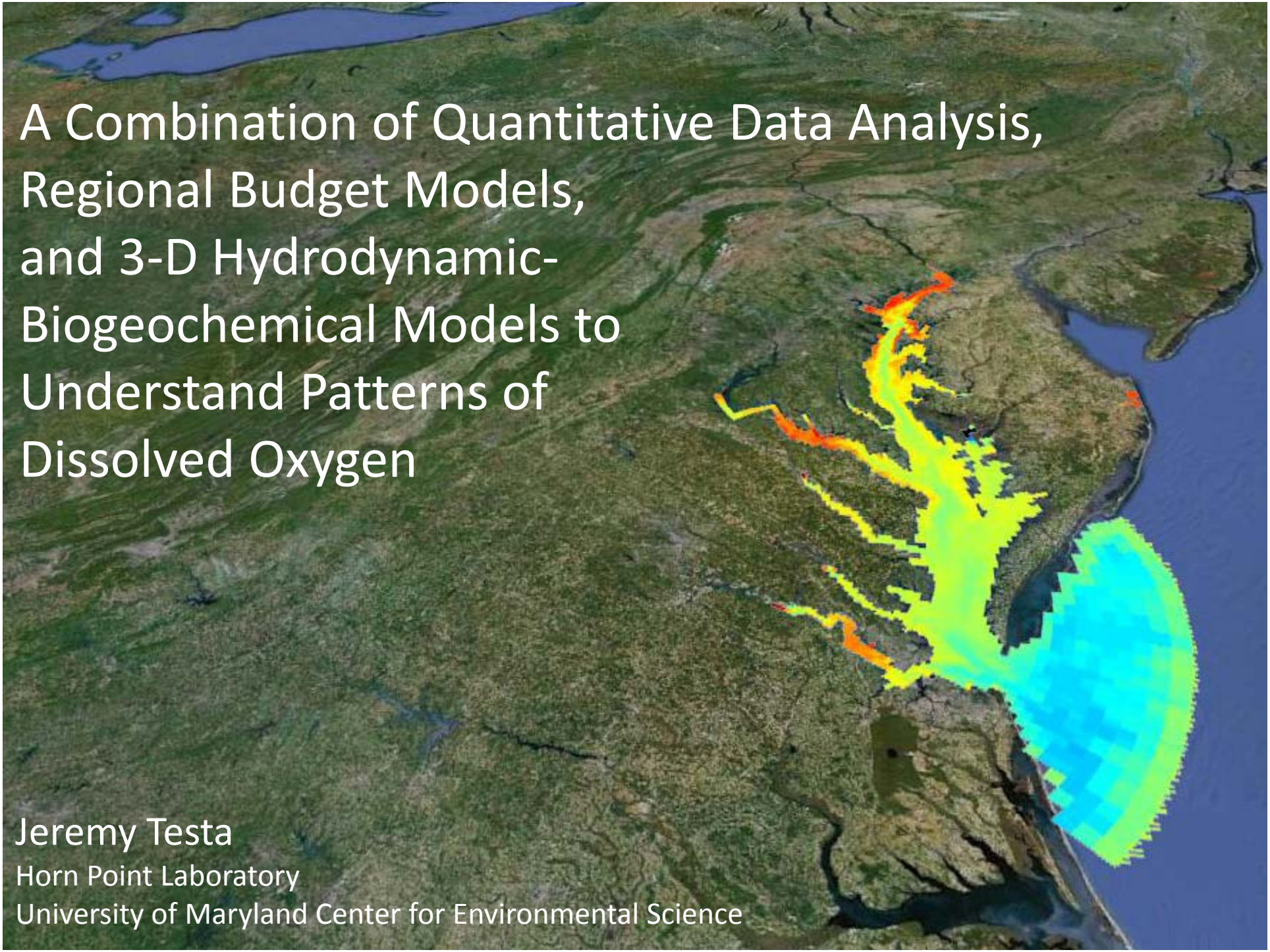
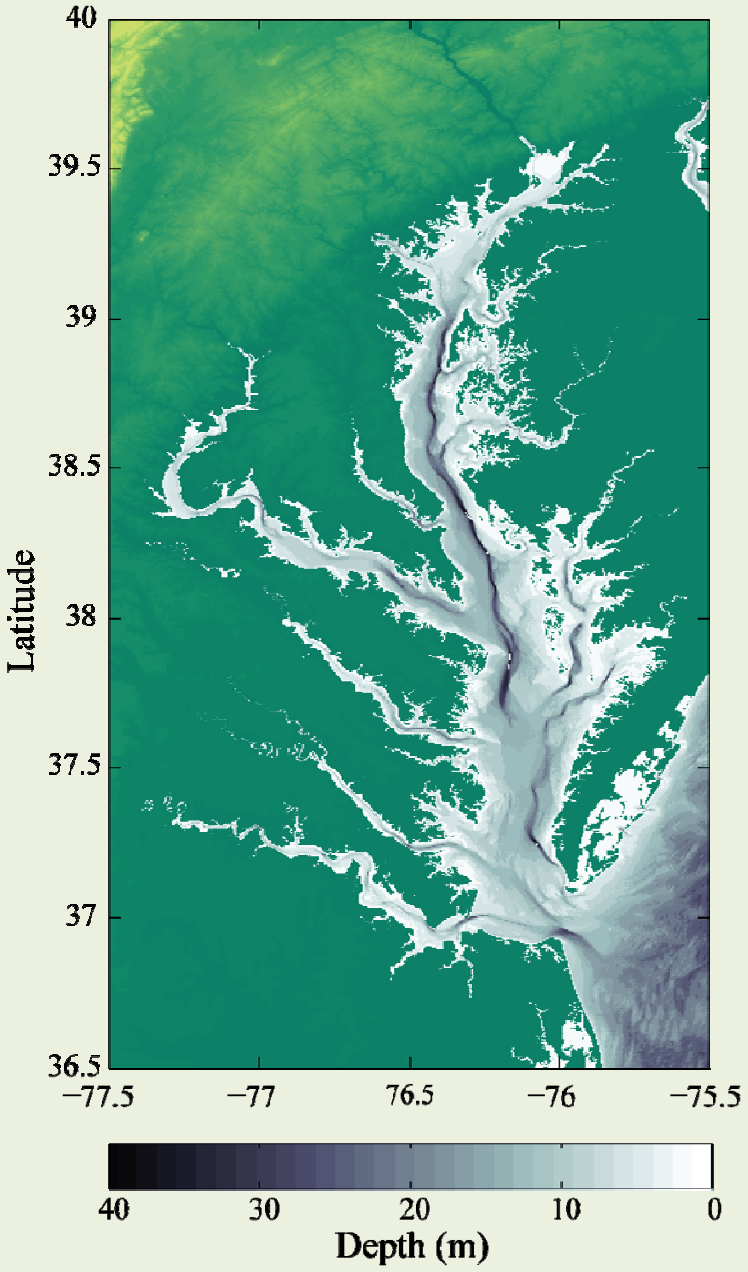
# A Combination of Quantitative Data Analysis, Regional Budget Models, and 3-D Hydrodynamic-Biogeochemical Models to Understand Patterns of Dissolved Oxygen



Jeremy Testa
Horn Point Laboratory
University of Maryland Center for Environmental Science




# Outline

***Data Analysis*:**

Analyze winter-spring $O_2$ dynamics to compute metrics of $O_2$ depletion

- Mainstem Chesapeake
- Patuxent

***Numerical Modeling:***

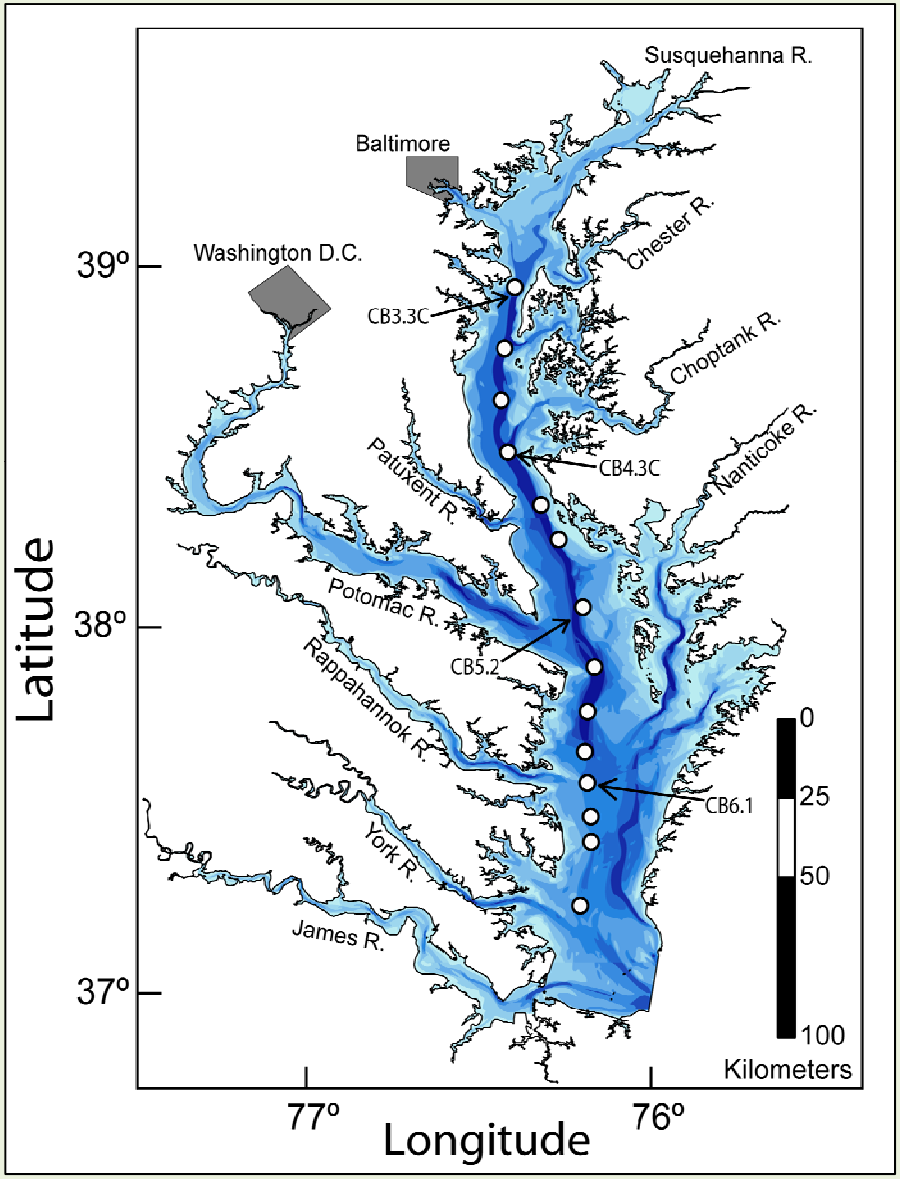
Investigate metabolic aspects of hypoxia responses to nutrient loading

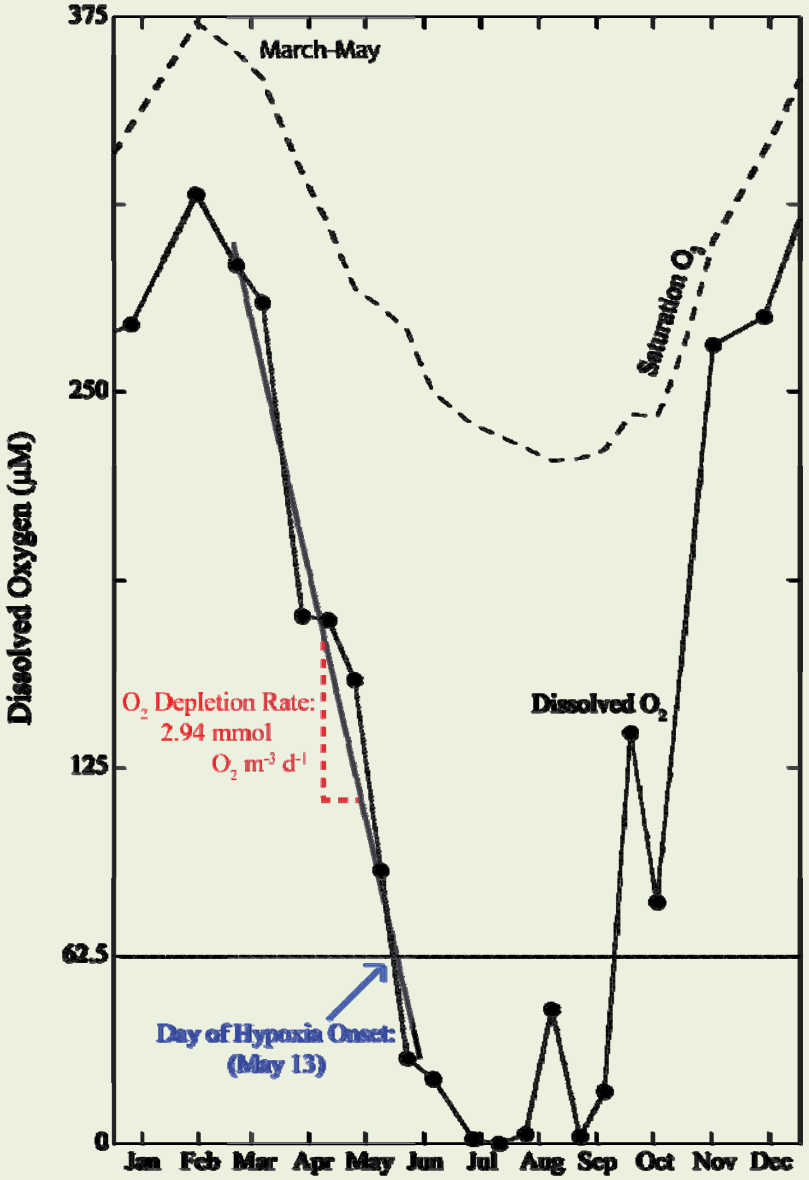
- Spatial and seasonal patterns
- Implications for load responses

# Controls on Winter-Spring $O_2$ Depletion and Links to Summer Hypoxia

- What is the inter-annual variability in winter-spring $O_2$ depletion?
- What controls the onset of hypoxia in Chesapeake Bay?
- Are winter-spring $O_2$ levels related to summer hypoxia?

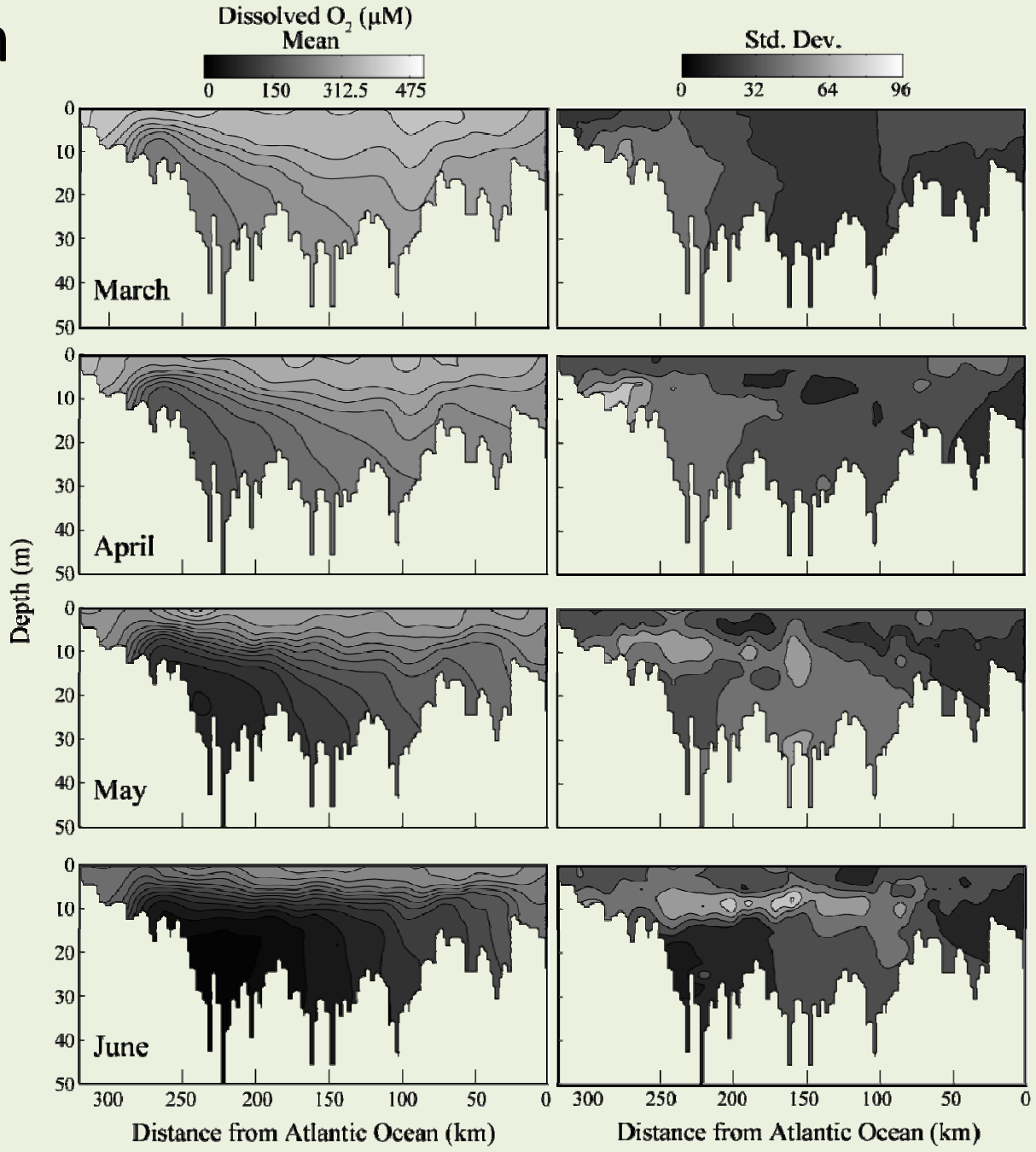
# $O_2$ Depletion Indices From Data



# Seasonal Evolution Of Oxygen-Depleted Water

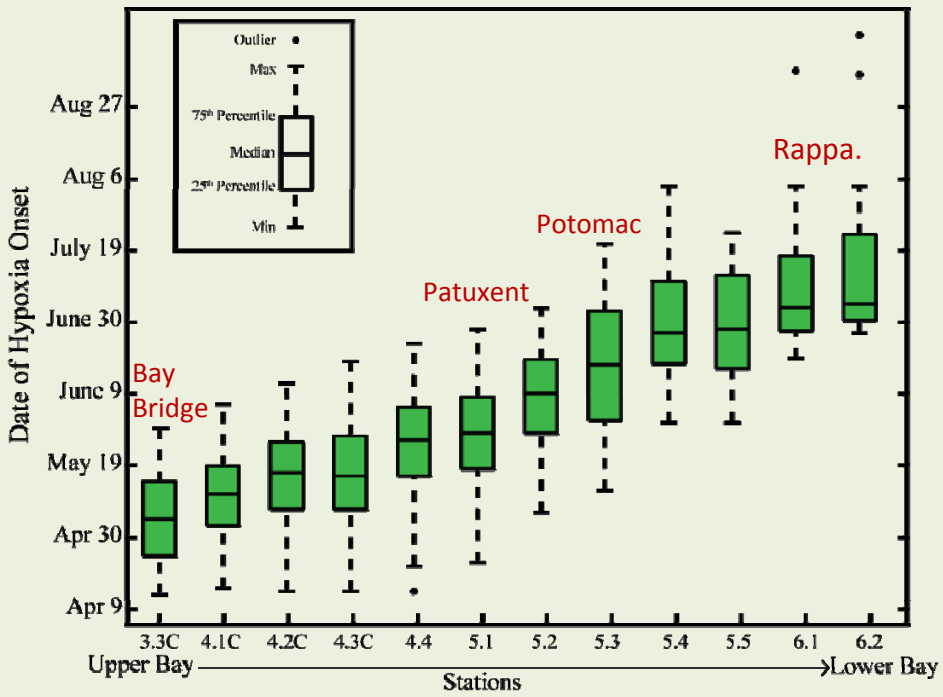
- Mean $O_2$ declines over spring
- Hypoxia starts in upper Bay, moves seaward over time
- Variability in $O_2$ starts low and increases along pycnocline

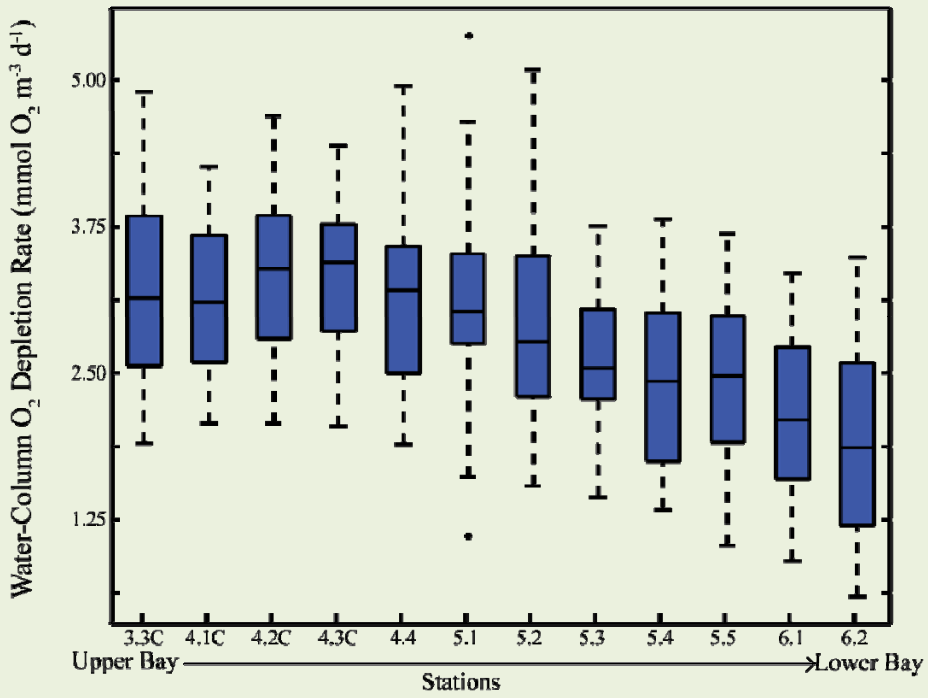



(Testa and Kemp, submitted)

Hypoxia initiates in upper Bay, migrates south

$O_2$ depletion rate spatially variable, but higher in upper Bay



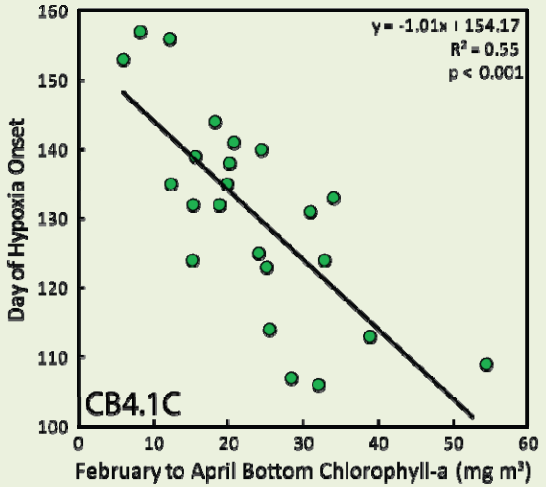




(Testa and Kemp, submitted)

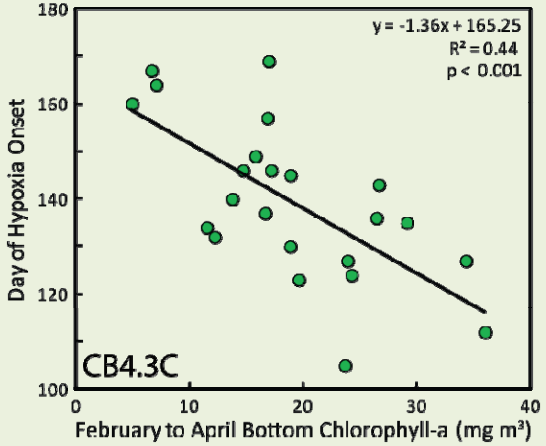
# Chlorophyll-a is the Strongest Predictor of Hypoxia Onset and $O_2$ Depletion

