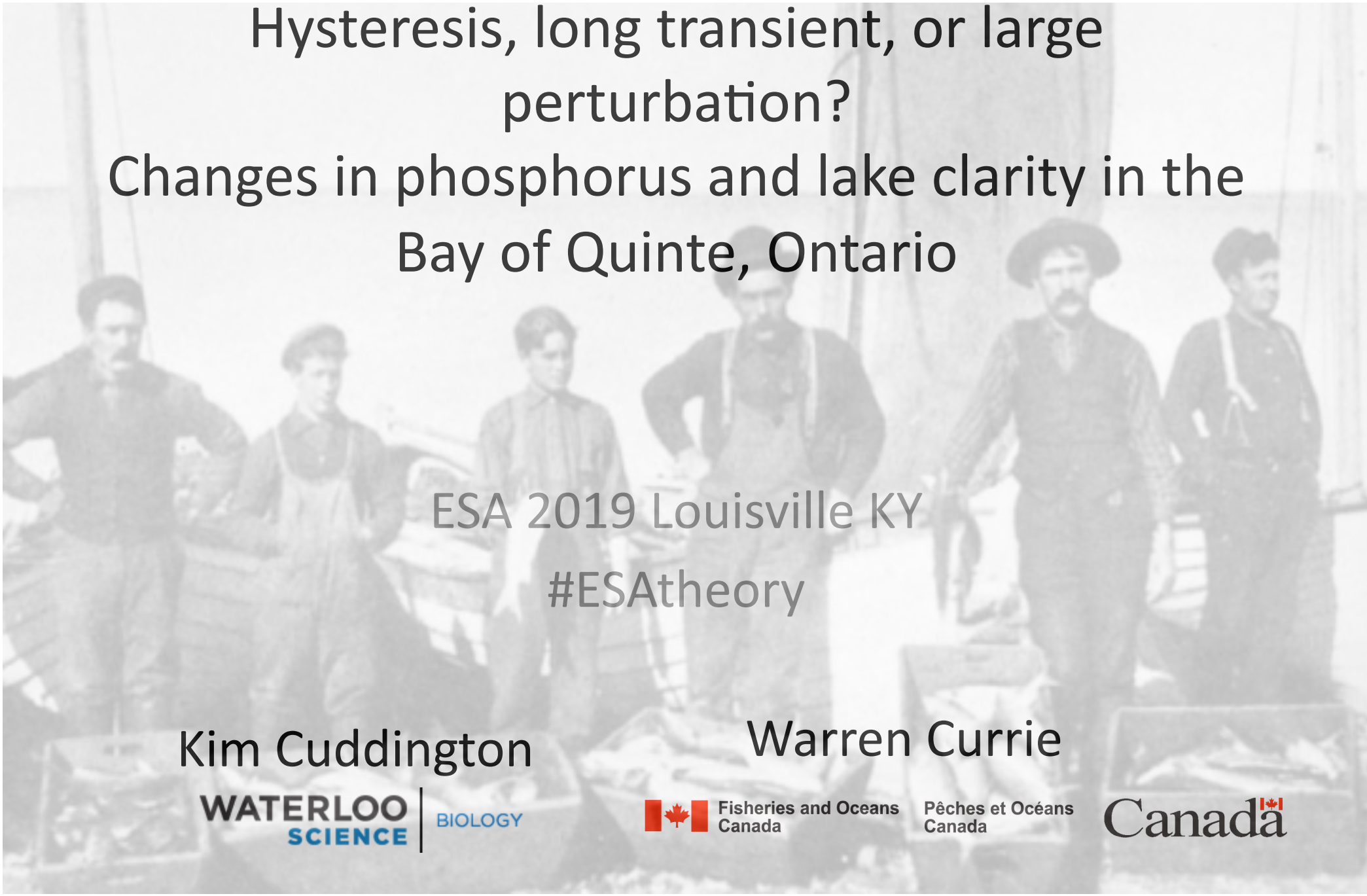
Hysteresis, long transient, or large perturbation?
Changes in phosphorus and lake clarity in the Bay of Quinte, Ontario



ESA 2019 Louisville KY

#ESAtheory

Kim Cuddington

WATERLOO SCIENCE | BIOLOGY

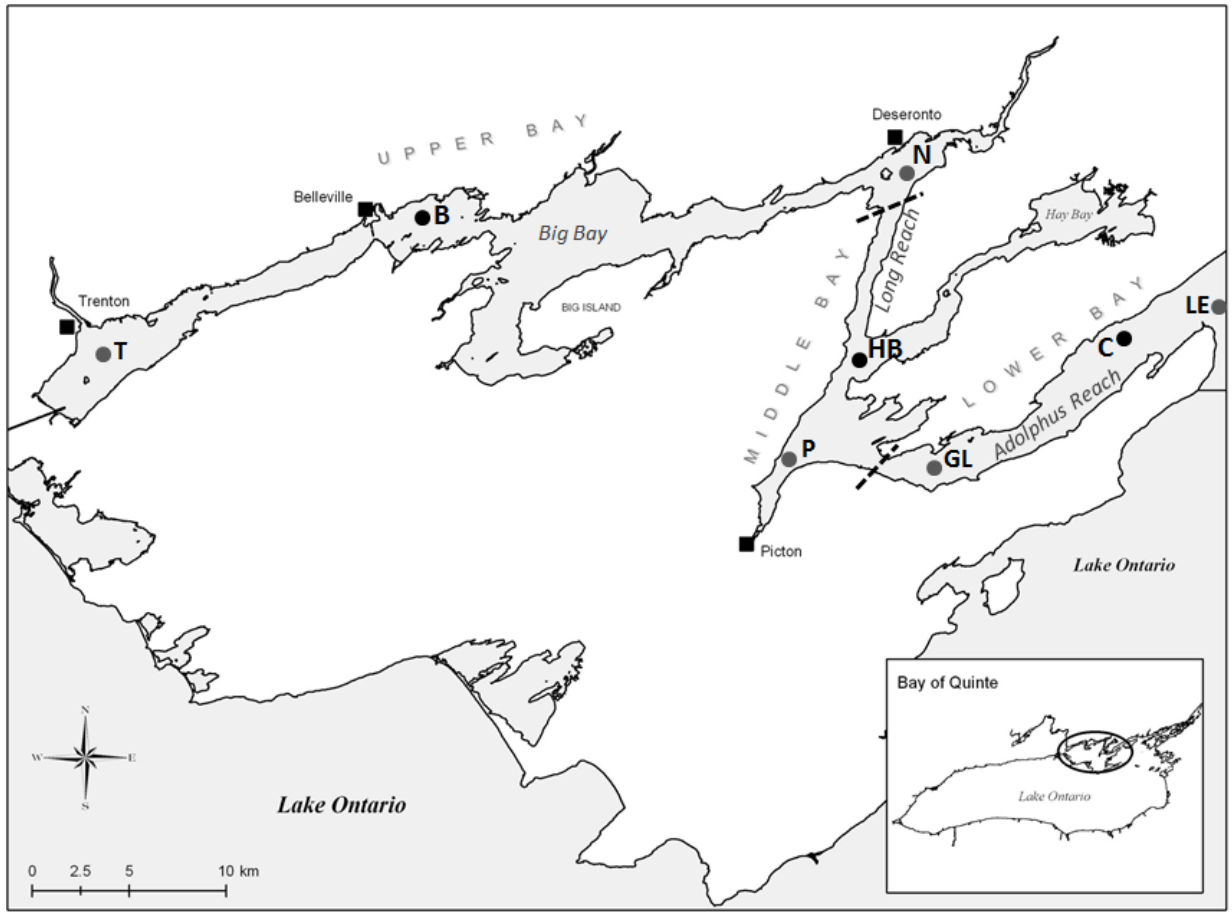
Warren Currie

Fisheries and Oceans Canada | Pêches et Océans Canada

Canada

Bay of Quinte

- Eutrophic embayment of Lake Ontario
- 90 km long
- Several tributaries
- Ranges from 4-5m deep to 40-50m near the lake
- Area of Concern



There's 28 slides total, is that too many?

History of Bay of Quinte conditions

- 1800s
  - Slight to moderate oligotrophic conditions. Eutrophic state by 1890
- 1930s-1950s
  - Water quality deteriorated
  - 1950s hypereutrophic.
- 1960s – early 1970s
  - Algal blooms and Secchi depths < 30cm
  - Macrophytes were restricted to a small euphotic zone
  - Fish kills and hypoxia in the late 60's.
  - Decline or loss of fisheries
- 1977-78 Point source control of phosphorus introduced
- 1994 Dressenid mussels first detected

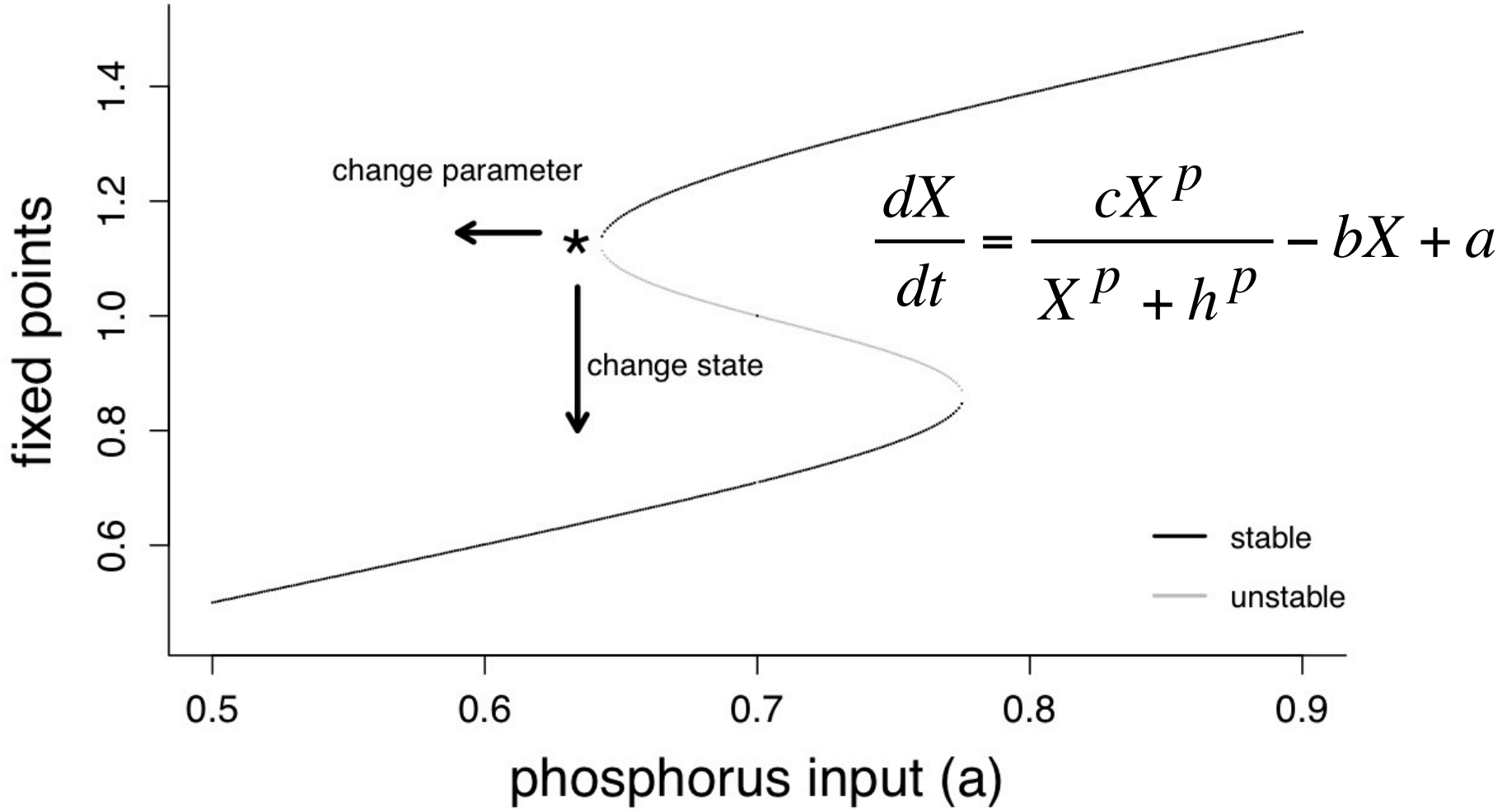
Mechanism: zebra mussels caused the change

- "In the mid- 1990s, zebra and quagga mussels (Dreissena spp.) invaded the area, **dramatically changing the water clarity because of their filter-feeding capacity**."
  - Bay of Quinte Remedial action plan (2017)

- Dreissenid **colonization induced precipitous decline of phytoplankton** and ultimately enabled macrophyte resurgence (Nicholls and Carney, 2011).

