Estimating continuous measures of ecological resilience from palaeoecological time series

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Acknowledgements

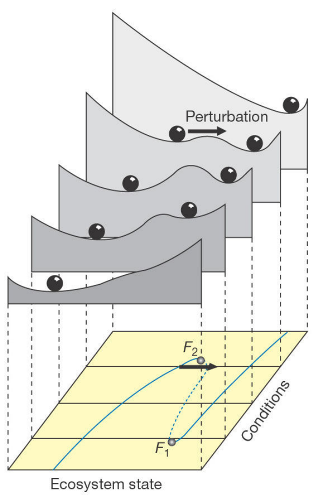
Slides: **bit.ly/inquaresilience**

Data: Lake 227 pigments, Peter Leavitt (Regina)

Resilience

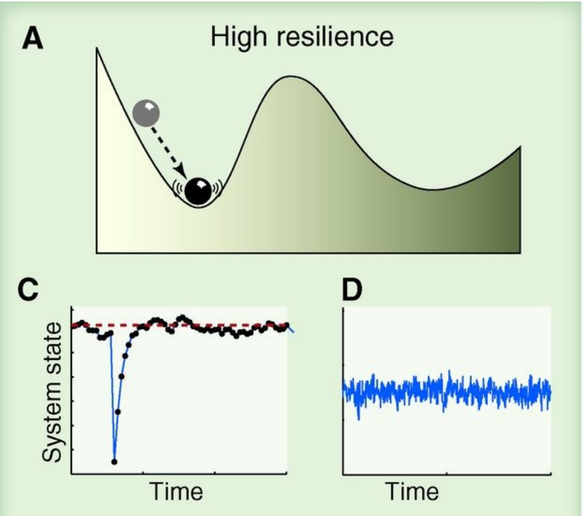
Alternative stable states — Marten Scheffer

- Under range of conditions multiple ecosystem states may exist
- Stability landscapes depict equilibria and basins of attraction
- Valleys are stable states
- External conditions alter the stability landscape
- Disturbances can kick a system between states



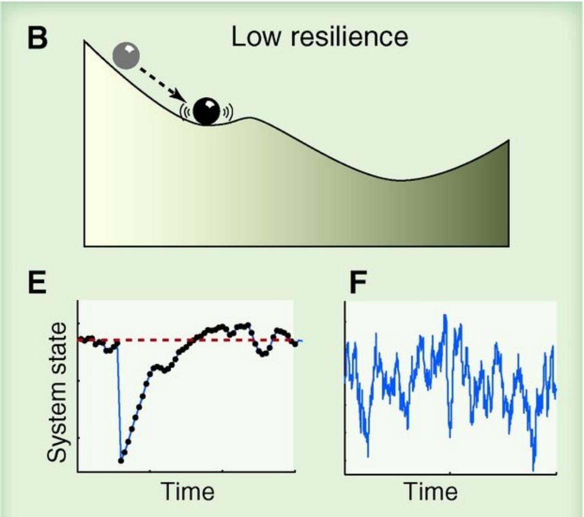
Source: Scheffer et al *Nature* 2001

Early warnings & Resilience to change



Source: Scheffer et al *Science* 2012

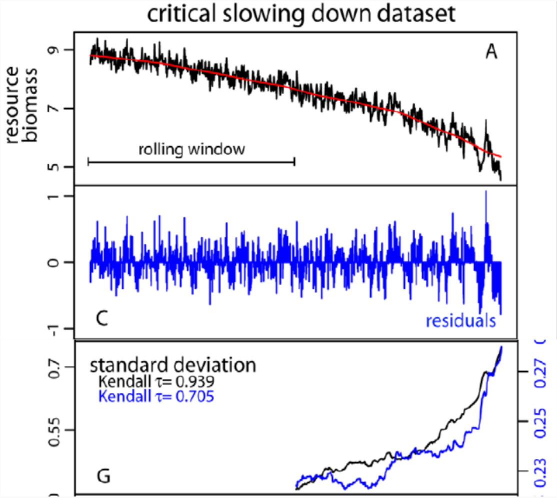
Early warnings & Resilience to change



Source: Scheffer et al *Science* 2012

Modelling variance

Estimating resilience using moving windows — probably shouldn't



Source: modified from Dakos et al *PLOS One* (2012)

Problems

Ad hoc

- What window width?
- How to detrend (method, compexity of trend, …)

Ideally regularly spaced data

- What to do about gaps, missing data?