- Spring bloom drives winter-spring $O_2$ depletion
- Relationship strongest in northern regions
- Stratification stronger predictor in lower Bay

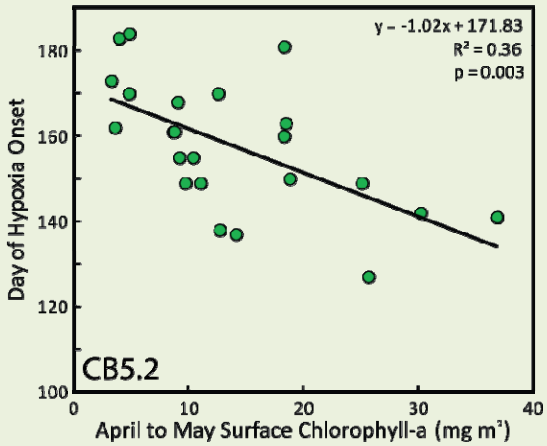
Upper Bay



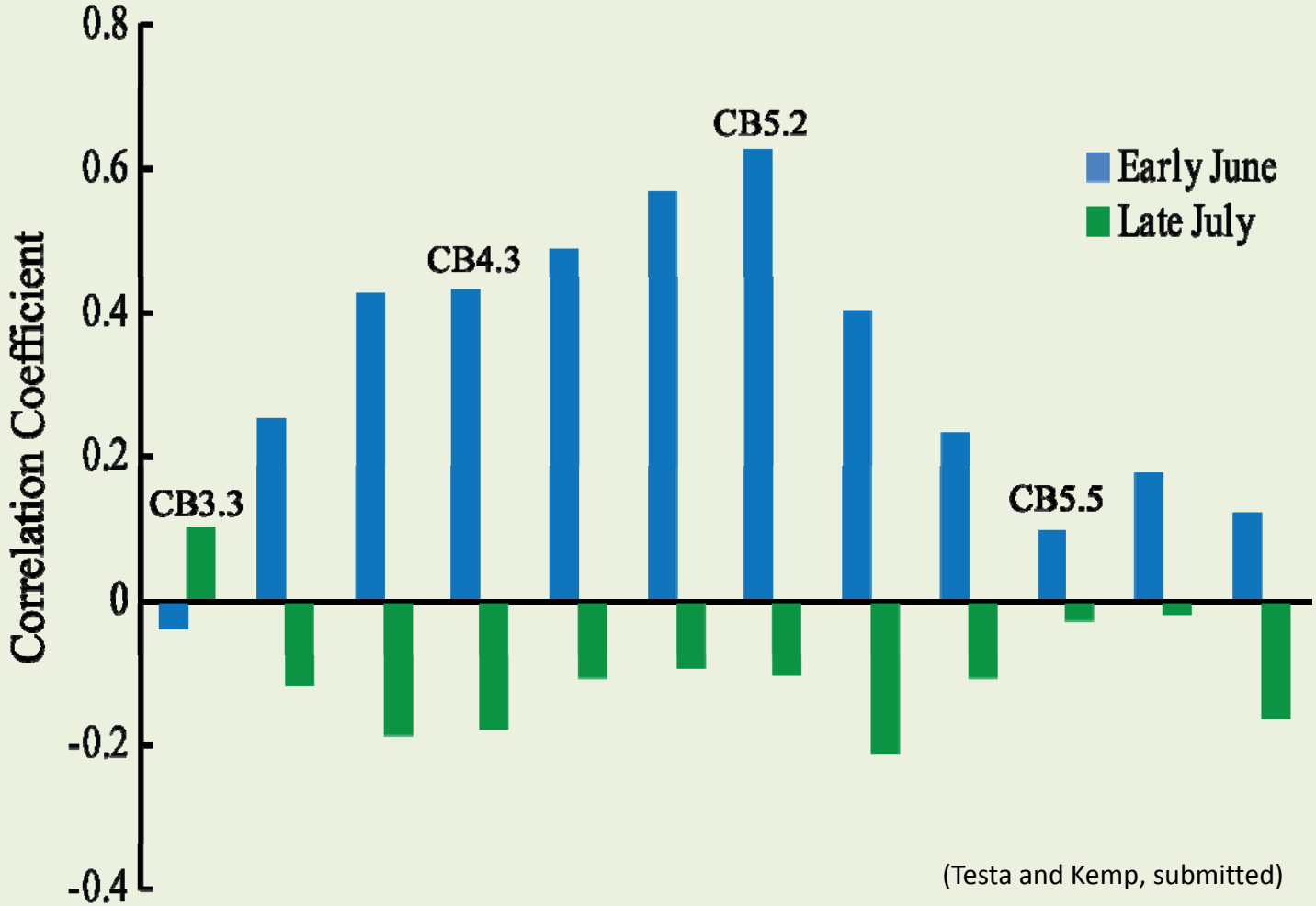

Middle Bay




Lower Bay

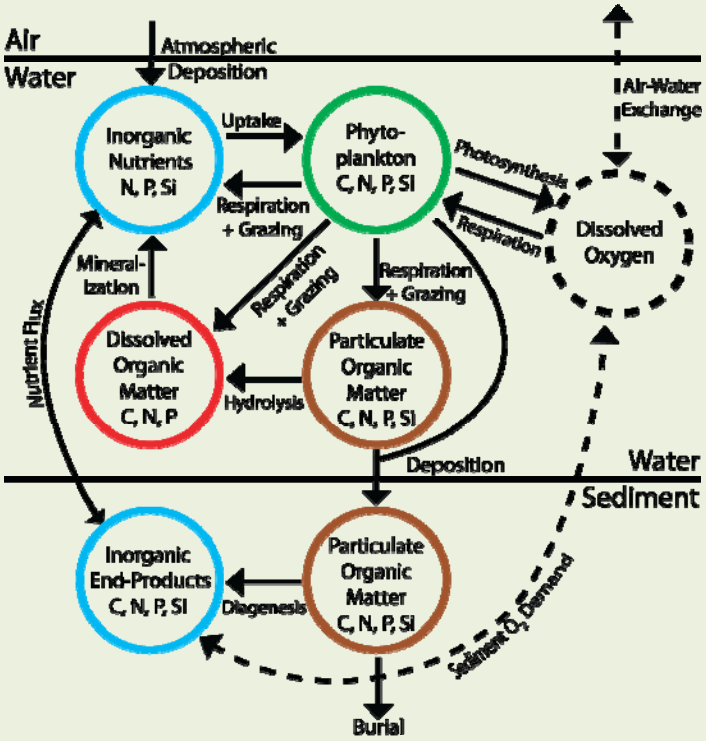


# Spring Depletion Metrics Weakly Correlated to Summer Hypoxic Volumes

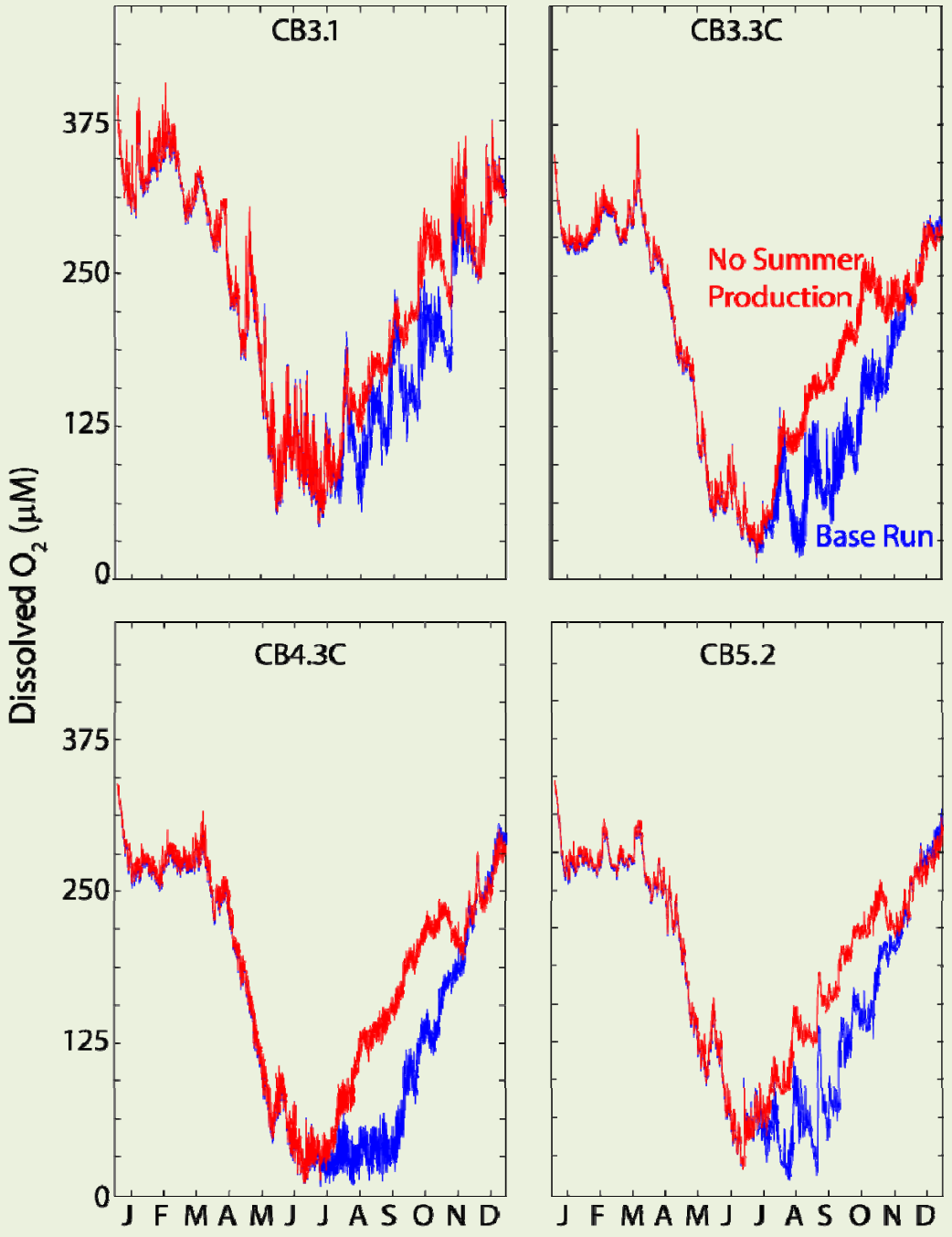



(Testa and Kemp, submitted)

# Summer Production Needed for Summer Hypoxia



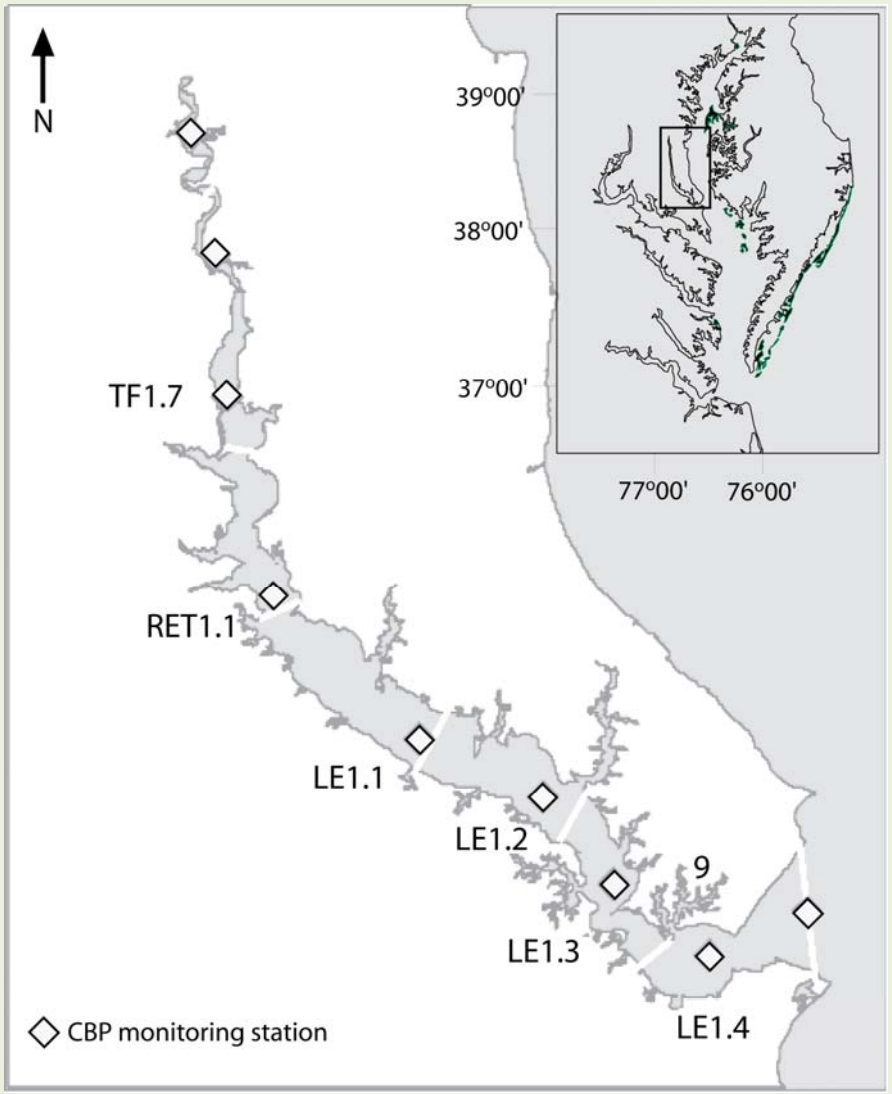

Biogeochemical Model, Row-Column AESOP

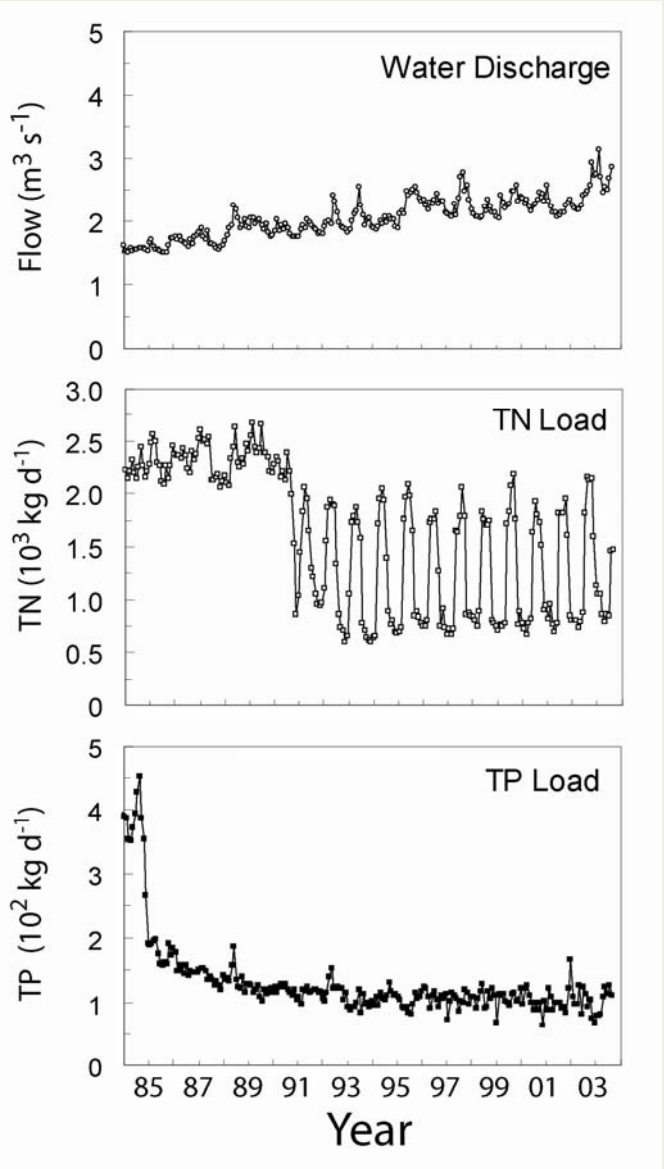


# Concluding Comments

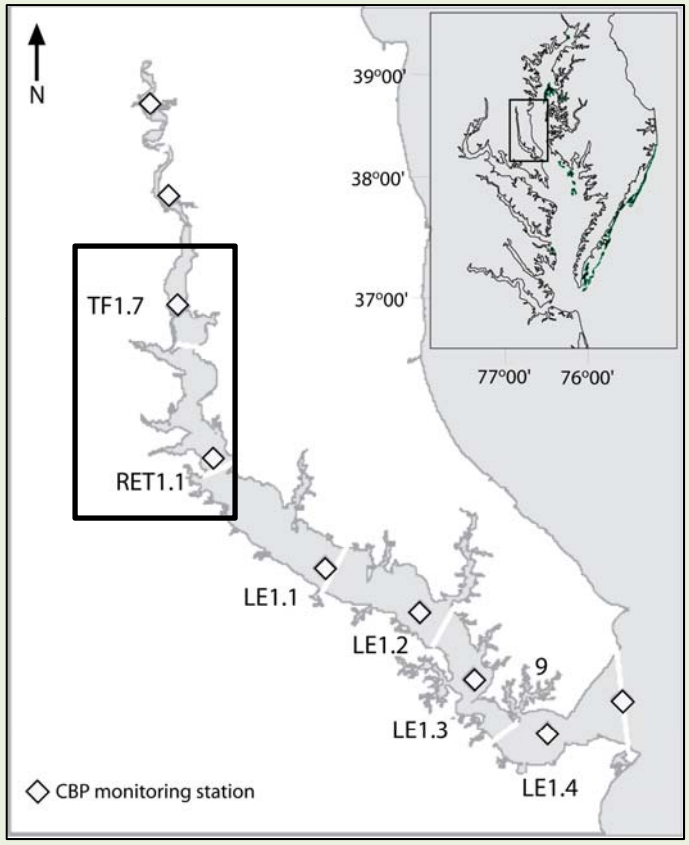
- Hypoxia consistently initiates in upper Bay and moves seaward
- Winter-spring algal biomass primary driver of spring $O_2$ depletion
- Winter-spring conditions weakly correlated to summer hypoxic volumes: Summer production, physical replenishment in intervening months important

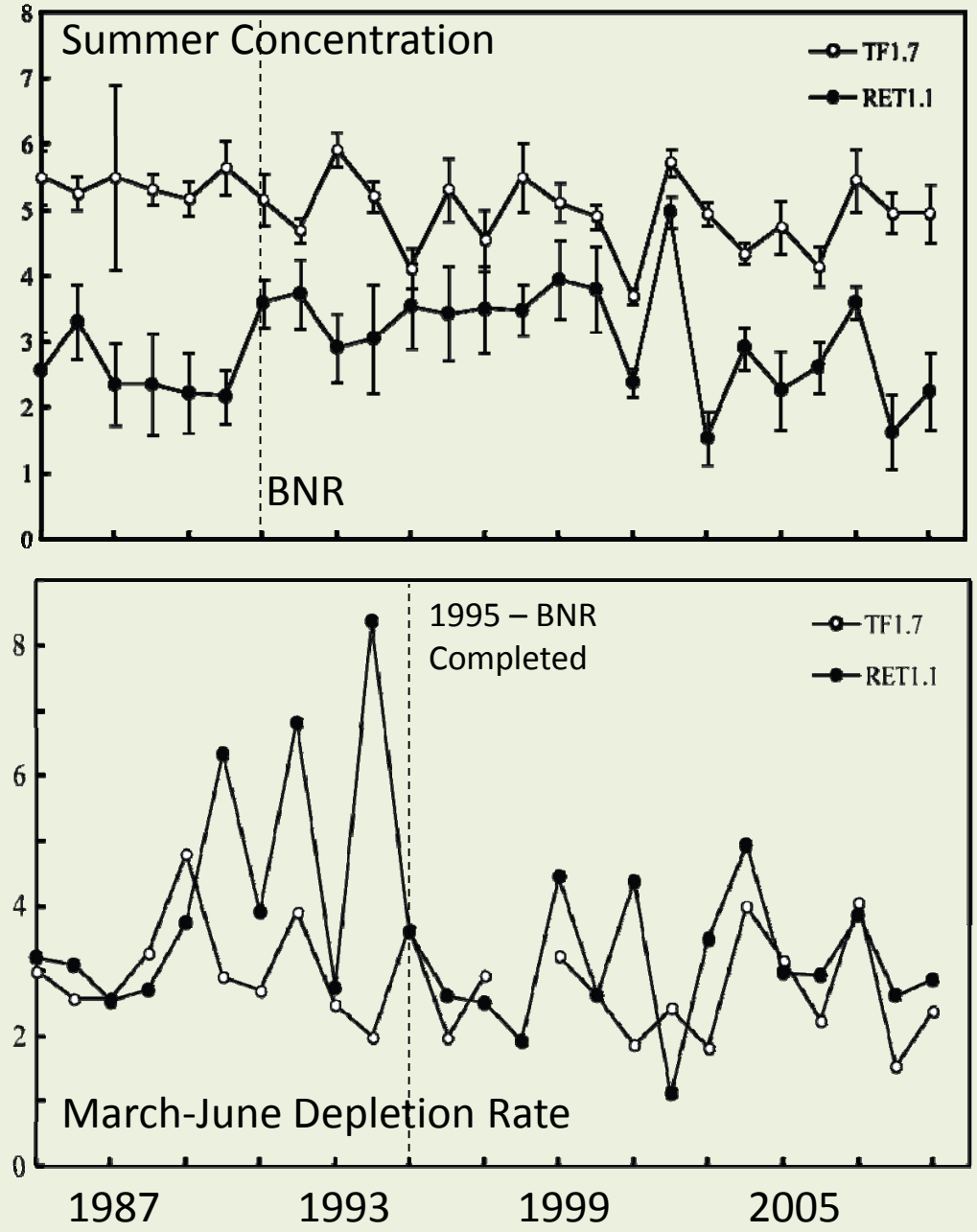
# Patuxent Estuary

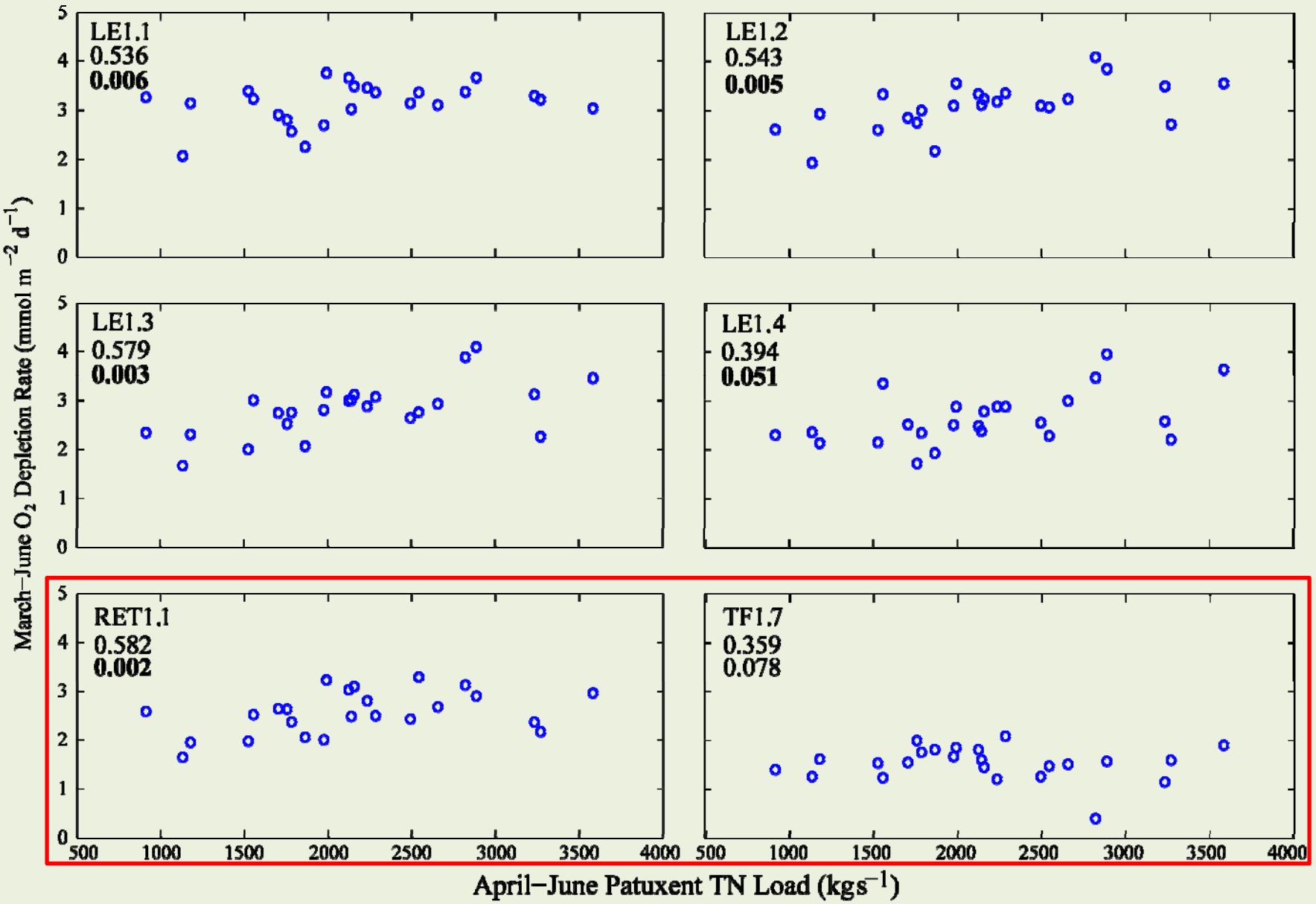


# $O_2$ concentration and depletion rate




LE1.1
0.536
0.006
LE1.2
0.543
0.005
LE1.3
0.579
0.003
LE1.4
0.394
0.051
RET1.1
0.582
0.002
TF1.7
0.359
0.078
March–June O2 Depletion Rate (mmol m−2 d−1)
April–June Patuxent TN Load (kgs−1)
0
1
2
3
4
5
500
1000
1500
2000
2500
3000
3500
4000