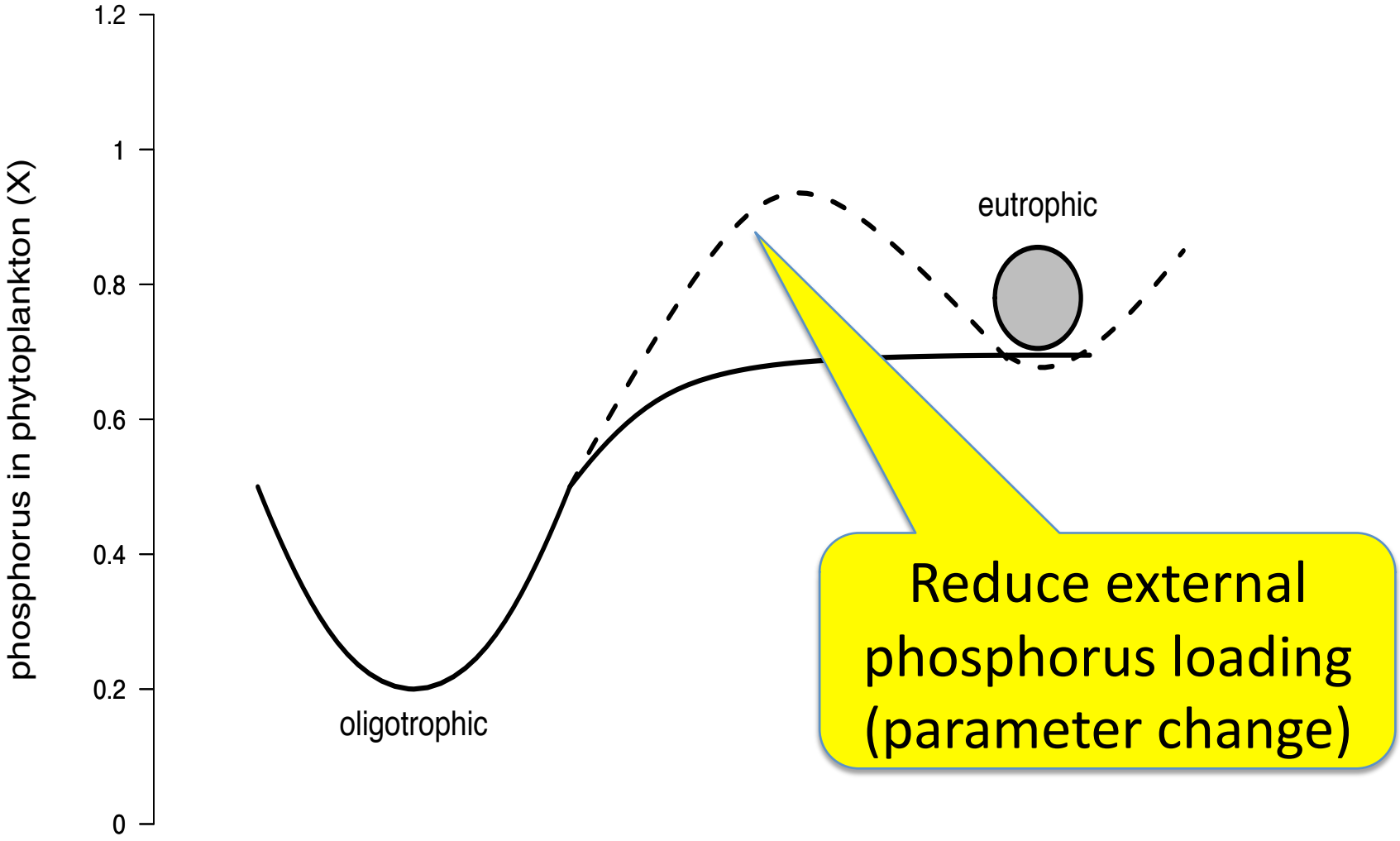
- **Only after zebra and quagga mussels arrived in 1993-4 … did macrophytes increase substantially.**
- filtering by the mussels….**reduced chlorophyll concentrations and greatly increased water clarity**. **Thus the hysteresis model of macrophytes is partially supported**."
  - Minns et al (2004)

Bistability and hysteresis in Scheffer et al. (2001)



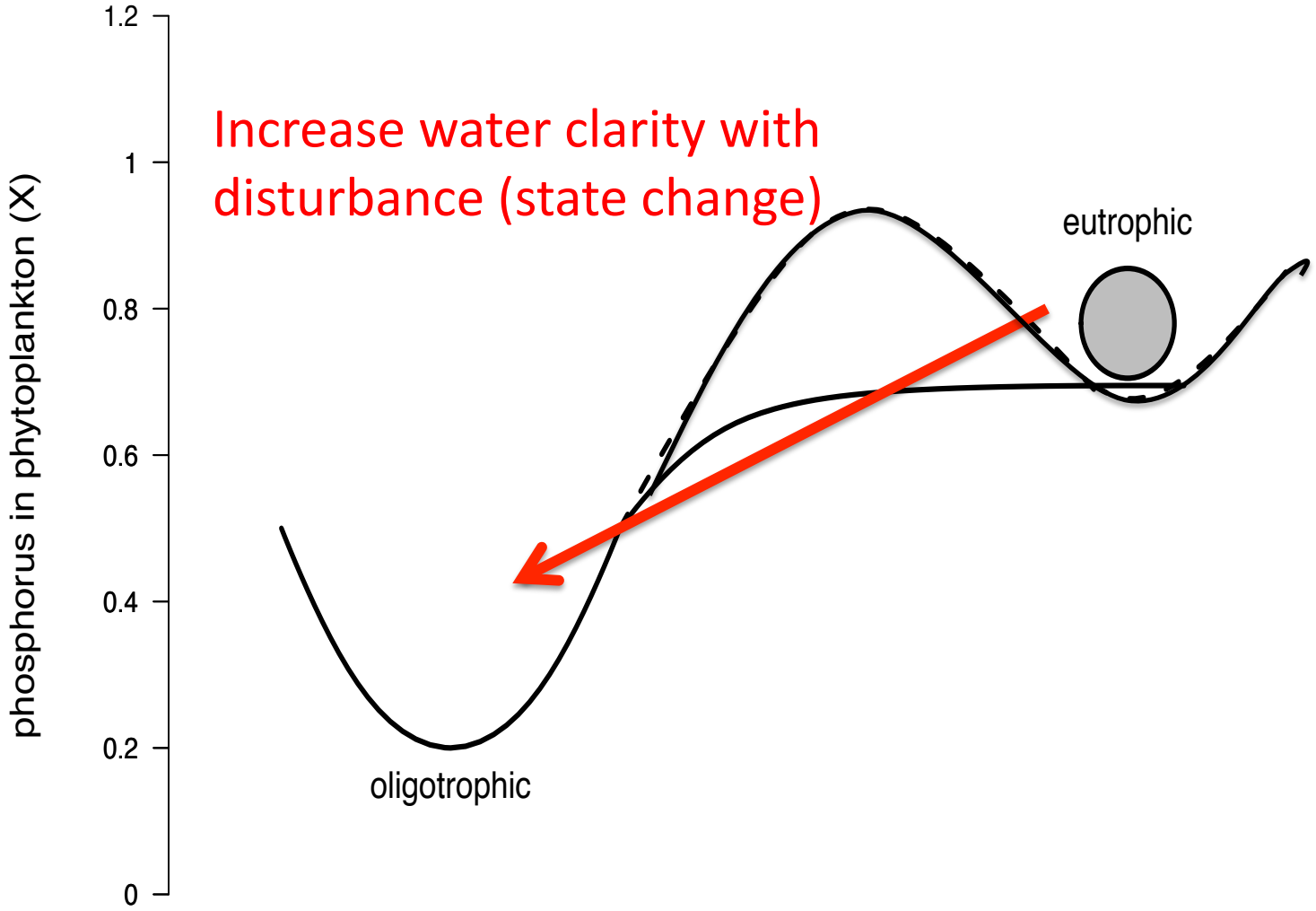
Francis et al. in prep

Scheffer et al. (2001) changing lake clarity: alter the system (1 stable state)



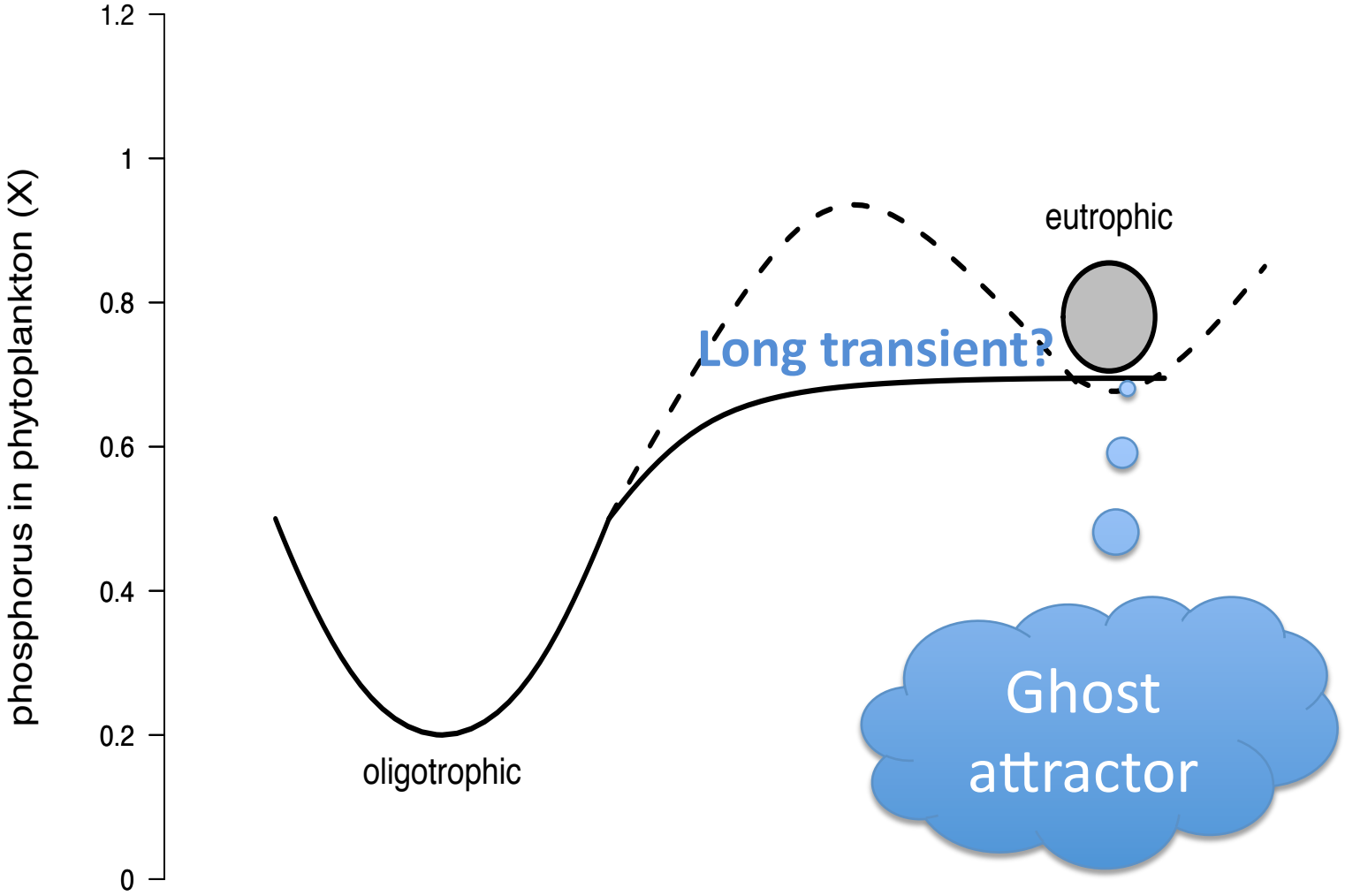
I probably SHOULD have cut this slide

Scheffer et al. (2001) changing lake clarity: Disturb the system (2 stable states)

