FIXED ON NITROGEN
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Abstract

Critical Loads for the Management of Nitrogen Acidification and Eutrophication

Dr. Chris Evans

Critical loads have been extensively used, particularly in Europe, as a tool for managing nitrogen emissions. Critical loads define the acceptable pollutant loading to an ecosystem. If the critical load is exceeded, long-term ecosystem damage is expected. Nitrogen deposition is relevant to: i) critical loads for acidity, which define the acceptable combined loading of sulphur and nitrogen deposition, beyond which acidification damage occurs in terrestrial or freshwater ecosystems; and ii) critical loads for nitrogen as a nutrient, which define the specific nitrogen loading beyond which biodiversity loss will occur due to eutrophication. Critical loads vary according to the sensitivity of the ecosystem. They have been used at large (e.g. European) scales to define the most cost-effective strategy for emissions reductions (i.e. that which will lead to the greatest reduction in critical load exceedance for the amount spent), and are also now being used at smaller scales, e.g. to protect and manage individual sites of conservation importance. Although they have proven effective as a policy tool, critical loads nonetheless have a number of limitations. Most importantly, they predict damage to the ecosystem at long-term steady state. Since many ecosystems have the capacity to accumulate nitrogen over very long periods, the lag between critical load exceedance and observable ecosystem damage (or indeed deposition reductions and ecosystem recovery) may be long. New approaches, which overcome some of these limitations using dynamic models, and more detailed vegetation models, are described.

Critical Loads for the Management of Nitrogen Acidification and Eutrophication

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Overview

1. The critical loads concept
2. Critical loads for N and acidity
3. Critical loads for N as a nutrient
4. Dynamic models
5. Critical loads in Alberta
6. Conclusions