# Response of Hypoxia to Nutrient Loading in Chesapeake Bay: A Modeling Analysis

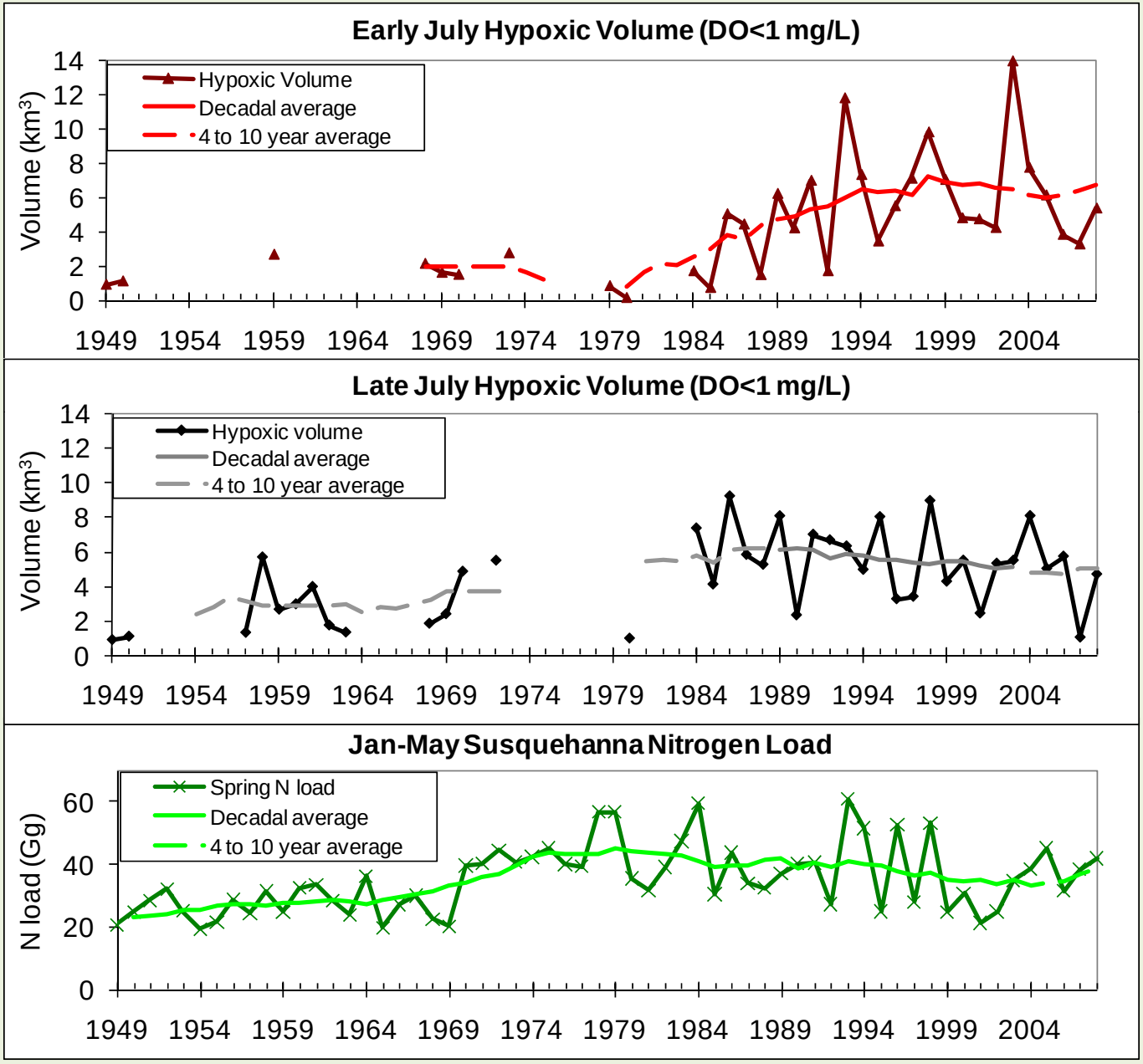
**Why?**

(1) Understand patterns and processes associated with eutrophication

(2) Perturbation study to test system response to changes in external forcing

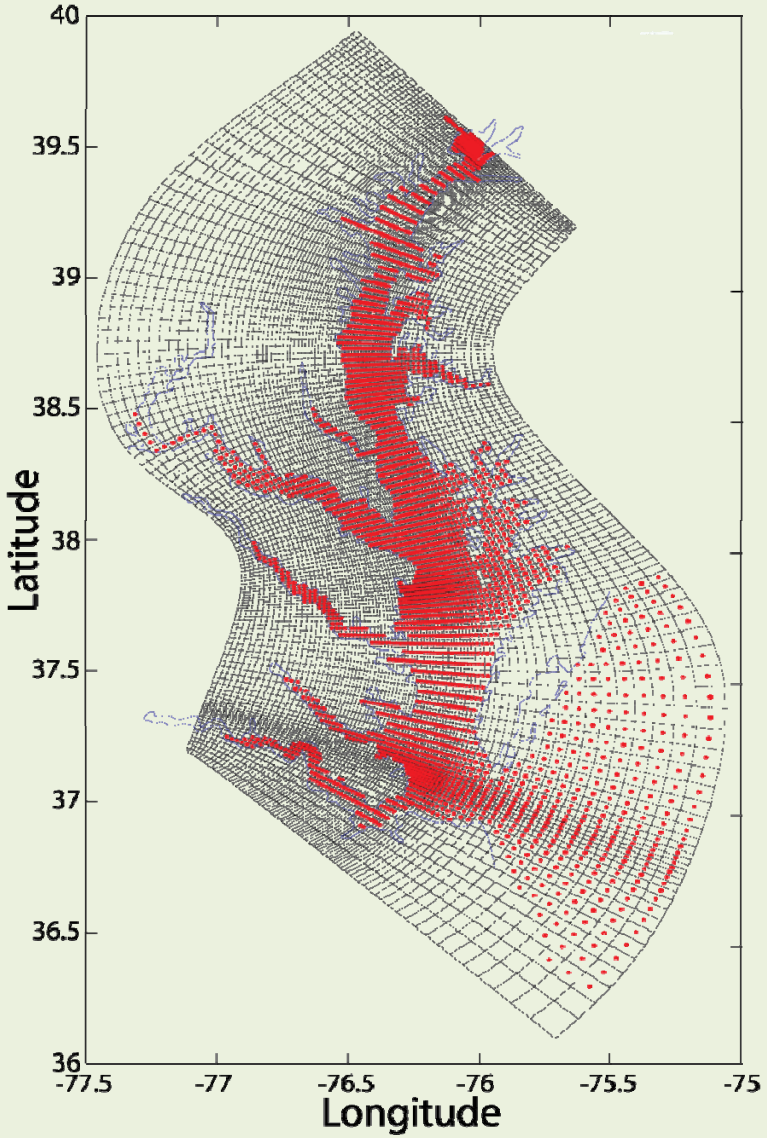
(3) Management aims to reduce nutrient loads – what do we expect to happen?

# Recent Evidence for Complex Hypoxia Time-Series



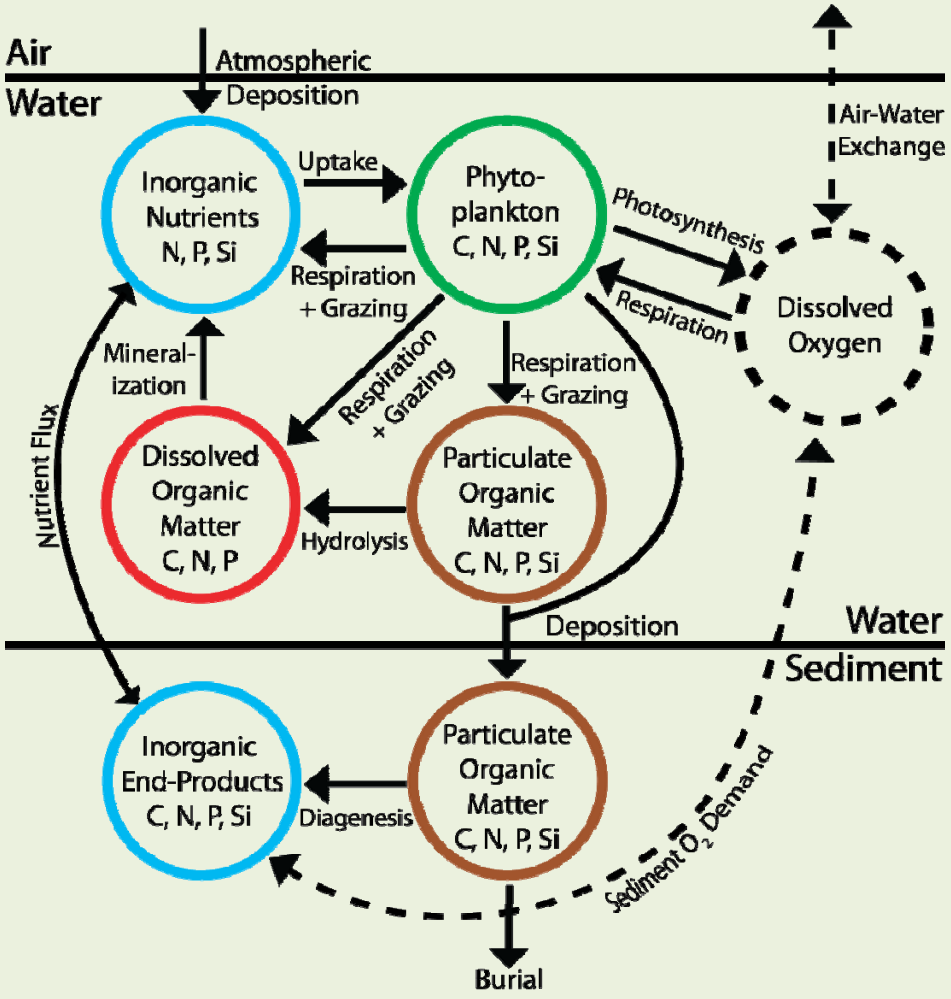

(Murphy et al. 2011 E&C)

# ROMS



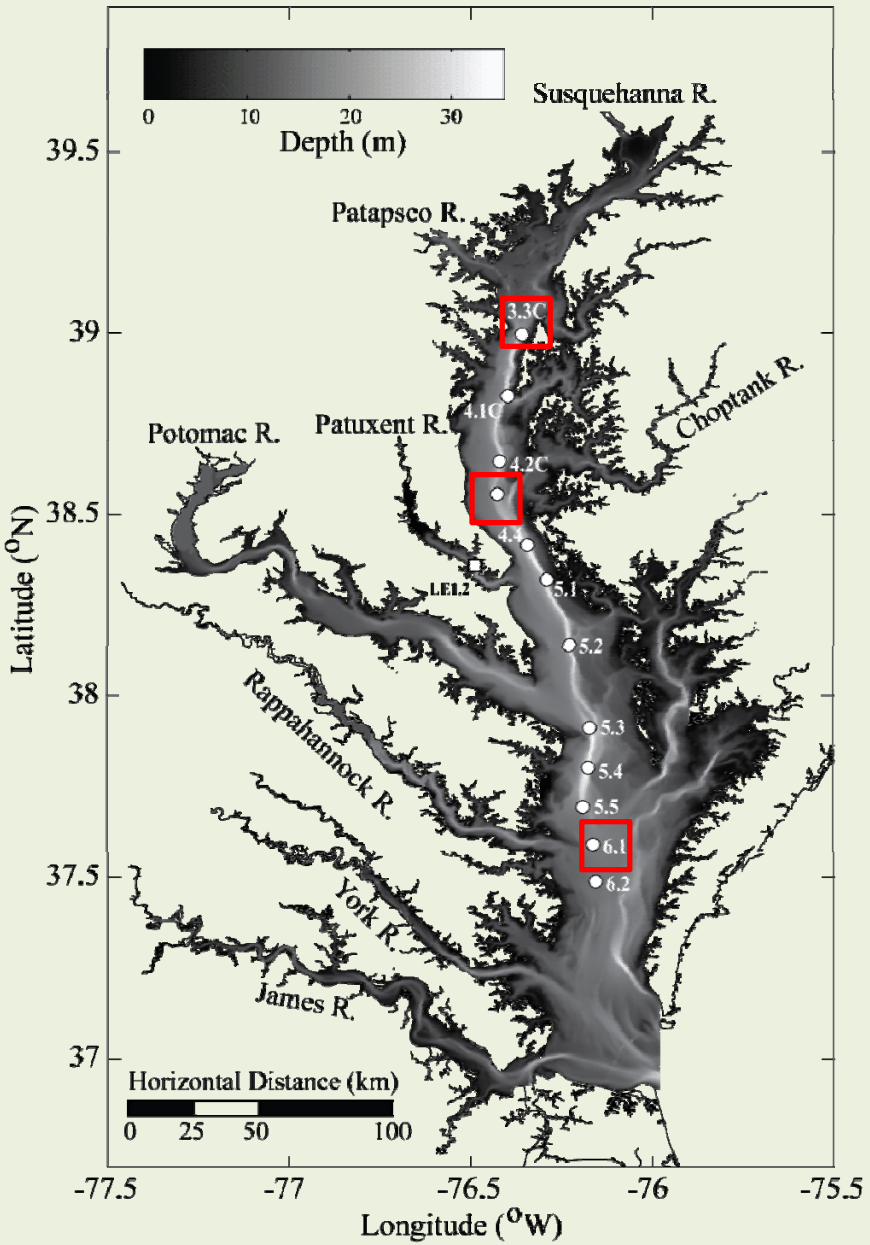

- Forced by freshwater from 8 major tributaries
- Resolution = 80 cells east-west, 120 cells north-south
  20 vertical layers, 68,000 Cells

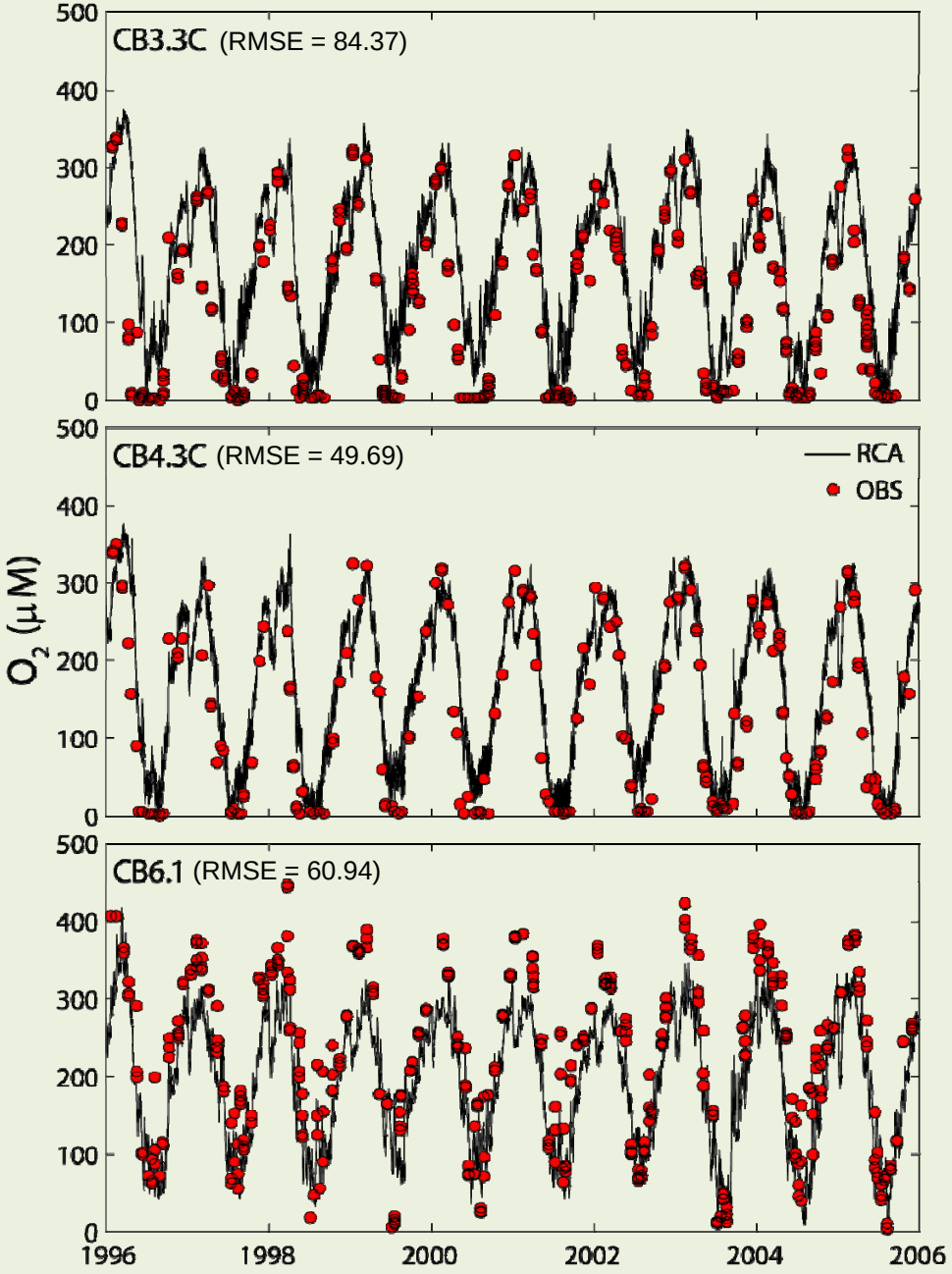
# RCA




- 23 state variables
- Coupled sediment biogeochemical model
- External loads from 8 tributaries, point sources, atmospheric deposition
- Calibrated to water-column concentrations, sediment and water-column metabolic rates

# 10-Year Model Simulations: 1996-2005



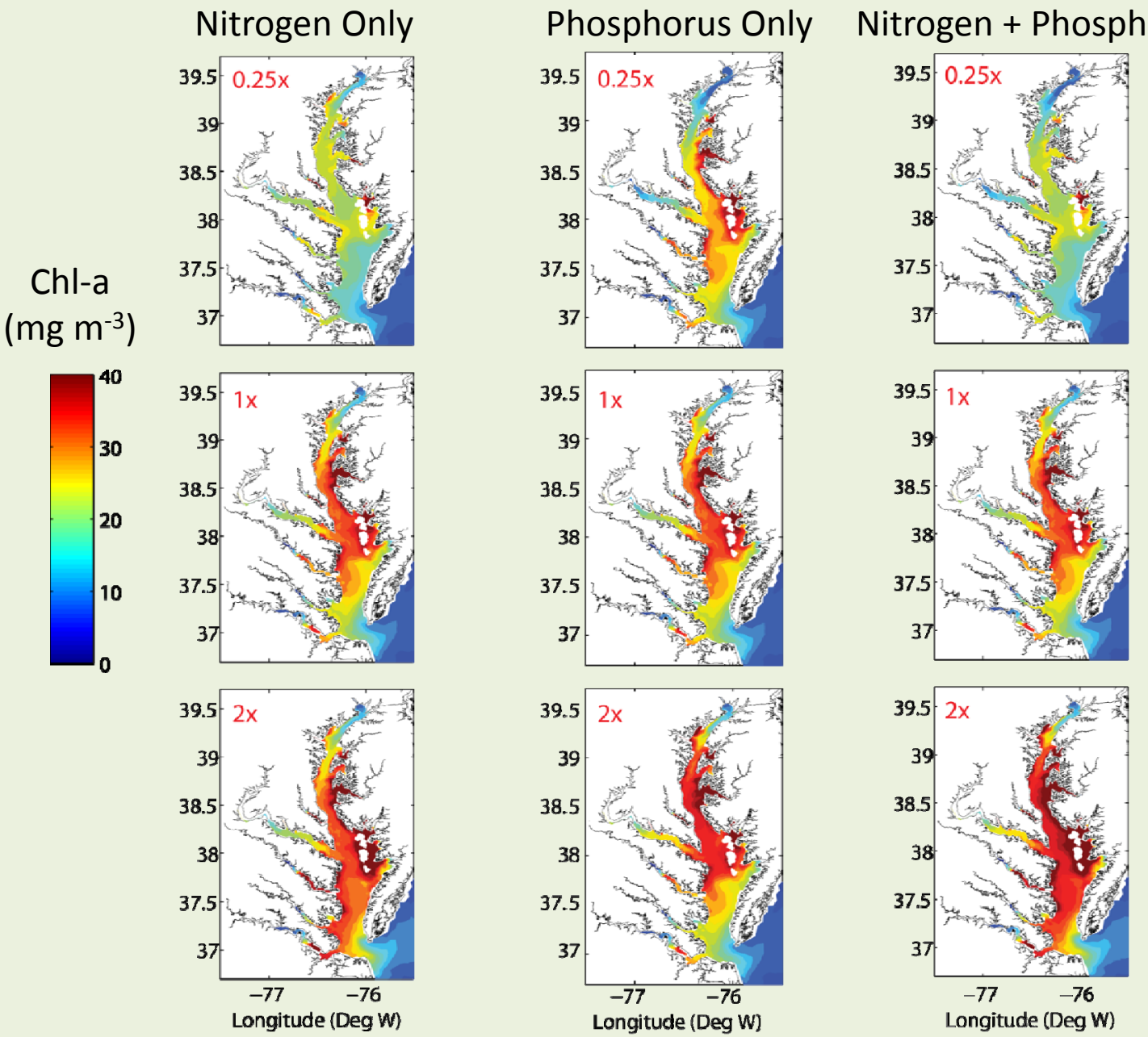



# Nutrient Load Experiments

*Three Sets of Nutrient Load Tests*

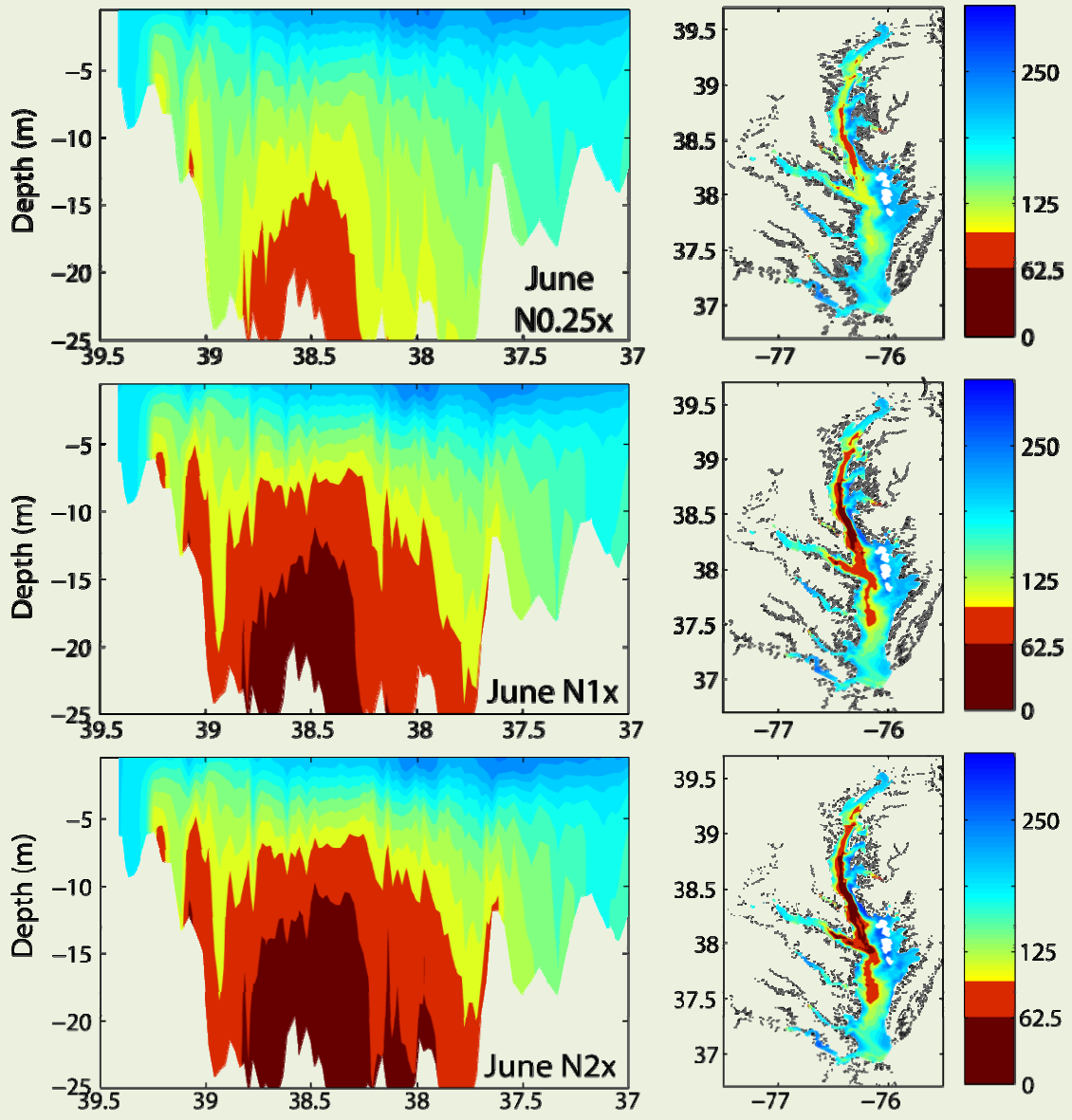
| | Load Relative to Observed | | | |
|---|---|---|---|---|
| (1) Nitrogen Load (N): | 0.25x | 1x | 2x | 4x |
| (2) Phosphorus Load (P): | 0.25x | 1x | 2x | 4x |
| (3) N+P Load (NP): | 0.25x | 1x | 2x | 4x |