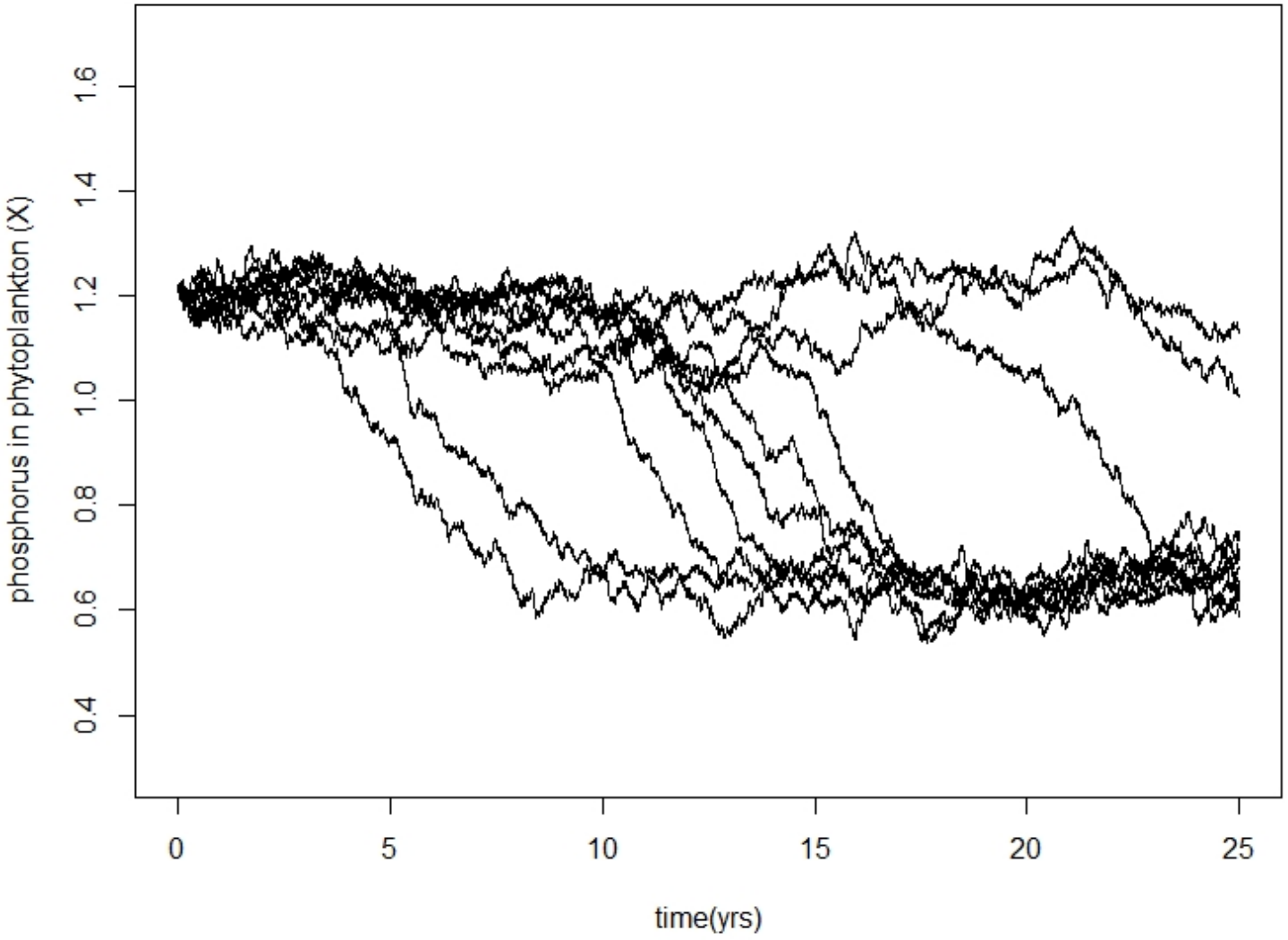


Or maybe this one

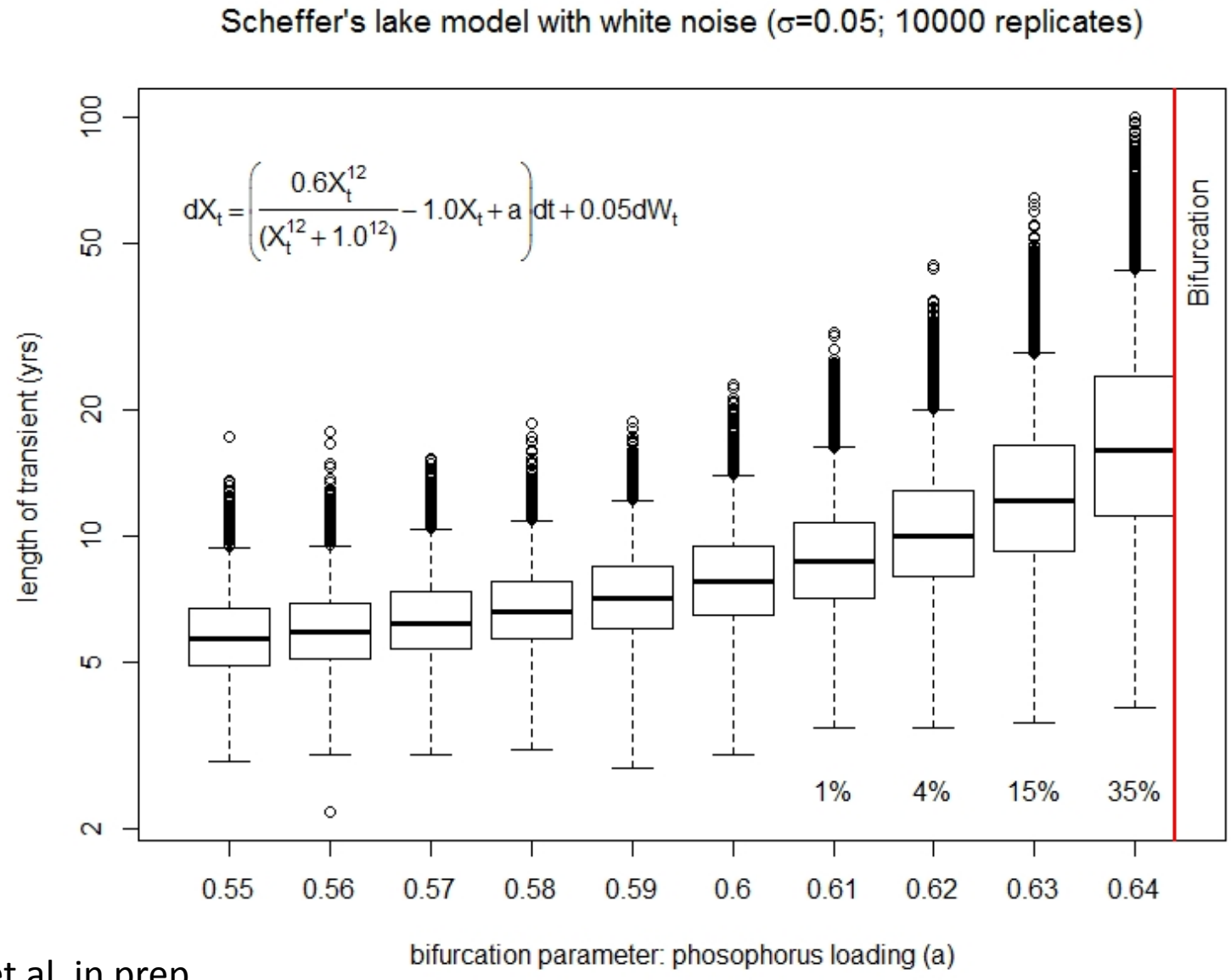
Scheffer et al. (2001) changing lake clarity: Long transient after alteration (1 stable state, 1 ghost attractor)



Long transients in the Scheffer model (eutrophic state is UNSTABLE)



Long transients close to bifurcation (eutrophic is UNSTABLE)



Francis et al. in prep

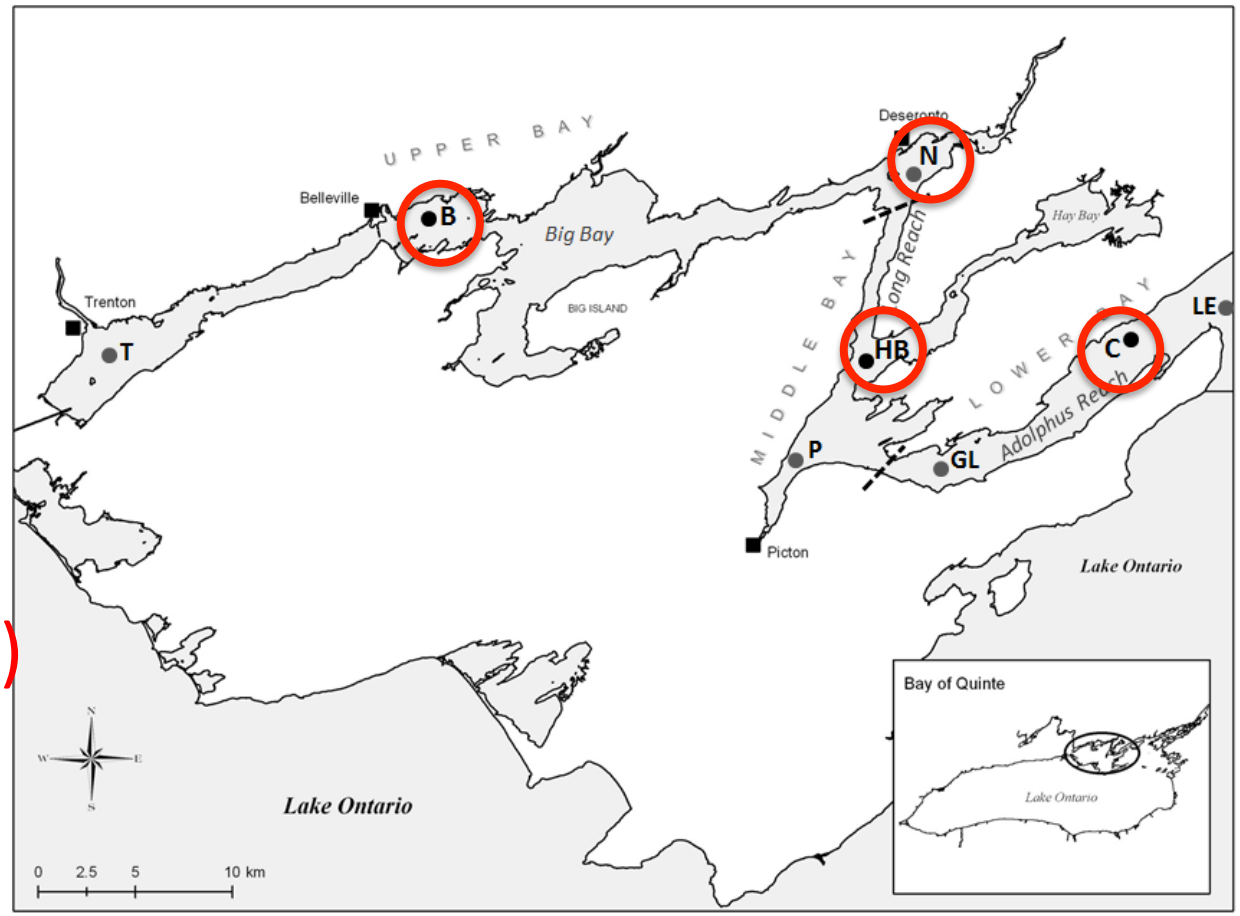
Project Quinte (DFO, MNRF, MOECC)

1972-present

- Belleville (upper)
- Hay Bay (middle)
- Conway (lower)

Early (1970s+)

- Trenton
- Napanee (middle)
- Picton
- Glenora



But really, some of the slides are quite quick…

Quinte Selected Data: Sampling May-Oct Weekly until 1980, then bi-weekly

GeoChem

- Conductivity
- Dissolved Oxygen
- pH, Alkalinity, Hardness
- Cl^-, Na^+, SO4-, Mg^{2+}, Ca^{2+}, K^+
- Iron, Silica
- $NO3^-$, $NO2^-$, $NH4^+$,TKN
- SRP, TP, TDP

