Thresholds in Recovery of Eutrophic Bay Sub-Systems: Five Case-Studies

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Chesapeake Bay STAC
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Research Support:
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Theoretical Ecosystem Responses to Nutrient Degradation & Remediation

- Linear Recovery
- Threshold Recovery
- Hysteresis with Threshold
- Shifting Baseline

Increased algae, hypoxia, turbidity

Increased Nutrient Load
Chesapeake Bay: Five Case Studies

- Back River—Muted response
- Upper Patuxent—Threshold
- Gunston Cove—Hysteresis?
- Main Bay—‘Regime shift’?
- Susq Flats—Abrupt resurgence
Back River Estuary

- Small tributary, Baltimore suburb
- Very eutrophic
- Point sources N & P dominate
- Ongoing WWTP upgrade
- **Muted response** (30-40%) in Chlorophyll-a
- N & P levels are still relatively high
- WWTP sometimes diverted to Patapsco
- Further nutrient control will yield big benefits
**Back River Declines in TN & TP Loading**

![Graph showing Back River Declines in TN & TP Loading](image)

**TN Load (PS, kg/d)**

**TP Load (PS, kg/d)**
Back River Improvements in Water Quality

![Graphs showing changes in surface water DIN and chlorophyll-a over time.]

- **Surface Water DIN, mg l$^{-1}$**
  - X-axis: Time, years (1984-2008)
  - Y-axis: Surface Water DIN, mg l$^{-1}$
  - Data points and line chart showing variability over time.

- **Chlorophyll-a, μg/L**
  - X-axis: Year (1985-2010)
  - Y-axis: Annual Average Surface Chlorophyll-a, μg/l
  - Bar chart showing annual averages with peaks and lows over the years.

**DIN conc. (mg/L)**

**Chlorophyll-a, μg/L**
Chlorophyll vs. TN Load: 3-Year Lag Response

Chl-a vs. TN Load: Lag vs. “r”

\[ (r^2 = 0.67) \]

Chl-a vs. TN Load: 3-Year Avg.

\[ (r^2 = 0.67) \]
Upper Patuxent Estuary

- Larger tributary (suburbs-rural watershed)
- Moderately eutrophic
- Point sources N & P dominate
- Recent WWTP upgrade
- Upper estuary decline (30-40%) in N & P
- Rapid Threshold SAV response (after 1992)
**Phosphorus & Nitrogen Point-Sources to Patuxent**

**Total N-Loading**

![Graph](Image)

**Total P-Loading**

![Graph](Image)
“Threshold Response” in SAV Recovery

Tidal Fresh SAV

Oligohaline SAV
Regression Models for Patuxent SAV

Y = \( f(\text{N & P Load, Temp}) \)

Y = \( f(\text{Salinity, Temp}) \)

(Regressions Only Use Data After 1992!!)
**Gunston Cove Estuary**

- Small brackish Potomac tributary (DC suburbs)
- Was very eutrophic
- Point sources N & P dominate
- STP upgrade in 1980s
- Possible inputs from Potomac (relatively small)
- P-limited algal growth
- Short Time-lag for Chlorophyll-a response
- Longer delay with Threshold SAV response
Gunston Cove P-Load, Phytoplankton, SAV

- Time-series of P-loading index includes periods of brief increase and gradual decline

- Phytoplankton chl-a shows response to P-load reduction after decade delay, probably due to slow purging of sediment DIP pools (hysteretic response pattern?)

- Reductions in phytoplankton chl-a brought improved water clarity until a light threshold is reached allowing growth and survival of submersed plants
• Phosphorus is the primary limiting nutrient in this tidal fresh or oligohaline region of Potomac River estuary.

• P-loading to Gunston Cove comes both from surrounding local watershed and from tidal exchange with adjacent Potomac.