# Nitrogen Versus Phosphorus Loading Impacts

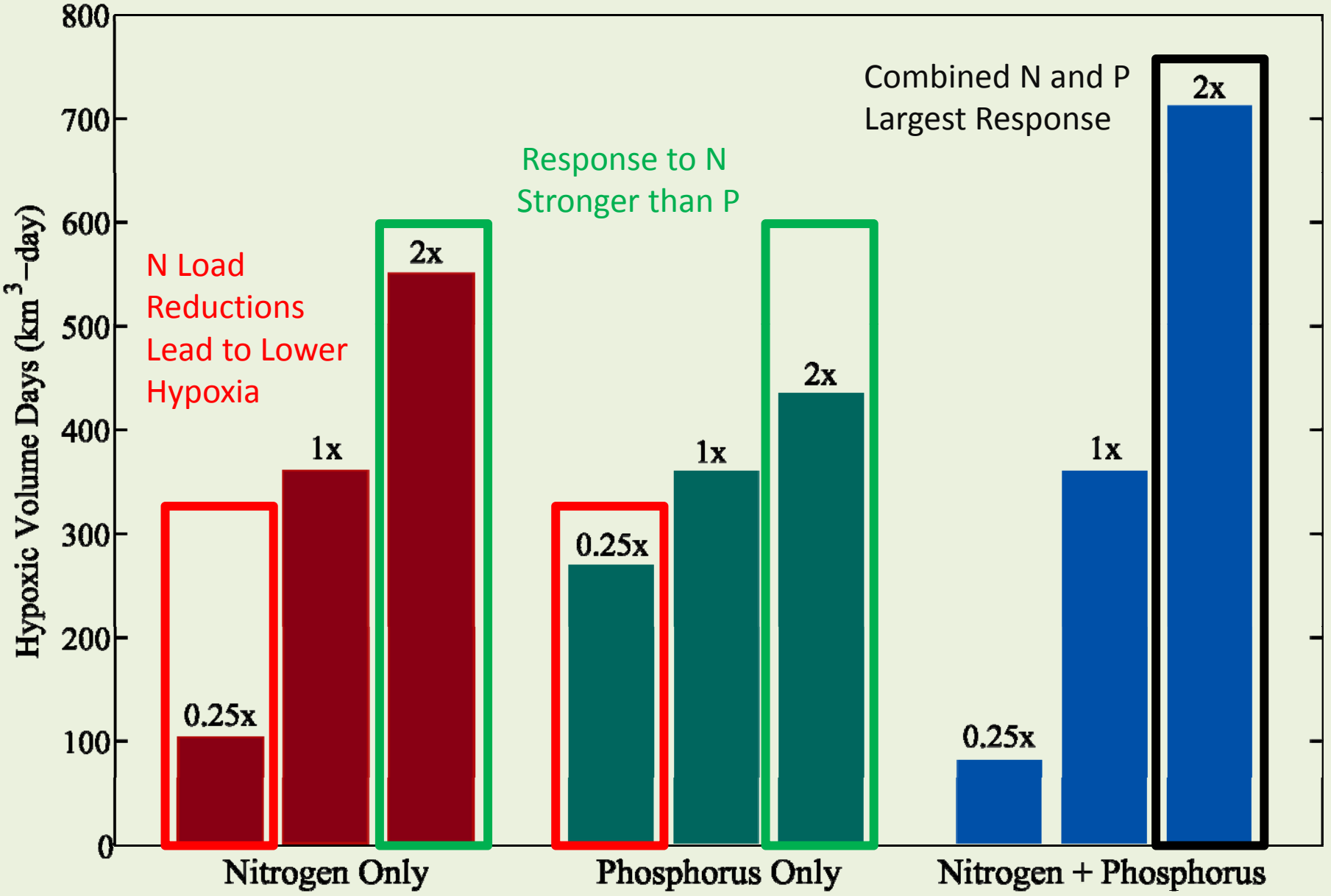


# Spatial Response of Hypoxia to N Loads

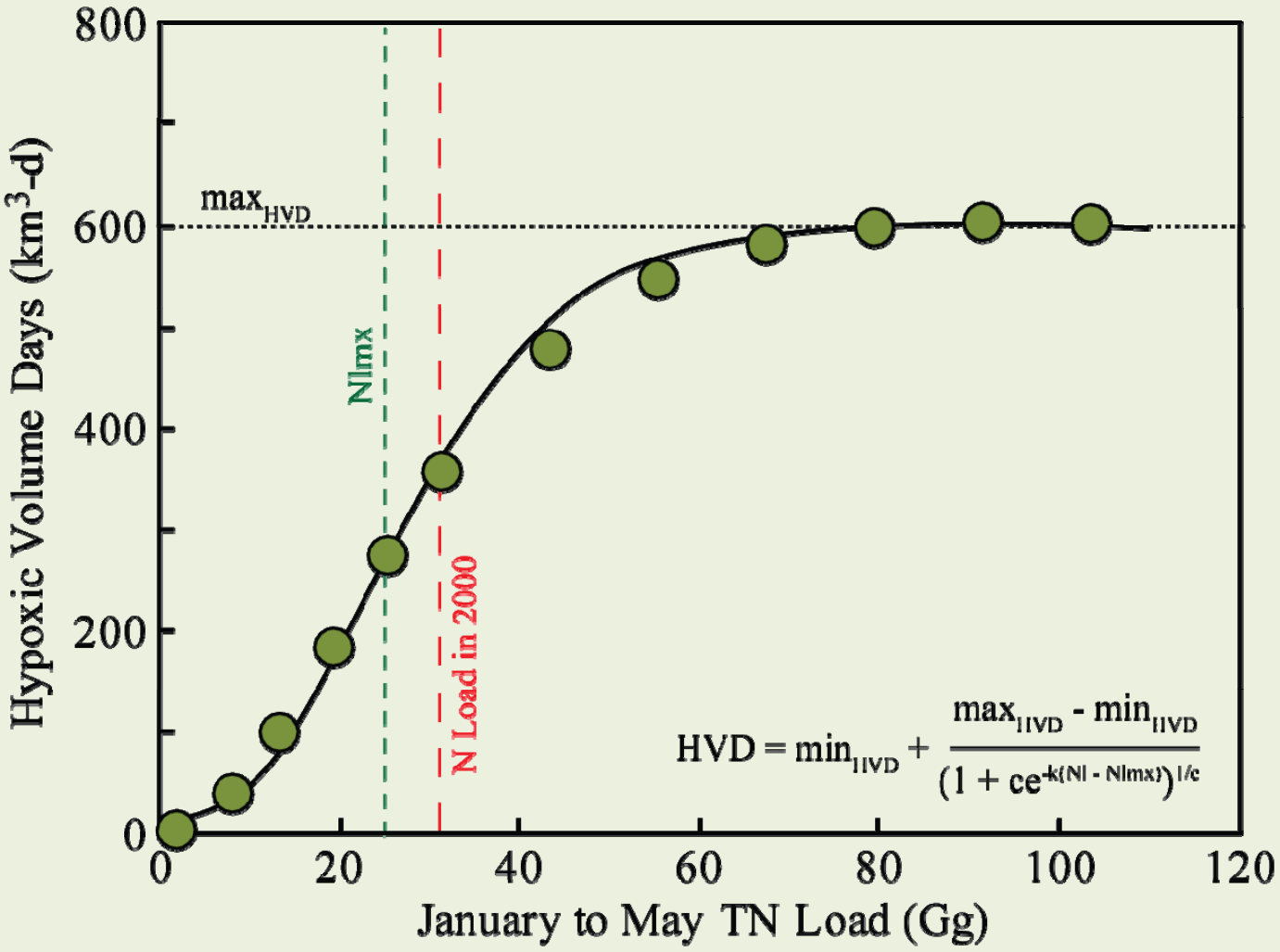
- N Loading drives deeper, more seaward hypoxia



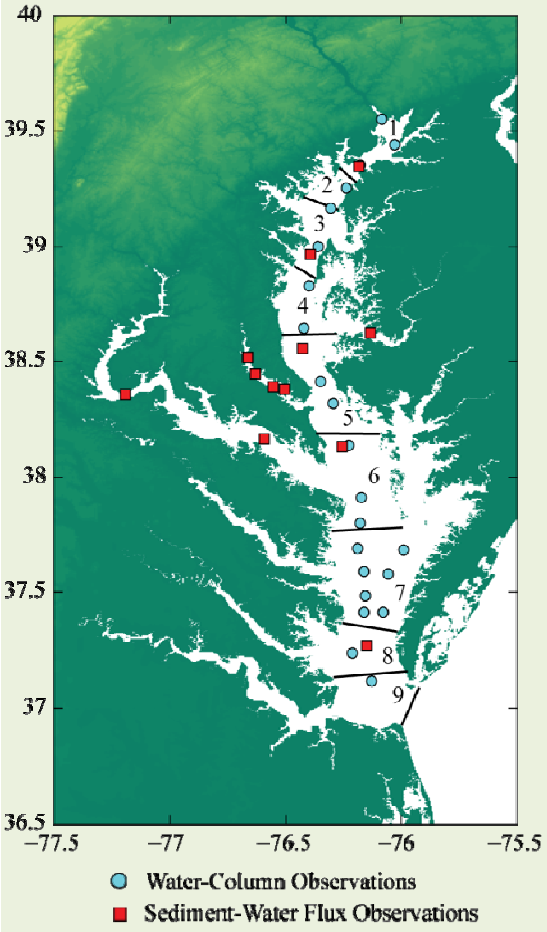
# Nutrient Loading Increases Hypoxic Volume

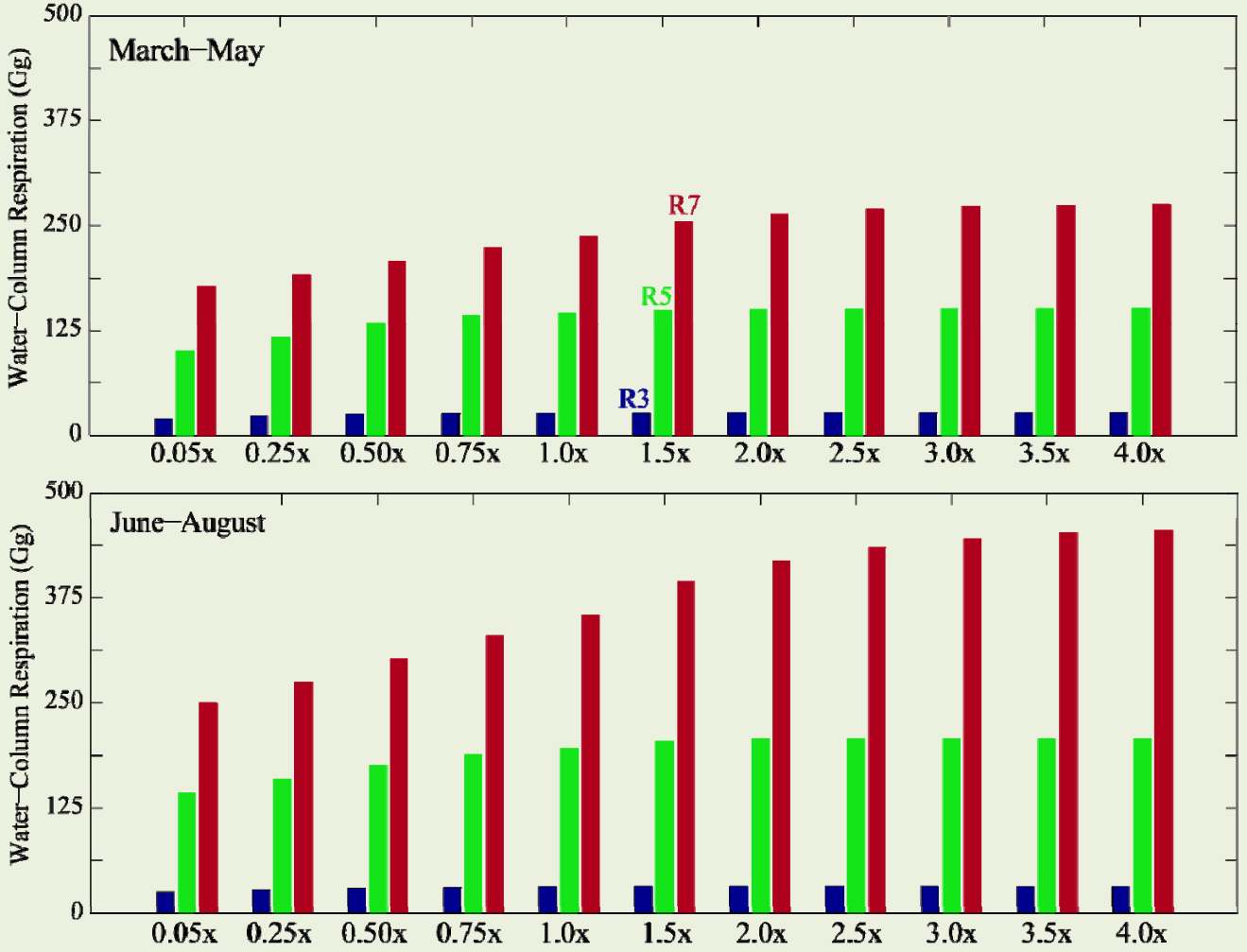


# Non-Linear Relationship Between Nutrient Loading and Hypoxic Volume



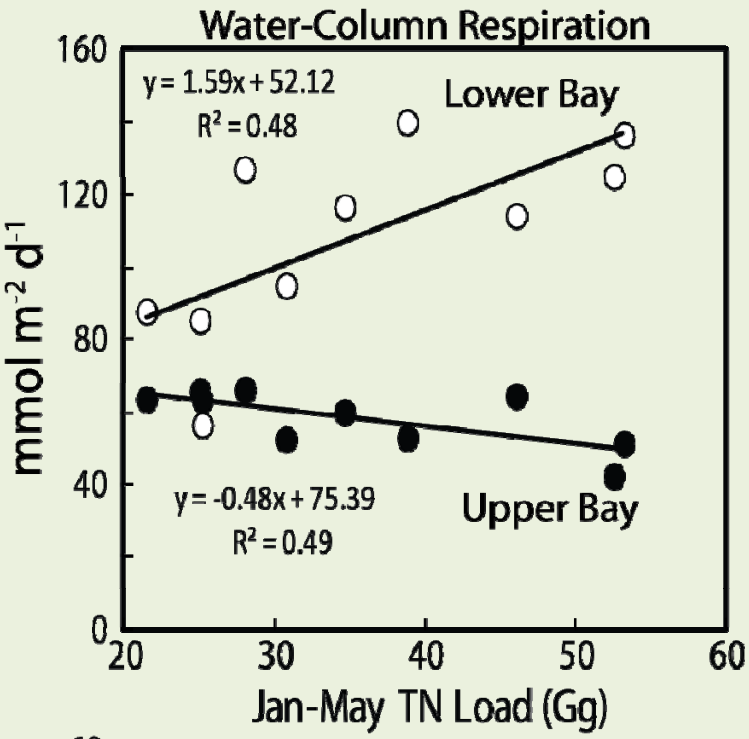
# Nutrient-Fueled Increases in Summer Respiration Drive Hypoxic Volume

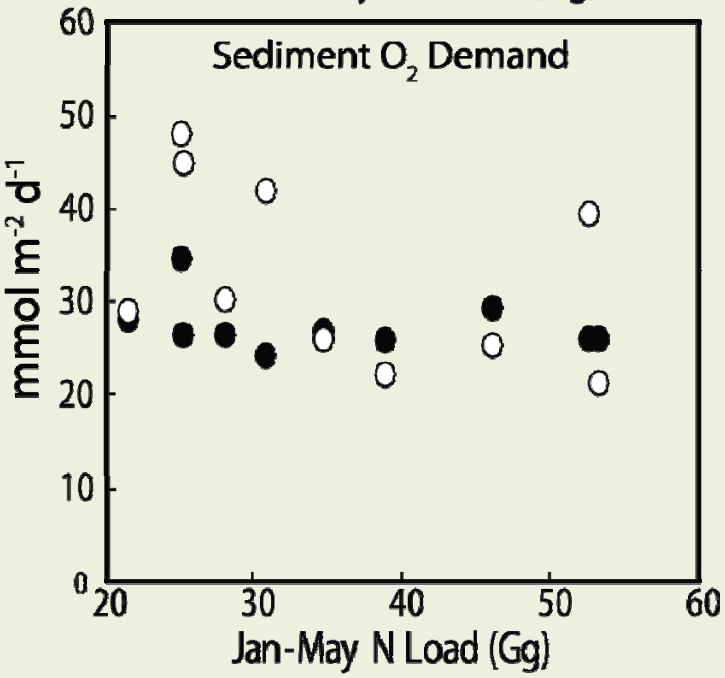


# Nutrient-Fueled Increases in Respiration Drive Hypoxic Volume

- Water-column respiration dominates $O_2$ uptake, inter-annual variations in hypoxia
- Increases in nutrient load elevate lower, Bay respiration, but reduce it in upper Bay
- Sediment oxygen demand not responsive to nutrient load



# Conclusions

- ROMS-RCA reproduces seasonal and inter-annual distributions of dissolved oxygen in Chesapeake Bay
- Hypoxic volume is more sensitive to nitrogen load than phosphorus
- Nutrient-load stimulation of respiration is strongest in the water-column in lower Bay, leads to larger hypoxic volumes

# *Acknowledgements*


- *Collaborators:* Michael Kemp, Walter Boynton, Jeff Cornwell, Dominic Di Toro, Ming Li, Damian Brady, Yun Li, Younjoo Lee, Rebecca Murphy, Jim Fitzpatrick, Eric Pearlman, Randall Burns, Bill Ball, Peter Stæhr, Jim Hagy, Dan Conley, Denis Gilbert, Jennifer Bosch, Cassie Gurbisz, Debbie Hinkle, Laura Murray, Carl Cerco

- *Data*: Maryland DNR, Chesapeake Bay Program, USGS

- *Funding*: National Science Foundation, NOAA CHRP, Maryland DNR , Horn Point Laboratory, MD Sea Grant, Izaac Walton League


CBEO
Chesapeake Bay Environmental Observatory

demonstrating the transformative power of cyberinfrastructure for environmental science and engineering

NSF

NCCOS
Modeling Hypoxia & Ecological Responses to Climate & Nutrients
CHRP

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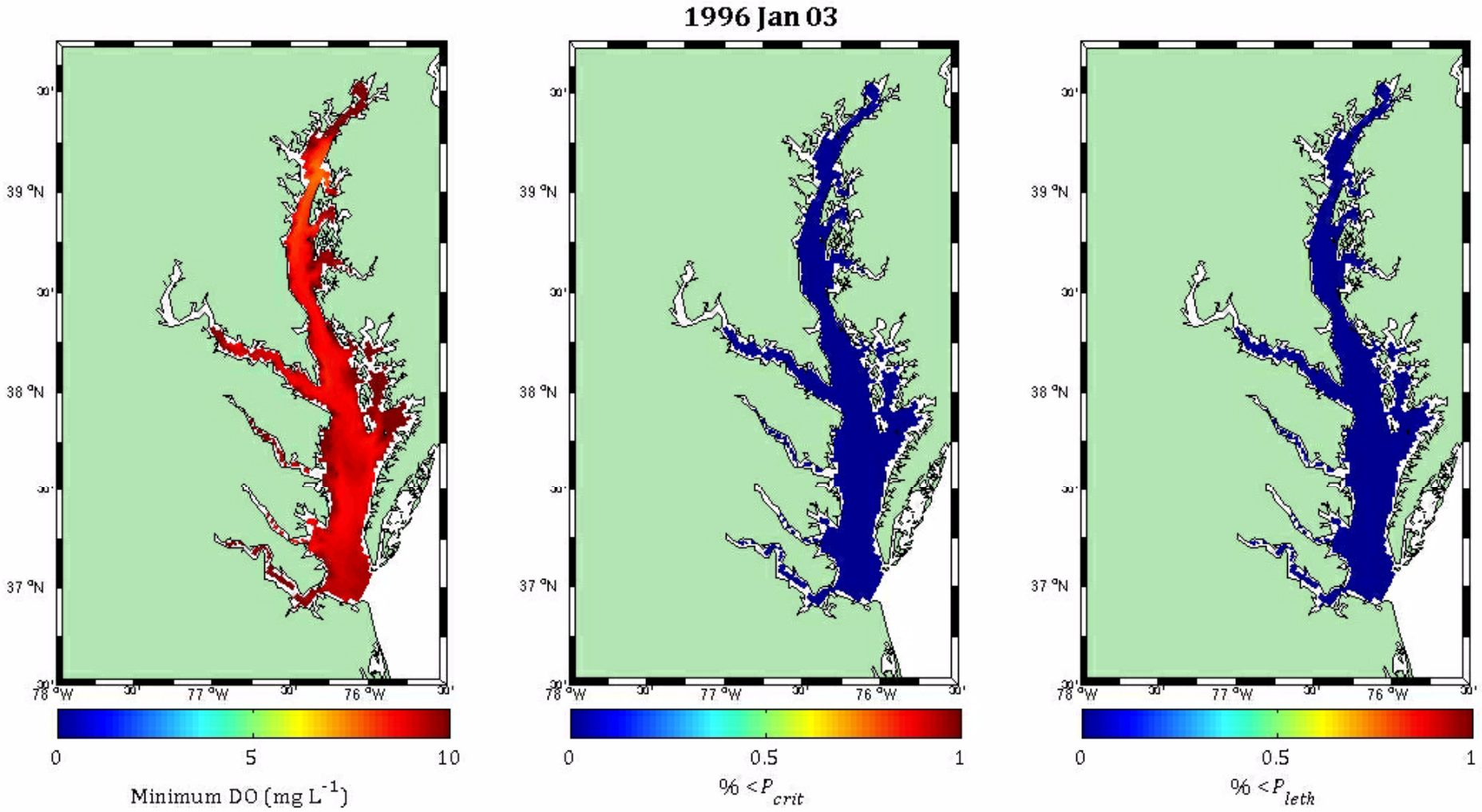
MARYLAND DEPARTMENT OF NATURAL RESOURCES

