Spatial and Temporal Patterns in Chesapeake Bay Resource Limitation

Qian Zhang (UMCES/CBPO)
and the Nutrient Limitation Team

July 17, 2019

Team Overview

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ICPRB	Claire Buchanan
MDDNR	Renee Karrh
CBPO	Qian Zhang Jennifer Keisman Emily Trentacoste Rebecca Murphy Cuiyin Wu Peter Tango Richard Tian Breck Sullivan

- Literature review
- Data compilation and analysis
- Conference calls (n=7)
- Email/phone discussions

Kemp et al. (2005)

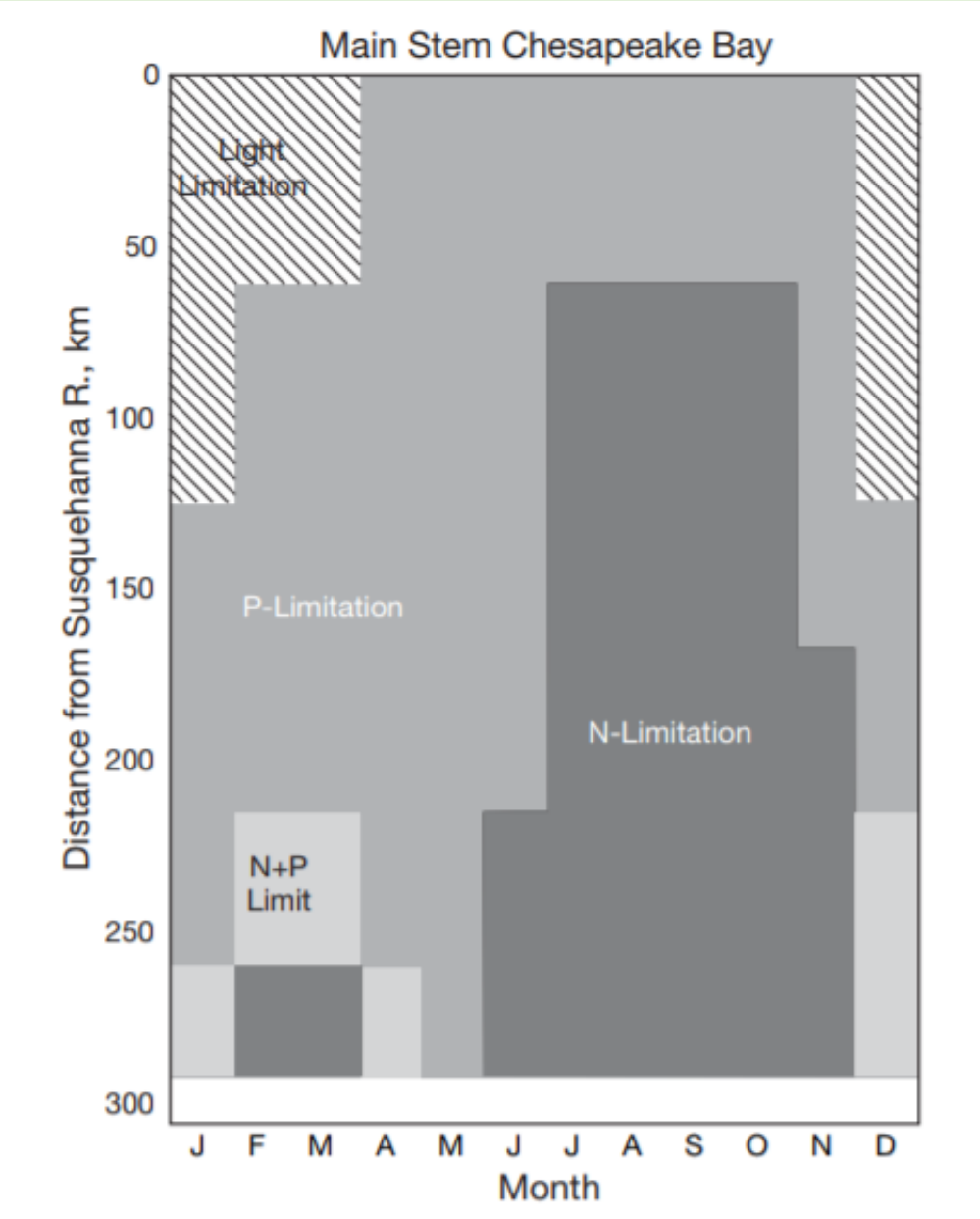
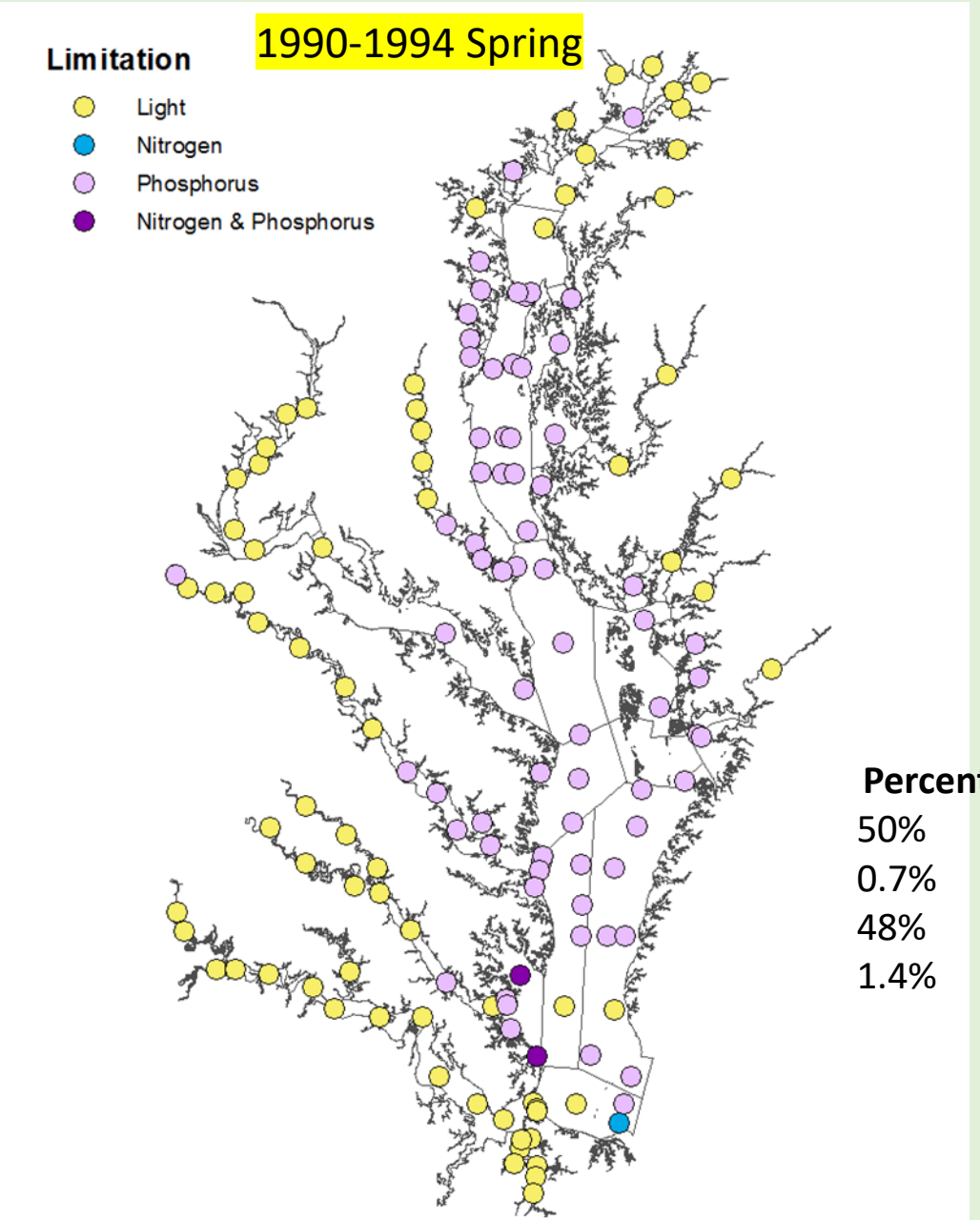
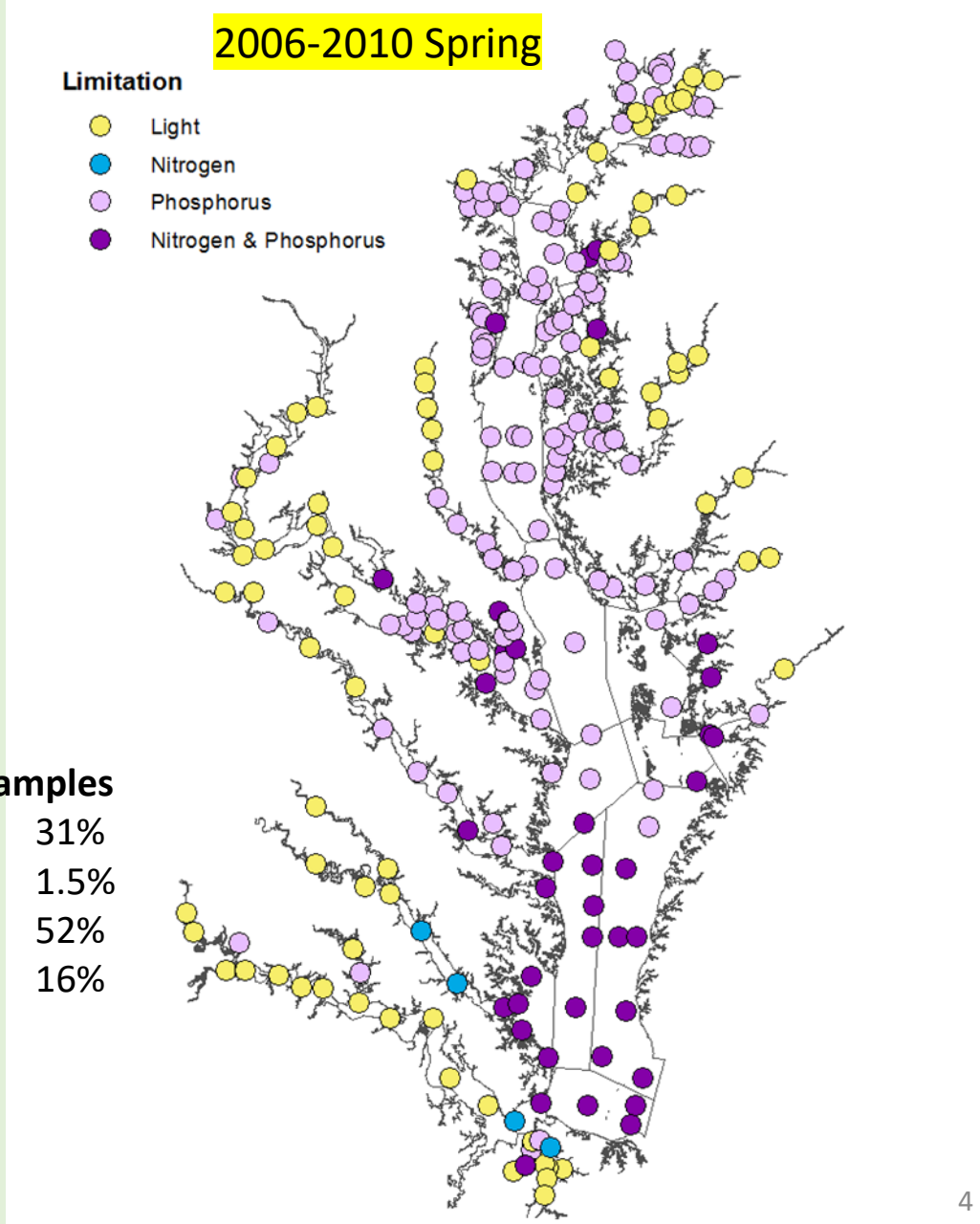


Figure 16: Seasonal and regional variations in nitrogen, phosphorous, or light limitation for phytoplankton growth synthesized from bioassay experiments conducted in mainstem of Chesapeake Bay between 1992 and 2002.

