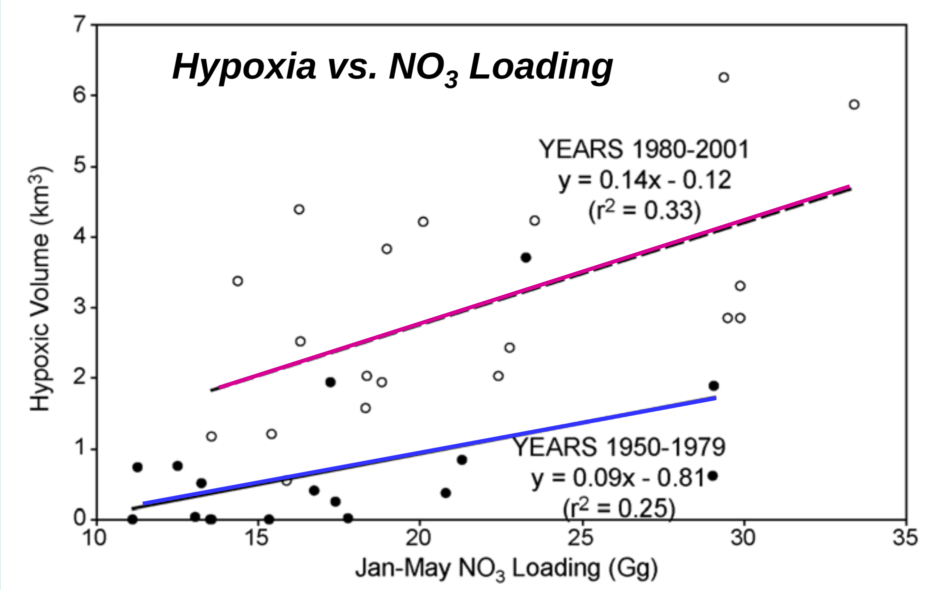
- **Volumes of summer hypoxic (O_2 < 1 mg/L) and anoxic (O_2 < 0.5 mg/L) clearly related to winter-spring river flow**

- **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)



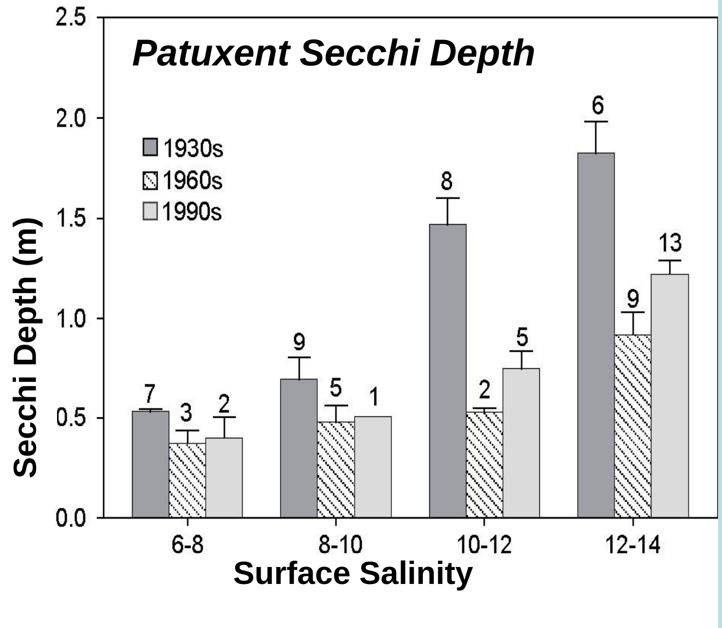


Loss of Benthic Habitats

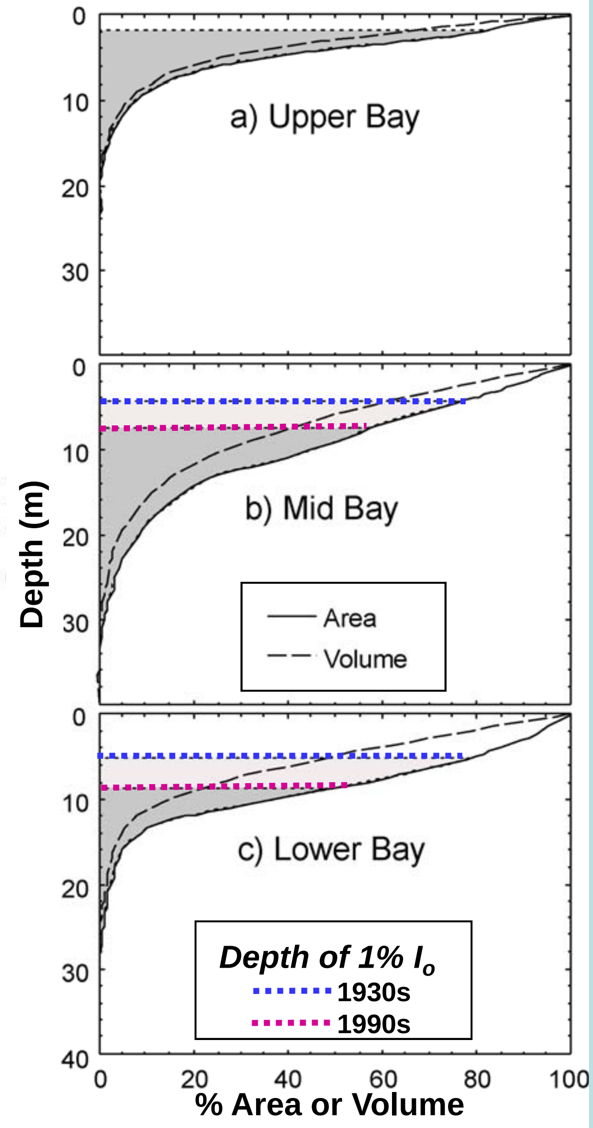
- *Shallow Water: Bottom Plants*

Eutrophication has Caused Increase in Water Clarity & Decreasing Light Reaching Sediments

- **Water was clearer in 1930s compared to the 1990s**
- **Little difference between 60s & 90s**
- **Difference in water clarity is more pronounced at seaward end**



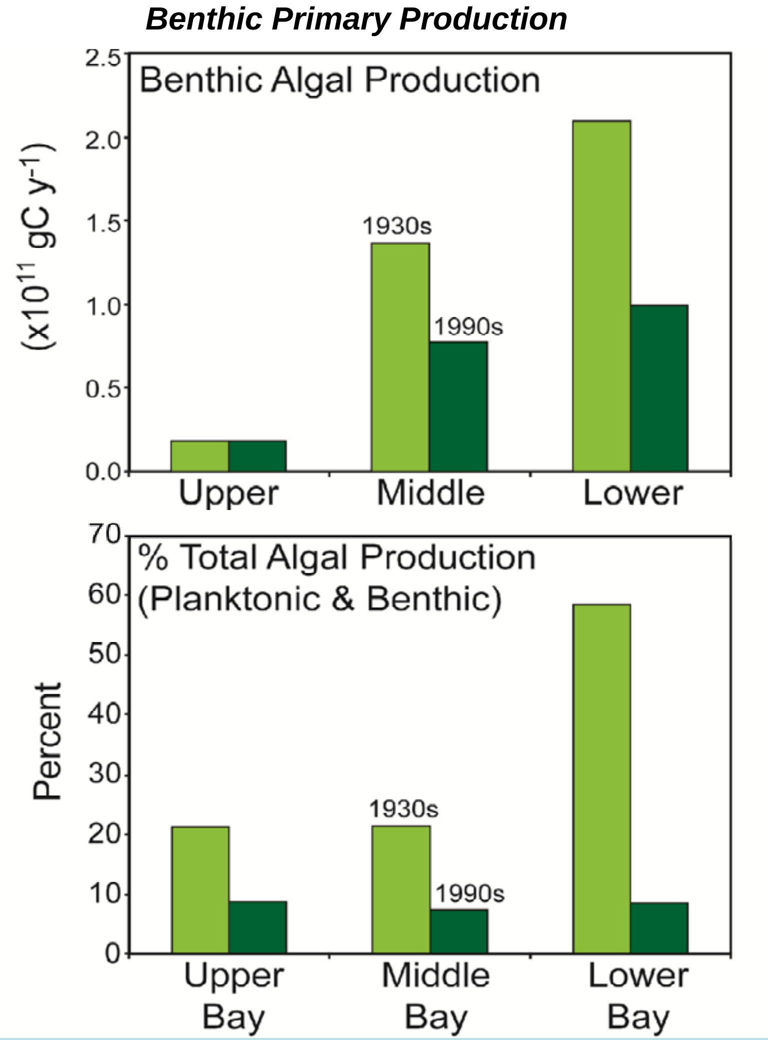
- **Regional hypsographs relate area & volume (% total) below given depth**
- **Differences in water clarity from 1930s to 1990s cause differences in Bay bottom receiving >1% surface light**



