Wiggly Things and Generic Resilience Indicators in Ecological Time Series

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Acknowledgements

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Community response to environmental change

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Community response to environmental change

Credit: NOAA George E. Marsh Album [Public domain], via Wikimedia Commons

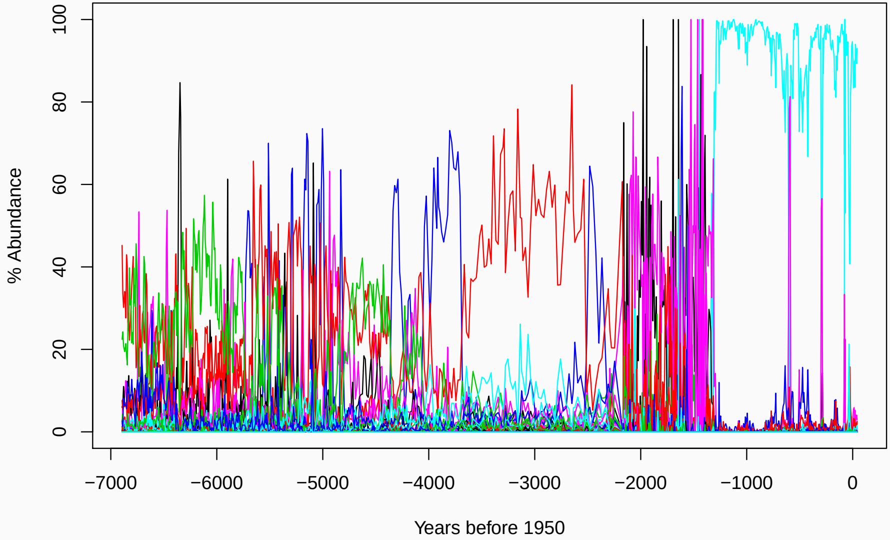
Community response to environmental change

Credit: Michael Knall [Public domain], via Wikimedia Commons

How do communities respond to rapid change?

How does resilience change over time?

Messy time series



Data provided by Jeffery Stone (Indiana State University)

Messy time series

Most long ecological & environmental time series are messy

- Collected irregularly
- Missing data — lab or field widget breaks, weather
- Multi-year gaps — loss of funding
- Methodological changes

They might be messy, but they’re still useful!

Complexity & Resilience

Logistic map

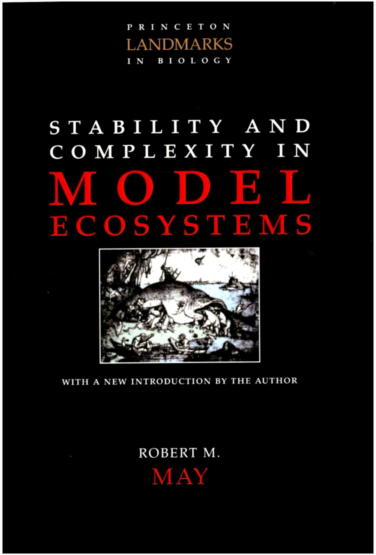
Complex behaviour from simple equations

$$x_{n+1} = rx_n(1 - x_n)$$

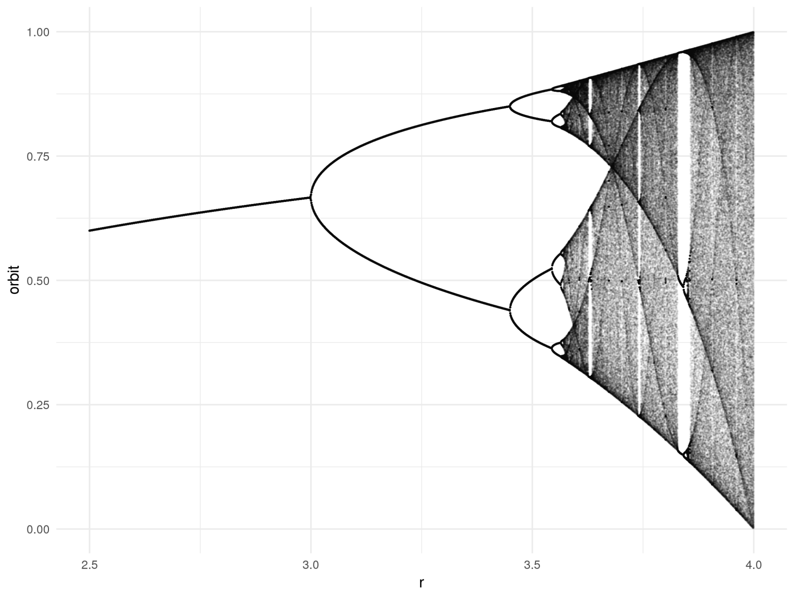
$0 < x_n < 1$ is the *fraction* of the carrying capacity of the ecosystem

r combines the birth and death rates

Interest is for values of r in the interval $[0, 4]$



Logistic map



Alternative stable states — Marten Scheffer

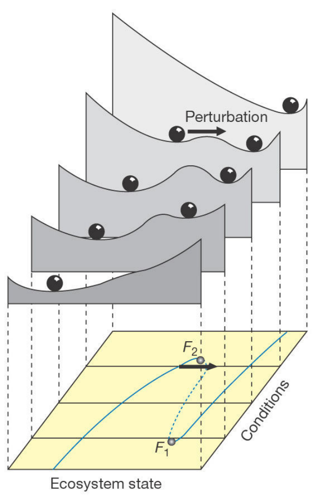
Under range of conditions multiple ecosystem states may exist

Stability landscapes depict equilibria and basins of attraction

Valleys are stable states

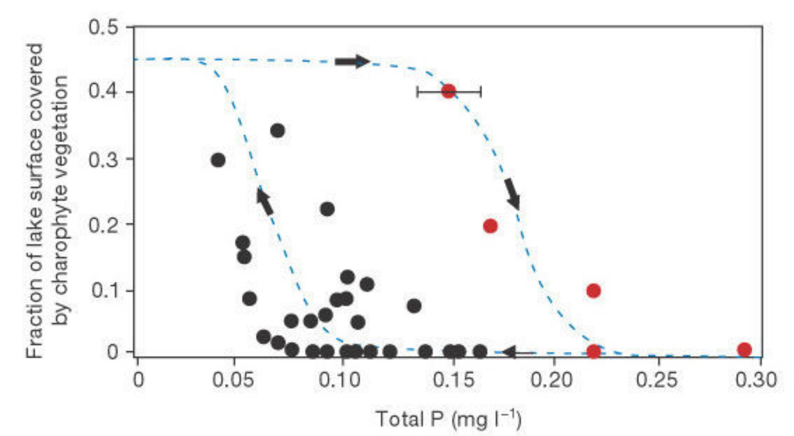
External conditions alter the stability landscape