- N- and P-limitations were defined as increases in phytoplankton productivity (PP) and biomass (PB) with N and P, respectively, additions to experimental containers;
- N+P limitation was defined as increases in PP and PB only with simultaneous additions of N plus P.
- Light-limitation was defined by the lack of significant responses to any combination of N and/or P addition, combined with a uniform response of increased PP and PB during incubations for controls and all treatments relative to initial ambient conditions.

CBP Long-term Tidal Monitoring Data





Percent of samples

50%	Light	31%
0.7%	N	1.5%
48%	P	52%
1.4%	N&P	16%

Hypothesis

Given the long-term efforts to reduce N and P inputs to the Bay, resource limitation patterns in the Bay may have changed temporally and spatially.

Objectives

- To re-visit the classical Chesapeake Bay resource limitation diagram of Kemp et al. (2005).
- To relate bioassay data collected by Fisher et al. to the CBP tidal monitoring data in the concurrent period of 1992-2002.
- To investigate changes in resource limitation in the mainstem and selected tributaries using the tidal monitoring data.

Roadmap

Step	Tasks	Goals
1	Tom Fisher's resource limitation diagram	More fully understand the temporal and spatial details of the bioassay data in Figure 16 of Kemp et al. (2005) to help inform our current analysis with the CBP tidal monitoring data.
2	Mainstem diagram (1992-2002)	Determine an approach that can reasonably produce a resource limitation diagram for 1992-2002 that mimics Figure 16.
3	Mainstem diagram (2006-2013)	Use the determined approach to produce a resource limitation diagram for a recent period and compare with the early period.
4	Tidal tributary diagram	Extend the analysis from the mainstem to selected tidal tributaries for which bioassay data are available.
5	Explanation	Explain the patterns and changes of resource limitation using information regarding watershed loads and tidal WQ trends.

Roadmap

1. Fisher's resource limitation diagram
2. Mainstem diagram (1992-2002)
3. Mainstem diagram (2006-2013)
4. Tidal tributary diagram
5. Explanation & mechanisms

Fisher et al. bioassay data

Vol. 303: 1–29, 2005 | MARINE ECOLOGY PROGRESS SERIES Mar Ecol Prog Ser | Published November 21

FEATURE ARTICLE: REVIEW

Eutrophication of Chesapeake Bay: historical trends and ecological interactions

W. M. Kemp[1,*], W. R. Boynton[2], J. E. Adolf[1], D. F. Boesch[3], W. C. Boicourt[1], G. Brush[4], J. C. Cornwell[1], T. R. Fisher[1], P. M. Glibert[1], J. D. Hagy[5], L. W. Harding[1], E. D. Houde[2], D. G. Kimmel[1], W. D. Miller[1], R. I. E. Newell[1], M. R. Roman[1], E. M. Smith[6], J. C. Stevenson[1]

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[6]University of South Carolina, Department of Biology, Columbia, South Carolina 29208, USA

Vol. 82: 51–63, 1992 | MARINE ECOLOGY PROGRESS SERIES Mar. Ecol. Prog. Ser. | Published May 14

Nutrient limitation of phytoplankton in Chesapeake Bay

Thomas R. Fisher[1], Emily R. Peele[1,*], James W. Ammerman[2,**], Lawrence W. Harding, Jr[3]

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[2] Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964, USA
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Marine Biology (1999) 133: 763–778

T. R. Fisher · A. B. Gustafson · K. Sellner · R. Lacouture · L. W. Haas · R. L. Wetzel · R. Magnien · D. Everitt · B. Michaels · R. Karrh

Spatial and temporal variation of resource limitation in Chesapeake Bay

Estuaries Vol. 19, No. 2B, p. 371–385 June 1996

Scales of Nutrient-Limited Phytoplankton Productivity in Chesapeake Bay

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Maryland Department of Natural Resources Chesapeake Bay Water Quality Monitoring Program

Nutrient/Bioassay Component

Covering the Period
August 1990 - May 2005

2005 Interpretive Final Report

Fisher et al. bioassay data

No.	Publication	Year	Outlet	Content	Period	Spatial Coverage	Limitation	References
1	Kemp et al.	2005	MEPS	Figure 16	Bioassay 1992-2002	unclear	N, P, N+P, Light	Fisher et al., 1992a, 1999, 2003
2	Fisher et al.	1999	Mar. Bio.	All tables and figures	Bioassay 1988-1994	18 stations (mainstem + tribs)	N, P, N+P, Light	Fisher et al., 1992a, 1992b
3	Boynton	2000	Book Chapter	Figure 8	Bioassay 1990-1993	unclear	N, P, N+P, Light	Fisher et al., 1992b
4	Malone et al.	1996	Estuaries	Figure 10	Bioassay	5 stations (mainstem)	N, P, N+P, Light	Fisher et al., 1992a, 1992b
5	Fisher et al.	1992a	MEPS	Table 3, 5	Bioassay 1987 only	6 stations (mainstem)	N, P, N+P, Light	Fisher et al., 1992b
6	Fisher et al.	2005	MDE Report	All tables and figures	Bioassay 1990-2005	16 stations (mainstem + tribs)	N, P, N+P, Light	Fisher et al., 1992a, 1992b, 1999a, 199b, 2003, 2004
7	Fisher et al.	2003	MDE Report	*Not found*	Bioassay 1990-2002	???	???	???
8	Fisher et al.	1999	MDE Report	*Not found*	Bioassay 1990-1998	???	???	???
9	Fisher et al.	1992b	MDE Report	*Not found*	Bioassay 1990-1993	???	???	???
10	Fisher et al.	1997	MDDNR Report	Table 1	Bioassay 1990-1996	9 stations (mainstem + tribs)	N, P, N+P, Light	???
11	Fisher et al.	1988	ECSS	Table 7	Water-column data 1982-1983	5 stations (mainstem)	N, P, Si	Fisher et al., 1992b

Fisher et al. bioassay data

Table 1. Station descriptions and sampling schedule for bioassays of resource limitation of phytoplankton growth. The number of samples at each station varied due to the sampling schedule (e.g., tidal fresh stations were sampled only 3 times per year), bad weather, boat mishaps, etc., and numbers of bioassays are cumulative since August, 1990. Turkey Point was sampled beginning in 2000, and several stations marked with "#" were sampled only in 2004. We discontinued sampling in Baltimore Harbor in 1993. Abbreviations: tidal fr. = tidal fresh.

sampling area	description	MDE sta.ID	sampling day	our ID#	# of Samples
Main Bay stations	Turkey Pt	CB 2.1	wed.	11	13
	Bay bridge	CB 3.3C	tues.	4	117
	R64 buoy	CB 4.3C	tues.	5	130
	Point-no-point	CB 5.2	mon.	1	131
Baltimore Harbor	Baltimore H.	WT 5.1	NA	8	26
Patuxent (tidal fresh)	Nottingham	TF1.5	thurs.	9	66
(tidal fresh)	Jug Bay	— #	thurs.	13	3
(mesohaline)	Jack Bay	LE1.1	thurs.	10	154
Potomac (tidal fresh)	Indian Head	TF2.3	mon.	2	64
(mesohaline)	Ragged Pt	LE2.2	mon.	3	143
Choptank (tidal fresh)	Ganey Wharf	ET5.1	tue.	6	64
(mesohaline)	Cambridge	ET5.2	tue.	7	159
Chester (tidal fresh)	Rt.290 Br.	ET4.1 #	varies	15	3
(mesohaline)	Deep Landing	— #	varies	14	3
Bush (tidal fresh)	Otter Point Cr.	— #	varies	16	2
(oligohaline)	E of Gum Pt.	WT1.1	varies	17	2
Total number	Stations:	16		Bioassays:	1070

Fisher et al. bioassay data

Table 4. Weighting factors used to compute indices of N, P, and light limitation of algal growth in Chesapeake Bay using nutrient addition bioassays. Each classified bioassay (see Table 2 and Fig. 2) contributed the amounts shown below to the index, which was then divided by the total number of bioassays. Each index of N, P, or light limitation = $(\sum w)/n$, where w is the weighting factor assigned to each of the n bioassays. This results in an index ranging from 0 (no limitation) to 1 (completely limited). Abbreviations: EXN = exclusive N; PRN = primary N; BNP = balanced NP; PRP = primary P; EXP = exclusive P; NOR = no response to added nutrients.

	weighting factors					
Type of Index	EXN	PRN	BNP	PRP	EXP	NOR
N limitation	1.00	0.75	0.50	0.25	0.00	0.00
P limitation	0.00	0.25	0.50	0.75	1.00	0.00
Light limitation	0.00	0.00	0.00	0.00	0.00	1.00