(Kemp et al 2005)

Decreases in Water Clarity Caused Declines in Benthic Micro-algal Primary Production

- **Contribution of benthic micro-algae to ecosystem production declined with increasing turbidity**
- **Most of effects was in mid & lower Bay because larger change in water clarity and abundant shallow water**
- **Proportion of total algal production (plankton & benthic) in lower Bay shifted from ~60% in 1930s to <10% at present**
- **Benthic algal communities support efficient secondary production, tight nutrient cycling, and more stable bottom sediments**


Benthic Primary Production

(Kemp et al 2005)

Dramatic Bay-Wide Decline of Seagrass (Submersed Aquatic Vegetation, SAV)

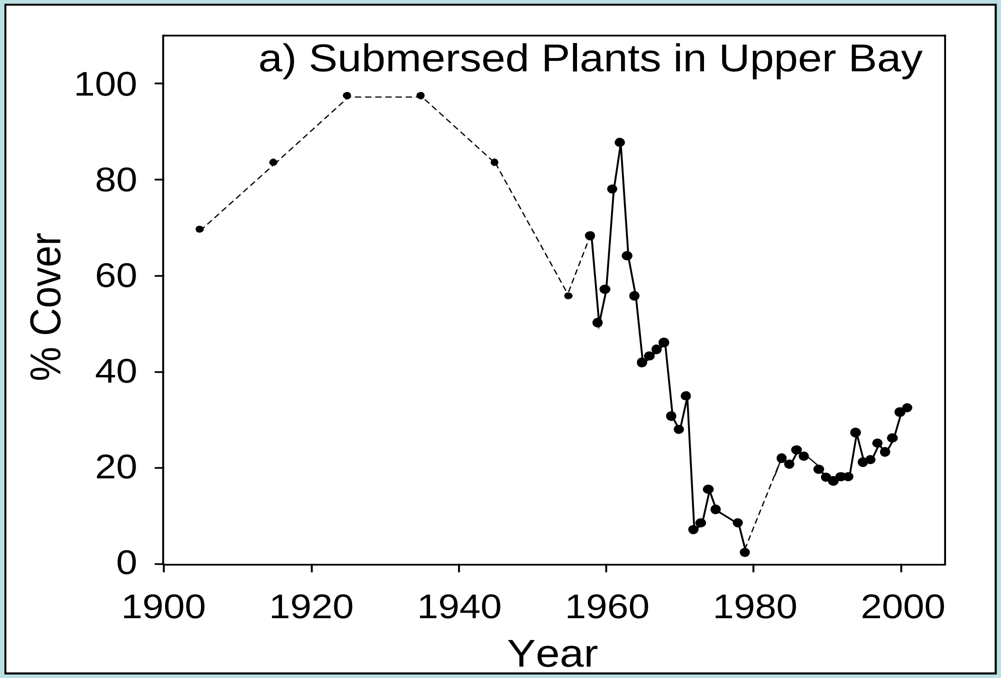
- **Prior to 1960 most of the Bay bottom at depths < 2 m was inhabited by diverse species of SAV**
- **SAV decline started in upper Bay and Western shore tributaries, then moved to lower Bay and Eastern shore systems**
- **Solomons Is., near mouth of Patuxent R. (CBL), was surrounded by SAV prior to 1965, but bare since 1975**
- **Huge loss of animal habitat**

Solomons Island 1933

Solomons Island 1999

Trends and Causes of SAV Decline in Bay

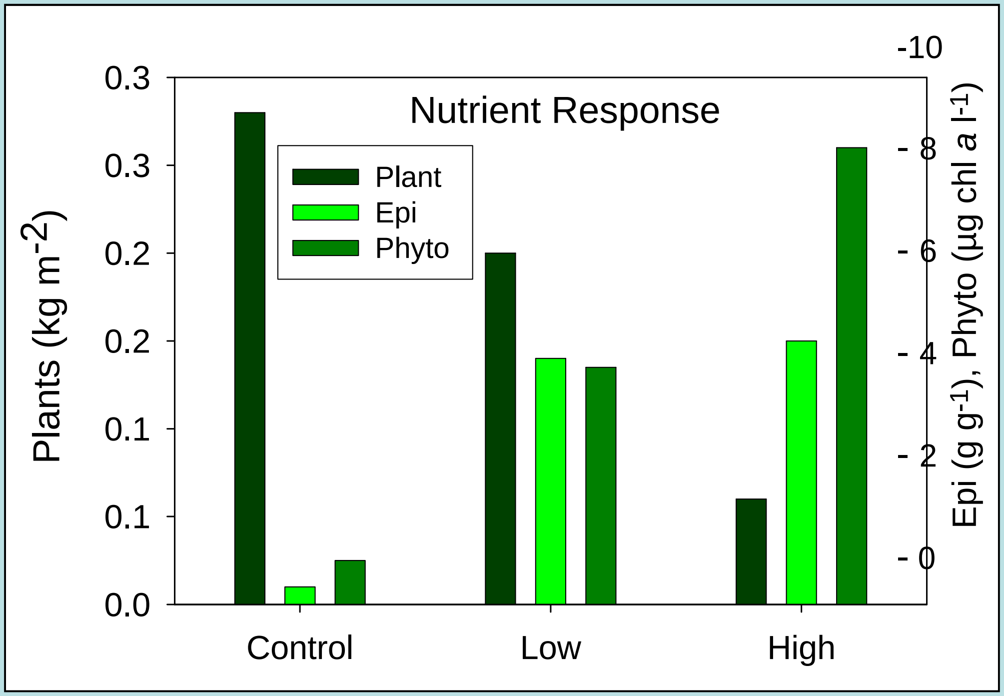
- **Sharp SAV decline in upper Bay in early 1960s**
- **Modest recovery since mid-1980s, but still only 30% of former levels**



- **Experiments and field studies reveal higher nutrients decrease light for SAV due both to:**

(1) decreased water clarity (phytoplankton)

