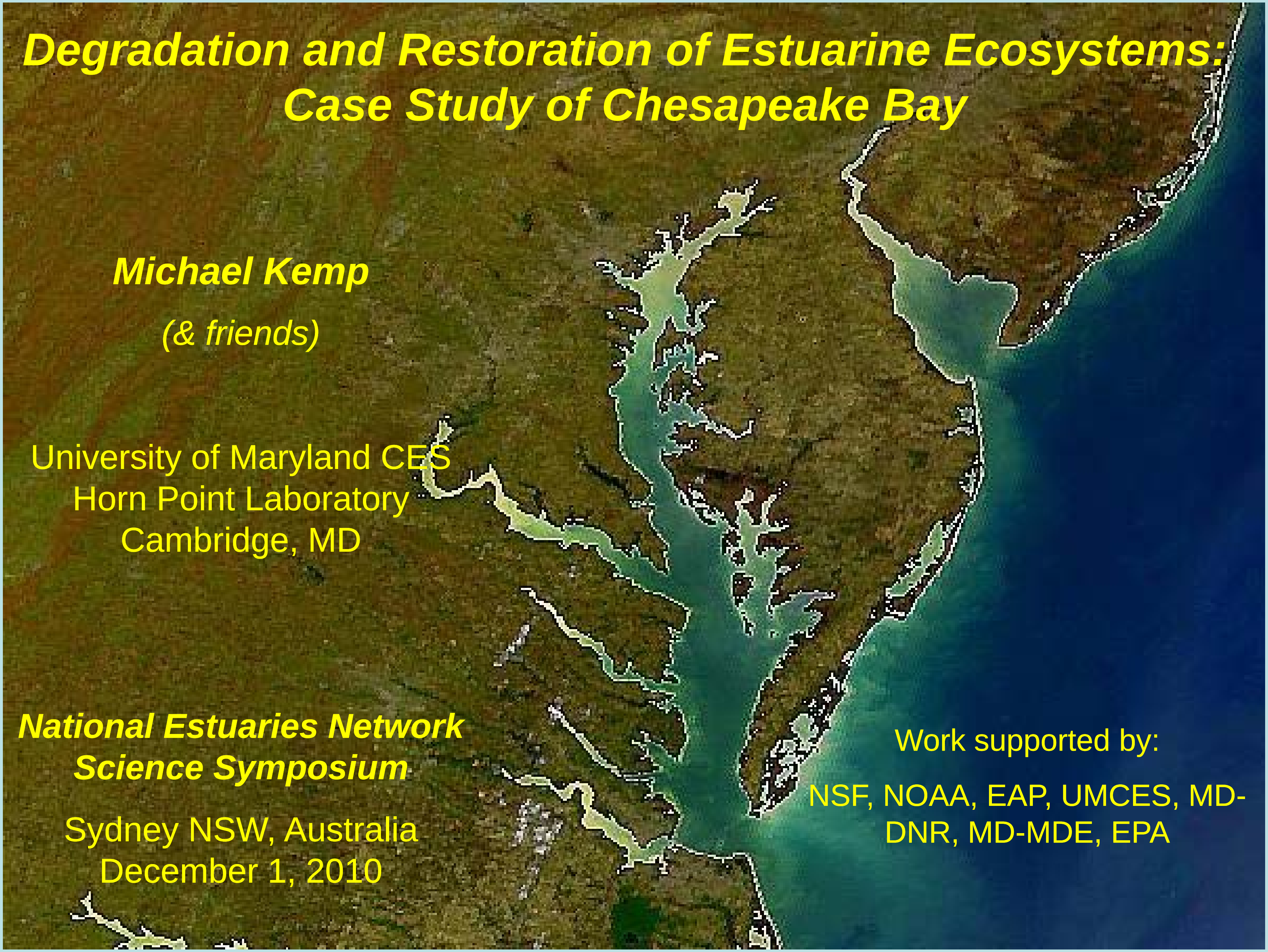
Degradation and Restoration of Estuarine Ecosystems: Case Study of Chesapeake Bay



Michael Kemp

(& friends)

University of Maryland CES
Horn Point Laboratory
Cambridge, MD

National Estuaries Network Science Symposium

Sydney NSW, Australia
December 1, 2010

Work supported by:

NSF, NOAA, EAP, UMCES, MD-DNR, MD-MDE, EPA

Outline

(1) Human disturbance alters estuarine ecosystems worldwide

(2) Chesapeake Bay case study: Physics, productivity, watershed

(3) Nutrient enrichment degrades water quality & habitat conditions

(4) Recovery of eutrophic ecosystems with nutrient management

(5) Declining fisheries populations & an example recovery

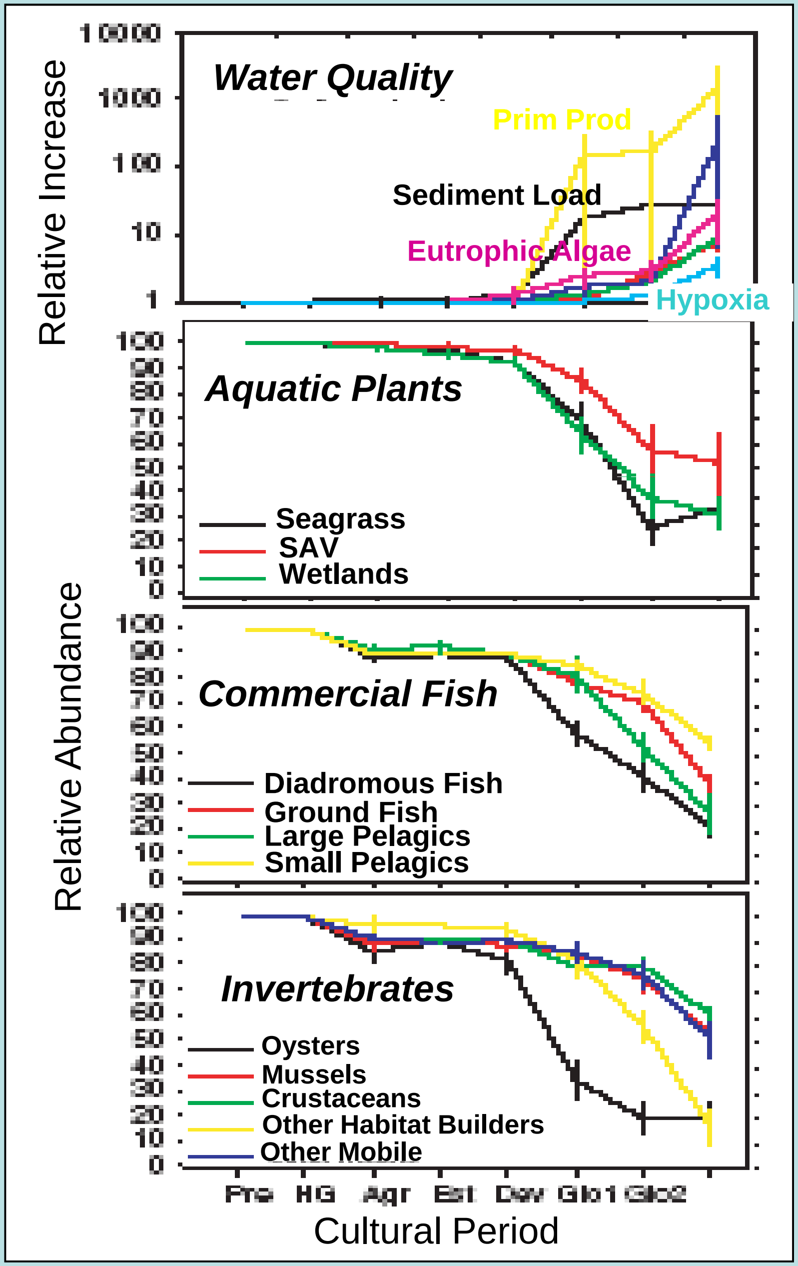
(6) Restoration by exploiting Nature’s self-regulation processes

(7) Direct and active restoration of vegetated habitats

(8) Synthesis and Conclusions

Human Alteration of Estuarine Ecosystems at Global Scales

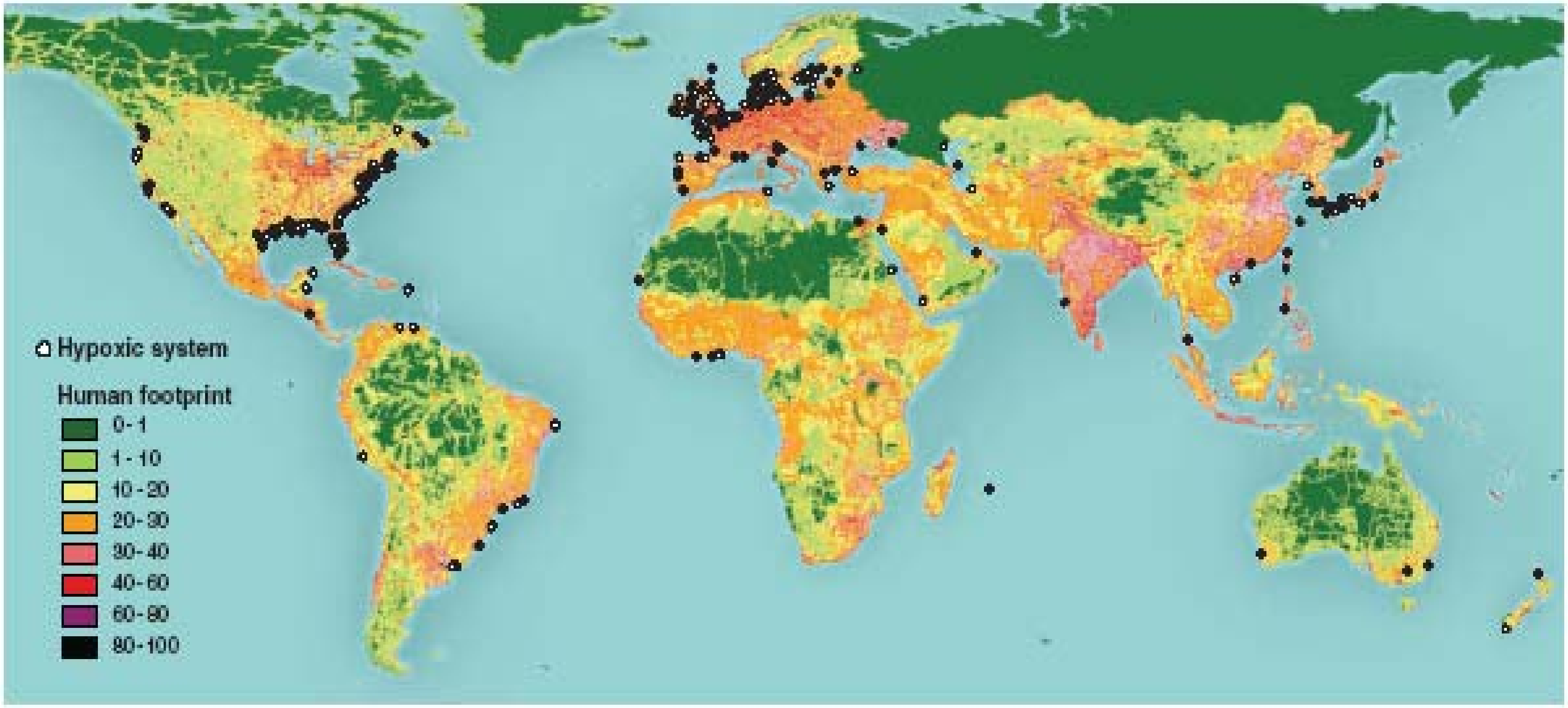
Long-Term Changes in Estuarine Ecosystems



- Human impact on coastal ecosystems was minimal until Development (colonial period ~1800)
- Water quality declined quickly with increasing nutrients, sediments, algae, & loss of aquatic plants (~1900)
- Other manifestations like hypoxia did not expand until recently (~1950)
- Fisheries declines started first with oysters and migrating fish (~1700)
- Other exploited fish & invertebrates have declined steadily from colonial times (~1700) through the present

(Loetz et al. '06)

Global Distribution of Hypoxic Systems



• Recent (2008) survey identified > 400 reported systems with hypoxia due to eutrophication; expanded to more regions covering ~250,000 km^2.

• Hypoxia distribution linked with watershed regions having large human "footprint" (i.e., intense human activity and influence).

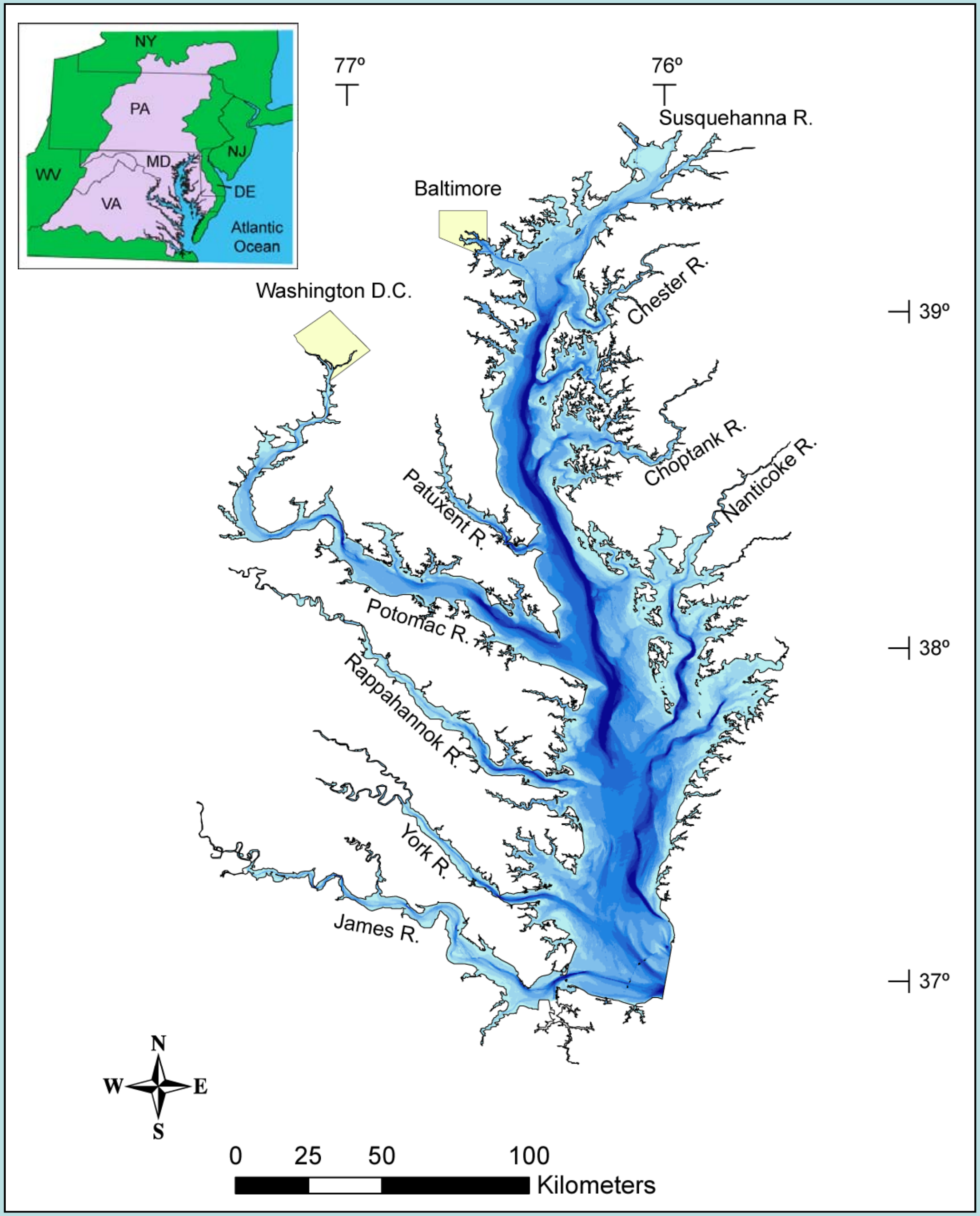
(Diaz & Rosenberg 2008)

(2) Introduction to Chesapeake Bay:

- ***Physics***
- ***Productivity***
- ***Watersheds***

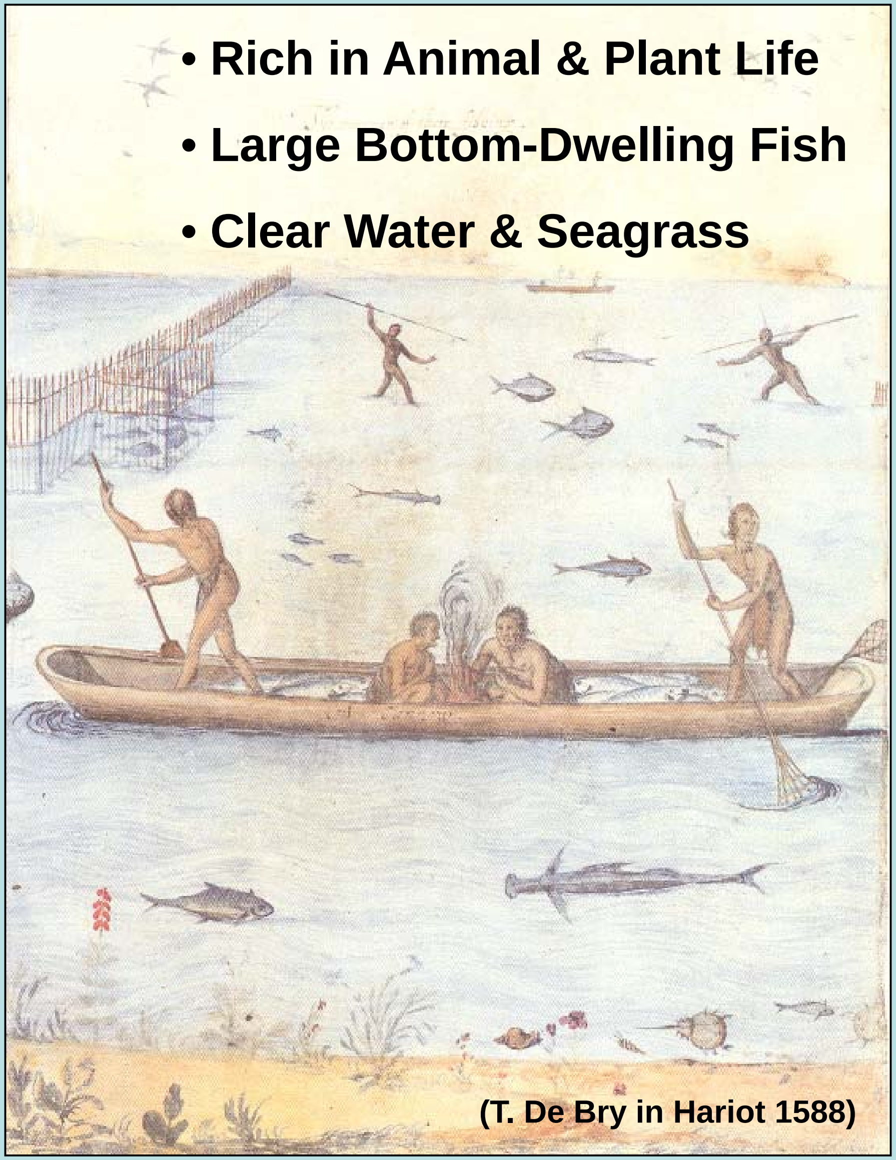
Key Bay Features

- Large ratio of watershed to estuarine area (~15:1)
- Seasonal stratification
- Broad shallows where light reaches sediment
- Relatively long water residence time (~ 6 mo)
- Highly productive ecosystem



Portrait of Early Chesapeake Bay

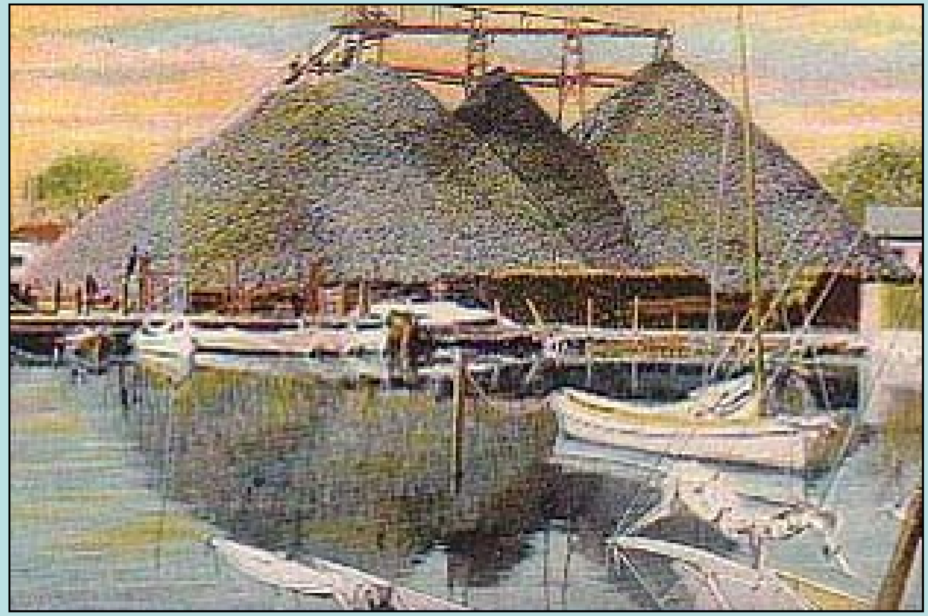
Pre-Colonial (ca. 1600)



- **Rich in Animal & Plant Life**
- **Large Bottom-Dwelling Fish**
- **Clear Water & Seagrass**