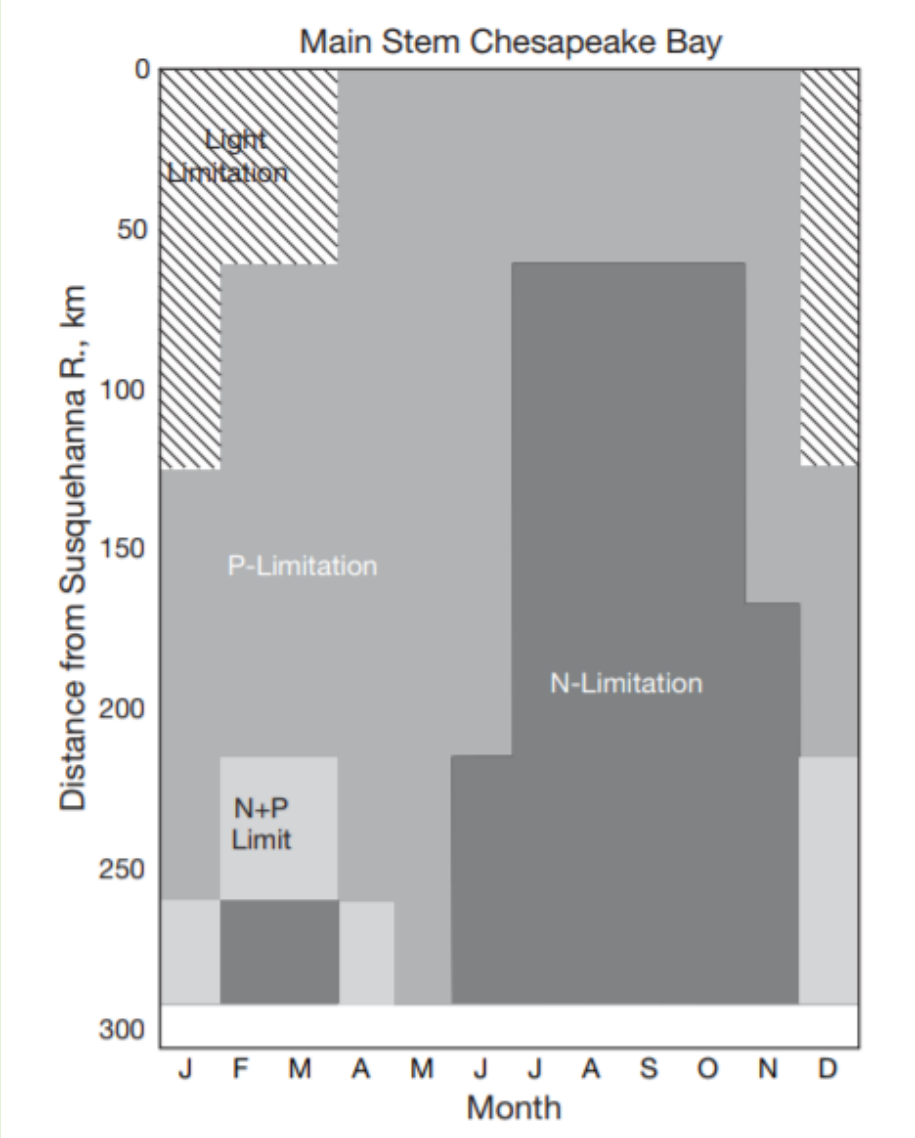
N limitation:
- N index > 0.5

P limitation:
- P index > 0.5

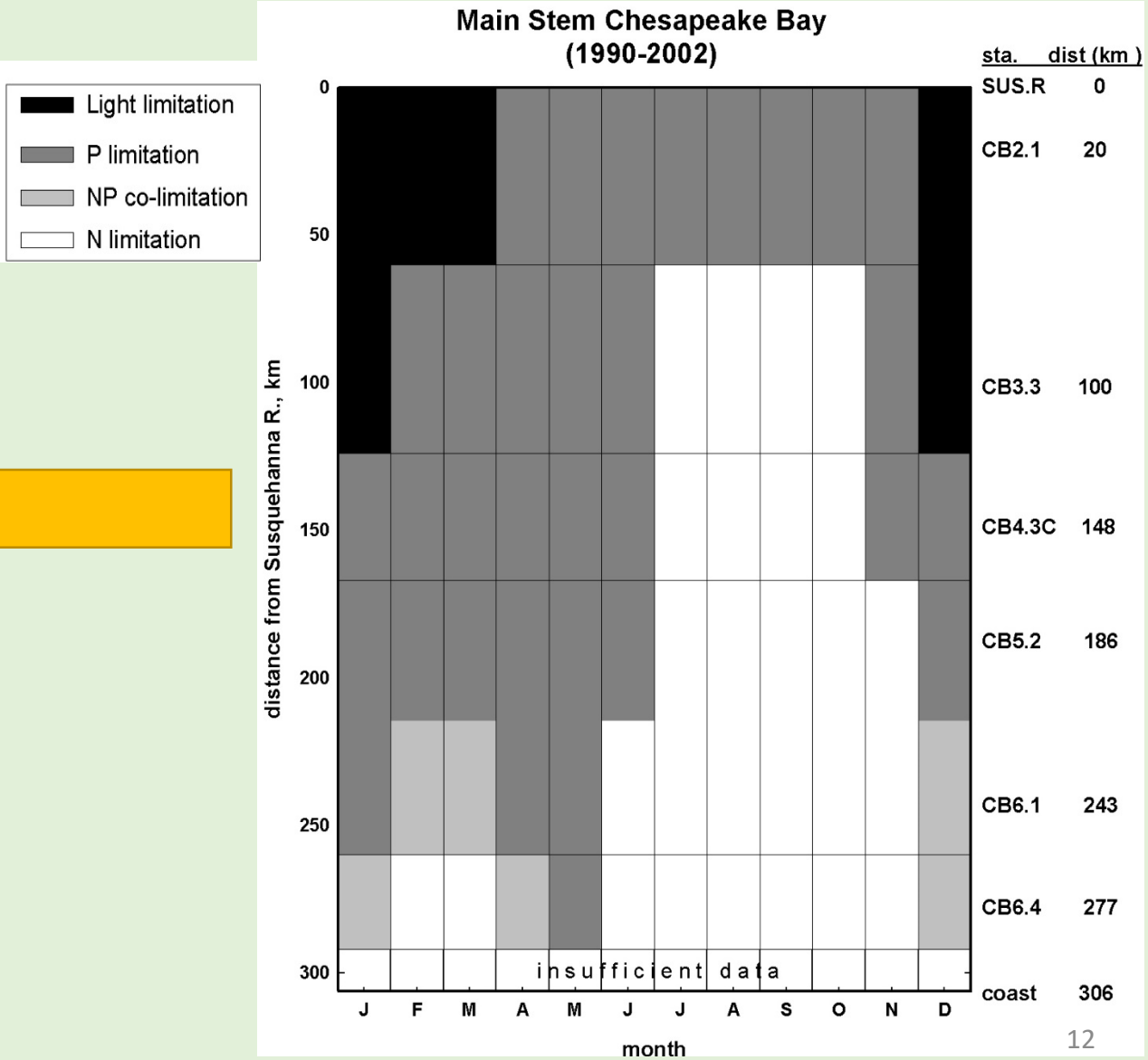
N+P limitation:
- both indices ~0.5

Light limitation
- others

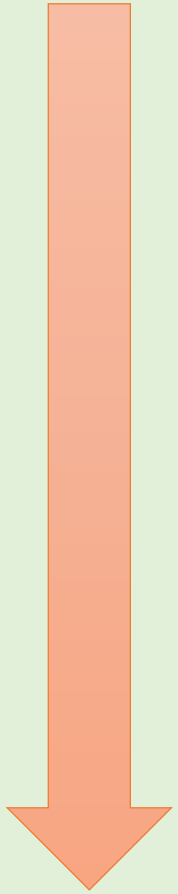
Kemp et al. (2005)



Fisher et al. Sigmaplot



Roadmap



1. Fisher's resource limitation diagram
2. Mainstem diagram (1992-2002)
3. Mainstem diagram (2006-2013)
4. Tidal tributary diagram
5. Explanation & mechanisms

Approach v1: A probabilistic approach

- For each station (mainstem only)
  - For each month (1 to 12)
    - Subset the applicable WQ data in 1992-2002
      - N conc. < 0.07 mg/L → N-limitation
      - P conc. < 0.007 mg/L → P-limitation
      - Both conditions met → N+P limitation
      - Else → Light limitation
    - Calculate the probability of each class for 1992-2002 (sum = 100%)
    - Assign limitation based on the probabilities:
      - N-limitation: p_N-limit >= 50%
      - P-limitation: p_P-limit >= 50%
      - N+P limitation: p_N-limit >= 40% & p_P-limit >= 40%
      - Light limitation: else

Limitation diagram (v1)

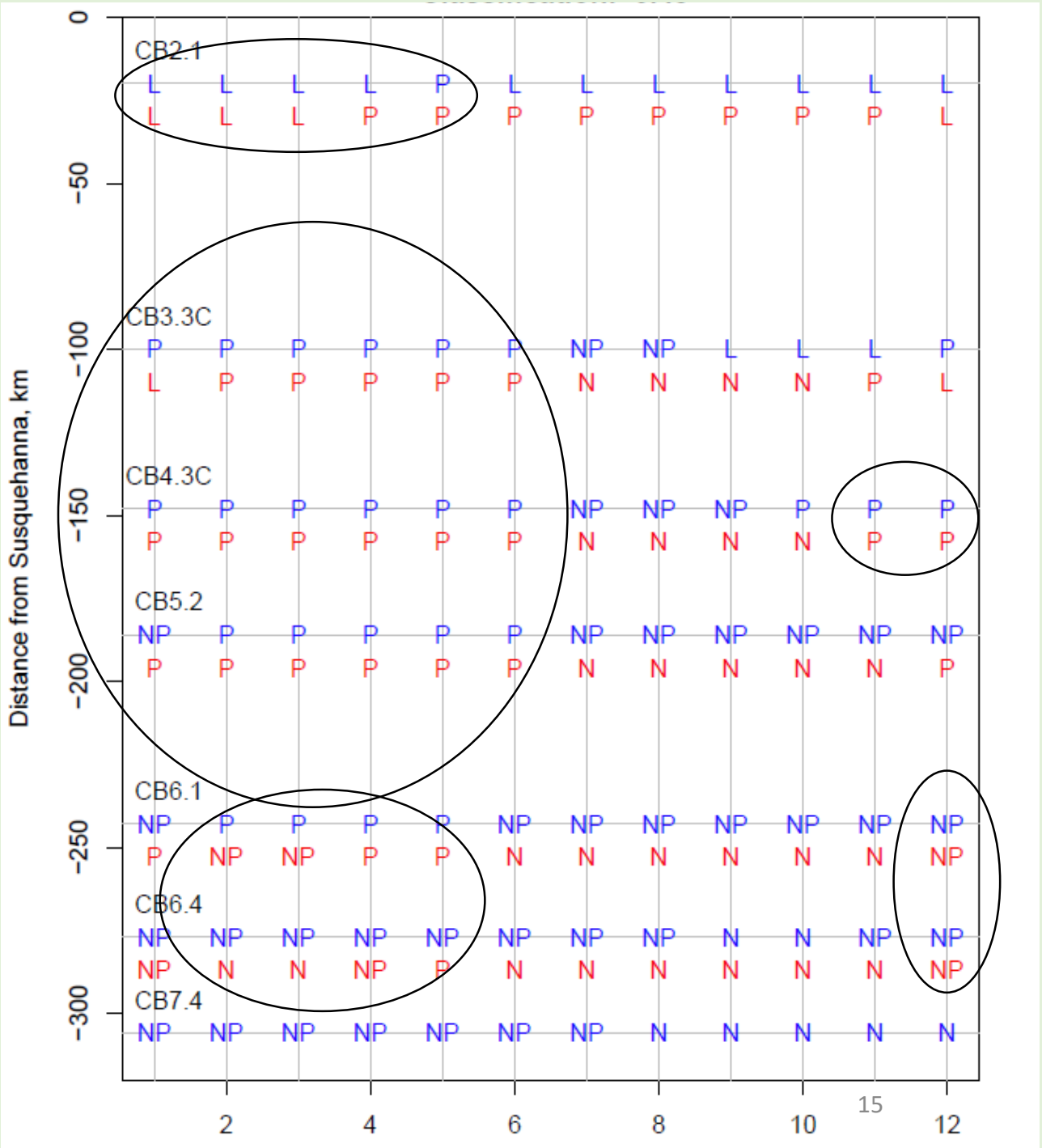
Main Stem Chesapeake Bay (1992–2002)
(blue = monitoring data; red = bioassay)

Count:

12 months * 6 stations = 72

Classification rate:

43% (n = 31) [v1]



Approach v2: N, P, and Light indices

- For each station (mainstem only)
  - For each month (1 to 12)
    - Subset the applicable WQ data in 1992-2002
      - N conc. < 0.07 mg/L → N, P, Light indices = (1, 0, 0)
      - P conc. < 0.007 mg/L → N, P, Light indices = (0, 1, 0)
      - Both conditions met → indices = (0.5, 0.5, 0)
      - Else → N, P, Light indices = (0, 0, 1)
    - Calculate the average N index, P index, and Light index (sum = 1)
    - Assign limitation based on indices:
      - N-limitation: N index >= 0.5
      - P-limitation: P index >= 0.5
      - N+P limitation: N index >= 0.4 & P index >= 0.4
      - Light limitation: else

Limitation diagram (v2)

