Mis-identification of regime shift in the Bay of Quinte?

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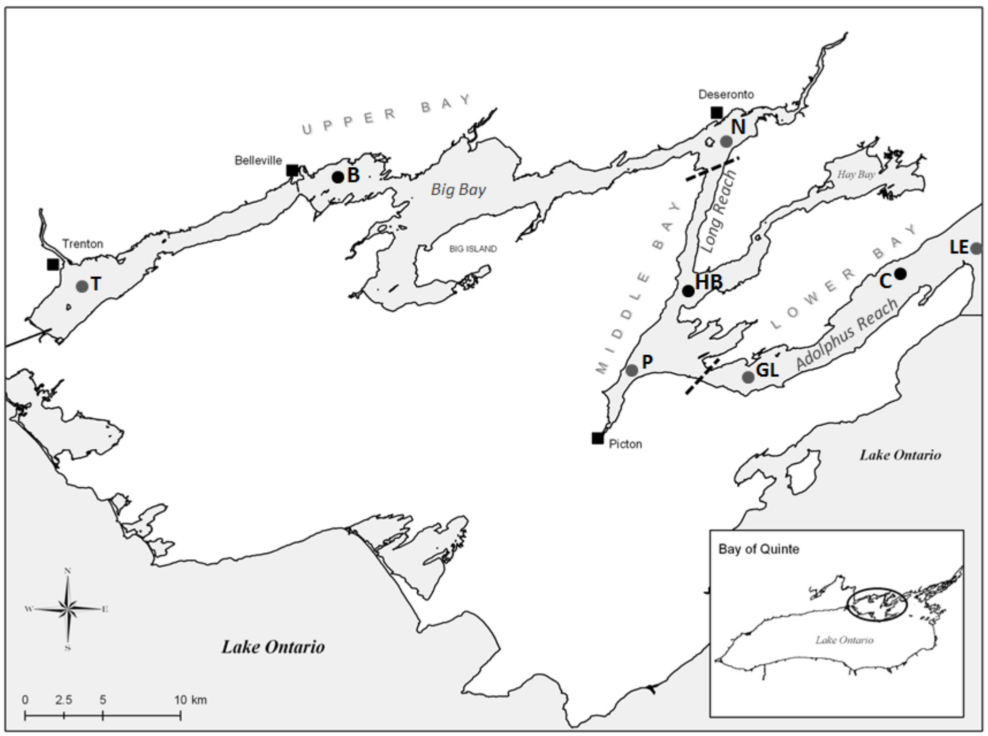
Today

1. Bay of Quinte overview
2. Review of regime shifts in a simple ecosystem model
3. Data available in Bay of Quinte
4. Analyzing temporal trends using gams and breakpoint models
5. Quinte analysis

1. Bay of Quinte Overview

Bay of Quinte

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



- B = Belleville (upper Bay)
- HB = Hay Bay (mid Bay)
- C= Conway (lower Bay)

Bay of Quinte

- history of being increasingly eutrophic
- phosphorus controls implemented 1978
- invaded by zebra mussels in 1994
- meostrophic following this

Bay of Quinte before and after mussel invasion

Standard explanation:

Disturbance shift to new stable state

“In the mid-1990s, zebra and quagga mussels (Dreissena spp.) invaded the area, **dramatically changing the water clarity because of the 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)

“… **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)

Regime shifts in freshwater systems

- frequently are cited as exemplars of regime shifts (Carpenter et al. 2011).
- classic shift is in a shallow temperate lake moving between a clear-water, macrophyte-dominated state and a turbid, phytoplankton-dominated state (Scheffer et al. 1993)
- **Capon et al. (2015) reviewed 135 papers on regime shifts in freshwater systems and found 85% of lacked appropriate data** or other supporting evidence for their claims.
- **however, Bay of Quinte described as having strong evidence of a regime shift** (Capon et al 2015)

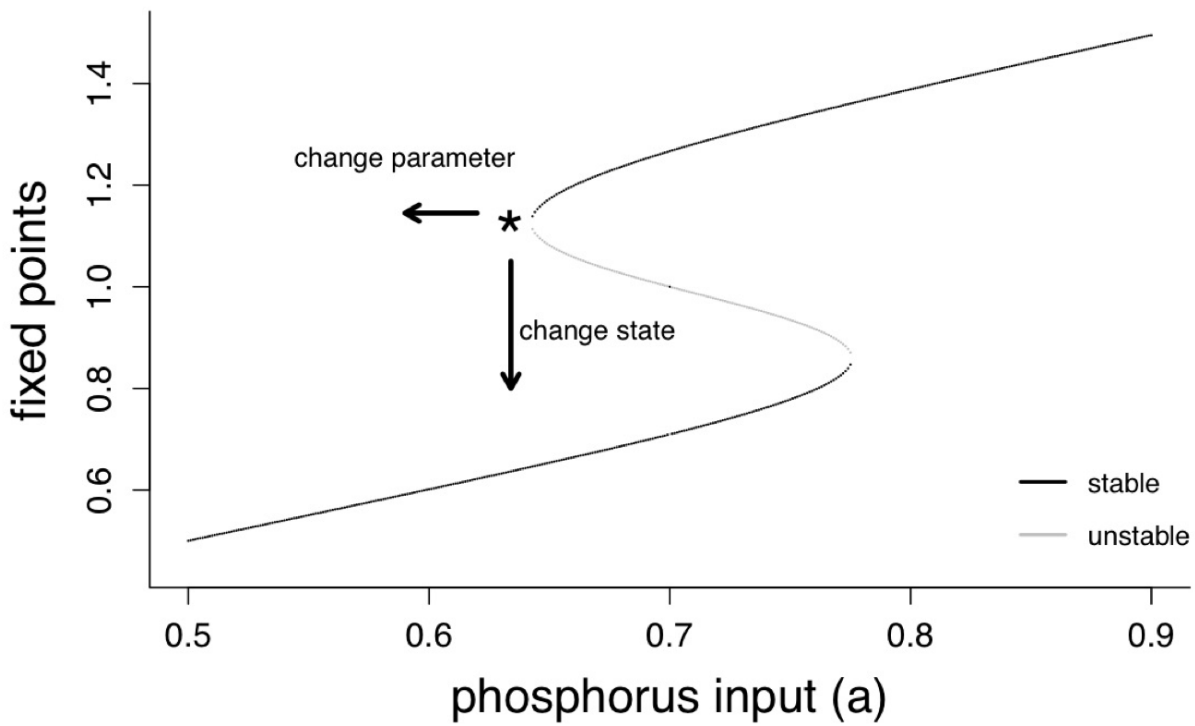
Linear response to phosphorus in freshwater systems

- recent analyses find sudden shifts between alternative stables states are a relatively rare phenomena
- **no evidence of regime shifts in 902 shallow lakes**
- instead, **a strong linear relationship between total phosphorus (TP) and phytoplankton** (Davidson et al. 2023)
- recommend a greater emphasis on nutrient reduction and a de-emphasis on regime shifts

2. Review of regime shifts in a simple ecosystem model

Regime shifts in bistable systems

- a "sudden" change in state, e.g., Scheffer (2001) $\frac{dx}{dt} = \frac{hx^{\varrho}}{x^{\varrho}+c} - bx + a$
- lake system moves from phytoplankton-dominated, eutrophic green water state to macrophyte-dominated, oligotrophic state



Francis et al. (2021)

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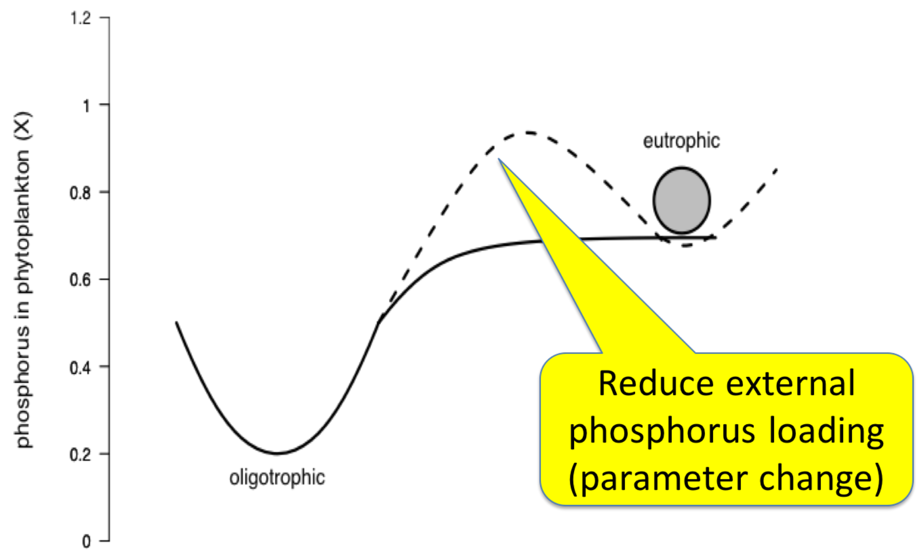
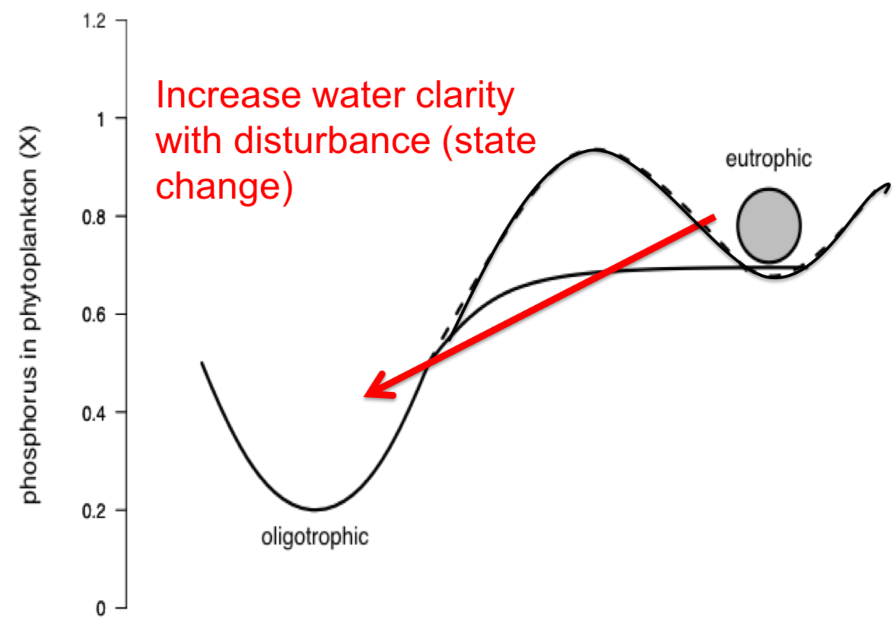
Two ways to get a regime shift