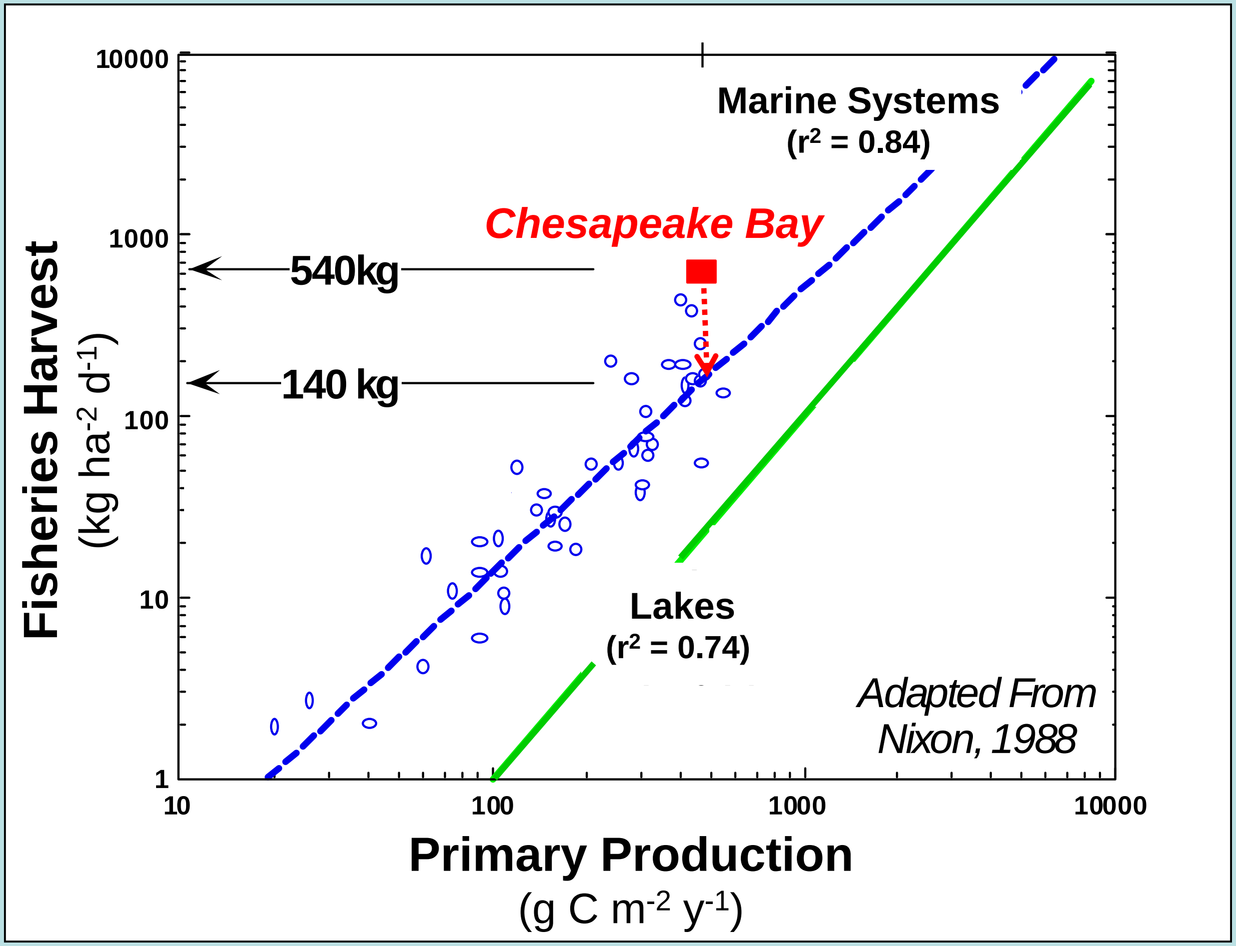
(T. De Bry in Hariot 1588)

Early Industrial (ca. 1900)



- **Mountains of Oyster Shell Attest to the once abundant filter-feeding reef-forming animals**

Chesapeake Bay: A Productive Ecosystems

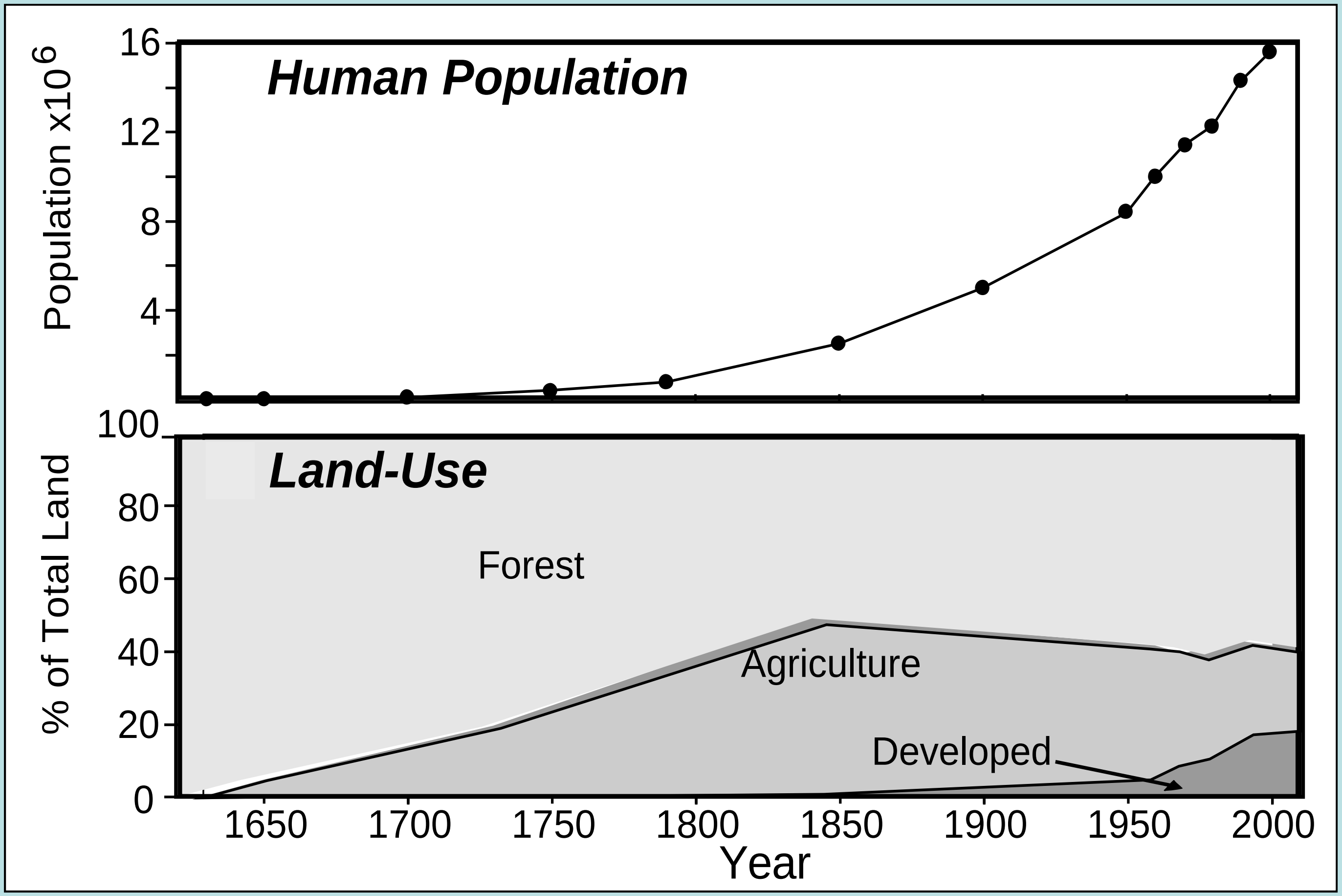


- Bay's Primary Production is among highest for aquatic ecosystems
- Fish Yields ~ 4-times average estuary with same productivity

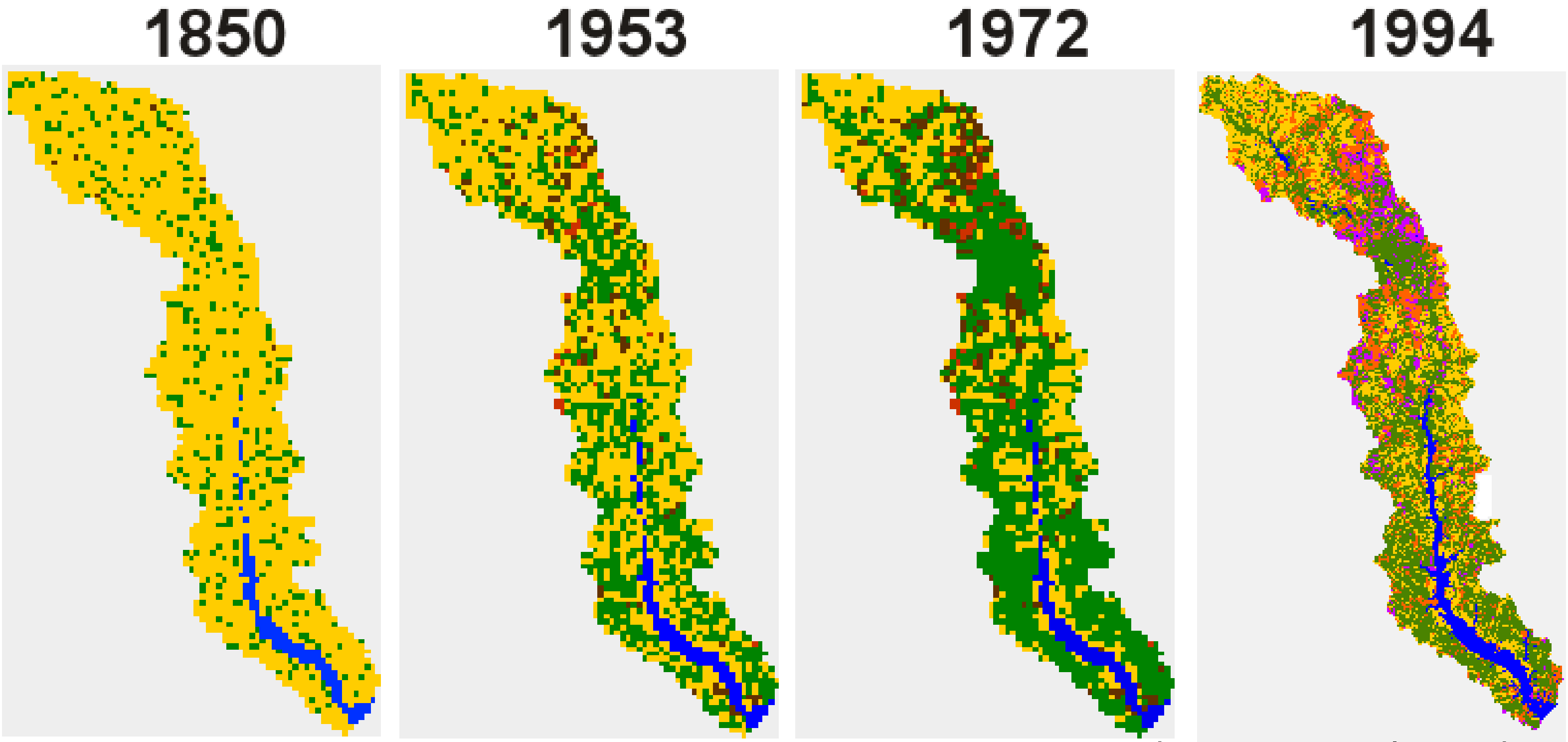
Chesapeake Bay Watershed Changes: Land-Use & Population Trends

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

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



Patuxent Watershed Land-Use Changes

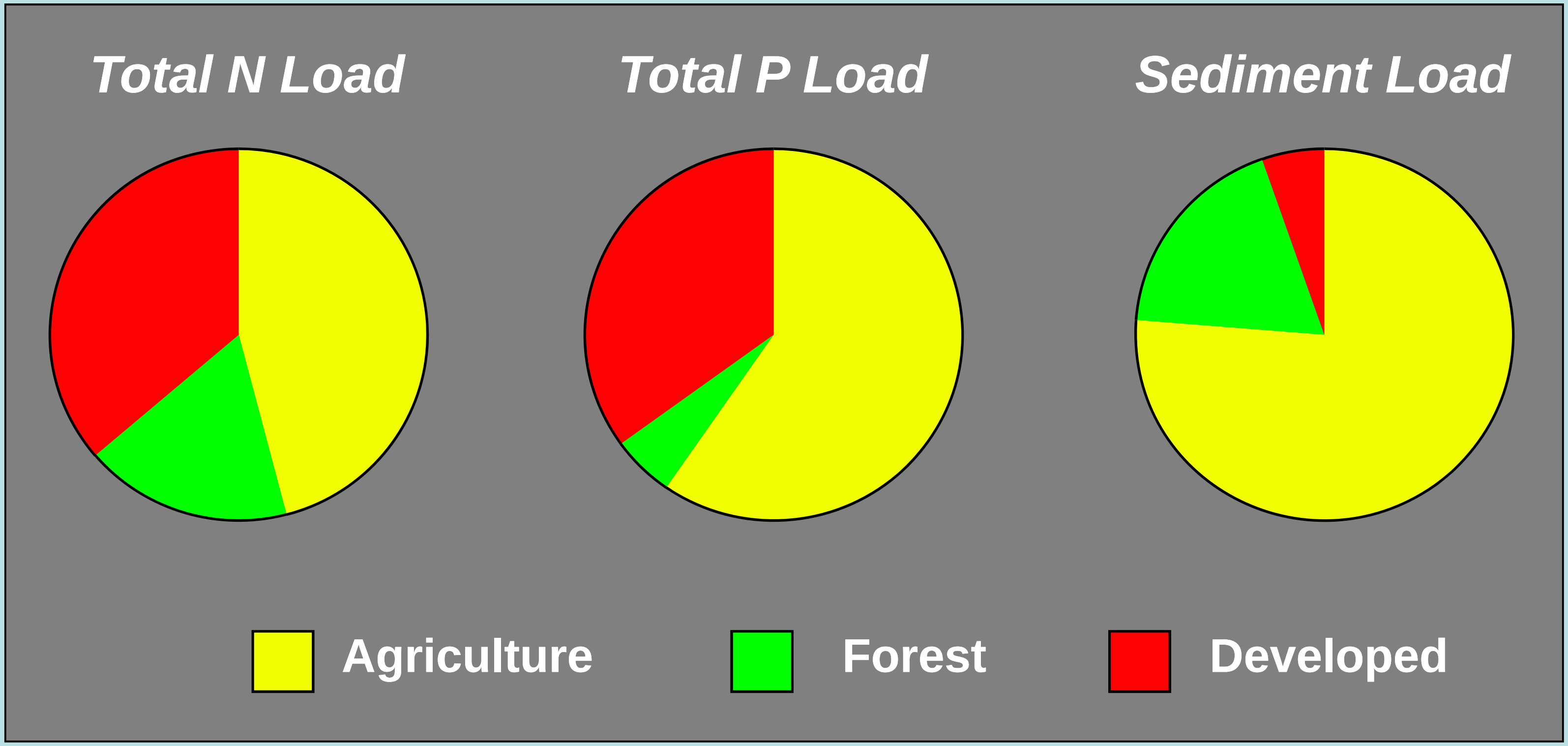


(Costanza et al. 2000)

	1850	1953	1972	1994
Forest	14.3%	37.3%	57.0%	51.6%
Residential	0.3%	4.6%	8.0%	15.5%
Urban	0.0%	1.2%	2.3%	4.3%
Agro	85.5%	57.0%	32.8%	28.5%

- Farm Land in 19th C transformed back to Forest thru 1970s
- Development transforms Farm Land to Residential & Urban Thru Present

Chesapeake Bay Watershed
Sources of Nutrients and Sediments

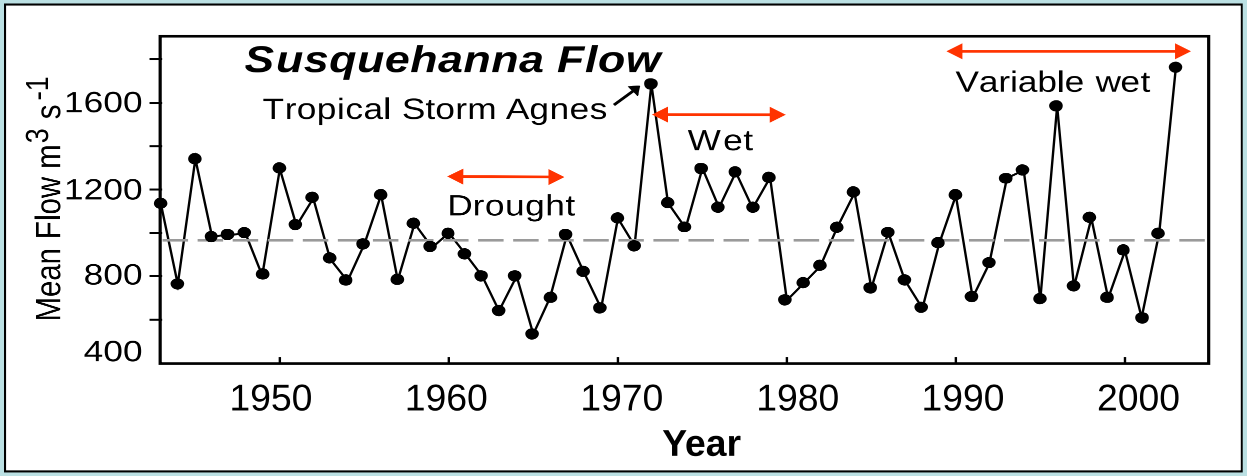


- **Nitrogen, Phosphorus & Sediment Loading from Watershed Land-Uses**
- **“Agriculture” major source of all 3, “Developed” major source of N & P**

River Flow Drives Bay Ecosystem

- **Susquehanna River is powerful driver carrying freshwater & associated nutrients, OM, buoyancy**

- (shown in flood-stage)

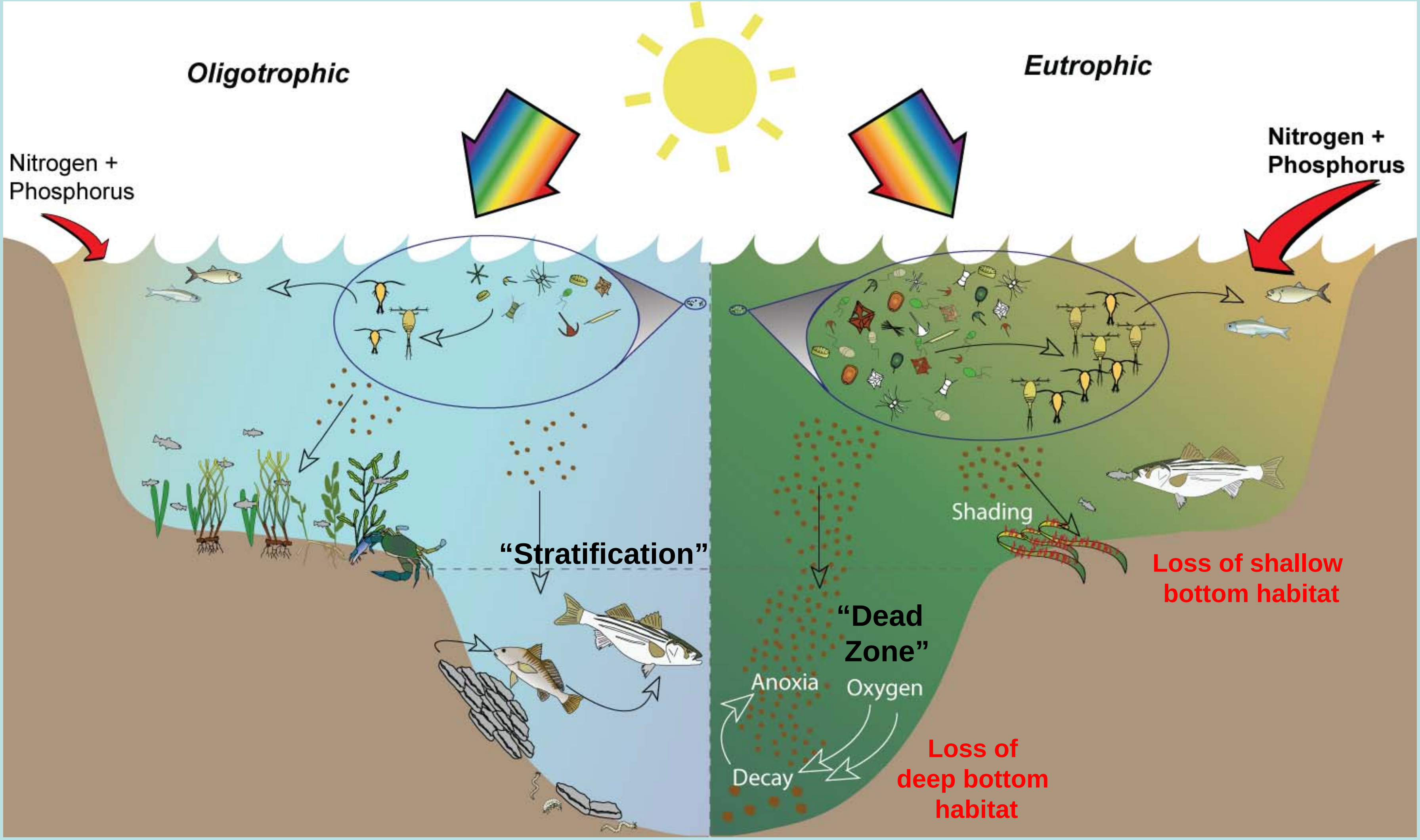


- **Large variations in river flow (~4X); with wet and dry decades but no long-term trends**

(3) Nutrient Enrichment Causes Degradation of Water Quality & Natural Habitats:

- ***Loss of Seagrass & Submersed Aquatic Vegetation (SAV)***
- ***Depletion of bottom oxygen (Hypoxia)***

Nutrient Enrichment Effects on Coastal Ecosystems

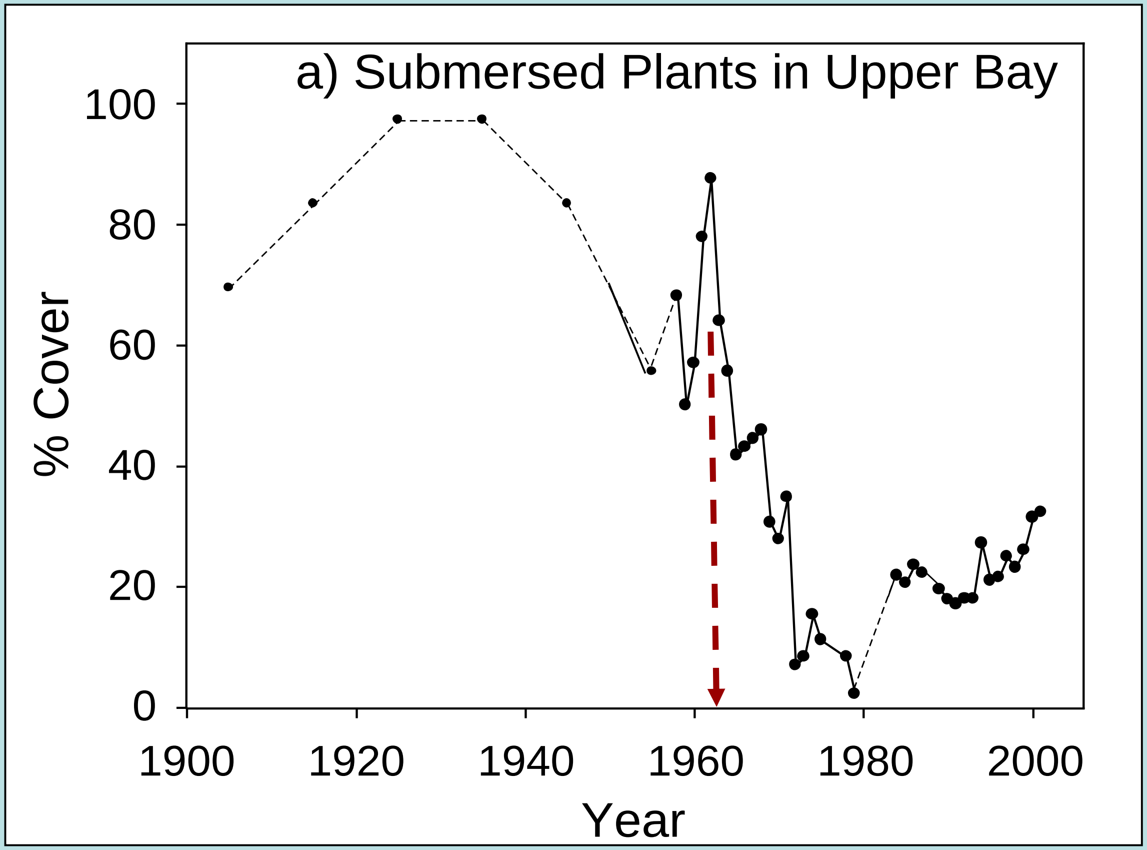


Dramatic Bay-Wide Decline of Seagrass & SAV (Submersed Aquatic Vegetation)