Statistic testing hard

- Kendall's τ assumes independence
- Surrogate time series assumes regular sampling, sensitive to choice of ARMA

Results in incomplete time series

Distributional models


MODEL
ALL THE THINGS
imgflip.com

Linear models

$$y = \beta_0 + \beta_1 \text{time} + \varepsilon$$


WIGGLY
THINGS

Generalized additive models (GAMs)

$$y = \beta_0 + f(\mathrm{time}) + \varepsilon$$

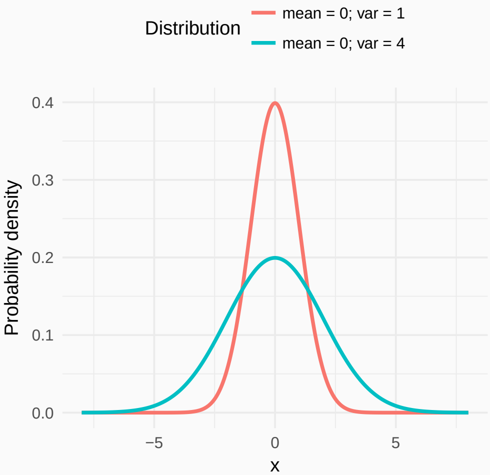
f is a smooth function

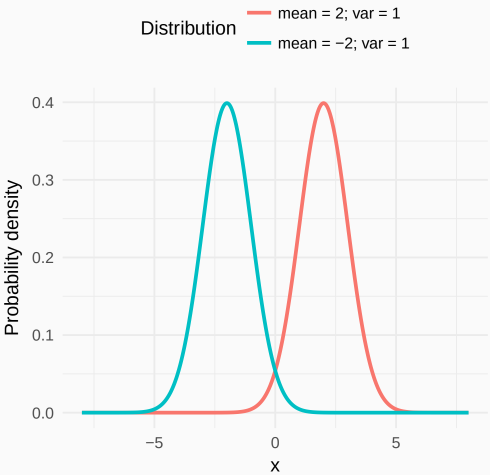
Learn about the shape of f from the data

Penalty on wiggliness to avoid overfitting

Gaussian distribution — defined by 2 parameters

- mean — μ and variance — σ^2





Distributional models — model all of the things

Allows, for certain suitable distributions, the ability to model one or more of the mean, variance, skewness, and kutosis.

$$y_i \sim \mathcal{N}(\mu = \eta_{1,i}, \sigma^2 = \eta_{2,i})$$

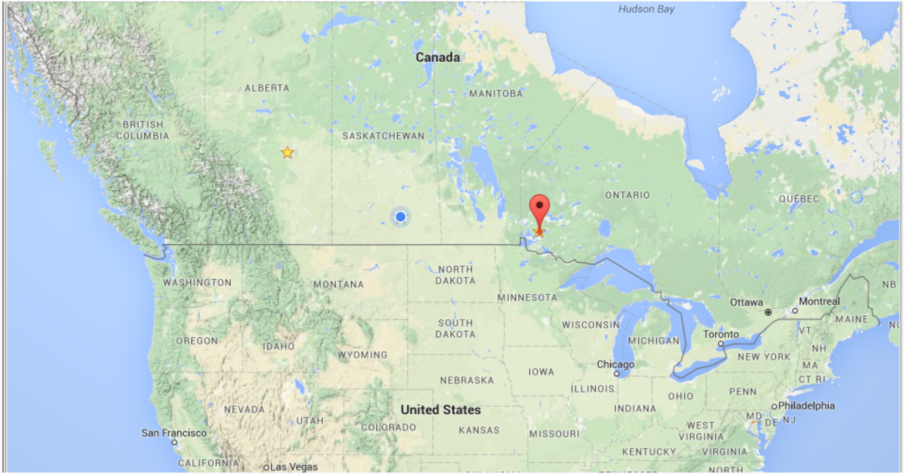
- GAMLSS models of Rigby and Stasinopoulos (2005)
- Vector GAM (VGAM) models of Yee (e.g. Yee and Mackenzie (2002))
- General smooth models of Wood/mgcv

E.g.: y_i are Gaussian with mean μ_i and variance σ_i^2, each of which are modelled via a linear predictor η of smooth functions of covariates x_j and z_j

Lake 227

Lake 227

Experimental Lakes Area, NW Ontario, Canada — Dilute headwater lake (5 ha, 10 m deep)

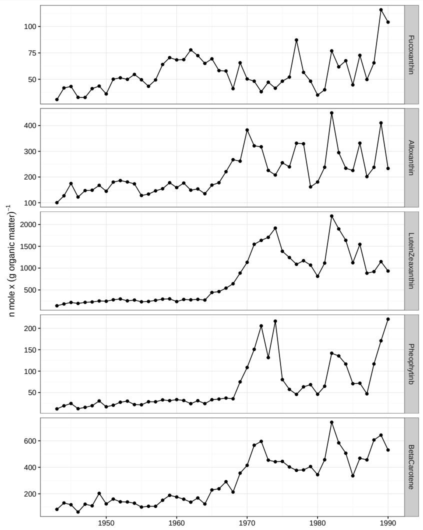


Lake 227

Experimental Lakes Area, NW Ontario, Canada — Dilute headwater lake (5 ha, 10 m deep)