1. The Critical Loads concept

Eagle Mountains, Czech Republic, 2005

Regulating long-range pollutant emissions

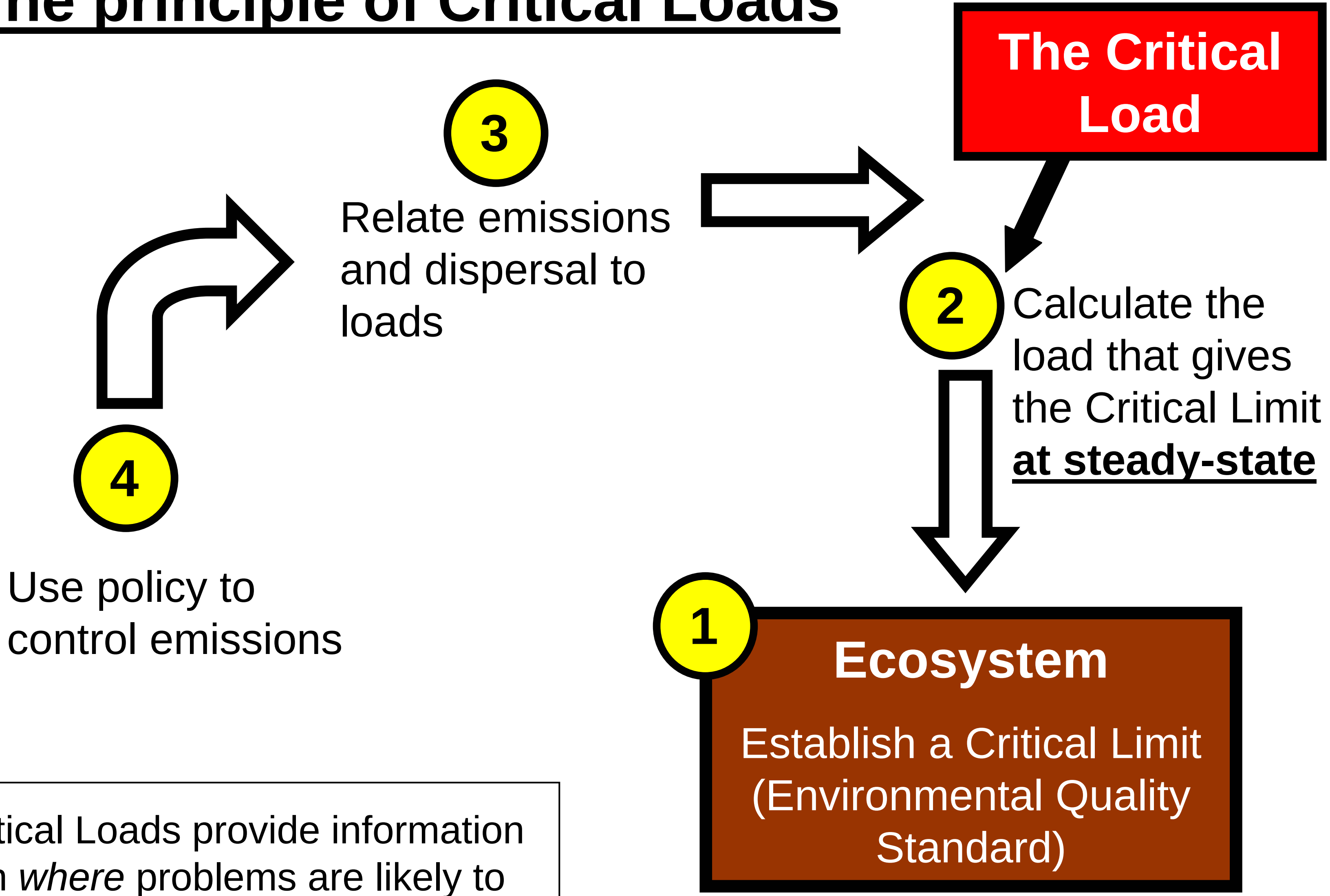
Option 1: Best-available technology

Option 2: Effects-based approach

Critical Load = the **highest annual input** of the pollutant that, **at steady-state**, does not cause unacceptable **ecological** [*or **human health***] effects

Critical Limit = the **highest steady-state concentration** of the pollutant that does not cause unacceptable **ecological** [*or **human health***] effects

The principle of Critical Loads



Critical Loads provide information on *where* problems are likely to occur

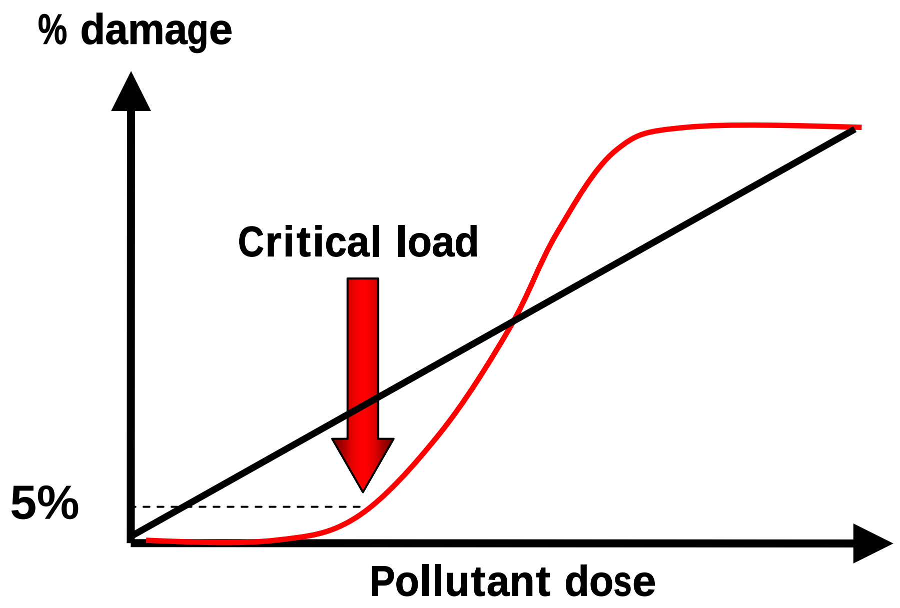
Setting critical loads

1. Define an indicator of change for the receptor of interest:

Ecosystem structure
Sensitive indicator species
Nitrate leaching
Soil acidification