Physical

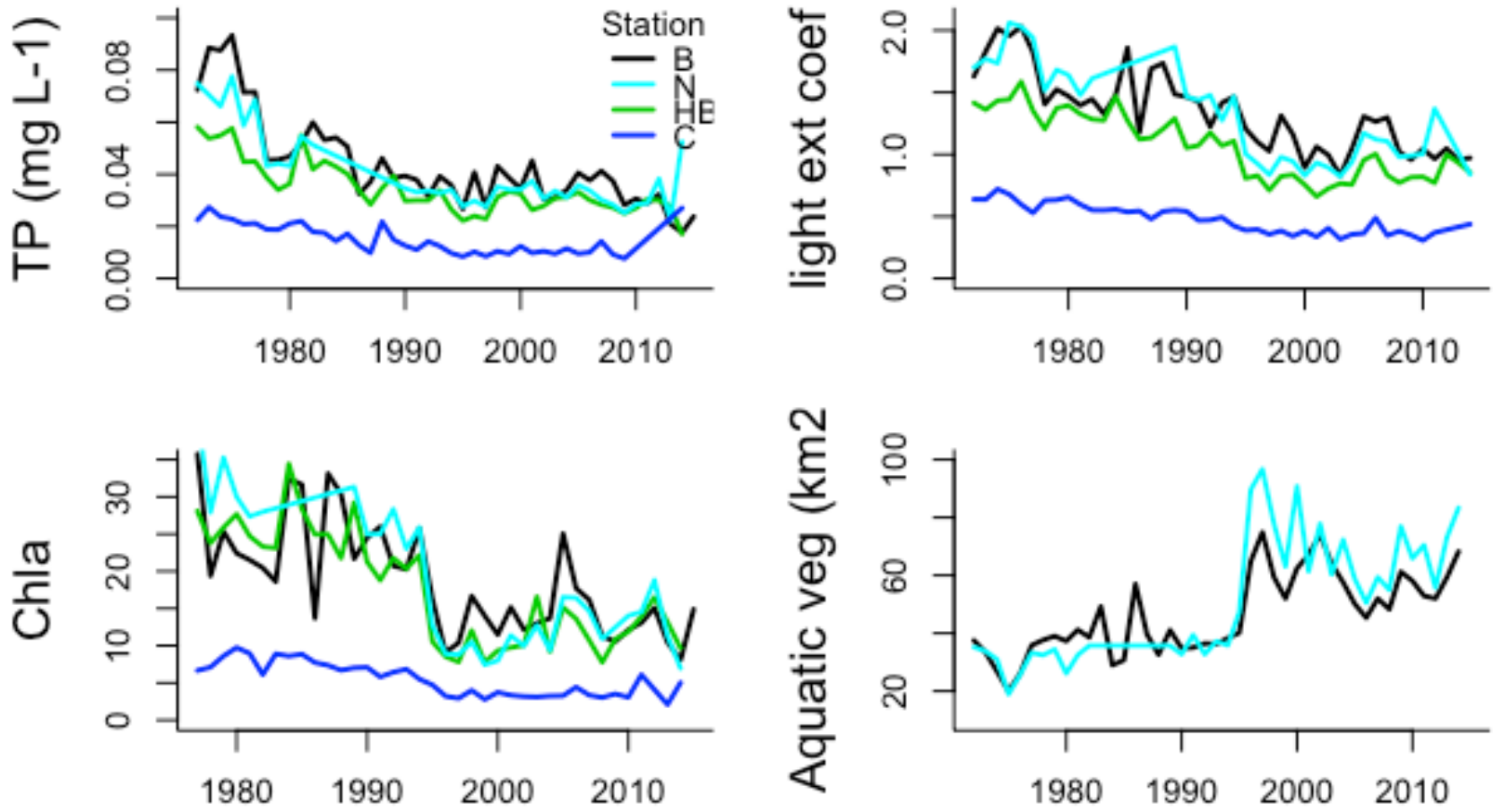
- Light Attenuation/Secchi
- Temperatures (epi, hypo)
- Station Depth, Z mixing
- Euphotic Z (1% & 0.5%)
- Weather, CFB Trenton
- PAR
- River discharge, water level

Bio and Carbon

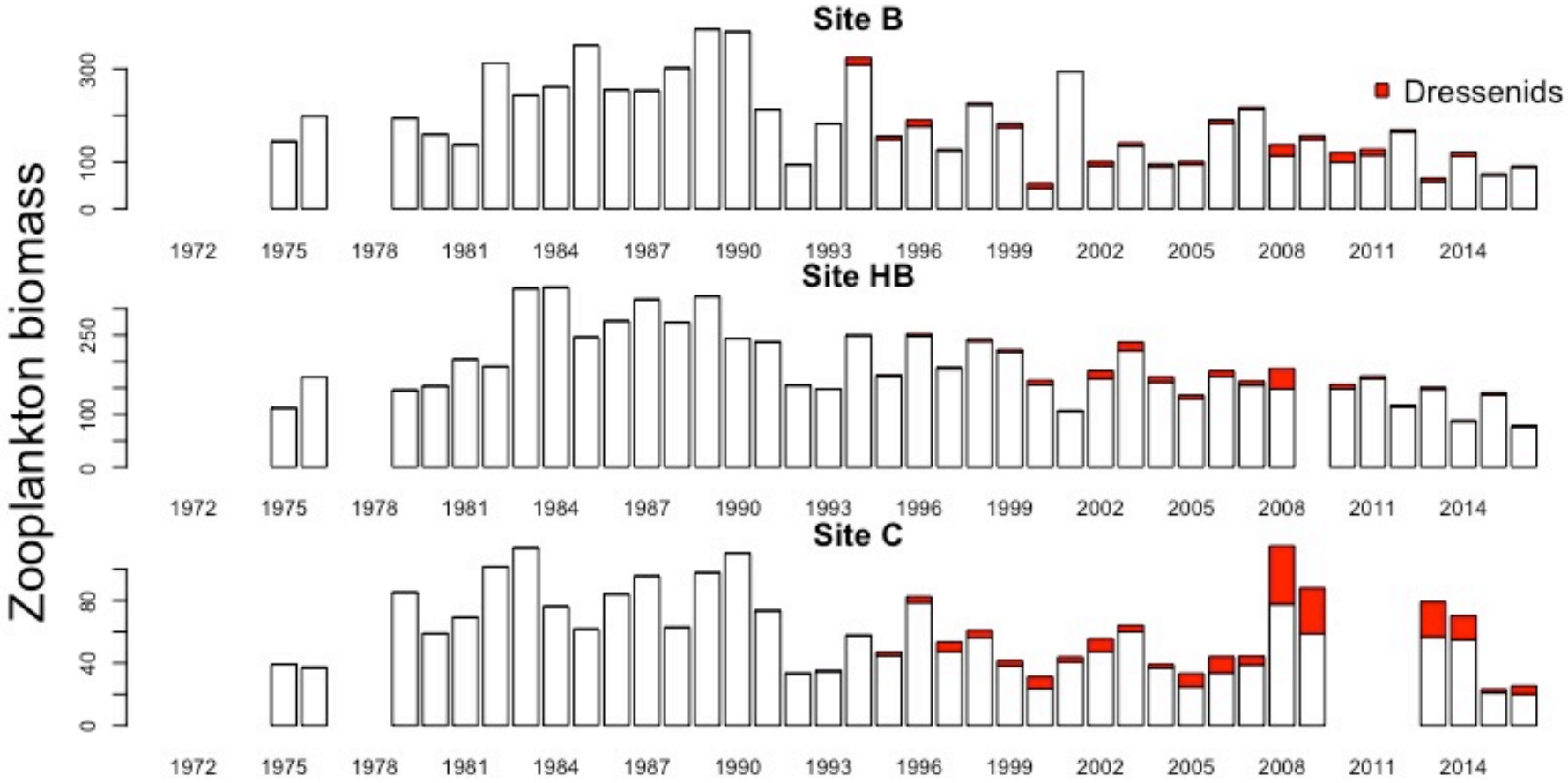
- DIC, DOC
- POC, PON
- Seston, AFDW
- Benthos density, biomass
- Macrophyte density, % cover
- Chl, Total Phyto Biomass, taxonomy
- Bacteria, APP, HNF, Ciliates
- Rotifers
- Zooplankton density, biomass, taxonomy
- Fish density, biomass
- Size-fractionated productivity
- Bacterial productivity
- Zooplankton production