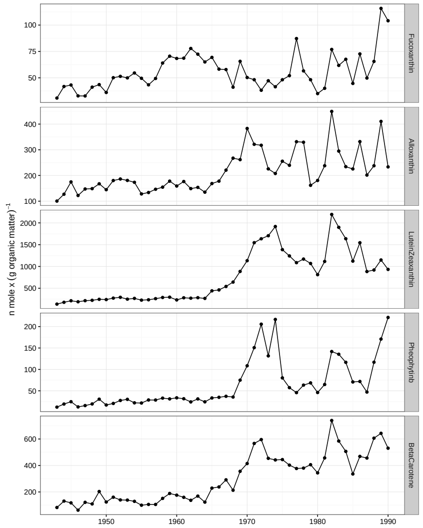
Lake 227 sedimentary pigments

- Experimentally manipulated
    - 1969– :~10x increase in P load
    - 1969–74: N added in 14:1 ratio
    - 1975–82: N load reduced to 5:1
- Annual sediment samples 1943–1990
- Analysed for fossil pigments
    - *Fucoxanthin*; diatoms, chrysophytes
    - *Alloxanthin*; cryptophytes
    - *Lutein-zeaxanthin*; cyano, chlorophytes
    - *Pheophytin* b; chlorophytes
    - *β carotene*; total algae
- Cottingham, Rusak, and Leavitt (2000)

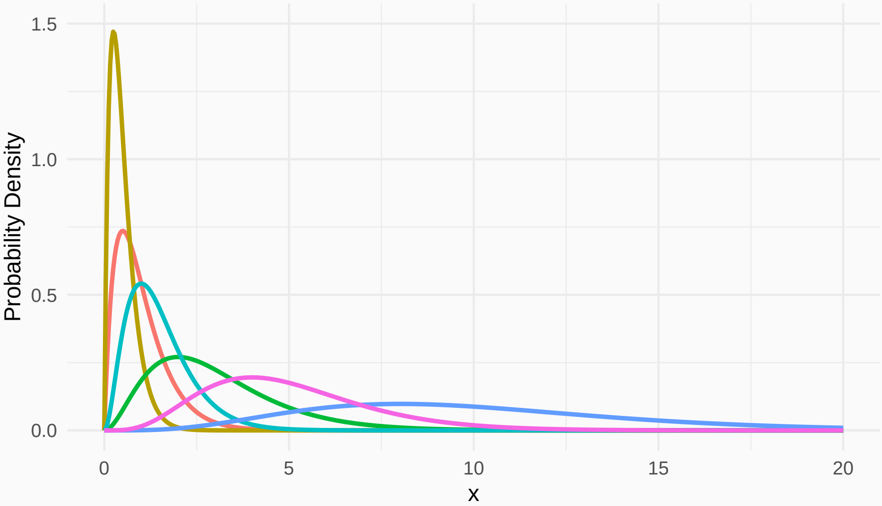


Pigment data

- Pigment data are strictly positive
    - Any value $x_i < c$ is censored
    - Aphanizophyll
- Treating these as Gaussian seems wrong
    - $\log(x_i)$ causes problems
- Use a different distribution
    - the gamma distribution



The Gamma distribution



Lake 227 sedimentary pigments

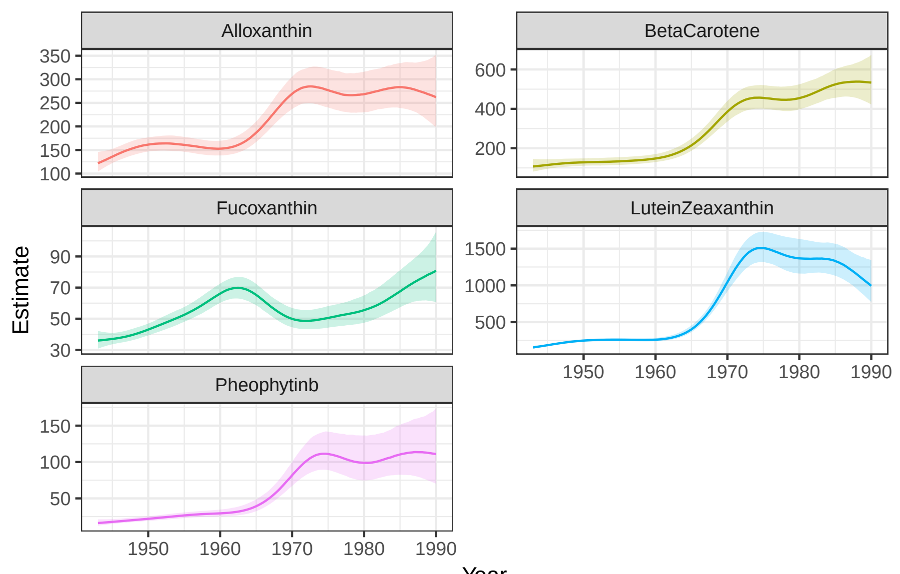
Fitted gamma distributional model using **brms** and **Stan**

$$
\begin{aligned}
y_t &\sim \mathcal{G}(\mu = \eta_{1,t}, \alpha = \eta_{2,t}) \\
\eta_{1,t} &= \exp(f_{1,\text{pigment}}(\text{Year}_t)) \\
\eta_{2,t} &= \exp(f_{2,\text{pigment}}(\text{Year}_t))
\end{aligned}
$$