Sea Grant Maryland

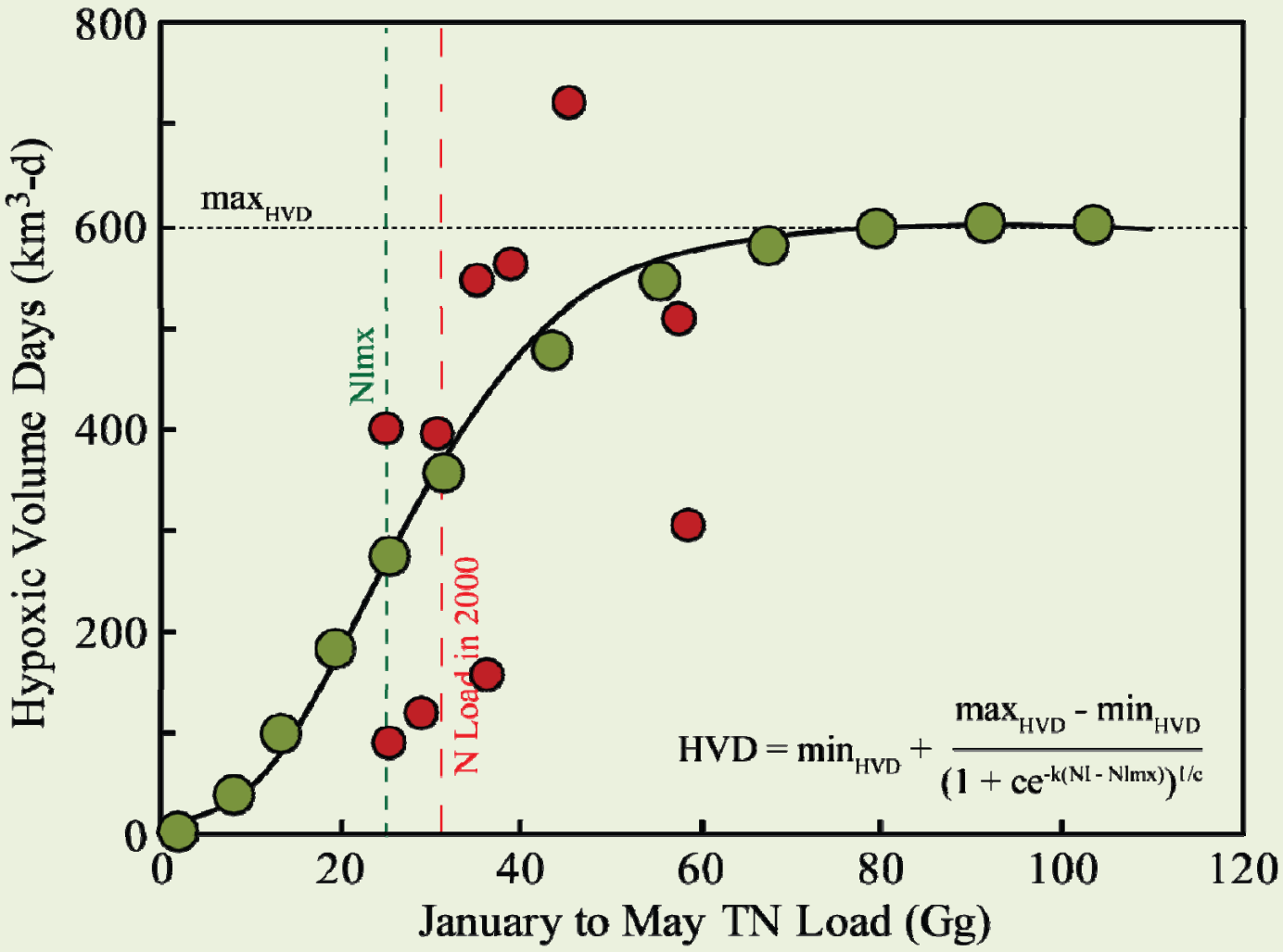
University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE
HORN POINT LABORATORY

# Extra Slides

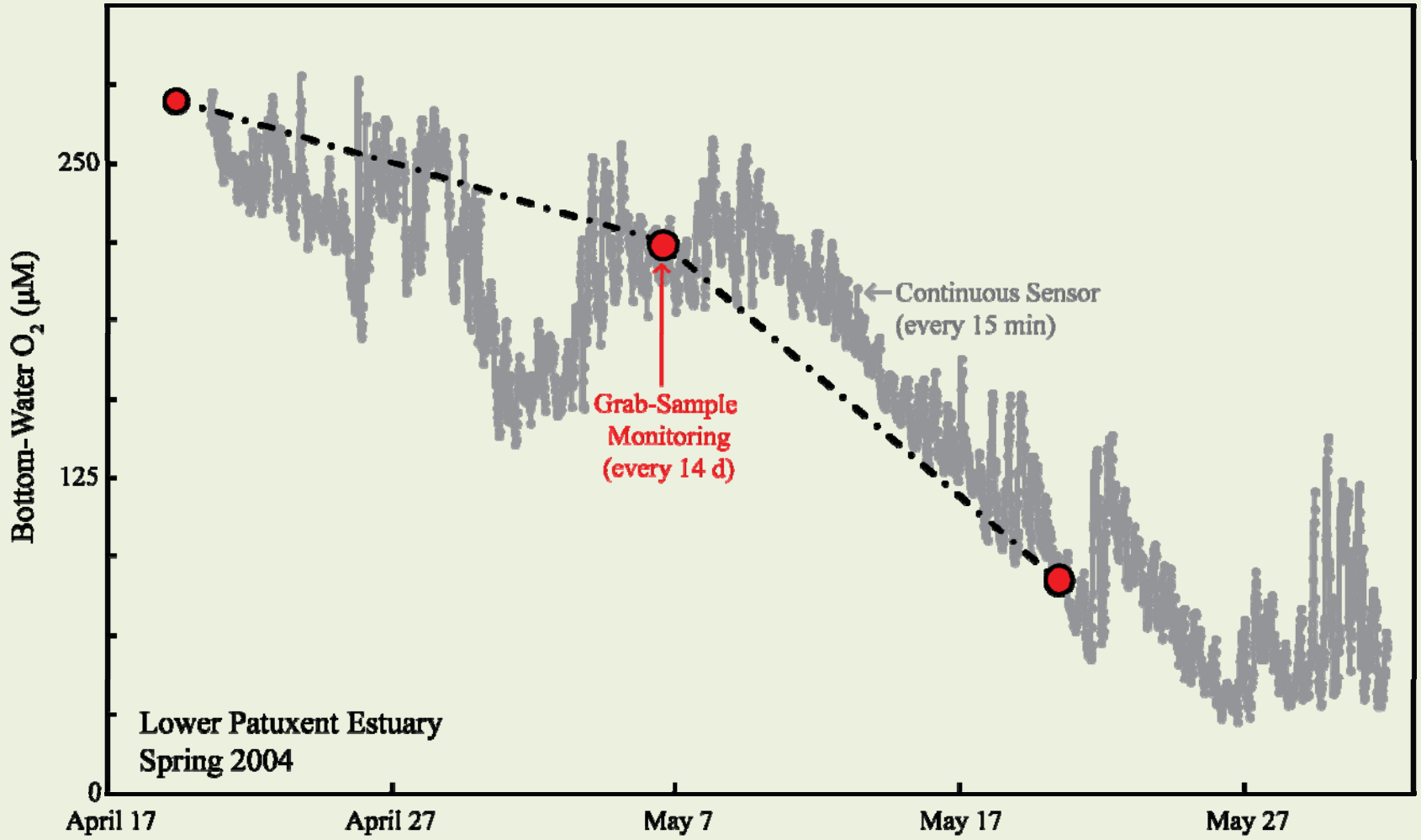
# Modeling Oxygen Impacts on Habitat




in collaboration with Drs. Jamie Pierson (UMCES-HPL) and David Elliot (ODU)


800
600
400
200
0
0
20
40
60
80
100
120
Hypoxic Volume Days (km3-d)
January to May TN Load (Gg)
maxHVD
Nlmx
N Load in 2000
HVD = minHVD + (maxHVD - minHVD) / (1 + ce-k(Nl - Nlmx))1/c

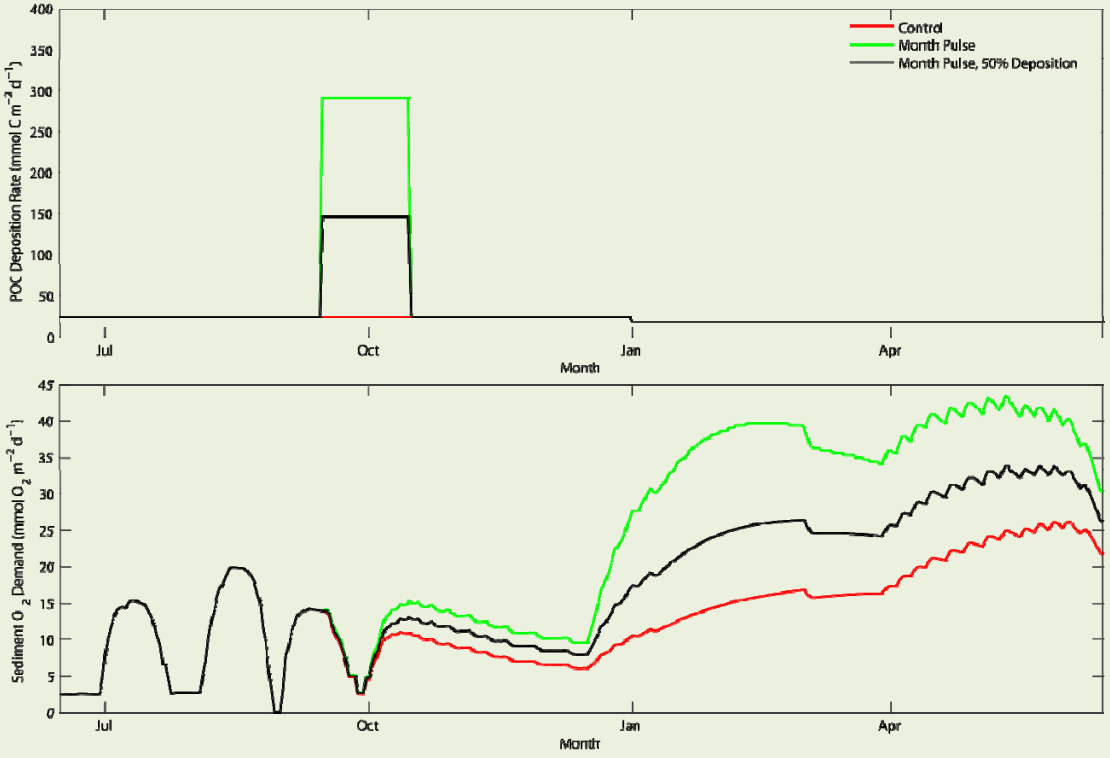
# Multiple Scales of Temporal Variability in $O_2$

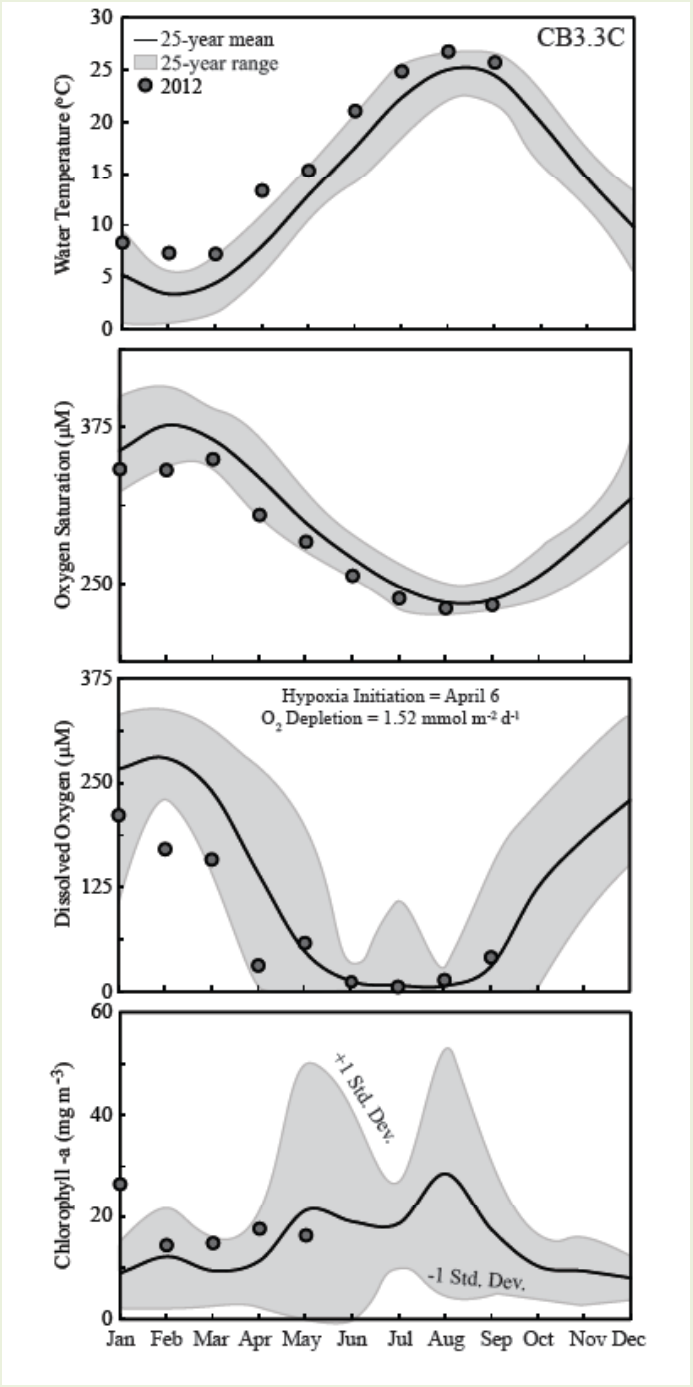


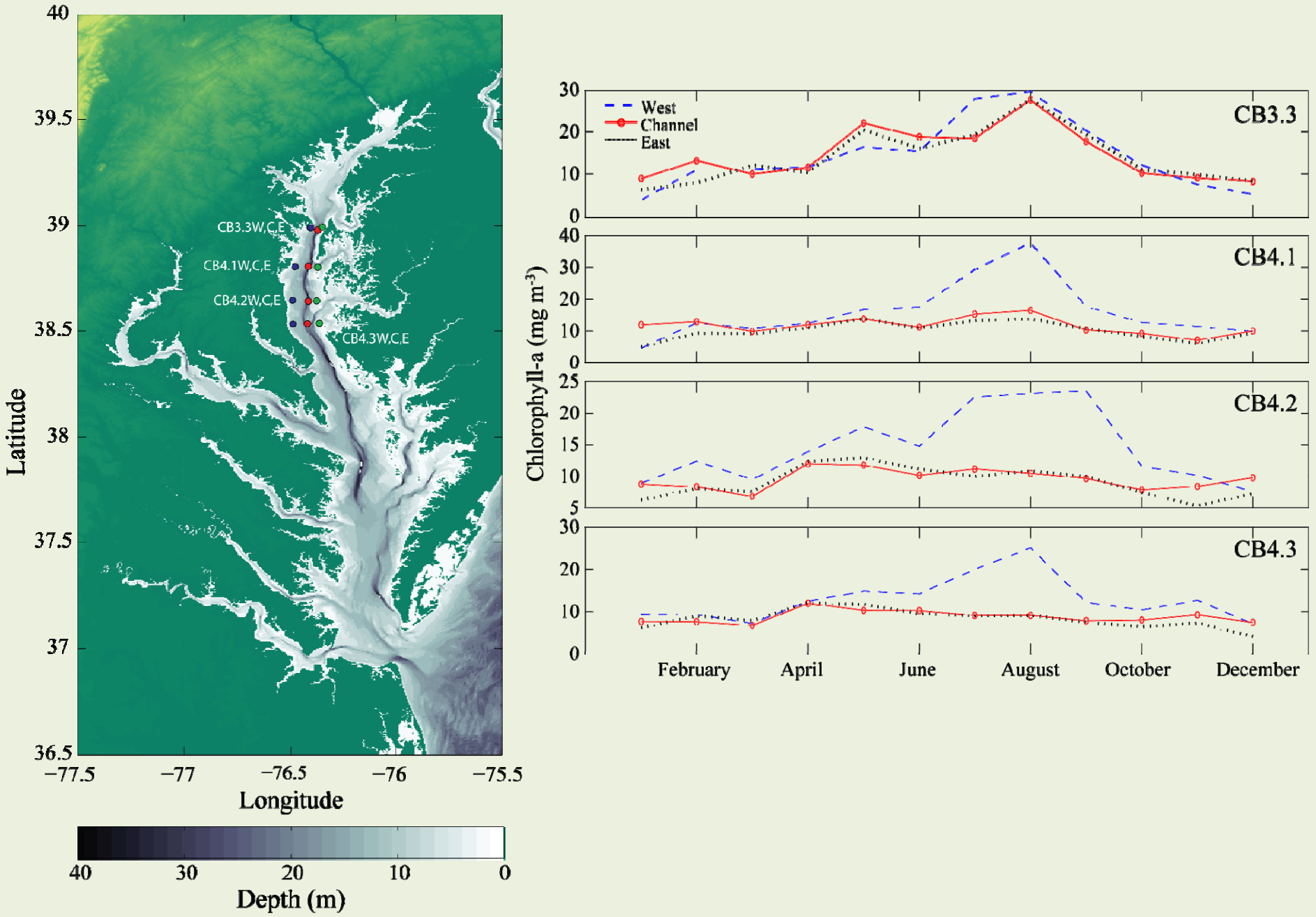

(Testa and Kemp, submitted)

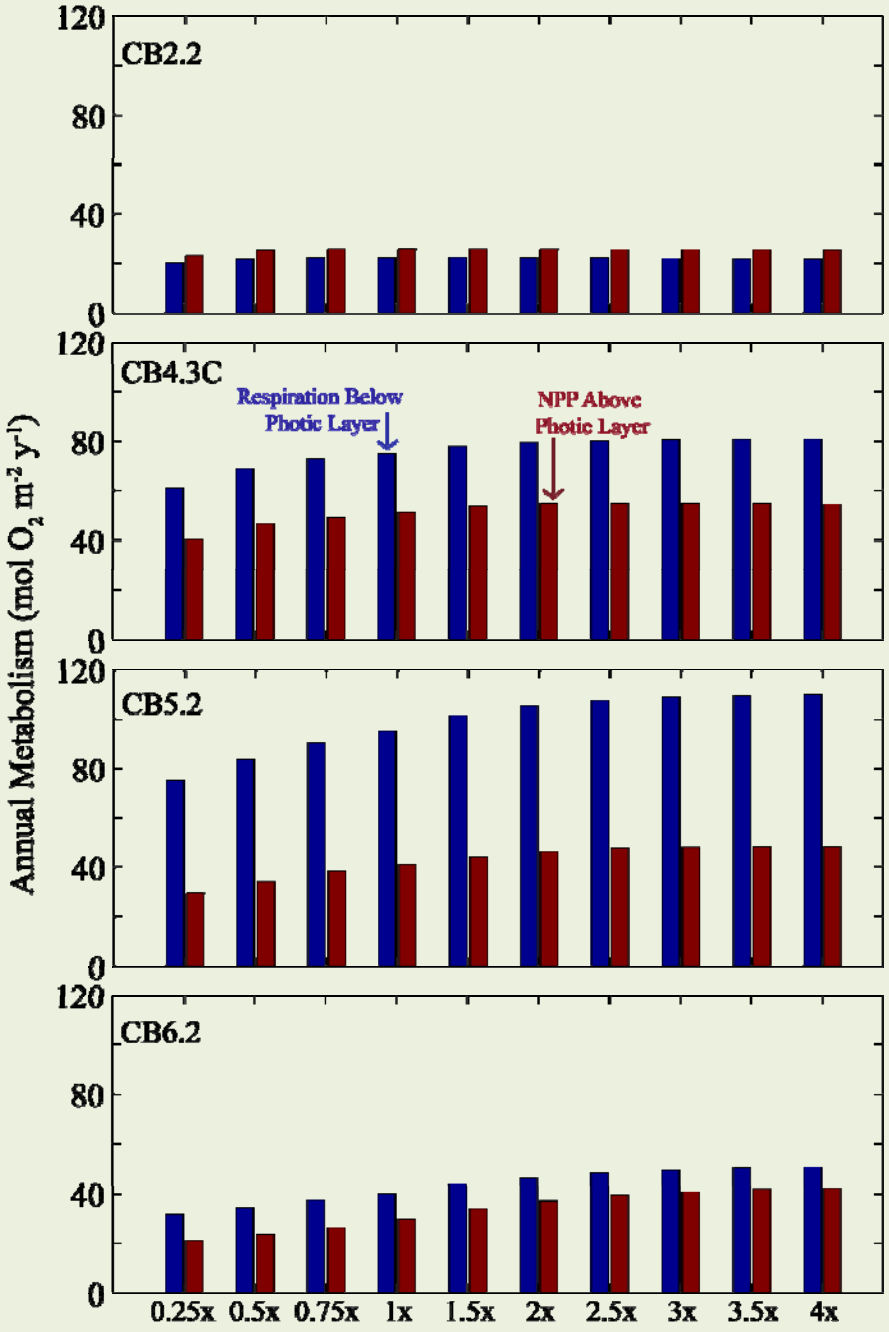
# Hypoxia Onset Earliest Ever Recorded in 2012

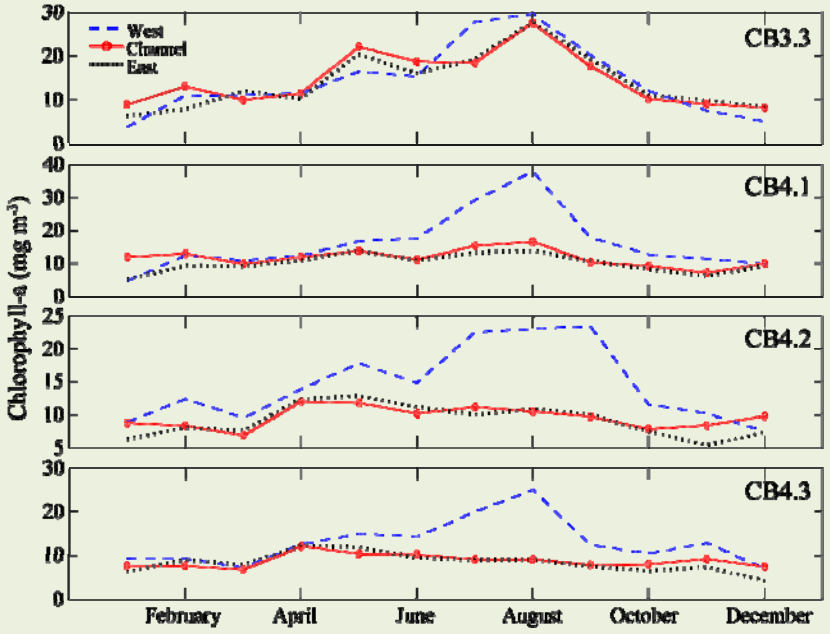
*Climate or*
*Delayed Impact of Tropical Storm Lee?*