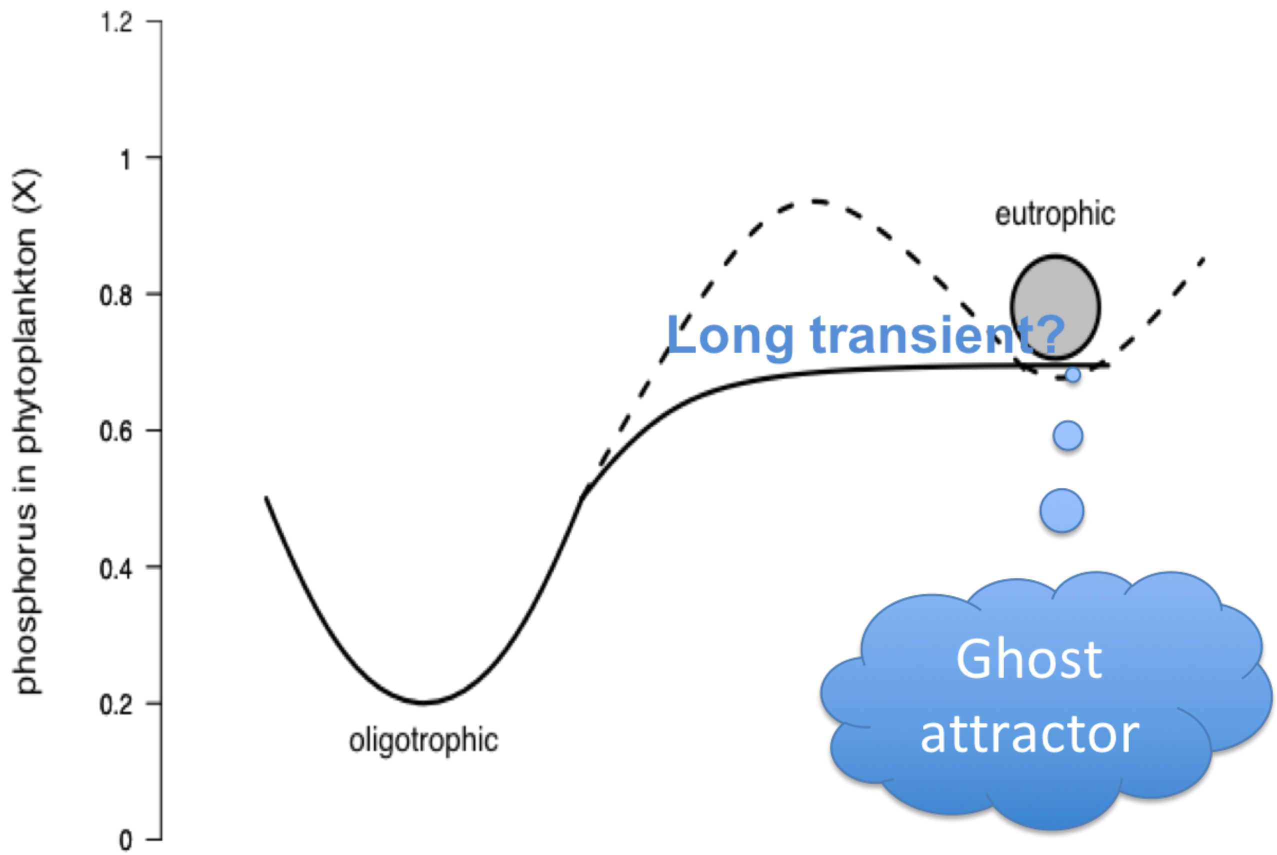
1. Erode stability of current equilibrium, or
2. Push system to second stable basin with a disturbance





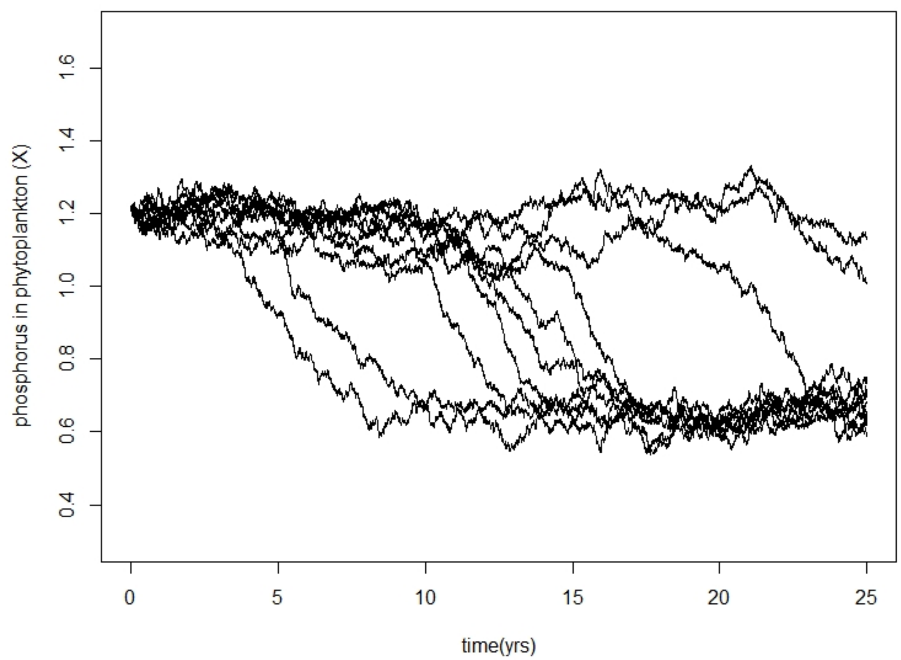
Wait… is that all the mechanistic model predicts?

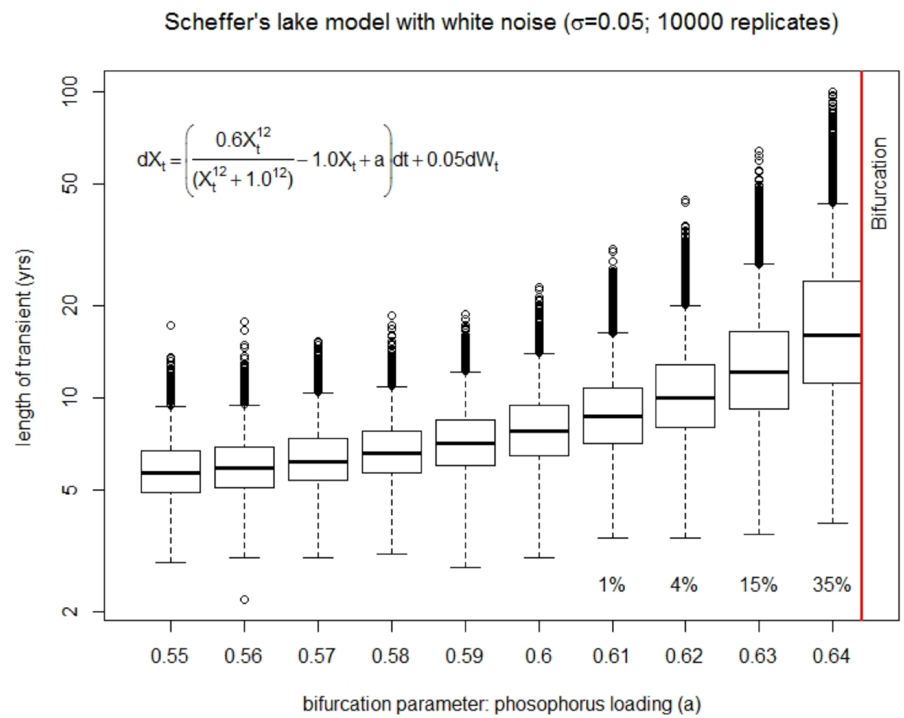
-asymptotic vs transient dynamics predicted by models



Long transients in a regime shift model

-long transients can be a quite common prediction





Alternative explanations

- all of which arise from the SAME mechanistic model

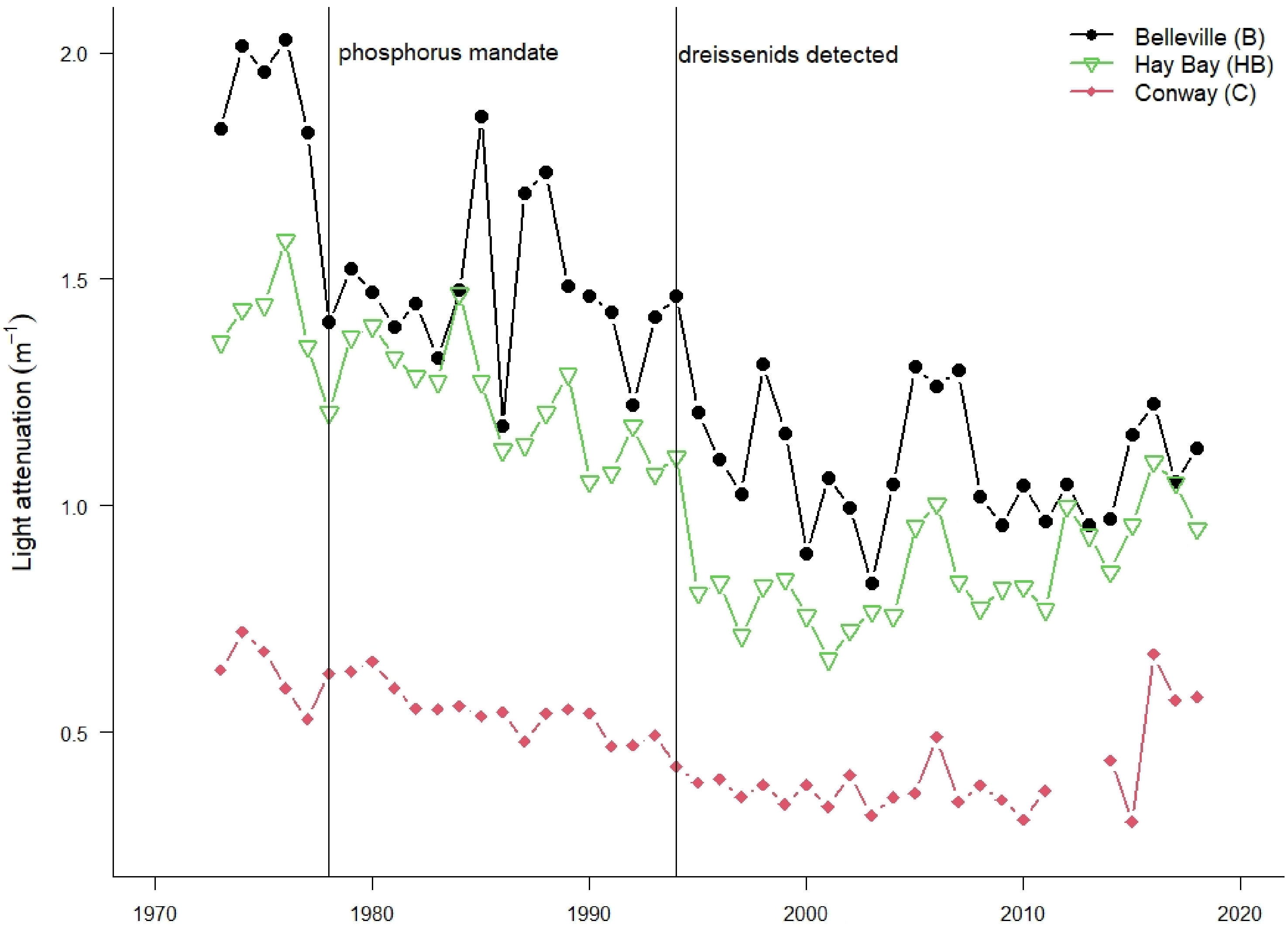
1. a regime shift to a 2nd stable state caused by the disturbance of the zebra mussel invasions
2. a long transient of the unstable eutrophic state following phosphorus control
3. slow change in phosphorus (i.e. the system does not have bistable dynamics)