(2) increased epiphytic algae on SAV leaves

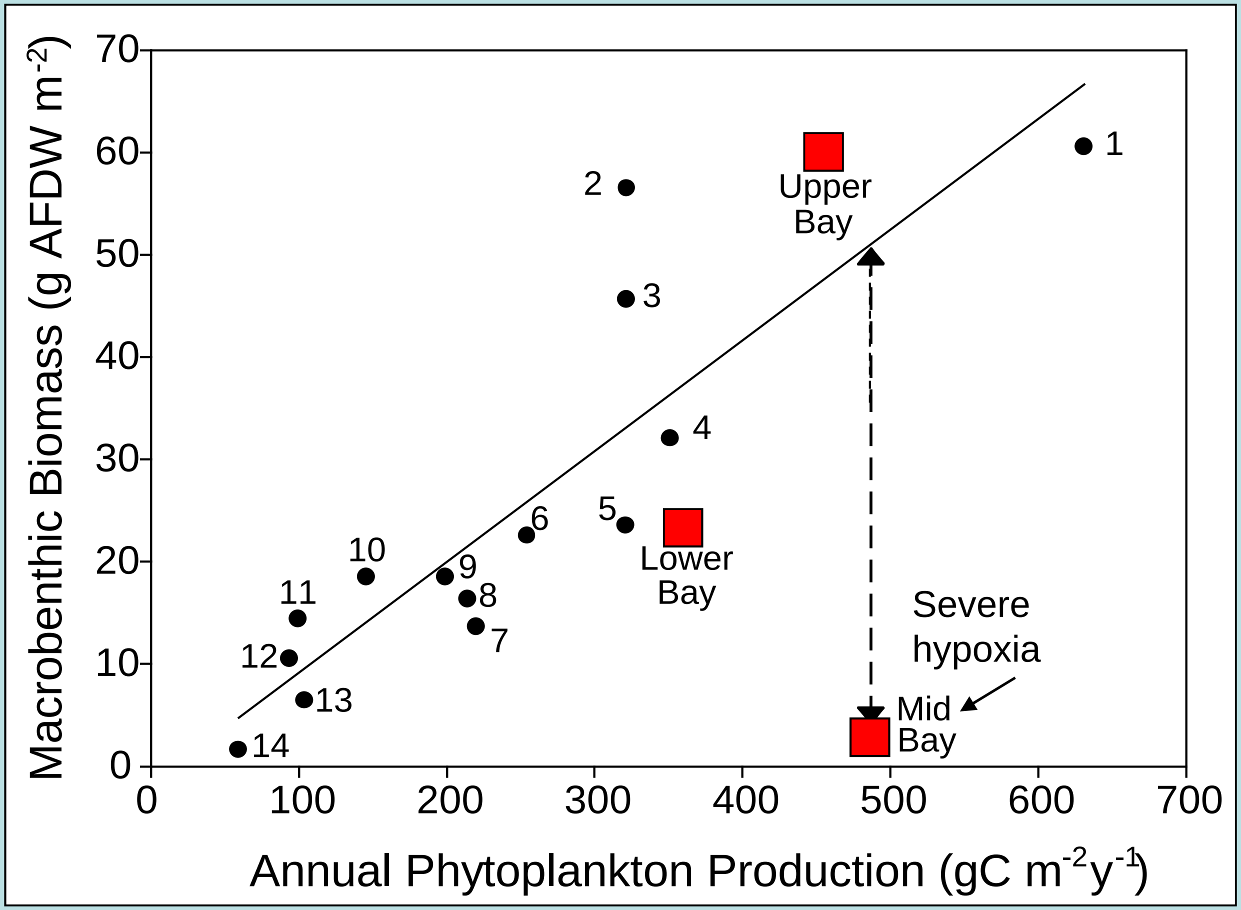


(Kemp et al 2005)

Impacts on Benthic Fauna and Food-Webs

Degraded Bottom Habitats Lead to Loss of Benthic Invertebrate Populations in Hypoxic Regions of 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)

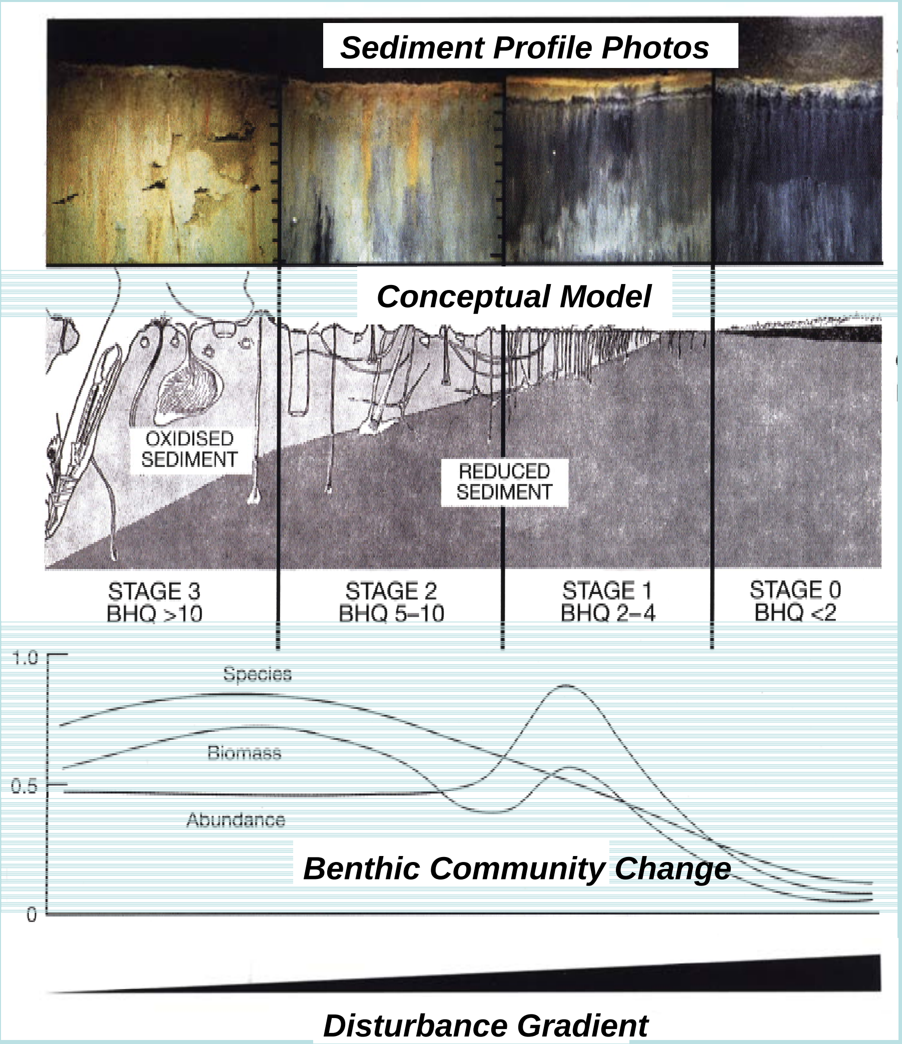
Degraded Bottom Habitats Lead to Loss of Benthic Invertebrate Populations in Hypoxic Regions of Bay

- **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**

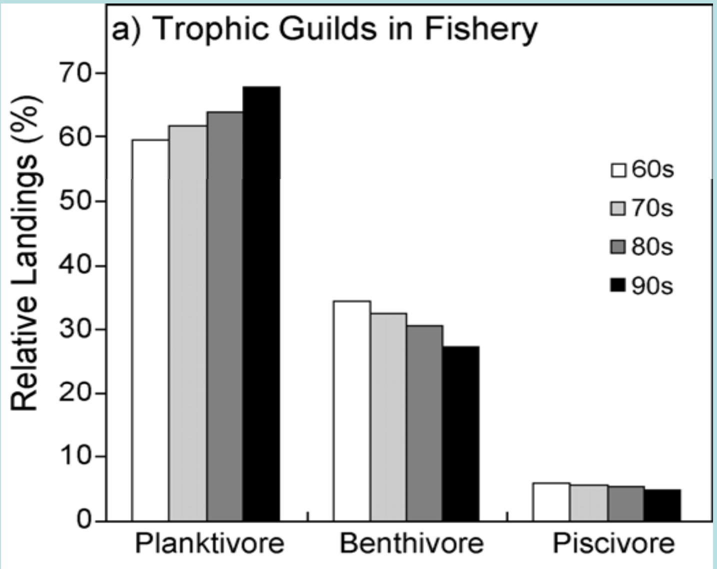
- **Model derived in part from work of by Don Rhoads in LIS**