Main Stem Chesapeake Bay (1992–2002)
(blue = monitoring data; red = bioassay)

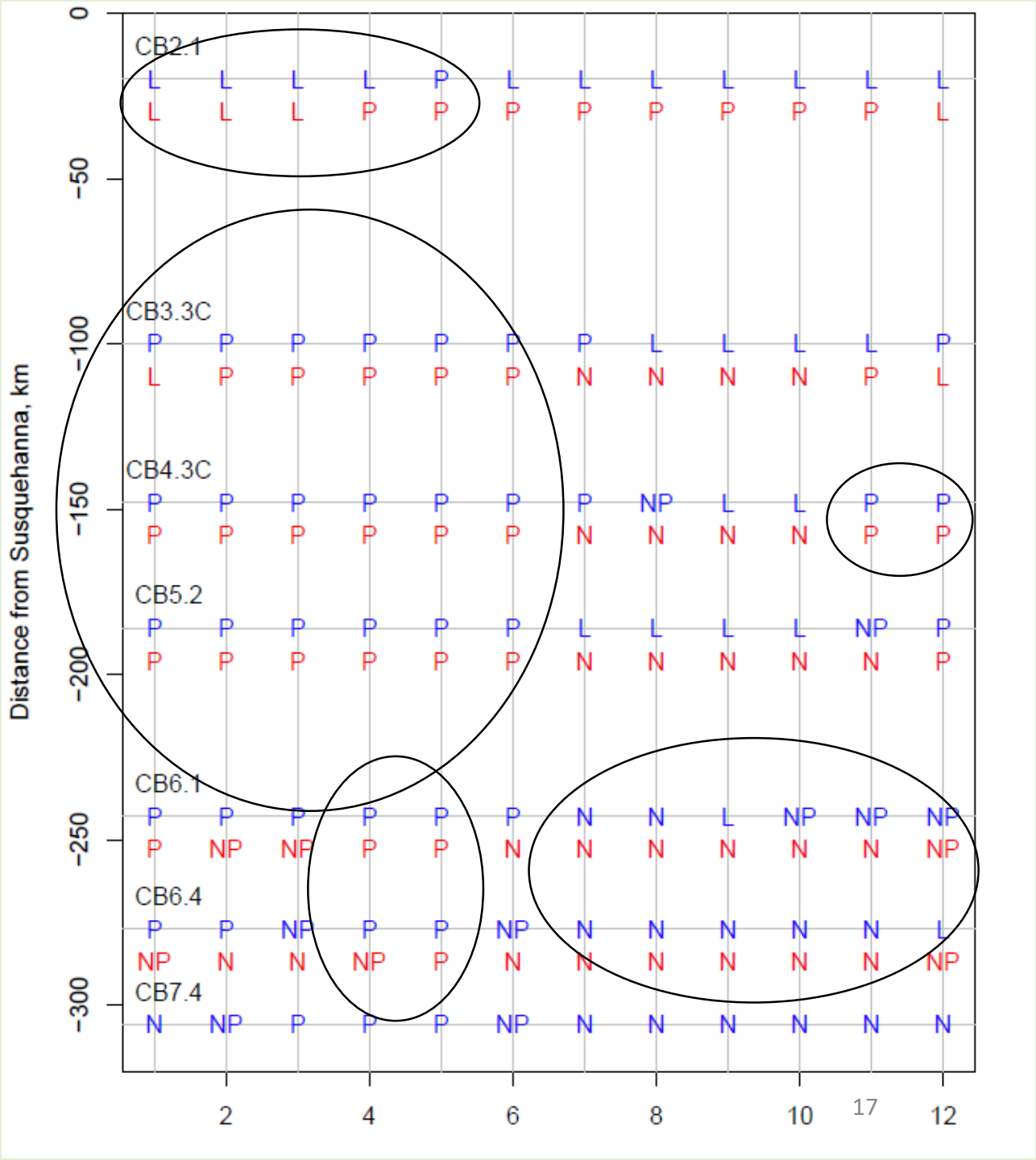
Count:

12 months * 6 stations = 72

Classification rate:

43% (n = 31) [v1]

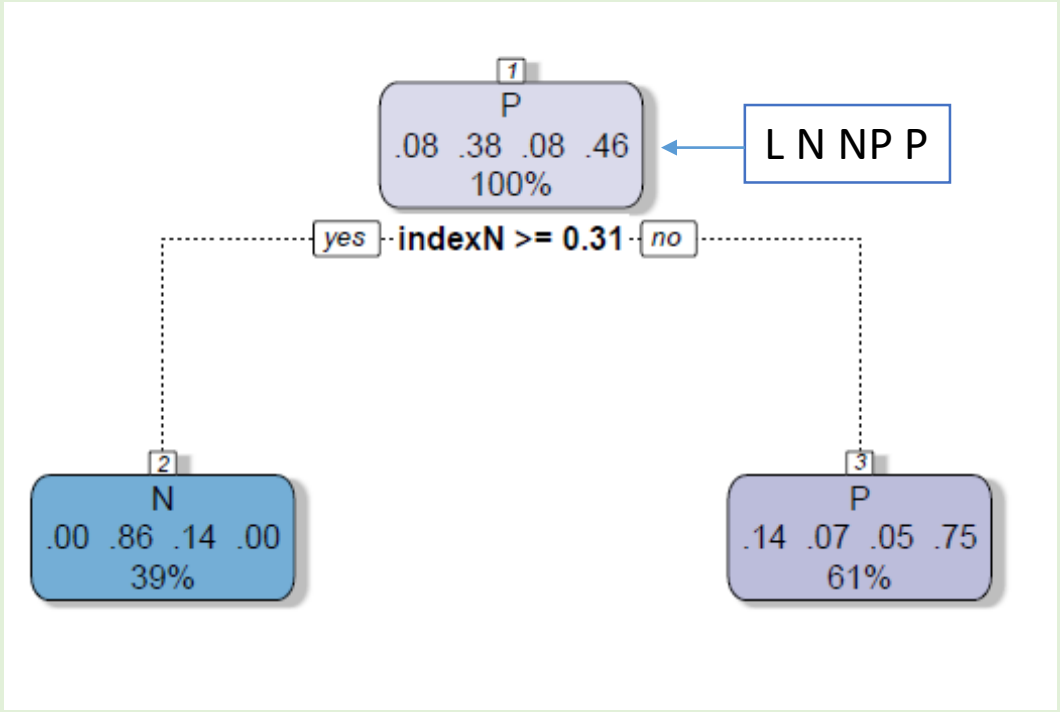
51% (n = 37) [v2]



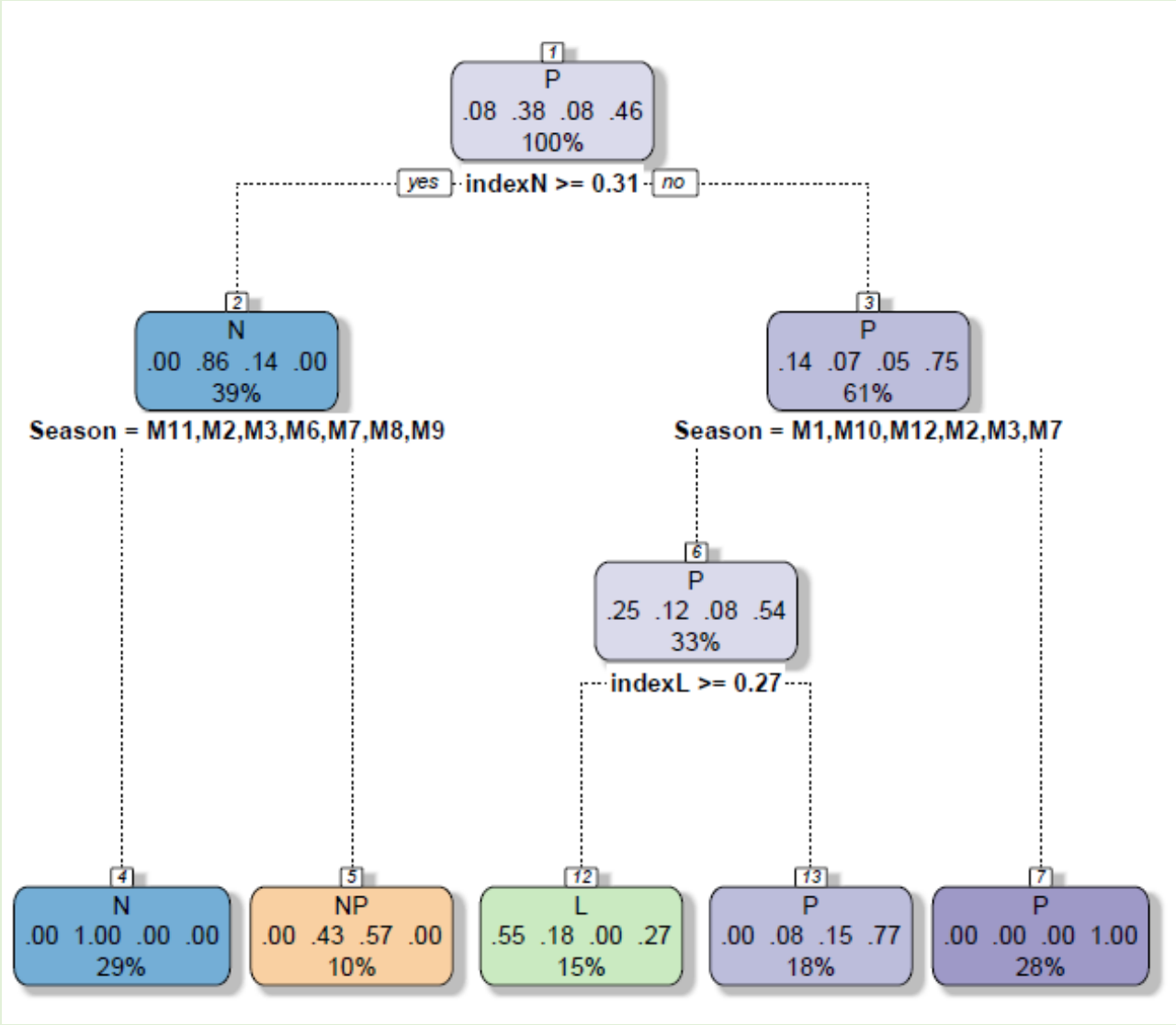
Approach v3: CART for assigning thresholds

- For each station (mainstem only)
  - For each month (1 to 12)
    - Subset the applicable WQ data in 1992-2002
      - N conc. < 0.07 mg/L → N, P, Light indices = (1, 0, 0)
      - P conc. < 0.007 mg/L → N, P, Light indices = (0, 1, 0)
      - Both conditions met → indices = (0.5, 0.5, 0)
      - Else → N, P, Light indices = (0, 0, 1)
    - Calculate the average N index, P index, and Light index (sum = 1)
    - Assign limitation using CART (Classification and Regression Trees)
      - Y variable: bioassay-based limitation class
      - X variables: N, P, and Light indices plus… season and other factors (salinity, Temp, light, DIN, DIP, distance from Susq.)