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 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

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

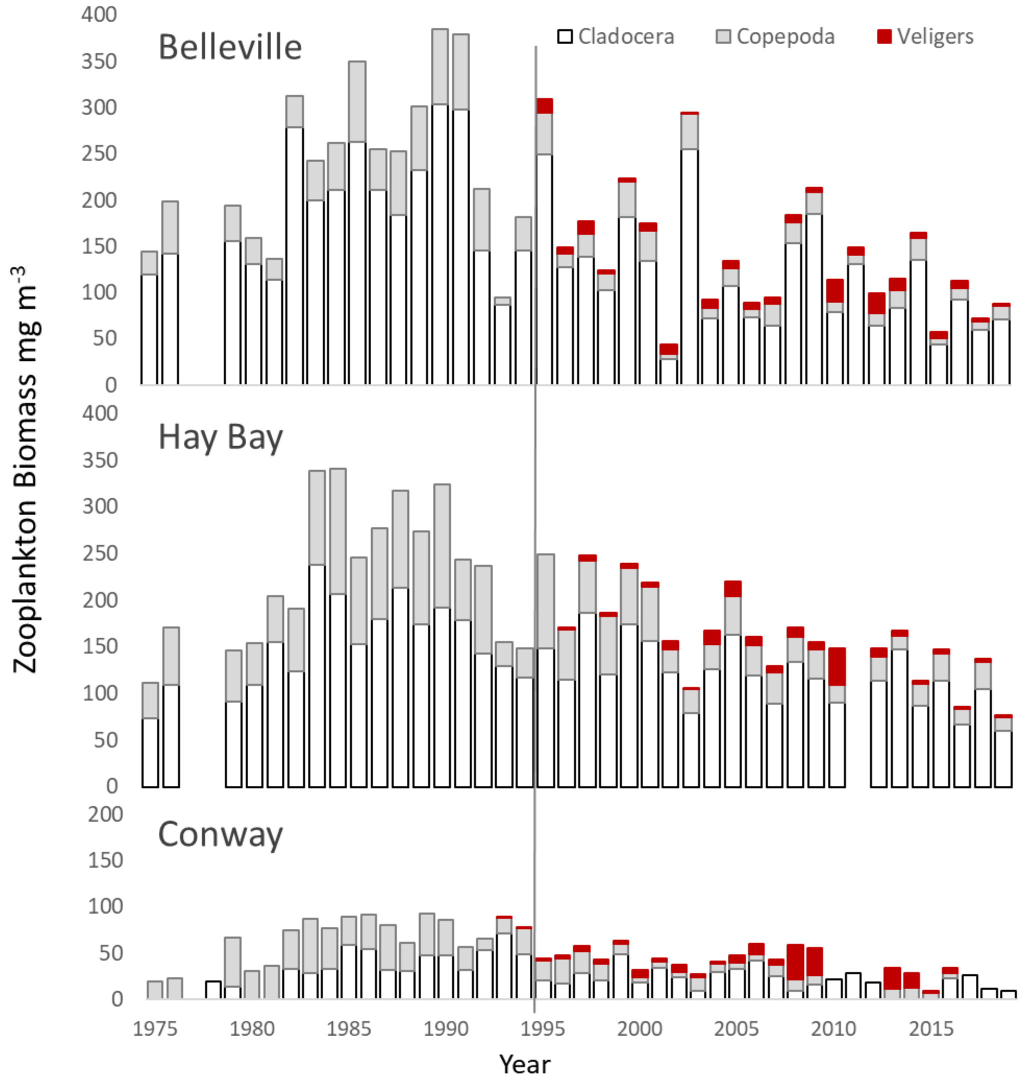
80+ Measures

Water clarity in Bay of Quinte



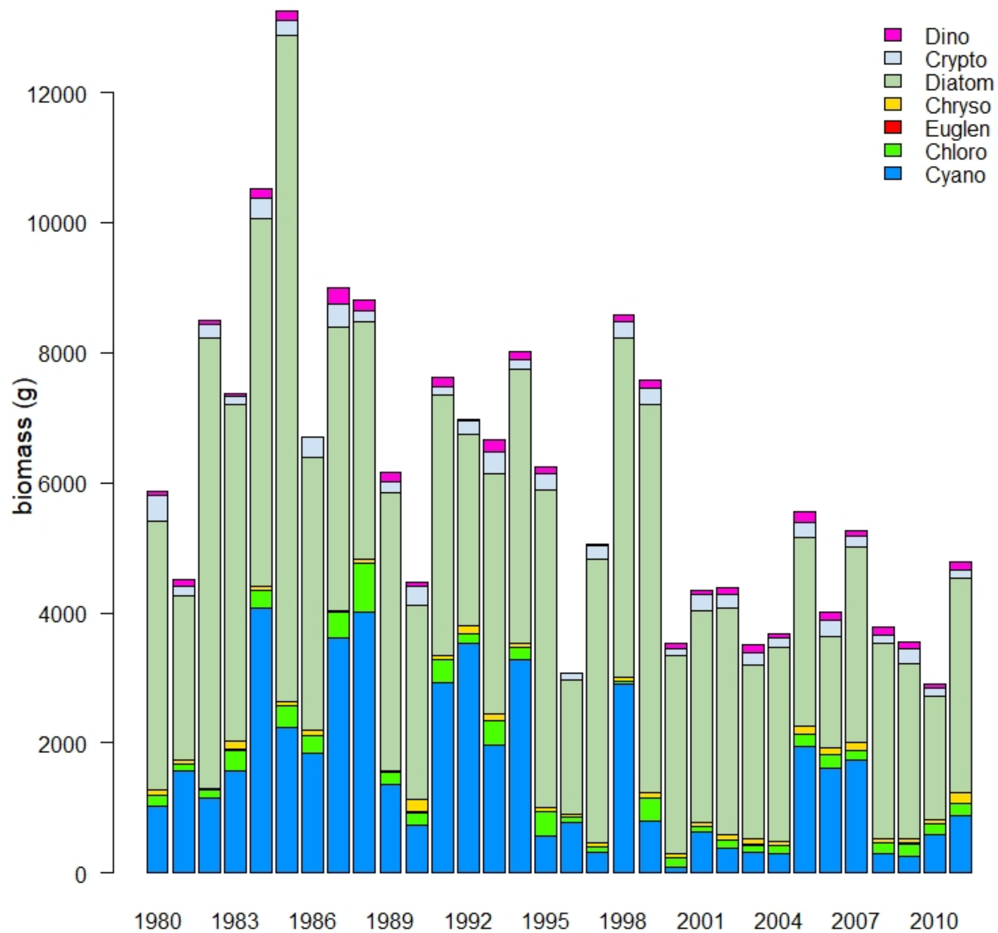
Dressenids in Quinte

- mussel veligers first detected in 1994
- very low densities



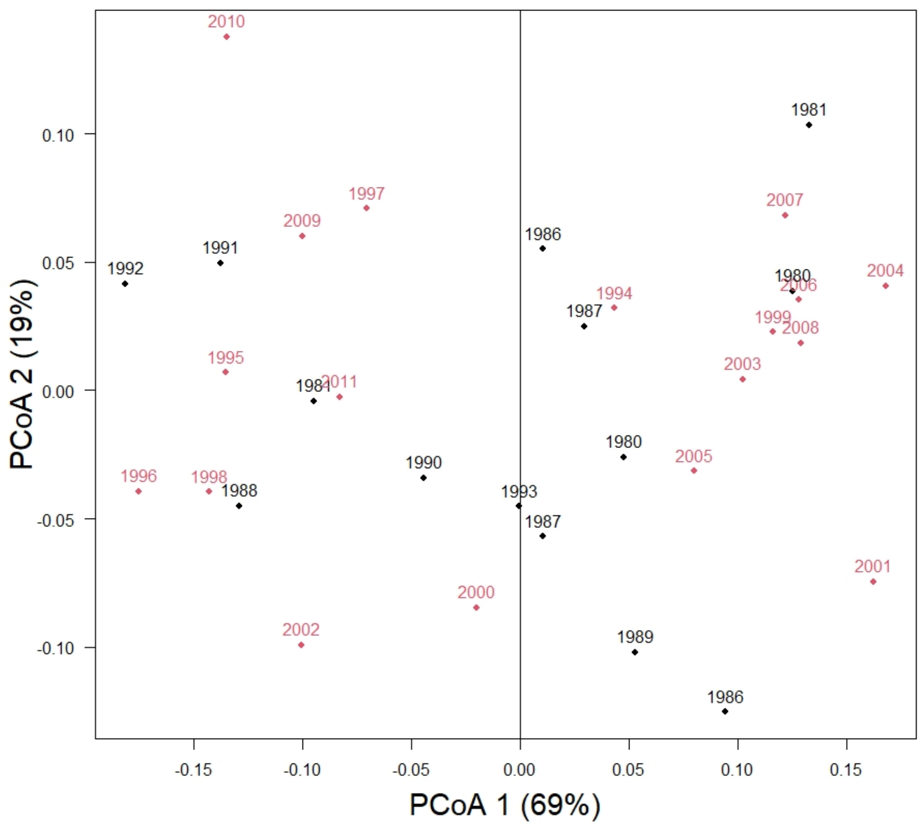
Changes to phyto community: Belleville

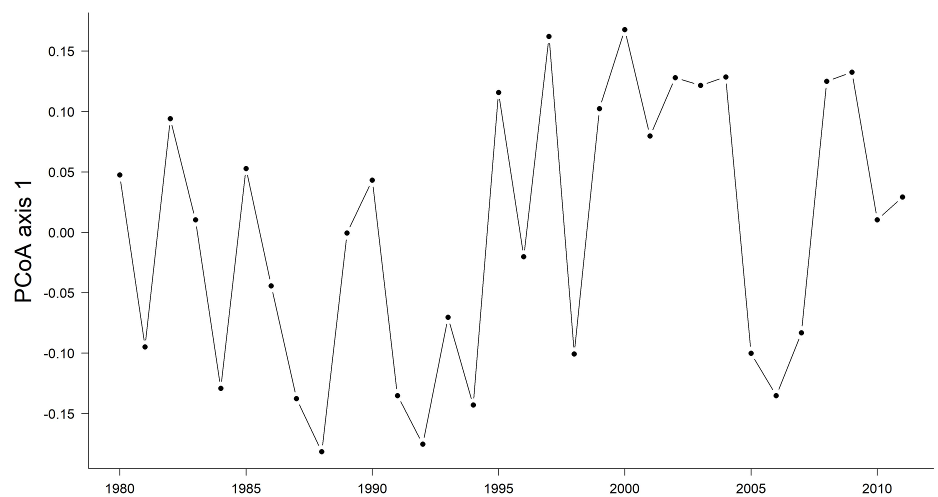
- decline in biomass over time
- greater decline in Cyanobacteria