2. Define a dose-response function

3. Define a damage threshold for the required level of ecosystem protection

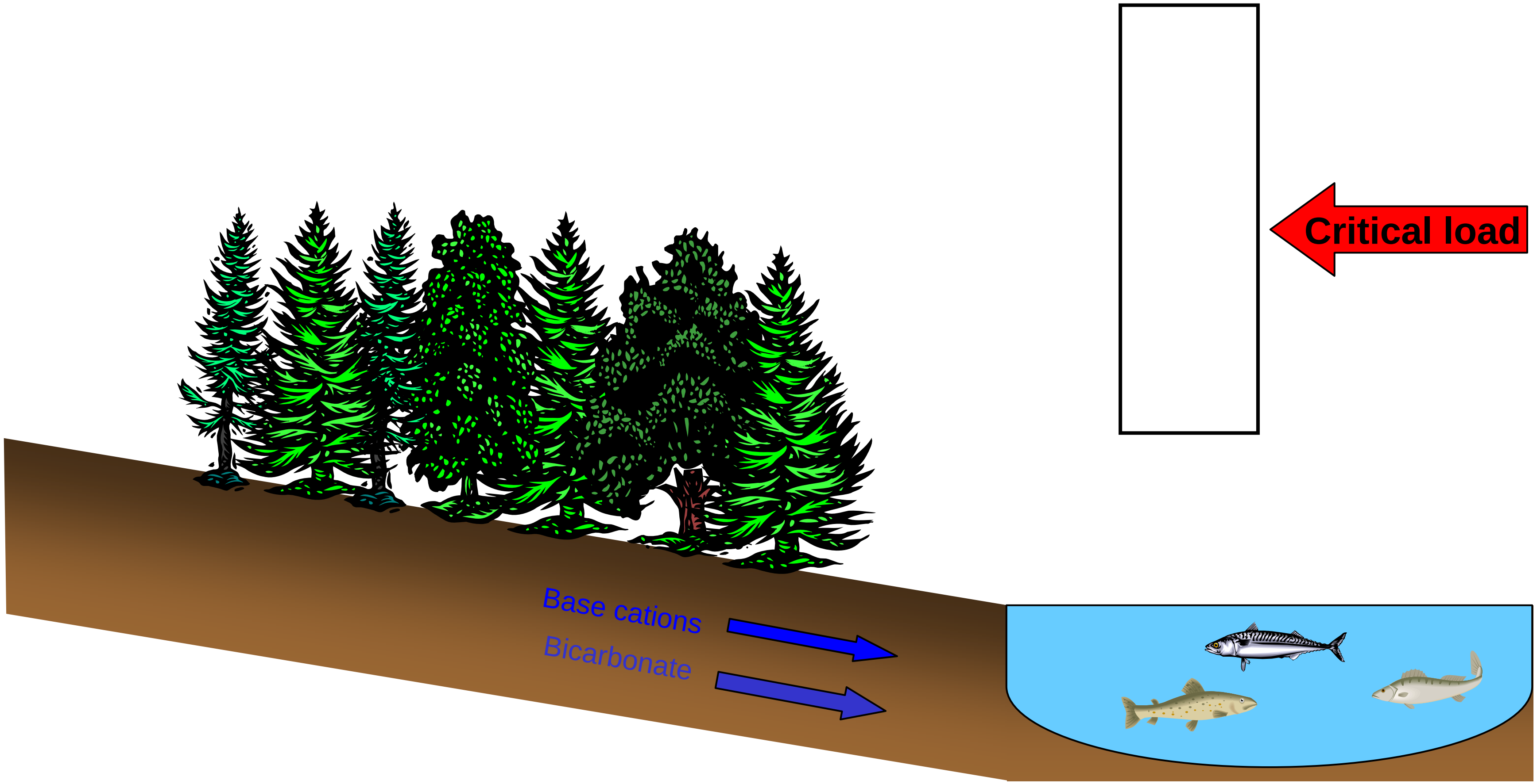


CLs assume a damage threshold exists – if dose vs damage is linear, we have more of a problem…

2. Critical Loads for acidification

Critical Loads and ecosystem damage

1) Sulphur and acidity



Critical Loads and ecosystem damage

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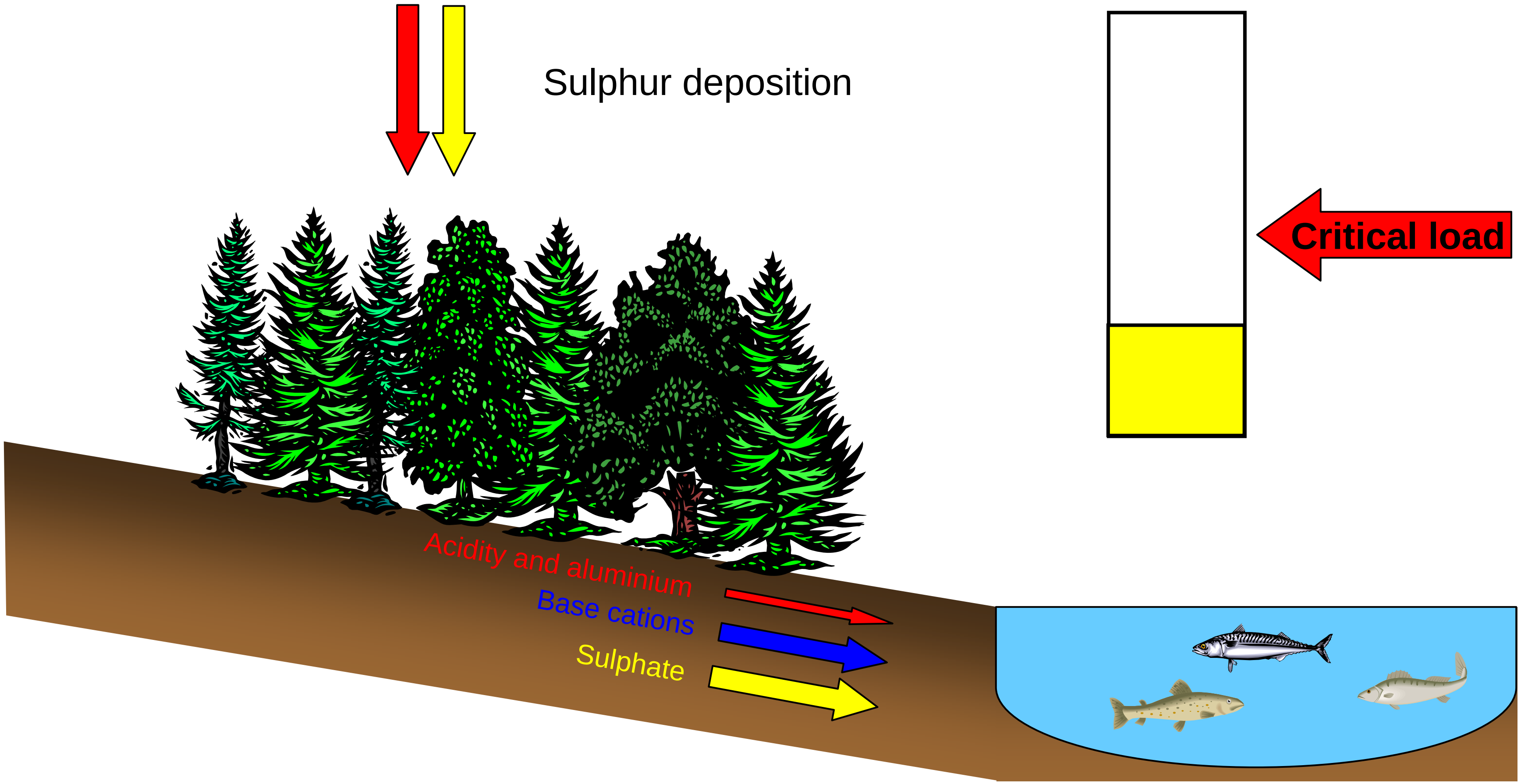