Disturbances can kick a system between states



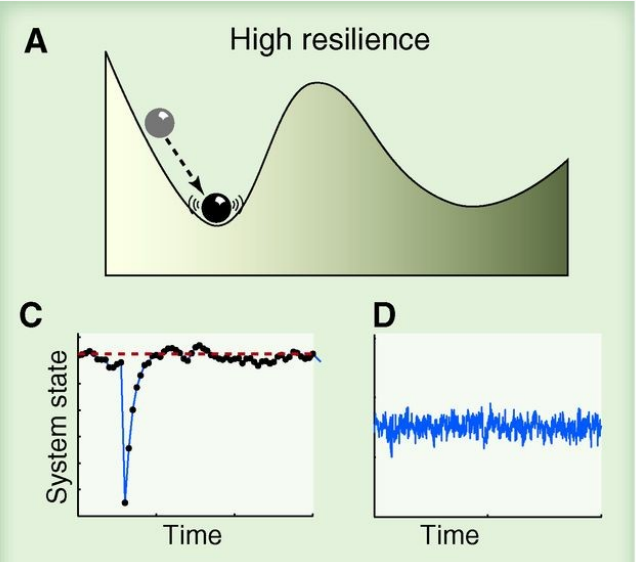
Source: Scheffer et al *Nature* 2001

Hysteresis



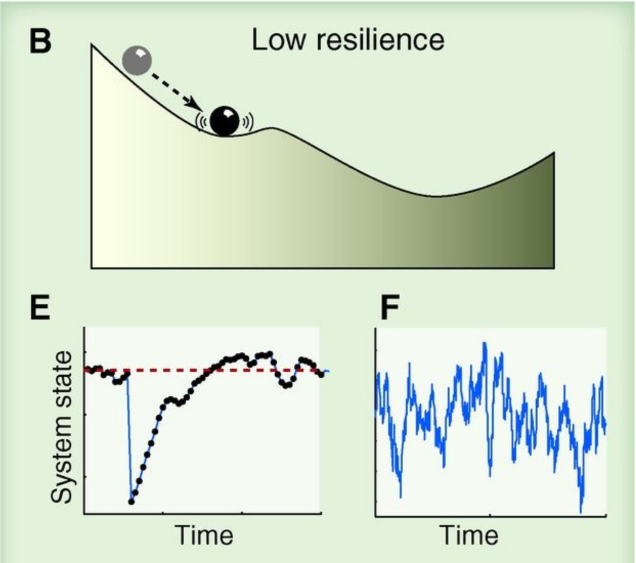
Source: Scheffer et al *Nature* 2001

Early warnings & Resilience to change



Source: Scheffer et al *Science* 2012

Early warnings & Resilience to change



Source: Scheffer et al *Science* 2012

Palaeoecology — Palaeolimnology

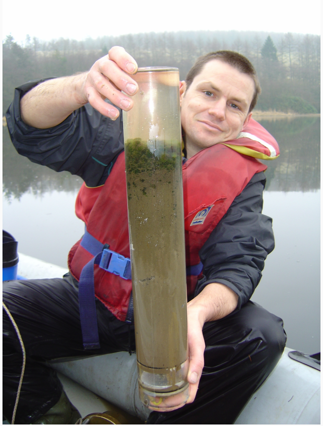
Palaeoecological data: valuable & unique source of data to study effects of environmental change

Most lakes not annually laminated

- mixing as a form of temporal averaging
- also age/dating uncertainty
- limits temporal resolution of data
- compaction of older sediments → varying time per sample

How do dynamics of species composition vary with environmental change?

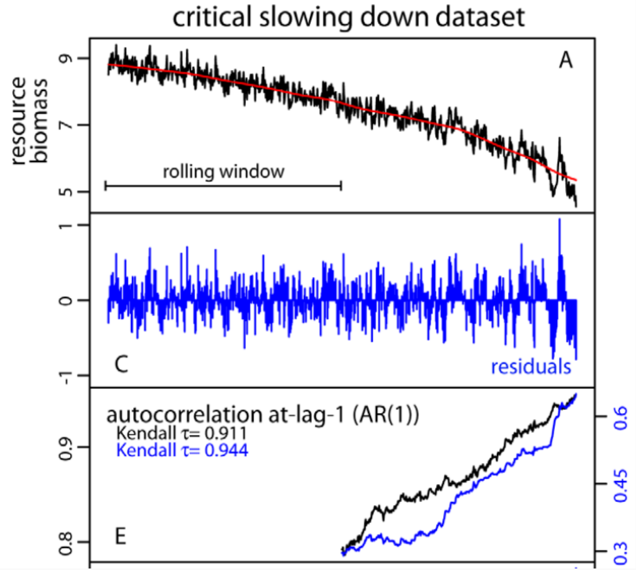
- Trend (mean), Variance, Higher moments...?