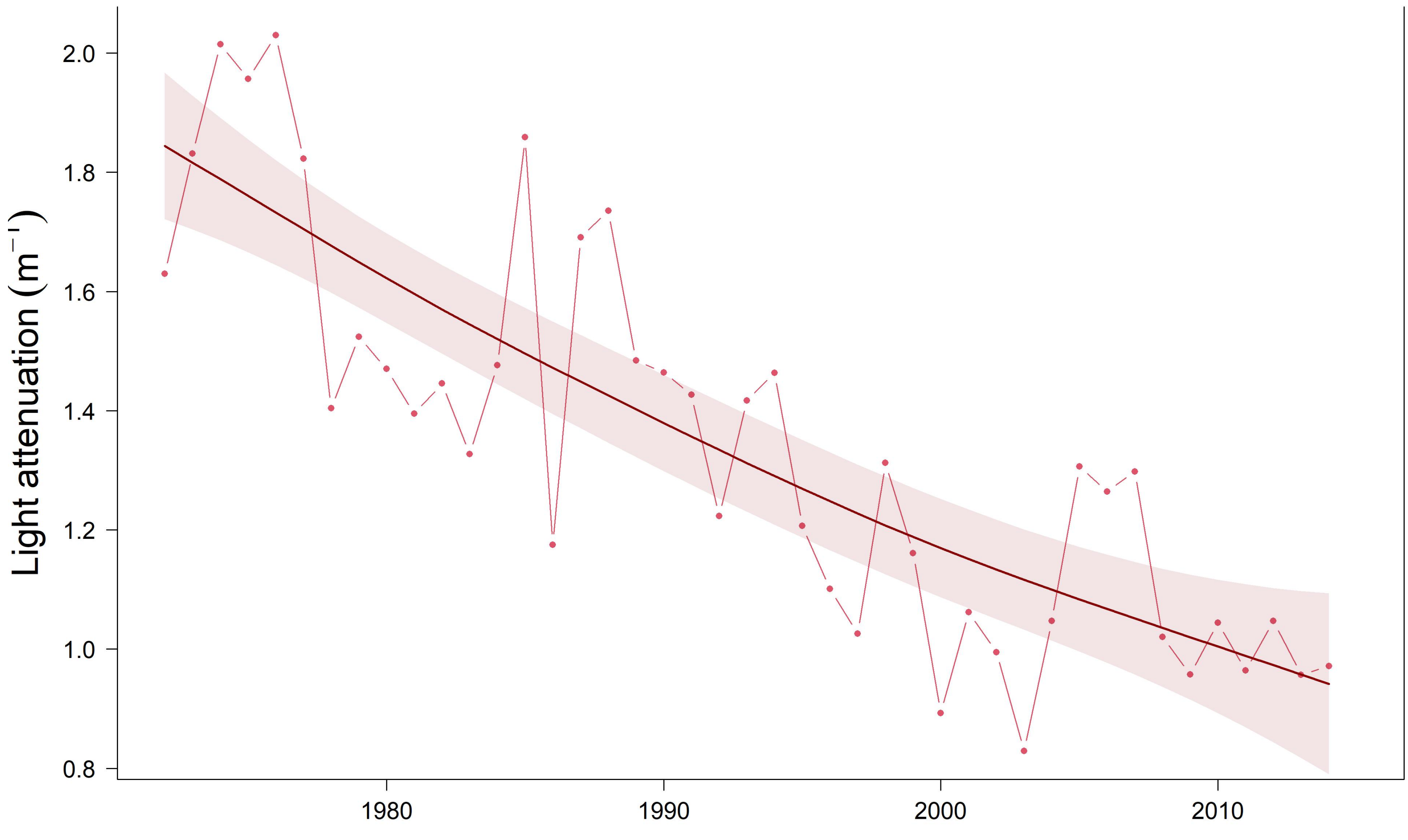
Whole community metrics

- no very clear trends



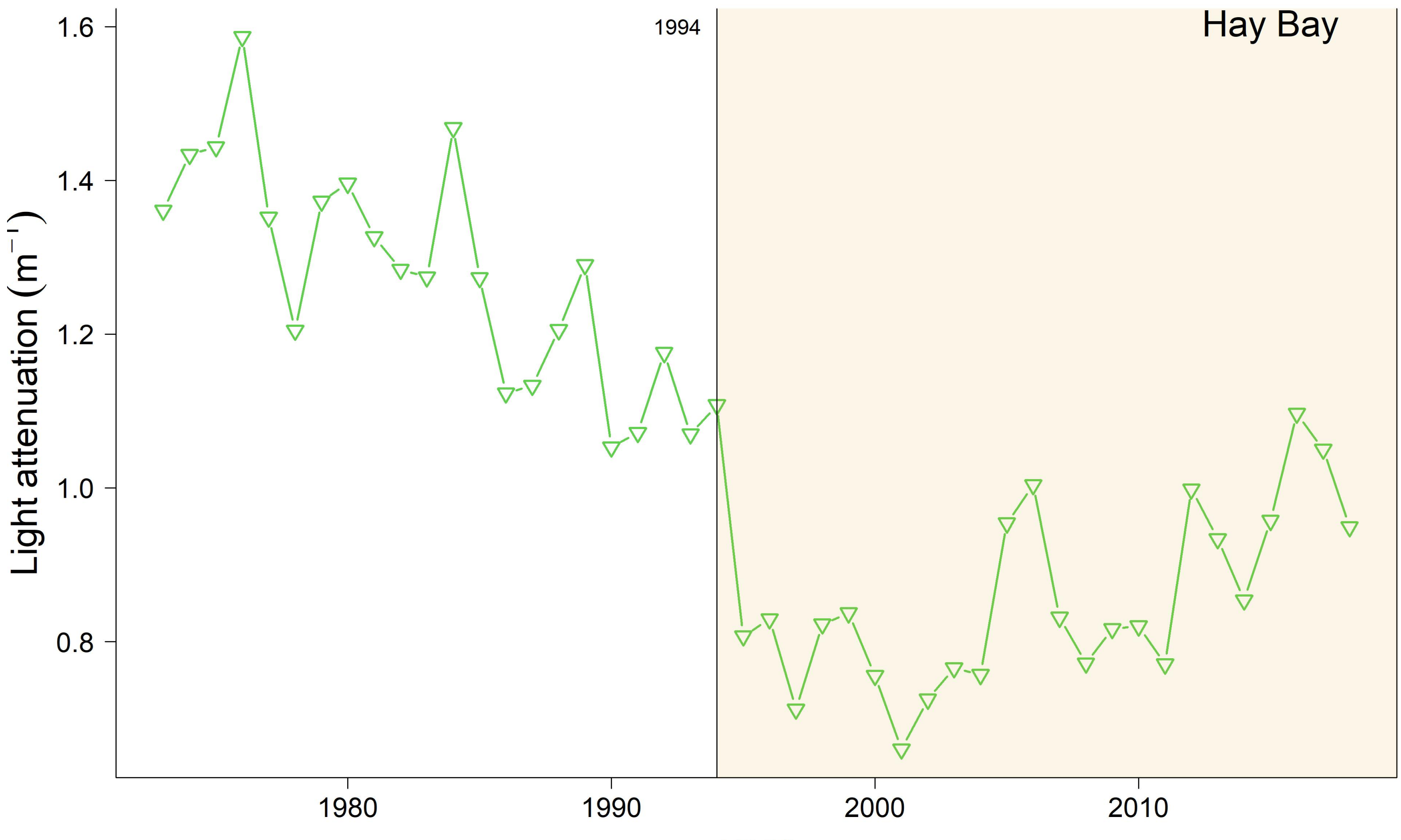


Change in water clarity: Belleville



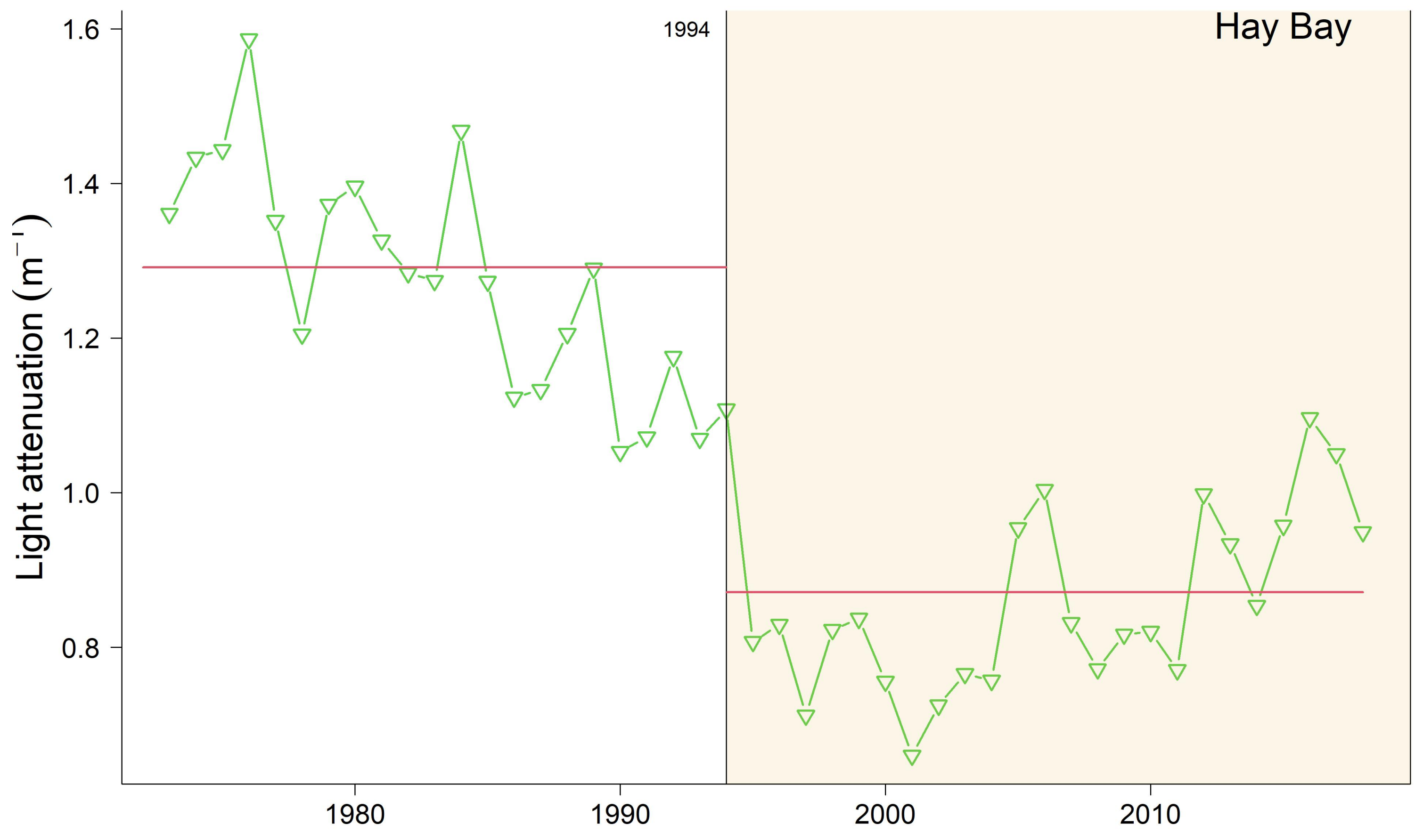
Change in water clarity: Hay Bay (our best candidate)

- two regimes?