CART models



Class ~ indexN + indexP + indexL
(2 limitation classes only)



Class ~ indexN + indexP + indexL + Season
(4 limitation classes)

Limitation diagram (v3)

Main Stem Chesapeake Bay (1992–2002)
(blue = monitoring data; red = bioassay)

Count:

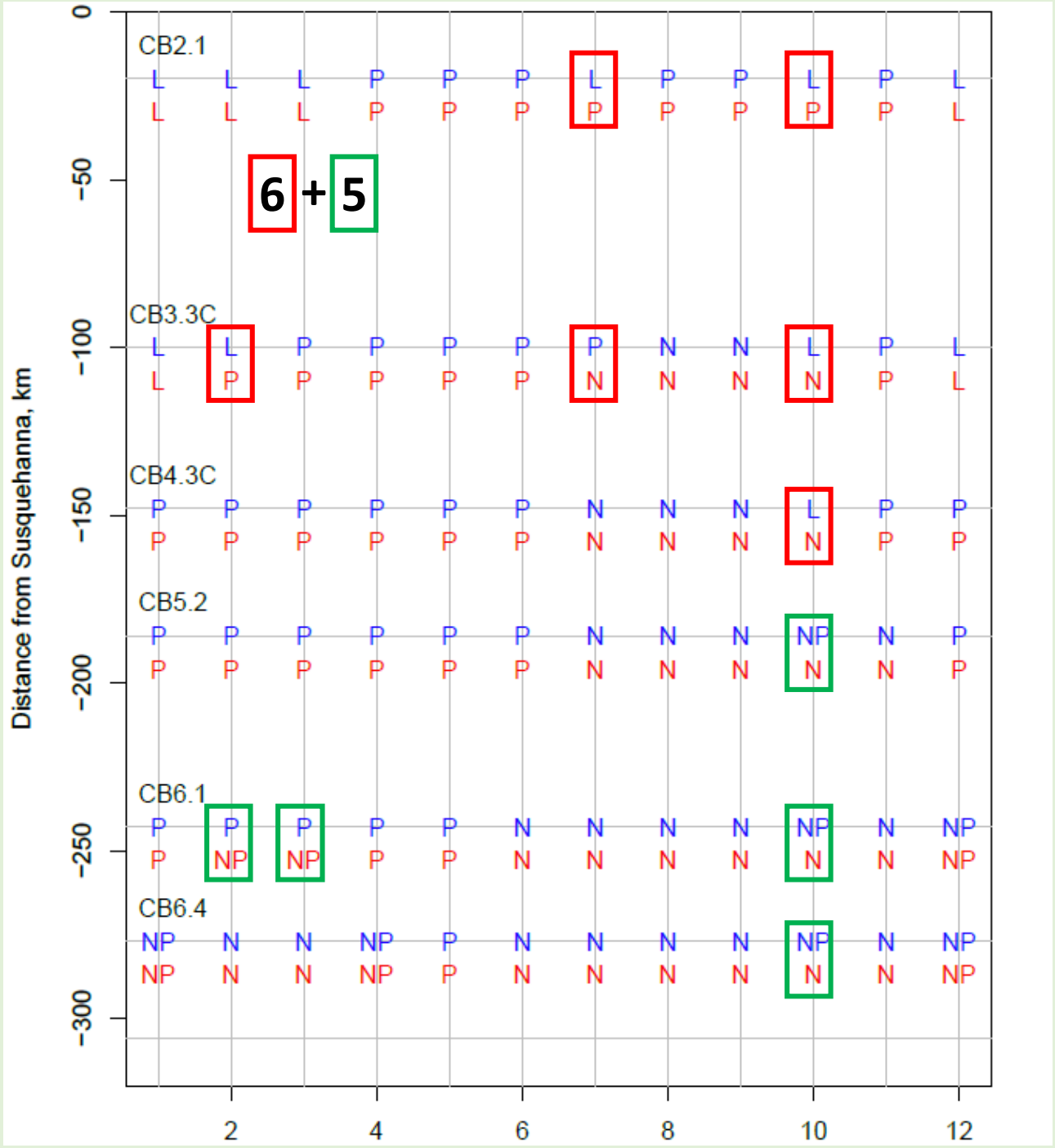
12 months * 6 stations = 72

Classification rate:

43% (n = 31) [v1]

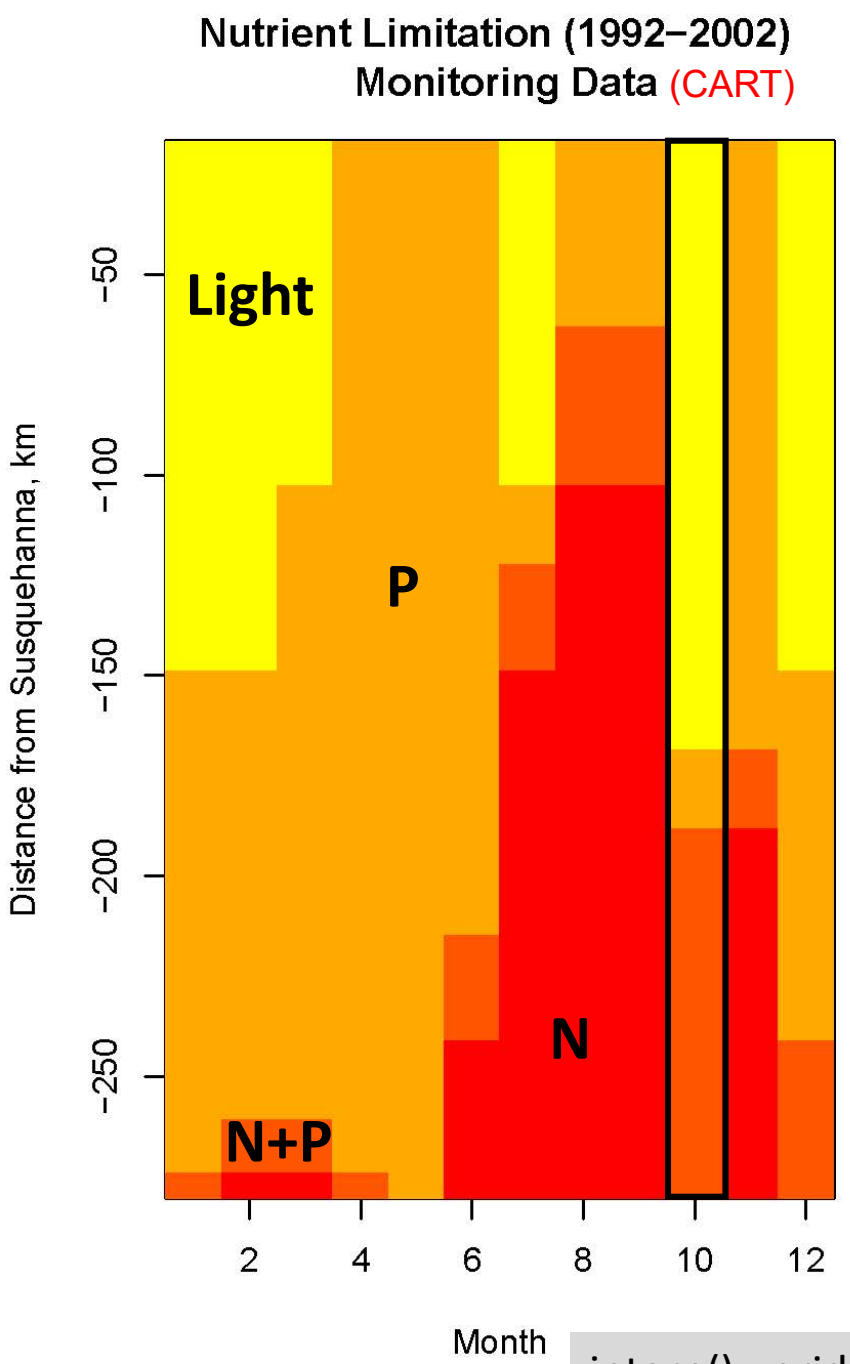
51% (n = 37) [v2]

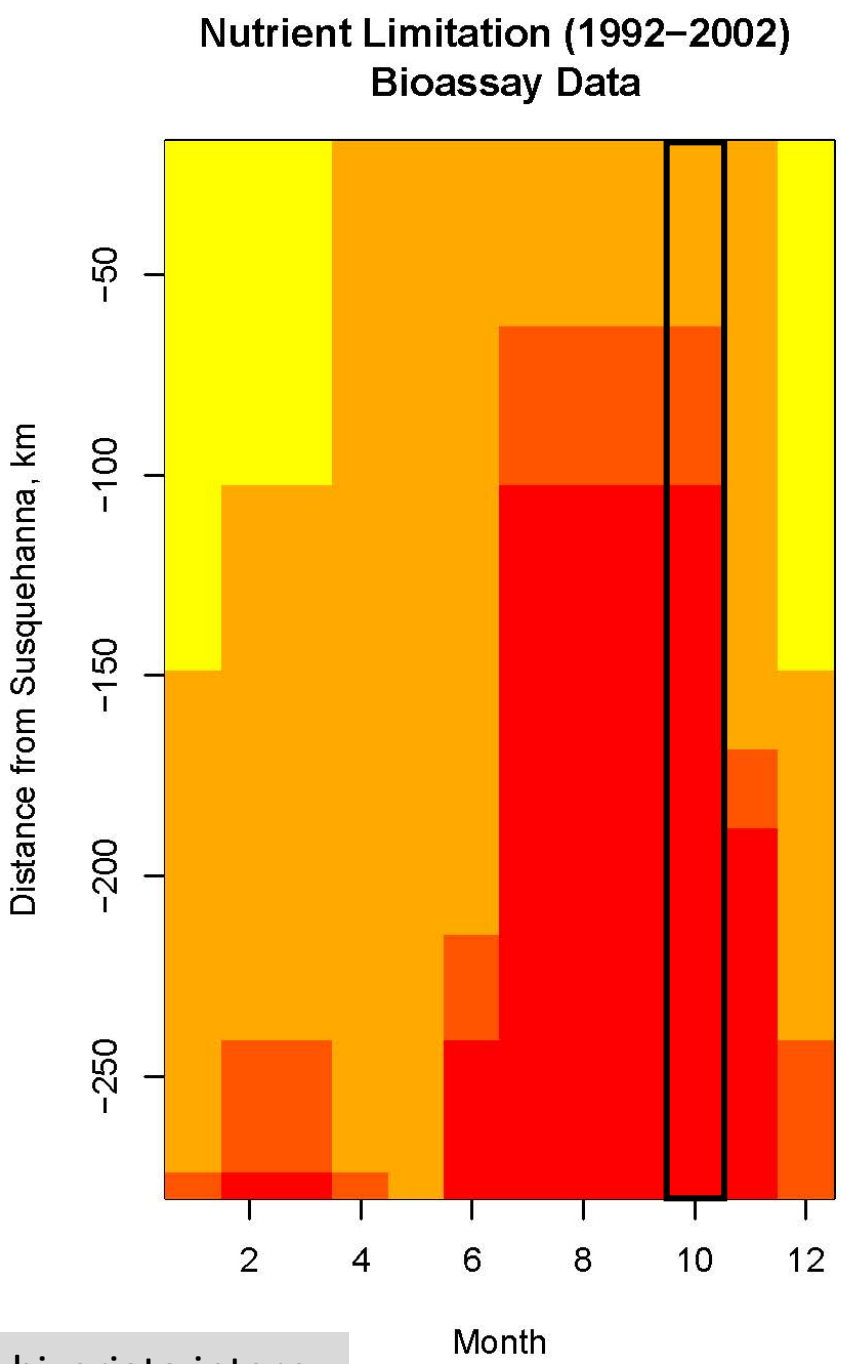
85% (n = 61) [v3] (model 2)