Source: © Ewan Shilland

Modelling variance

Moving windows



Source: Dakos et al *PLOS One* 2012

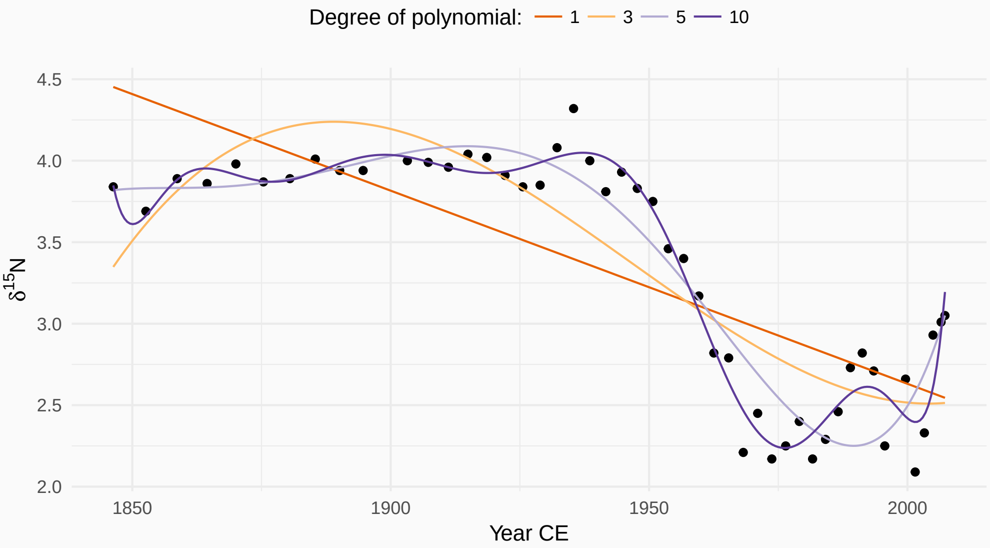
Problems

- 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
  - τ assumes independence
  - Surrogate time series assumes regular sampling, sensitive to choice of ARMA
- Results are incomplete time series


WIGGLY
THINGS

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

Linear models don’t fit well



Generalized additive models (GAMs)

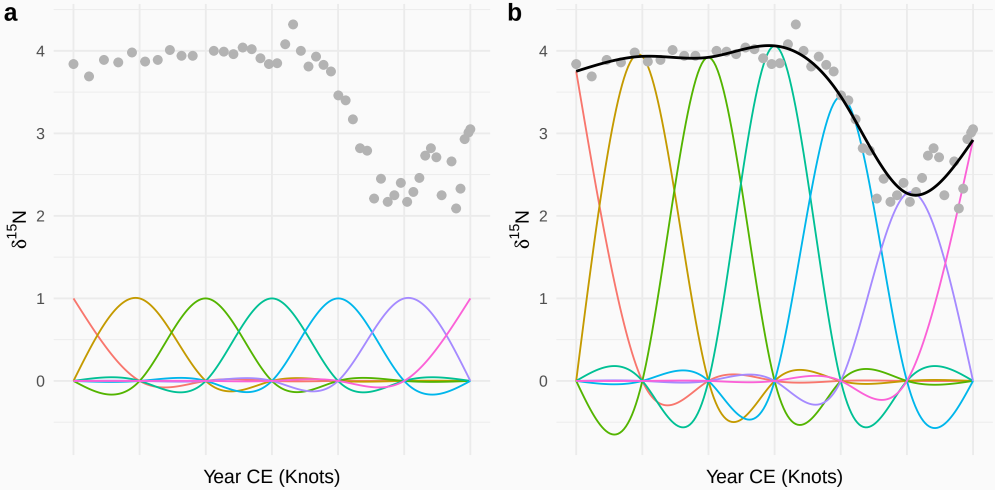
$$y = \beta_0 + f(\text{time}) + \varepsilon$$

f is a smooth function

Learn about the shape of f from the data

Penalty on wiggliness to avoid overfitting

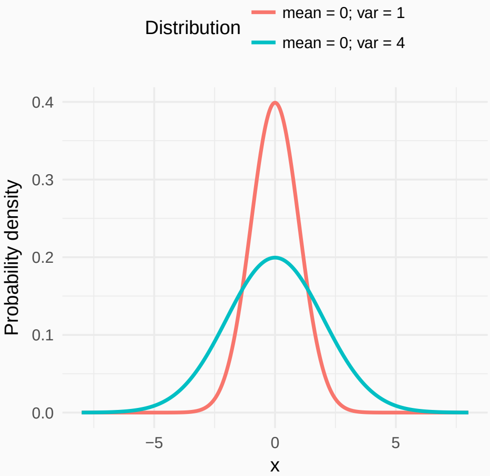
Generalized additive models

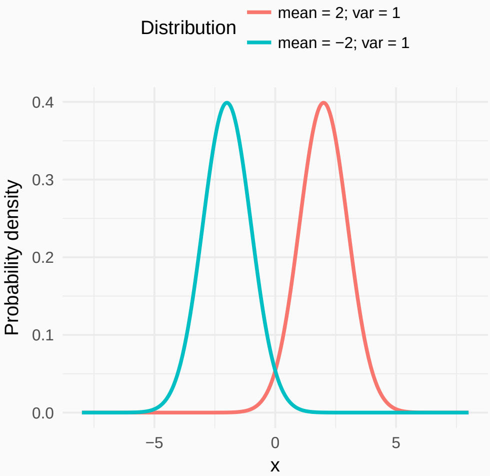


Location scale models

Gaussian distribution — defined by 2 parameters

- mean — μ
- variance — σ^2





Generalized additive model for location, scale, and shape

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

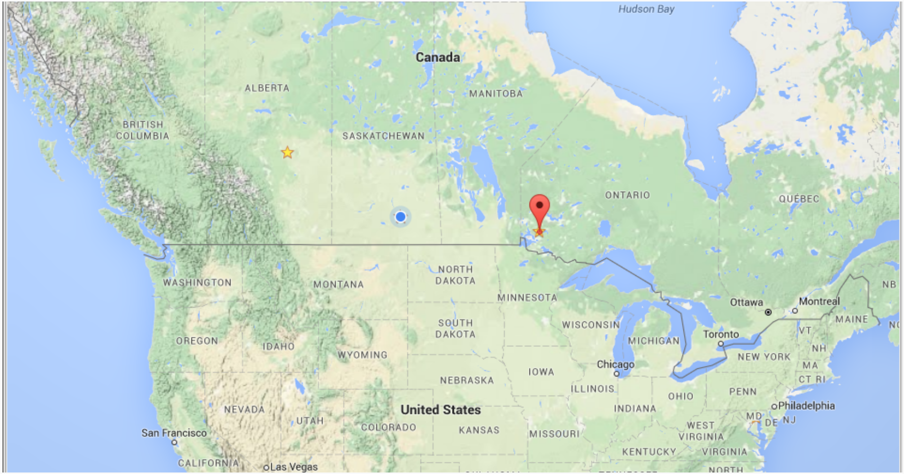
$$y_i \sim \mathcal{N}(\mu = \eta_{1,i}, \sigma^2 = \eta_{2,i})$$

- 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)