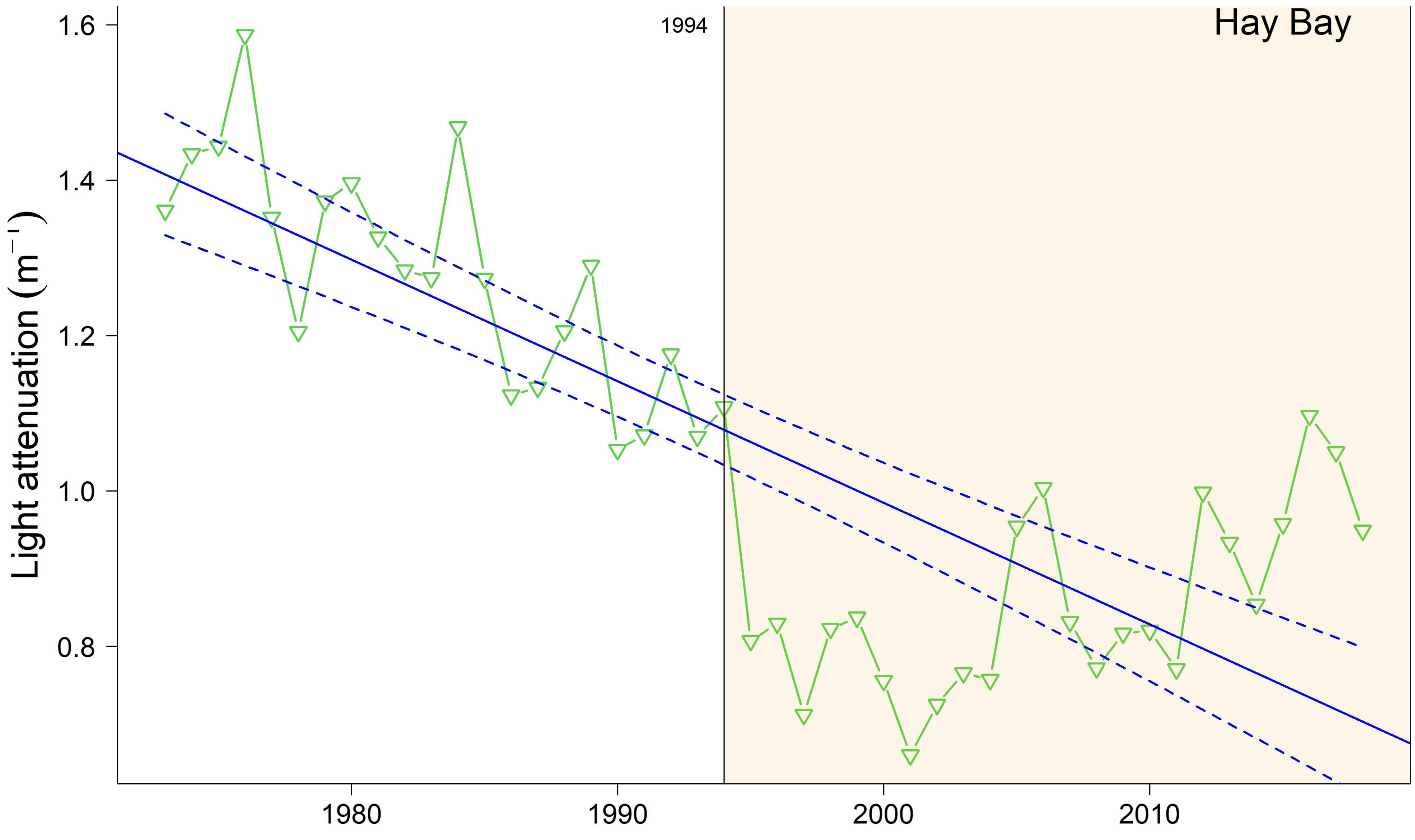
Change in water clarity: Hay Bay (our best candidate)

- two regimes?
- compare means?

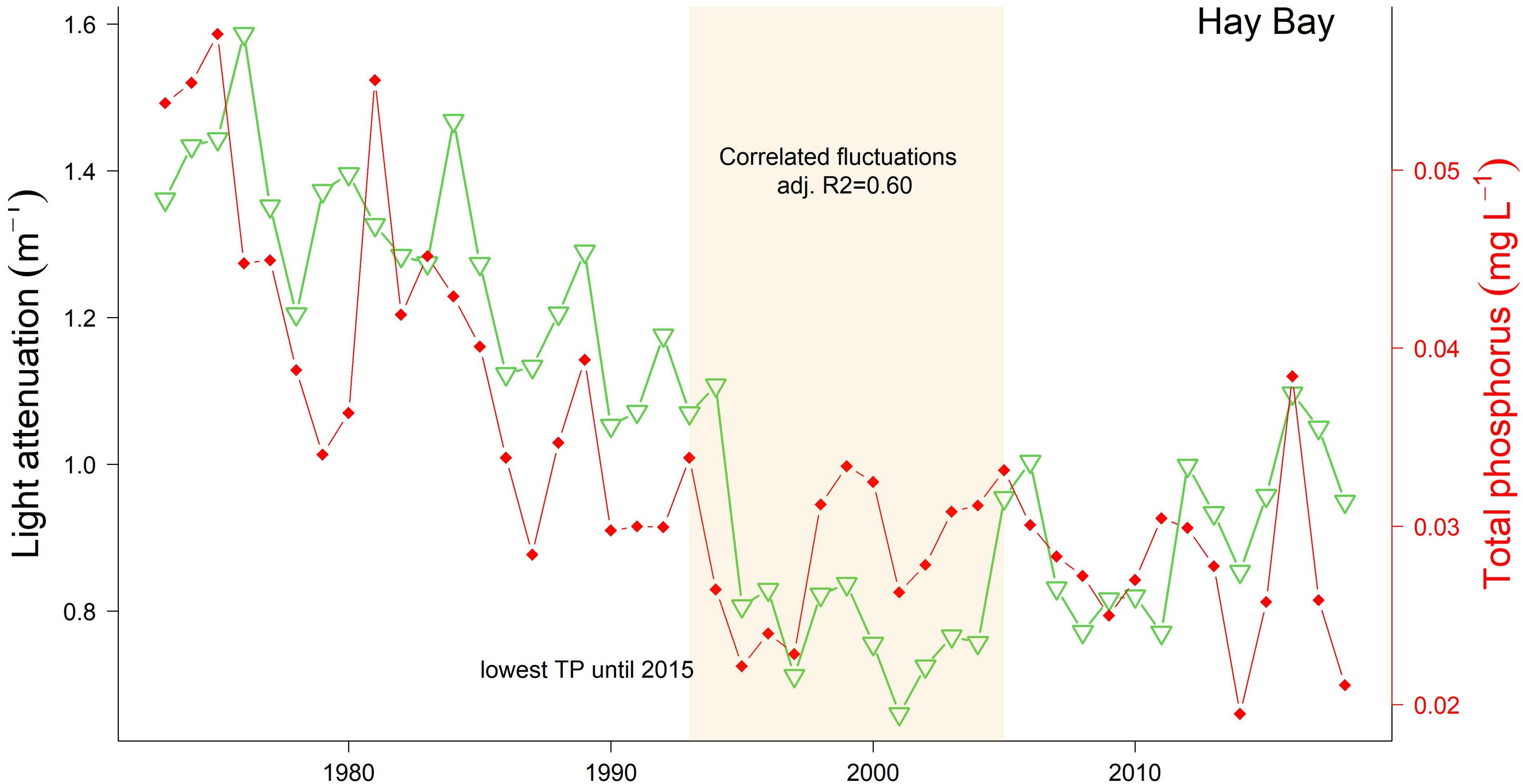


Water clarity: Hay Bay (our best candidate)

- two regimes?
- linear change confounds mean comparison



Water clarity & total phosphorus: Hay Bay



4. Analyzing temporal trends using GAMS and breakpoint models

Linear breakpoint models

$$y_{i,b} = \mathrm{breakperiod}_b + \beta_b x_{i,b}$$

- breakpoint (piecewise) linear regressions to test if linear model with abrupt change in mean or slope fits best
- did not select breakpoint years *a priori*
- estimate the number and position of multiple breakpoints where the optimal number of breaks was selected using BIC (Bai and Perron 1998)

Generalized Additive Models (GAMS) for regime shifts

- Thin plate regression splines fit using REML
- Simpson (2018), Pedersen et al (2019)

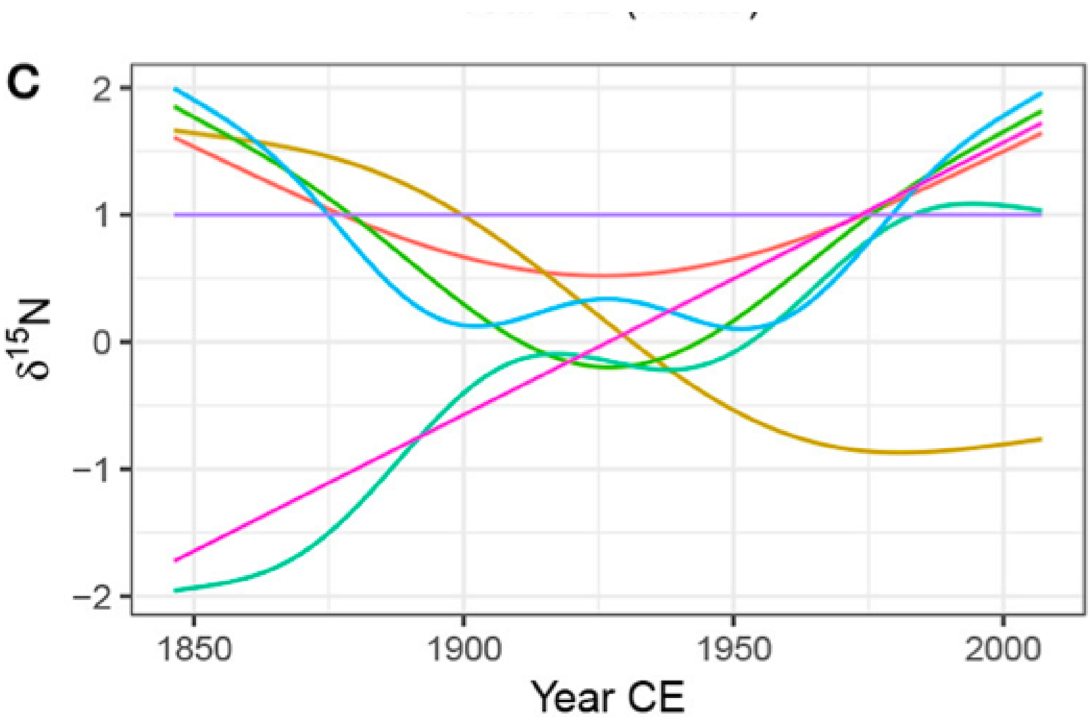
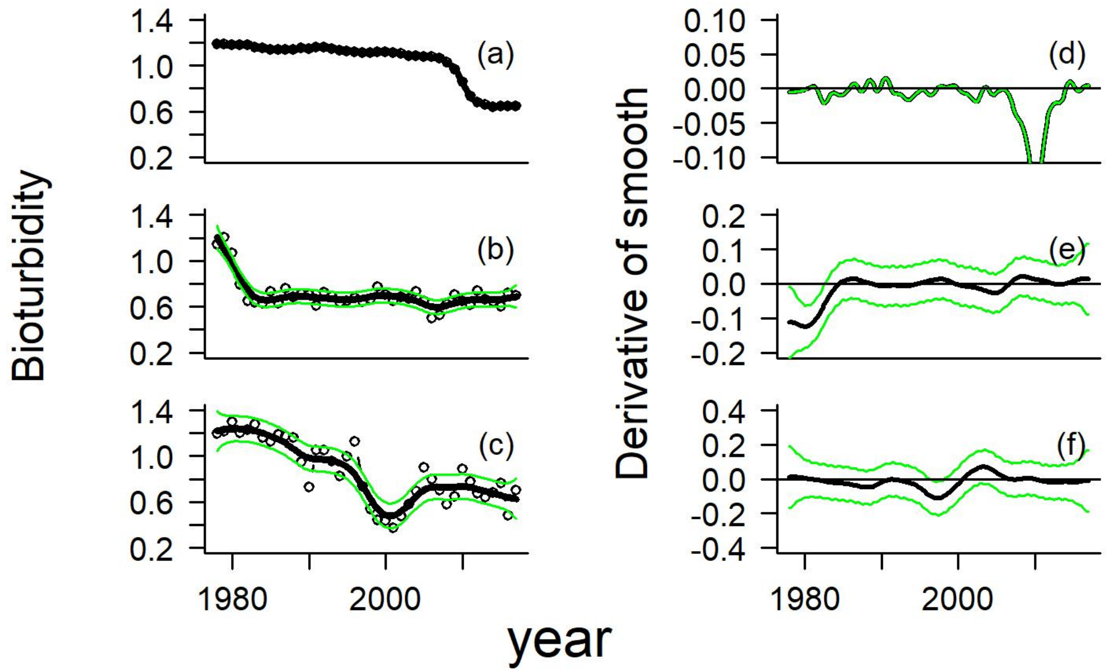