Solomons Island 1933

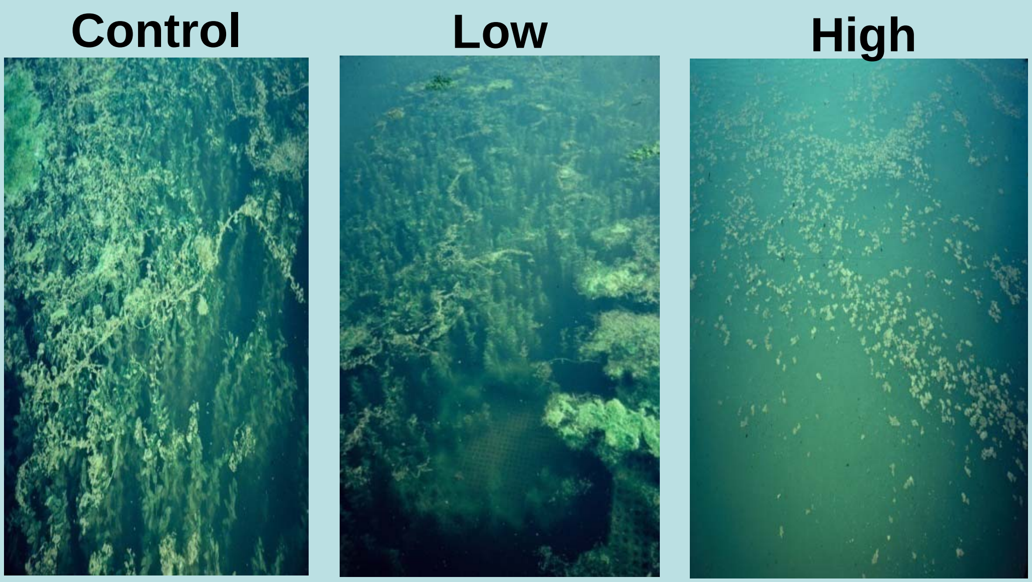
Solomons Island 1999

Seagrass (SAV) Decline & Partial Recovery

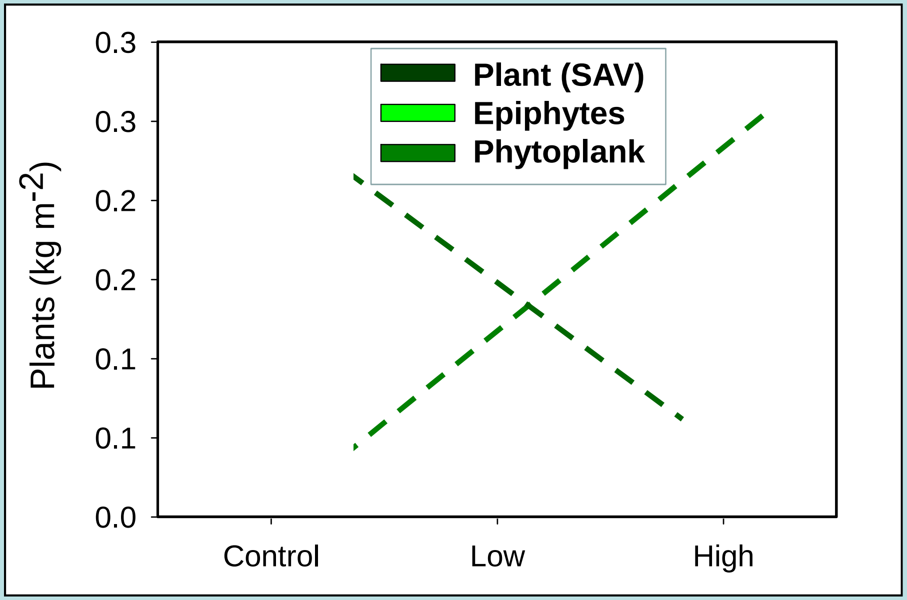


- **Sharp SAV decline in upper Bay in early 1960s**
- **Huge degradation of Shallow Habitat**
- **Modest recovery since mid-1980s (~30% former)**

Experiments Reveal Role of Nutrient Enrichment



- Control units had clear water and lush SAV growth
- Low-Nutrient units had heavy epiphyte growth
- High-Nutrient units, thick phytoplankton blooms; epiphytes shaded out



- Data confirm visual sense
- Epiphytes were shaded in High-Nutrient units

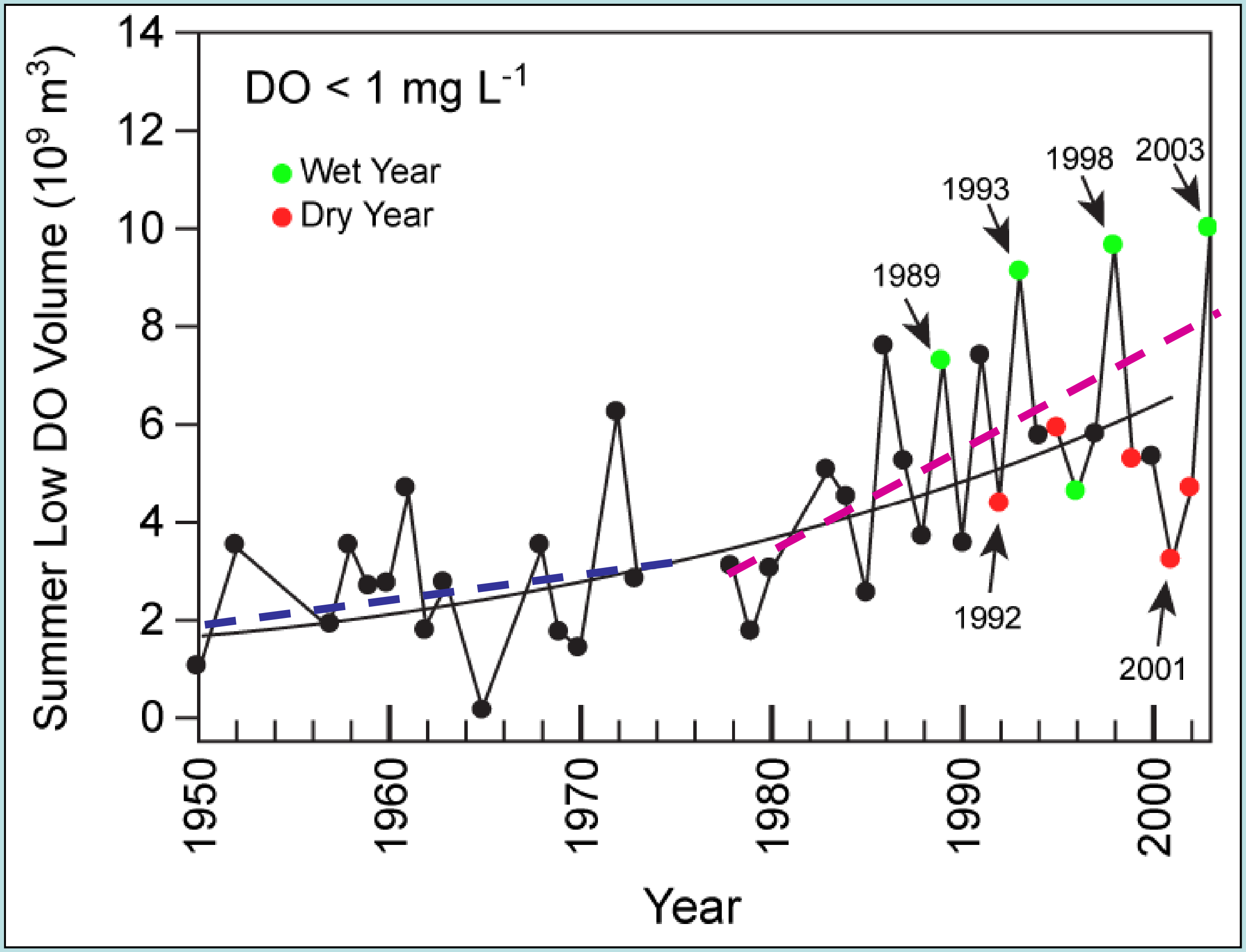
(Kemp et al. 1983)
(Twilley et al. 1985)

Historical Increase in Volume of Summer Hypoxic Water from 1950 to 2003

- **Significant trend shows increased volume (4x) of severely hypoxic (O_2 < 1 mg/L) from 1950-2003**

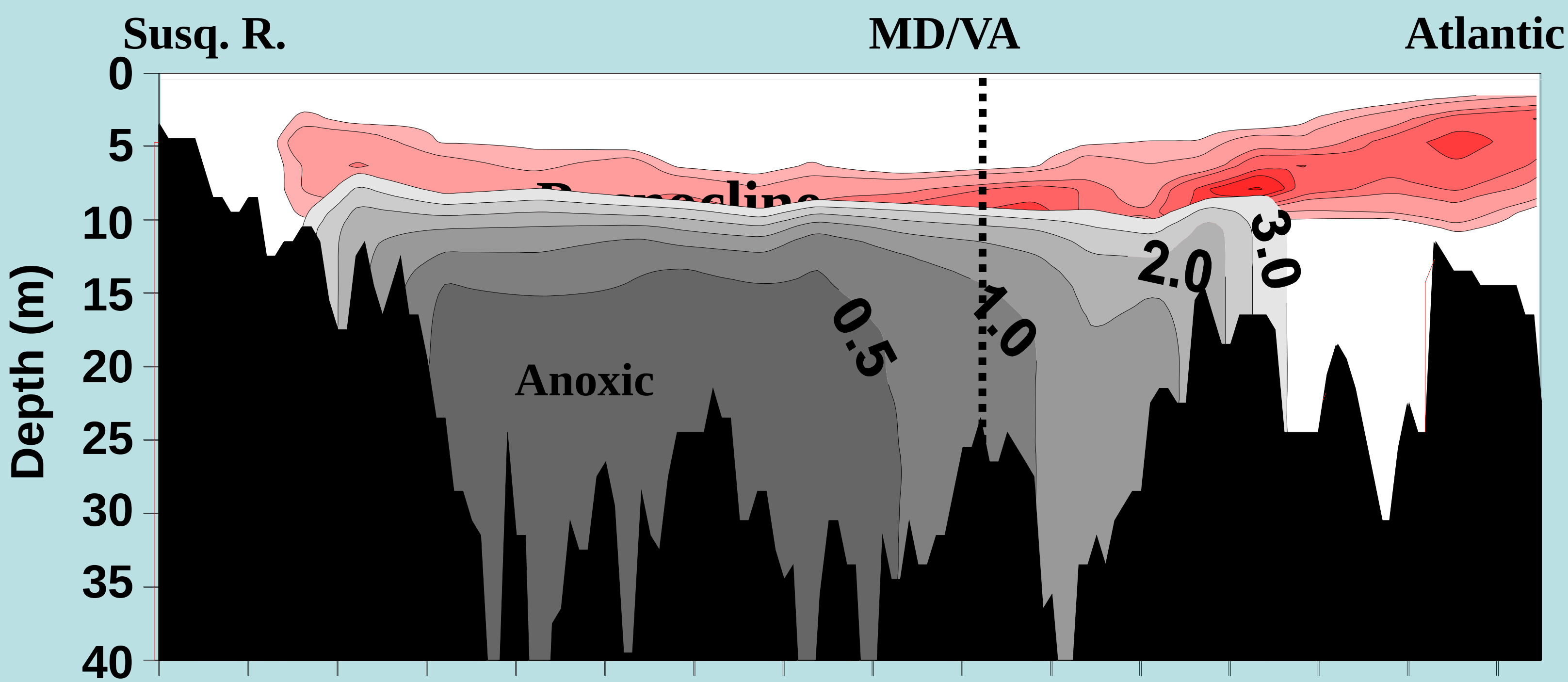
- **Within long-term trend, hypoxia is greater in high flow years (wet = green dot) compared to low flow years (dry = red dot)**

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



(After Hagy et al. 2004)

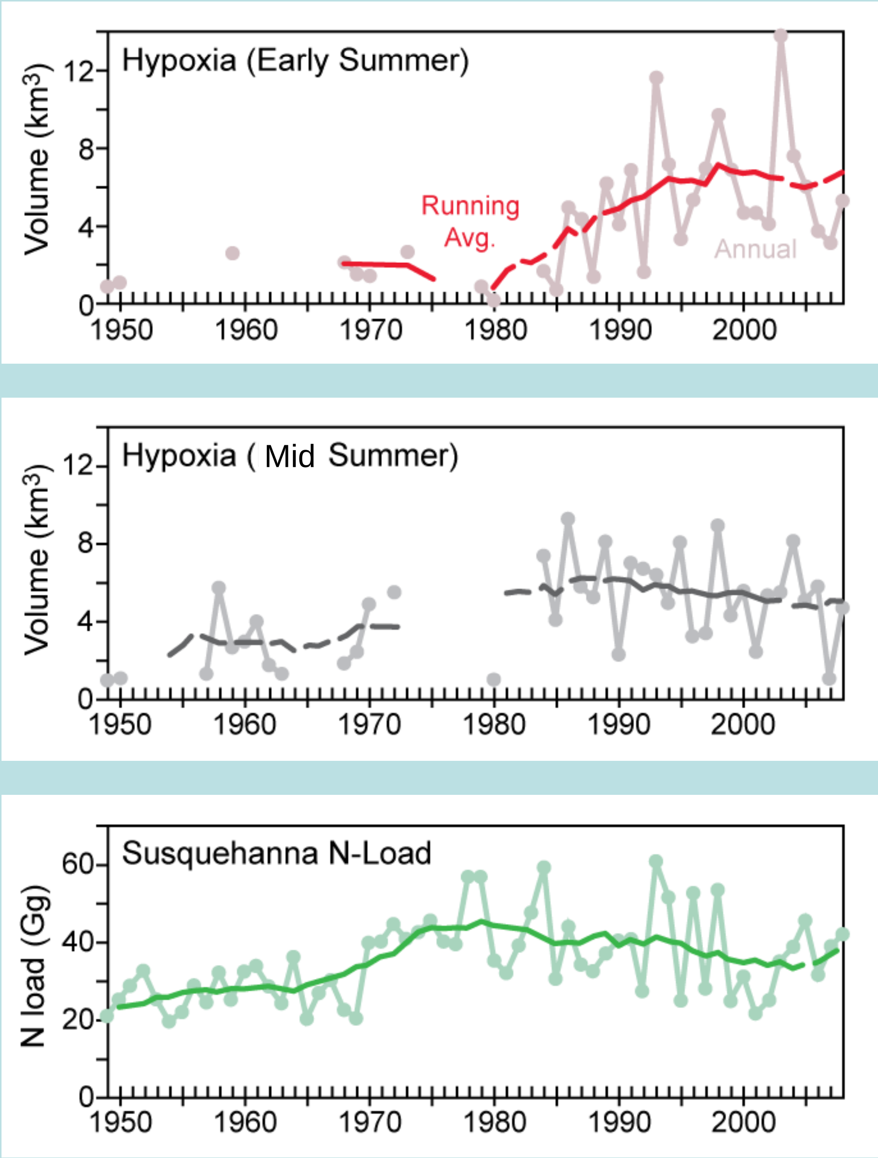
Stratification Control of Hypoxia



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

(After Hagy 2002)

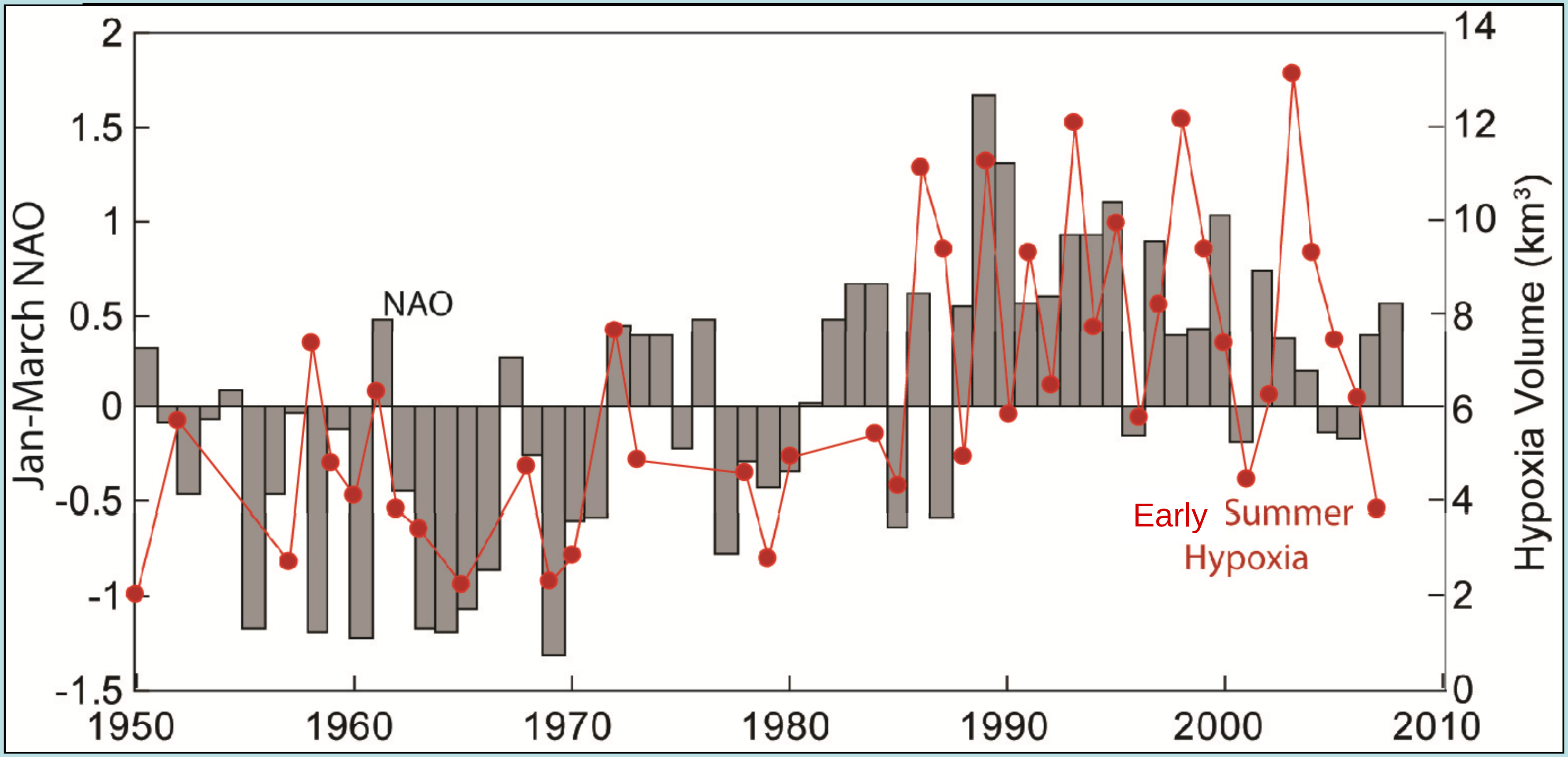
Hypoxia Trends Related to N-Loading



- **Inter-annual variations blur long-term trends; clarify with running means**
- **Early summer hypoxia shows rapid increase since 1980 (earlier graph)**
- **Mid-summer hypoxia has actually declined parallel to the decline in N-load**
- **N-Loading increased until mid-1980s, then declined gradually into 2000s**
- **Hypoxia & N-Load highly correlated (r^2 = 0.77)**

(Murphy et al. 2010)

Climate Effects on Mid-Summer Hypoxia: North Atlantic Oscillation Index



- **Winter NAO Index reflects direction of prevailing summer winds**

- **NAO shift from negative to positive associated with physical conditions that inhibit vertical O_2 mixing, thereby increasing early summer hypoxia**

(Testa 2009)

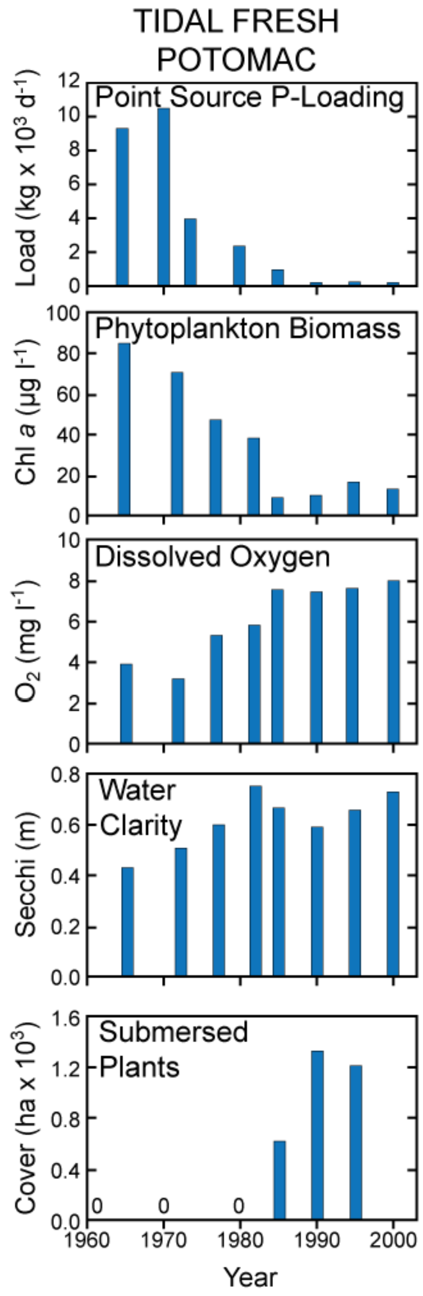
(4) Ecosystem Recovery & Nutrient Management:

- ***Potomac Estuary Case Study***
- ***Patuxent Estuary Case Study***

Example Ecosystem Recoveries with Nutrient Management

- Two Bay tributaries (Potomac & Patuxent) where nutrient sources ('Point') were reduced
- Potomac—rapid phytoplankton decline w/ reduced P input
- Potomac—Improved DO & Secchi in 10 yrs; SAV in 20 yrs
- Patuxent—Water quality declined w/ N-load increase;
- Patuxent—Phytoplankton and Secchi decreased with N-load reduction, but DO and SAV recovery were delayed

(Kemp et al. 2005)



(5) Fisheries Population Declines (& Recoveries)

- ***Atlantic Menhaden***
- ***Atlantic Sturgeon***
- ***Eastern Oyster***
- ***Striped Bass***
- ***Blue Crab***

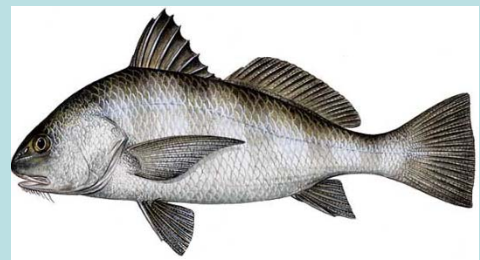
Chesapeake Bay Fisheries in Decline

sturgeon

striped bass

shad

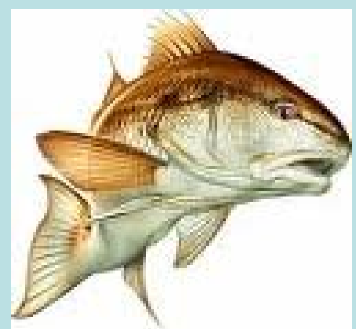
blue crab



black drum

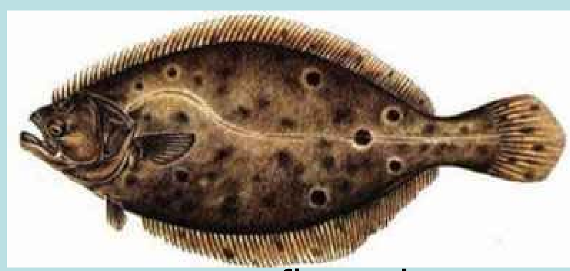
terrapin

menhaden



red drum

oyster



summer flounder

Atlantic Menhaden: Abundant Forage Species

Prime food for striped bass and many other valuable fish, but are now in a major decline

Menhaden schools are spotted by airplanes, caught in large purse seines for oil & pet-food, and removed from Bay food-web

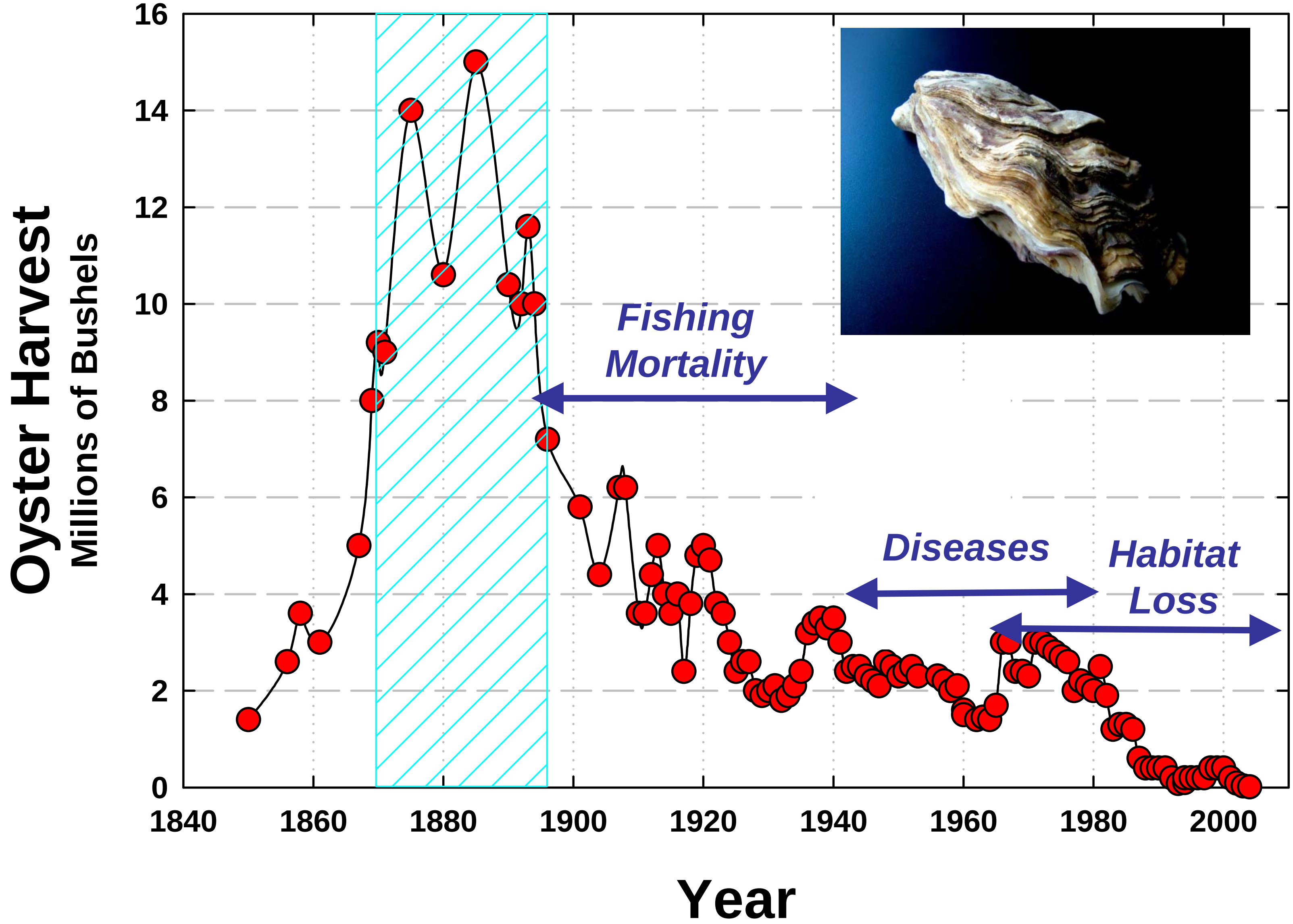
Menhaden filter algae from water for food, thereby cleaning eutrophic waters of excess algae

Fishing pressure increases with modern fleet, & overfishing threatens fish populations

Chesapeake Bay's Oyster Harvest

- ***Symbol of Estuary's Bounty***
- ***Pride of the Regional Culture***

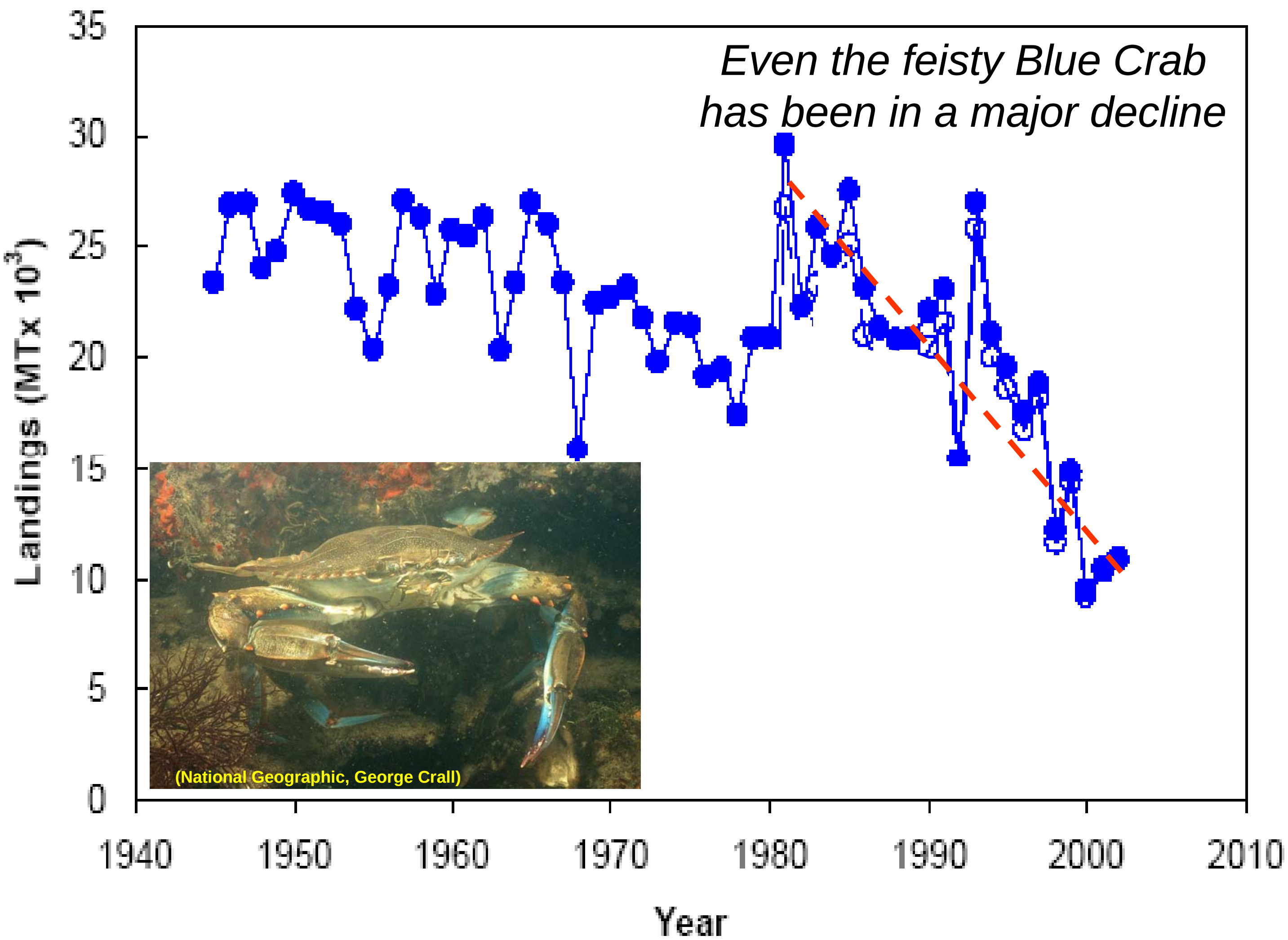
History of Maryland Oyster Harvest



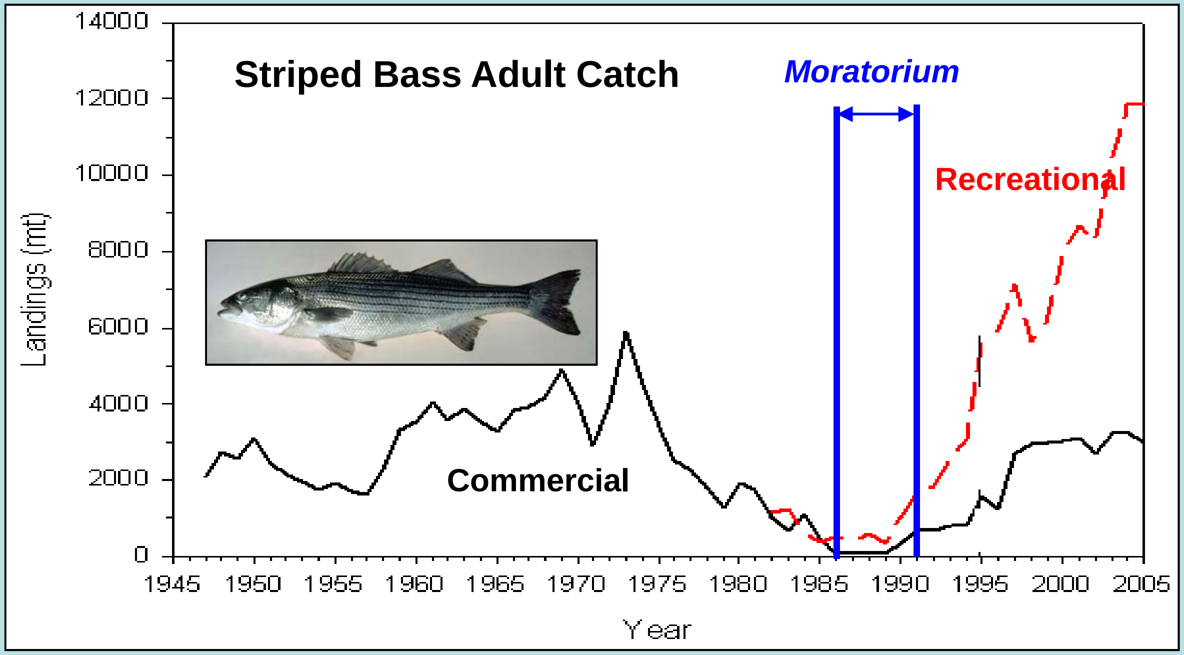
Atlantic Sturgeon: A Highly Vulnerable Species

- Last harvested female from Potomac River estuary in 1970
- Vulnerability: Long-lived, slow growing, easily captured, habitat sensitive (hypoxia)
- Restoration potential: readily reared in captivity

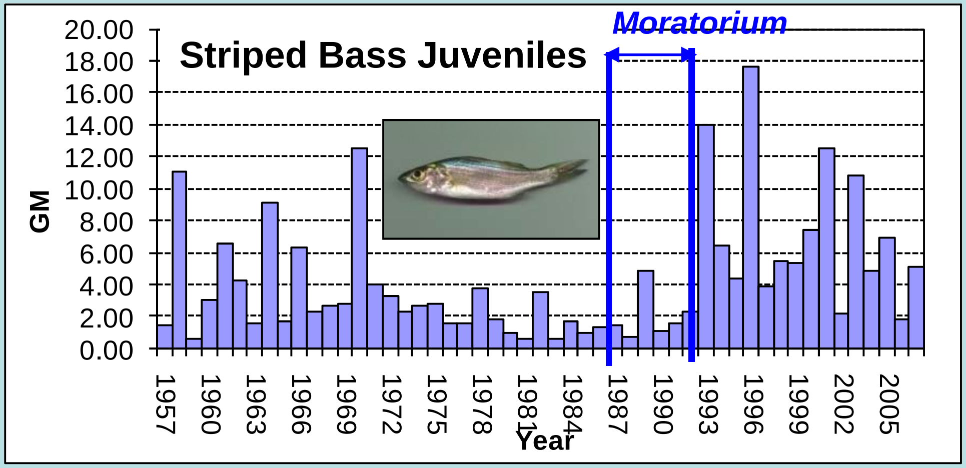
Blue Crab: Chesapeake Bay Landings



Atlantic Striped Bass Landings: 1945 to 2005



- Dramatic decline in striped bass catch starts in early 1970s
- Restoration action taken in 1986 banning all fishing along Atlantic seaboard for 5 years
- Adult stock & harvest increased (1991-present)

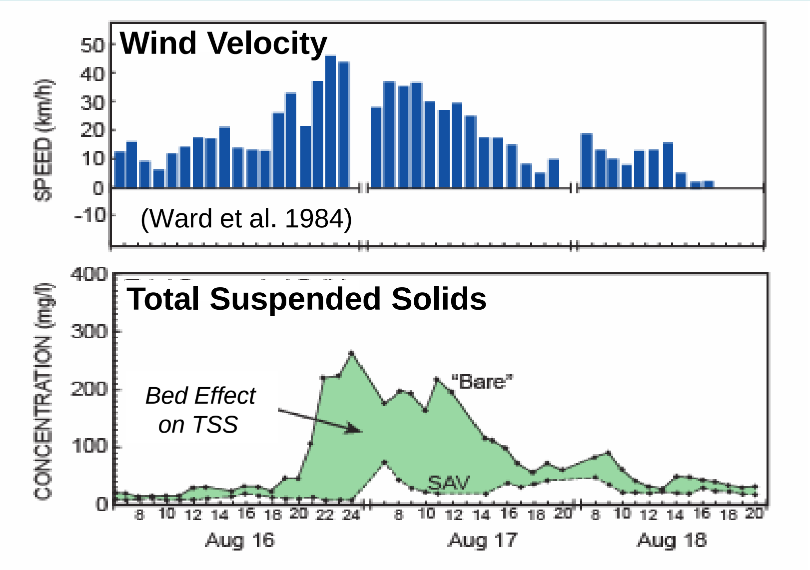


- Juvenile index (mean & peaks) increased with moratorium (1993)
- Restoration effort is great success!

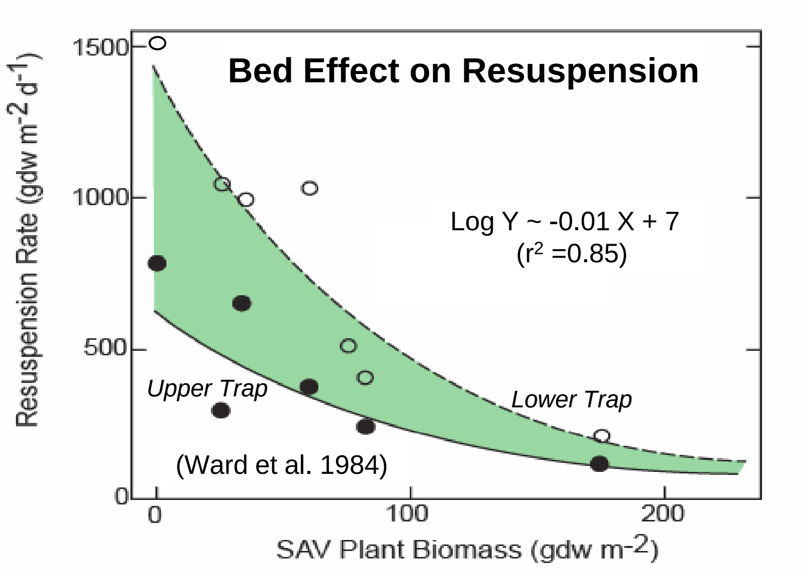
(6) Restoring Bay Ecosystem by Exploiting Nature's Self-Regulating Processes:

- ***Oxygen control on nutrient recycle***
- ***Oyster Reef plankton filtration***
- ***Tidal Marsh nutrient sequestering***
- ***SAV Bed particle and nutrient trapping***

Positive Feedback: SAV Beds Clear Water & Enhance SAV Plant Growth

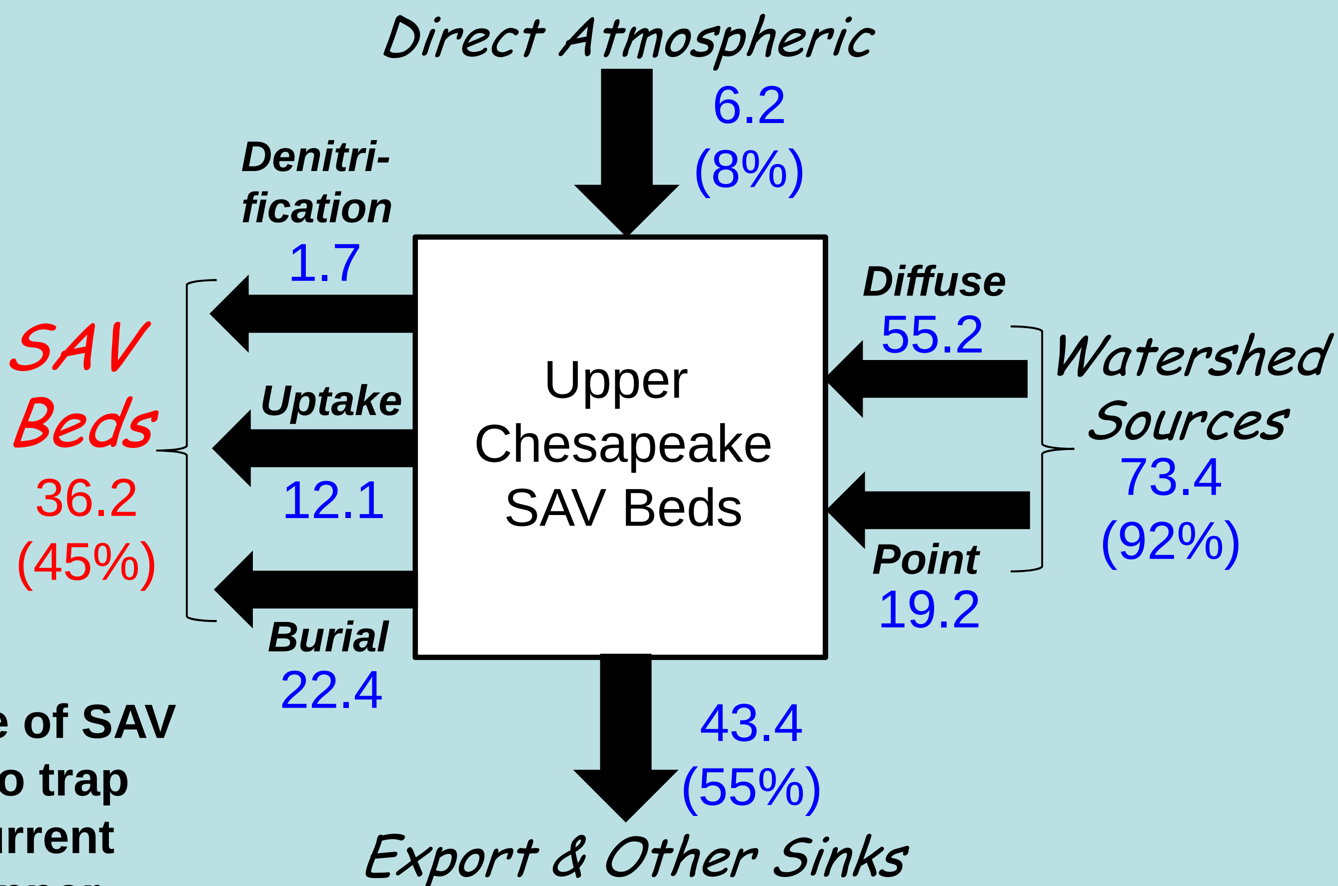


- **Suspended particles control water clarity in much of the Bay**
- **Wind resuspension of bottom sediment is largest TSS source in shallow Bay**
- **TSS levels are reduced (by 5-50 x) in SAV because of bed friction effects**



- **Resuspension of bottom sediments declines with increasing SAV biomass**
- **Thus, plant beds strongly reduce levels of TSS and associated turbidity**
- **Healthy SAV beds with denser plant biomass tend to have clearer overlying water and higher photosynthetic rates**

SAV Beds Remove Nitrogen from Bay Water



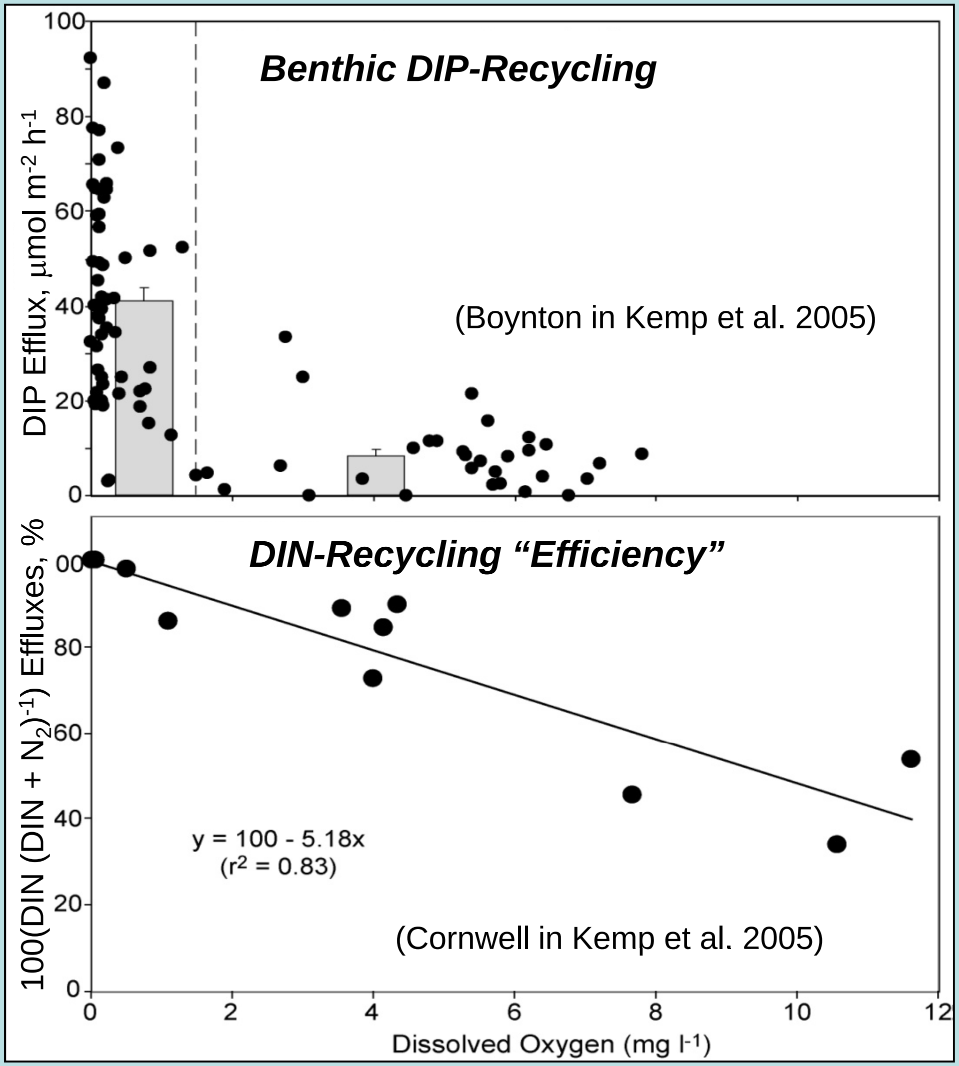
Historical abundance of SAV beds was sufficient to trap and store ~45% of current inputs of total N to Upper Chesapeake Bay, thus reducing eutrophication.