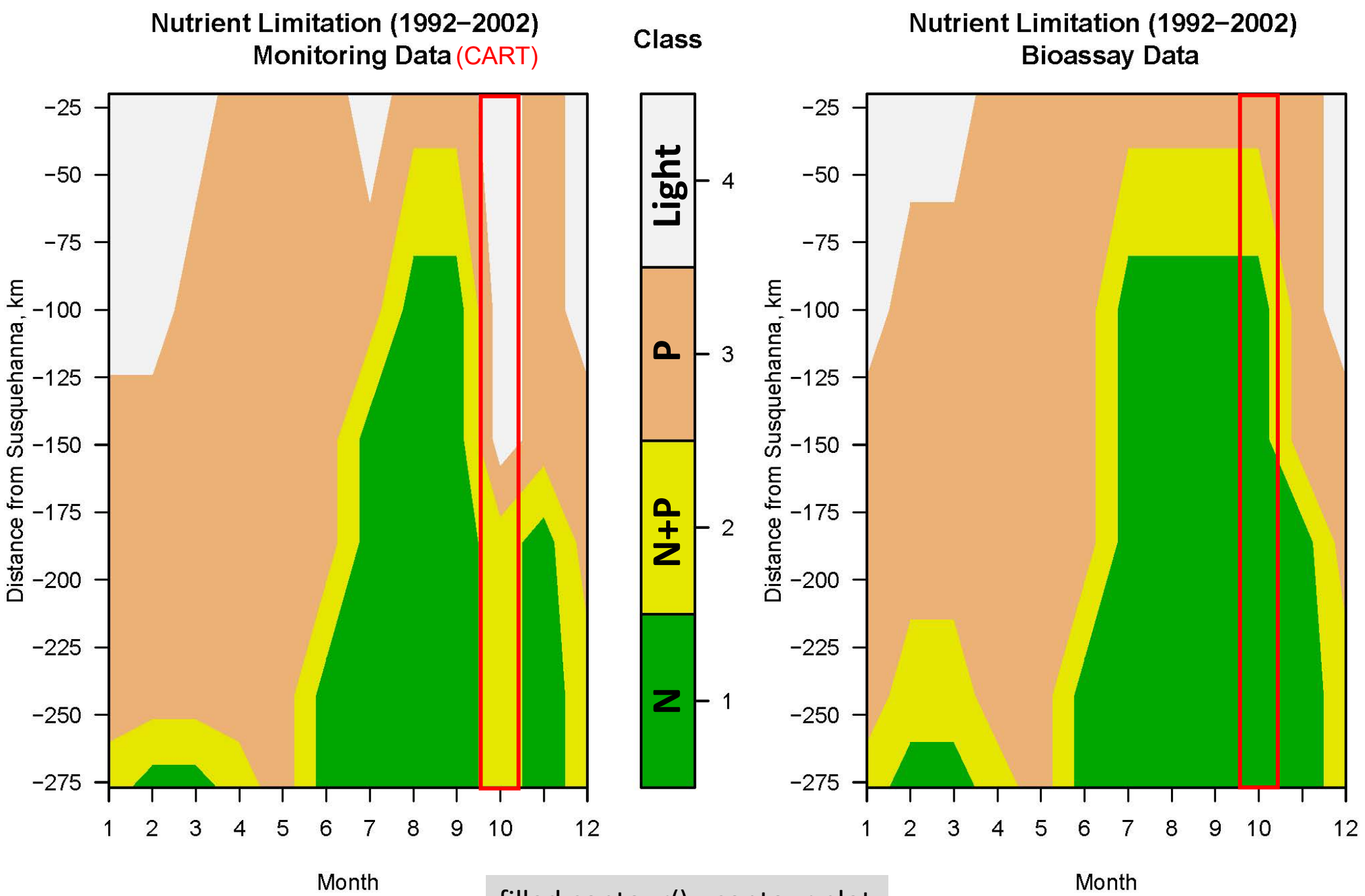
Comments on CART

- More complex trees (i.e., more variables) were developed.
  - Did not improve the model, according to 100-fold cross validation.
- Duplicated monitoring data were aggregated.
  - Did not affect the results above at all.
- Seasonality was accounted for using other means, including temperature, numerical month 1-12.
  - Did not improve the model performance.
- Several analyses were done to add confidence to the model.
  - Including: (A) 100-fold cross-validation, (B) adjustment of the nutrient thresholds (0.07 mg N/L and 0.007 mg P/L), and (C) use of odd (or even) years.



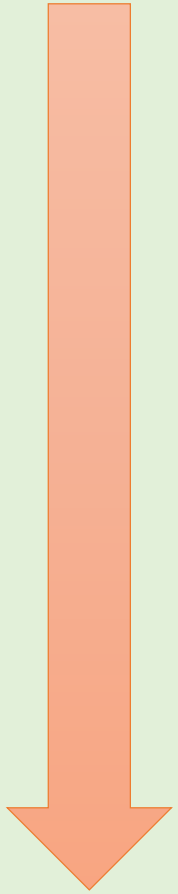


interp() - gridded bivariate interp.



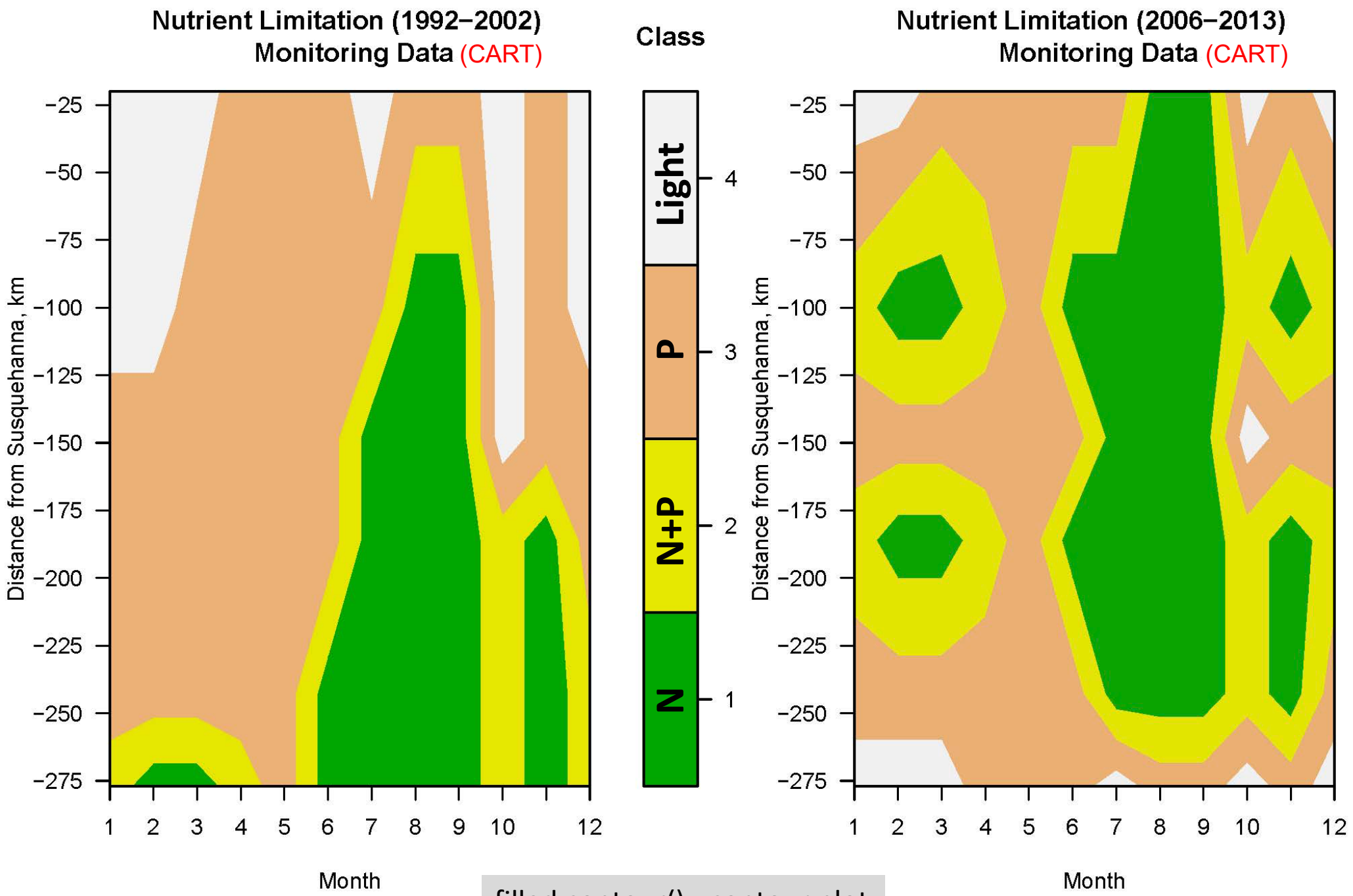
filled.contour() - contour plot

Roadmap



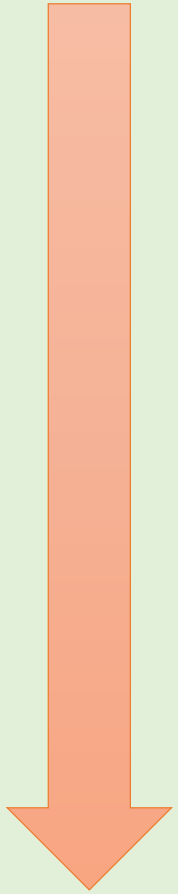
1. Fisher's resource limitation diagram
2. Mainstem diagram (1992-2002)
3. Mainstem diagram (2006-2013) *
4. Tidal tributary diagram
5. Explanation & mechanisms