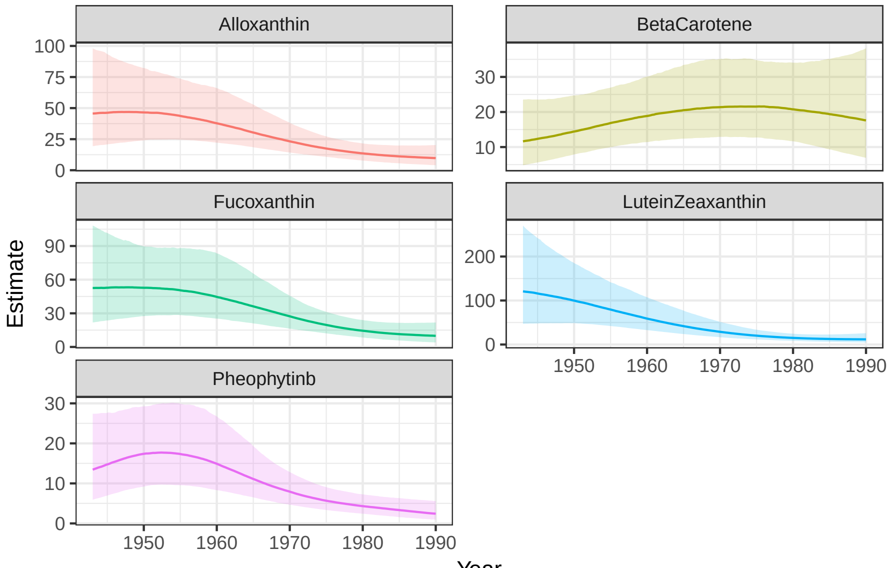
Mean (μ) & shape (α) each modelled with:

- “Random effect” spline (spline-factor interaction `bs = "fs"`)
- Fully Bayesian
- In this example no censoring

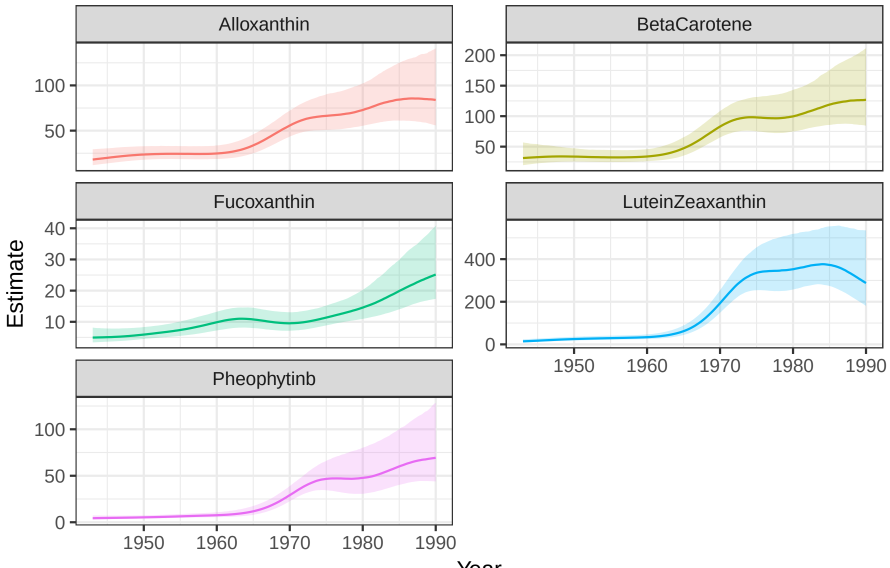
Lake 227 sedimentary pigments — fitted mean functions



Lake 227 sedimentary pigments — fitted shape functions



Lake 227 sedimentary pigments — fitted variance functions



Summary

Ecosystems are under threat from a range of natural and anthropogenic factors

Research over the past 40–50 years suggests that ecosystems respond in a myriad complex ways

GAMs have proven useful for testing some of these ideas with long time series & palaeo data

GAMs can estimate trends in variance in difficult data without very complex models or *ad hoc* solutions

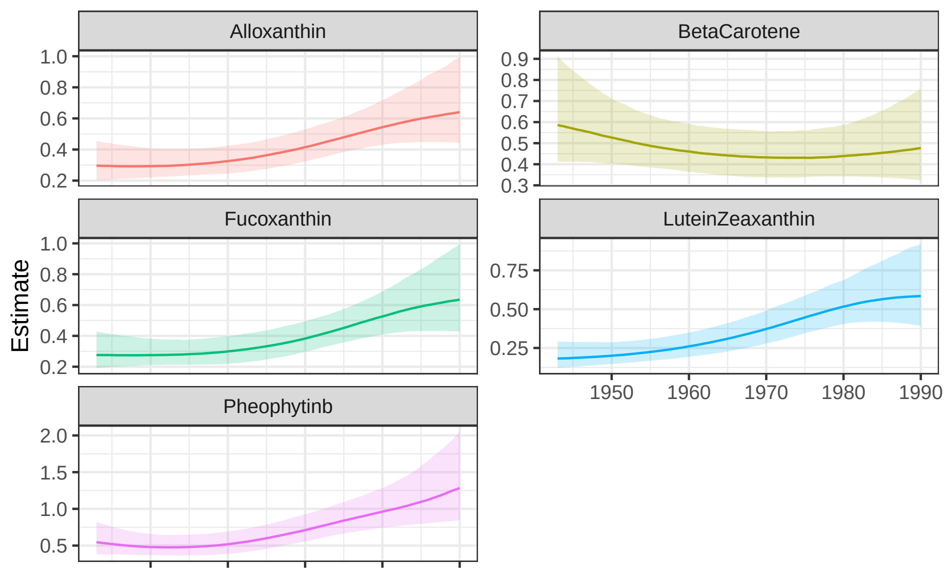
What's next...?

