Ecological resilience in messy time series

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Acknowledgements

Slides: **bit.ly/muntalk2018**

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

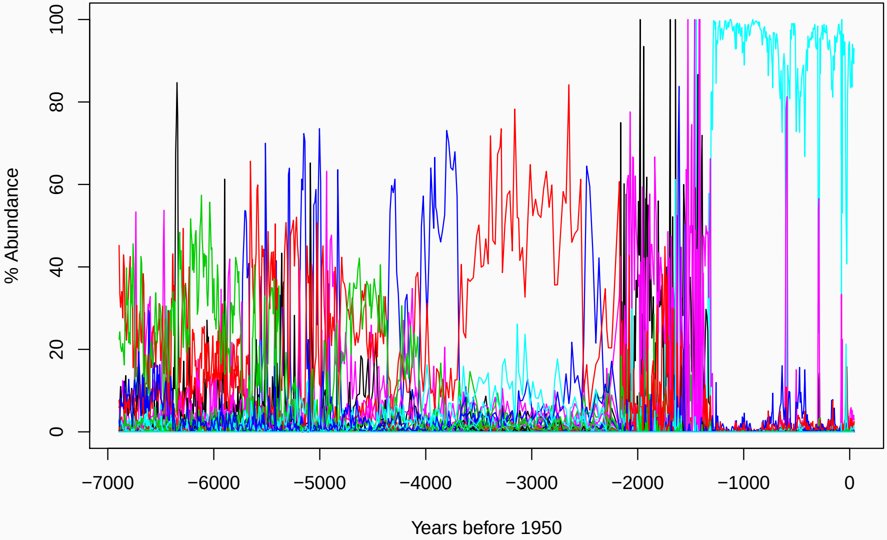
Community response to environmental change

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

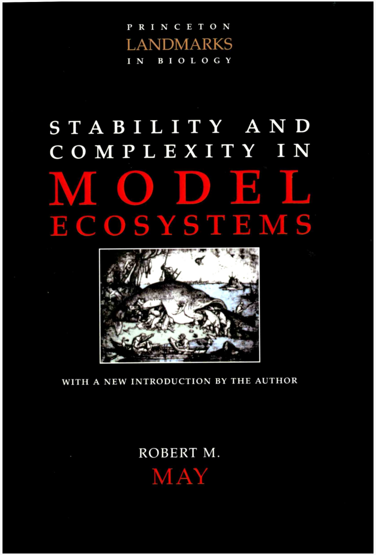
Complex behaviour from simple equations

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

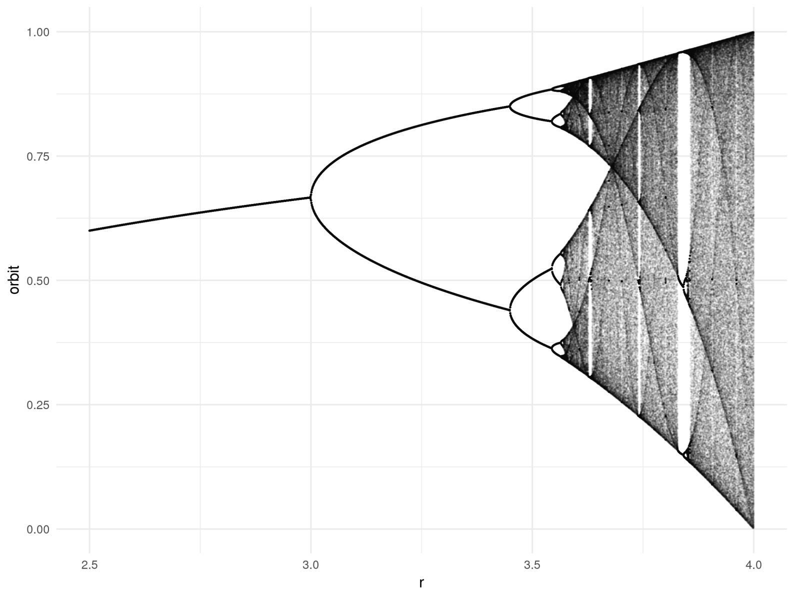
$0 < x_n < 1$ is the *fraction* of the carrying capacity of the ecosystem

r combines the birth and death rates

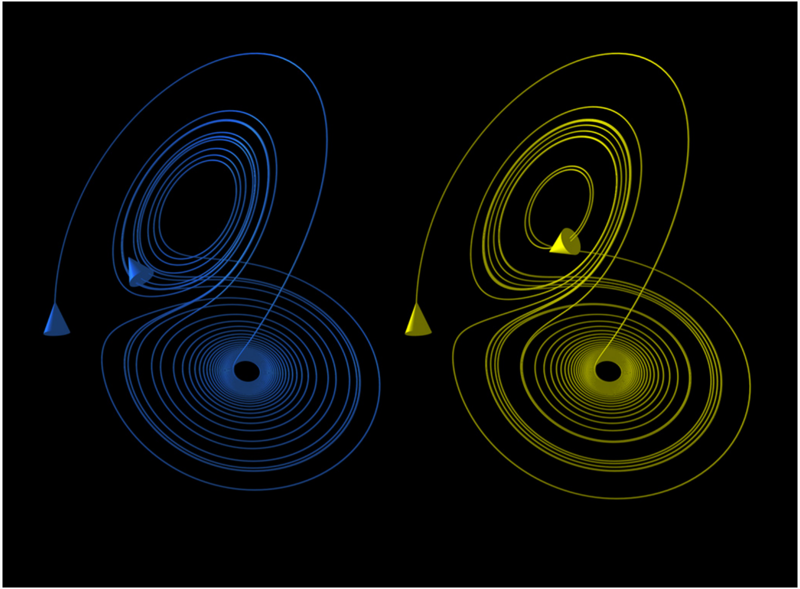
Interest is for values of r in the interval $[0, 4]$