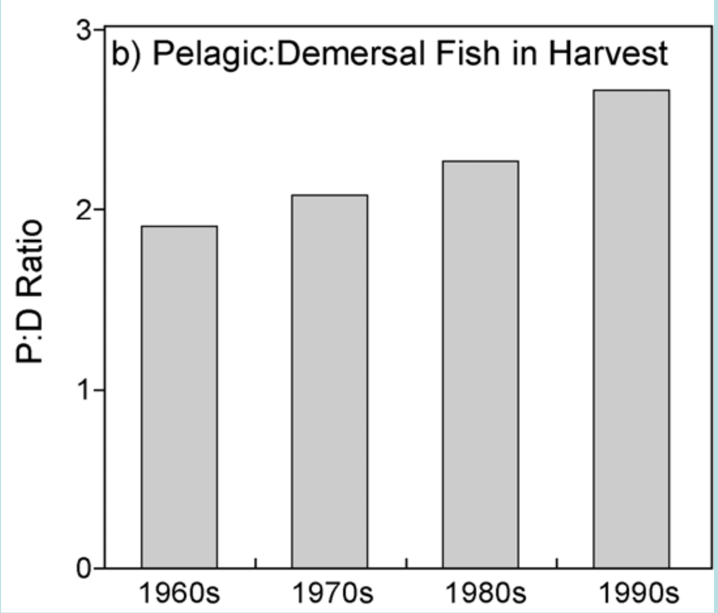


(Nilsson and Rosenberg 2000)

Degraded Bottom Habitats Lead to Shifts in 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)**



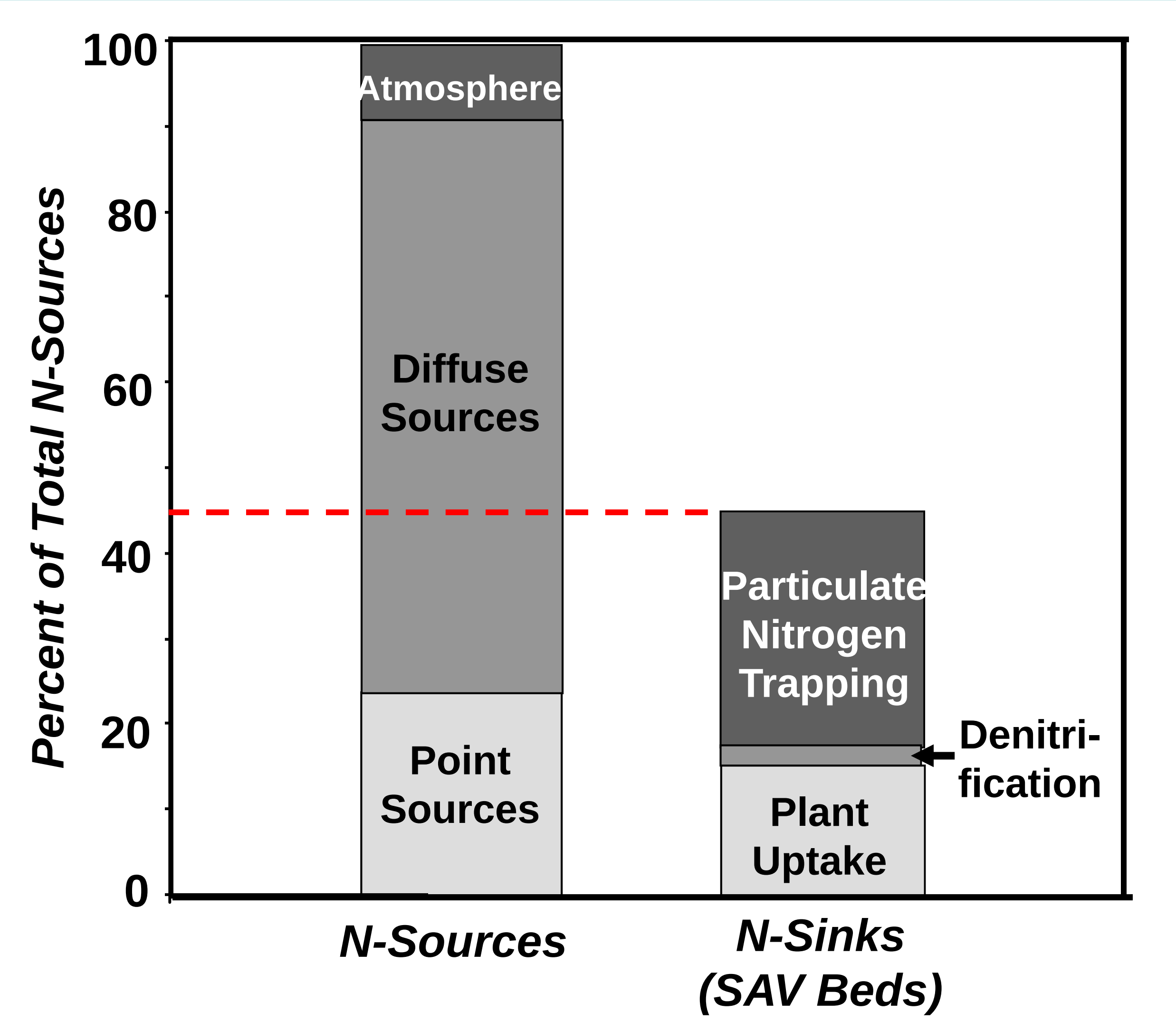


(Houde in Kemp et al 2005)

Ecological Feedback Processes

Although Excess N-input has Contributed to Loss of SAV, Healthy Beds are Sinks for N-Loading

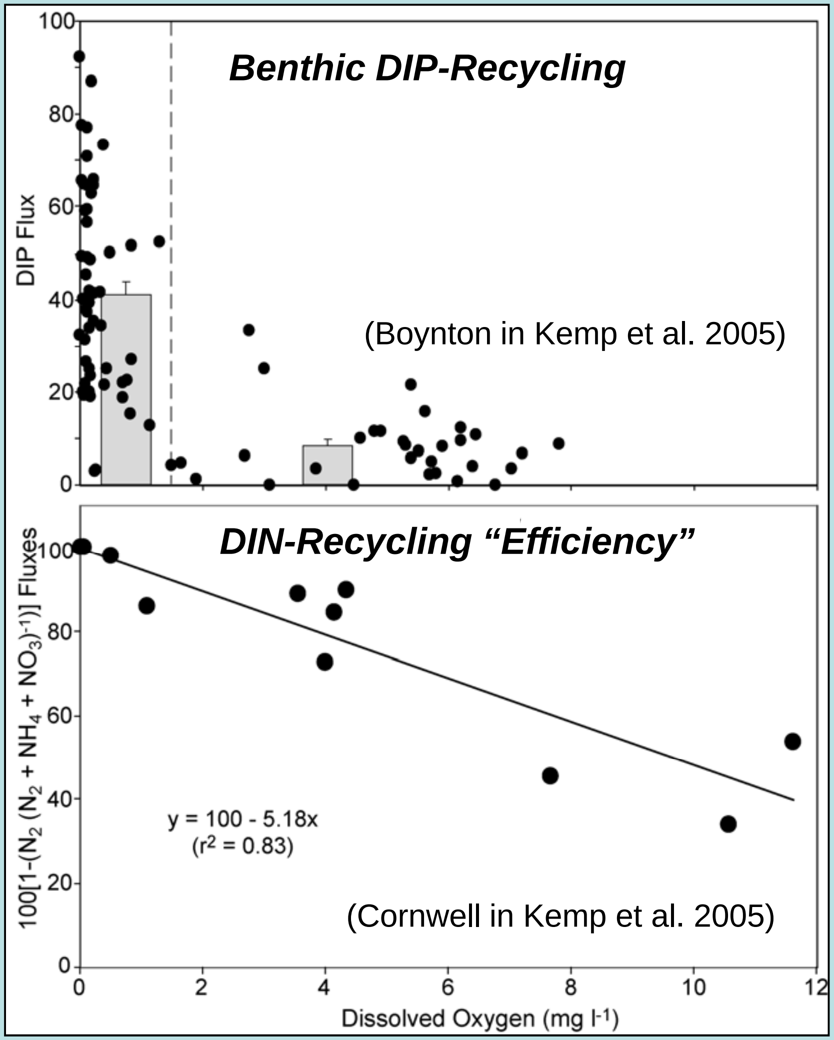
- **Historical Bay SAV beds were capable of ‘removing’ ~45% of current N Loading**
- **Primary pathways of N removal would be trapping particulate N & direct assimilation**
- **Calculation only considers mainstem upper (MD) Bay**
- **N removal rates would be larger if whole Bay were considered**