Image from Simpson (2018)

Generalized additive models for Quinte (GAMs)

- $y_i = \beta_0 + f(x_i)$
- thin plate splines
- examine the first derivative of fitted smooth to find periods of rapid change

Simulated data from the Scheffer model (2001). The initial condition is previously stable high turbidity state

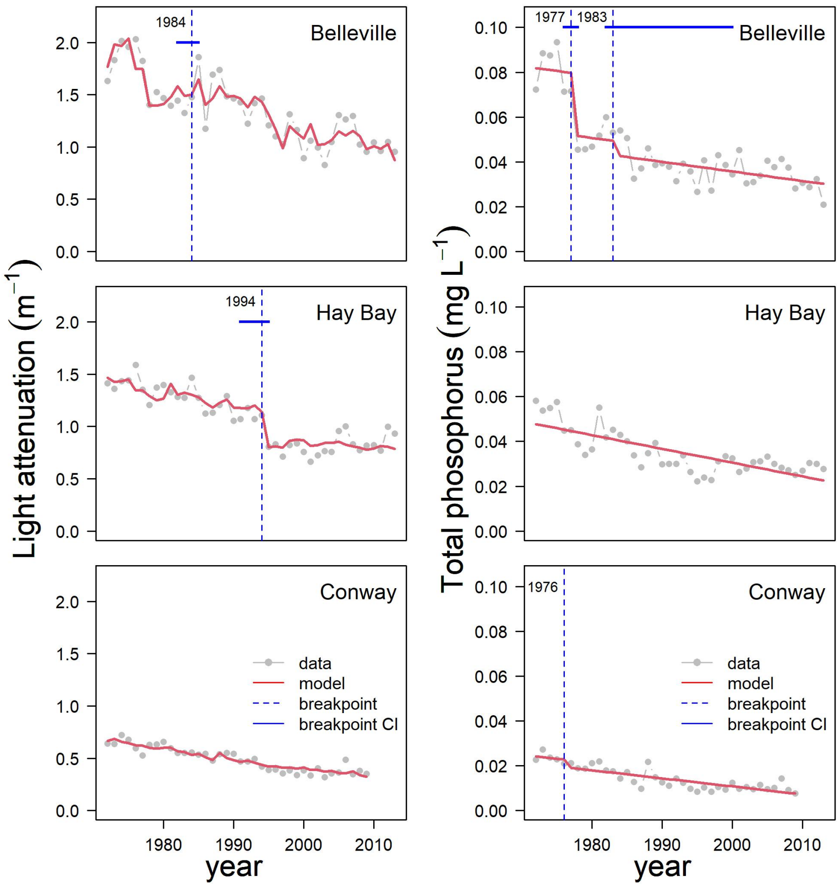


5. Quinte analysis

Linear breakpoint model for water clarity

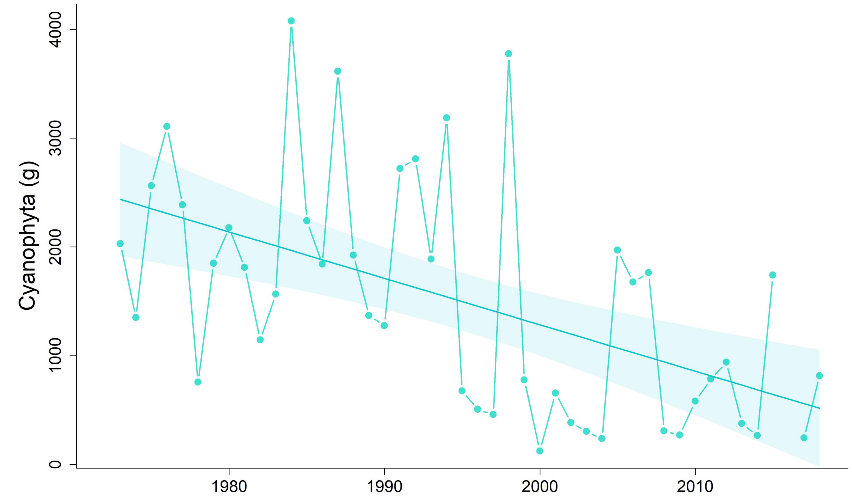
$$\text{light}_{i,s} = \text{breakperiod}_s + \beta_{1,s}\text{year}_{i,s} + \beta_{2,s}\text{TP}_{i,s}$$

- Use total phosphorus as a covariate
- Belleville 1984 response to phosphorus controls in the 70s? (no break 1994)
- Hay Bay: maybe rapid change in 1994 after mussels at Hay Bay?
- Conway: no break (as expected)



Change in Cyanophyta: Belleville

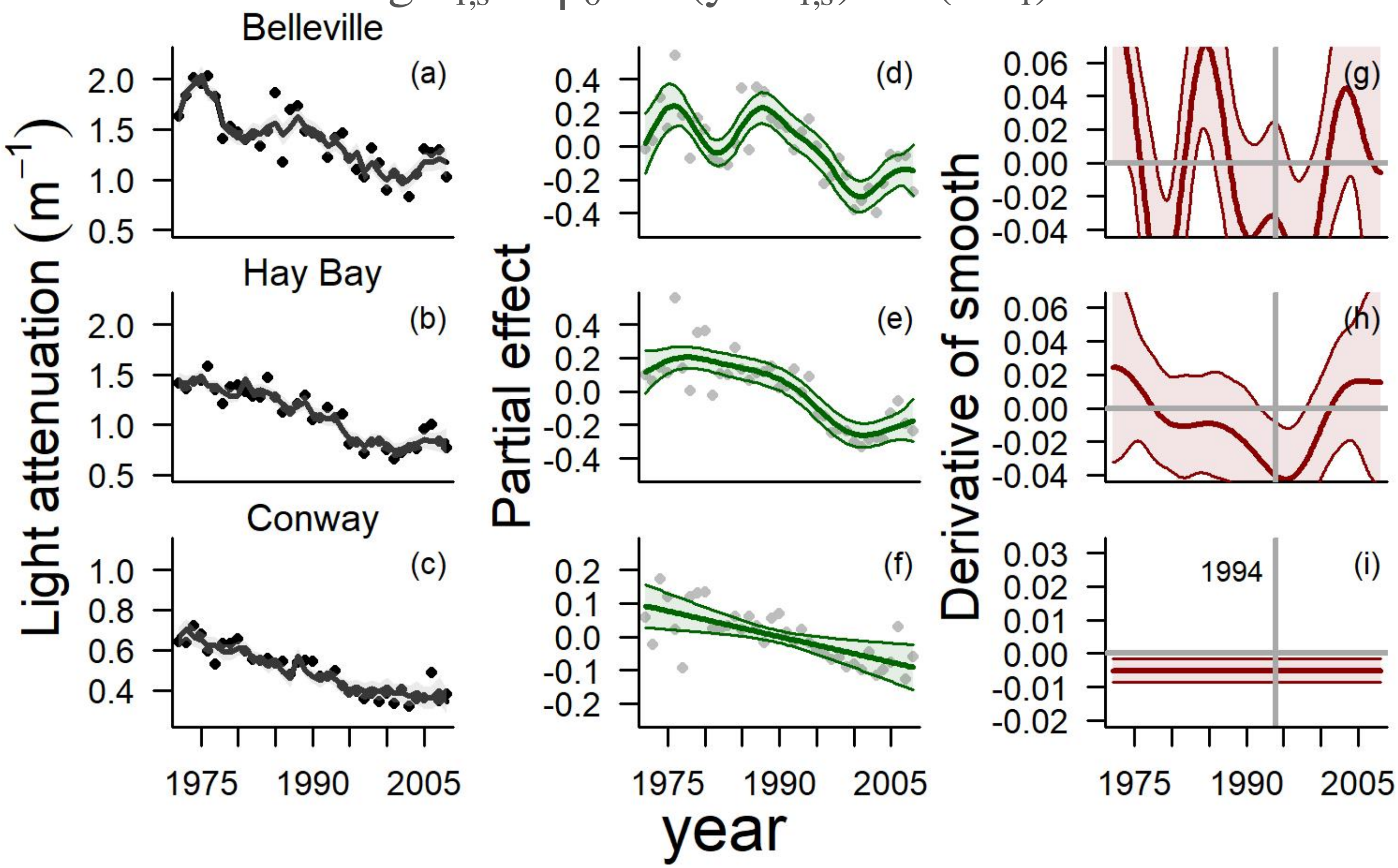
phyto	TP pvalue	TP Dev	Year pvalue	Year Dev
Cyano	**0.02**	**0.22**	**0.02**	**0.40**
Chloro	0.04	0.00	0.04	0.36
Chryso	0.71	0.33	0.71	0.03
Diatom	0.12	0.23	0.12	0.19
Crypto	0.11	0.01	0.11	0.08
Dino	0.29	0.01	0.29	0.04
Total	0.01	0.22	0.01	0.39