Critical Loads and ecosystem damage

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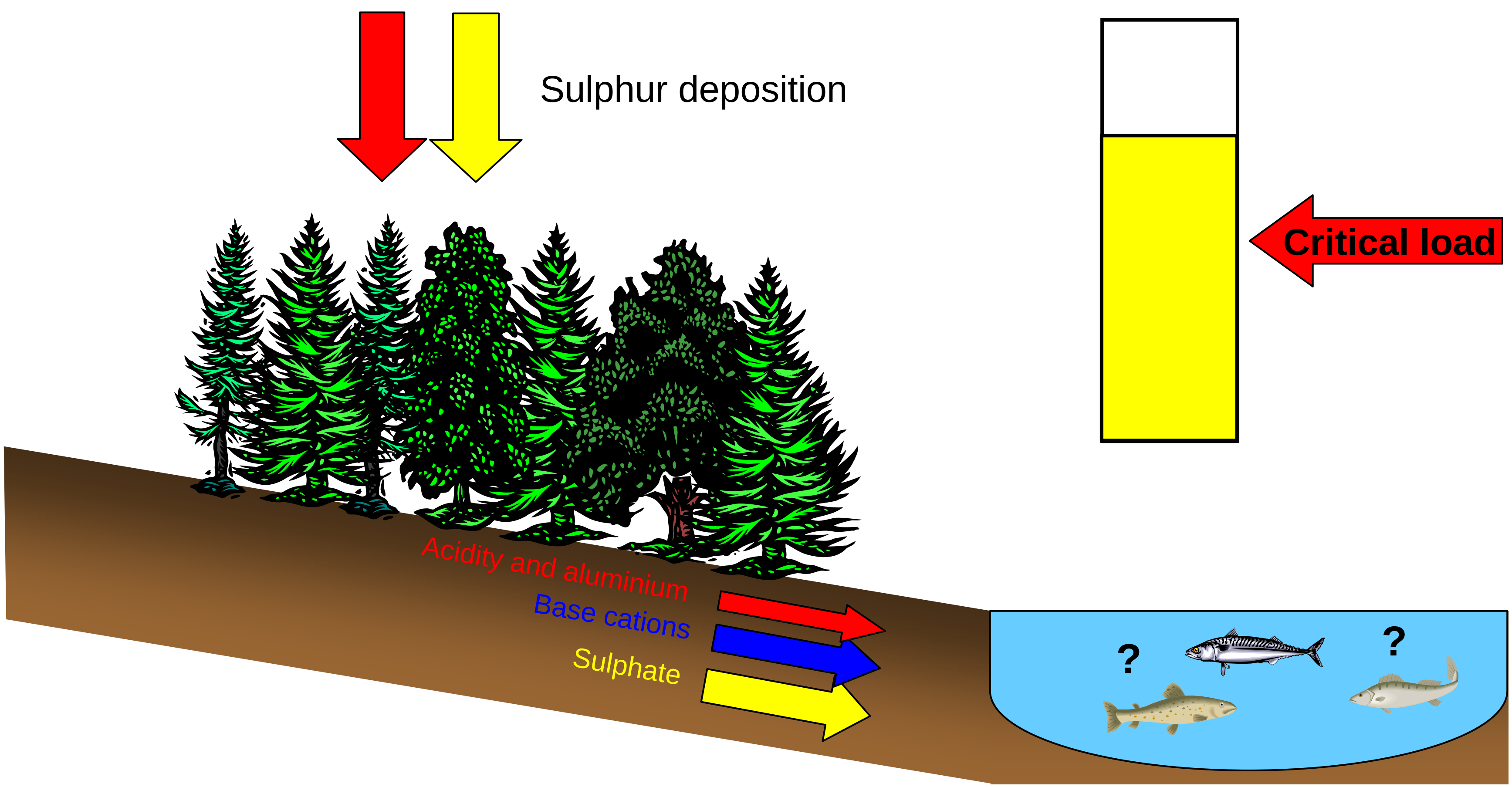