(Kemp et al 2005)

Hypoxic Bottom Water Tends to Enhance Benthic Recycling of 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**



Benthic DIP-Recycling

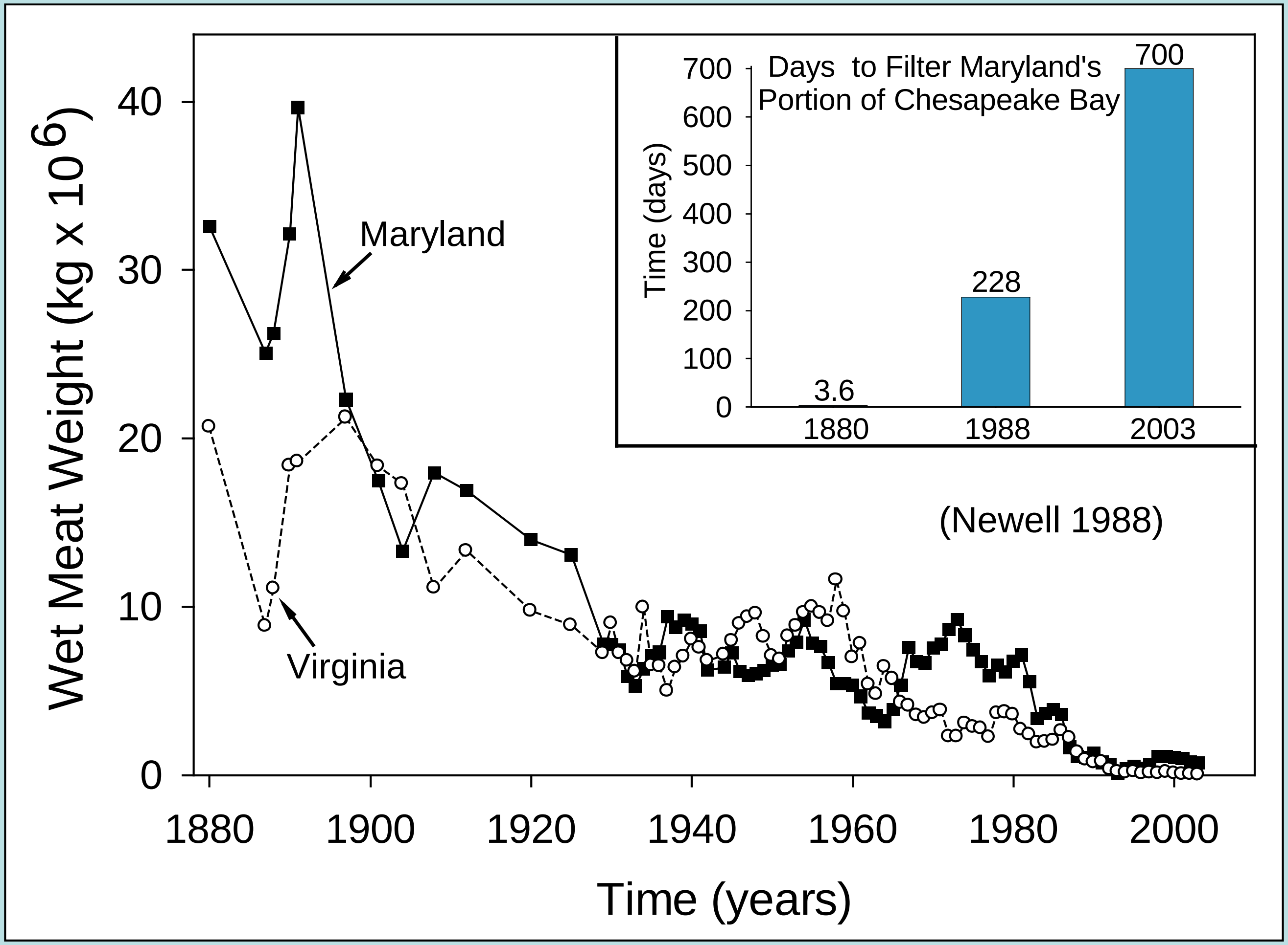
(Boynton in Kemp et al. 2005)

DIN-Recycling "Efficiency"

(Cornwell in Kemp et al. 2005)

Declining Abundance of Oysters: Consequences for the Bay's Nutrient Filtration Capacity

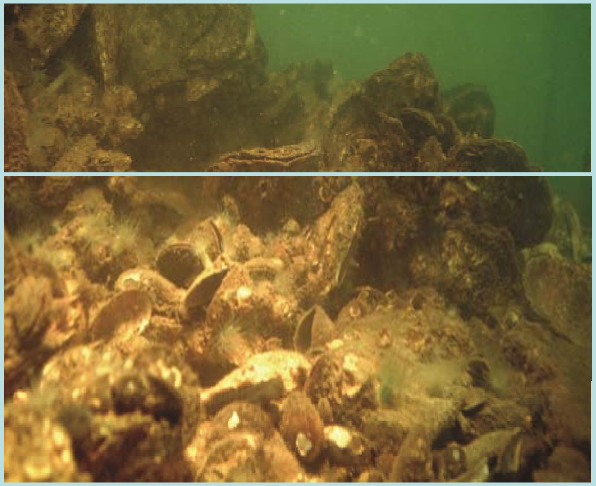
- **Decline in oyster abundance has caused loss of nutrient filtration capacity**
- **Oyster declines due primarily to over-fishing and disease**
- **Historic oyster populations were able to filter Bay water volume in days**
- **Current oyster populations filter Bay water in months-years**
- **Oyster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

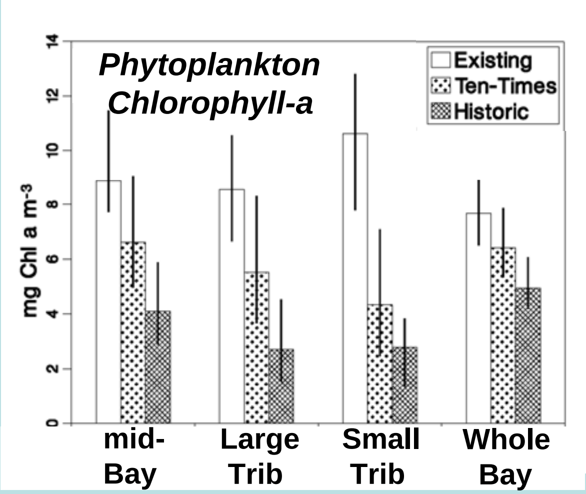


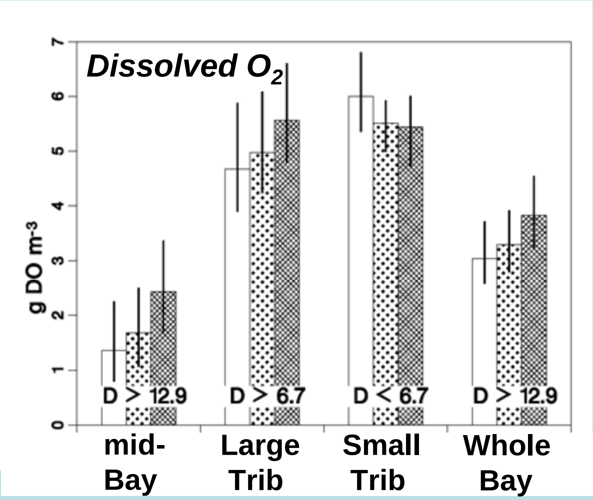
(Kemp et al 2005)