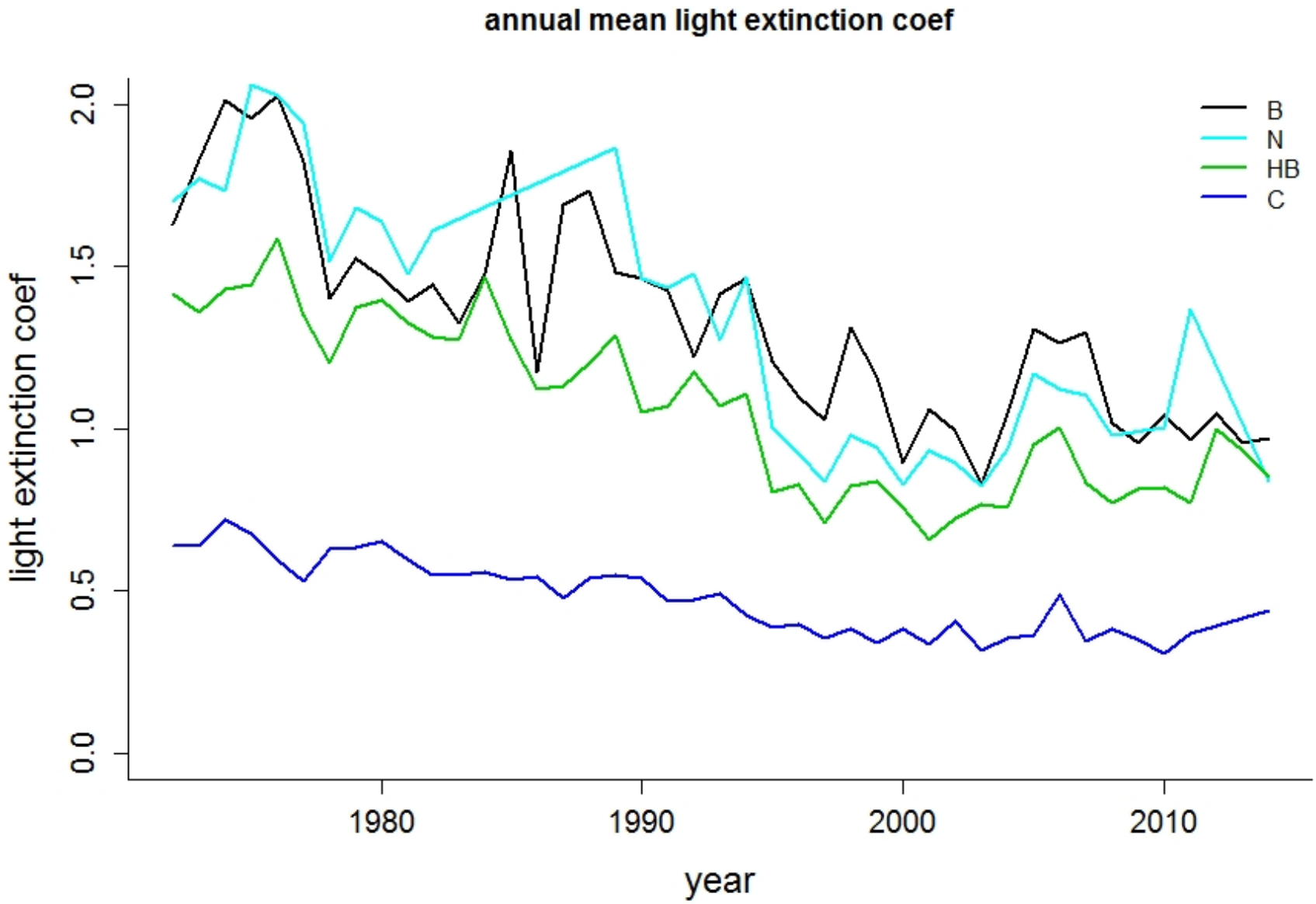
80+ Measures

Focus on 4: TP, light, Chla, macrophytes

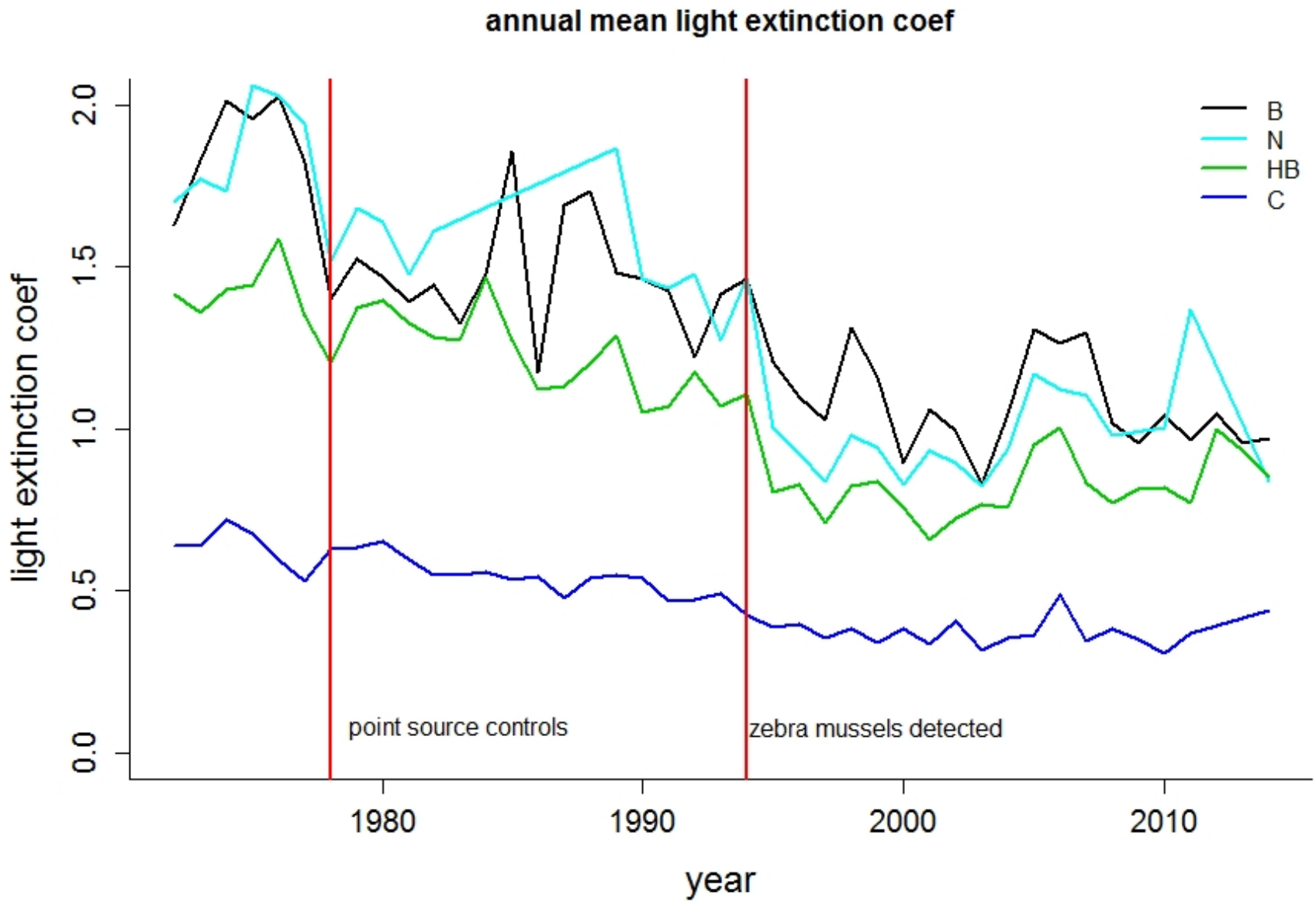


Did dressenid mussels increase water clarity (or decrease Chla), and cause the increase in macrophytes?



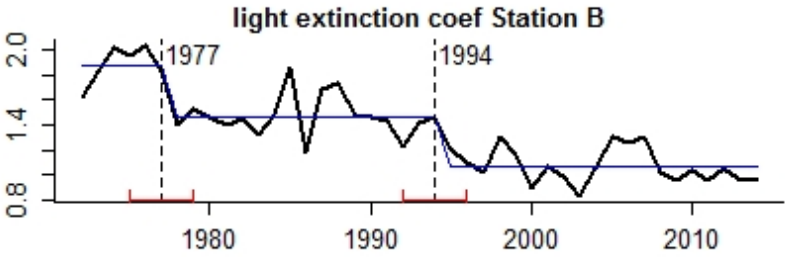


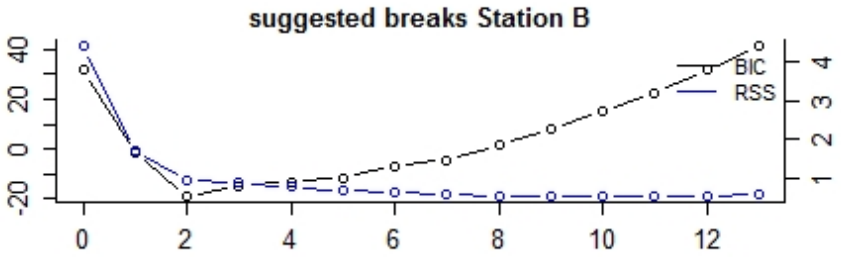
Like this one… WAAAY less than 1 minute per slide

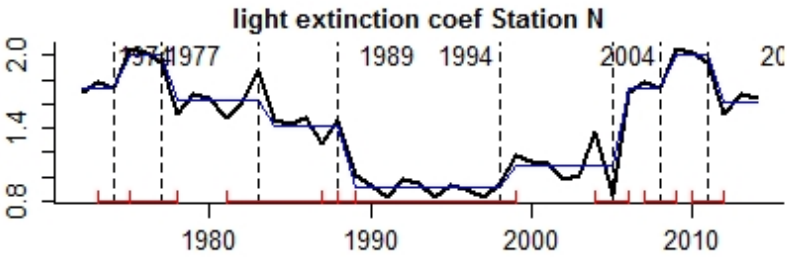


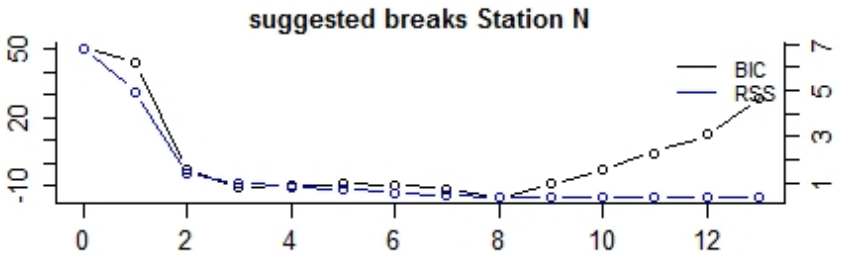
See what I mean?