Logistic map



Butterfly effect — Ed Lorenz

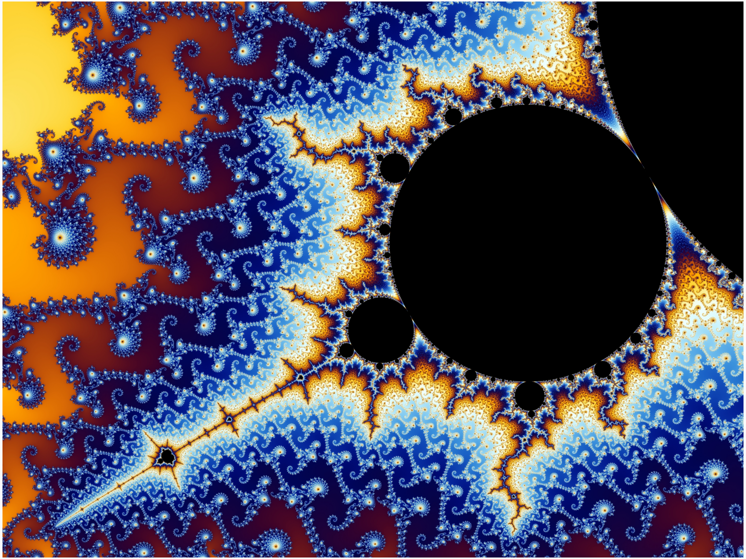


Credit: Hellisp [CC-BY], via Wikimedia Commons

Turbulent flow — Lev Landau

Credit: NASA [Public domain], via Wikimedia Commons

Fractal geometry — Benoit Mandelbrot



Credit: Wolgangbeyer [CC BY-SA], via Wikimedia Commons

Alternative stable states — Marten Scheffer

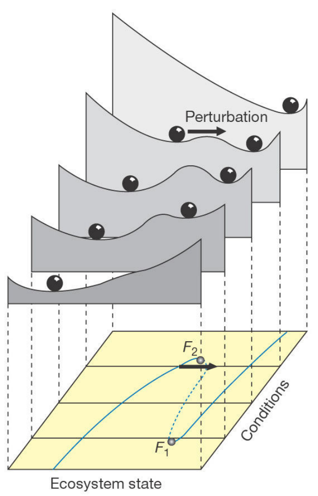
Under range of conditions multiple ecosystem states may exist

Stability landscapes depict equilibria and basins of attraction

Valleys are stable states

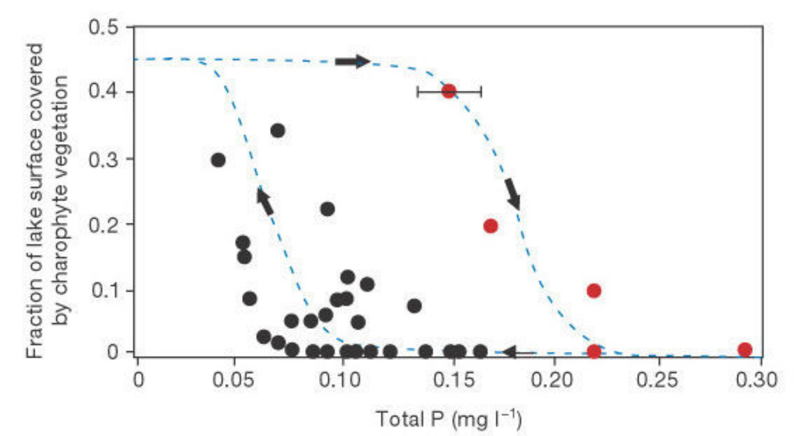
External conditions alter the stability landscape