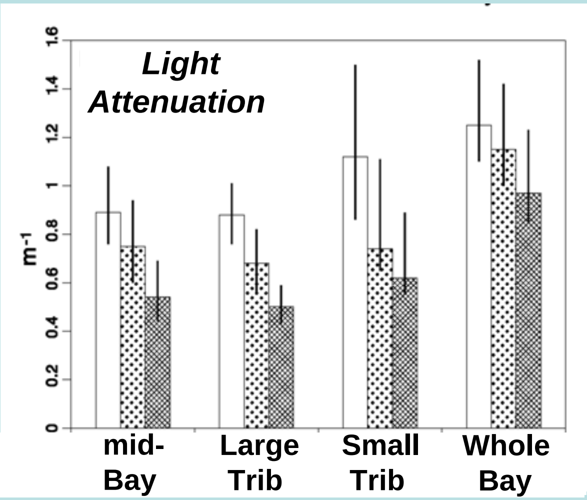
Oyster Restoration Potential Effects on Hypoxia & SAV: A Modeling Study

- **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**





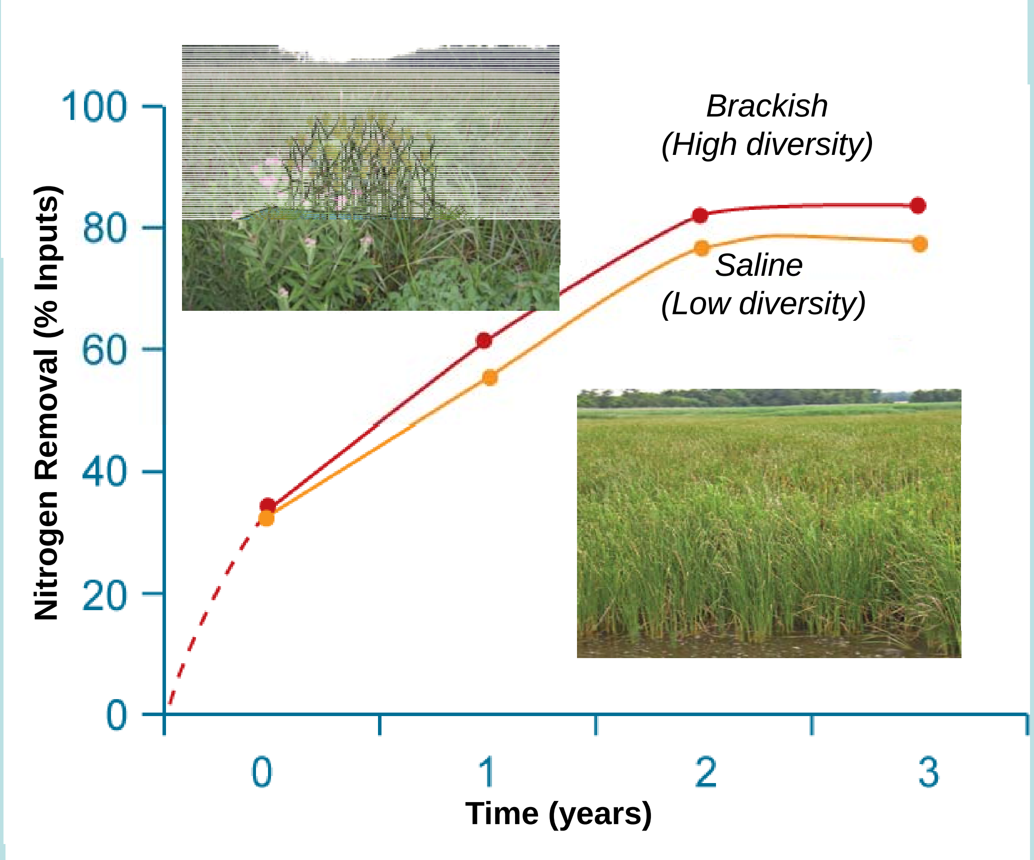




(Cerco and Noel 2007)

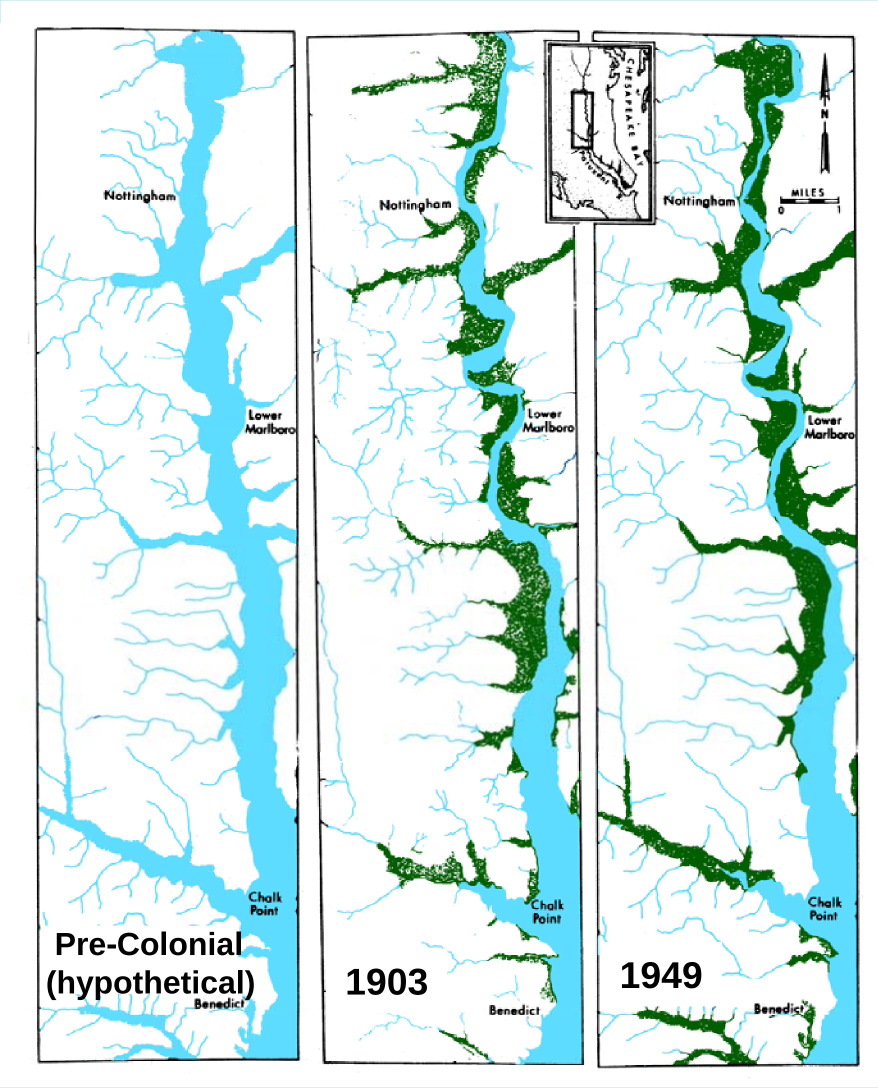
Tidal Marshes Serve as Nutrient Filters at Watershed-Estuary Margins

- 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



Marsh Cover Increased Since Colonial Times with Soil Erosion But is Now Declining 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**
- **Marsh restoration would help re-establish lost filtration capacity**



Prospects for Ecosystem Recovery

Signs of Ecosystem Recovery in Some Bay Tributaries Where Nutrient Loading has been Reduced