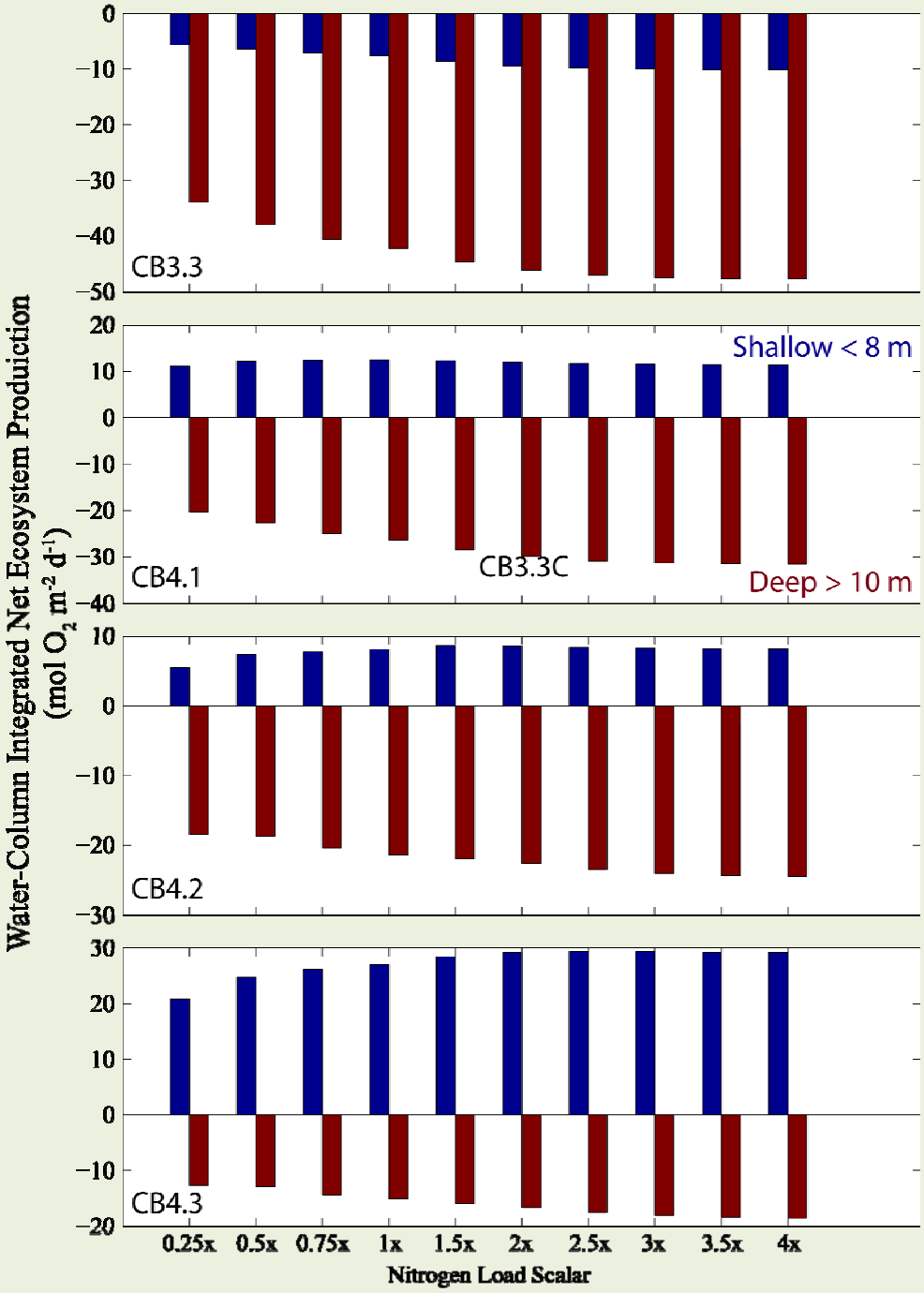


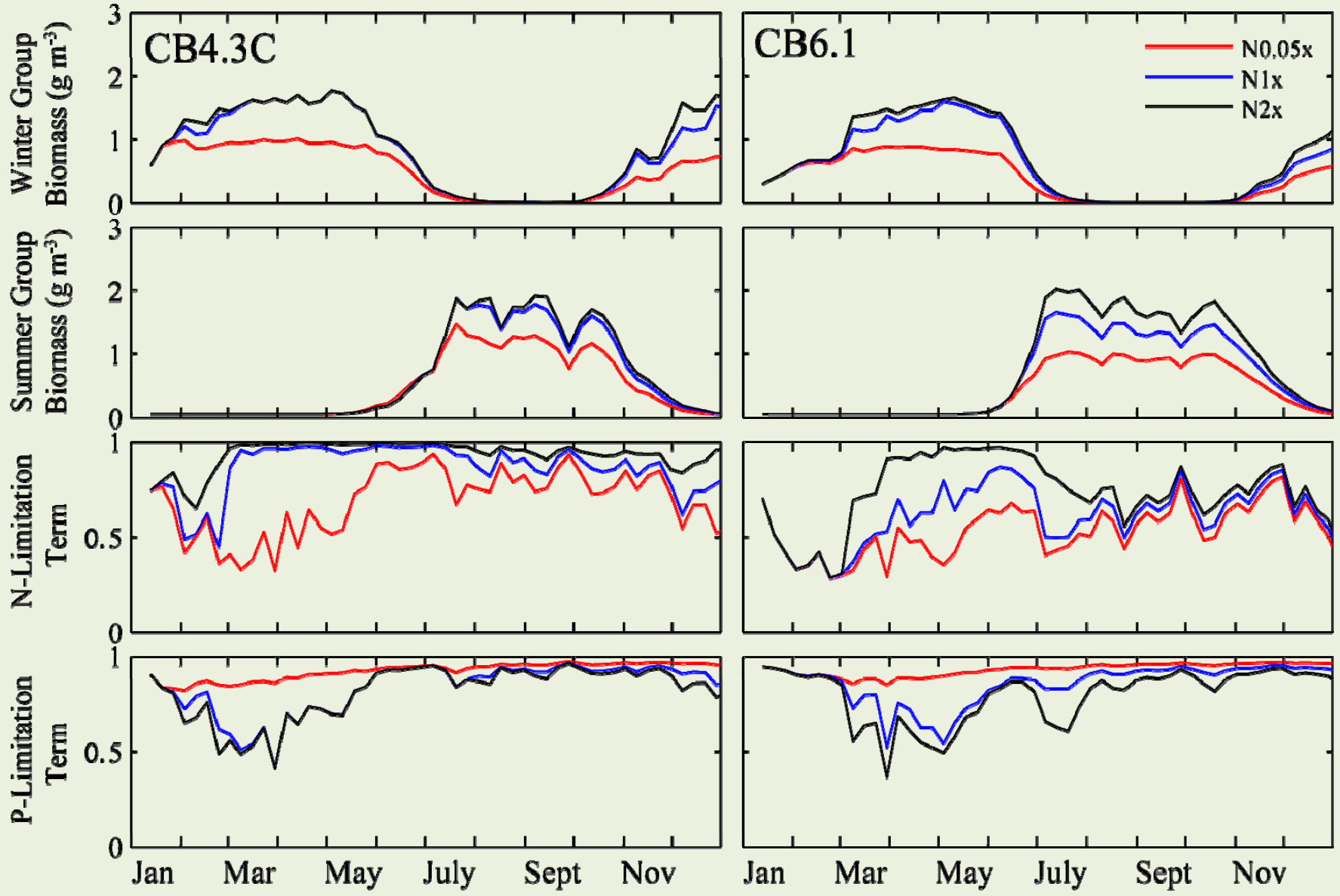



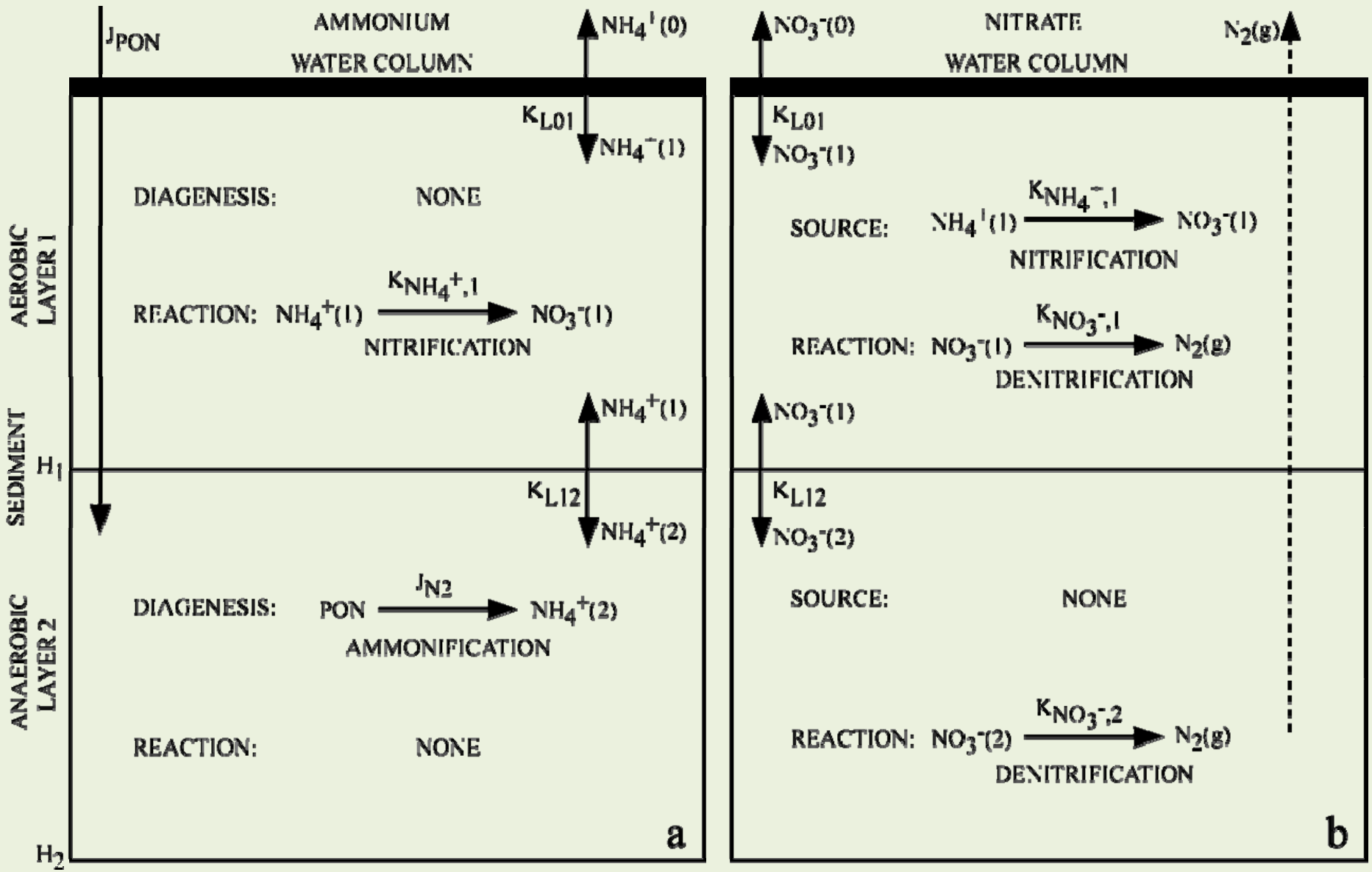

CB3.3W,C,E
CB4.1W,C,E
CB4.2W,C,E
CB4.3W,C,E
Latitude
Longitude
Depth (m)
West
Channel
East
Chlorophyll-a (mg m-3)
CB3.3
CB4.1
CB4.2
CB4.3
February
April
June
August
October
December

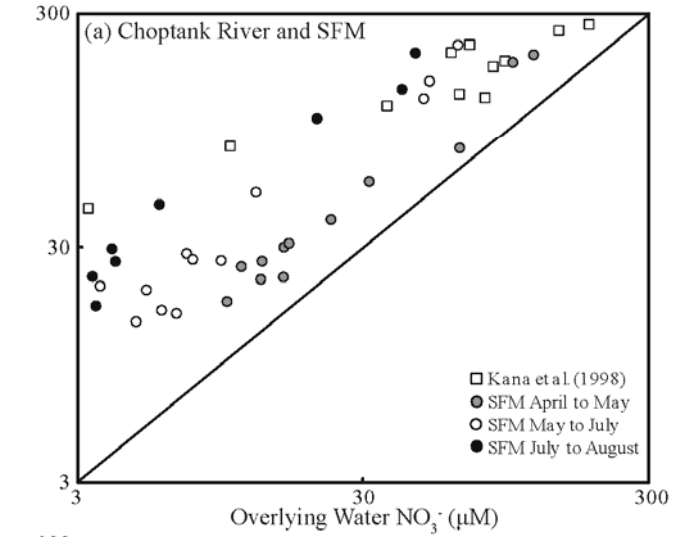

CB2.2
CB4.3C
Respiration Below Photic Layer
NPP Above Photic Layer
CB5.2
CB6.2
Annual Metabolism (mol O2 m-2 y-1)
0.25x
0.5x
0.75x
1x
1.5x
2x
2.5x
3x
3.5x
4x

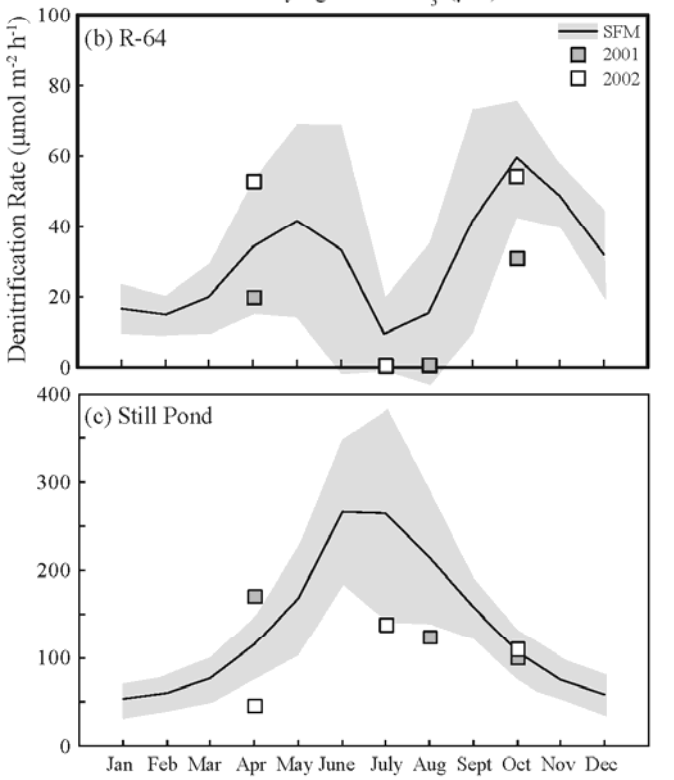

West
Channel
East
CB3.3
CB4.1
CB4.2
CB4.3
Chlorophyll-a (mg m-3)
February
April
June
August
October
December

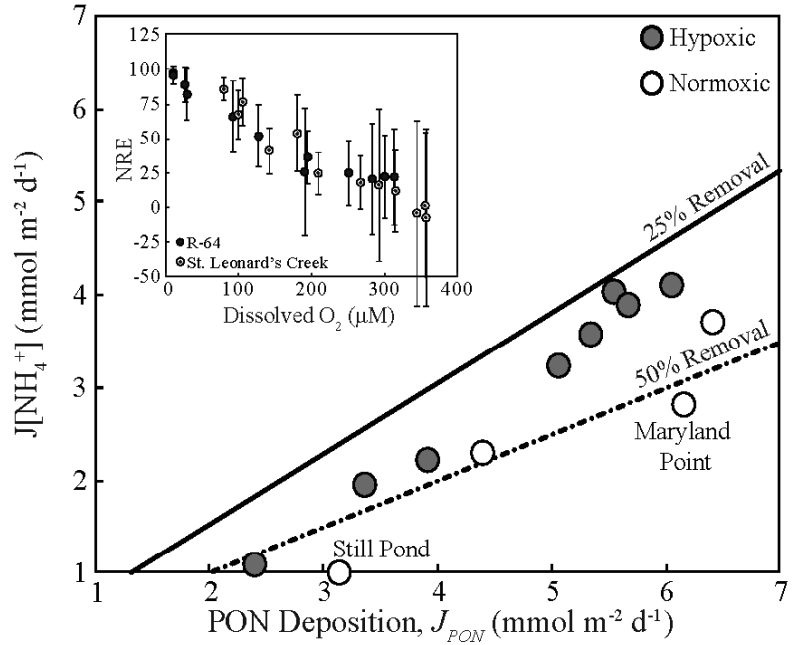

Water-Column Integrated Net Ecosystem Produiction
(mol O2 m-2 d-1)
CB3.3
CB4.1
CB3.3C
CB4.2
CB4.3
Shallow < 8 m
Deep > 10 m
0.25x
0.5x
0.75x
1x
1.5x
2x
2.5x
3x
3.5x
4x
Nitrogen Load Scalar

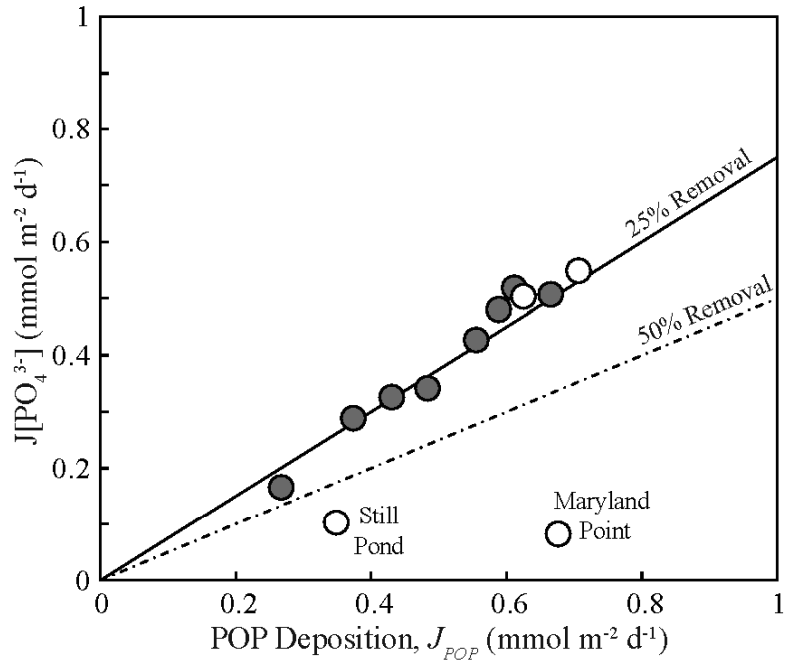

CB4.3C
CB6.1
N0.05x
N1x
N2x
Winter Group Biomass (g m-3)
Summer Group Biomass (g m-3)
N-Limitation Term
P-Limitation Term
0
1
2
3
0.5
Jan
Mar
May
July
Sept
Nov

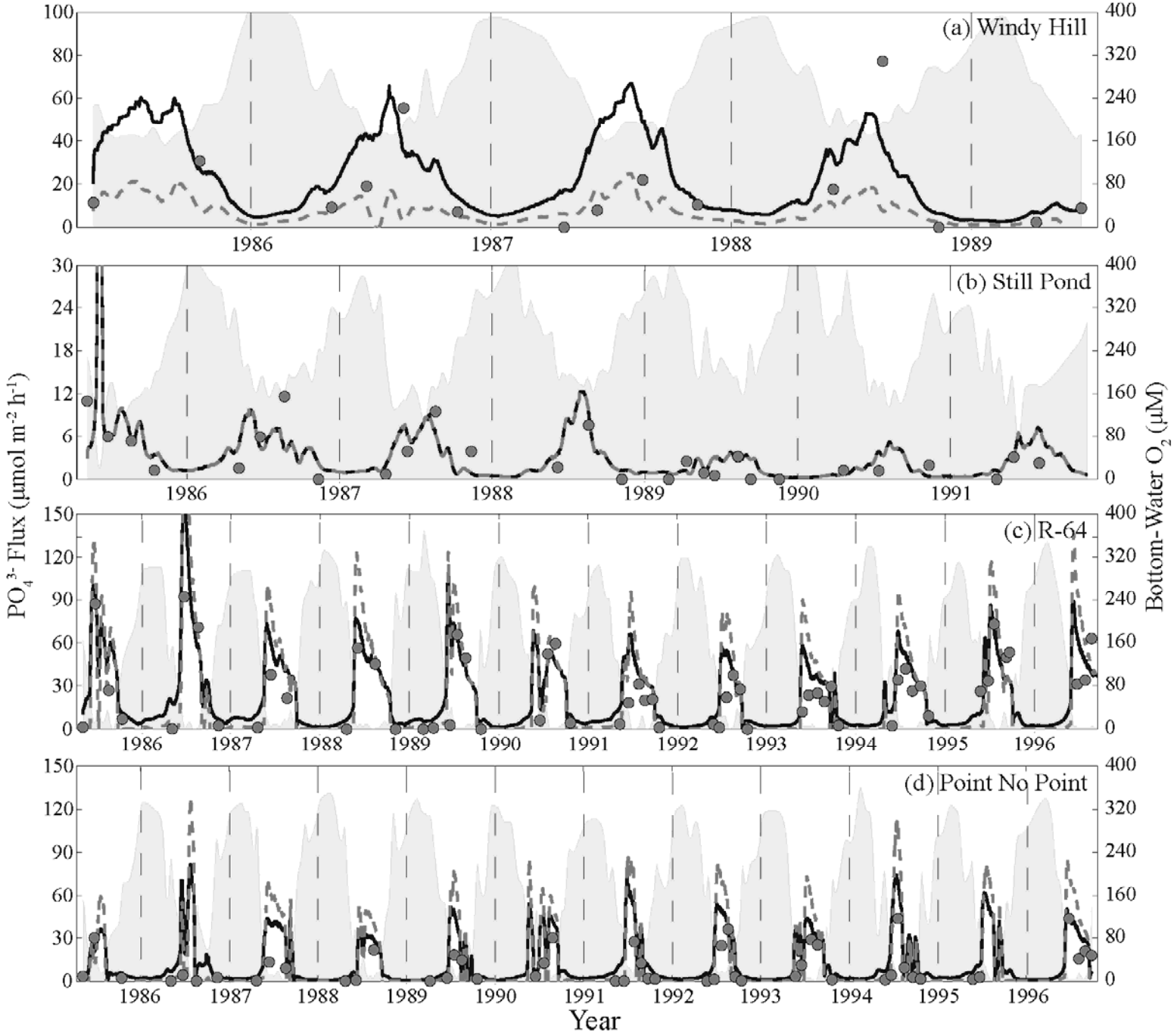

AMMONIUM
WATER COLUMN
$J_{PON}$
$NH_4^+(0)$
$K_{L01}$
$NH_4^+(1)$
DIAGENESIS: NONE
AEROBIC LAYER 1
REACTION: $NH_4^+(1) \xrightarrow{K_{NH_4^+,1}} NO_3^-(1)$
NITRIFICATION
$NH_4^+(1)$
SEDIMENT
$H_1$
$K_{L12}$
$NH_4^+(2)$
ANAEROBIC LAYER 2
DIAGENESIS: $PON \xrightarrow{J_{N2}} NH_4^+(2)$
AMMONIFICATION
REACTION: NONE
$H_2$
a
$NO_3^-(0)$
NITRATE
WATER COLUMN
$N_2(g)$
$K_{L01}$
$NO_3^-(1)$
SOURCE: $NH_4^+(1) \xrightarrow{K_{NH_4^+,1}} NO_3^-(1)$
NITRIFICATION
REACTION: $NO_3^-(1) \xrightarrow{K_{NO_3^-,1}} N_2(g)$
DENITRIFICATION
$NO_3^-(1)$
$K_{L12}$
$NO_3^-(2)$
SOURCE: NONE
REACTION: $NO_3^-(2) \xrightarrow{K_{NO_3^-,2}} N_2(g)$
DENITRIFICATION
b