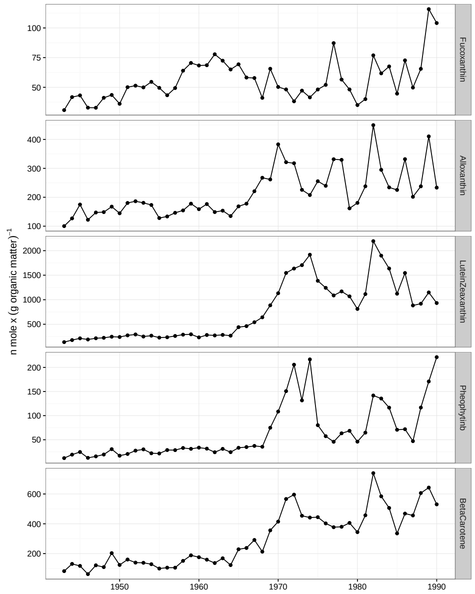


Lake 227

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

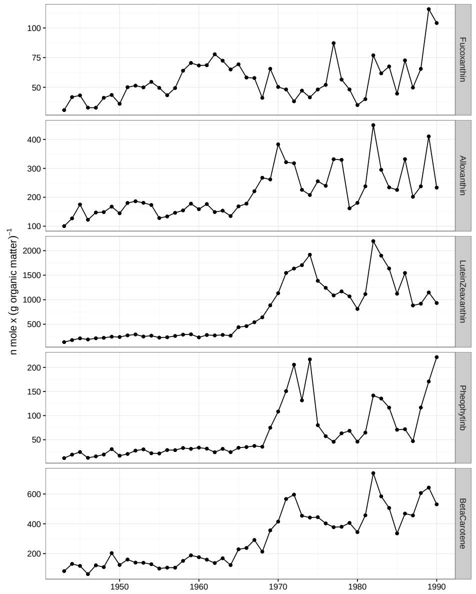
Lake 227 sedimentary pigments

- 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)

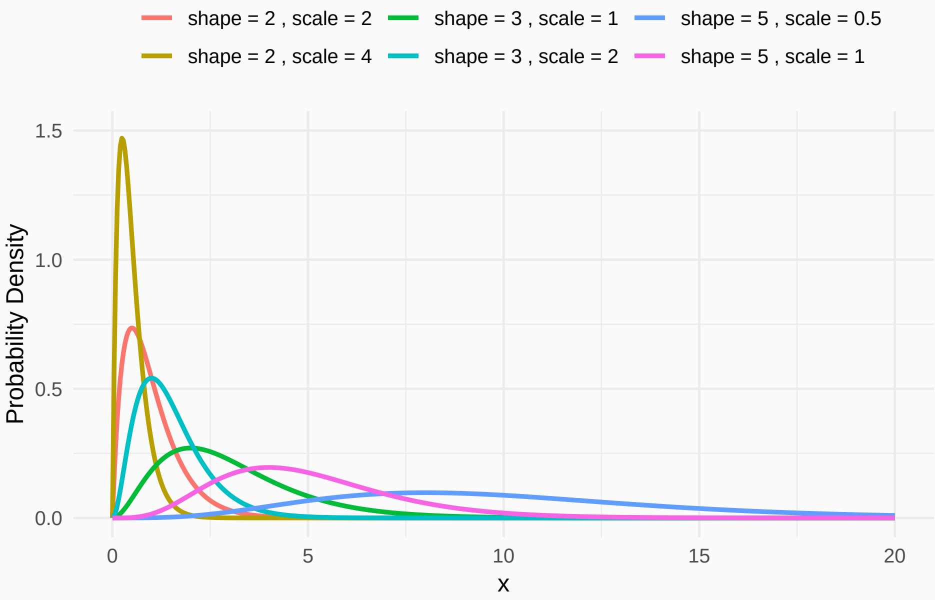


Pigment data

- 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

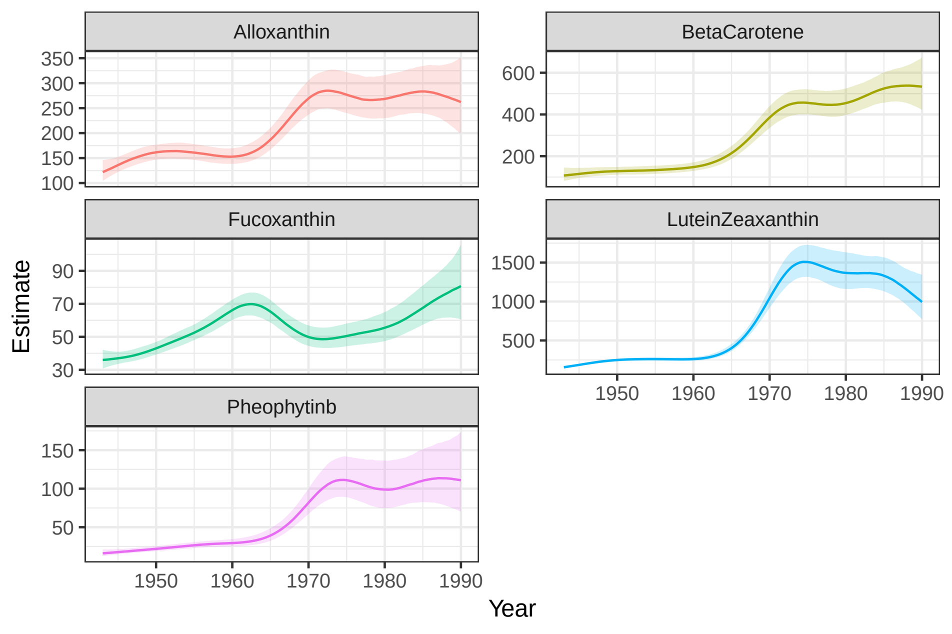
Fitted gamma location, scale additive model using **brms** and **Stan**