Disturbances can kick a system between states



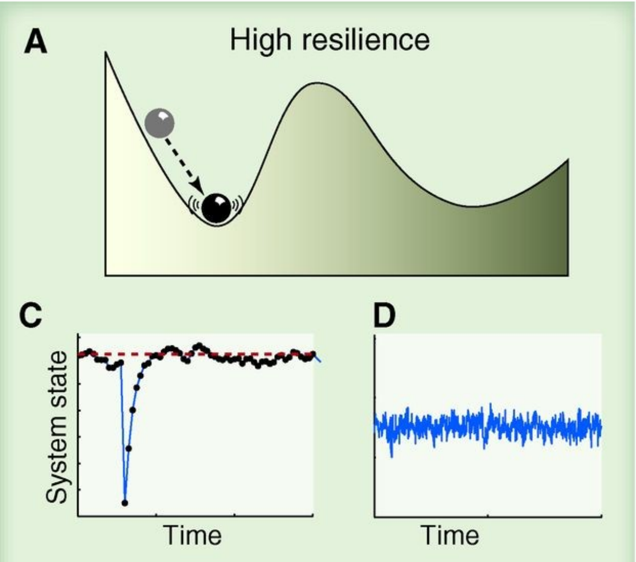
Source: Scheffer et al *Nature* 2001

Hysteresis



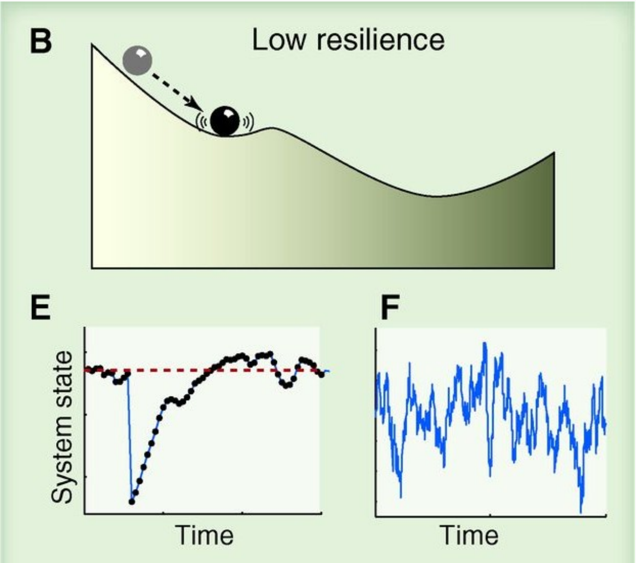
Source: Scheffer et al *Nature* 2001

Early warnings & Resilience to change



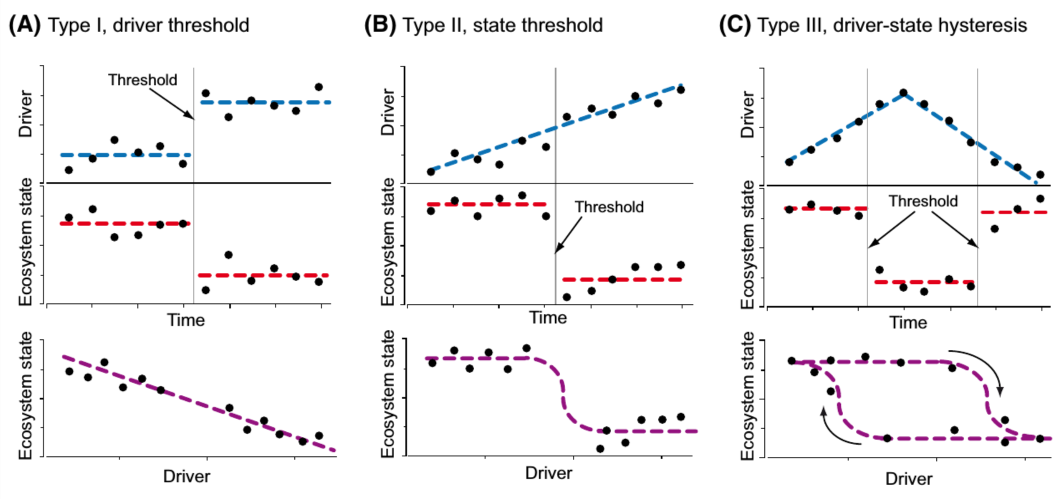
Source: Scheffer et al *Science* 2012

Early warnings & Resilience to change



Source: Scheffer et al *Science* 2012

Regime shifts



Source: Randsalu-Wendrup et al *J. Paleolimnology* 2016

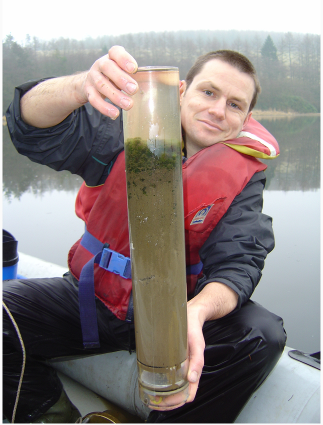
Palaeoecological data: valuable & unique source of data to study effects of environmental change

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?

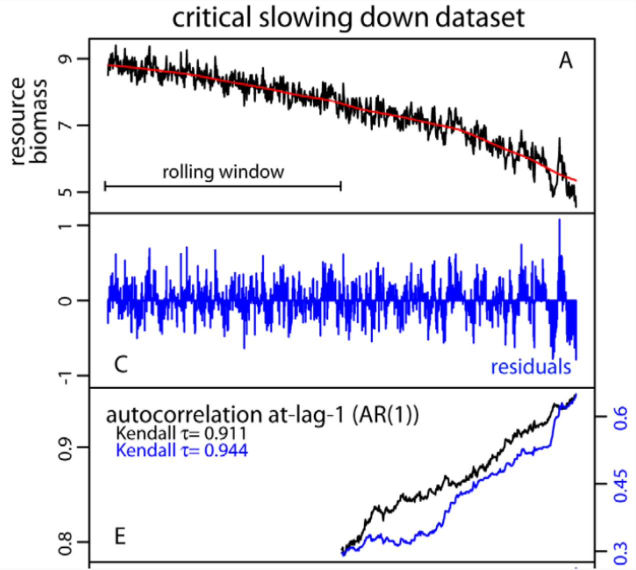
- Trend (mean), Variance, Higher moments...?