Critical Loads and ecosystem damage

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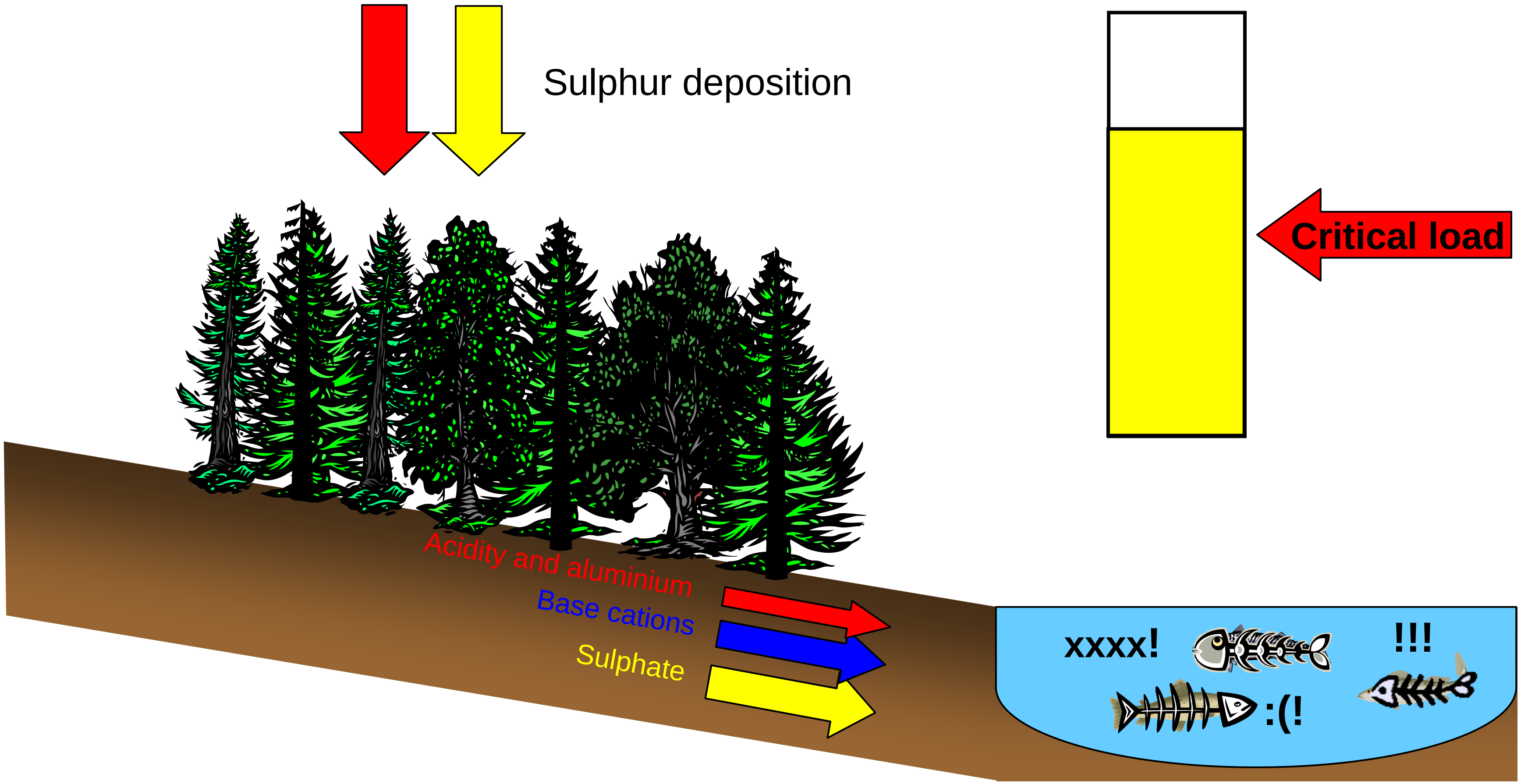
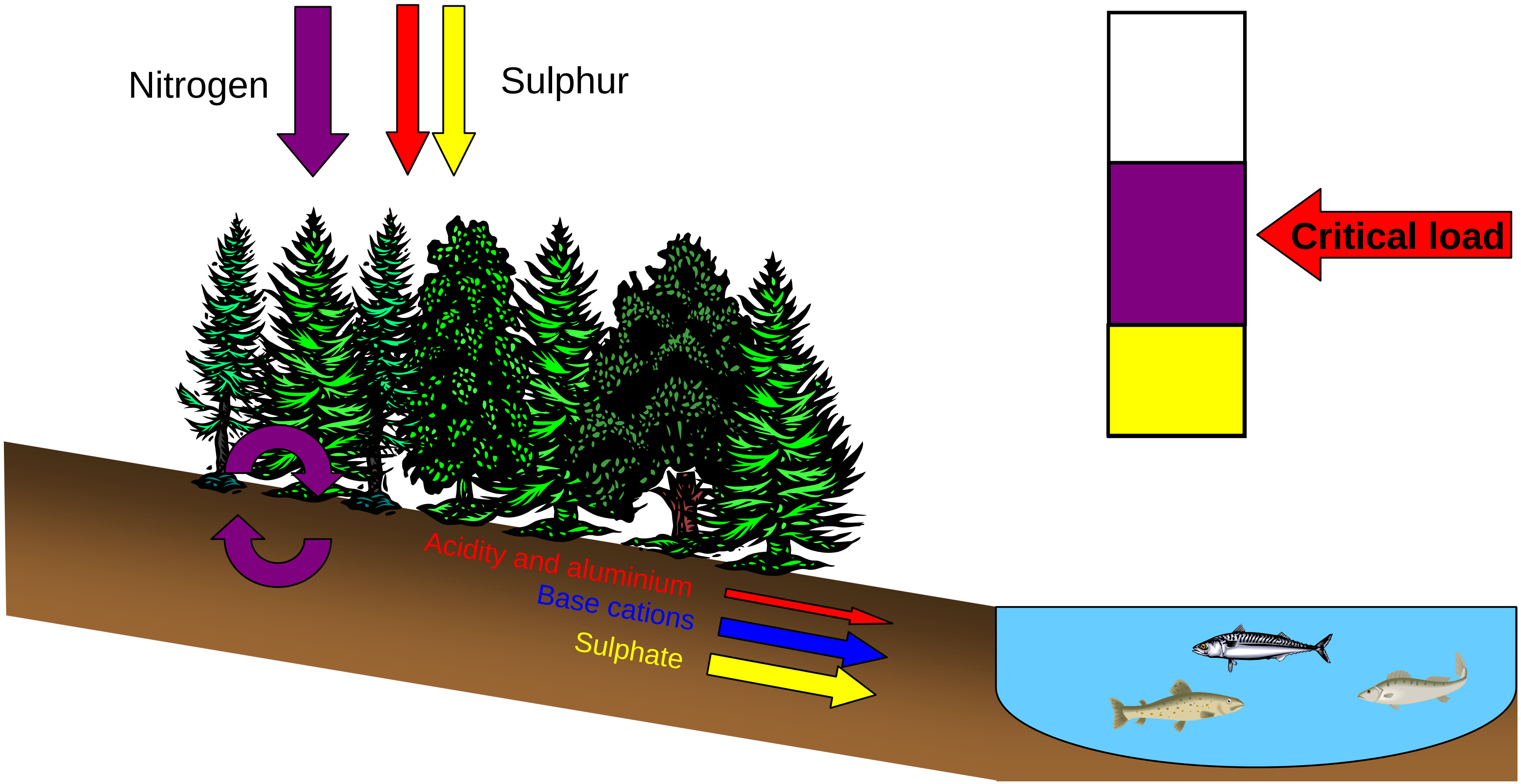