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

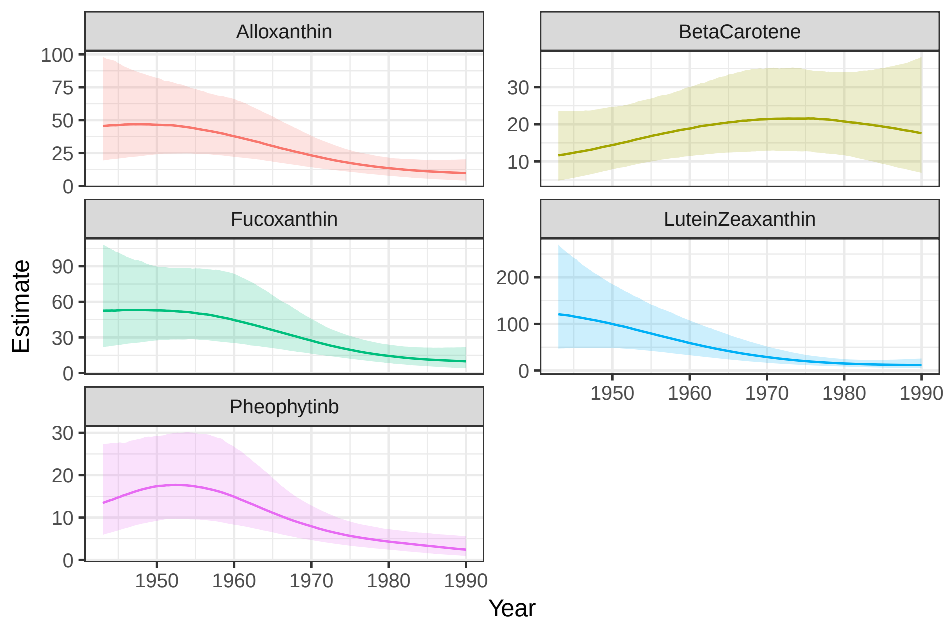
Mean (μ) & shape (α) each modelled with:

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

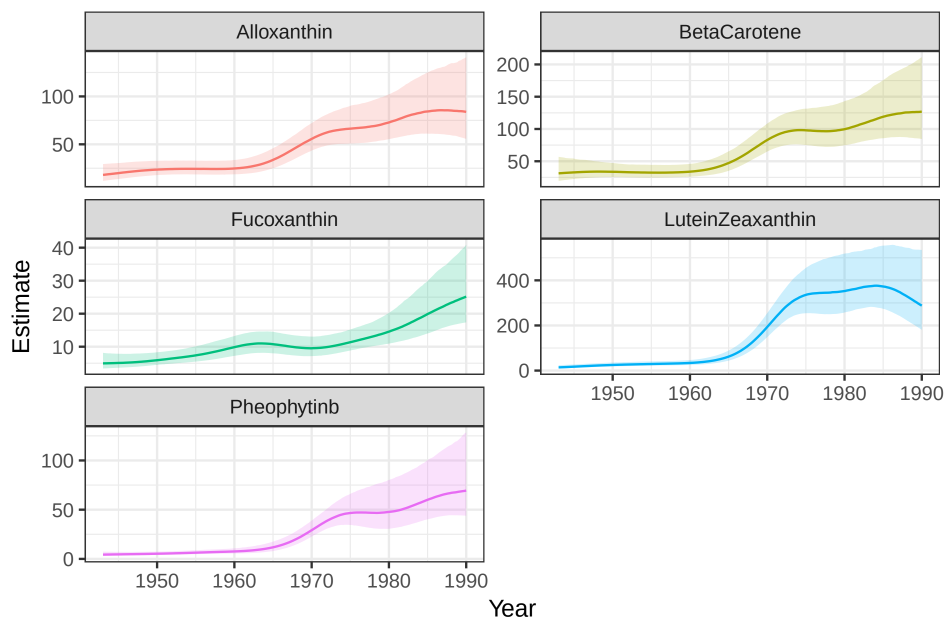
Lake 227 sedimentary pigments — fitted mean functions



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

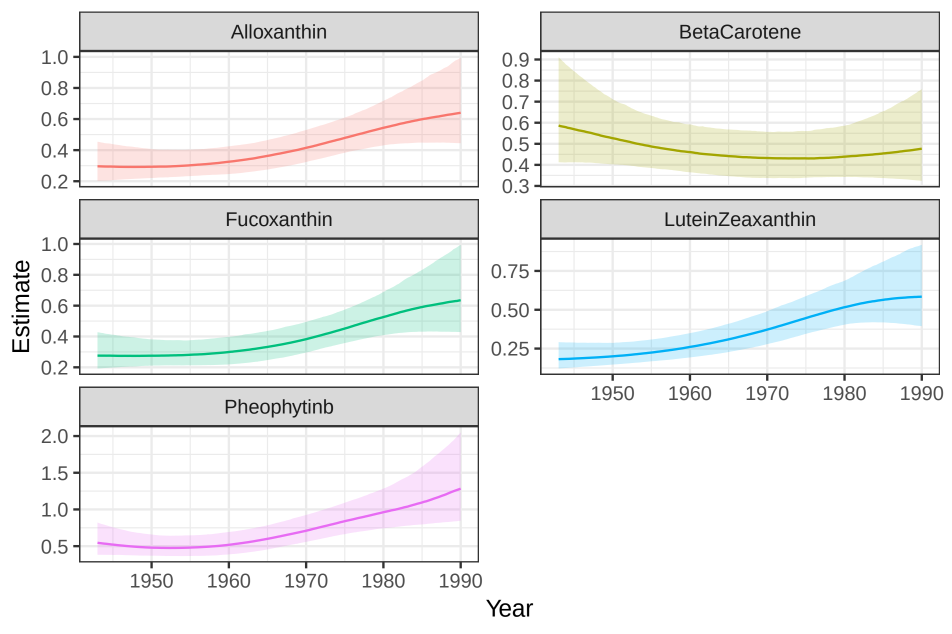
What's next...?

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

- Autocorrelation
- Skewness & kurtosis

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

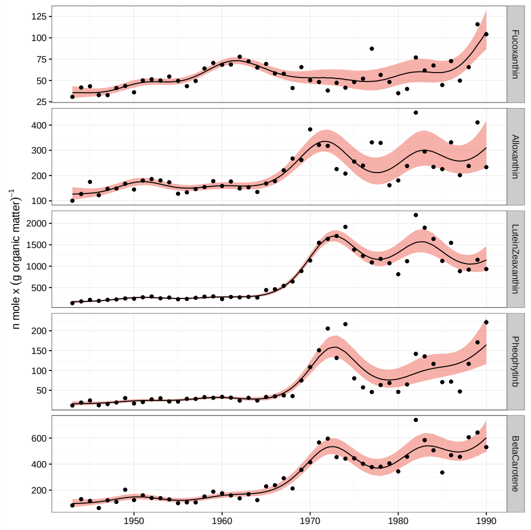
Lake 227 sedimentary pigments — estimated skewness functions