GAM-based models for other Early Warning Signals / Resilience indicators?

- Autocorrelation
- Skewness & kurtosis

Other distributional models & recently-developed quantile GAM approaches might work

Lake 227 sedimentary pigments — estimated skewness functions



Extra examples / slides

Baldeggersee

Baldeggersee

- Nutrient rich, hardwater lake, located on the central Swiss Plateau
- Developed anoxic bottom waters in 1885
- Intensive farming & agriculture in catchment
- Artificial oxygenation & circulation as remediation from 1982
- Cored in 1993 · 91 samples · 75 diatom taxa
- Source: Lotter (1998) *The Holocene* 8(4), 395–405

Source: © Andy Lotter

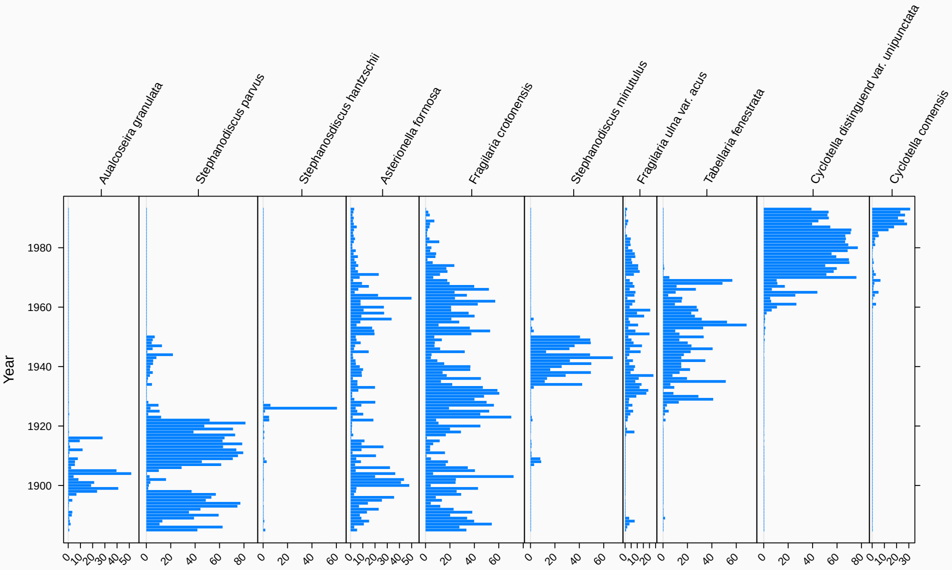
Baldeggersee

- Iconic example of a critical transition
- Deep lakes can exhibit bistable conditions
  - Nutrients increase phytoplankton
  - Decomposition can increase anoxia
  - Stimulates P release from sediments
- Marl lake
- Flickering (?)

Are early warning signals (increased variance) present?

Source: © Andy Lotter

Baldeggersee — Stratigraphy



Baldeggersee

Long gradients of temporal change in diatom abundances & composition

PCA not a good decomposition of the data — temporal trend spread over multiple PCs

Principal Curves are one non-linear approach related to PCA

Fits a non-linear curve that passes through the data minimising the orthogonal distance between samples & the curve, subject to some constraints

Baldeggersee — Stochastic Volatility Model

Stochastic Volatility — an econometric time series model of variance or *volatility*

In a SV model, each observation y_t assumed to have its own variance e^{h_t} & h_t assumed to follow an AR(1) process

$$y_t | h_t \sim \mathcal{N}(0, \exp h_t) \tag{1}$$

$$h_t | h_{t-1}, \mu, \phi, \sigma_\eta \sim \mathcal{N}(\mu + \phi(h_{t-1} - \mu), \sigma_\eta^2) \tag{2}$$

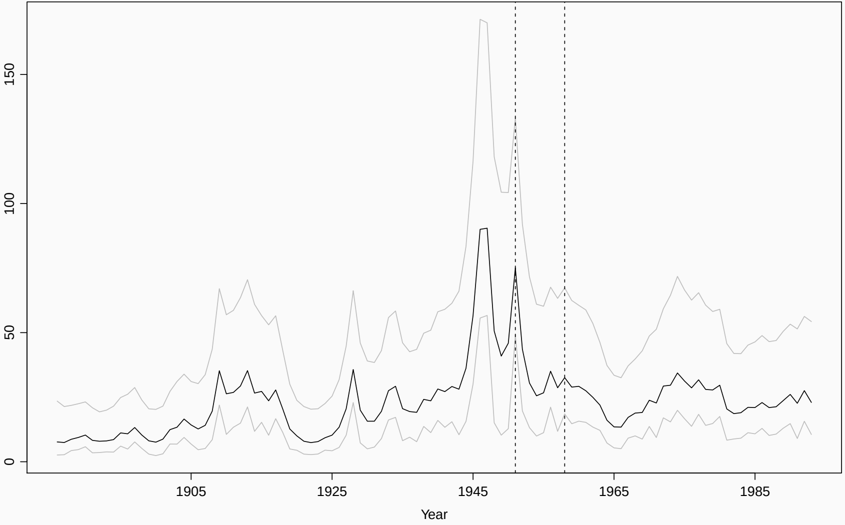
$$h_0 | \mu, \phi, \sigma_\eta \sim \mathcal{N}(\mu, \sigma_\eta^2 / (1 - \phi^2)) \tag{3}$$