• Recent declines in P-loading cause recovery of plankton, water clarity and SAV.
Gunston Cove N & P Loading Budgets

- **Nitrogen Flux (kg/d)**
  - Point Source Contributions
  - Non-Point Source Contributions
  - Exchange with Potomac River

- **Phosphorus Flux (kg/d)**
  - Time periods: '84, '85 - '89, '93 - '97, '01 - '05
Susquehanna Flats

- Large shallow region of upper main Bay
- Direct inputs from Susquehanna River
- Diffuse sources N & P dominate
- Modest decline in TN loading since 1990
- Recent small improvement in water quality
- Abrupt resurgence of large SAV bed
- Currently unexplained, but Thresholds involved
- Rare opportunity to study unexpected SAV recovery
- Possible insights into SAV restoration strategies
Submersed Plant Trends in Susquehanna Flats

% COVER:  < 10  10-40  40-70  70-100
Abrupt Resurgence of SAV in Susquehanna Flats

Submersed Plant Biomass Index

\[ \text{Biomass} \approx \sum [\text{Cover} \cdot \text{Density}] \]

Rapid Change

\[ \sim \text{No Change} \]
SAV Resurgence & Water Quality Improvements

- **Secchi**: $y = 0.0312x - 61.771$, $R^2 = 0.45617$
- **Total nitrogen**: $y = 0.0769x + 155.81$, $R^2 = 0.890259$
- **Total phosphorus**: $y = 0.0018x + 3.5736$, $R^2 = 0.43211$
Feedback Effects of SAV Beds on Water Quality

Bed Effects on Nitrogen Levels

(www.eyesonthebay.net)
Mesohaline Mainstem Bay

- Deep Channel of middle region of main Bay
- Direct inputs from Susquehanna River
- Diffuse sources N & P dominate
- Abrupt increase in hypoxia yield per N load to Bay (~1982)
- “Regime Shift” implies more nutrient reduction needed
- Shift applies to Early Summer hypoxia
- Shift linked to Climate Change (stratification, ventilation)
- Mid Summer hypoxia directly linked to N-Loading
- Seasonally different responses to Climate vs. Nutrients
Trend in Bay July Hypoxic Volume

(Kemp et al. 2009)
Hypoxia Trends Related to N-Loading

- N-Loading increased until mid-1980s, then declined gradually into 2000s
- 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
- Hypoxia & N-Load highly correlated ($r^2 = 0.77$)

(Murphy et al. 2011)
Winter NAO Index reflects regional climate and ocean circulation

NAO measured as atmospheric pressure difference Iceland-Azores

NAO correlates well \((r^2 = 0.51, p < 0.01)\) with early summer Bay hypoxia

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

(Testa 2009)
Decadal shifts in Hypoxia vs. N-Loading

(Murphy et al. 2011)
Concluding Comments

• Small, low-salinity estuarine tributaries of Chesapeake Bay (with urban-suburban watersheds) are prime candidates for restoration.

• Algal growth in low-salinity regions is often limited by P, where sediment storage & biogeochemical *feedbacks* may cause decadal delays.

• Recovery of low-salinity SAV beds is likely to exhibit *threshold* responses to improved water quality (apparent propagule banks).

• Positive *feedback* effects of SAV beds on water quality appear to accelerate recovery once initial environmental *thresholds* are crossed.

• For mainstem Bay, modest improvements in water quality may spark rapid recovery of SAV and hypoxia, reinforced by positive feedback mechanisms.

• Why have Susquehanna River nutrient loads declined? Who knows?

• Improve understanding of how *climate cycles and changes* modulate ecological responses to nutrient management.

• Continue ‘mining’ historical data (monitoring time-series & paleo-ecological proxies) for evidence of nutrient response trajectories & environmental controls.
Duration of Hypoxia vs. N-Loading

(Murphy et al. 2011)
Nutrient Pools per Load vs. Hypoxia Volume

**NH₄ per TN Load**
\[ (r^2 = 0.57) \]

**PO₄ per TP Load**
\[ (r^2 = 0.37) \]
Trend in Bay July Hypoxic Volume

(after Hagy et al. 2004)
Results: Stratification Trends

Stratification strength, BVF (s^-2)

June Main Channel Stratification Strength

Stratification strength, BVF (s^-2)