Critical Loads and ecosystem damage

1) Nitrogen and acidity



Critical Loads and ecosystem damage

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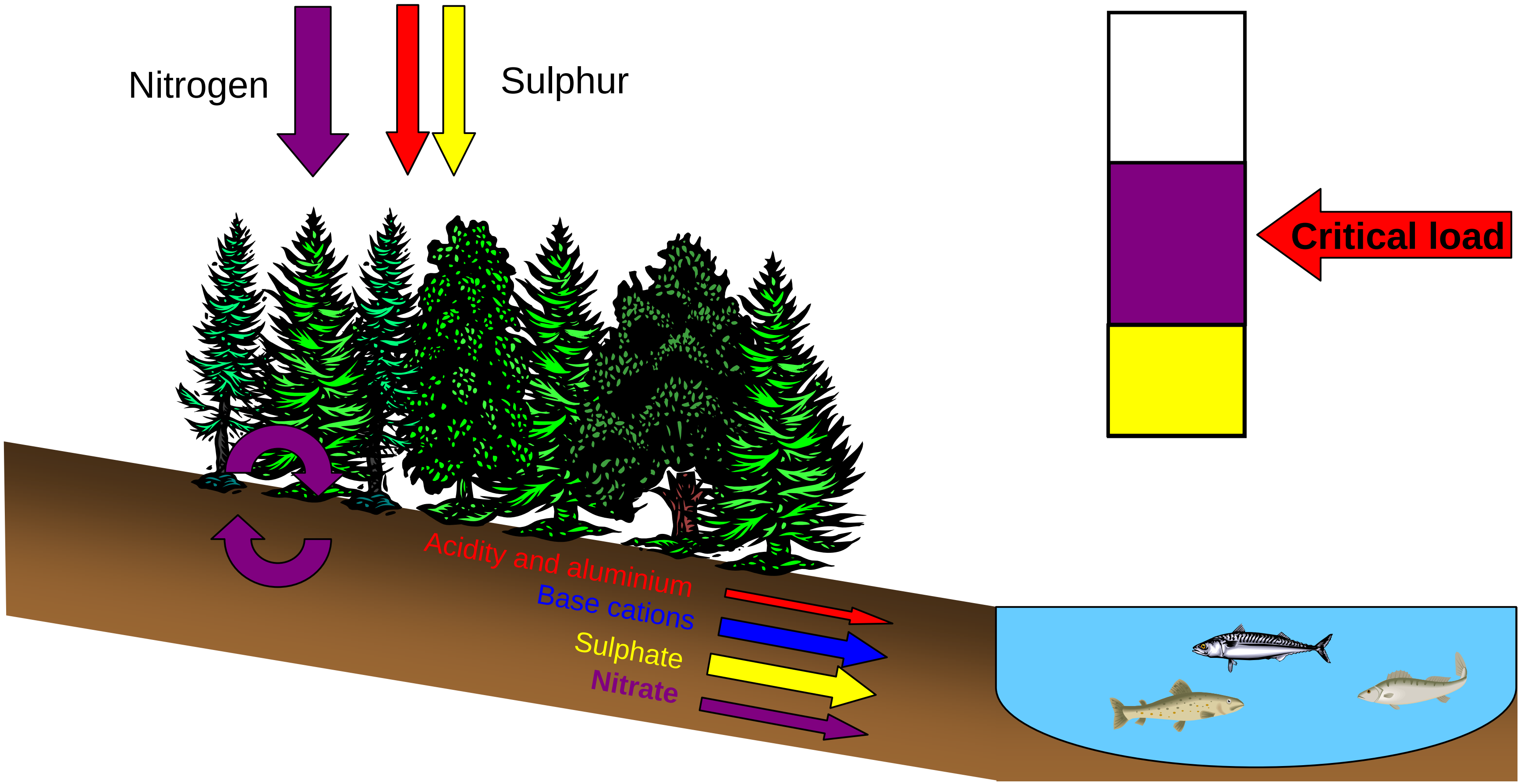