Extra examples / slides

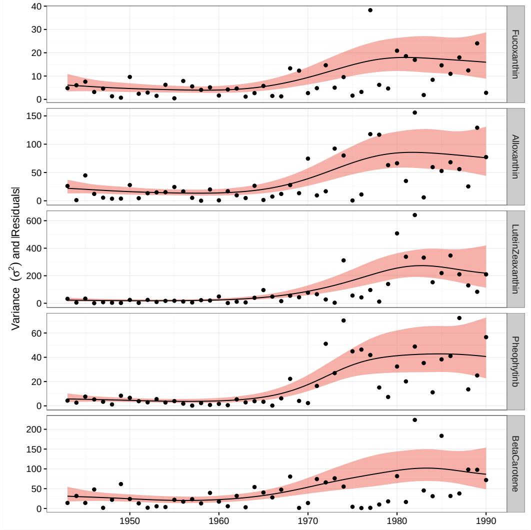
Lake 227 sedimentary pigments — fitted mean functions

- Random effect spline provides better fit of trend (mean)
- Undersmoothing of several pigments if separate models fit
- Increase in most algal groups following fertilization



Lake 227 sedimentary pigments — fitted variance functions

- Increasing variance in pigment concentration following manipulation
- Stabilisation post manipulation
- Consistent with median-log Levene's test (Cottingham, Rusak, and Leavitt 2000)



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

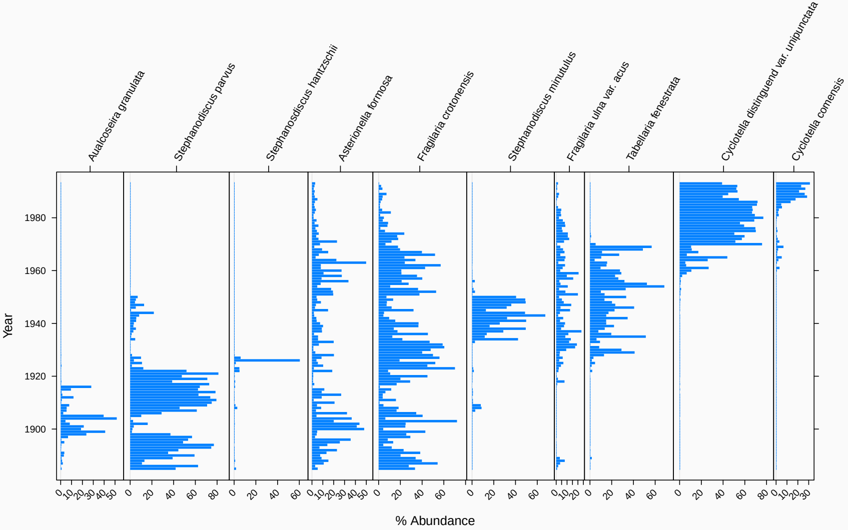
Baldeggersee

- 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

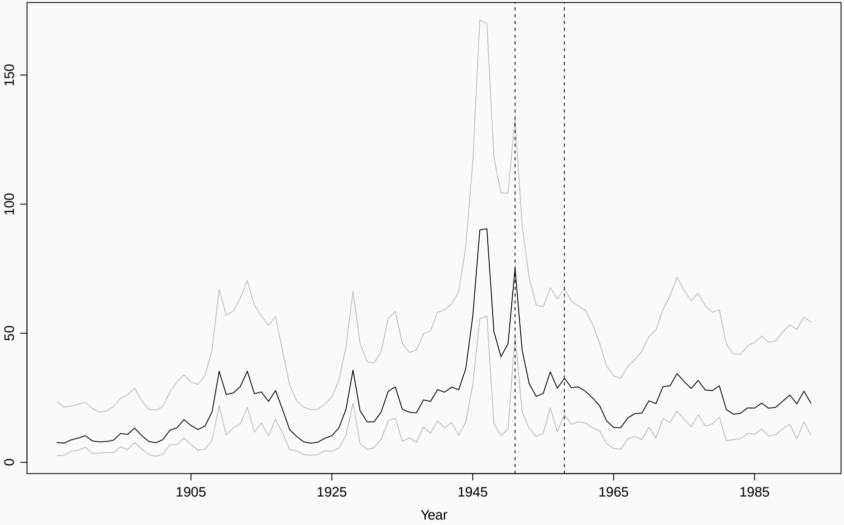
$$
\begin{aligned}
y_t | h_t &\sim \mathcal{N}(0, \exp h_t) && (1)\\
h_t | h_{t-1}, \mu, \phi, \sigma_\eta &\sim \mathcal{N}(\mu + \phi(h_{t-1} - \mu), \sigma_\eta^2) && (2)\\
h_0 | \mu, \phi, \sigma_\eta &\sim \mathcal{N}(\mu, \sigma_\eta^2 / (1 - \phi^2)) && (3)
\end{aligned}
$$

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

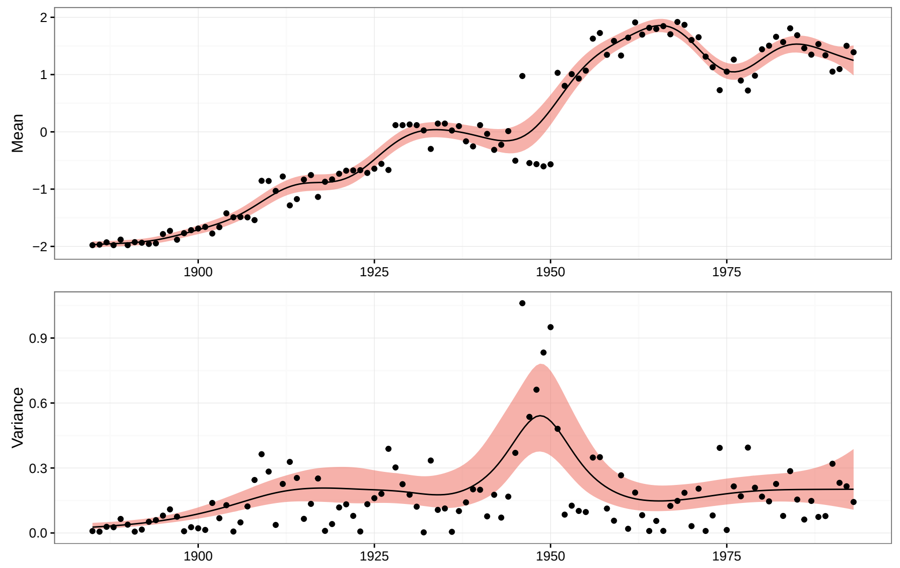
h is *unobserved* and modelled as a latent process