Early July Main Channel Stratification Strength

(Murphy et al. 2011)
Climate: Summer Wind Direction Affects Hypoxia

• Cross-section looking up-Bay
• With no wind Coriolis causes fresher water to pile on west side
• Wind from South pushes surface water up-Bay causing up-tilt to West
• Hypoxic bottom water approaches air-water surface & is oxygenated

(Malone et al. 1986 MEPS)

• Using ROMS circulation model with simple respiration algorithm
• Apply 3-day wind pulse from different directions
• Hypoxia volume declines for all winds, but most from South and least from West

(Scully 2010 E&C)
Present Susquehanna Flats SAV
Form Broad Dense Meadow

(P. Bergstrom)
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)
Submersed Plant Trends in Susquehanna Flats

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

- **Downstream of Bed**
- **Upstream of Bed**
- **SAV Bed**

(www.eyesonthebay.net)
Regional NEP Trends Driven by Different N Sources

**Middle Estuary**

- Nitrogen Inputs to the Lower Patuxent
  - Surface Layer
  - Bottom Layer

**Lower Estuary**

- Nitrogen Inputs from Chesapeake Bay

- DIN Input from Chesapeake Bay $(10^3 \text{ kg d}^{-1})$
- NEP (mmol m$^{-3}$ d$^{-1}$)

**Graphs**

- Middle Estuary: $r^2 = 0.57$, $P < 0.01$
- Lower Estuary: $r^2 = 0.53$, $p < 0.01$
Responses to N&P-Reduction: Back R. Tidal Fresh

- **Back R. Estuary** located north of Baltimore in oligohaline region of Bay
- TN loading decreased by ~50% from 1985 to 2005
- Phytoplankton Chl-a decreased by 30% during that time, with strong inter-annual variability
- Chl-a was weakly related to DIN (annual means) with shallow slope
- Chl-a was not related to DIP, and no trend over two decades
- Note that mean 2005 levels of DIN (~75 μM) & DIP (0.6 μM) are well above limiting levels
Small Increase in Water Clarity Stimulates SAV Growth in Shallow Habitats

- Water still turbid in open water, but enough light penetrates to ~0.7m

- Once growth is initiated, SAV expand to deeper water due to ‘feedback effect’ clearing water

- Note this effect in aerial photograph
Declining Trends in DIN Concentration

- Strong DIN decline in upper estuary, especially in early 1990s
- Weak DIN decline in middle estuary, especially in lower estuary
- Similar declines in DIP
Threshold Nutrient Level for SAV Recovery

SAV Cover vs. Nutrient Loading
Motivation—Why is this an Important Problem?

• Coastal eutrophication is a globally pervasive problem!

• Coastal systems are tightly linked to their watersheds.

• Major societal initiatives are underway to reduce watershed nutrient loading.

• We need to know what to expect in terms of timing and magnitude of response to expensive nutrient remediation.
Chesapeake Bay: Back River Estuary

- Urban watershed near Baltimore city
- Low salinity tributary of Chesapeake Bay
- Point source inputs dominate from treatment facilities
- Recent Reductions in N and P loading
Upper Patuxent R: ‘Rapid Response’

- Tributary of Ches. Bay
- Mostly suburban land-use in watershed
- Major reduction in point source N and P inputs
- Large & rapid response in low salinity region of estuary
- Reduced turbidity and recovery of shallow SAV
- More saline regions show complex response
Gunston Cove: ‘Hysteretic Response’

- Small shallow tributary of Chesapeake Bay & Potomac River estuary (tidal fresh)
- Reduced P loading from Wash, DC point sources and local diffuse sources
- Response to in P-load reductions were delayed with hysteresis
- Purging of P pools in estuarine sediments has caused delayed response
Chesapeake Bay
Susquehanna Flats: ‘Spontaneous Recovery’

• Very large shallow area at the head of Ches. Bay

• Dominated by shallow water (< 2m depth)

• Broad near-shore areas (mean depth 0.5-1.0 m)

• Sparse SAV beds in 1980s showed explosive growth after 2000
Chesapeake Bay

Mid-Bay Mainstem: ‘Regime Shift’

• Deep channel is seasonally *stratified*

• North-South orientation with large fetch to prevailing winds

• Relatively long water residence time (~ 6 mo)