(Flows: 10^6 kg N yr^{-1})

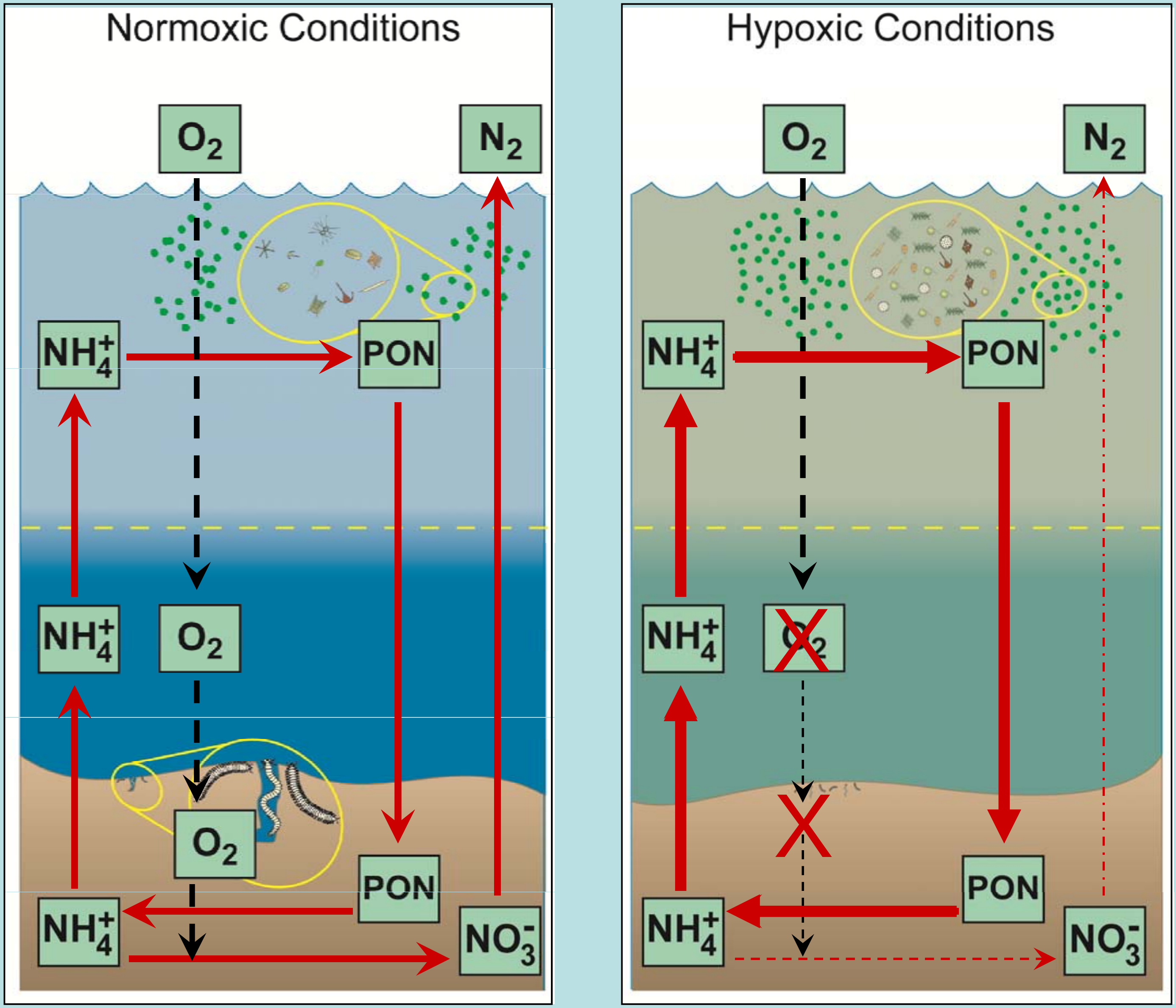
(Kemp et al. 2005)

Positive Feedback: Hypoxia Increases Nutrient Recycling and Algae Production

- **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**

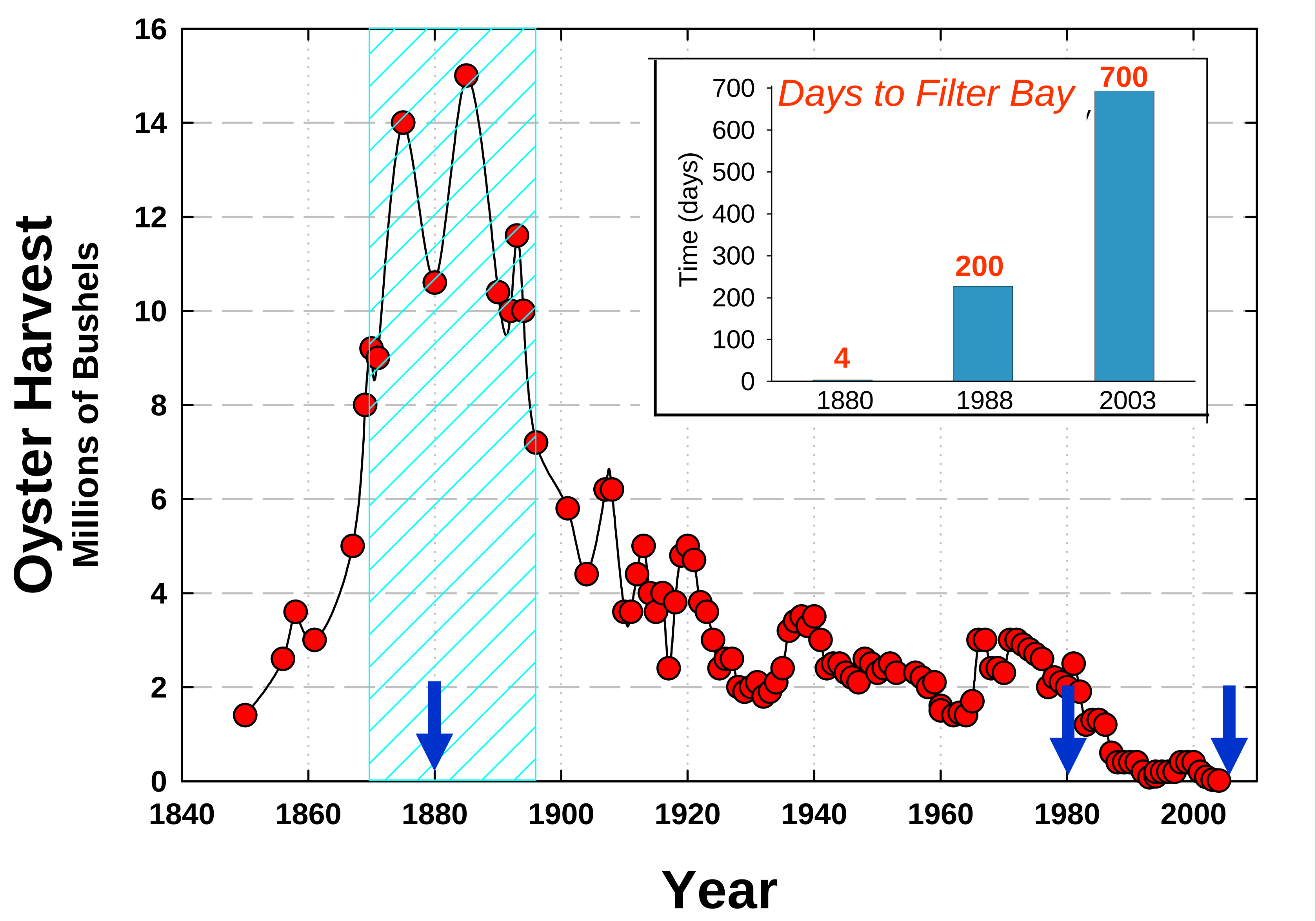


Conceptual Model of O_2 Controls on N-Cycling



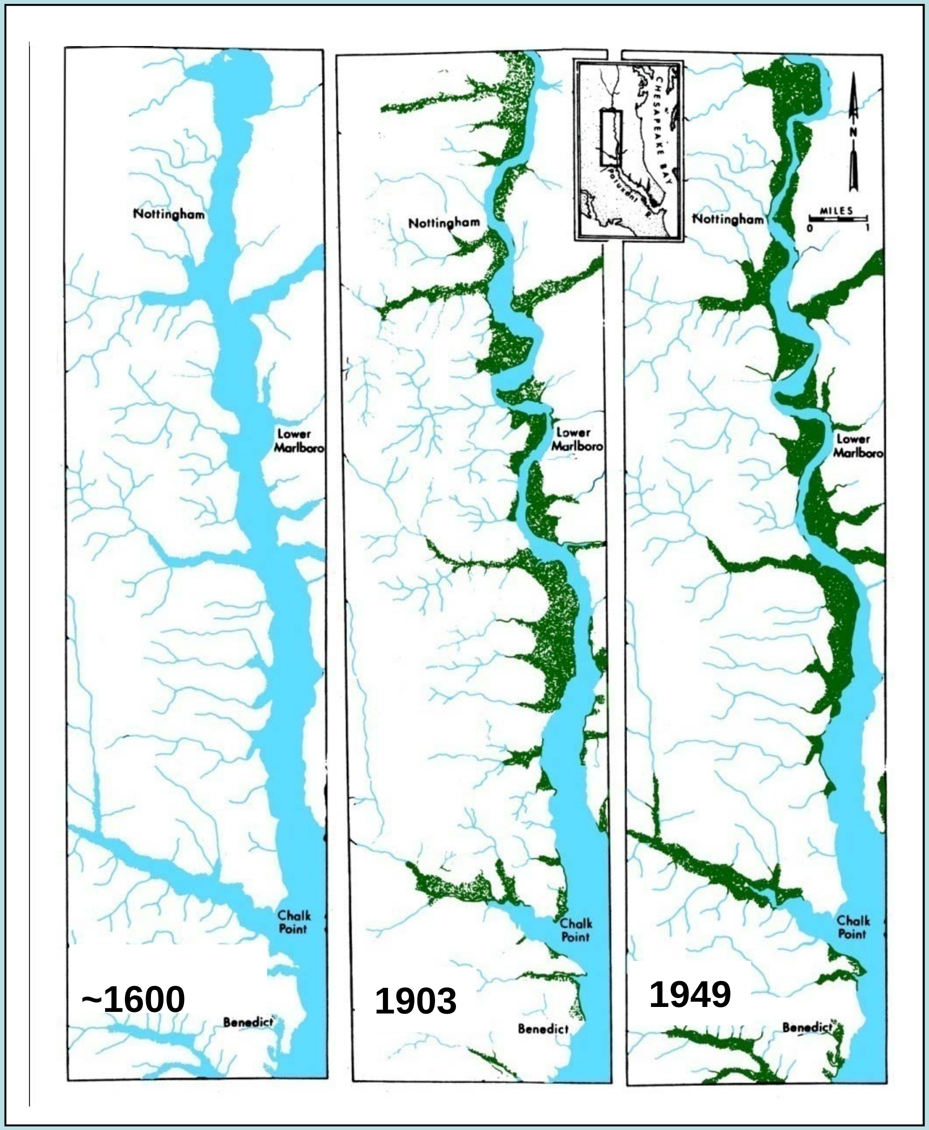
(Testa & Kemp 2009)

Negative Feedback: Bivalves (e.g., Oysters) Control Phytoplankton

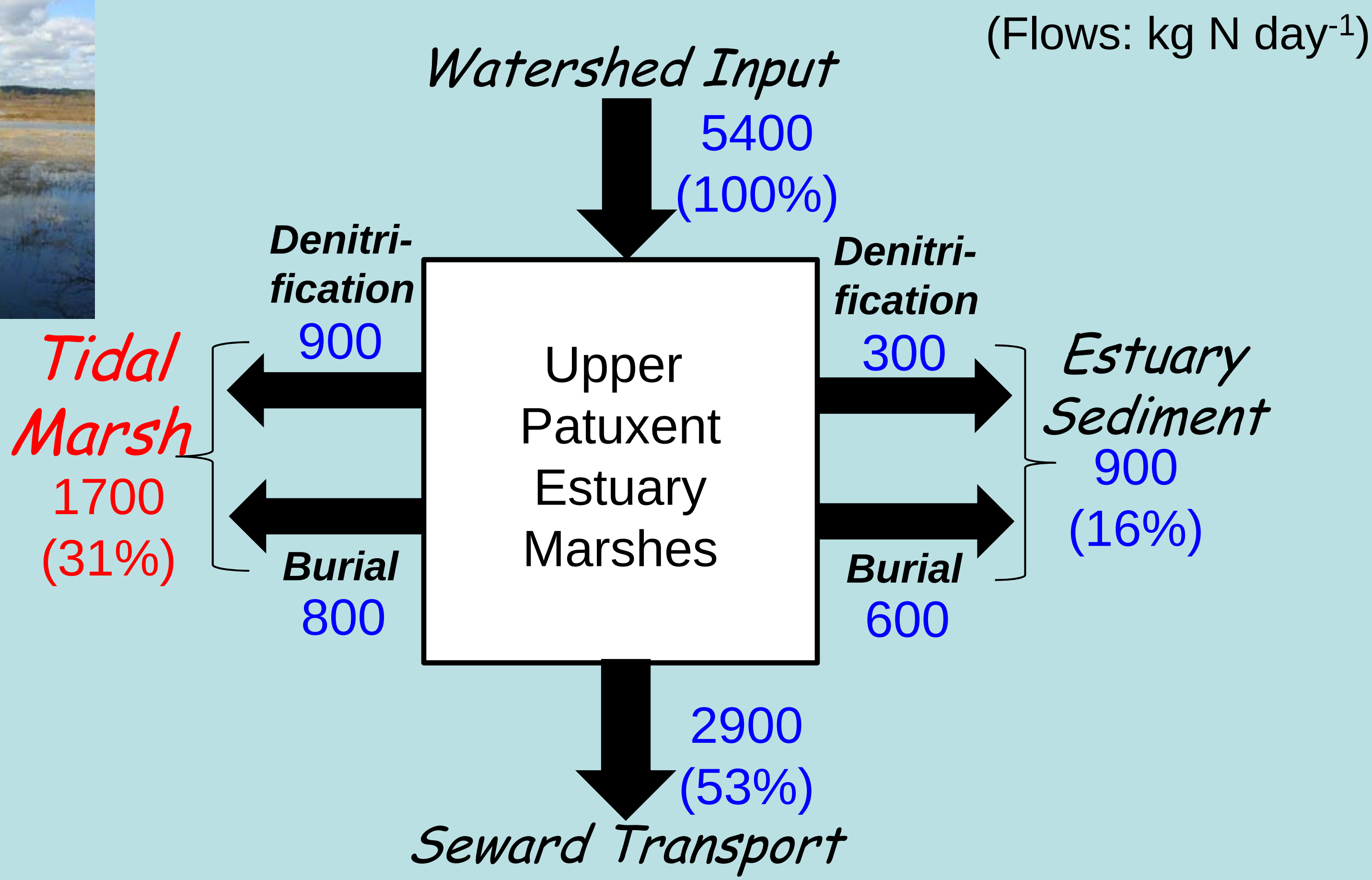


Positive Feedback: Watershed Soil Erosion Feeds Marsh Growth & Maintenance

- **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**



Negative Feedback: Tidal Marshes act as Filter that Removes Nitrogen from Bay



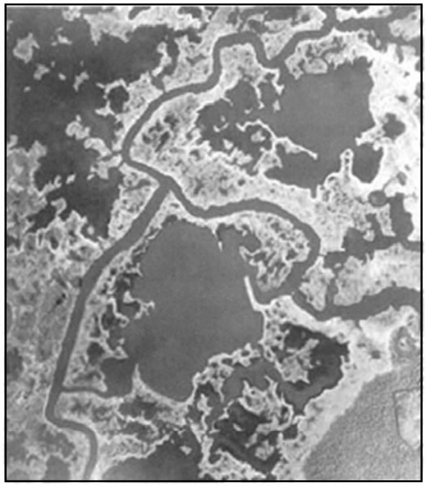
(Boynton et al. 2008)

(7) Direct Restoration of Vegetated Habitats:

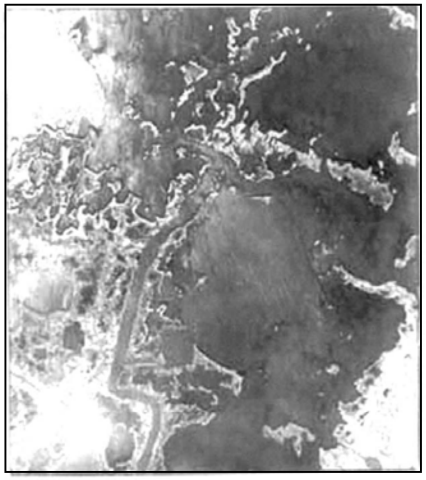
- ***Sediment addition to Tidal Marshes***
- ***Transplanting and seeding SAV beds***

Trend of Marsh-Loss at Blackwater NWR

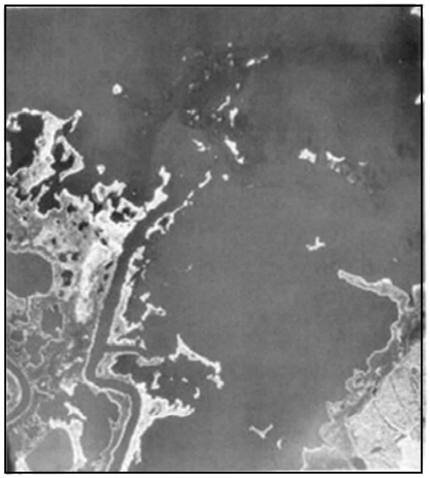
1938



1957



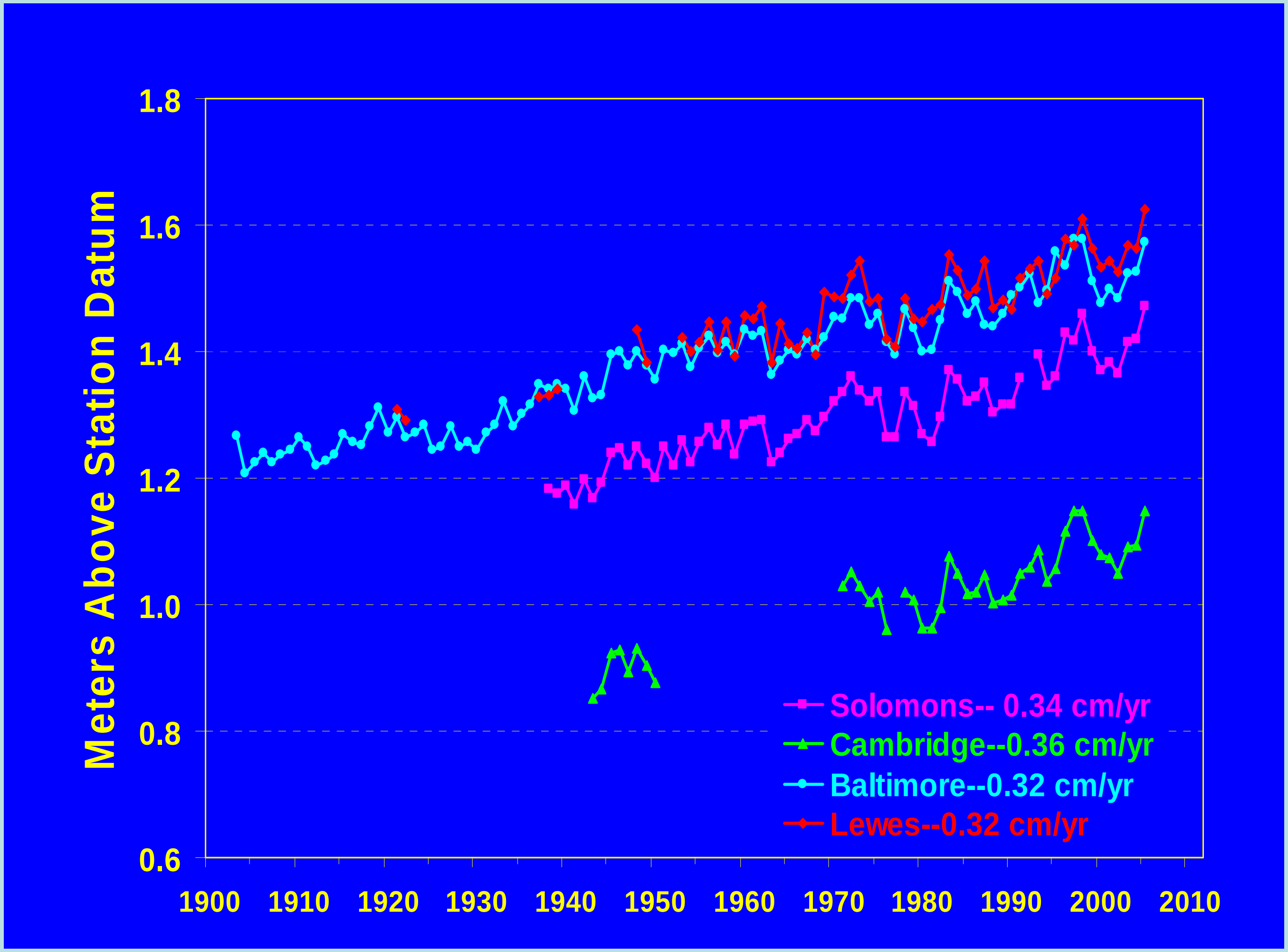
1972



1988

(Stevenson, unpublished)