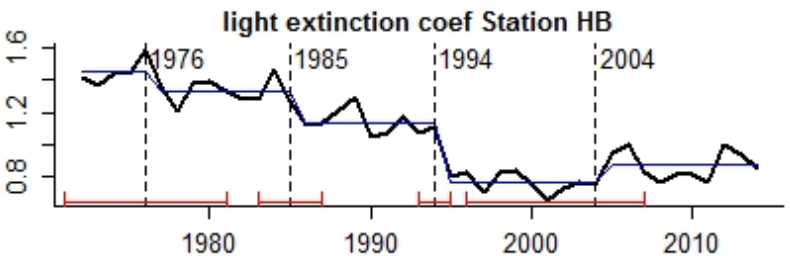
Breakpoint Analysis: Water Clarity

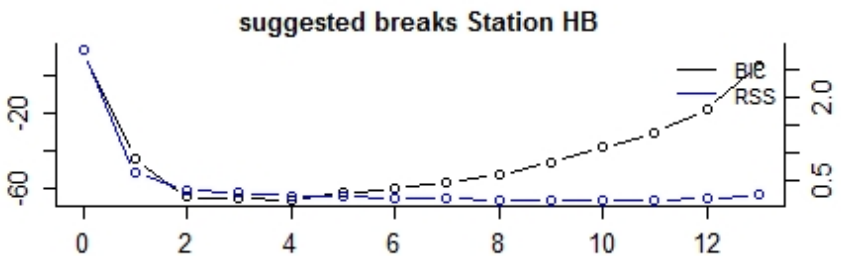


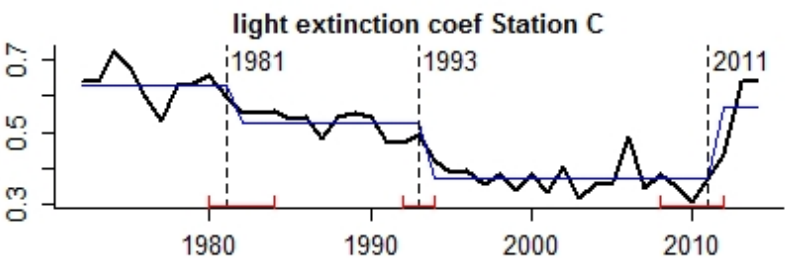


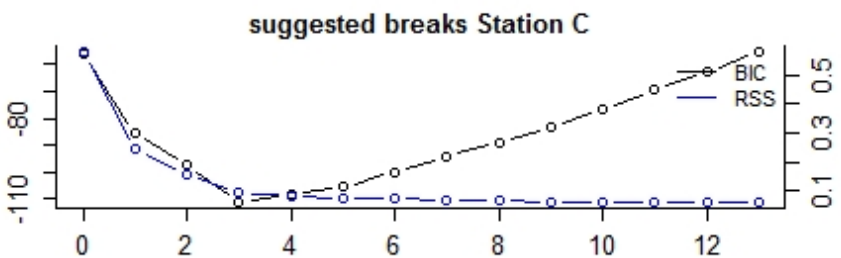




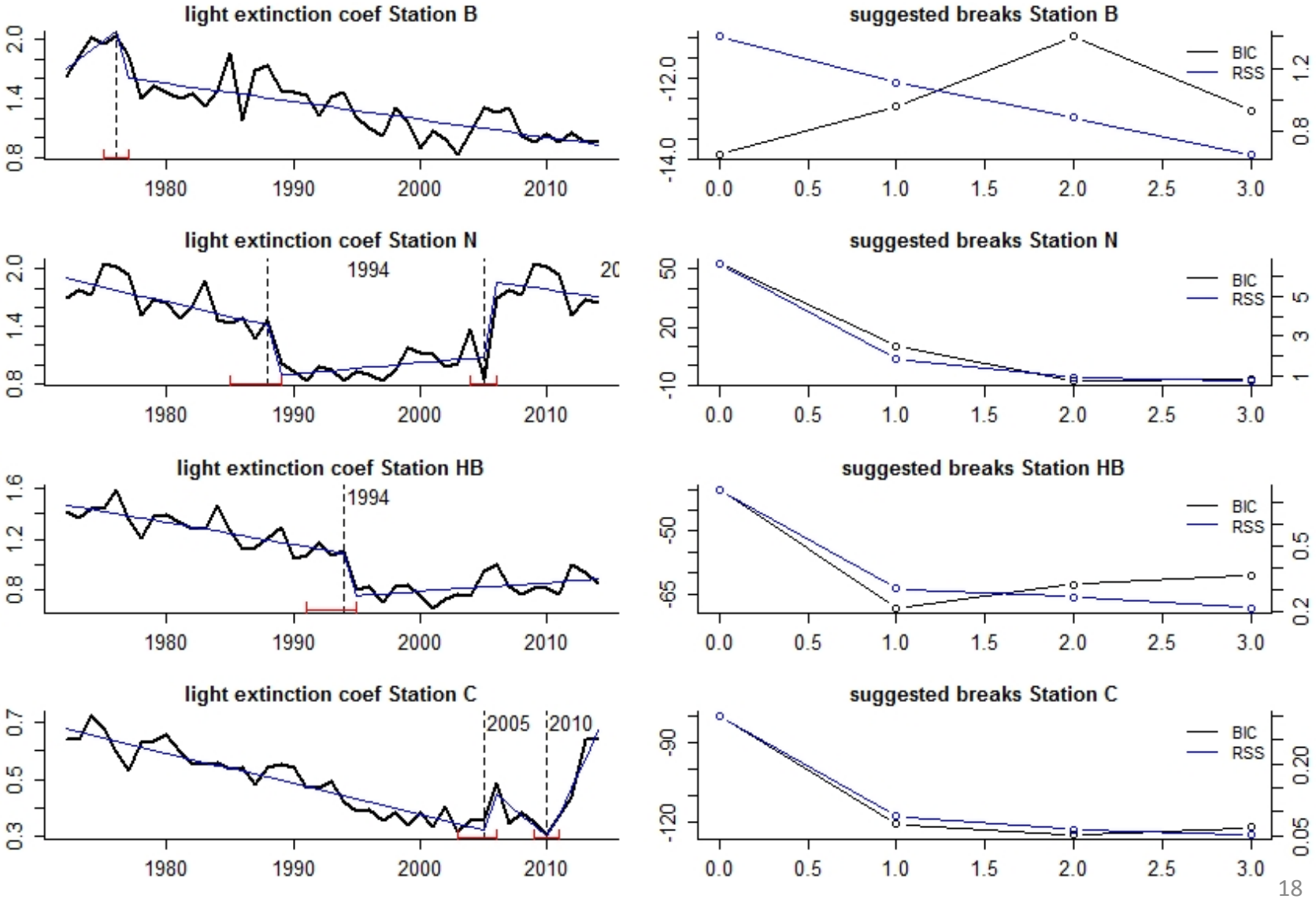








3 Breakpoints: Level and slope



Use GAMs to look at rates of change in Bay of Quinte

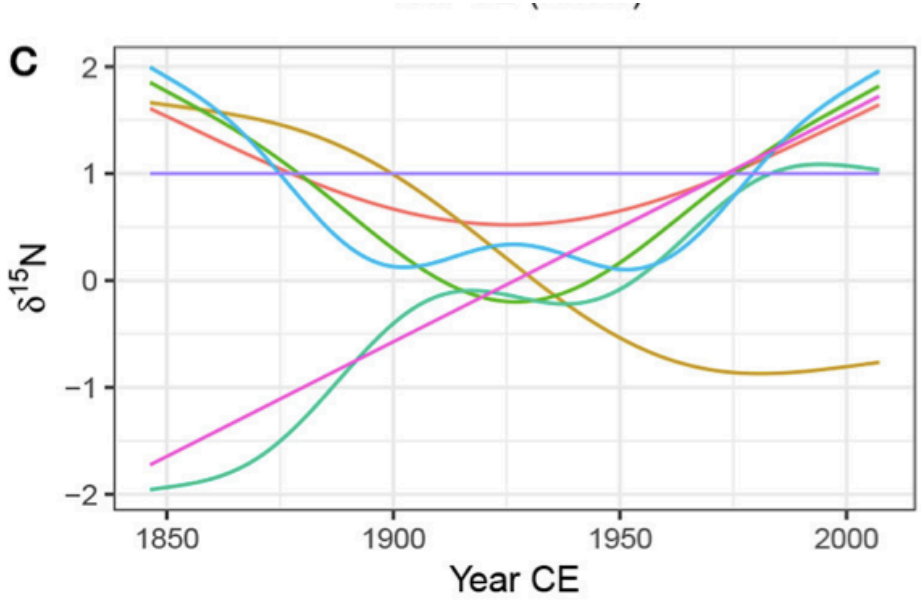
- Linear trend $$\mathrm{E}(y_i) = \beta_0 + \beta_1 x_i$$

- GAM $$\mathrm{E}(y_i) = \beta_0 + f(x_i) x_i$$

- If f(x) is a smooth trend, we can differentiate to get the rate of change as a function of year
- Determine if the fastest rates of change are associated with introduction of zebra mussels (i.e., is the rate of change diff from zero?, +ve, -ve?)

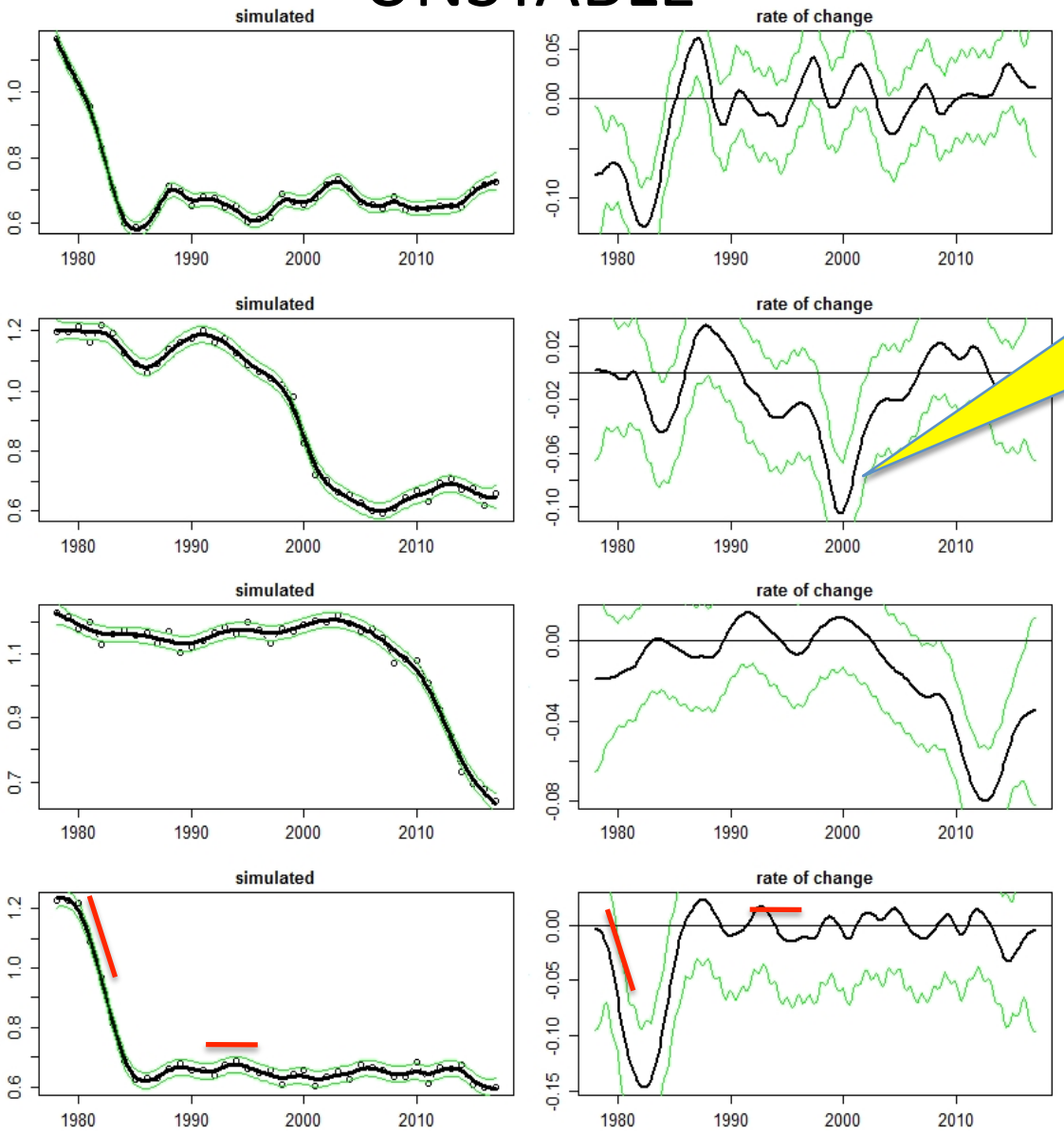
Generalized Additive Models (GAMS) for Quinte

- Thin plate regression splines fit using REML



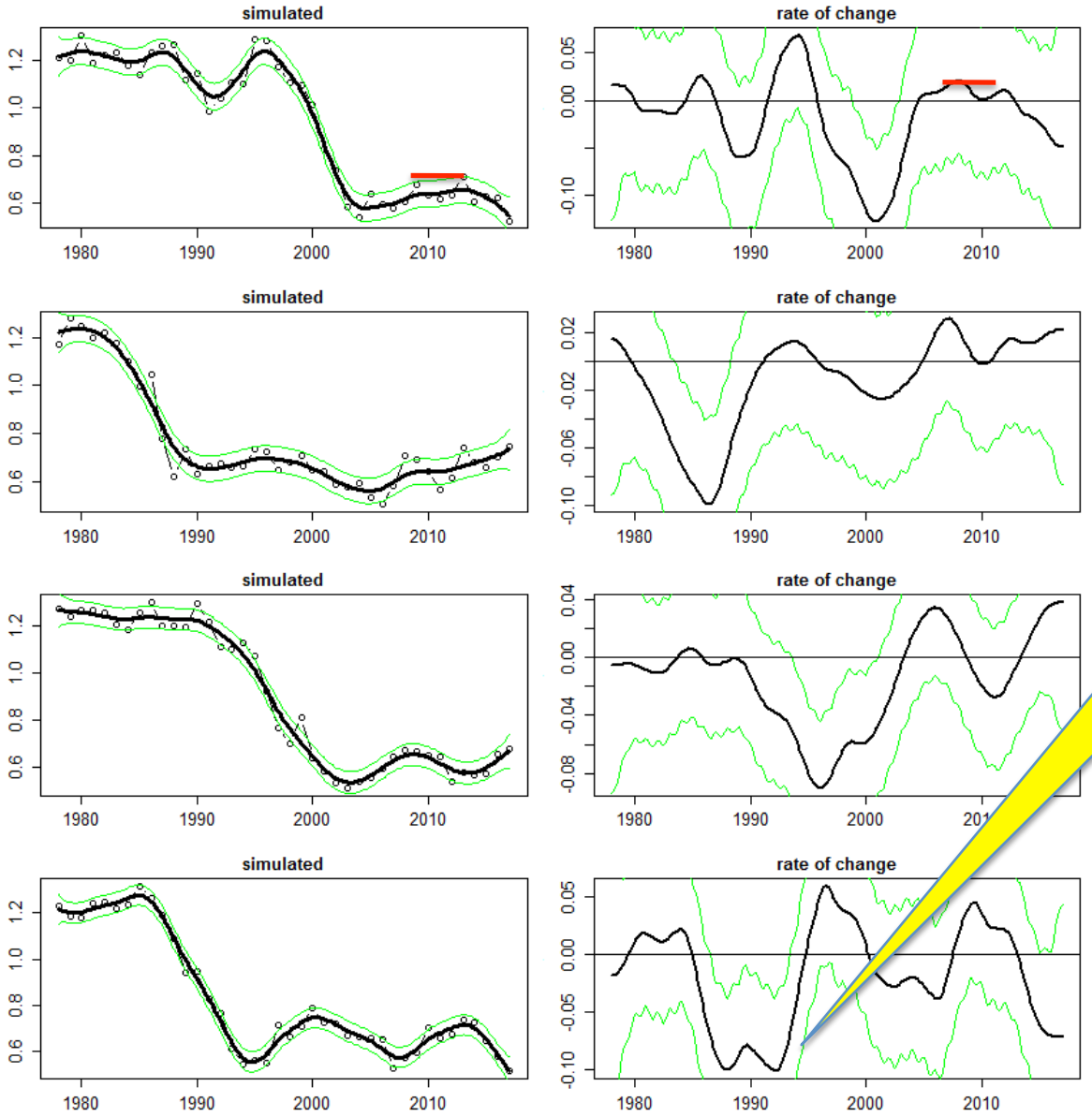
Simpson, G. (2018) *Frontiers in Ecology and Evolution* 6: a149
Pedersen, E. J., Miller, D. L., Simpson, G. L., & Ross, N. (2019) *PeerJ*, *7*, e6876.
Pedersen, E.J., Koen-Alonso, M. & Tunney, T. (in review) Detecting regime shifts in communities using estimated rates of change.