Fitted using stochvol R Package (Gregor Kastner)

Baldeggersee — Stochastic Volatility Model



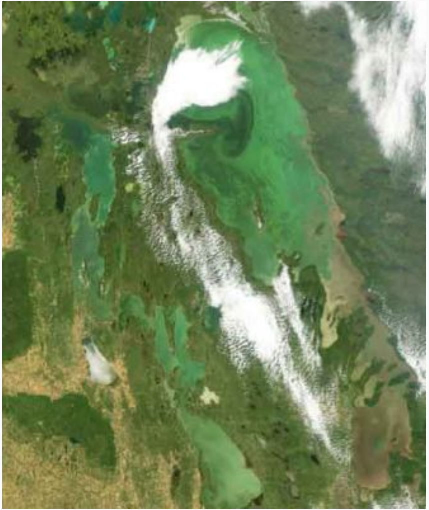
Baldeggersee — GAM Location and Scale fits



Lake Winnipeg

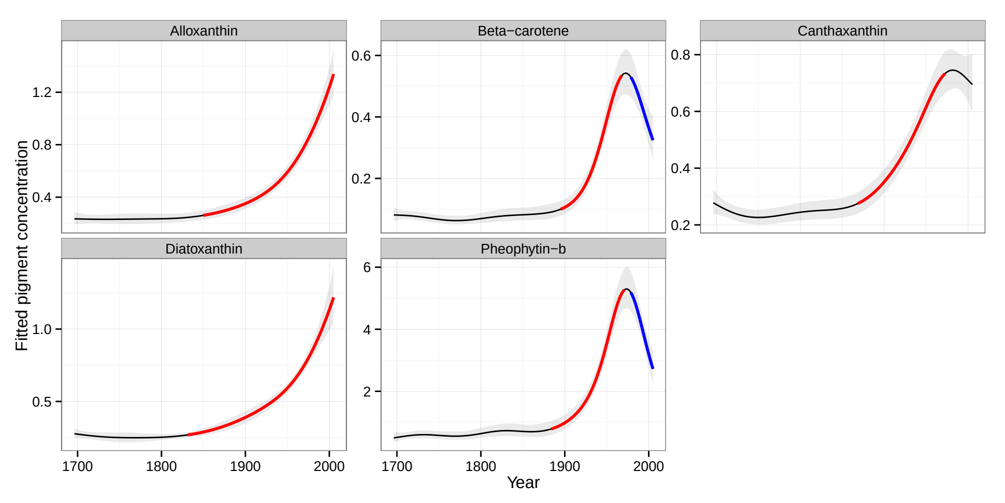
Has Lake Winnipeg suffered a catastrophic regime shift?

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



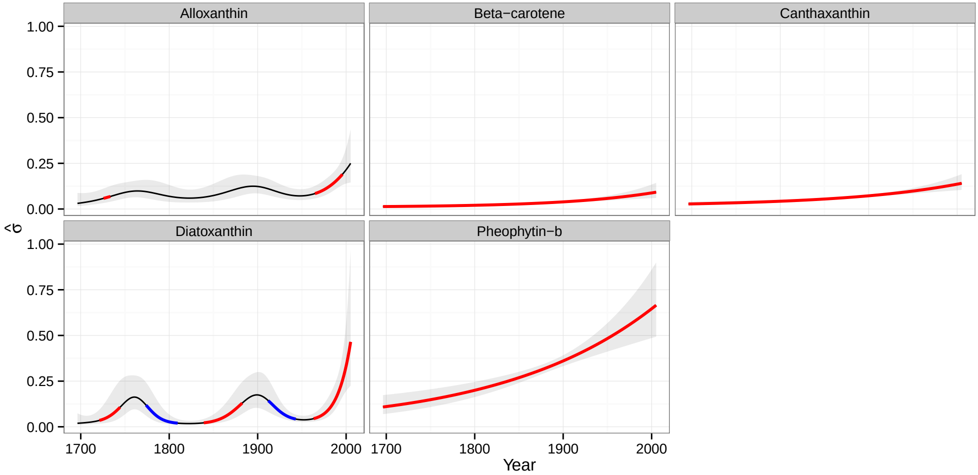
Source: Public domain

Has Lake Winnipeg suffered a catastrophic regime shift?



Source: Bunting et al *Limnology & Oceanography* 2016

Has Lake Winnipeg suffered a catastrophic regime shift?