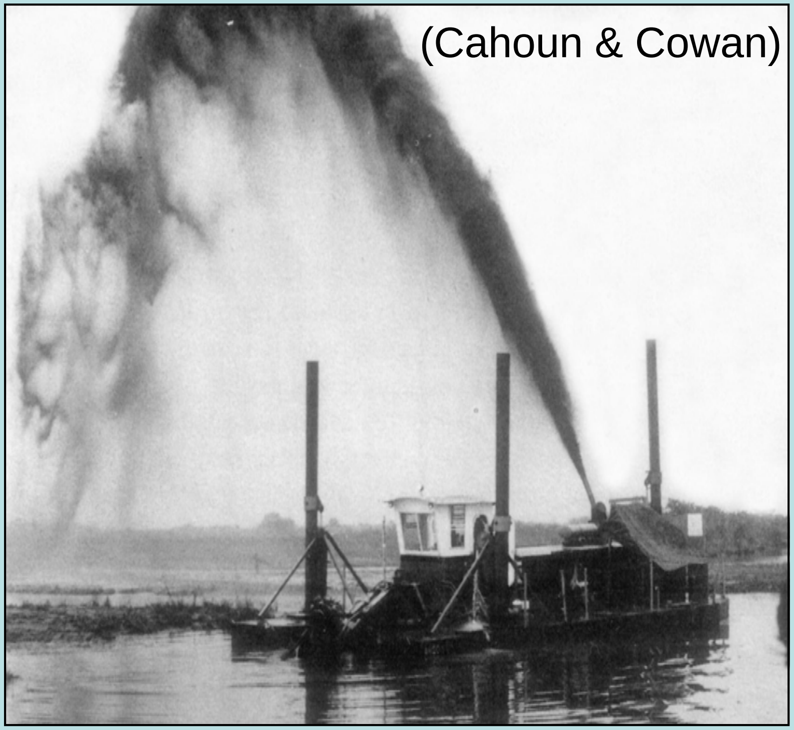
Sea Level Rise in Chesapeake Bay Region



- **During last 100 years SLR has been steady at ~ 3 mm/yr**
- **During next 100 years SLR is predicted to increase to ~6-20 mm/yr**

(Stevenson, unpublished)

Can Declining Marshes at Blackwater NWR be Enhanced using Local Dredged Materials?

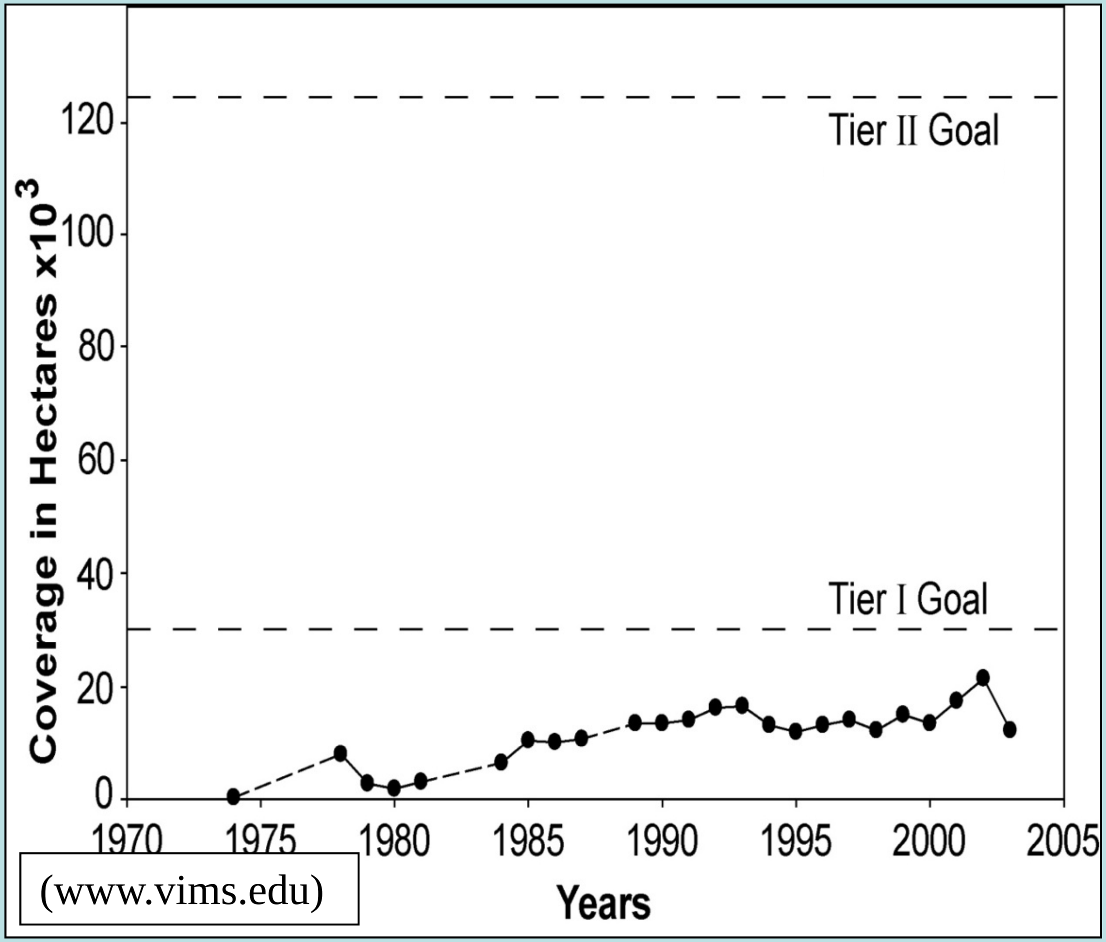


Thin-layer spraying of dredged materials on marshes has been used in Louisianna for >20 yrs.

Marsh at Blackwater Wildlife Refuge one year after thin-layer application of sandy dredged materials.

Can Dredge Spoils be Used to Re-create Tidal Marsh Islands?

Can Transplanting & Seeding Enhance SAV Recovery in Mid-salinity Region of Bay?



- Slow & variable increase in SAV cover in mesohaline since 1980, but still well below goals.
- Most of SAV in mesohaline is mono-specific stands of *Ruppia maritima.*
- *R. maritima* is a less stable SAV species, with limited habitat value.
- Will it work as a “Nursery Bed” for restoration of more stable SAV species?

SAV Transplanting & Seeding for Restoration

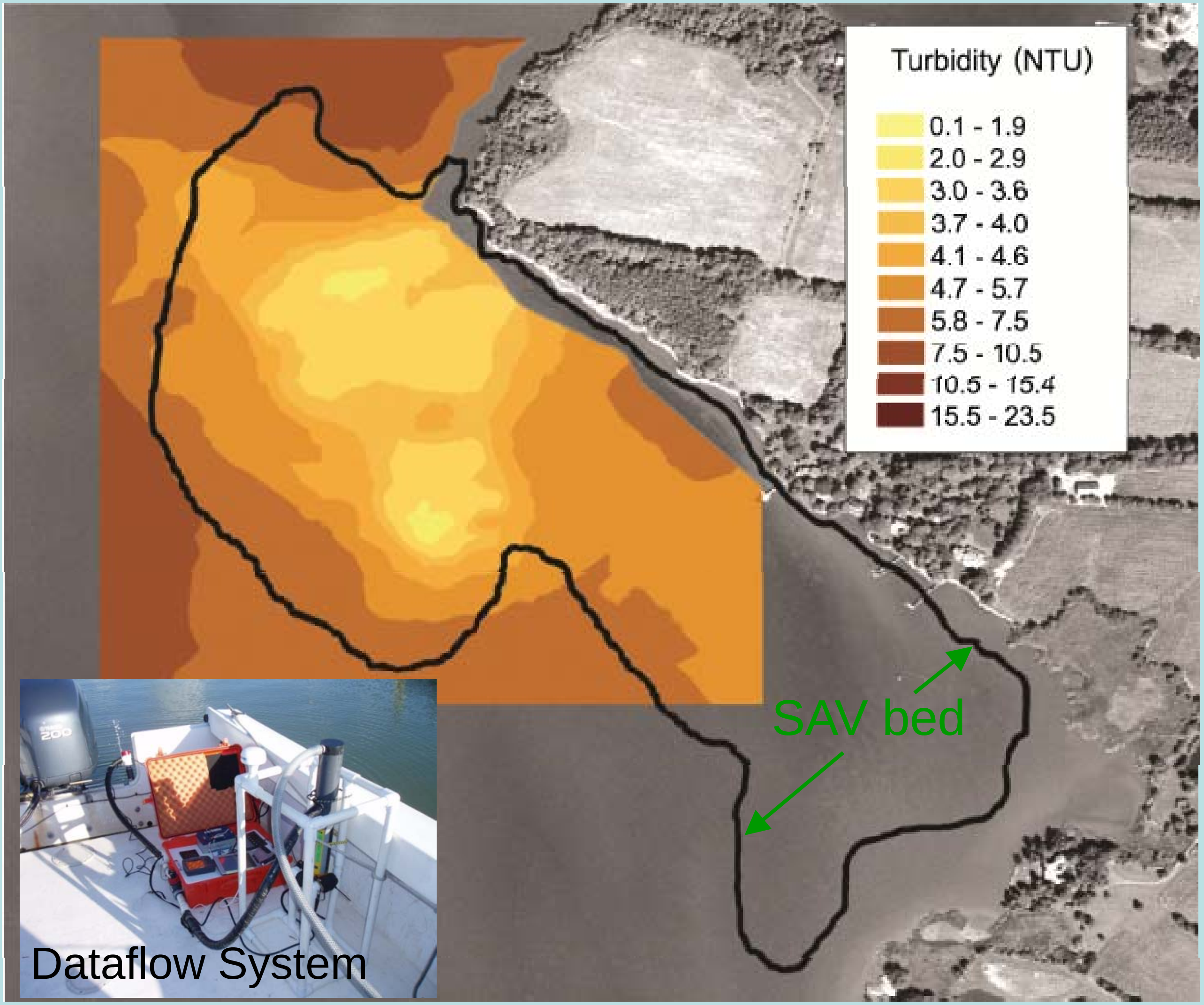
•Transplanting is labor-intensive & costly.

• Seed viability is low for most SAV species in region.

• *Overwintering buds & tubers are best propagules for effective field application*.

• How did these efforts work?

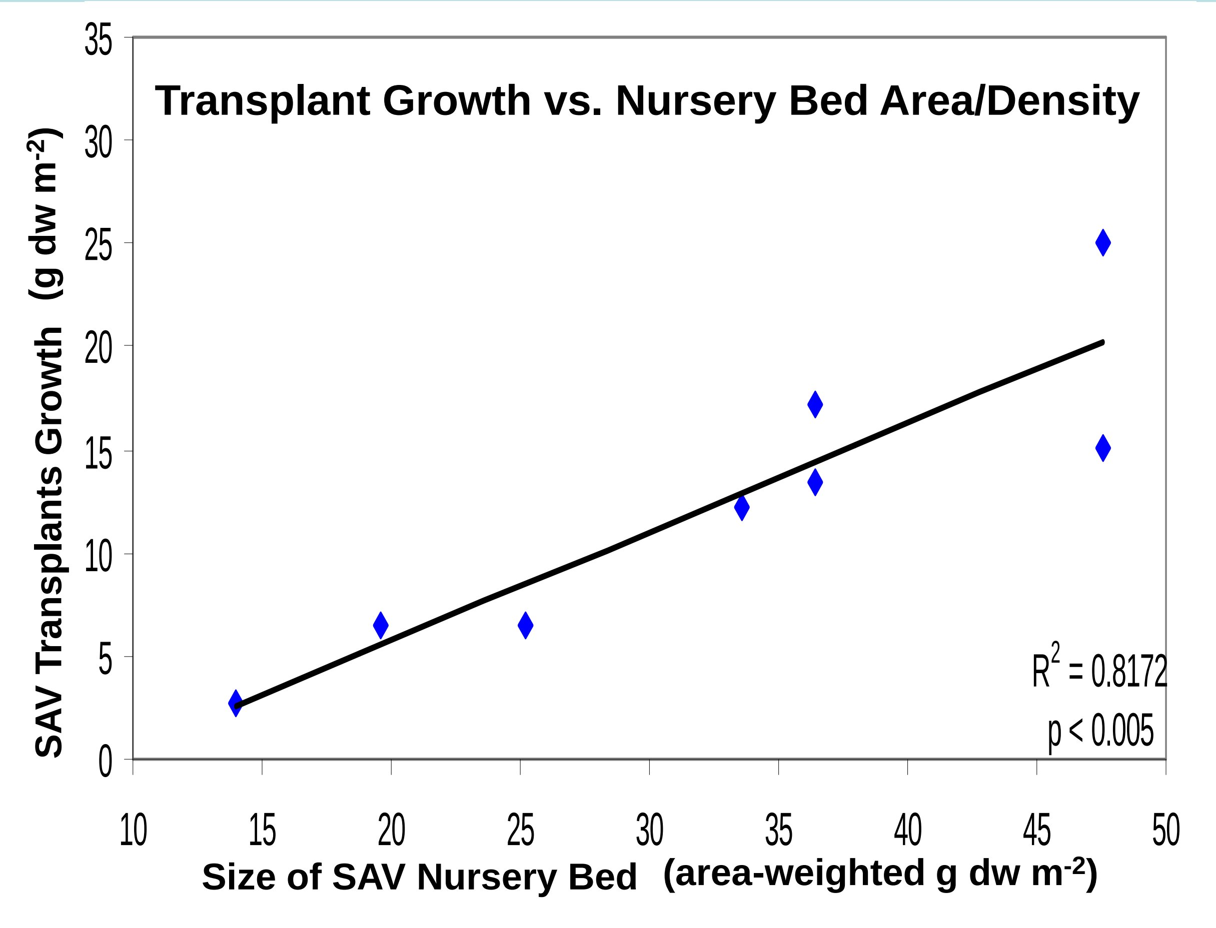
Positive Feedback: SAV/Seagrass Beds Trap Particles and Clear Water



- Large healthy SAV bed in Choptank
- "Dataflow" mapping of water quality at fine-scale around bed
- Water clarity higher (turbidity lower) within SAV bed
- More light for plant growth within bed

(Gruber 2009)

Transplanted P. perfoliatus Growth in *R. maritima* Beds of Various Size & Density



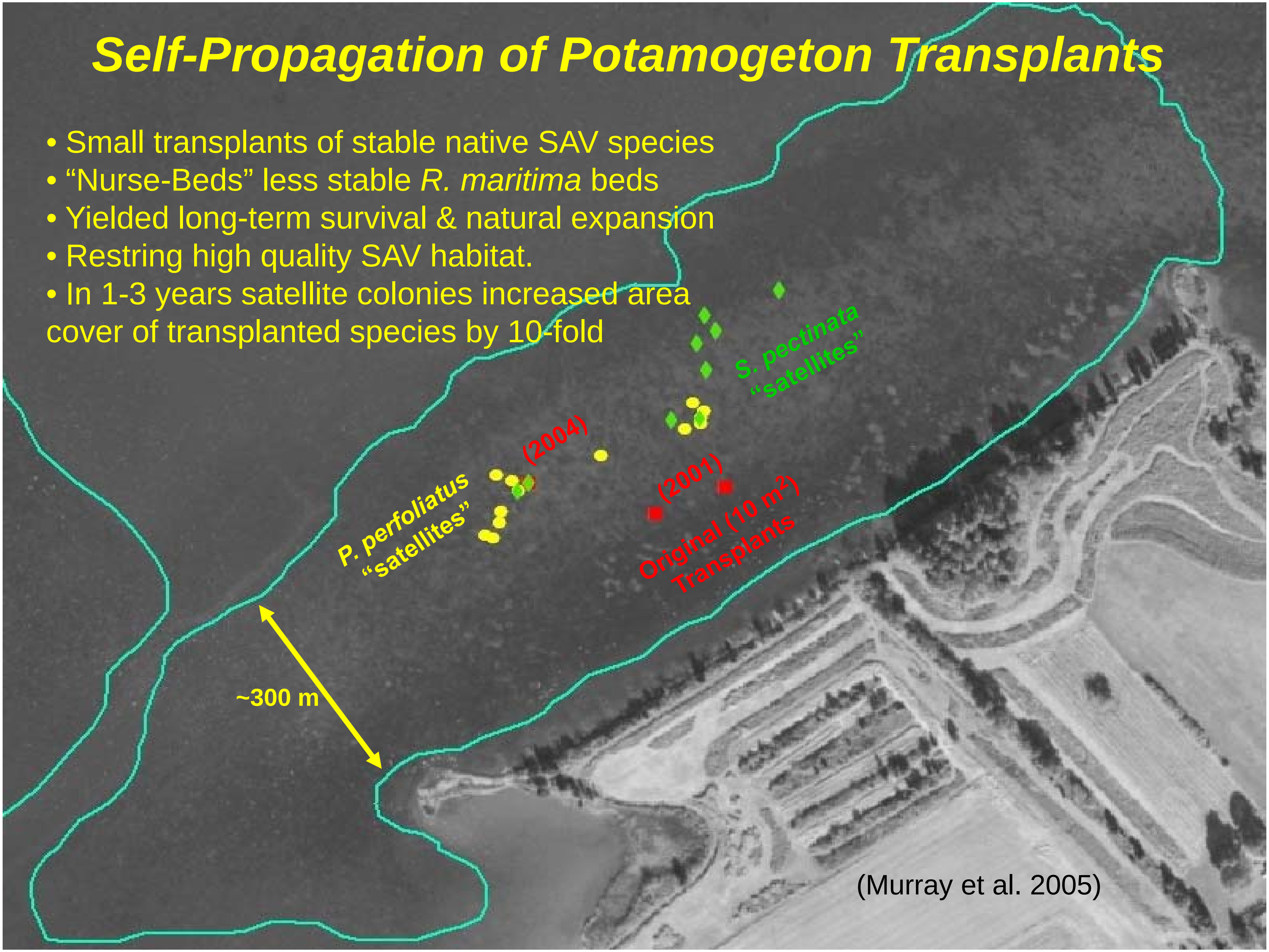
- ***Ruppia maritima* was effective as "Nursery Bed," with improved water & sediment quality.**

- **Transplant success increased with nursery bed size & density.**

(Hengst et al. 2010)

Self-Propagation of Potamogeton Transplants

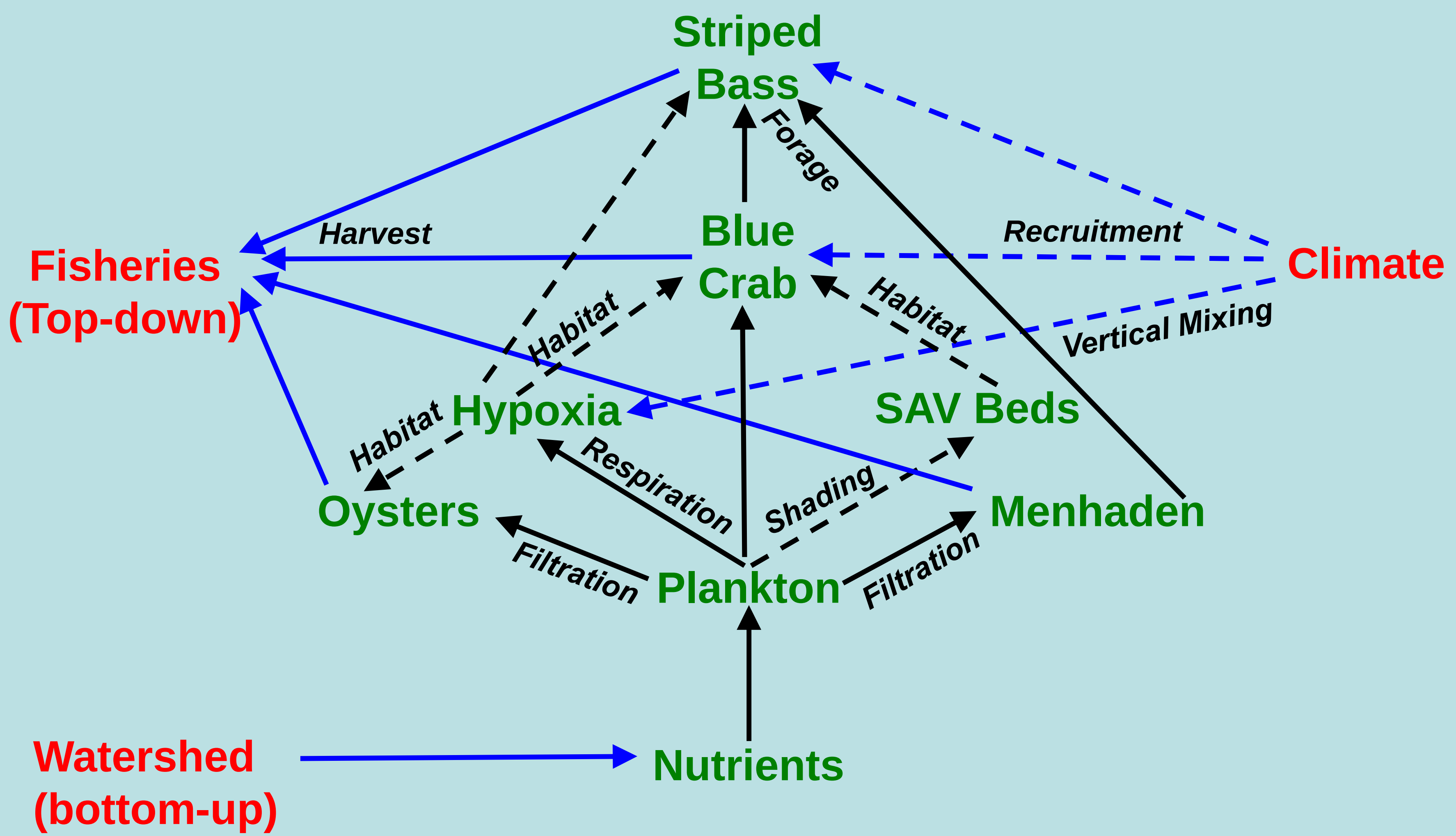
- Small transplants of stable native SAV species
- "Nurse-Beds" less stable *R. maritima* beds
- Yielded long-term survival & natural expansion
- Restring high quality SAV habitat.
- In 1-3 years satellite colonies increased area cover of transplanted species by 10-fold