Scheffer model: small noise, eutrophic state is UNSTABLE

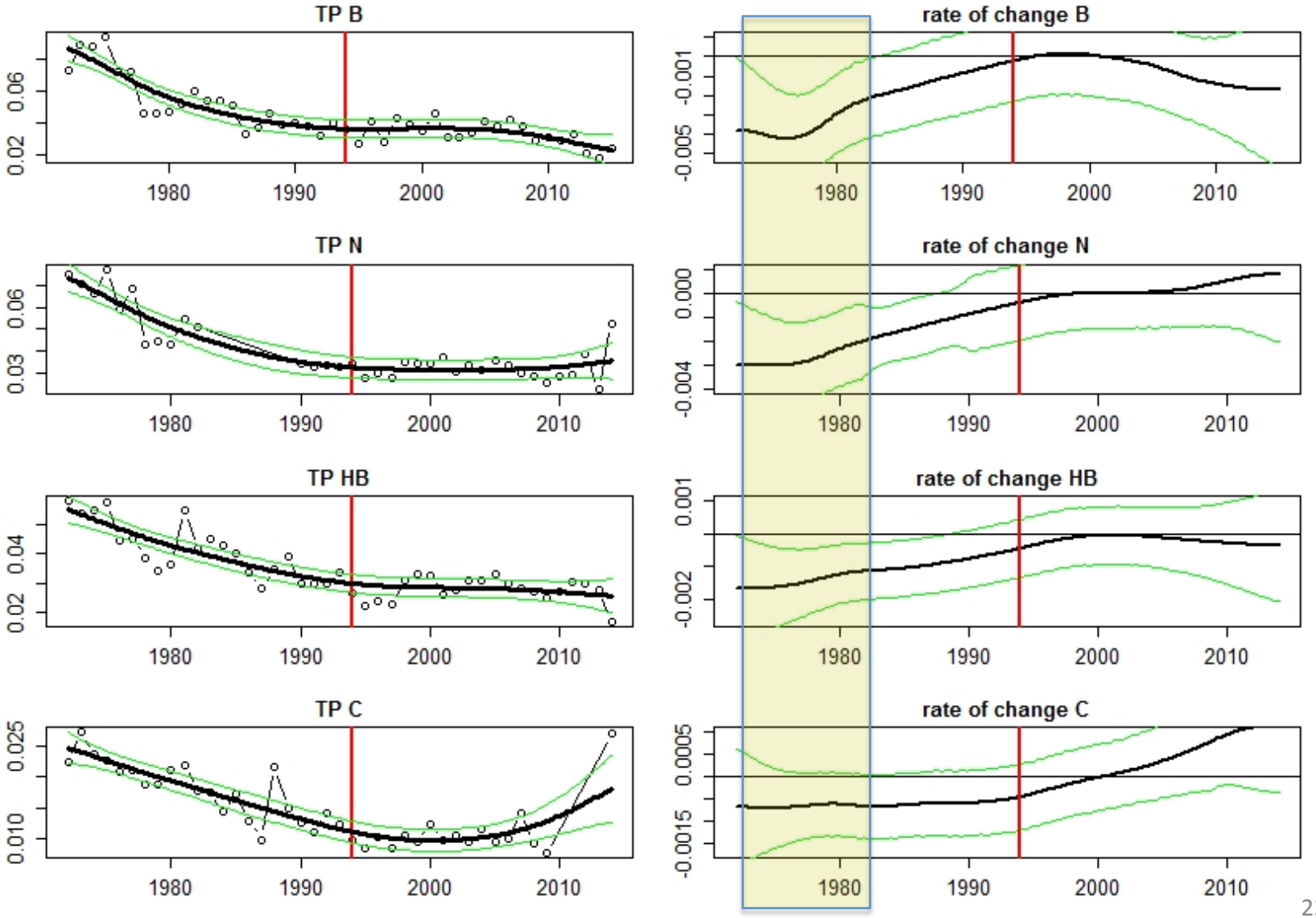


Change in system state

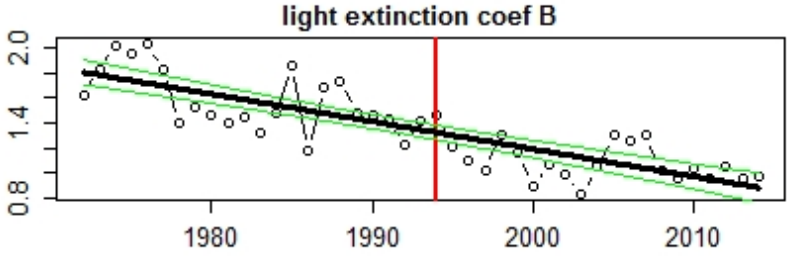
Scheffer model: large noise, eutrophic state is UNSTABLE



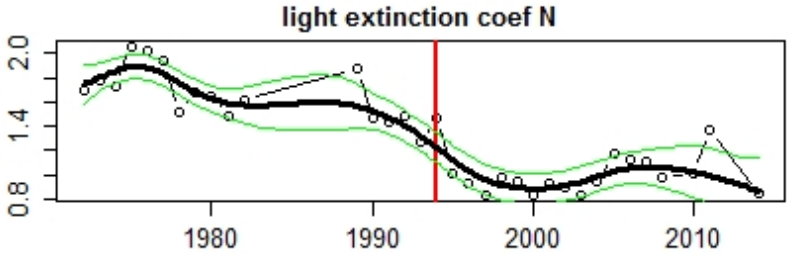
Total phosphorus: decline until early 80s

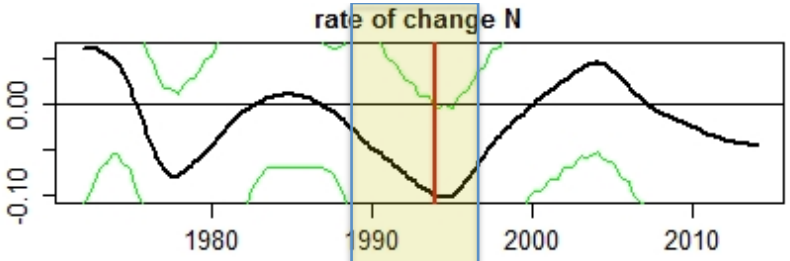


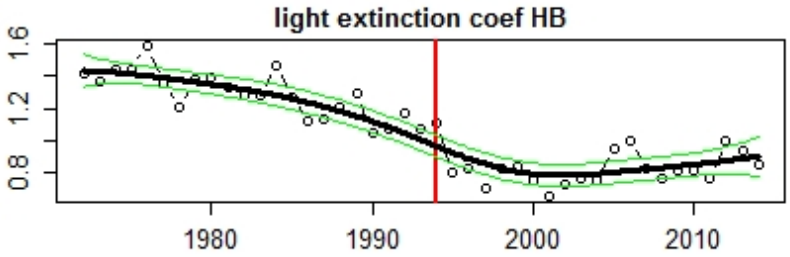
Clarity: increasing in late 80s to early 90s (decline in light extinct coef)

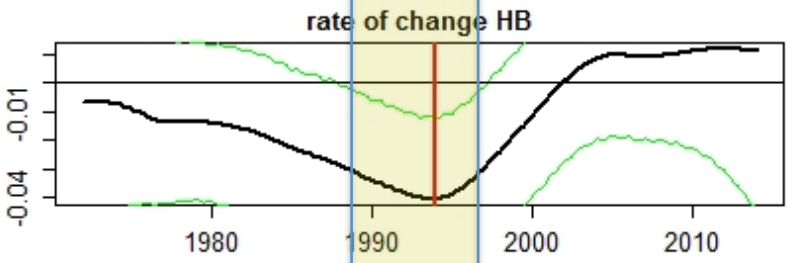


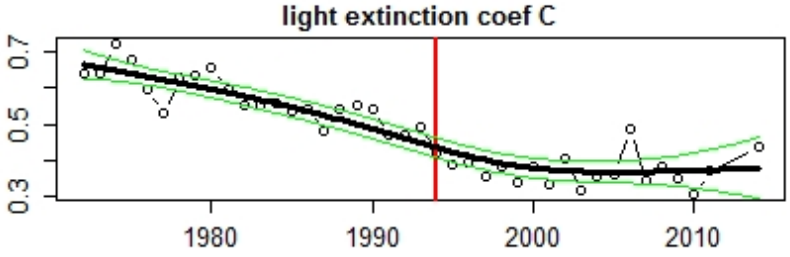
→ **Steady decline**

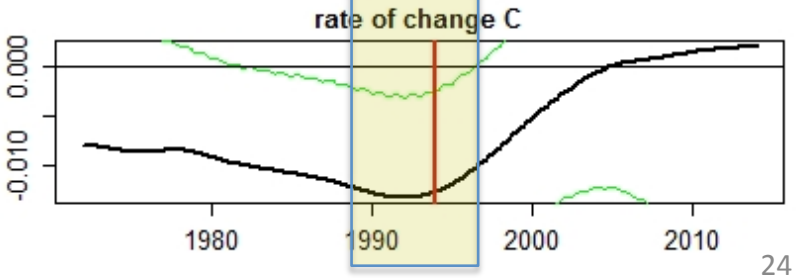




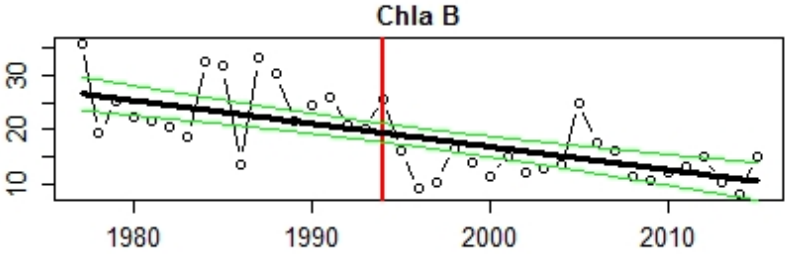




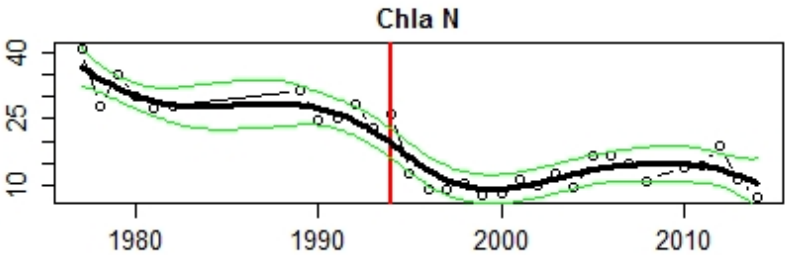


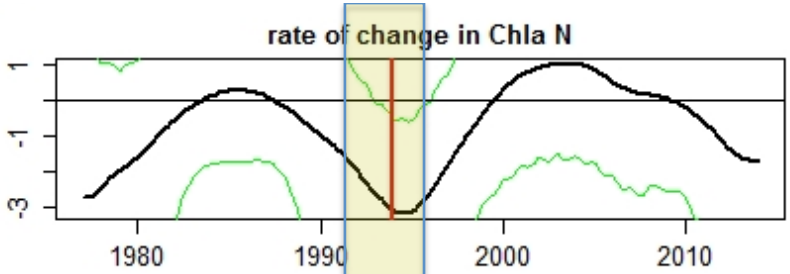


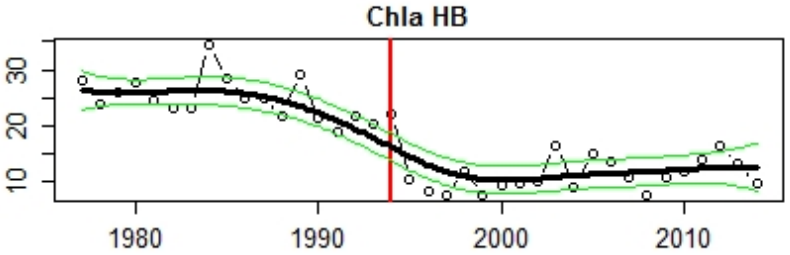
Phytoplankton (Chla): decreasing in mid 90s