* Average flow: 77,573 vs. 80,450 m3/s



filled.contour() - contour plot

Roadmap



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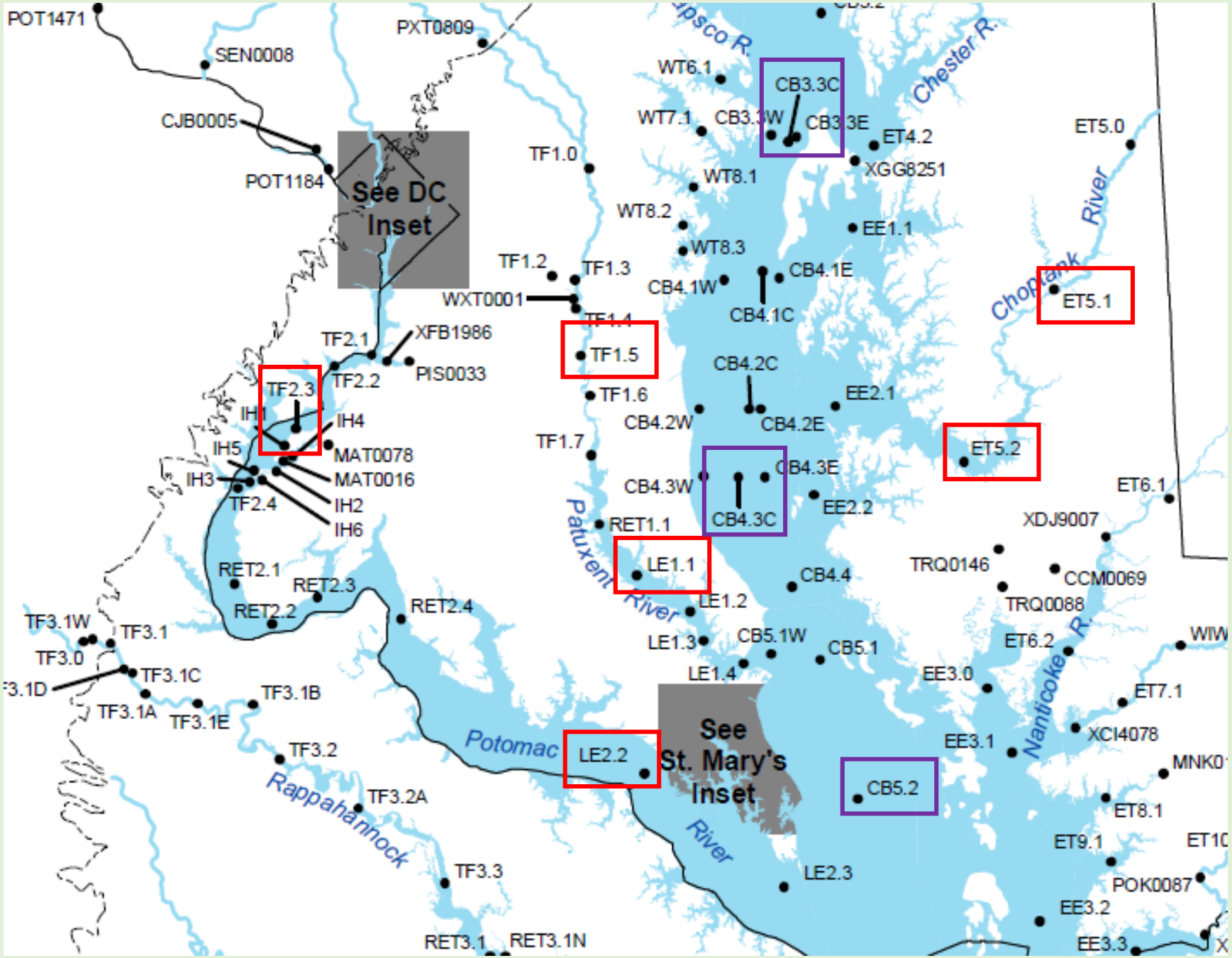
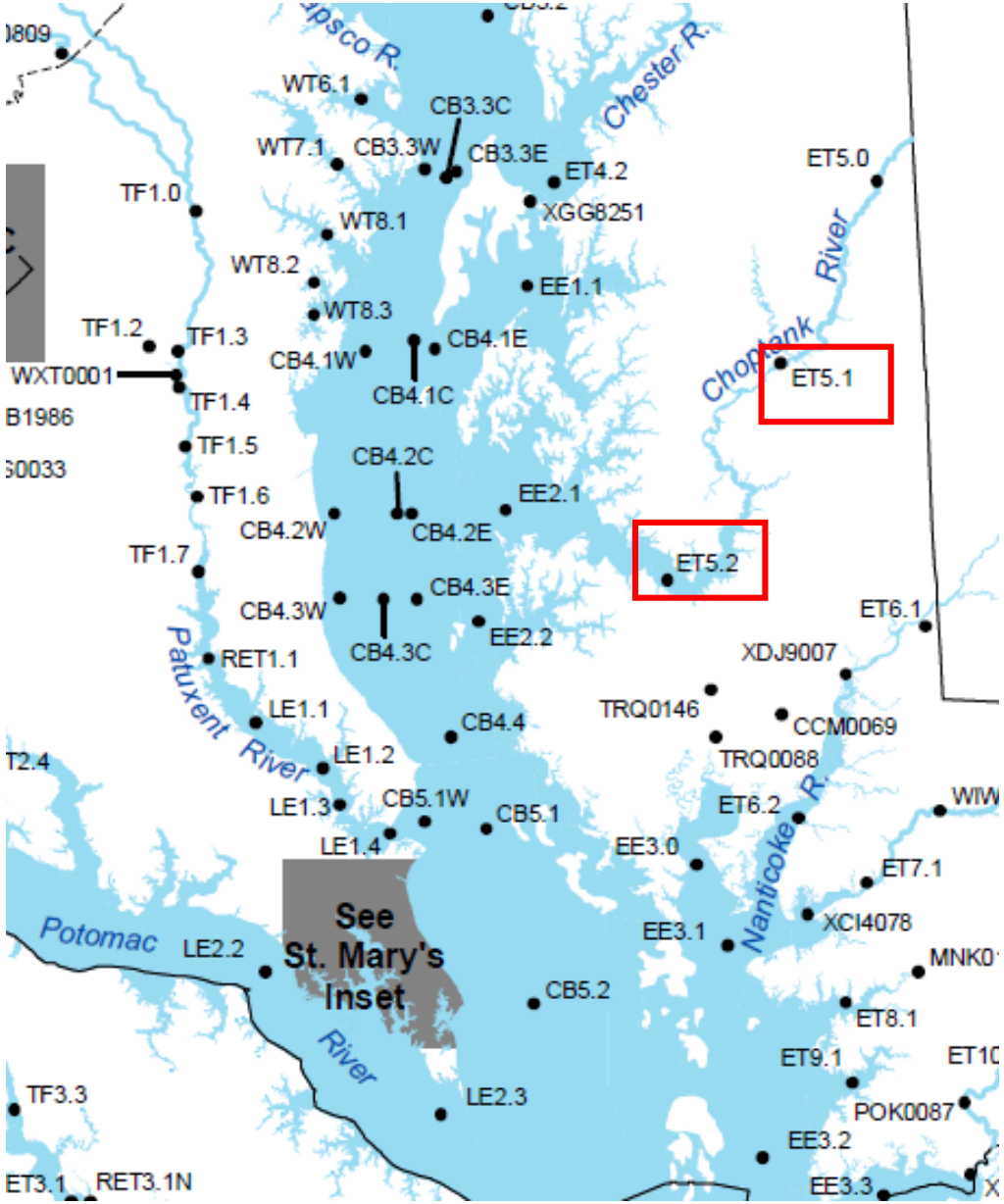
Summary of Tributary Data Availability

Station (> 50 Samples)	Tributary	# of Qualified Bioassay Samples (1990-2004)	# of Qualified Tidal Monitoring Samples (1990-2004)	# of Matched Data Pairs (1990-2004)
ET5.1	Choptank	105	281	81
ET5.2	Choptank	272	276	225
TF1.5	Patuxent	112	276	104
LE1.1	Patuxent	290	307	273
TF2.3	Potomac	109	295	92
LE2.2	Potomac	283	282	207
CB3.3C	Main	240	264	212
CB4.3C	Main	277	261	255
CB5.2	Main	265	257	255


POT1471
SEN0008
PXT0809
CJB0005
POT1184
See DC Inset
TF1.0
WT6.1
CB3.3C
WT7.1
CB3.3W
CB3.3E
ET4.2
XGG8251
ET5.0
WT8.1
WT8.2
EE1.1
WT8.3
TF1.2
TF1.3
CB4.1E
CB4.1W
CB4.1C
WXT0001
TF1.4
TF1.5
ET5.1
Choptank River
TF2.1
XFB1986
PIS0033
TF2.2
TF2.3
IH1
IH4
IH5
MAT0078
IH3
MAT0016
TF2.4
IH2
IH6
TF1.6
CB4.2C
EE2.1
CB4.2W
CB4.2E
TF1.7
ET5.2
CB4.3E
CB4.3W
CB4.3C
EE2.2
ET6.1
RET1.1
Patuxent River
XDJ9007
LE1.1
TRQ0146
CCM0069
CB4.4
TRQ0088
LE1.2
RET2.1
RET2.3
RET2.2
RET2.4
TF3.1W
TF3.1
TF3.0
LE1.3
CB5.1W
CB5.1
ET6.2
Nanticoke R.
LE1.4
EE3.0
ET7.1
TF3.1C
TF3.1D
TF3.1A
TF3.1E
TF3.1B
EE3.1
XCI4078
TF3.2
Potomac
LE2.2
See St. Mary's Inset
CB5.2
MNK0
Rappahannock
TF3.2A
ET8.1
ET9.1
River
LE2.3
TF3.3
POK0087
EE3.2
RET3.1
RET3.1N
EE3.3

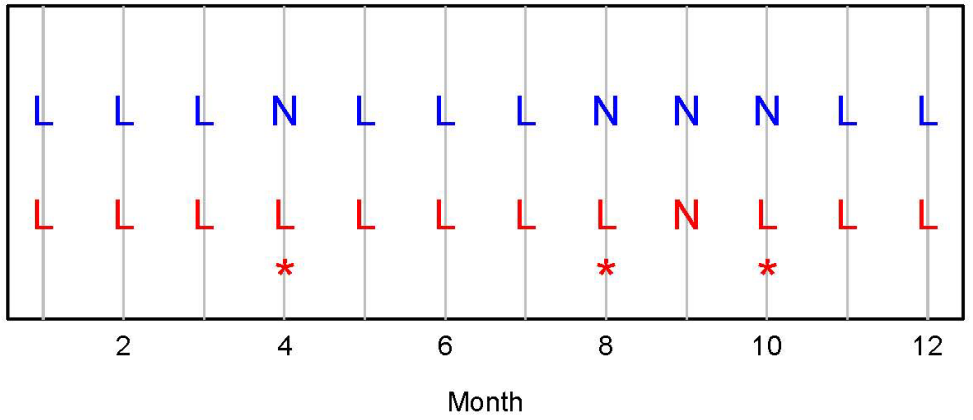
Approach:

1. Match bioassay and tidal monitoring data for **1990-2003**.
2. Develop six CART models for bioassay category using all data pairs:
   - Model 1: LIM ~ indexN + indexP + indexL
   - Model 2: LIM ~ indexN + indexP + indexL + Month
   - Model 3: LIM ~ indexN + indexP + indexL + Month + Salinity + Temp
   - Model 4: LIM ~ indexN + indexP + indexL + Month + Salinity + Temp + Light
   - Model 5: LIM ~ indexN + indexP + indexL + Month + Salinity + Temp + Light + N + P
   - Model 6: LIM ~ indexN + indexP + indexL + Salinity + Temp + Light + N + P
3. Select the *best model* using 100-fold cross validation (test = 30%).
4. Convert the six bioassay categories to N, P, and L indexes and then aggregate for each month to determine limitation class for bioassay and monitoring data (based on *best model*), respectively.