(Murray et al. 2005)

(8) Synthesis and Conclusions

Integrated Ecosystem Management & Restoration



Trajectories of Response to Nutrient Loading

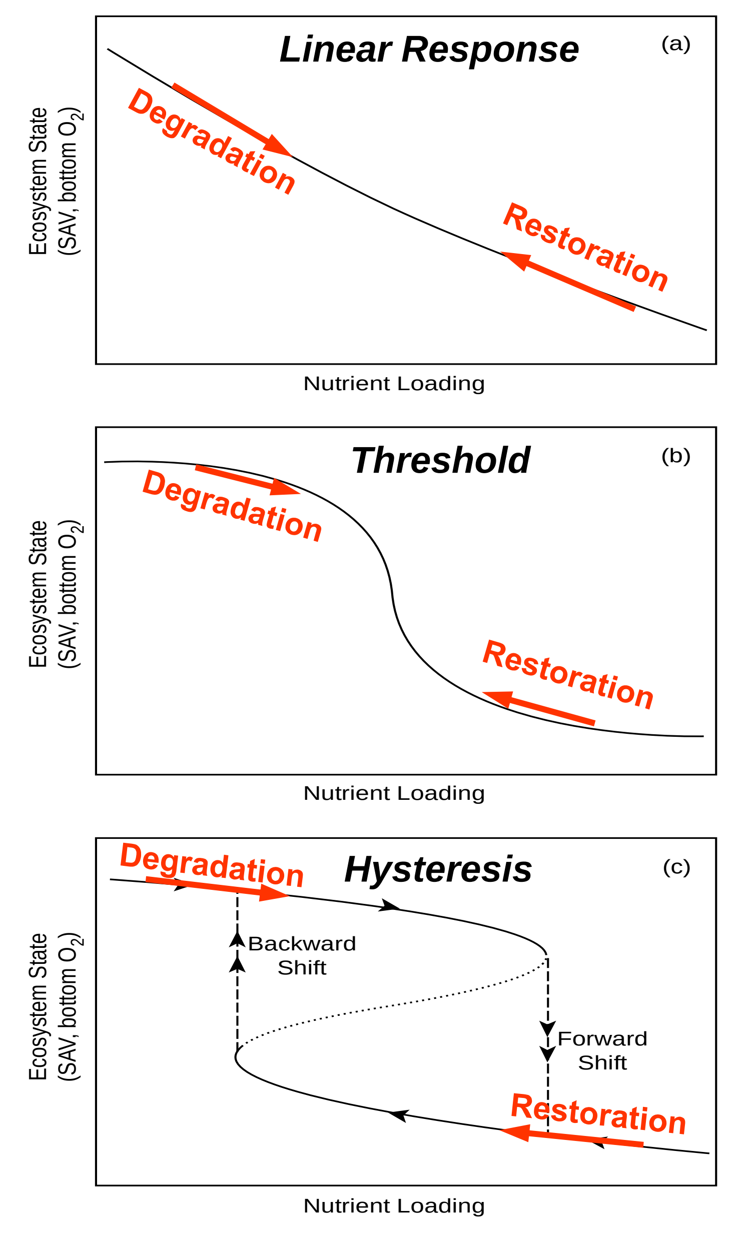
- **Theory suggests alternative ecosystem response to changes in environmental conditions (e.g., nutrient loading, climate)**

- **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**

- **Understanding of alternative trajectories for effective management of ecosystems and human expectations**

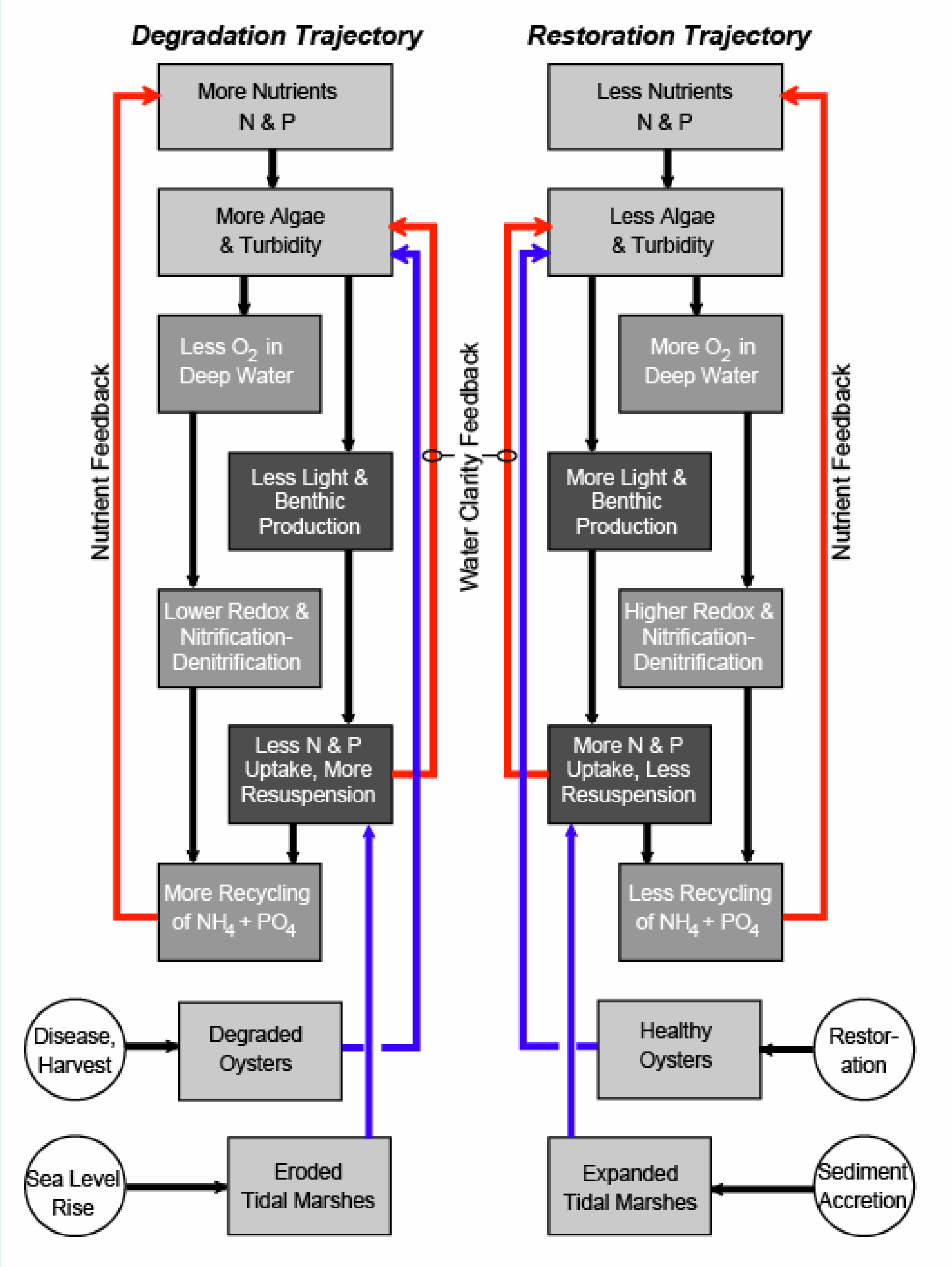


(Scheffer et al. 2001)

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**



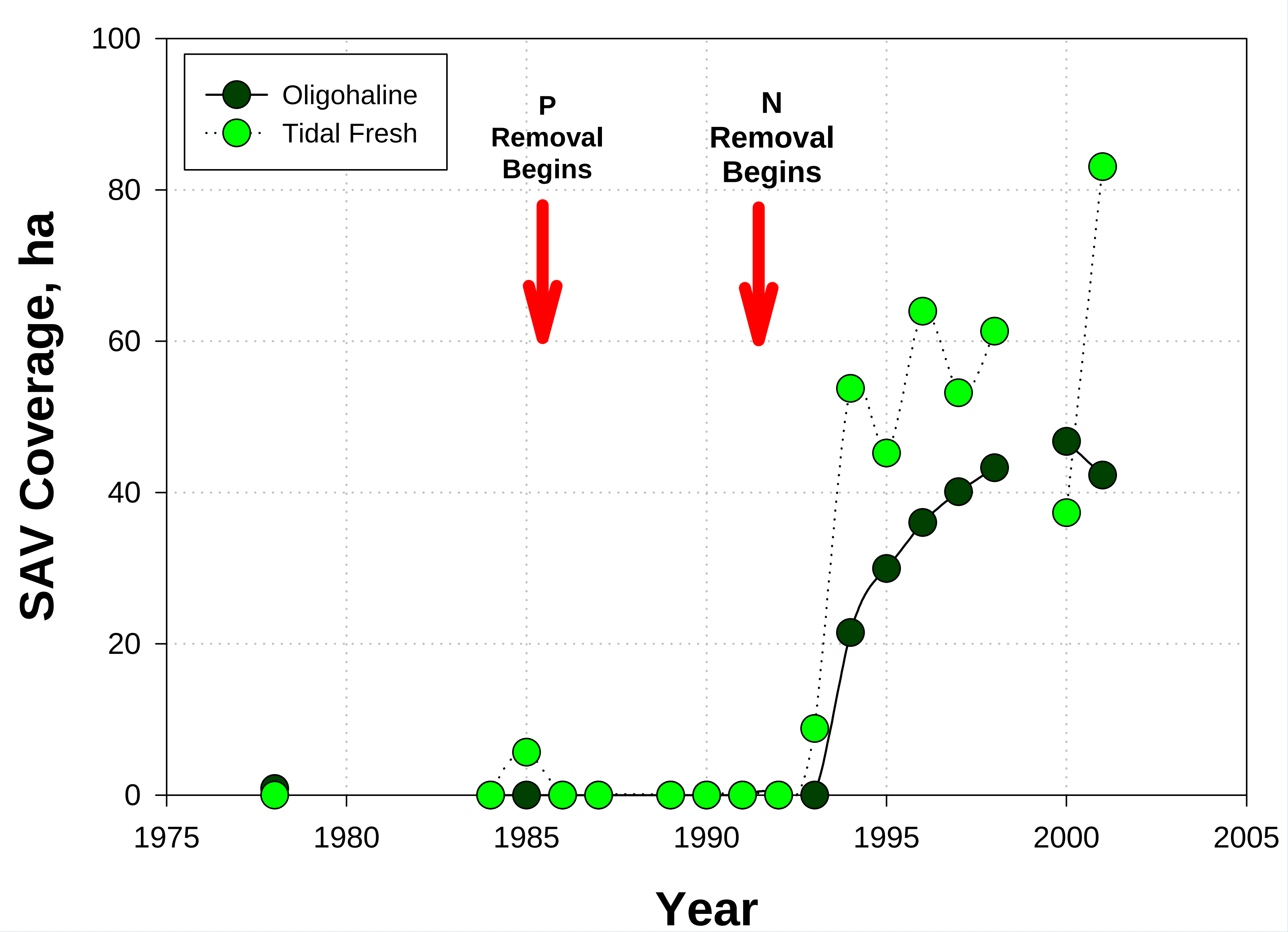
(Kemp et al. 2005)

Concluding Comments

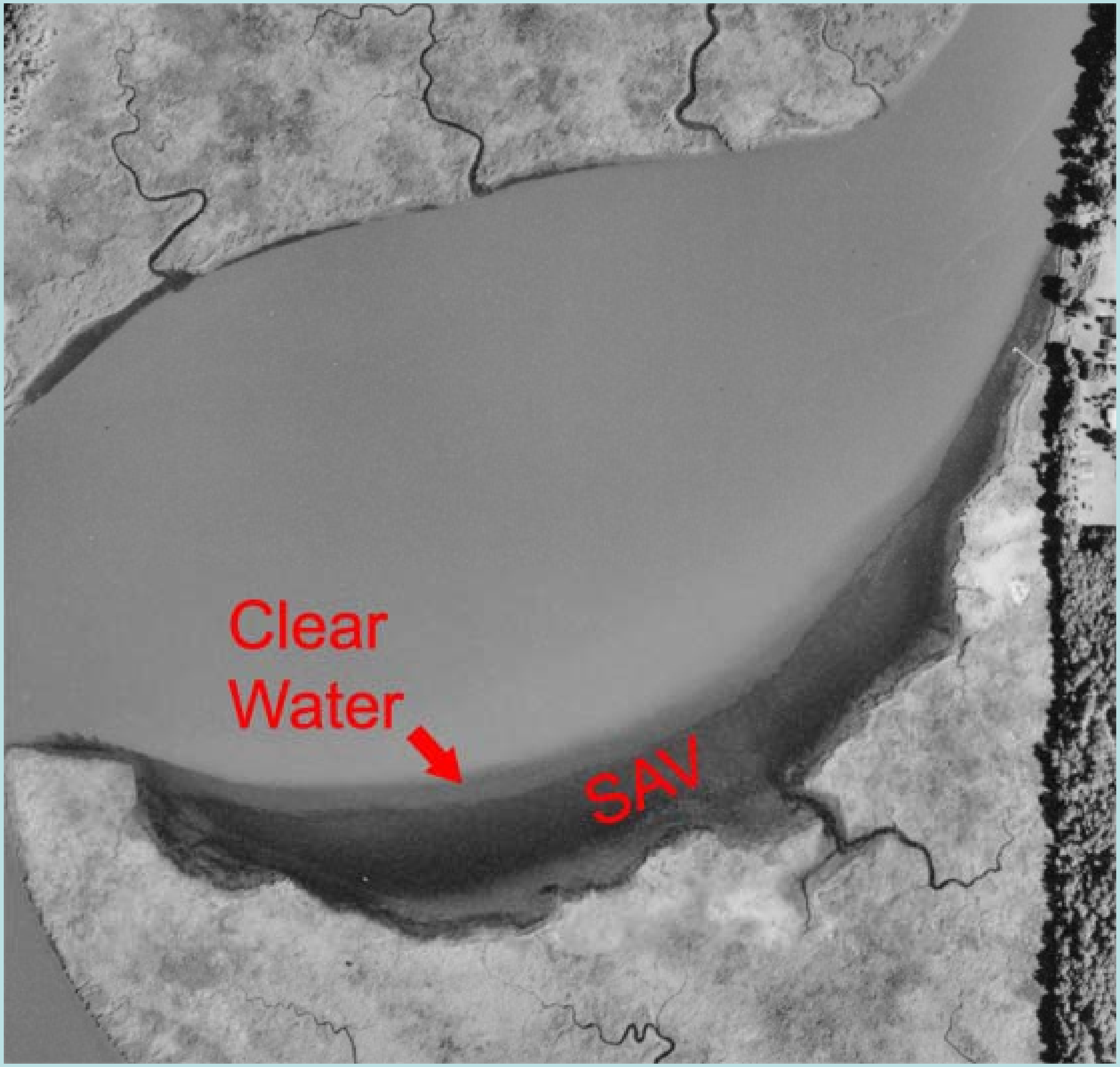
- **Human degradation of estuarine coastal ecosystems is global**
  - **-Need to learn from many documented examples**
  - **-Need to fit restoration option to nature of problem**
- **Eutrophication is manifest in many forms but two stand out**
  - **-Decline of seagrass/SAV**
  - **-Depletion of bottom water oxygen**
- **Fisheries population declines for diverse species**
  - **-Disease & habitat-loss complicate**
  - **-Harvest control can allow recovery**
- **Restoration by exploiting nature's *Self-Regulating Feedbacks***
  - ***-Positive feedbacks***
  - ***-Negative feedbacks***
- **Direct (active) restoration of vegetated habitats**
- **Synthesis and conclusions**
  - **- Integrated management**
  - **- Nature's self-regulation & recovery trajectories**

Thank You!

Upper Patuxent SAV Response to Decreased N & P

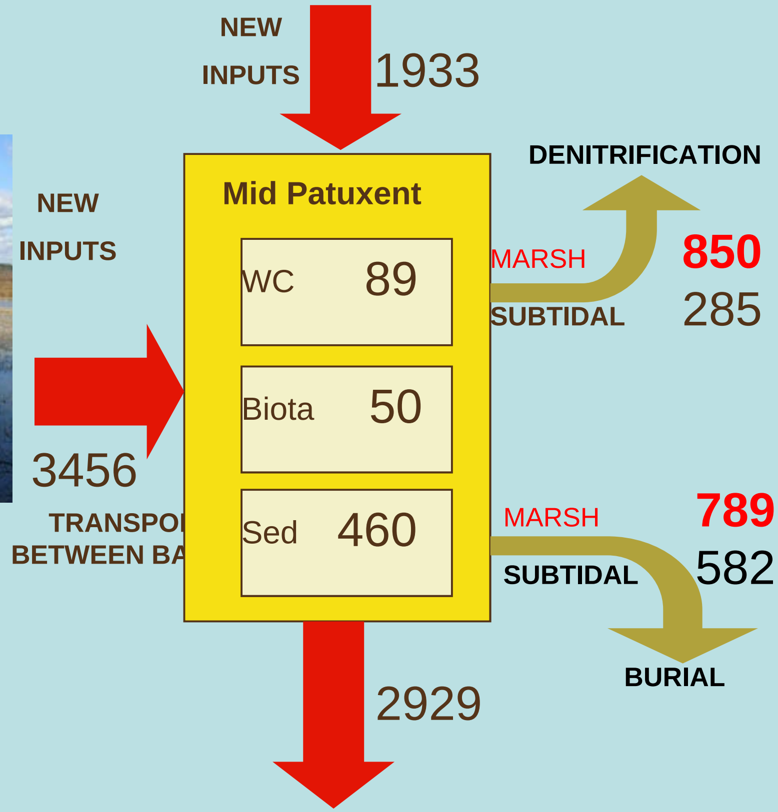


Upper Patuxent SAV Re-Invasion



- **Re-Invasion started in shallow waters**
- **SAV trapped suspended sediments**
- **Near-shore water becoming clearer**
- **Likely a THRESHOLD response to N load reduction**

Total nitrogen inputs, transport, stocks and losses in the Patuxent estuary

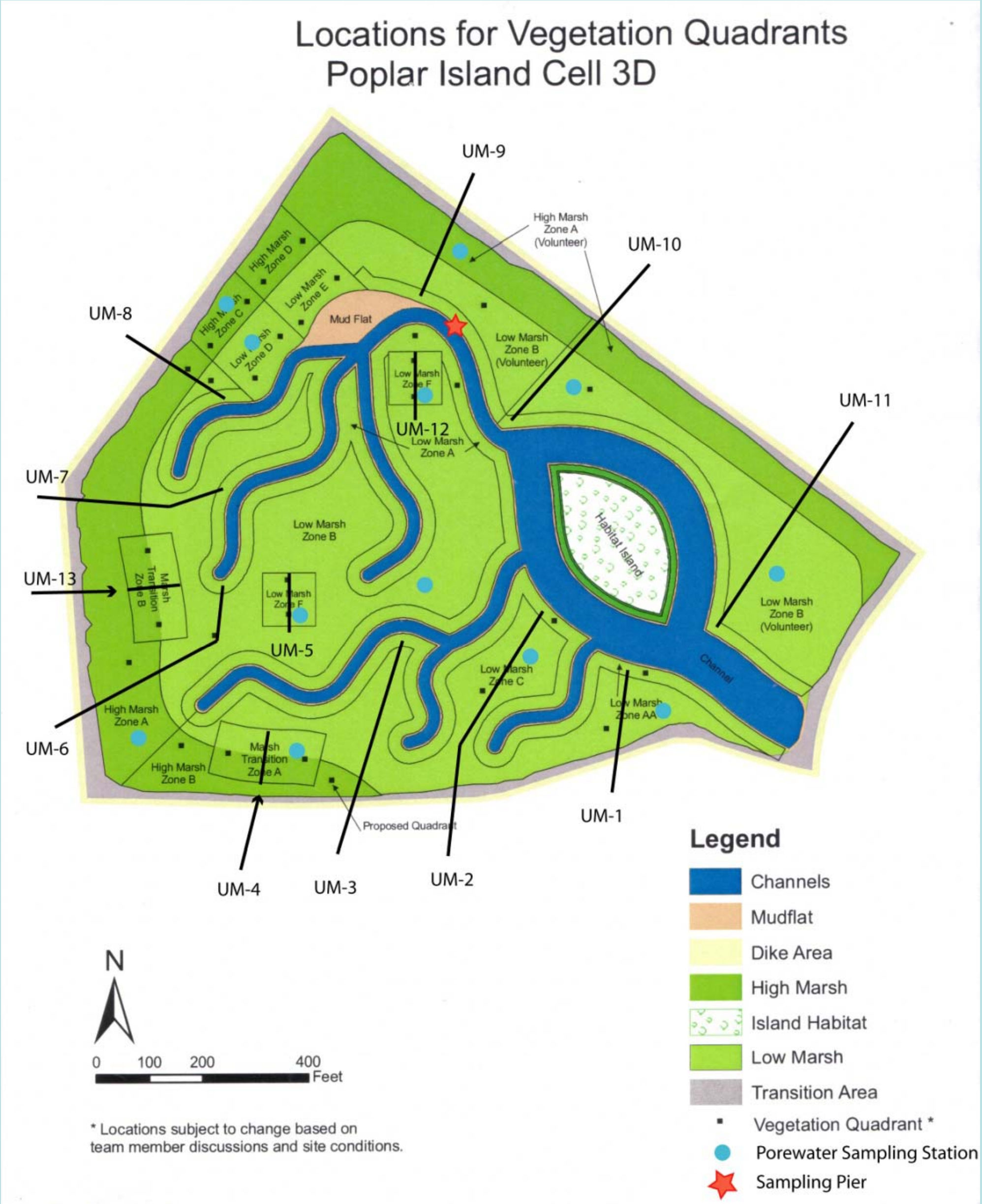


Mid Patuxent	
Inputs	**+5389**
Denitrification	**-1135**
Burial	**-1371**
Export	-2929
Net	46