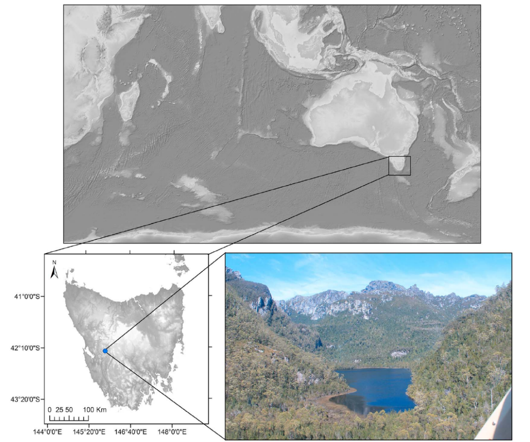


Source: Bunting et al *Limnology & Oceanography* 2016

Lake Vera, Tasmania

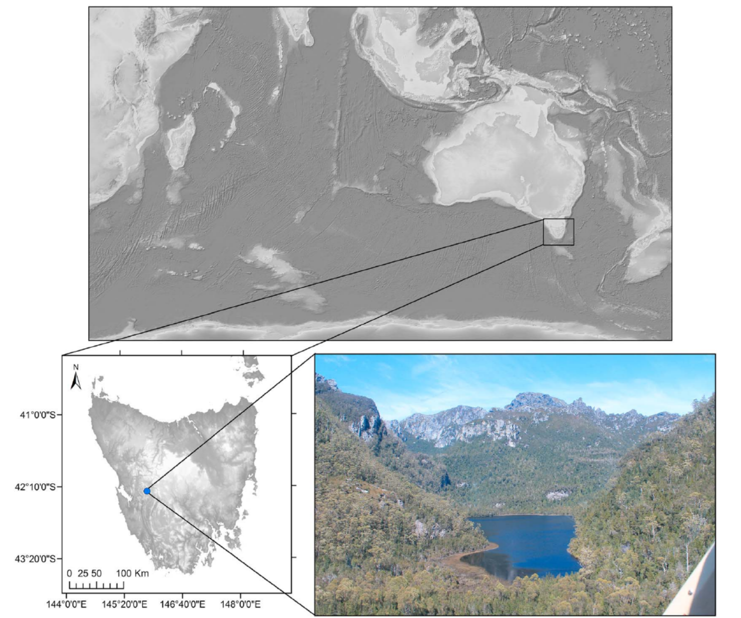
Lake Vera

- 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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43°20'0"S
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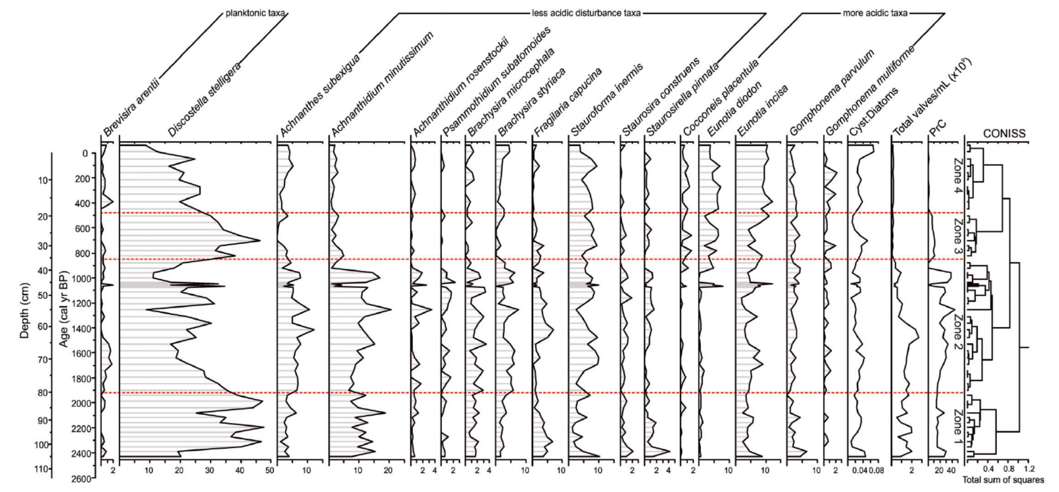
145°20'0"E
146°40'0"E
148°0'0"E

Lake Vera

Lake Vera



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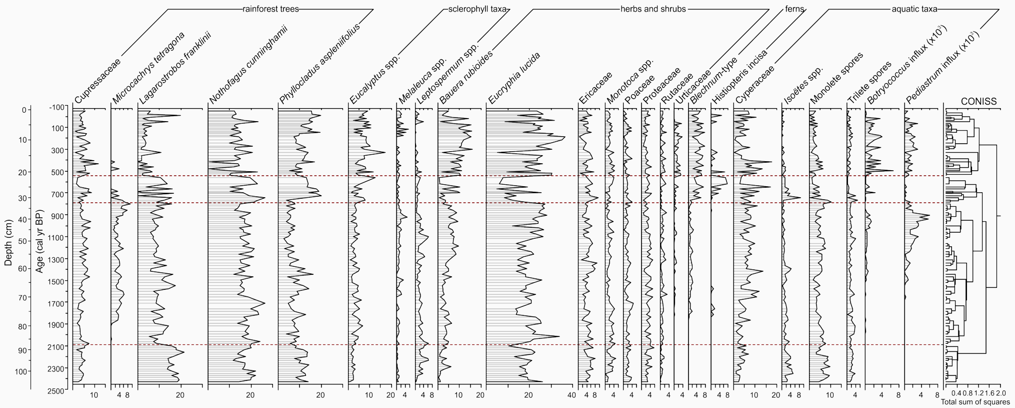
Lake Vera



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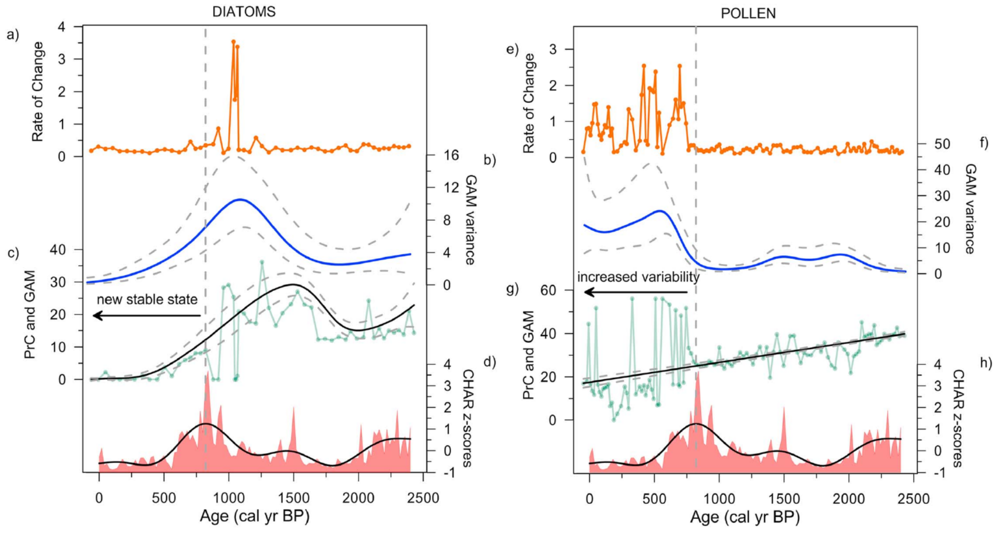
Lake Vera



Source: Beck et al *J Geophysical Research: Biogeoscience* 2018

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). Blackwell Science Ltd: 340–48. doi:10.1046/j.1461-0248.2000.00158.x.

Rigby, R A, and D M Stasinopoulos. 2005. "Generalized Additive Models for Location, Scale and Shape." *J. R. Stat. Soc. Ser. C Appl. Stat.* 54 (3). Blackwell Publishing Ltd: 507–54.

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