μ, ϕ, σ_η^2 are the *level*, *persistence*, & *volatility* of the log-variance

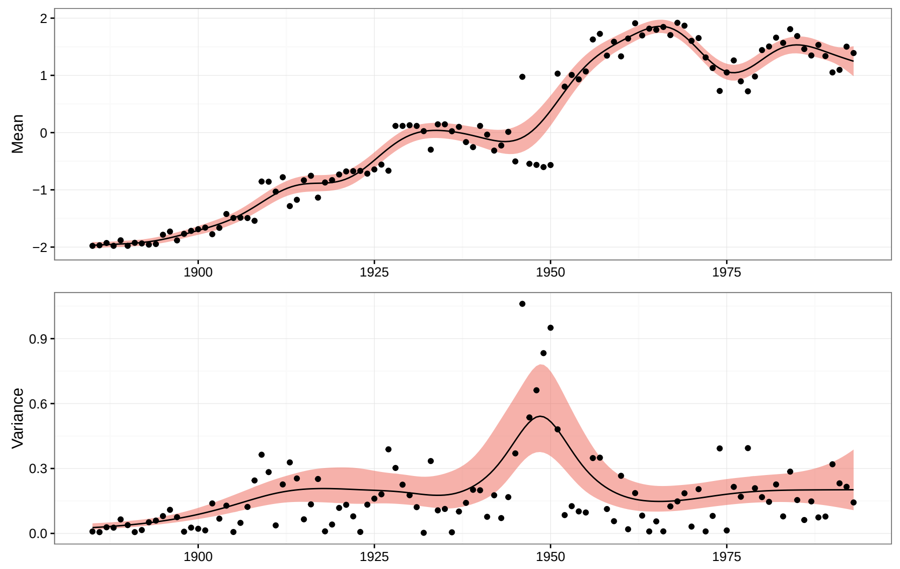
h is *unobserved* and modelled as a latent process

Fitted using stochvol R Package (Gregor Kastner)

Baldeggersee — Stochastic Volatility Model



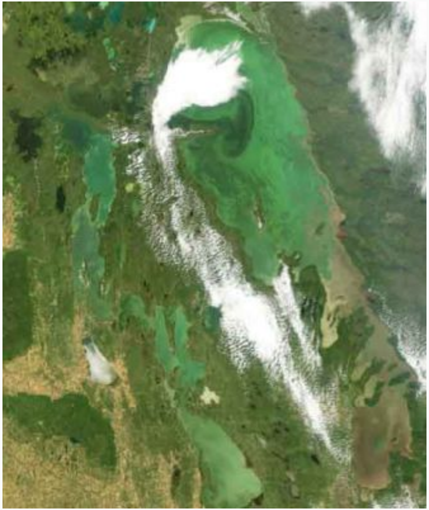
Baldeggersee — GAM Location and Scale fits



Lake Winnipeg

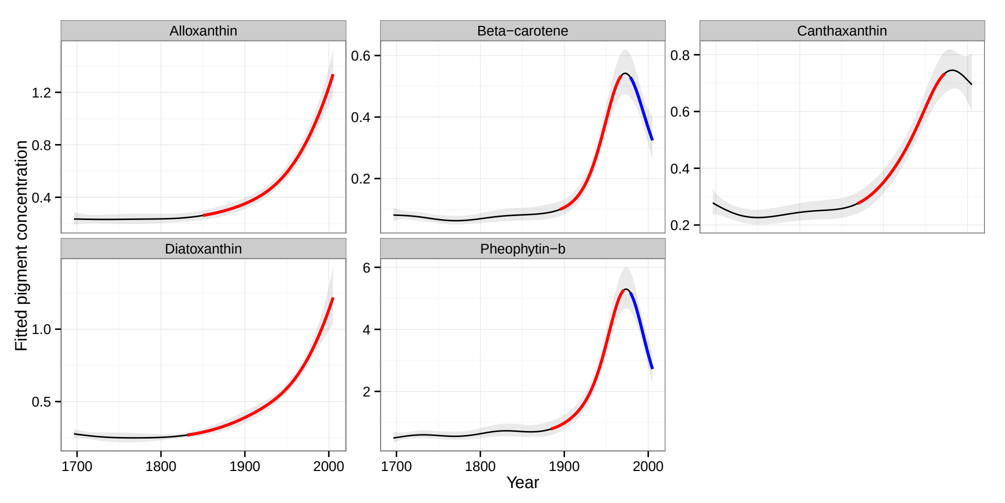
Has Lake Winnipeg suffered a catastrophic regime shift?