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

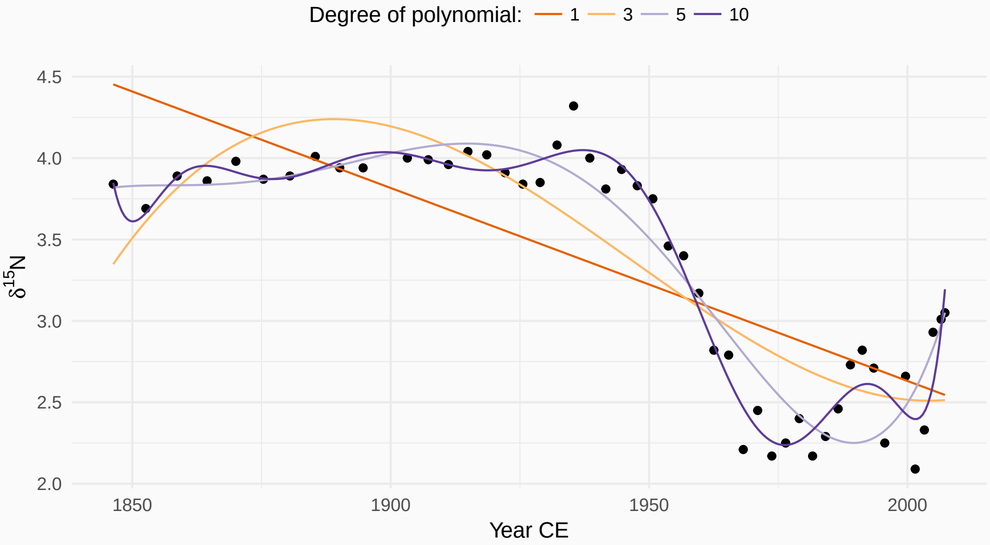
Linear models

{

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

}

Linear models don't fit well



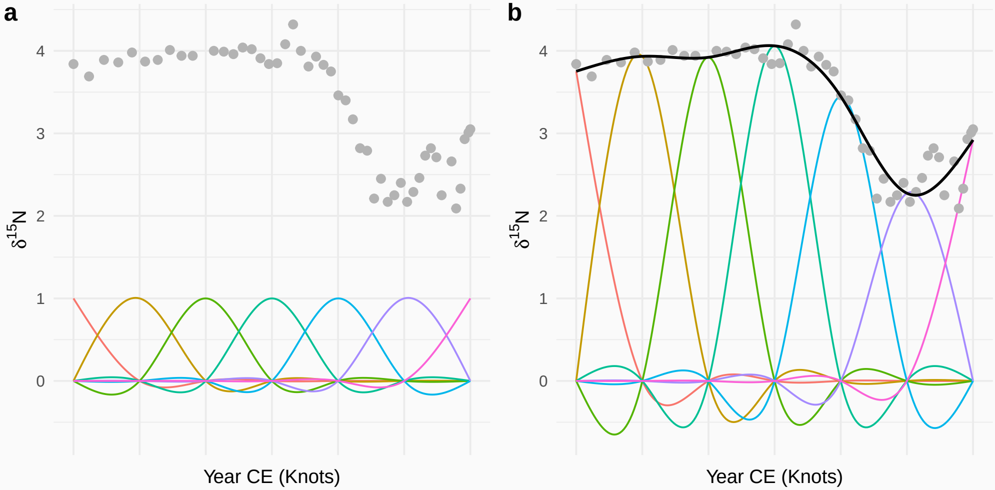
{

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

}

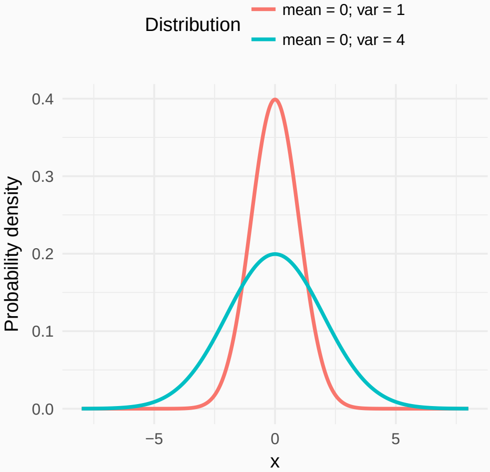
f is a smooth function
Learn about the shape of f from the data

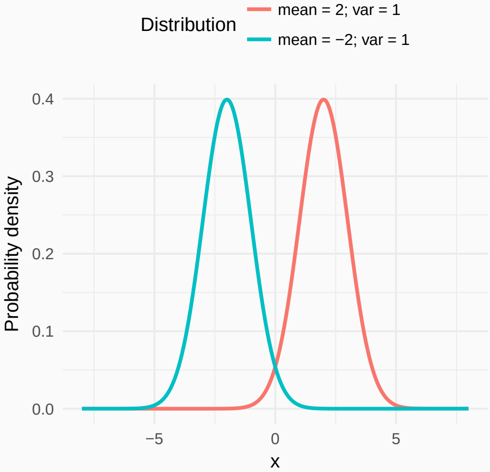
Generalized additive models



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.