Critical Loads and ecosystem damage

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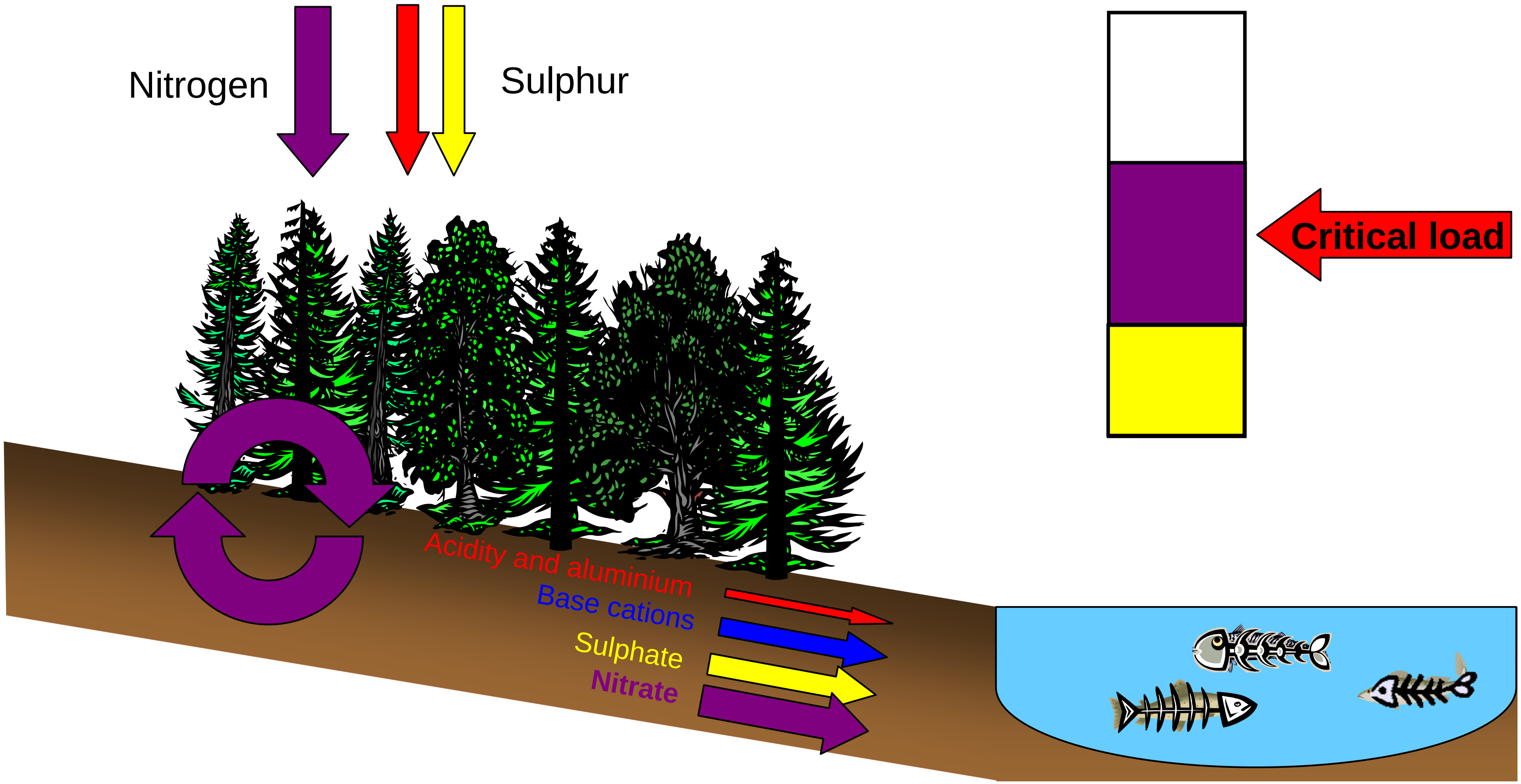