- Large, shallow, polymictic, lake
- Eutrophic
- Algal blooms
- Regime shift / critical transition?
- Increased destabilization with increased N & P?



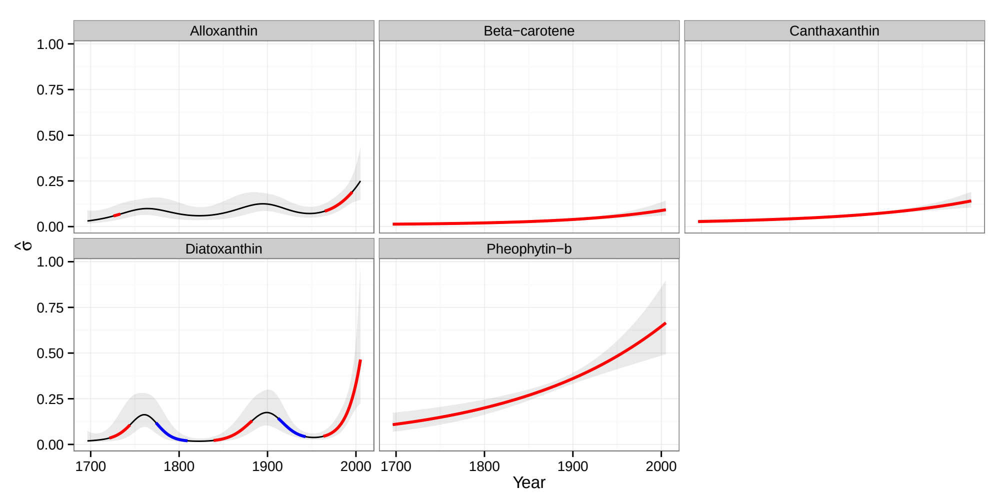
Source: Public domain

Has Lake Winnipeg suffered a catastrophic regime shift?



Source: Bunting et al *Limnology & Oceanography* 2016

Has Lake Winnipeg suffered a catastrophic regime shift?

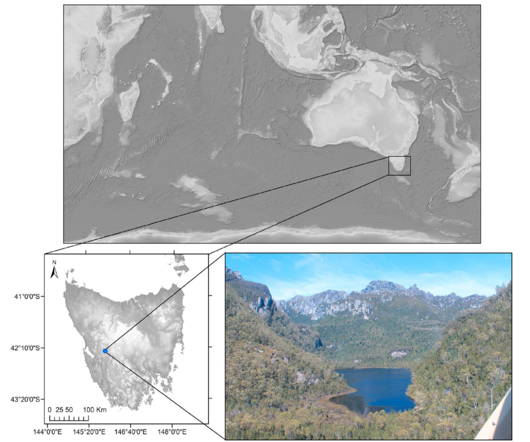


Source: Bunting et al *Limnology & Oceanography* 2016

Lake Vera, Tasmania

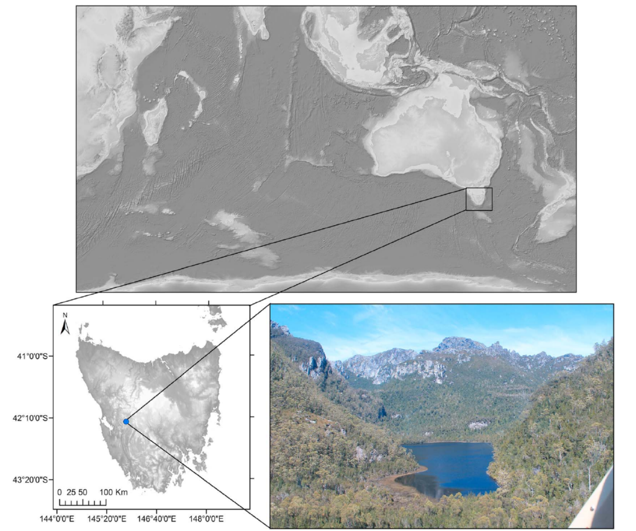
Lake Vera

- Small, moraine-bound lake
- Deep (48 m)
- Oligotrophic, acidic
- Fire is major driver of terrestrial change
- What affect on the lake?