(a) Choptank River and SFM
Kana et al. (1998)
SFM April to May
SFM May to July
SFM July to August
Overlying Water $NO_3^-$ (μM)

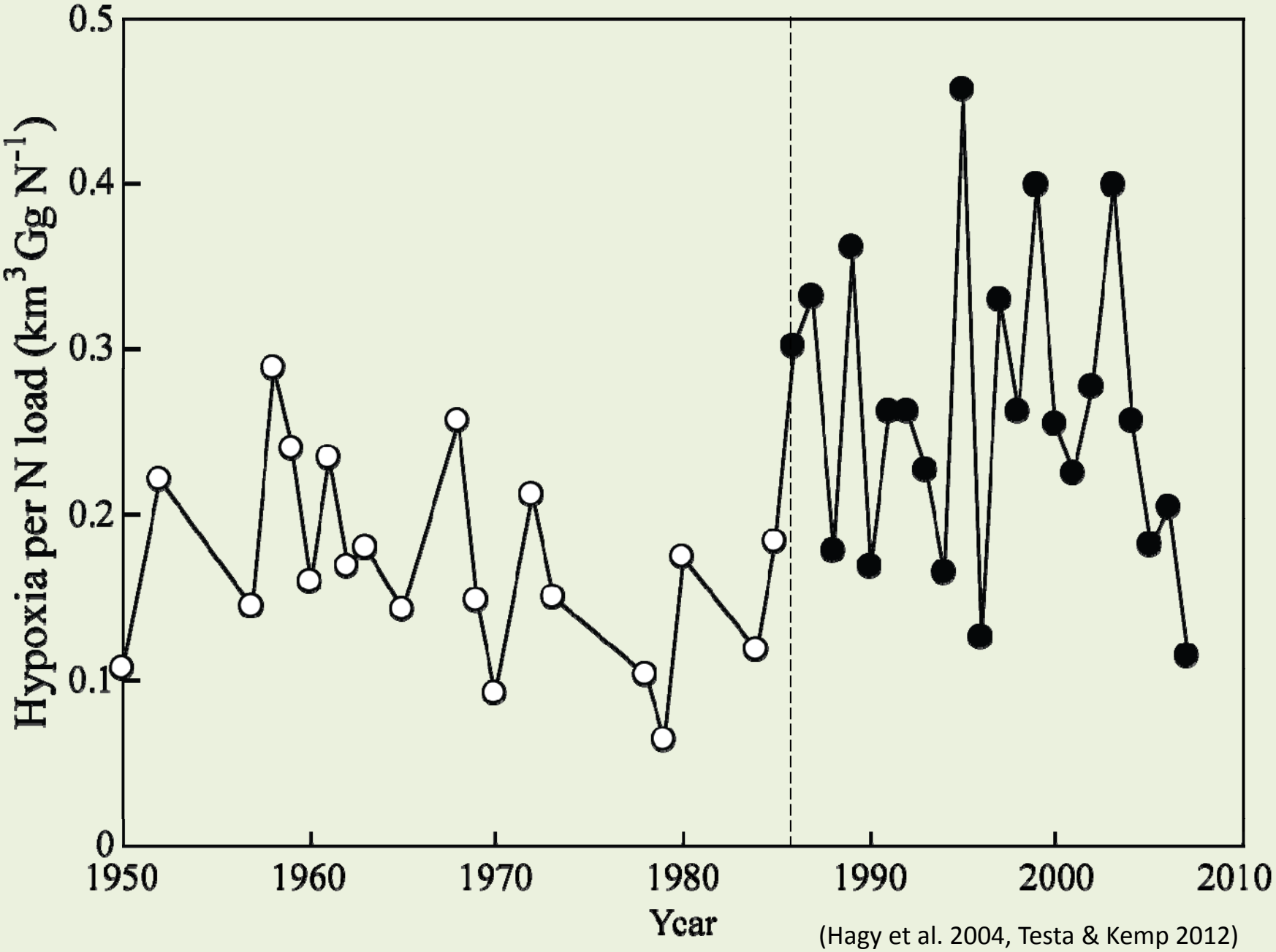

(b) R-64
SFM
2001
2002
Denitrification Rate (μmol m$^{-2}$ h$^{-1}$)
(c) Still Pond
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Hypoxic
Normoxic
25% Removal
50% Removal
Maryland Point
Still Pond
NRE
R-64
St. Leonard's Creek
Dissolved $O_2$ (μM)
J[$NH_4^+$] (mmol m$^{-2}$ d$^{-1}$)
PON Deposition, $J_{PON}$ (mmol m$^{-2}$ d$^{-1}$)


25% Removal
50% Removal
Still Pond
Maryland Point
J[$PO_4^{3-}$] (mmol m$^{-2}$ d$^{-1}$)
POP Deposition, $J_{POP}$ (mmol m$^{-2}$ d$^{-1}$)


(a) Windy Hill
(b) Still Pond
(c) R-64
(d) Point No Point
$PO_4^{3-}$ Flux (μmol m$^{-2}$ h$^{-1}$)
Bottom-Water $O_2$ (μM)
Year
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996

# Long-Term Increase in Chesapeake Bay Hypoxia




(Hagy et al. 2004, Testa & Kemp 2012)

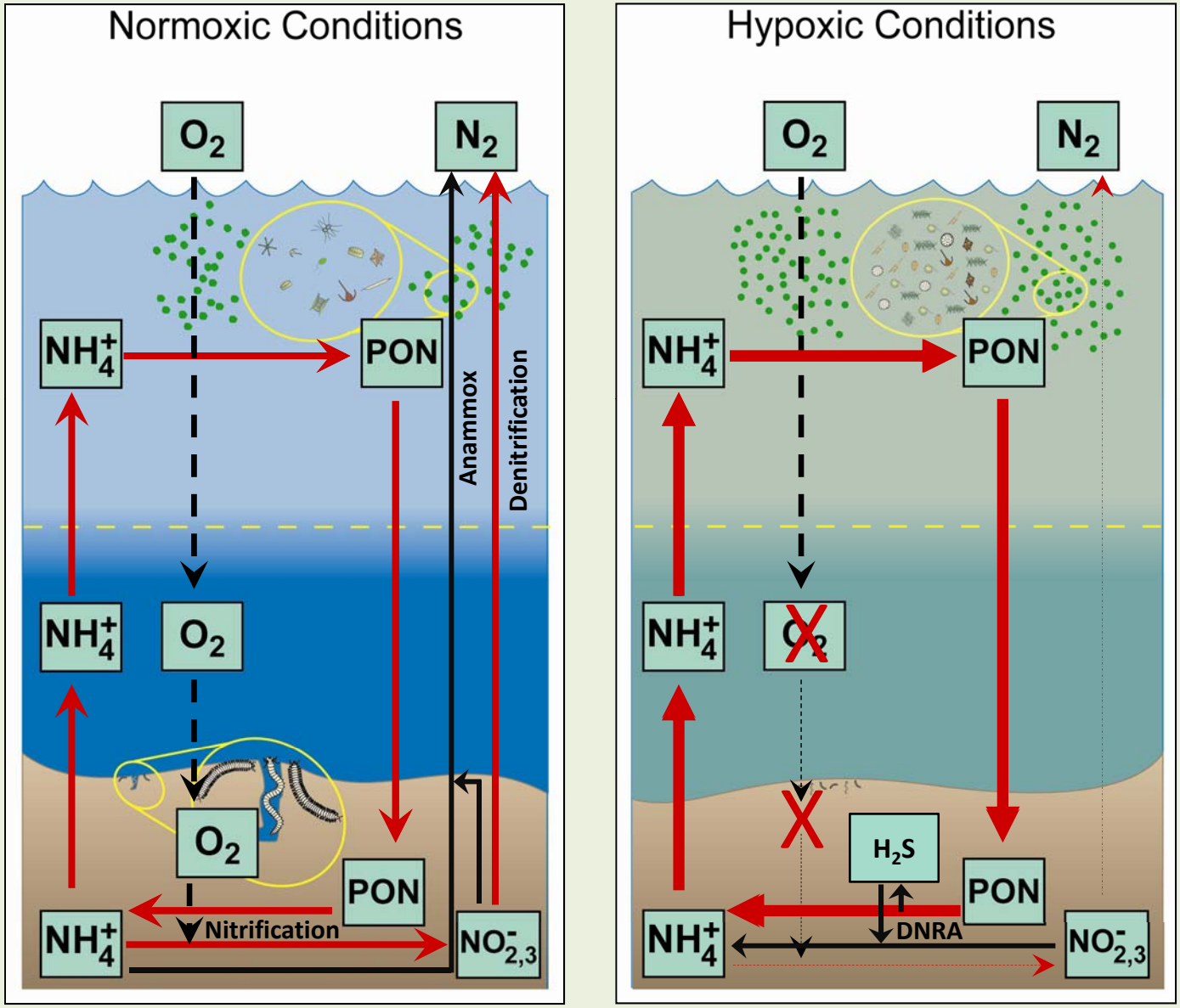
# *Hypotheses to Explain Apparent Regime Shift*

- ***Artifact Hypotheses*: Modern monitoring program began in 1985 with increased data density: interpolation artifacts = higher computed volumes**

- ***Climate Hypotheses*: Enhanced hypoxia linked climatic changes, such as increased temperature and or flow or changes in wind patterns**

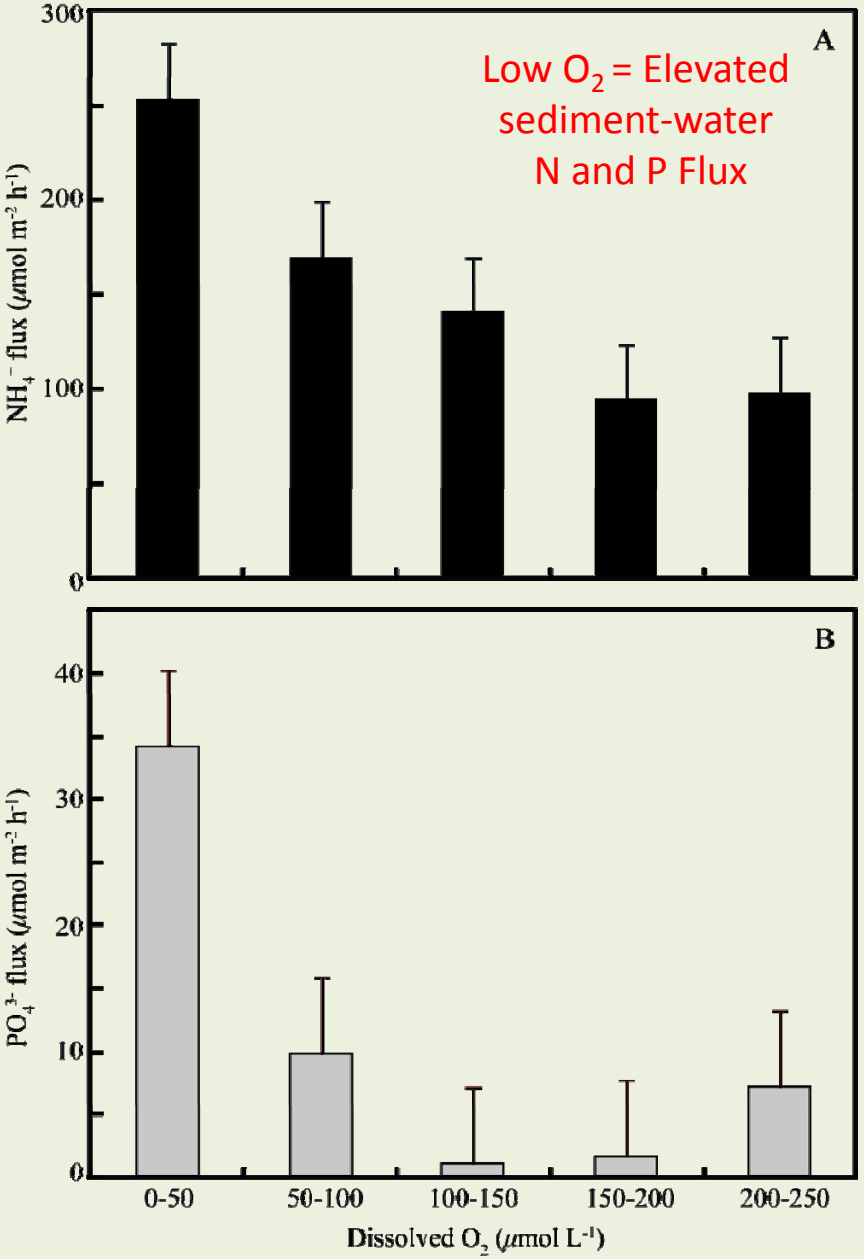
- ***Ecological Hypotheses*: More hypoxia per unit N load due to reduced grazing (oysters), reduced nutrient retention (SAV, marshes), or *enhanced nutrient recycling under low* $O_2$**

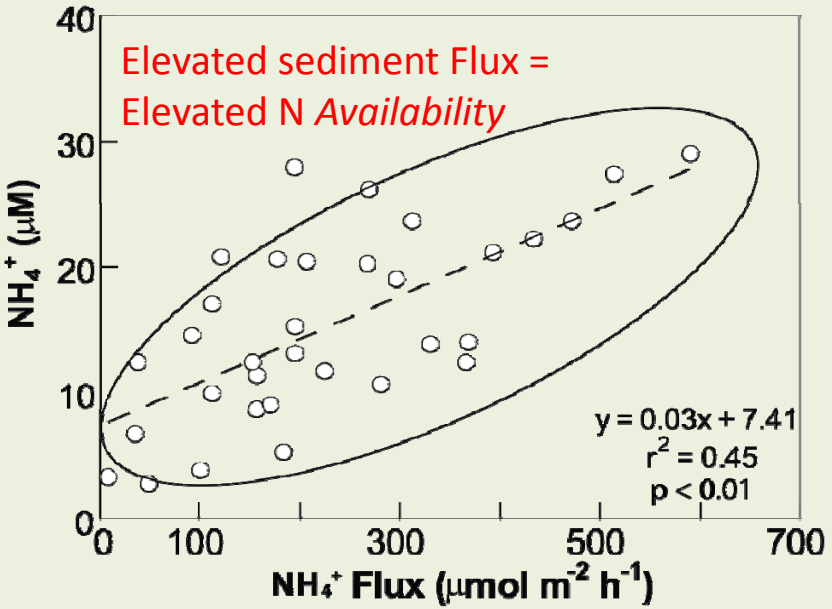
# Conceptual Model of $O_2$ Interactions with N-Cycle




*Similar impact on phosphorus, but different mechanisms*

# Observations Reveal Hypoxia Stimulation of Nutrient Cycling

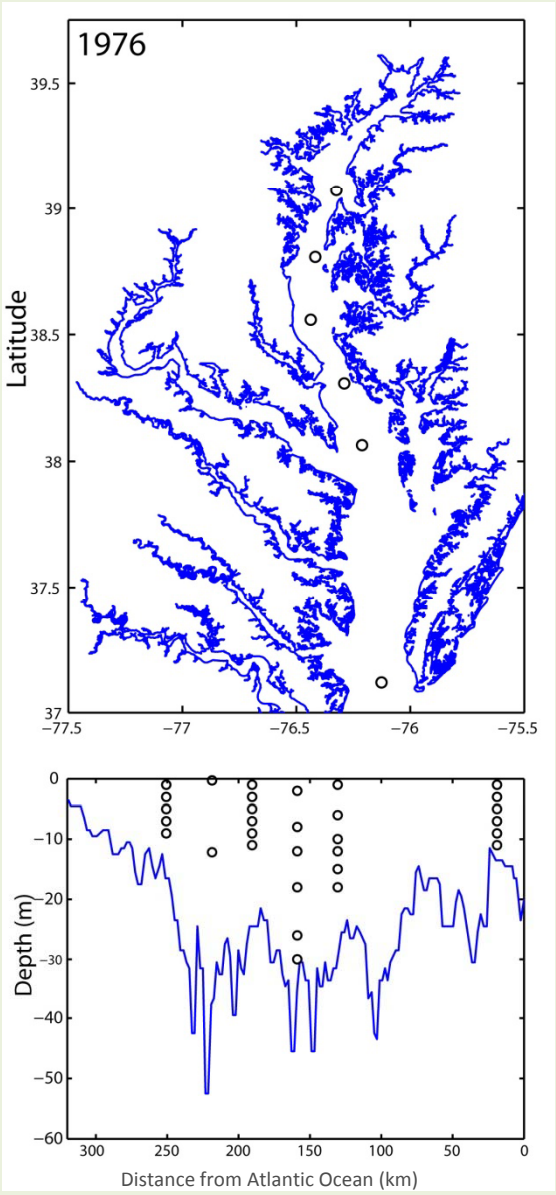


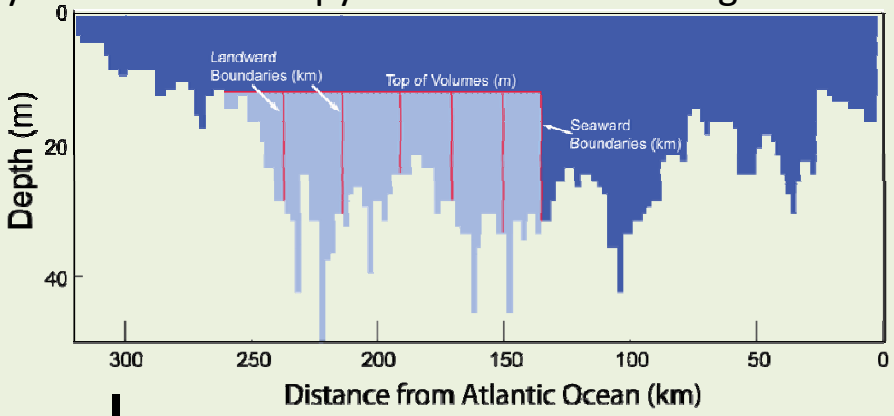

(Testa and Kemp 2012, L&O)

# Computing $NH_4^+$-N Mass in Chesapeake Bay

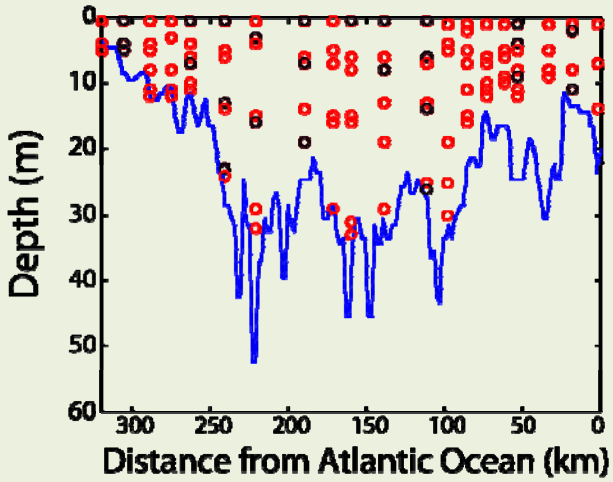
(1) $NH_4^+$ Observations in summer 1965-1980 and 1985-2007

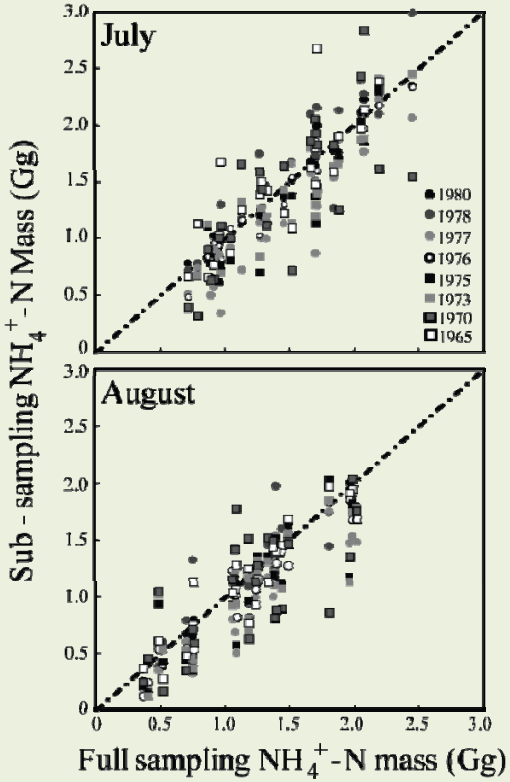



2) Interpolate $NH_4^+$ observations to 3D grid (kriging) and compute monthly mass below the pycnocline in several regions