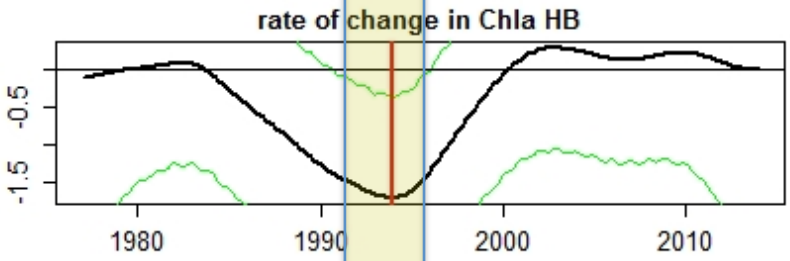


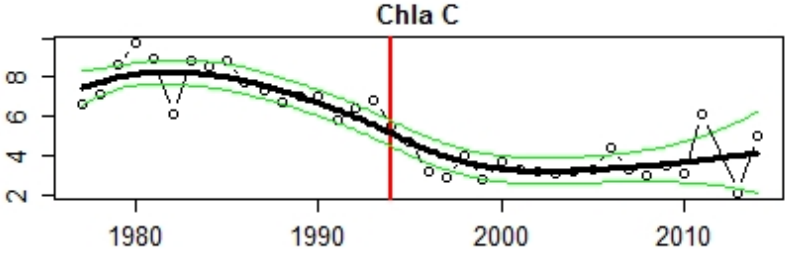
→ **Steady decline**

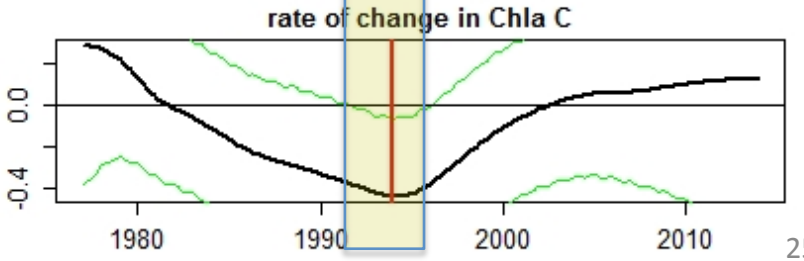




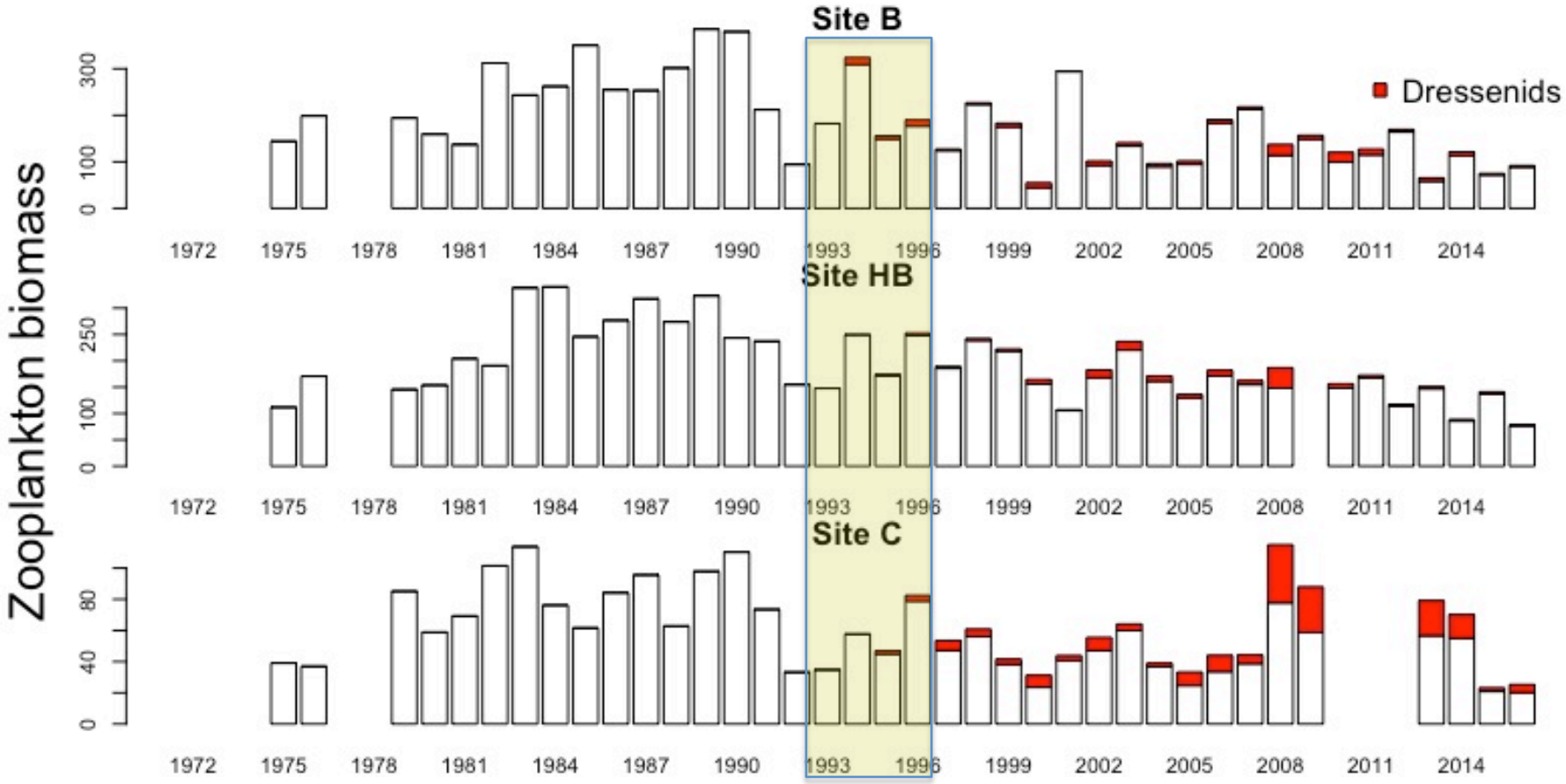






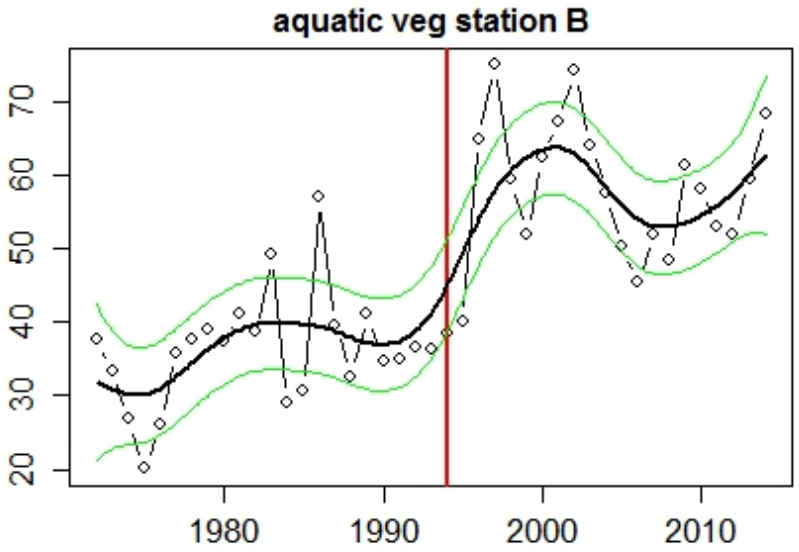


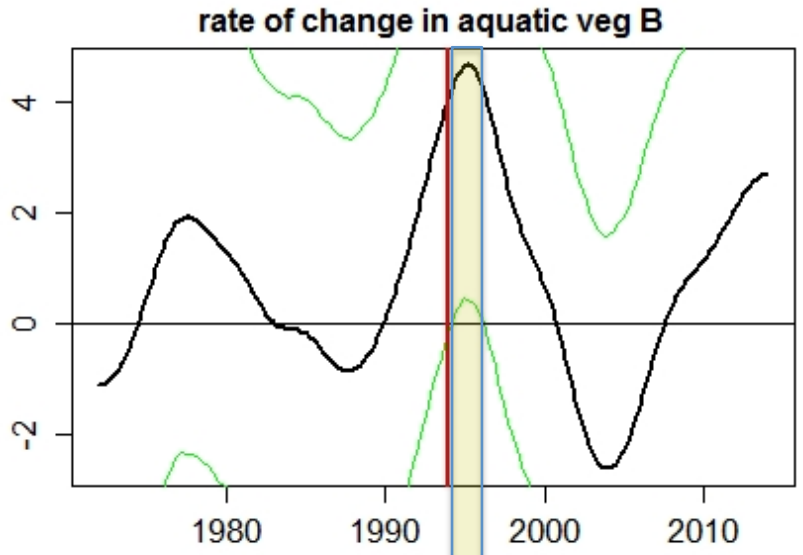
Did zebra mussels increase water clarity (or decrease Chla), and cause the increase in macrophytes?

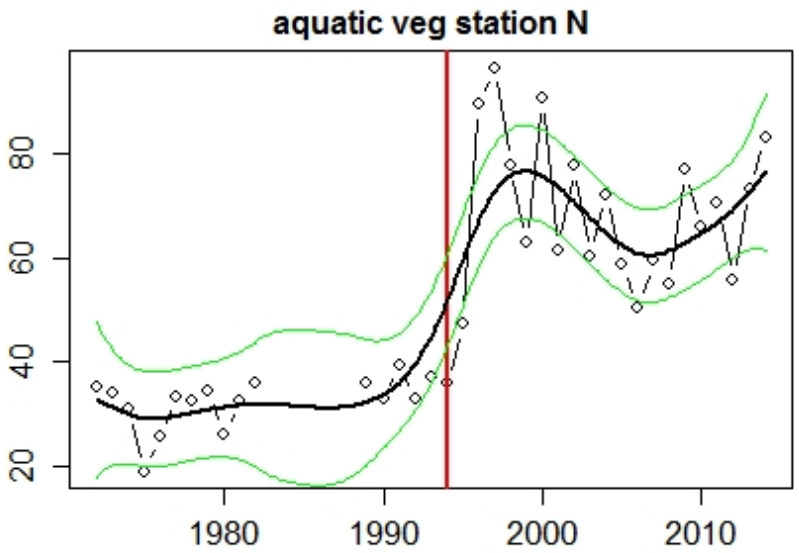


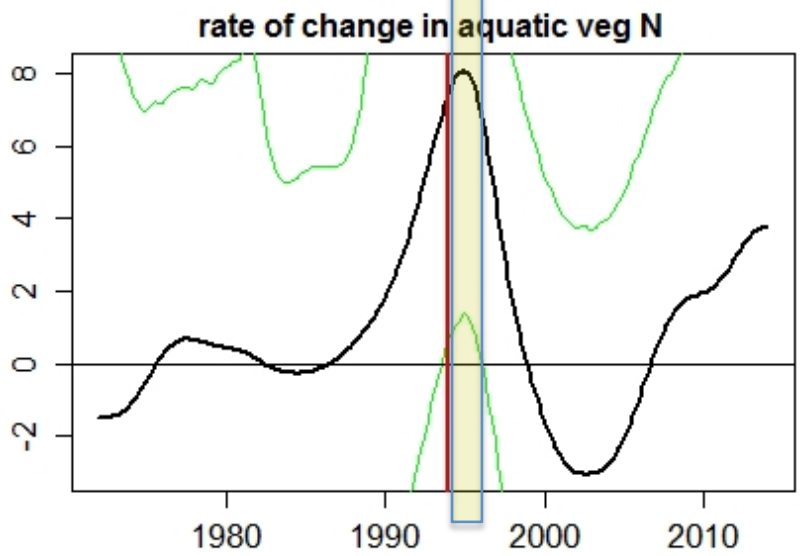
Two more….

Aquatic veg: increased in 1995-7









Rates of change different from zero

- Phosphorus decreased until ~1984
- Sites N,HB,C: Rates of change in water clarity different from zero only 1988~1996, and chla 1992~1997, when dressenid densities were still very low
- Site B: continual increase in clarity & decrease in Chla since 1977
- Macrophyte state change 1995 Site B and N

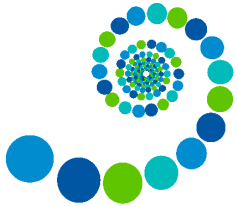
Transient or Zebra mussels?

- "Zebra mussels only" mechanism requires effects on clarity as early as 1988 at Site N (1977 at site B?)
- Also requires large effect at undetectable density, but no further effect at larger density
- Rates of change ARE consistent with a "phosphorus only" mechanism if we allow for long transients in clarity and Chla

Okay…. NOW I'm done

Thanks!

- The long line of ecologists that collected this data….
- NIMBioS Working Group: Long Transients and Ecological Forecasting (Alan Hastings, Andrew Morozov, Sergei Petrovskii, Tessa Francis, Mary Lou Zeeman, Karen Abbott, Gabe Gellner)



NIMBioS
National Institute for Mathematical and Biological Synthesis

Fisheries and Oceans Canada

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Questions?