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

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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)
Recent (2008) survey identified > 400 reported systems with hypoxia due to eutrophication; expanded to more regions covering ~250,000 km².

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

Early Industrial (ca. 1900)

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

(T. De Bry in Hariot 1588)
Chesapeake Bay: A Productive Ecosystems

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

Adapted From Nixon, 1988
Chesapeake 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)
Patuxent Watershed Land-Use Changes

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

(Costanza et al. 2000)
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 a 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

- **Oligotrophic**
  - Nitrogen + Phosphorus
  - "Stratification"
  - Loss of shallow bottom habitat

- **Eutrophic**
  - Nitrogen + Phosphorus
  - "Dead Zone"
  - Shading
  - Loss of shallow bottom habitat
  - Loss of deep bottom habitat
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 O₂ 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-Loading 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 O₂ 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
- menhaden
- terrapin
- oyster
- summer flounder
- red drum
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

The graph shows the historical data of Maryland oyster harvest in millions of bushels from 1840 to 2000. Key factors influencing the harvest include fishing mortality, diseases, and habitat loss.

- **Fishing Mortality** increased significantly around 1880, leading to a decline in harvests.
- **Diseases** contributed to further reductions in the 1920s and 1930s.
- **Habitat Loss** was a major factor from the 1940s onwards, with a significant decline in harvests by 2000.
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
Even the feisty Blue Crab has been in a major decline
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
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

[Graph showing Benthic DIP-Recycling and DIN-Recycling “Efficiency”]
Conceptual Model of $O_2$ Controls on N-Cycling

(Testa & Kemp 2009)
Negative Feedback: Bivalves (e.g., Oysters) Control Phytoplankton

Oyster Harvest (Millions of Bushels) vs. Year

Days to Filter Bay (700 days)

Time (days)

0 100 200 300 400 500 600 700

1880 1988 2003

Year

1840 1860 1880 1900 1920 1940 1960 1980 2000
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

Watershed Input
5400 (100%)

Denitrification
900

Upper Patuxent Estuary Marshall (31%)

Denitrification
300

Estuary Sediment
900 (16%)

Burial
800

Seward Transport
2900 (53%)

(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

(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 Louisiana 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?

Poplar Island – July 2006

(Photo: Jane Thomas)
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?

(www.vims.edu)
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

- **Striped Bass**
  - Forage
  - Recruitment

- **Blue Crab**
  - Habitat
  - Shading
  - Vertical Mixing

- **SAV Beds**
  - Habitat
  - Filtration

- **Menhaden**
  - Recruitment

- **Plankton**
  - Respiration
  - Filtration

- **Oysters**
  - Habitat
  - Hypoxia

- **Harvest**

- **Fisheries (Top-down)**

- **Climate**

- **Nutrients**
  - Watershed (bottom-up)
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

Graph showing the response of SAV coverage, ha, to decreased N & P. The graph indicates that P removal begins in 1985 and N removal begins in 1988. The coverage data shows a notable increase post-1985.
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**

- **NEW INPUTS** 1933
- **DENITRIFICATION**
  - WC: 89 kg N day$^{-1}$
  - Biota: 50 kg N day$^{-1}$
  - Sed: 460 kg N day$^{-1}$
- **MARSH**
  - Sed: 789 kg N x10$^3$ N
- **SUBTIDAL**
  - Sed: 582 kg N x10$^3$ N

**Flows kg N day$^{-1}$**
- WC: +5389
- Biota: -1135
- Sed: -1371
- Export: -2929
- **Net**: 46

**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)
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 transplanted 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)
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