- 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

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

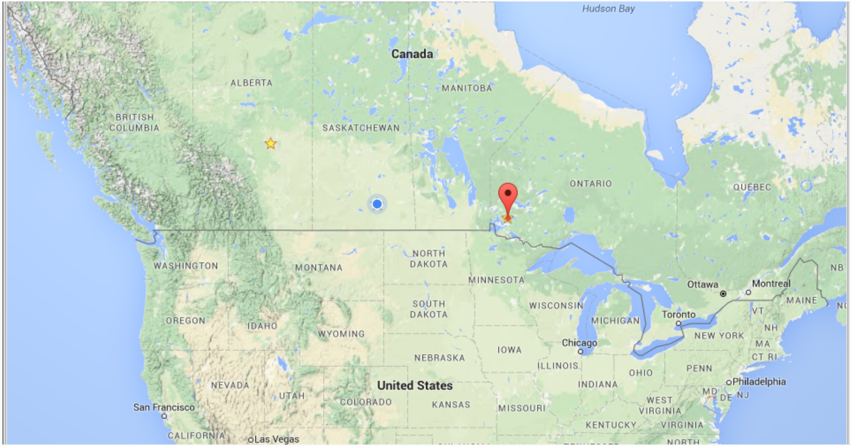
$$\eta_{1,i} = g\left(\sum_{j=1}^{k} f_j(x_{ij})\right)^{-1}$$

$$\eta_{2,i} = g\left(\sum_{j=1}^{k} f_j(z_{ij})\right)^{-1}$$

Lake 227

Lake 227

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

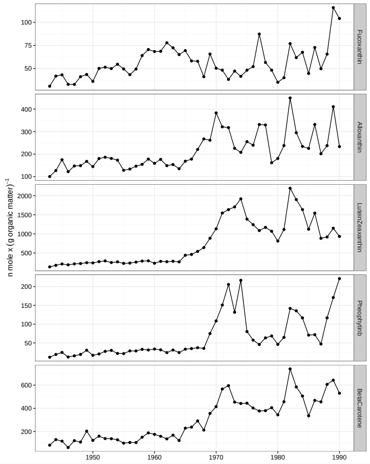


Lake 227

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*; cyanobacteria, chlorophytes
    - *Pheophytin* b; chlorophytes
    - *β carotene*; total algae
- Cottingham, Rusak, and Leavitt (2000)



Lake 227 sedimentary pigments

Fitted Gaussian location, scale additive model using **mgcv**

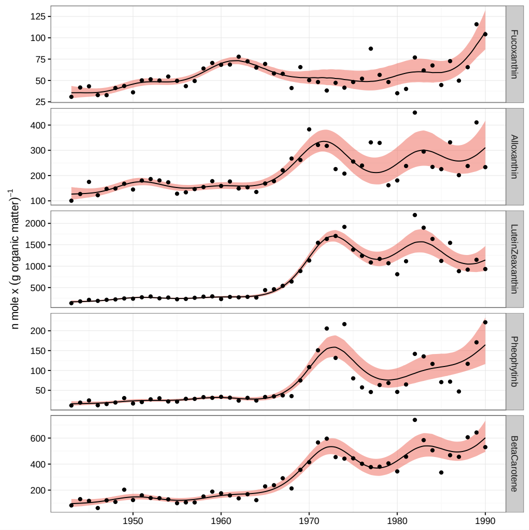
$$
\begin{aligned}
y_t &\sim \mathcal{N}(\mu = \eta_{1,t}, \sigma^2 = \eta_{2,t}) \\
\eta_{1,t} &= \exp(f_1(\text{Year}_t) + f_{1,\text{pigment}}(\text{Year}_t)) \\
\eta_{2,t} &= g(f_2(\text{Year}_t) + f_{2,\text{pigment}}(\text{Year}_t))^{-1}
\end{aligned}
$$

Mean & variance modelled with:

1. Global function of Year, plus
2. “Random effect” spline (spline-factor interaction `bs = "fs"`) with penalty on first derivative — penalizes departures from global function
3. $g()$ is a log link function modified to avoid $\hat{\sigma}^2 = 0$

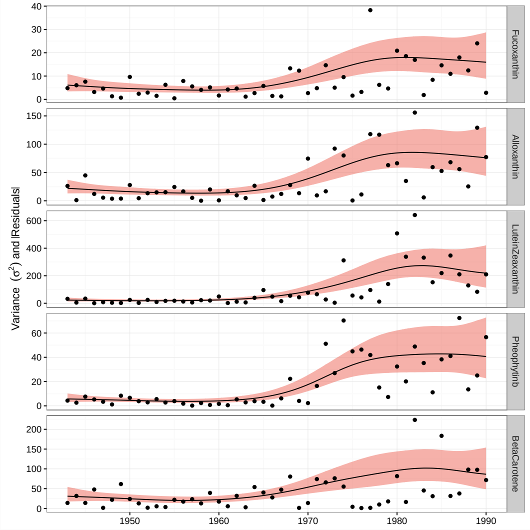
Lake 227 sedimentary pigments — fitted mean functions

- 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

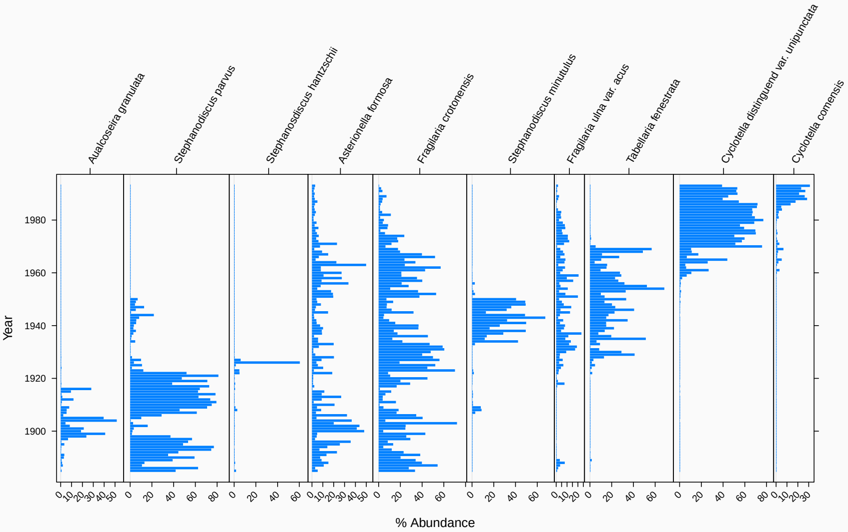
Baldeggersee

- 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 (?)