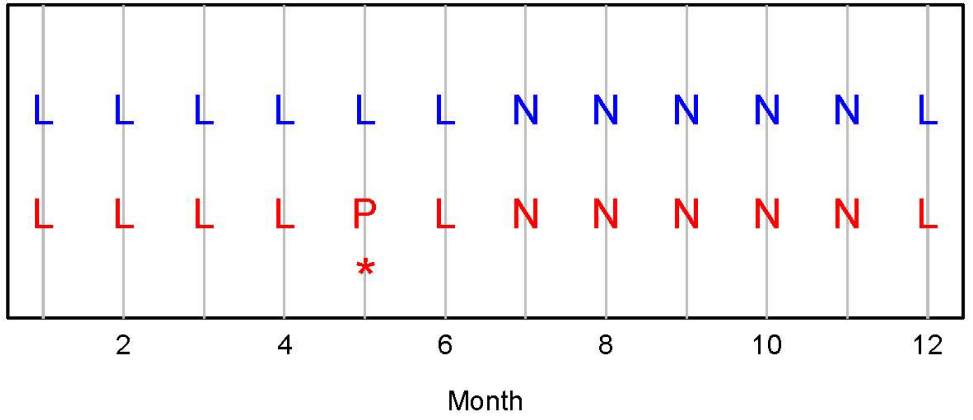
Choptank ET5.1 (1990–2003)
(blue = CART; red = bioassay)
Classification: 0.77

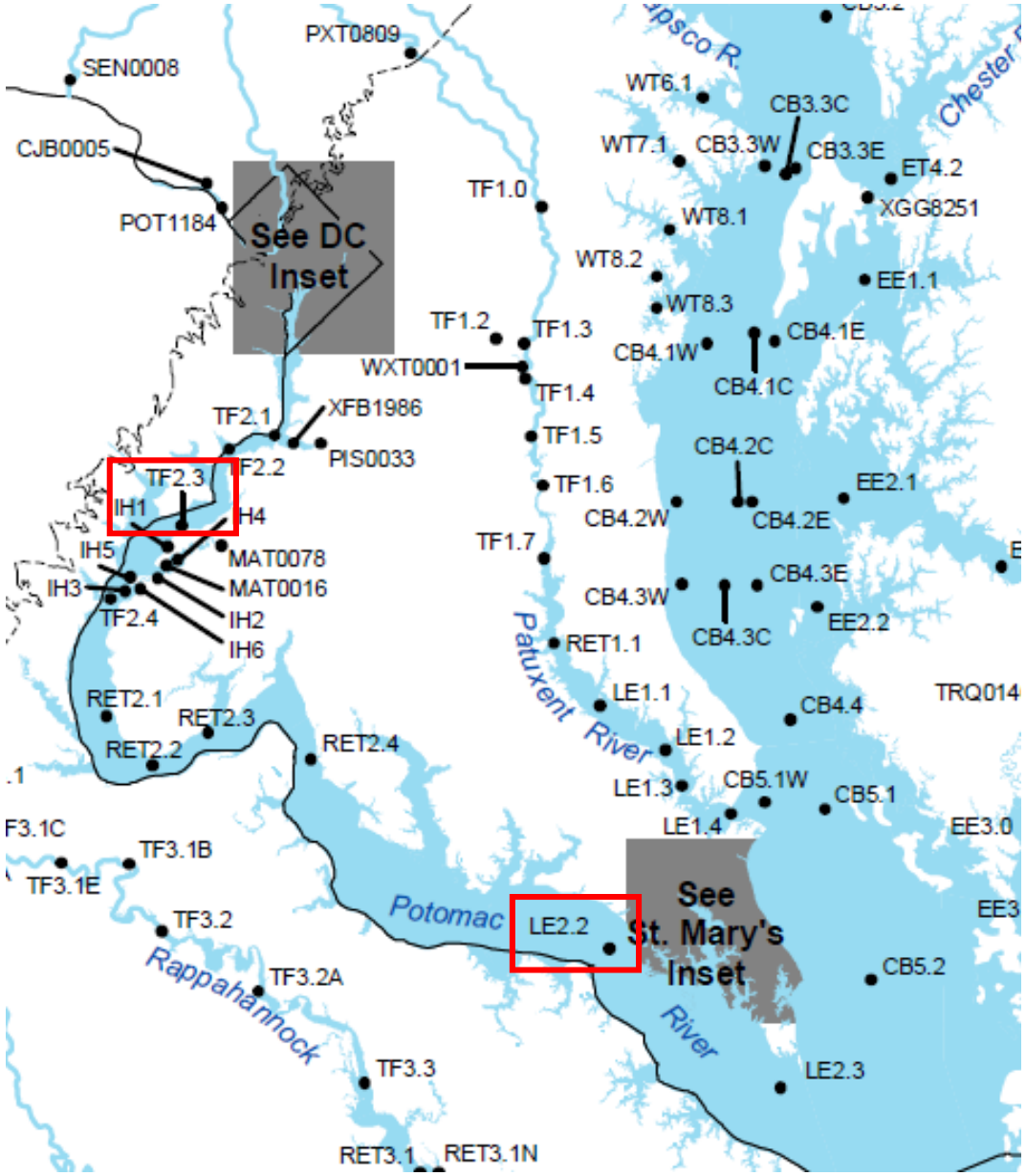
9/12

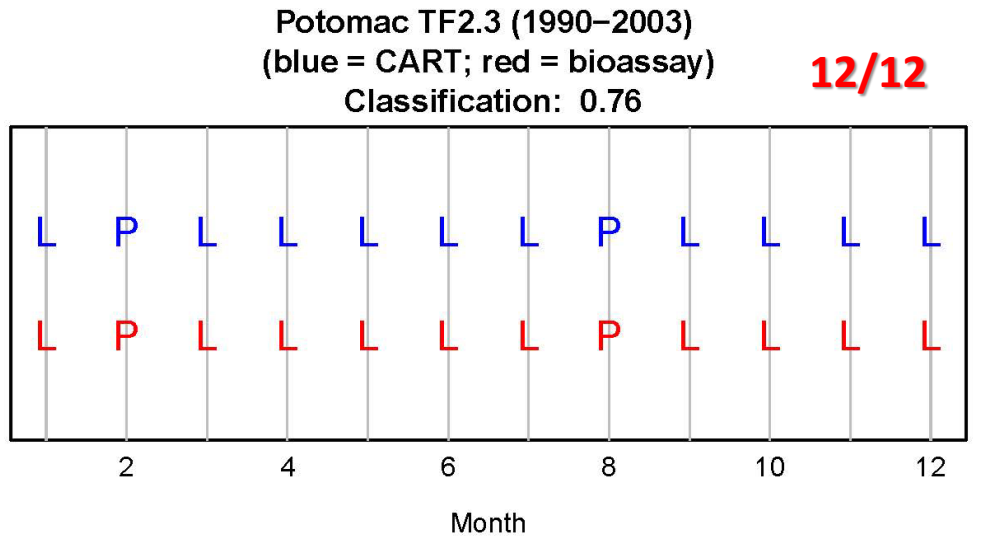


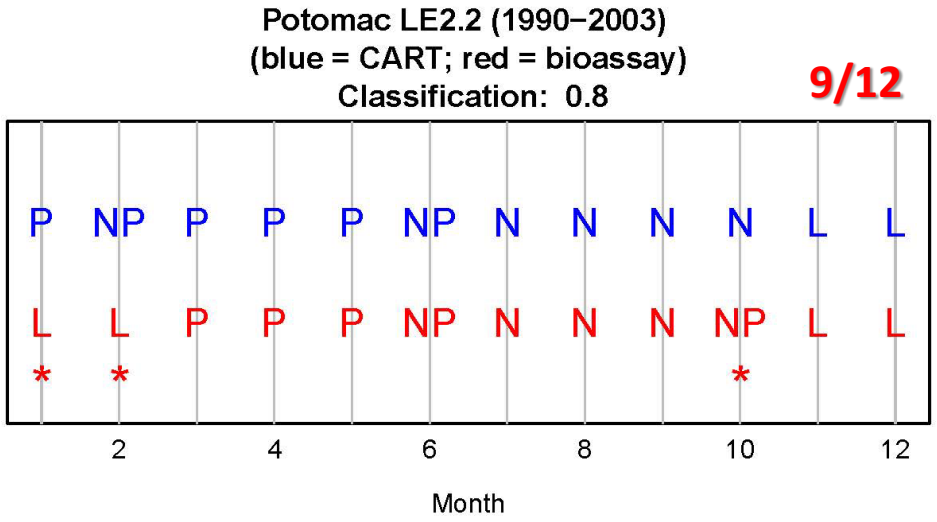
Choptank ET5.2 (1990–2003)
(blue = CART; red = bioassay)
Classification: 0.72

11/12




PXT0809
SEN0008
CJB0005
POT1184
See DC Inset
TF1.0
WT6.1
CB3.3C
WT7.1
CB3.3W
CB3.3E
ET4.2
XGG8251
WT8.1
WT8.2
EE1.1
WT8.3
TF1.2
TF1.3
CB4.1E
CB4.1W
WXT0001
CB4.1C
TF1.4
TF2.1
XFB1986
TF1.5
PIS0033
CB4.2C
TF2.2
TF2.3
TF1.6
EE2.1
IH1
IH4
CB4.2W
CB4.2E
TF1.7
IH5
MAT0078
CB4.3E
IH3
MAT0016
CB4.3W
TF2.4
EE2.2
IH2
CB4.3C
IH6
RET1.1
Patuxent River
RET2.1
LE1.1
TRQ014
RET2.3
CB4.4
RET2.2
RET2.4
LE1.2
CB5.1W
LE1.3
CB5.1
LE1.4
EE3.0
F3.1C
TF3.1B
TF3.1E
See St. Mary's Inset
TF3.2
Potomac
LE2.2
EE3
CB5.2
Rappahannock
TF3.2A
River
TF3.3
LE2.3
RET3.1
RET3.1N

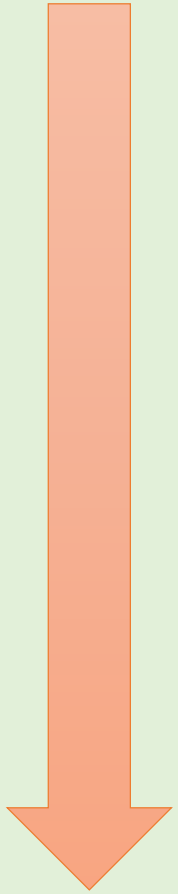

Potomac TF2.3 (1990–2003)
(blue = CART; red = bioassay)
Classification: 0.76
12/12
L P L L L L L P L L L L
L P L L L L L P L L L L
2 4 6 8 10 12
Month


Potomac LE2.2 (1990–2003)
(blue = CART; red = bioassay)
Classification: 0.8
9/12
P NP P P P NP N N N N L L
L L P P P NP N N N NP L L
* * *
2 4 6 8 10 12
Month

Summary of Tributary Results

Station	Tributary	Classification Rate for Bioassay Categories (1990-2003)	Classification Rate for Limitation Classes (1990-2003)
ET5.1	Choptank	77% of data pairs	9 of 12 months
ET5.2	Choptank	72% of data pairs	11 of 12 months
TF1.5	Patuxent	80% of data pairs	10 of 12 months
LE1.1	Patuxent	73% of data pairs	9 of 12 months
TF2.3	Potomac	76% of data pairs	12 of 12 months
LE2.2	Potomac	80% of data pairs	9 of 12 months
CB3.3C	Mainstem	74% of data pairs	11 of 12 months
CB4.3C	Mainstem	81% of data pairs	11 of 12 months
CB5.2	Mainstem	83% of data pairs	10 of 12 months

Roadmap



1. Fisher's resource limitation diagram
2. Mainstem diagram (1992-2002)
3. Mainstem diagram (2006-2013)
4. Tidal tributary diagram
5. Explanation & mechanisms (upcoming)

Next Steps

- Improving CART
  - Account for mixing/stratification based on the monitoring data.
  - Account for riverflow conditions (e.g., Jan-May) using flow classes.
- Comparing dry years vs. wet years
  - Develop limitation diagrams for dry and wet years, respectively, using the bioassay data and the tidal monitoring data.
- Predicting limitation for the more recent period
  - Compile station GAM trends and riverine load trends to inform interpretation.

Implications

- Help explain changes (or lack of changes) in water quality (e.g., Chl-a) in different parts of the Bay.
- Provide information for future development of Chesapeake estuarine models.
- Motivate for collecting new bioassay data for model validation.
- Set an example on how (more available) WQ monitoring data can be used in combination with (often less available) bioassay data to inform analysis of resource limitation in estuaries.

Questions?
Comments?