Flows kg N day^{-1}

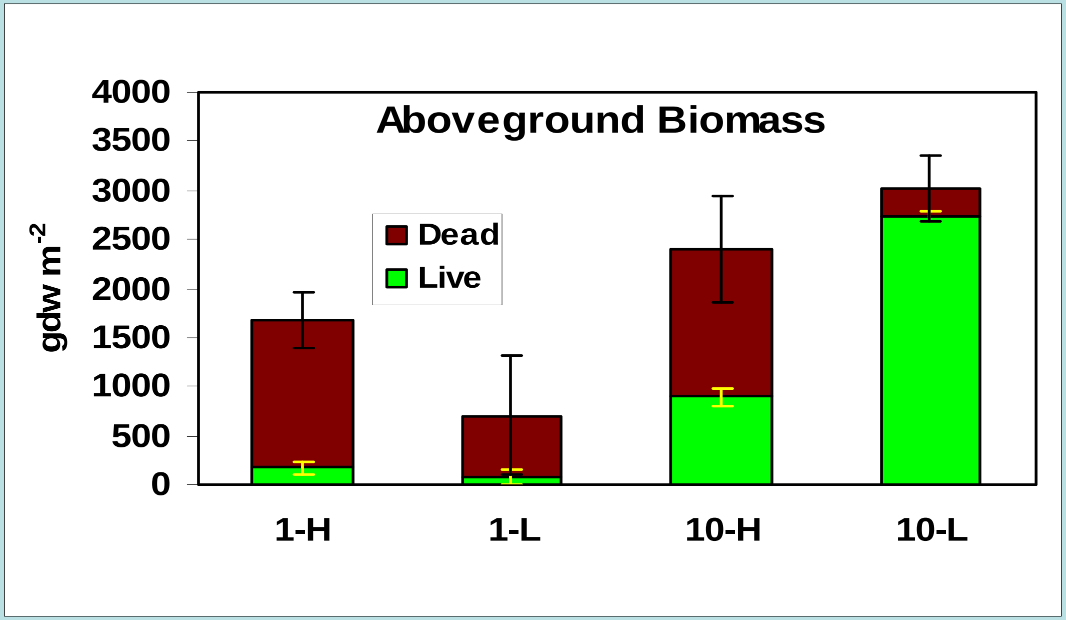
Stocks kg $x10^{3}$ N

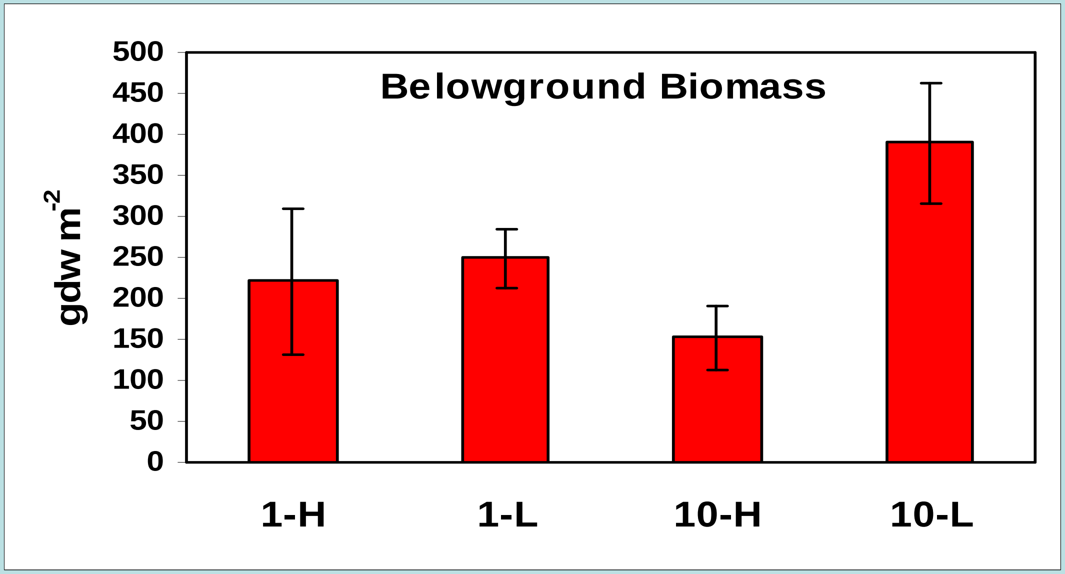
Marsh Creation Plan for Poplar Island



(Stevenson, unpublished)

Poplar Is. Tidal Marsh Biomass after 2 years

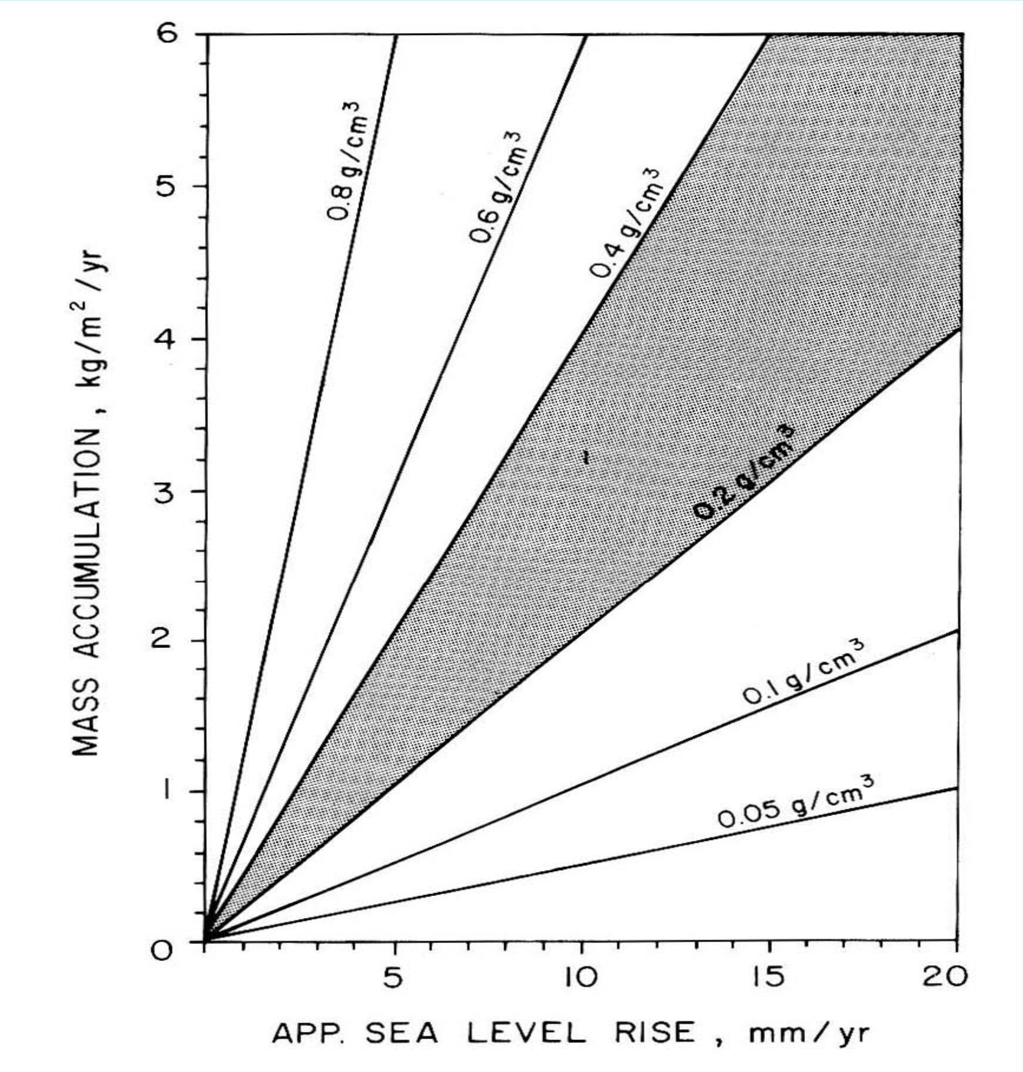




- **Aboveground biomass reached remarkably high levels after 2 years**
- **However, belowground biomass was only 10-15% of aboveground plant material**
- **This appears to be due to the use of eutrophic nutrient-rich dredge sediments**
- **Very high ratios of aboveground;belowground biomass makes plants vulnerable to erosion**

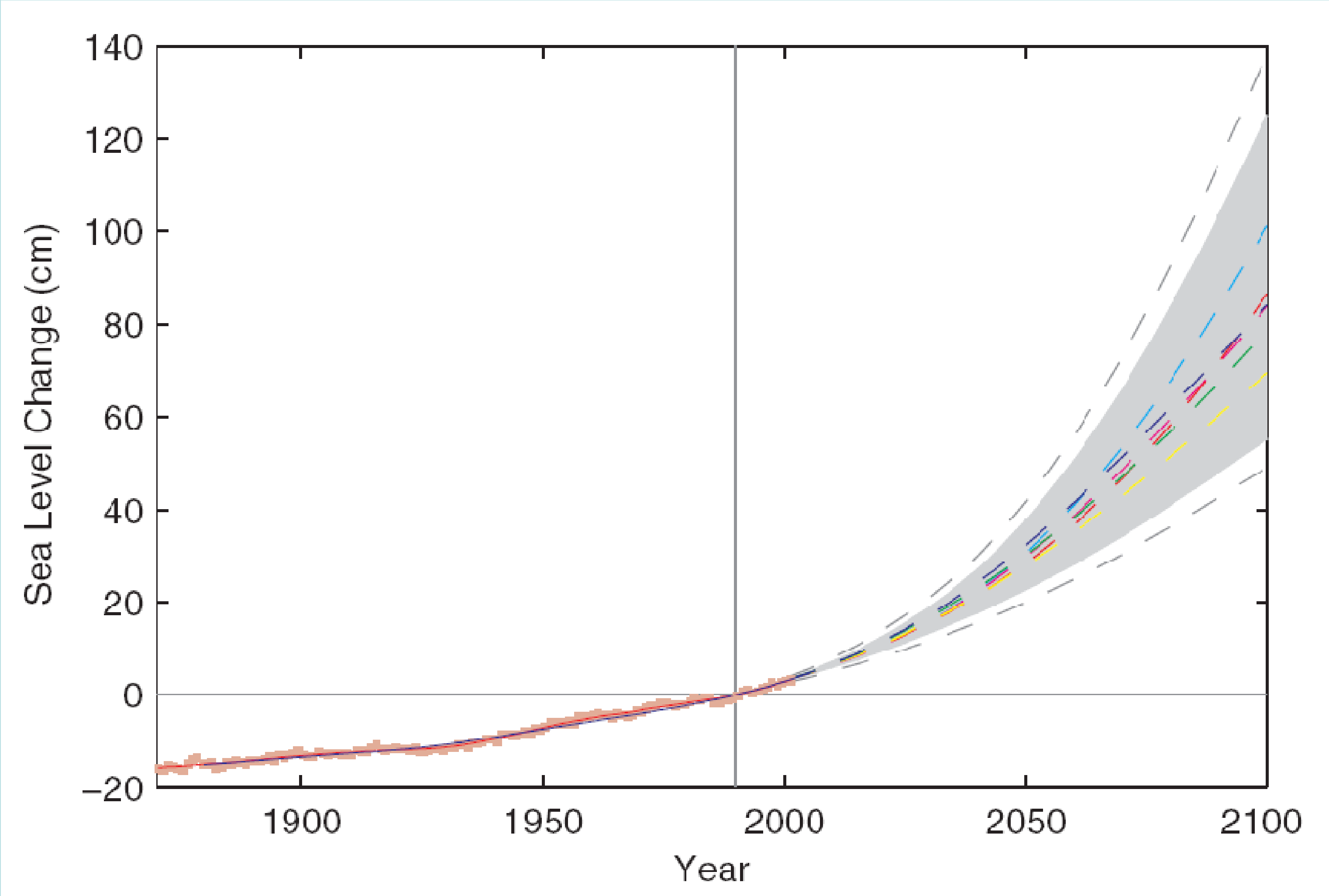
(Stevenson, unpublished)

Tidal Marshes Need Sediments to Keep Up with SLR



(Stevenson et al. 1986)

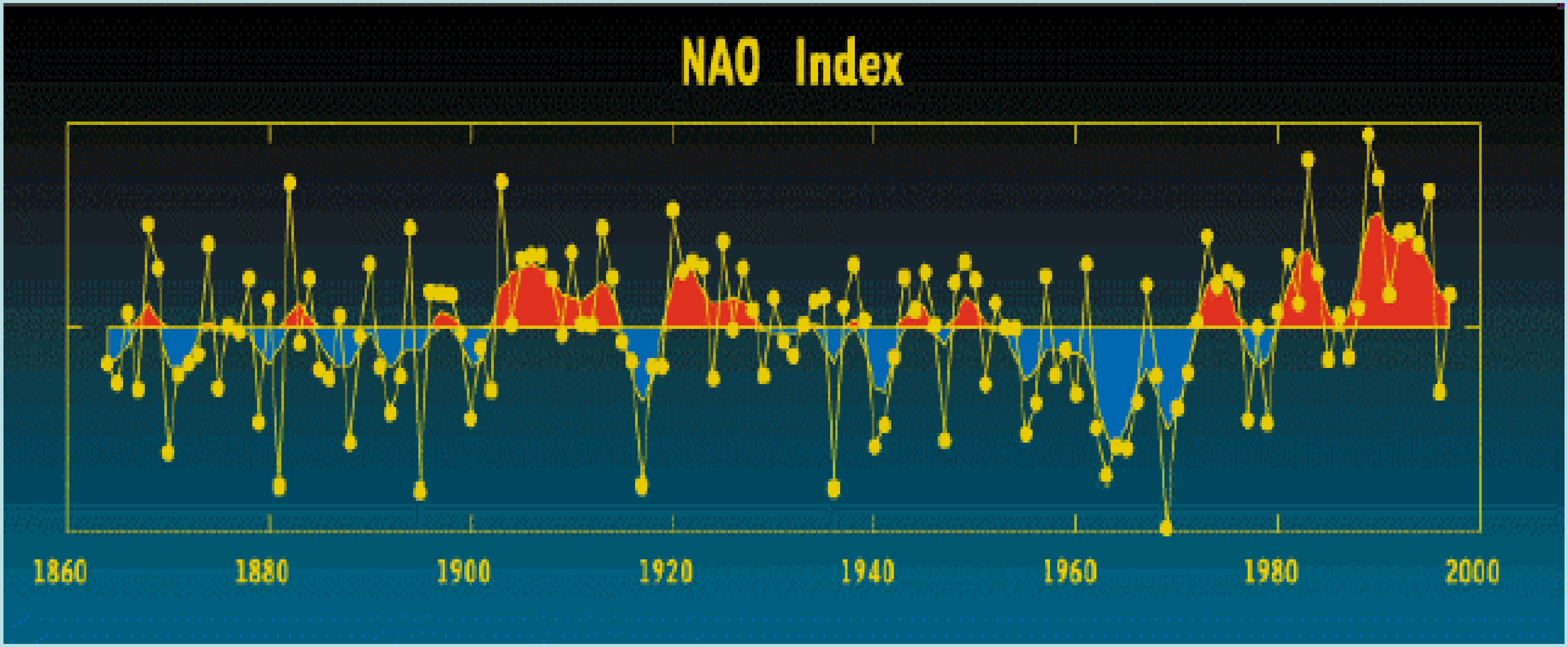
IPCC Estimates Global Sea-Level Rise (20 – 60 cm) by 2100



We are entering a new period where rates of SLR are beginning to increase with global warming. Where will tidal marshes get sediments needed to keep pace?

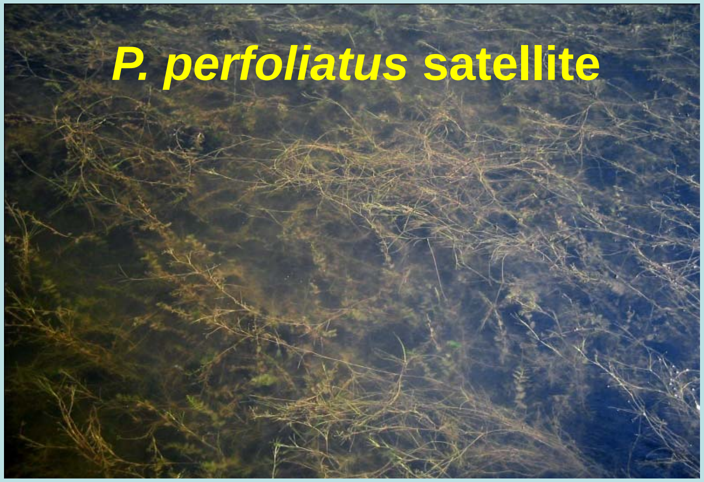
(Stevenson, unpublished)

Winter NAO Index: Longer Time-Series

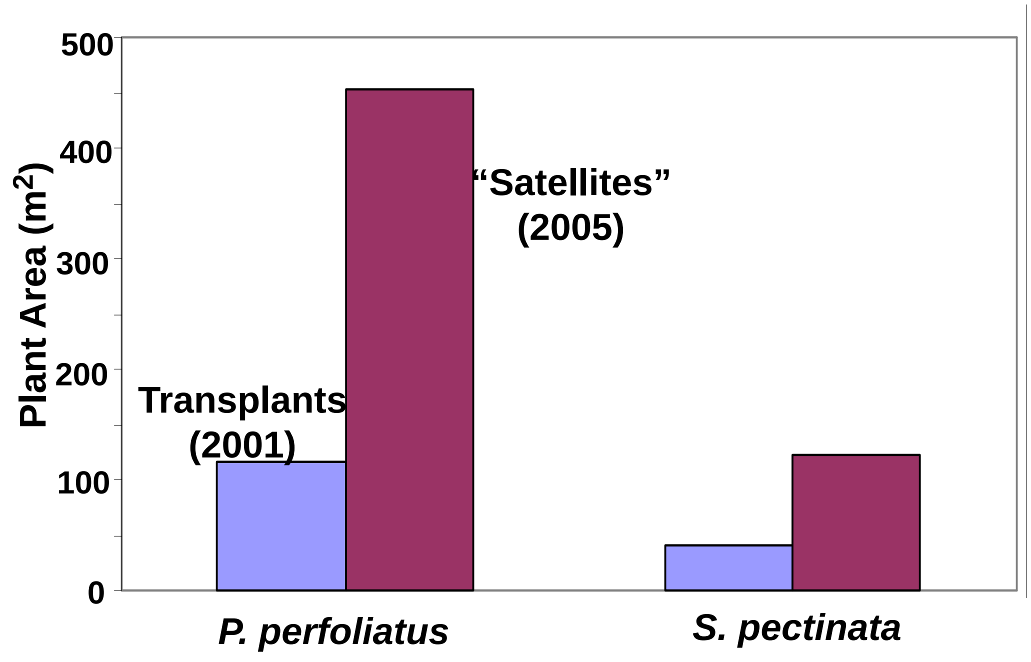


- Longer term trends in Winter NAO index shows variations and periodic (~10-30 yr) shifts between positive and negative phases.
- Last major shift coincides with Bay “regime shift” in hypoxia per N-loading
- Index in recent years suggests a shift back down to negative phase (& possible increase in vertical mixing and weakening of stratification).

Self-Propagation of Potamogeton Transplants



- Satellite patches of trans-planted spp. arise in area around transplant site
- Natural self-propagation of both transplanted spp. within Ruppia beds
- Within 4 years restored area had increased by a 5-10 fold (minimum)



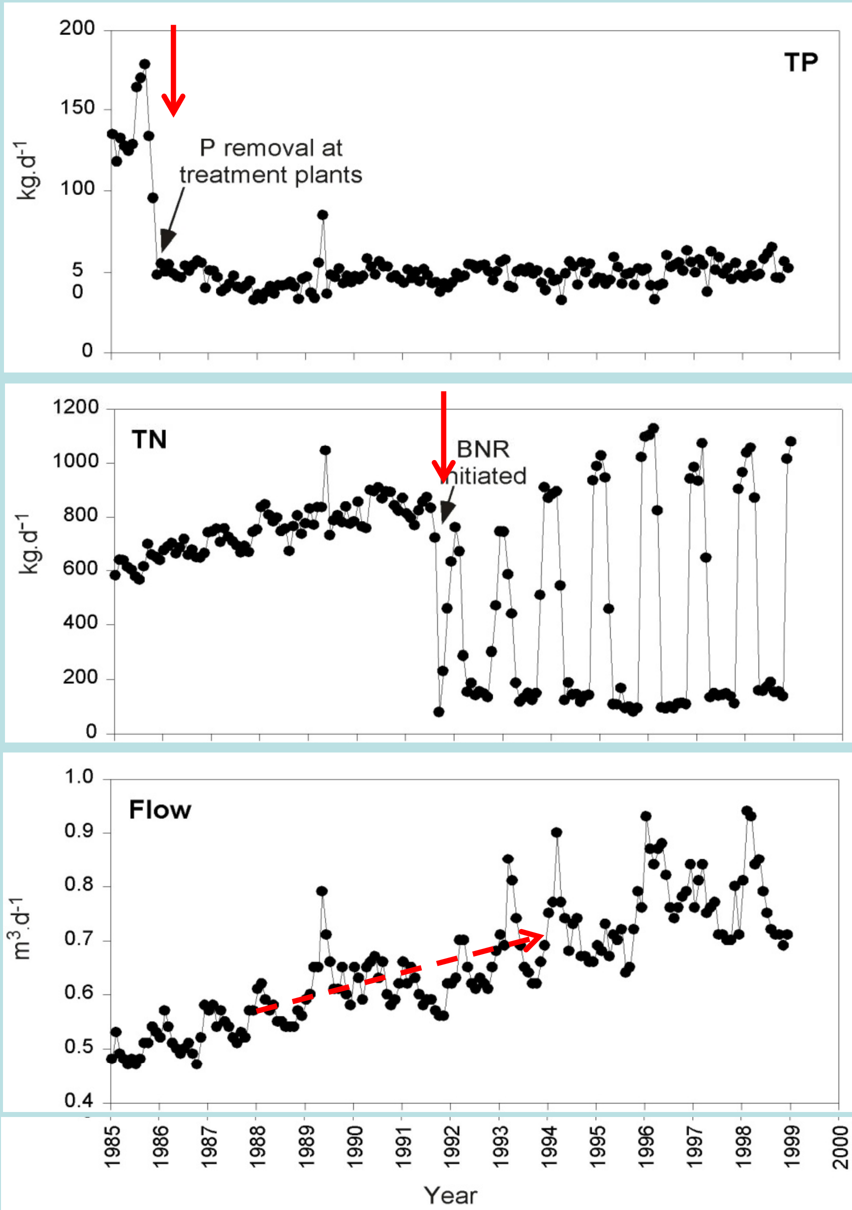
Dredge Spoil Spray Effects on Blackwater NWR

Marsh plant biomass initially enhanced in sprayed region of Blackwater NWR.

Within two years patches of plant die-off appeared in treated marshes.

(Stevenson, unpublished)

Point-Source Nutrient Loading to Upper Patuxent



OMIT?

- **P removal (phosphate ban from detergents) in 1986**

- **N removal (BNR) seasonally reduced N inputs in 1992**

- **Sewage flow increases with human populations**