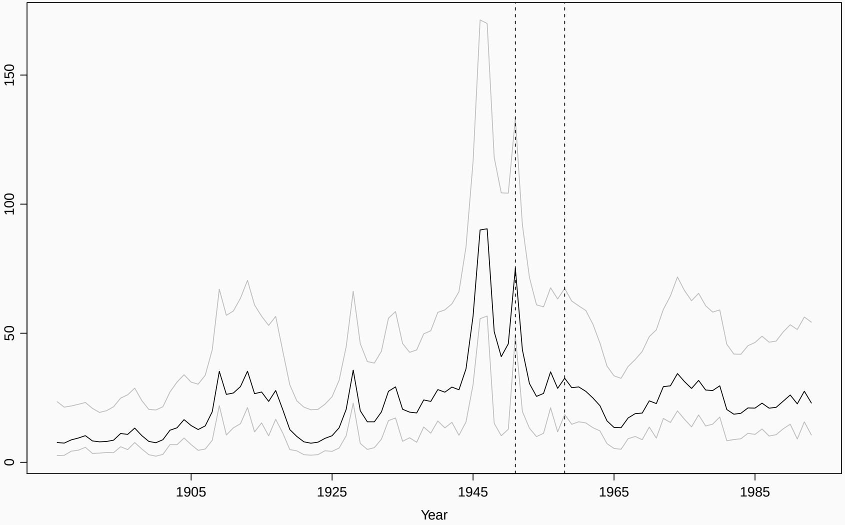
Are early warning signals (increased variance) present?

Source: © Andy Lotter

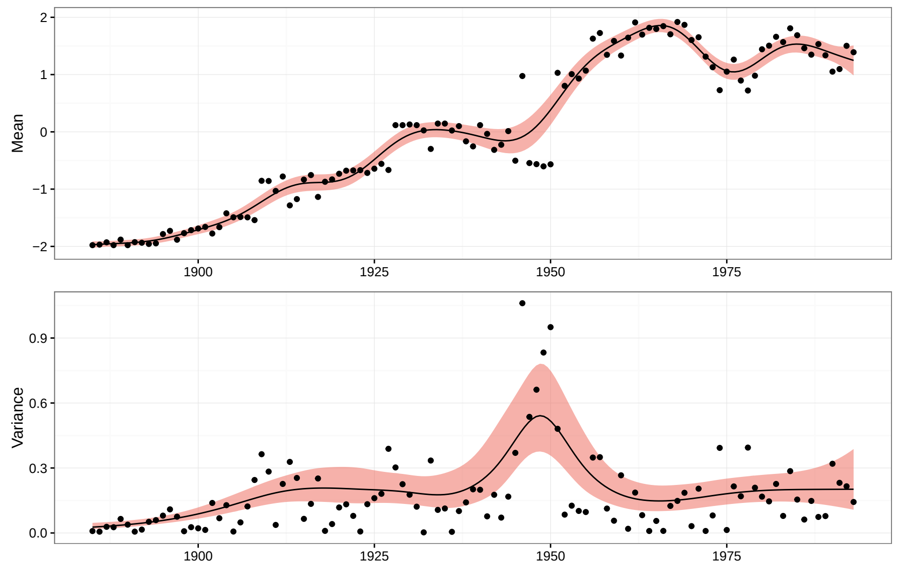
Baldeggersee — Stratigraphy



Baldeggersee — Stochastic Volatility Model



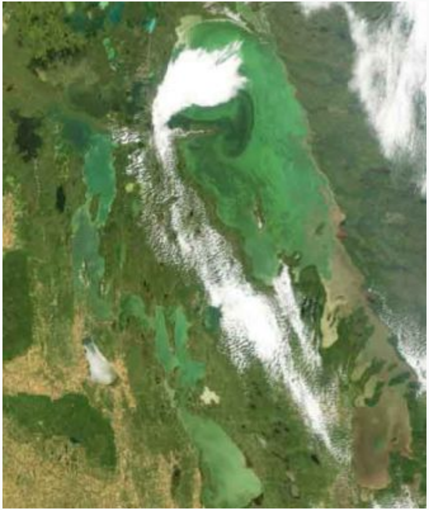
Baldeggersee — GAM Location and Scale fits