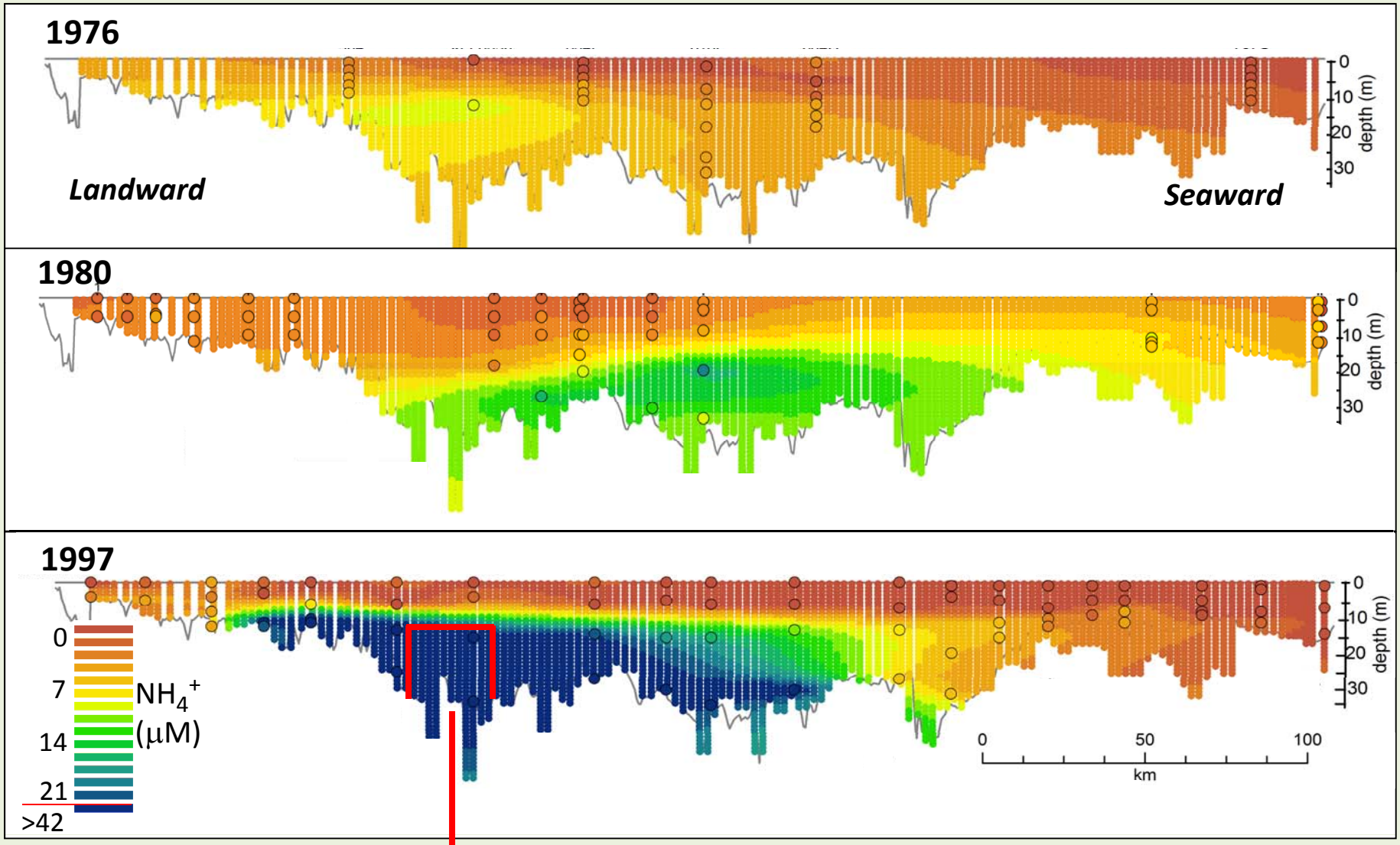



3) Sub-sample modern data at historical density to test sampling bias



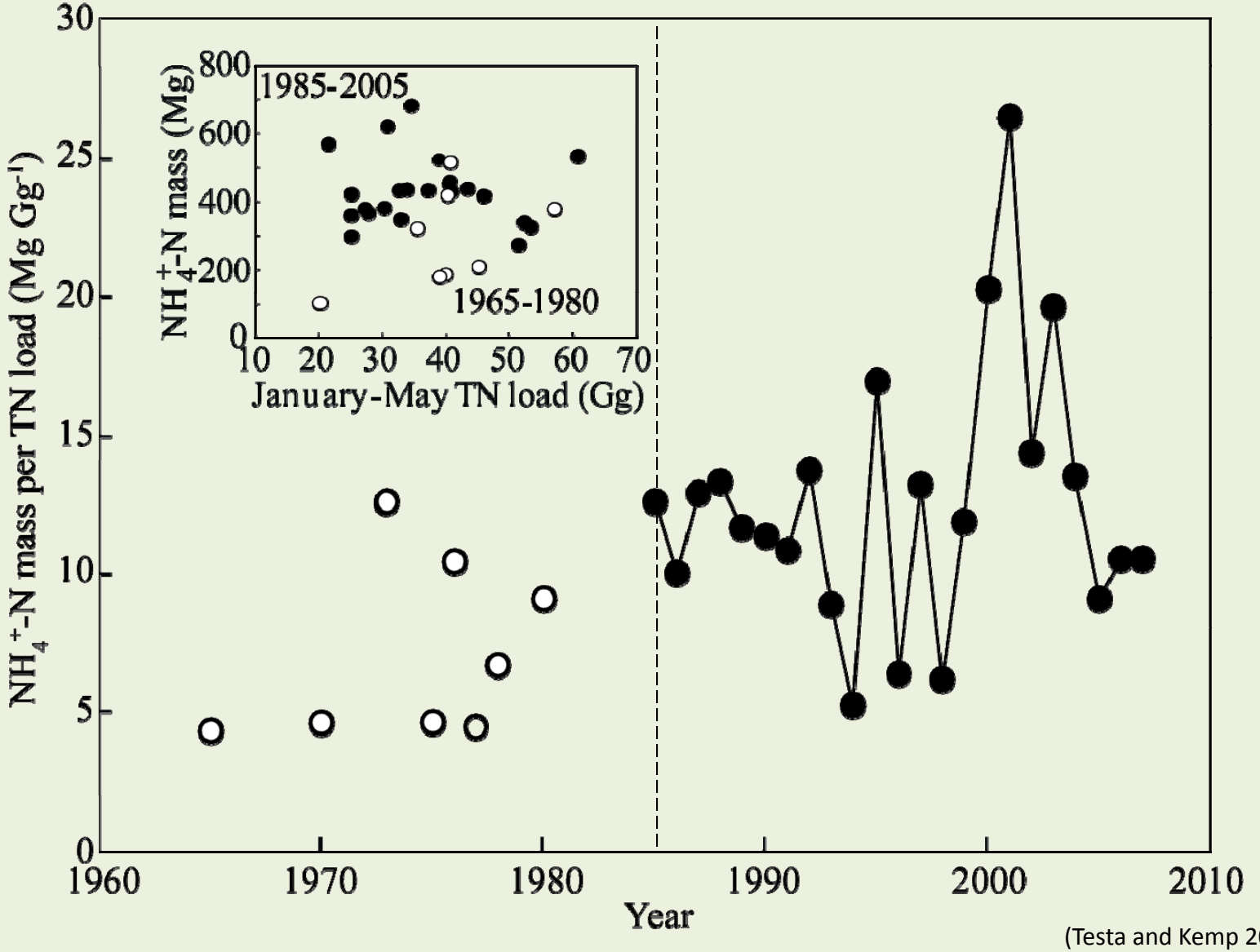



# Decadal Change in July Distribution of [$NH_4^+$]




$$\frac{NH_4^+\text{-N Mass}}{\text{TN Load}} = \text{Recycling Index}$$

# Apparent Long-Term Increase in $NH_4^+$ Mass/TN Load, but Data Sparse Prior to Regime Shift

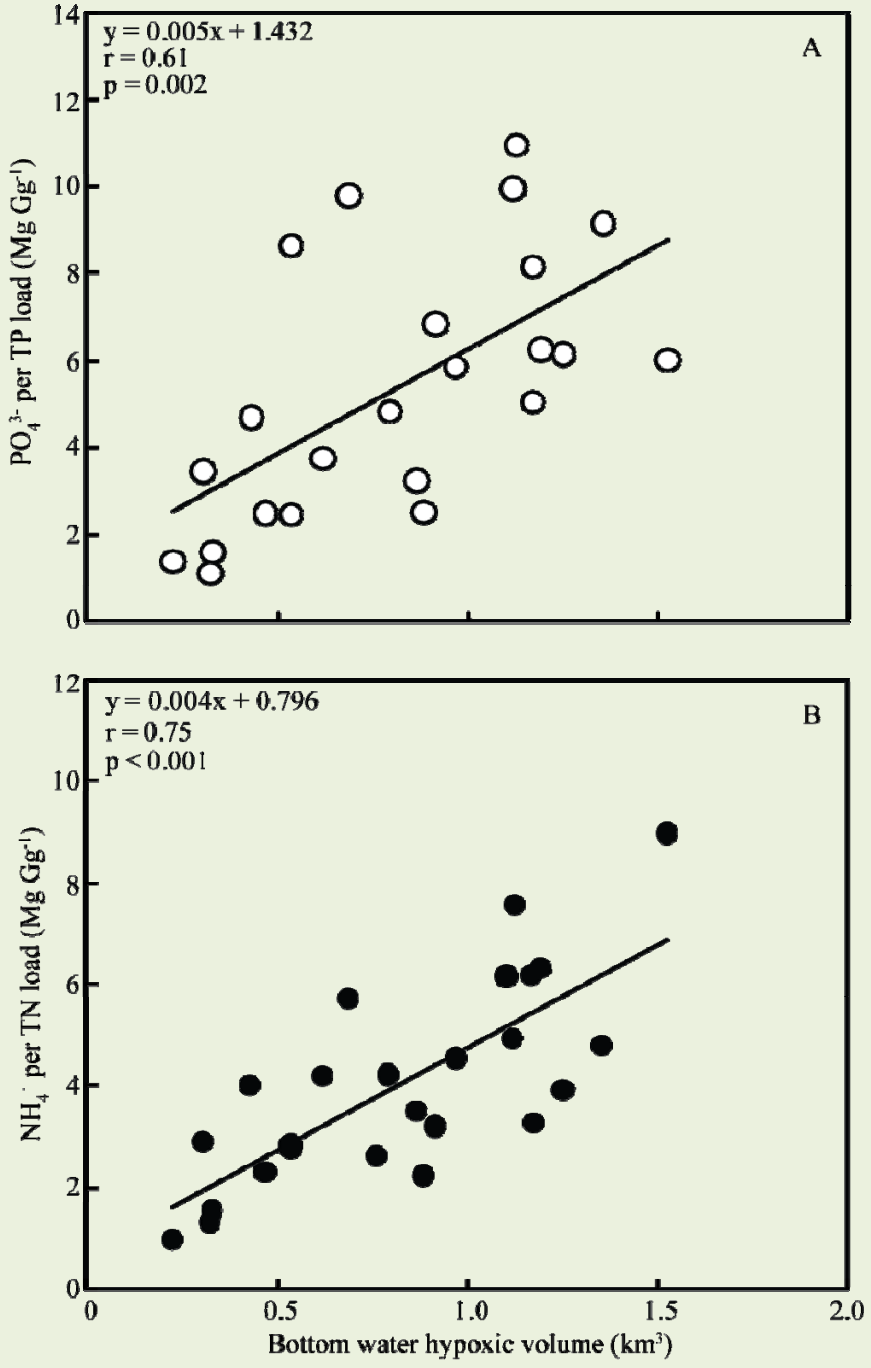



(Testa and Kemp 2012, L&O)

# Nutrient Pools per Load vs. Hypoxia Volume

- In the upper-middle regions of Chesapeake Bay, years with ***higher hypoxic volumes*** have a ***larger N and P pool*** relative to the winter-spring N and P Load

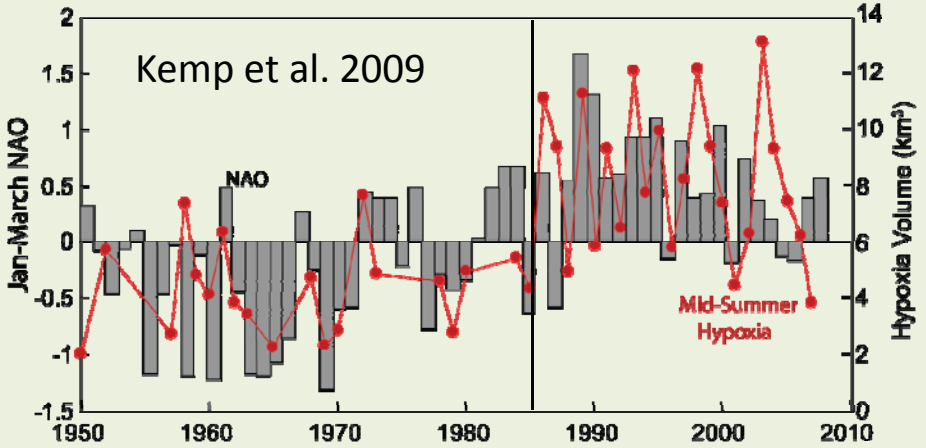
- Thus hypoxia increases nutrient availability in Chesapeake Bay in specific places and time

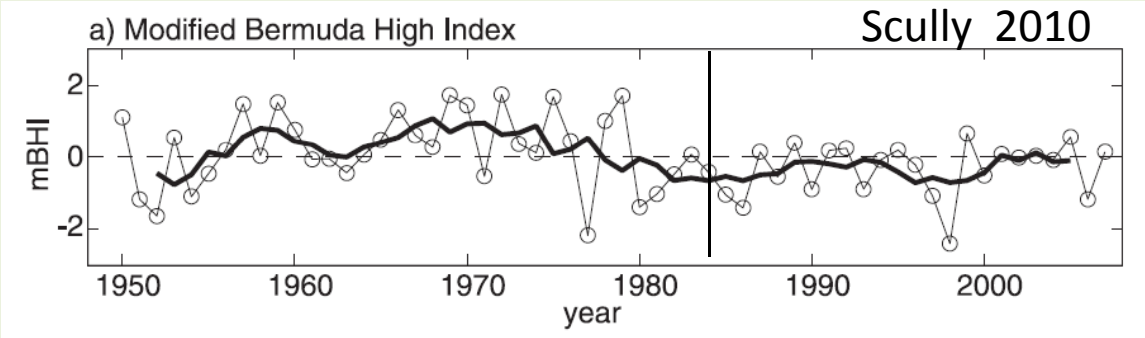


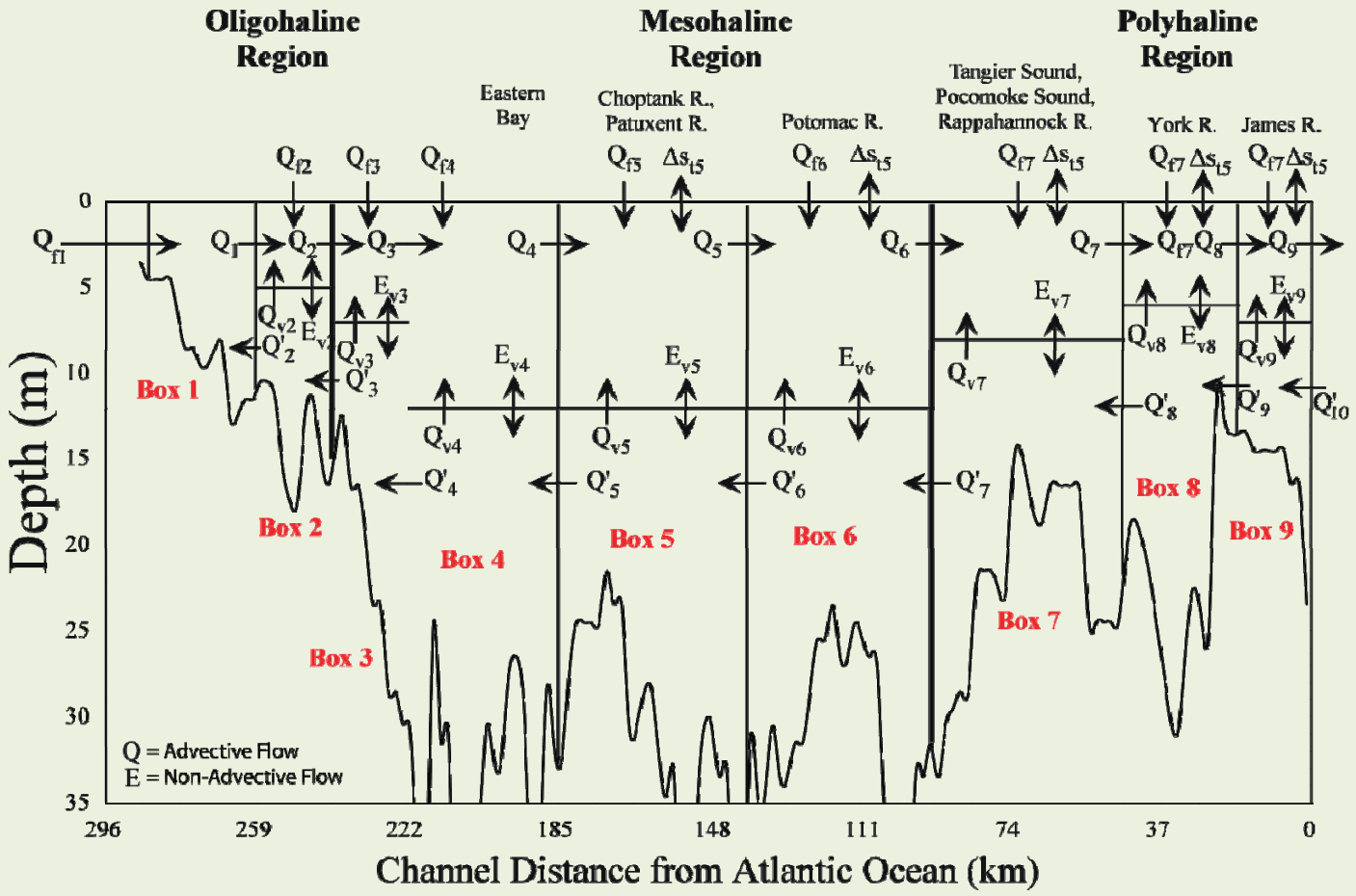

(Testa and Kemp 2012, L&O)

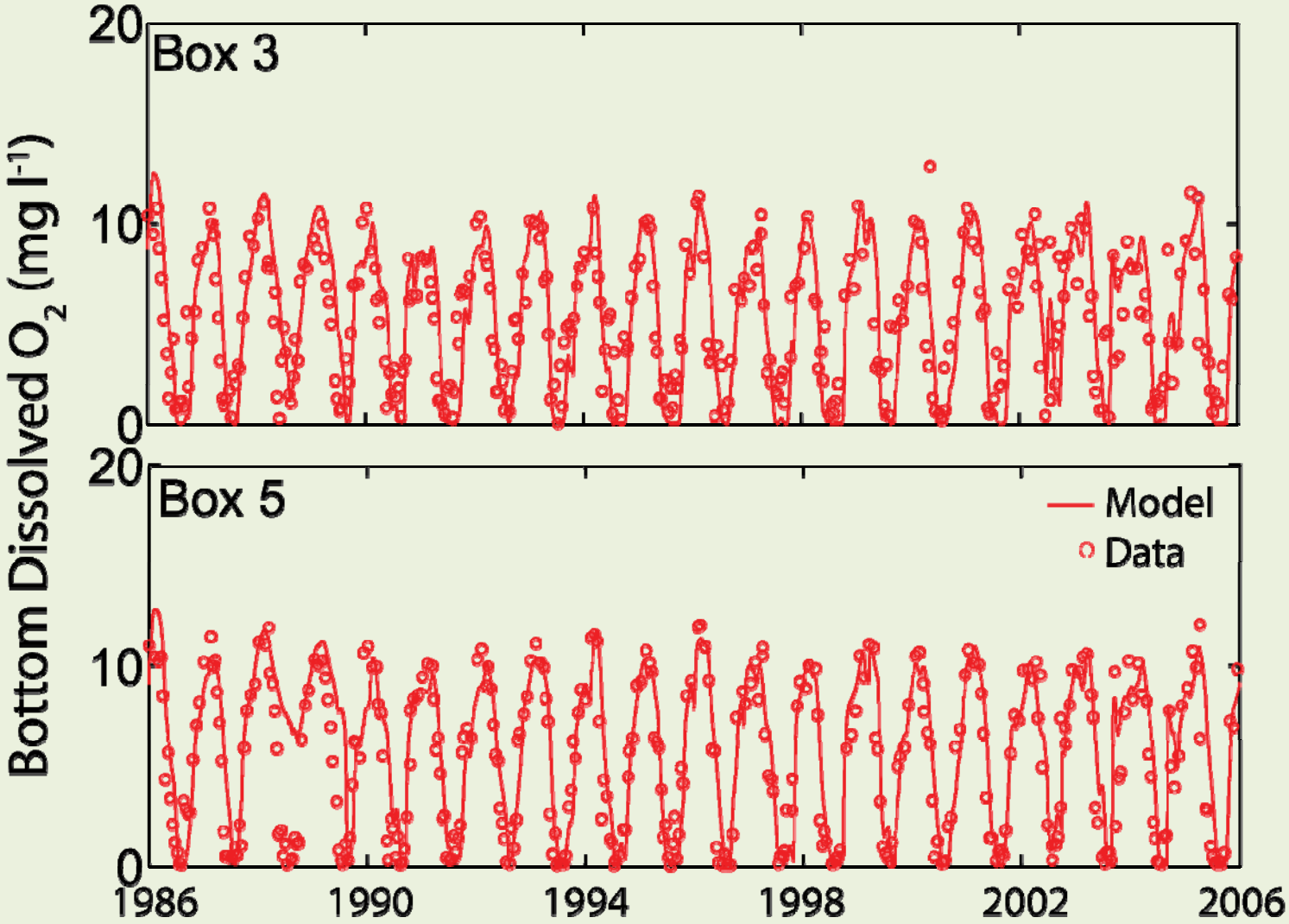
# Concluding Comments

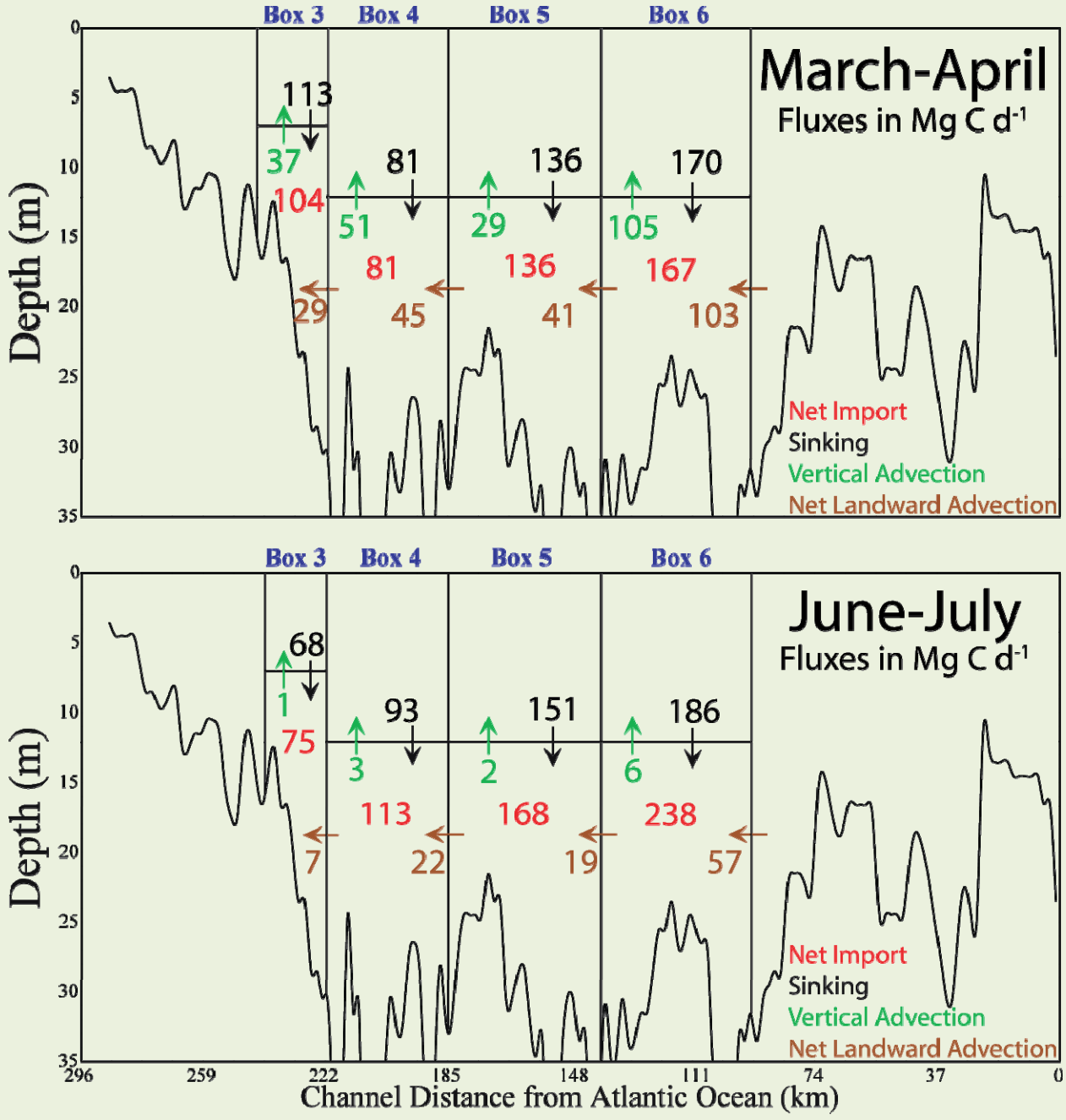
- A “regime shift” in Chesapeake hypoxic volume occurred in mid-1980s
- Hypoxia increased N & P recycling , generating higher nutrient availability for a given nutrient load – this is the first display of this feedback at the system scale and likely supported regime shift
- Subsequent research has suggested alternative explanations for the regime shift




Oligohaline Region
Mesohaline Region
Polyhaline Region
Eastern Bay
Choptank R., Patuxent R.
Potomac R.
Tangier Sound, Pocomoke Sound, Rappahannock R.
York R.
James R.
Box 1
Box 2
Box 3
Box 4
Box 5
Box 6
Box 7
Box 8
Box 9
Q = Advective Flow
E = Non-Advective Flow
Depth (m)
Channel Distance from Atlantic Ocean (km)
0
5
10
15
20
25
30
35
296
259
222
185
148
111
74
37
0


Box 3
Box 5
Model
Data
Bottom Dissolved $O_2$ (mg $l^{-1}$)
20
10
0
1986
1990
1994
1998
2002
2006


Box 3
Box 4
Box 5
Box 6
March-April
Fluxes in Mg C d-1
113
37
104
81
51
81
29
45
136
29
136
41
170
105
167
103
Net Import
Sinking
Vertical Advection
Net Landward Advection
Depth (m)
0
5
10
15
20
25
30
35
Box 3
Box 4
Box 5
Box 6
June-July
Fluxes in Mg C d-1
68
1
75
93
3
113
151
2
168
186
6
238
7
22
19
57
Net Import
Sinking
Vertical Advection
Net Landward Advection
Depth (m)
296
259
222
185
148
111
74
37
0
Channel Distance from Atlantic Ocean (km)