GAM analysis of water clarity

- suggests rapid change at Belleville and Hay Bay

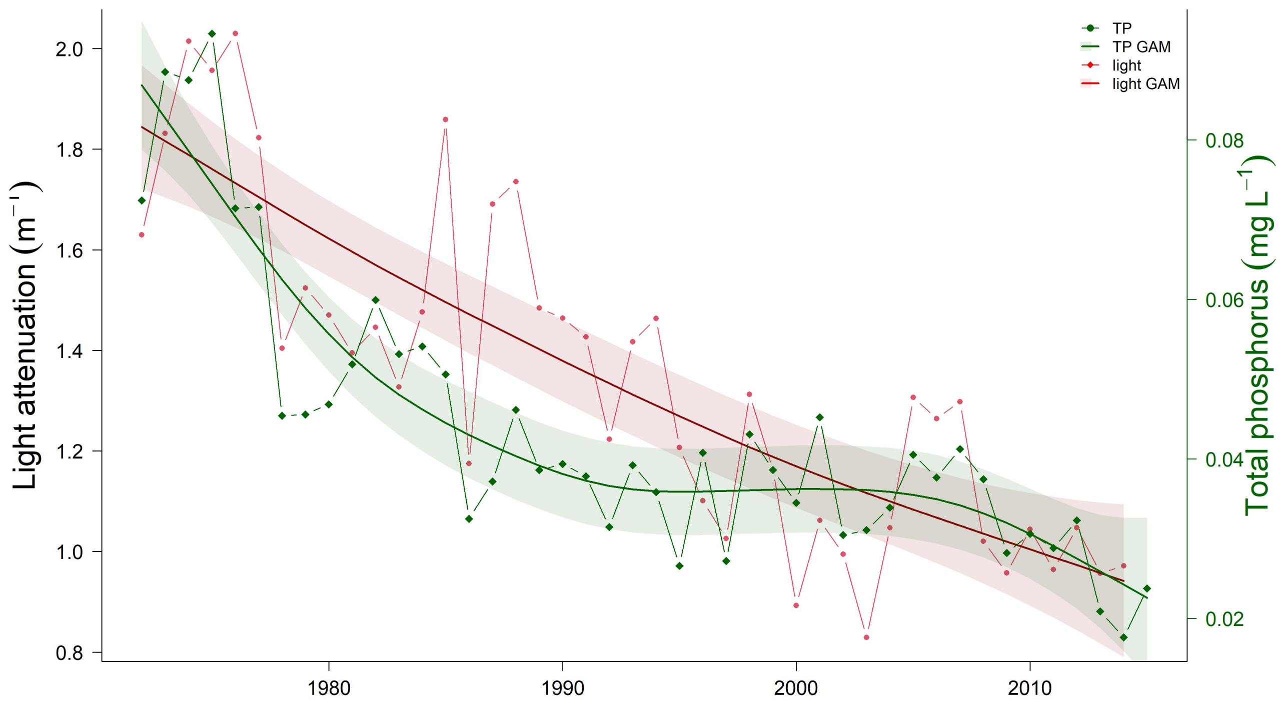
$$\text{light}_{i,s} = \beta_0 + f(\text{year}_{i,s}) + f(\text{TP}_i)$$



Problem 1: Identifiability

Concurvity between TP and year

- rapid response to management in the 70s
- slow change after that
- also collinearity

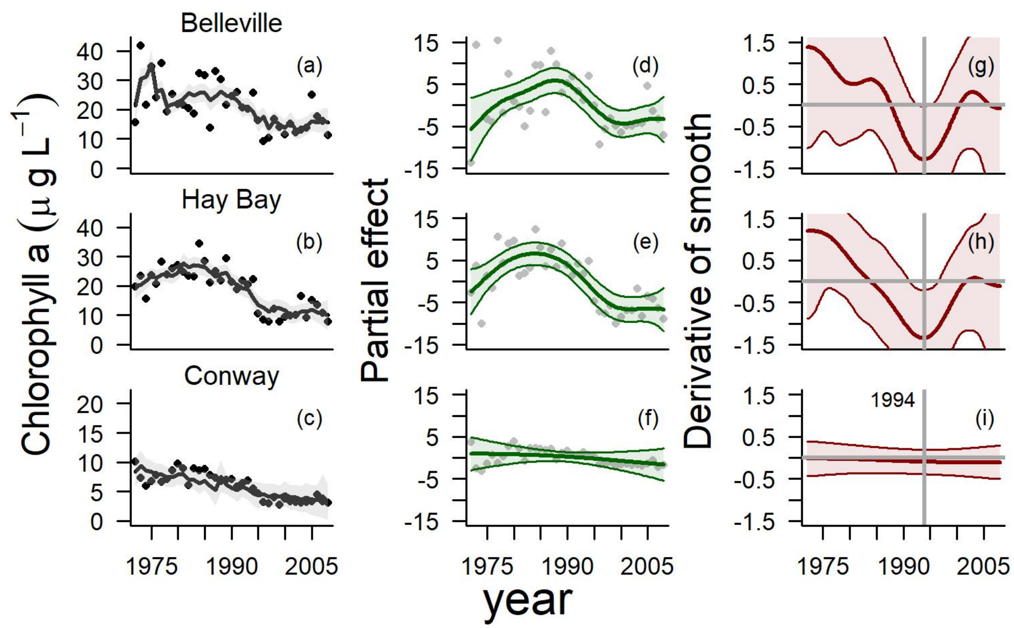


Concurvity

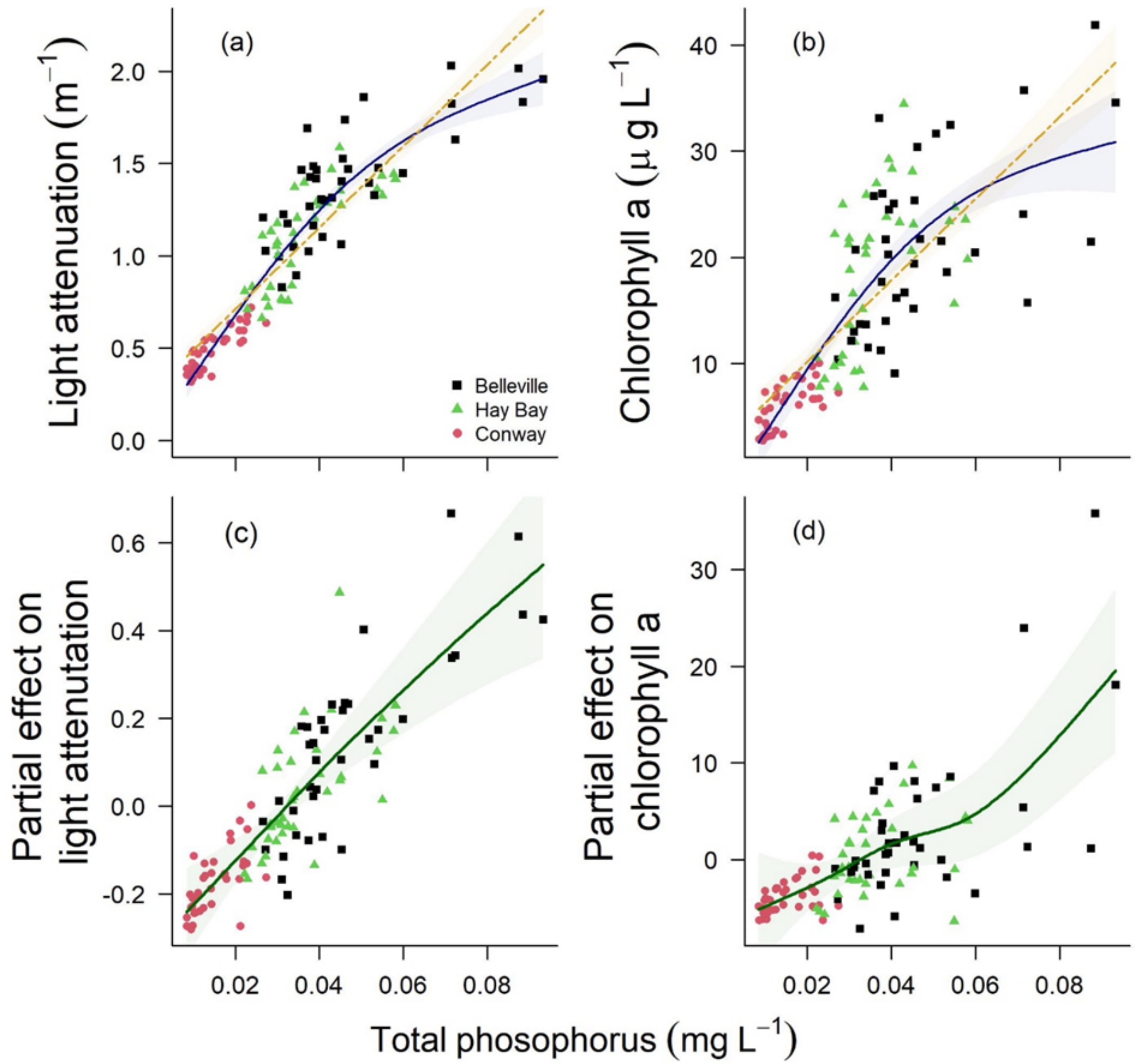
$$\text{light}_{i,s} = \beta_0 + f(\text{year}_{i,s}) + f(\text{TP}_i)$$