Lake Winnipeg

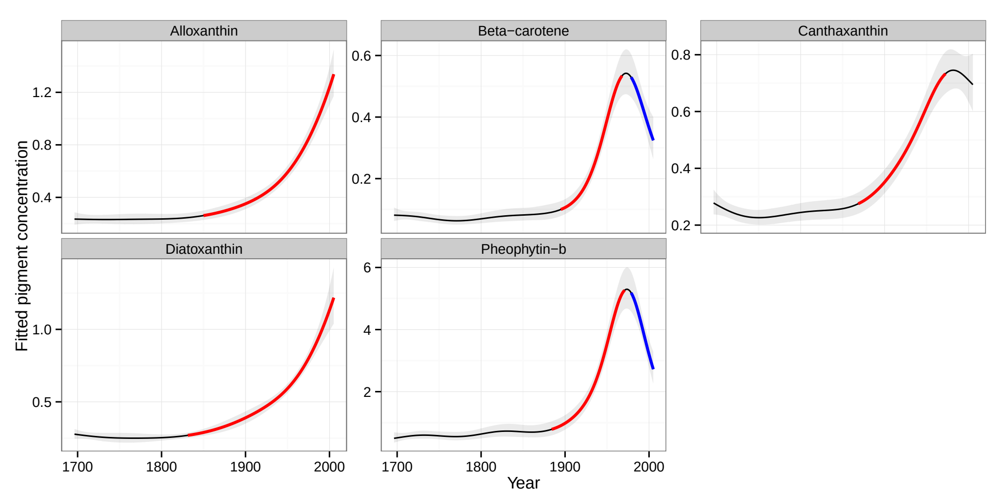
Has Lake Winnipeg suffered a catastrophic regime shift?

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



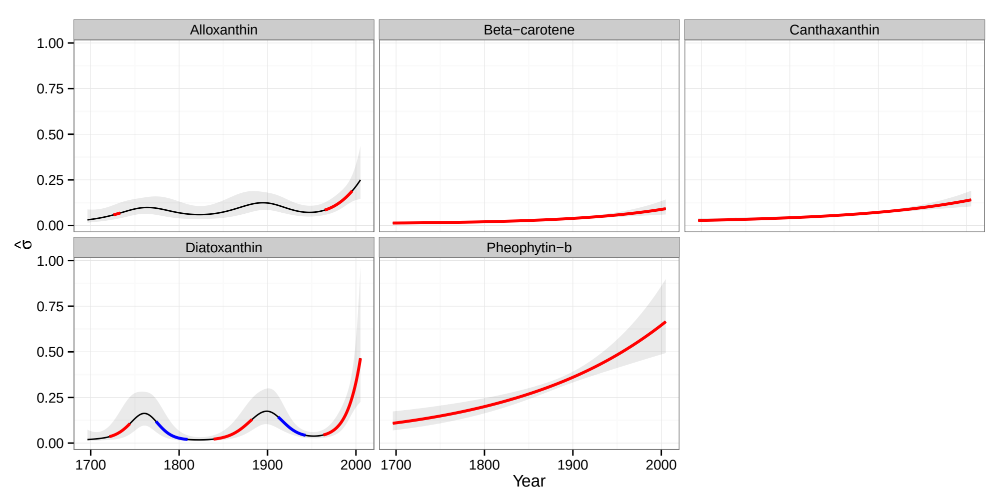
Source: Public domain

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

Summary

What’s next…?

GAM-based models for other EWS?