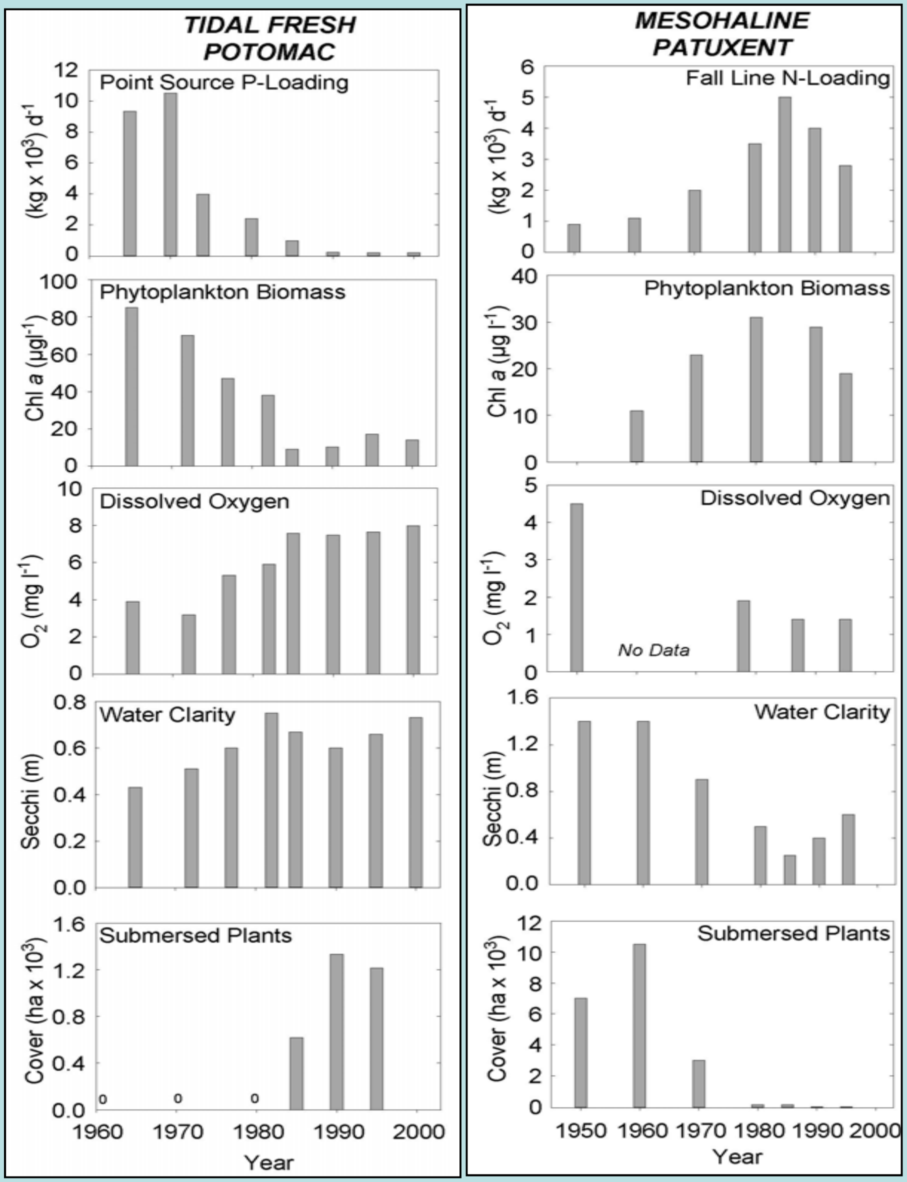
- **Two examples of significant reductions in nutrient loading in Bay tributaries: Potomac & Patuxent**

- **Potomac showed immediate decline in phytoplankton w/ reduced P input**

- **Potomac DO and water clarity improved w/in 10 years; SAV returned within 20 years**

- **Patuxent time-series w/ declining conditions as N-loading increased, and clear but slow recovery after reductions in N-loading**

- **Bay ecosystems respond to reductions in both N and P, but responses are delayed for some variables and conditions**



Trajectories of Response to Nutrient Loading

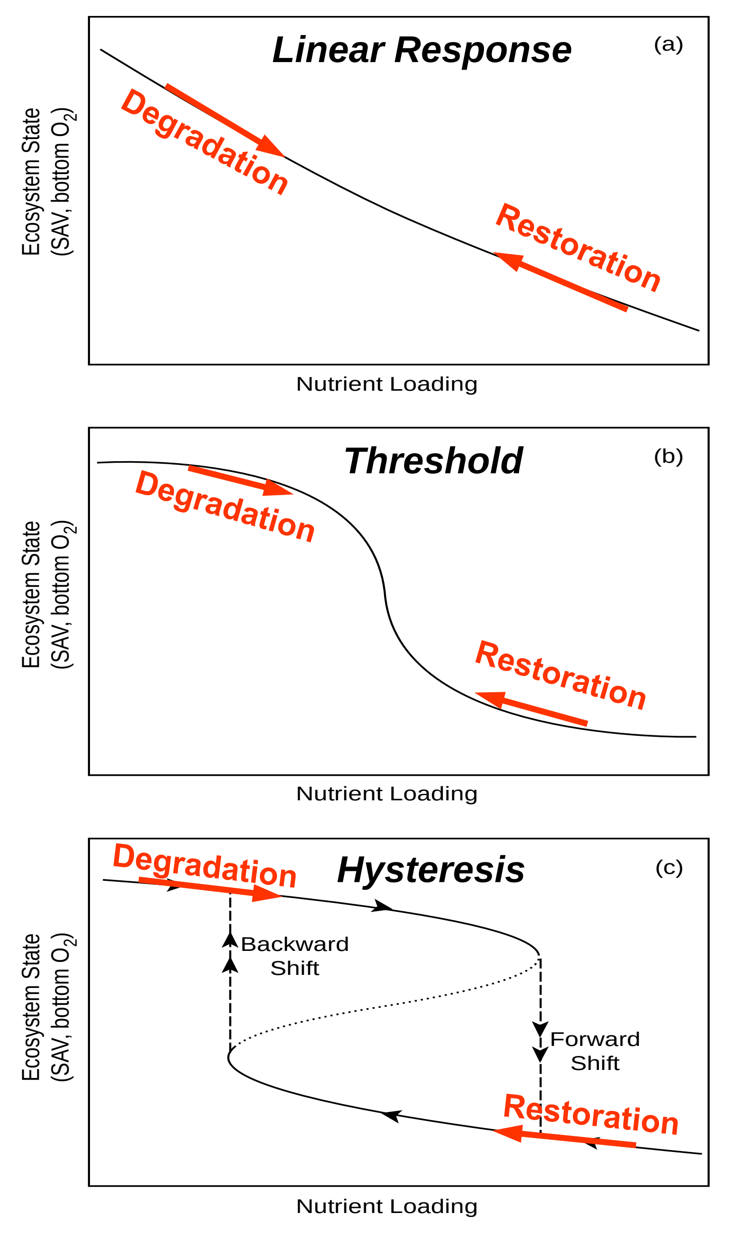
- **Theory suggests alternative ecosystem response to changes in environmental conditions (e.g., nutrient loading, climate)**

- **Responses can follow ~linear pathways with direct proportional response (a)**

- **Responses can follow “sigmoidal” shape w/ apparent threshold shift within narrow range of environmental conditions**

- **Responses can exhibit multiple stable-states w/ abrupt transitions and hysteretic patterns where degradation and restoration follow different trajectories**

- **Distinguish thresholds & hysteresis only w/ data for nutrient increase & decrease**