	s(TP)	s(year)
worst	0.96	0.96
observed	0.84	0.21
estimate	0.80	0.69

- GAM purports to explain 97% of deviance!
- certainly inflated

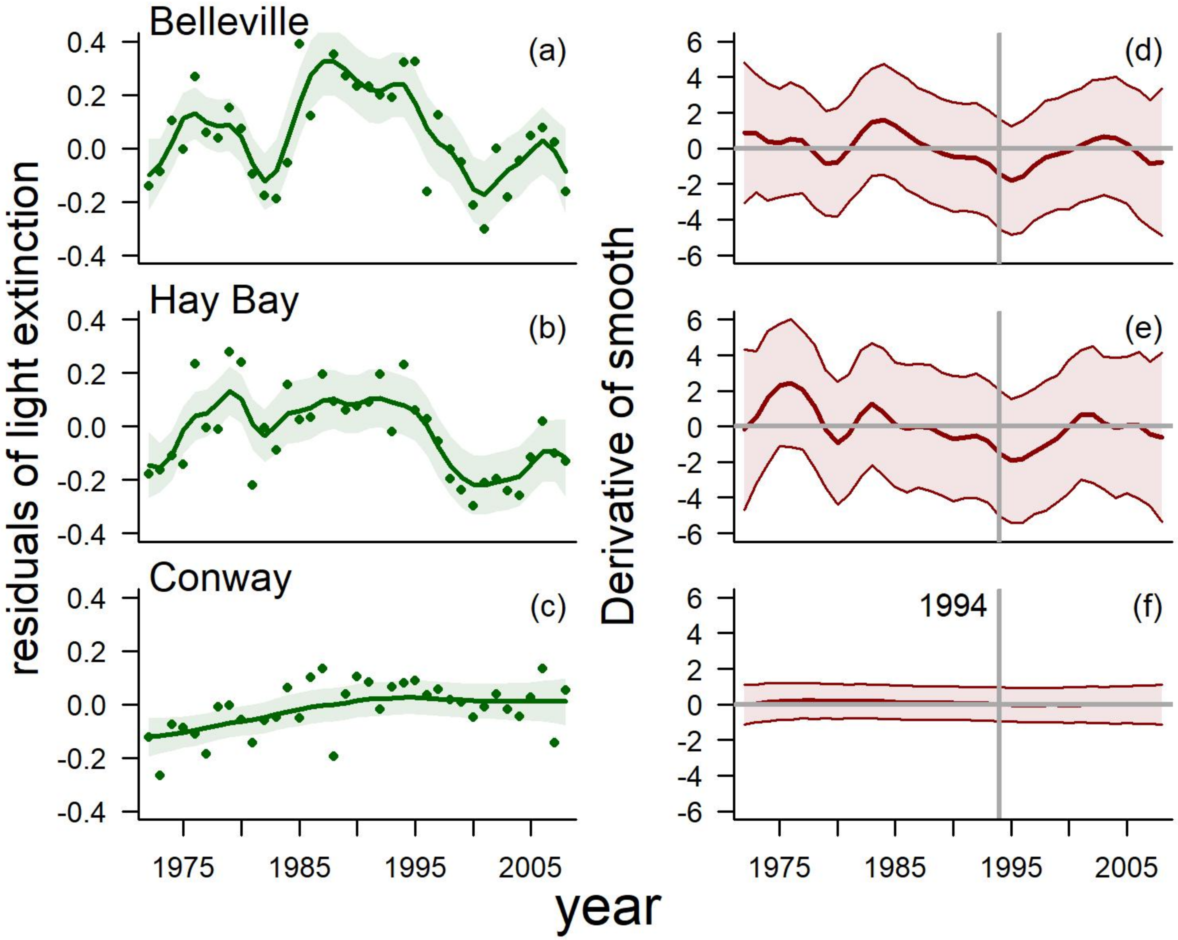


Possible solution: Fit TP and use residuals?



Gam on residual from TP

- rapid change magnitude becomes pretty small when we control for concurvity in phosphorus impacts

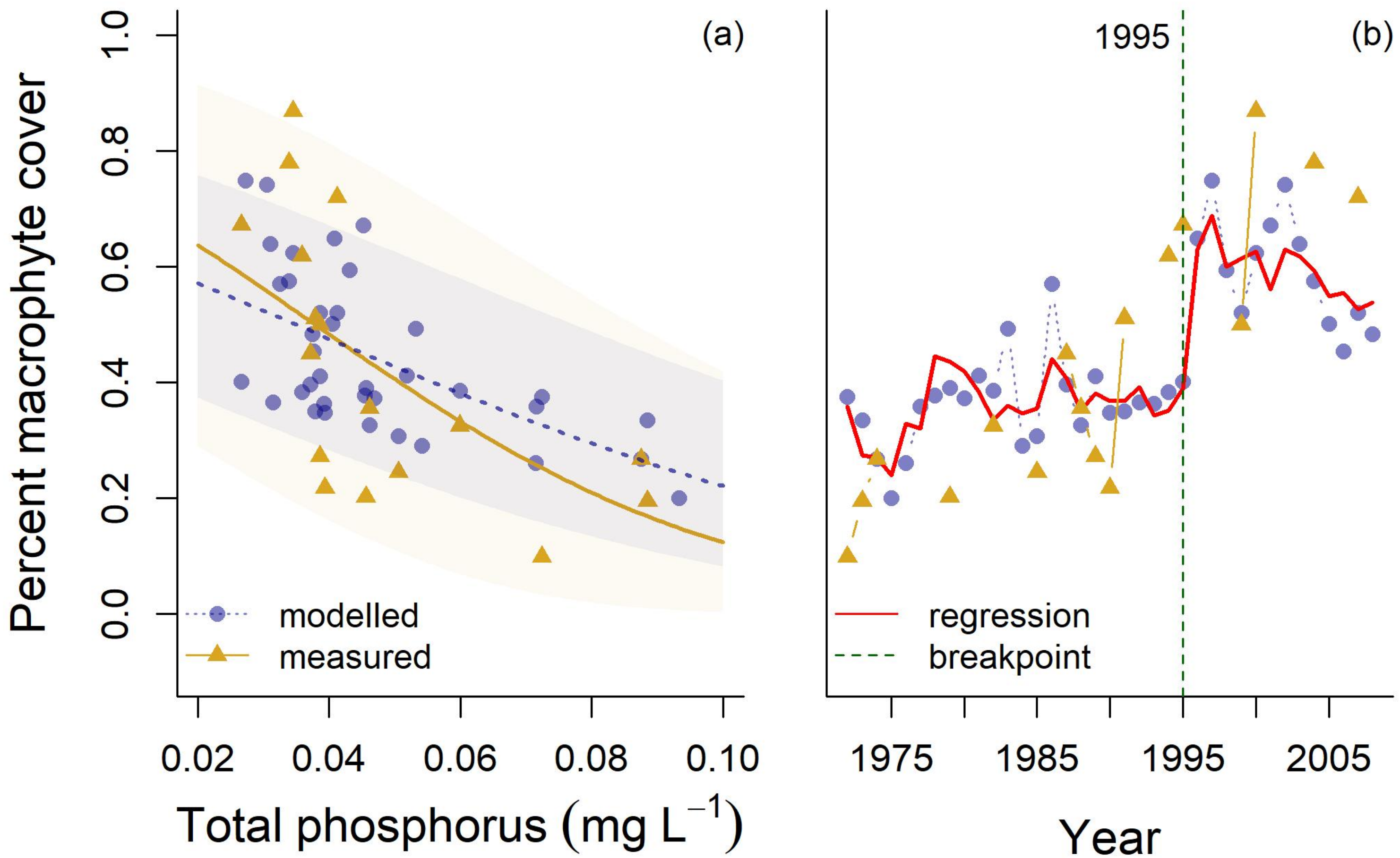


Problem 2: Missing data

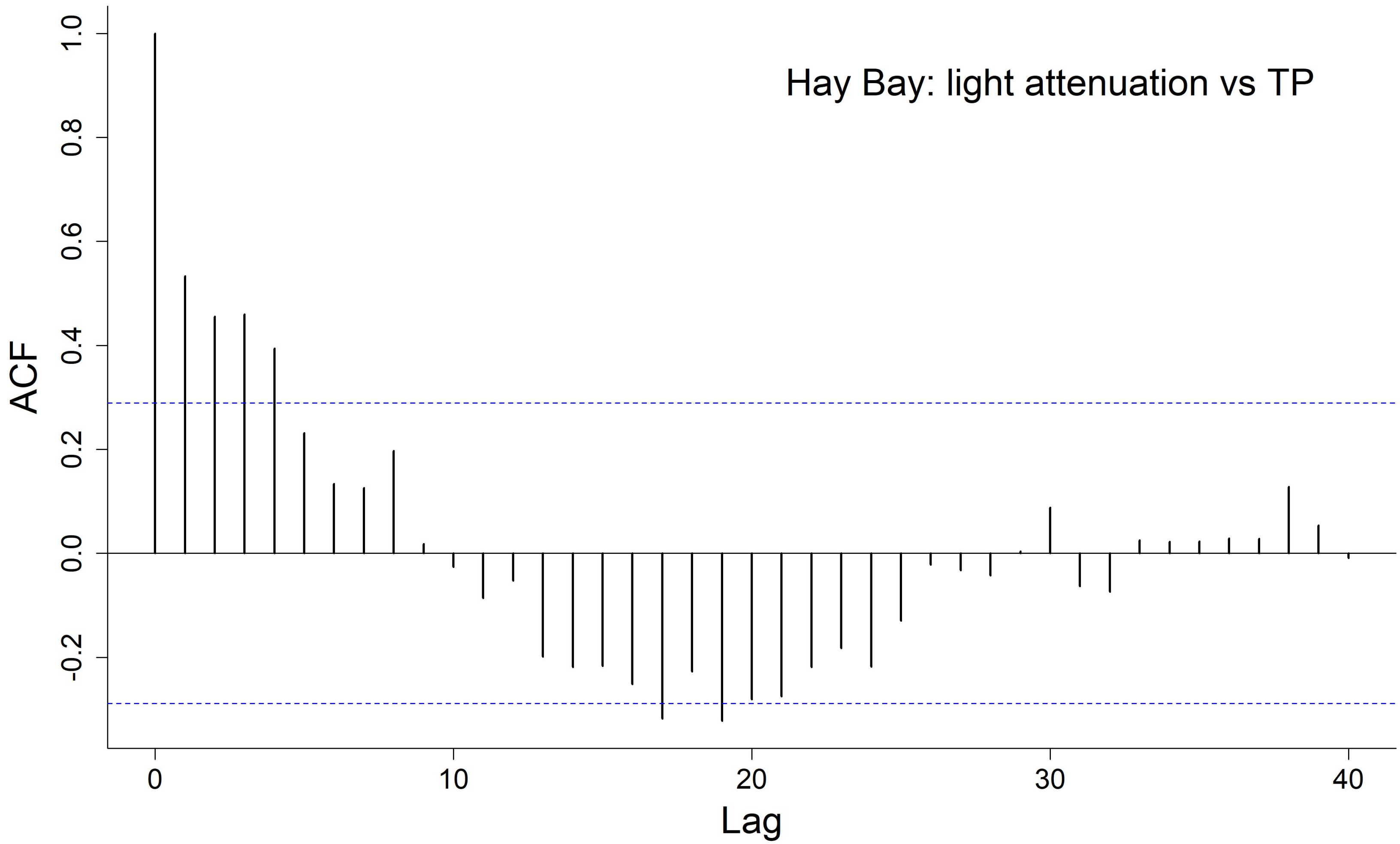
- disasterous for breakpoint analysis
- use modelled data: Macrophytes
- shorten period of analysis: Phyoplankton
- rely on GAMs

Macrophytes: Belleville

- both TP and year are significant predictors (breakpoint beta regression)
- modelled data suggests a regime shift, measured data??



Problem 3: Autocorrelation in residuals



Solution: AR1 on errors

- haven't yet found AR1 or ARMA that actually reduces!

Conclusion: Probably just slow change and a small disturbance in Hay Bay

1. Slow change in TP from 1977 with very low concentrations in 1994
2. Belleville: Concomittant slow change in light
3. When analysis completed on residuals from TP: some indication of small scale change
4. More rapid change in modelled macrophyte data

Overall

- Could be a small magnitude distrubance in Hay Bay, but if so, probably did affect TP too (can't claim this with current analaysis)
- Identifiability is a huge issue, but small magnitude of dreissenid density means only likely to contribute as a small scale disturbance

Transient or Zebra mussels?

- "Zebra mussels only" mechanism requires effects on clarity as early as 1984 at Belleville
  - 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 moderately long transients in clarity and chla

Next:

Make reviewers happy

- “bombarded with statistics”

Perhaps the is no clarity to be had

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WATERLOO SCIENCE | BIOLOGY

NSERC CRSNG

Fisheries and Oceans Canada

Pêches et Océans Canada

Canada

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- BIRS Workshop 19w5108 New Mathematical Methods for Complex Systems in Ecology

NIMBioS National Institute for Mathematical and Biological Synthesis

Banff International Research Station for Mathematical Innovation and Discovery

Questions?

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