- Autocorrelation
- Skewness & kurtosis

Distributional models & recently-developed quantile GAM approaches might work

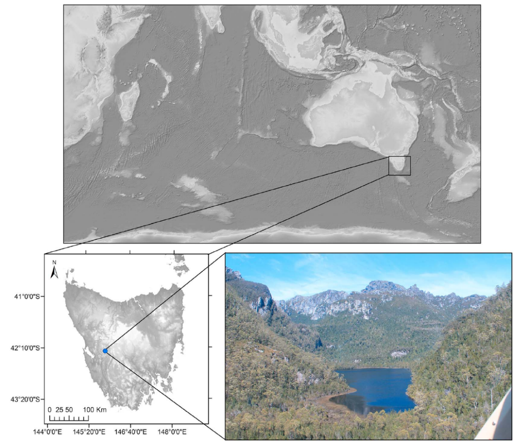
Extra examples / slides

Extra Slides

Lake Vera, Tasmania

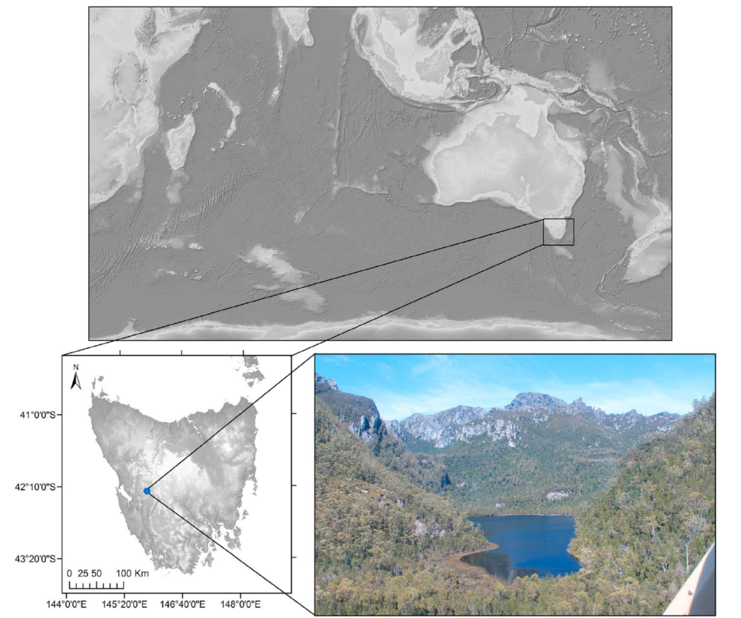
Lake Vera

- 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

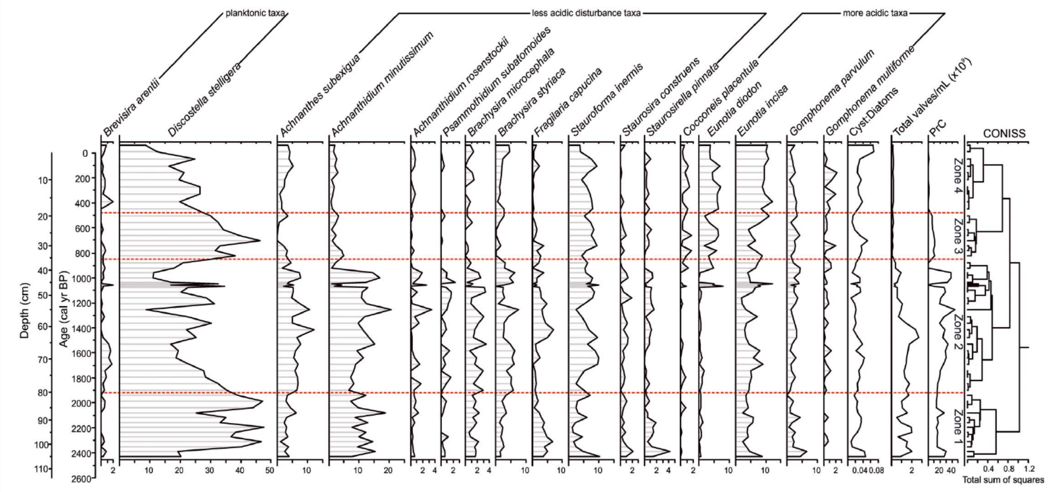
Lake Vera



N
41°0'0"S
42°10'0"S
43°20'0"S
0 25 50 100 Km
144°0'0"E
145°20'0"E
146°40'0"E
148°0'0"E

Lake Vera

Lake Vera



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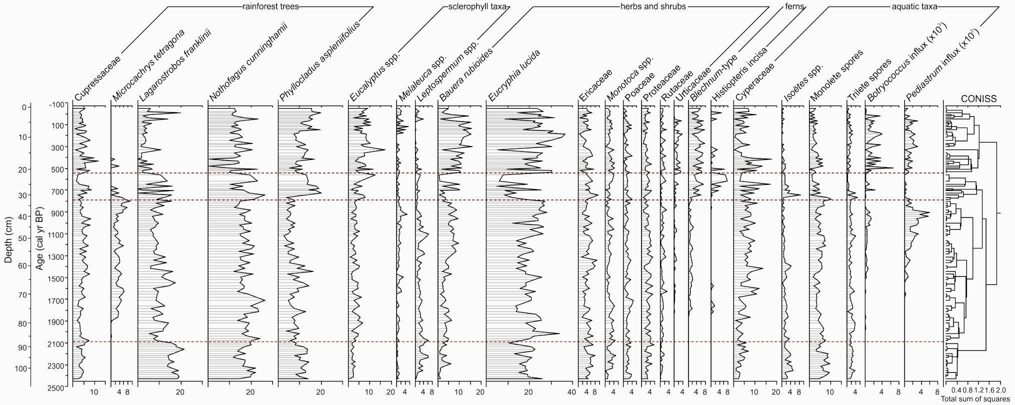
Lake Vera



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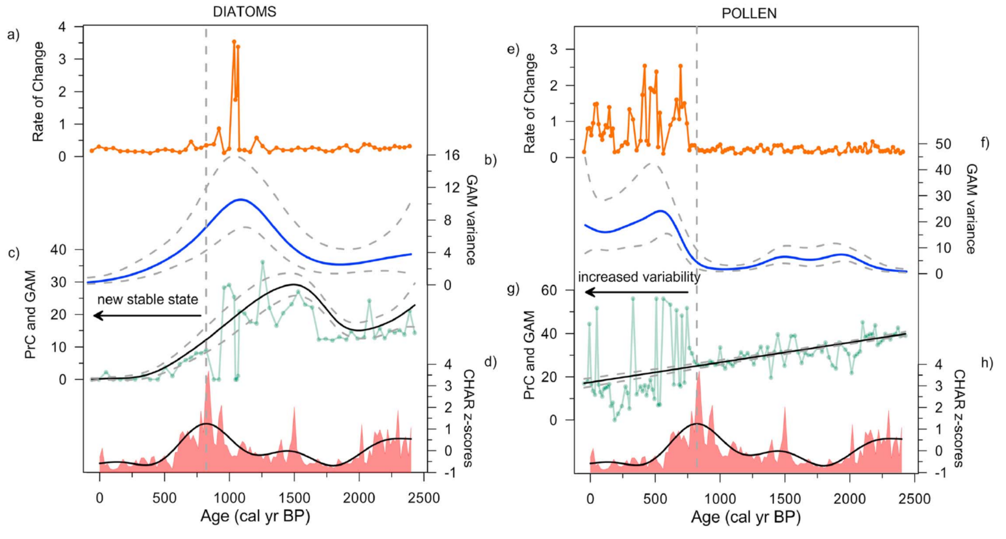

Source: Beck et al *J Geophysical Research: Biogeoscience* 2018

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.