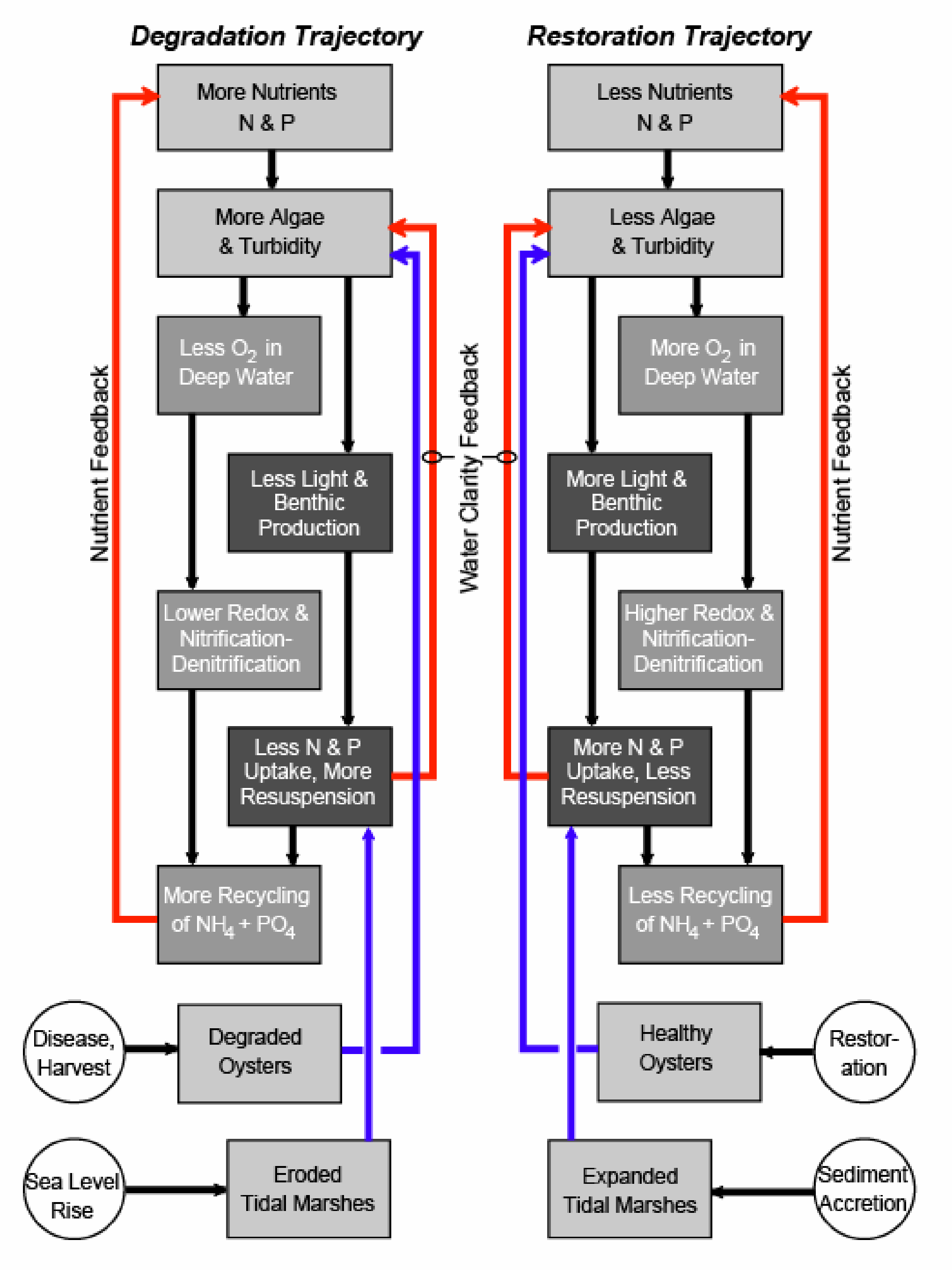


(Scheffer et al. 2001)

Summary of Nutrient-Related Feedbacks in Bay Ecosystem

- **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**



Degradation Trajectory

More Nutrients N & P

More Algae & Turbidity

Less O_2 in Deep Water

Less Light & Benthic Production

Lower Redox & Nitrification-Denitrification

Less N & P Uptake, More Resuspension

More Recycling of NH_4 + PO_4

Disease, Harvest

Degraded Oysters

Sea Level Rise

Eroded Tidal Marshes

Nutrient Feedback

Water Clarity Feedback

Restoration Trajectory

Less Nutrients N & P

Less Algae & Turbidity

More O_2 in Deep Water

More Light & Benthic Production

Higher Redox & Nitrification-Denitrification

More N & P Uptake, Less Resuspension

Less Recycling of NH_4 + PO_4

Healthy Oysters

Restor-ation

Expanded Tidal Marshes

Sediment Accretion

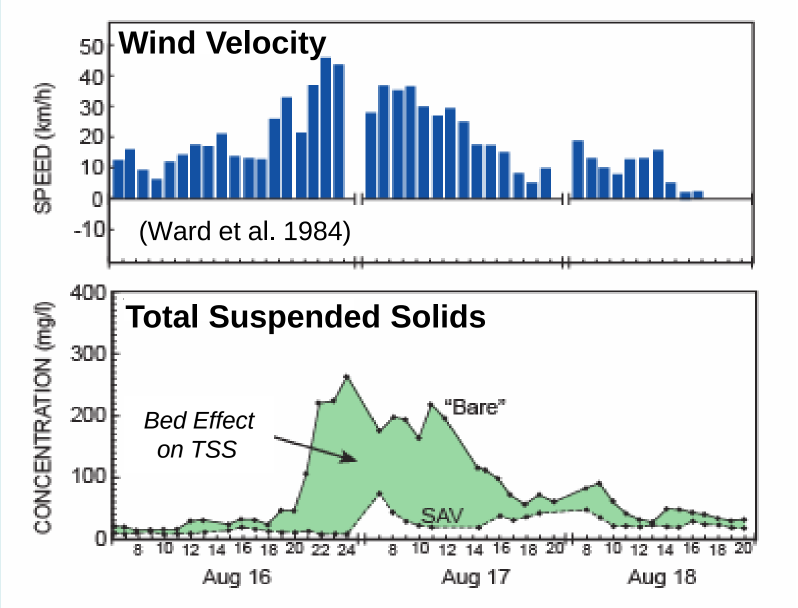
Nutrient Feedback

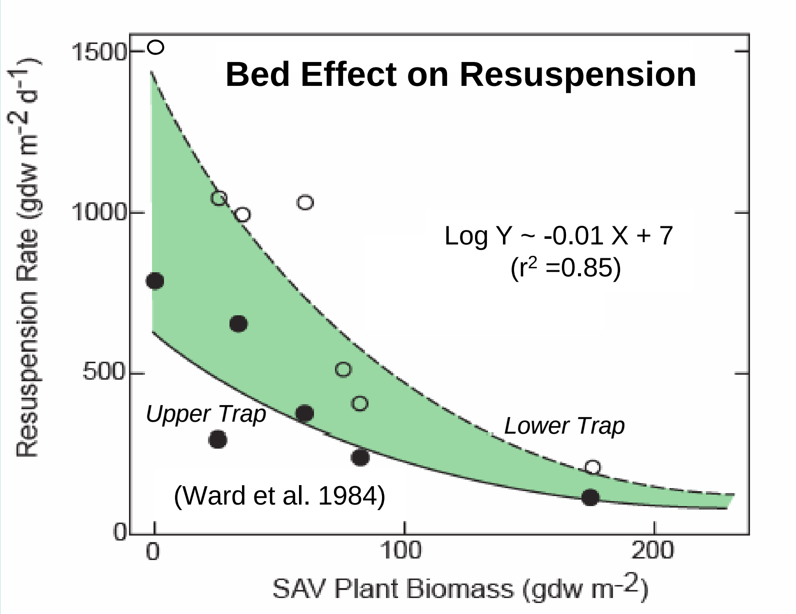
(Kemp et al. 2005)

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**

Feedback Effects: (1)Lower turbidity in SAV Beds





- Suspended particles tend to control water clarity in much of the Bay
- Wind resuspension of bottom sediment is largest source of TSS in shallow Bay
- TSS levels are reduced (by 5-50 x) in SAV because of bed friction effects

- Resuspension of bottom sediments is inversely related to SAV biomass
- Thus, plant beds strongly reduce levels of TSS and associated turbidity
- Healthy SAV beds of high plant biomass tend to have clearer overlying water and higher photosynthetic rates