Source: Beck et al *JGR: Biogeoscience* 2018

Lake Vera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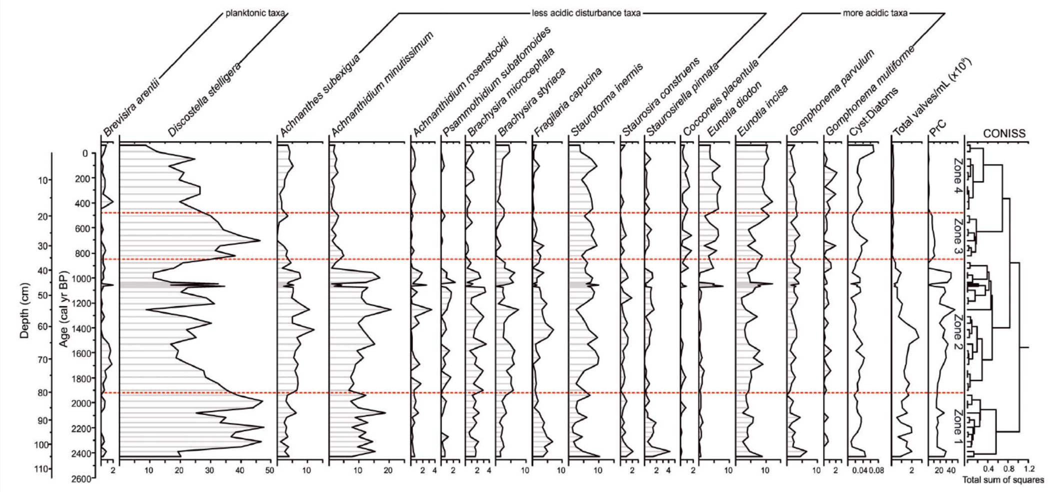
148°0'0"E

Lake Vera

Lake Vera



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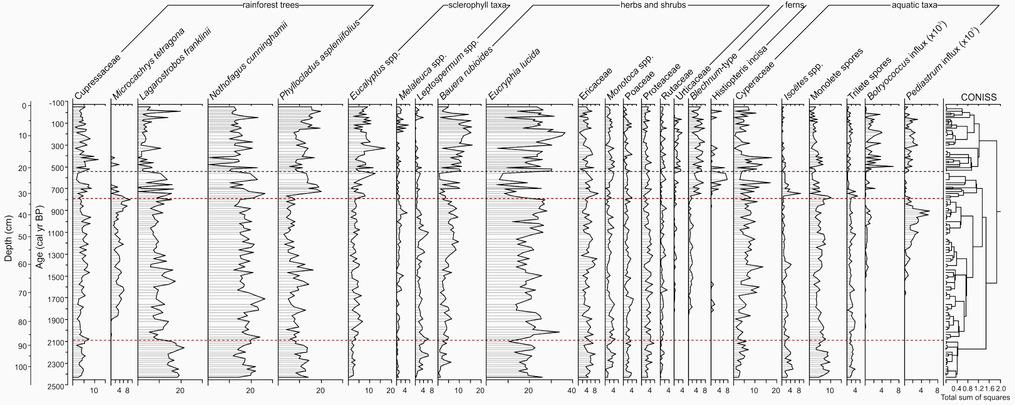
Lake Vera



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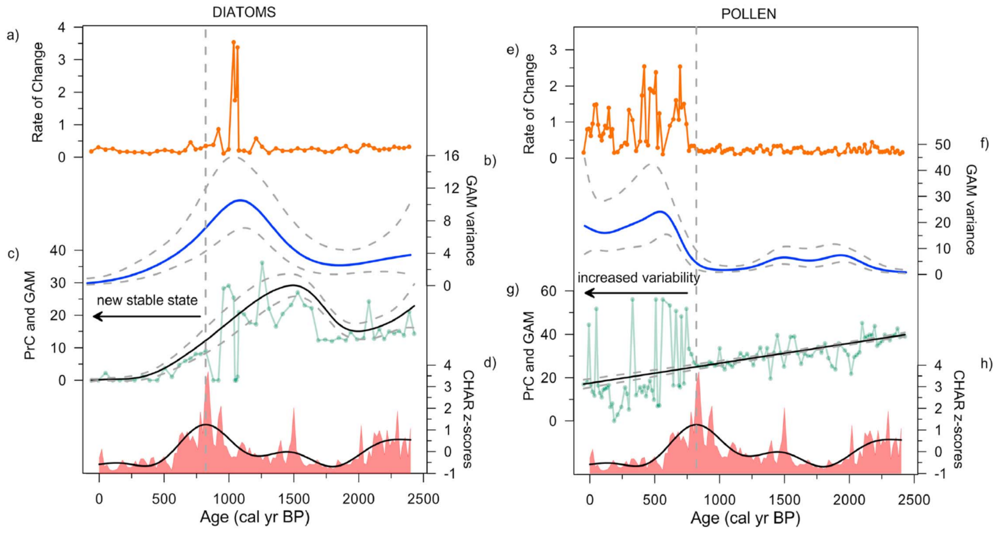
Lake Vera



DIATOMS
POLLEN
a)
b)
c)
d)
e)
f)
g)
h)
Rate of Change
GAM variance
PrC and GAM
CHAR z-scores
new stable state
increased variability
Age (cal yr BP)

References i

Cottingham, K L, J A Rusak, and P R Leavitt. 2000. "Increased Ecosystem Variability and Reduced Predictability Following Fertilisation: Evidence from Palaeolimnology." *Ecology Letters* 3 (4): 340–48. `https://doi.org/10.1046/j.1461-0248.2000.00158.x`.

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Yee, Thomas W, and Monique Mackenzie. 2002. "Vector Generalized Additive Models in Plant Ecology." *Ecol. Modell.* 157 (2-3): 141–56.