Calculating critical loads for acidity

UK Methods

- Skokloster classes
  - Heathland and grassland
  - Basically estimates of long-term buffering provided by weathering in different soils
  - 5 sensitivity classes
- Simple mass balance (SMB)
  - Forests

Simple mass balance (SMB) model

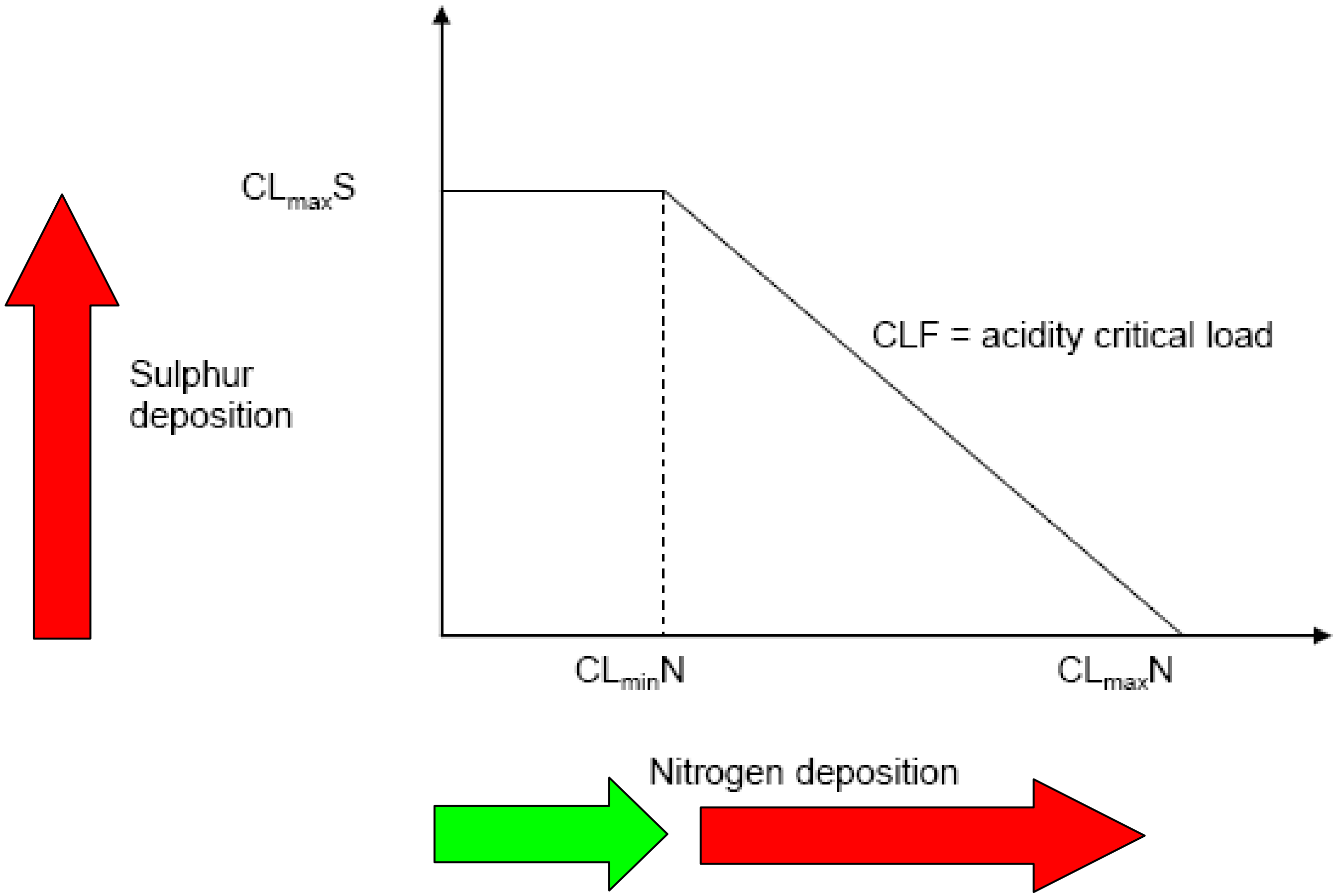
- Based on a critical limit – for UK forests this is Ca:Al = 1
- Balances acid inputs and outputs to derive a critical load that ensures the critical limit is not exceeded
- And the equations are…

$CL_{max}(S) = BC_{dep} – Cl_{dep} + BC_w – BC_u + (1.5\times Ca_{le}/(Ca{:}Al)_{crit}) + Q^{2/3}(1.5\times Ca_{le}/((Ca{:}Al)_{crit}\times K_{Gibb})$

$CL_{min}(N) = N_i + N_{de} + N_u$

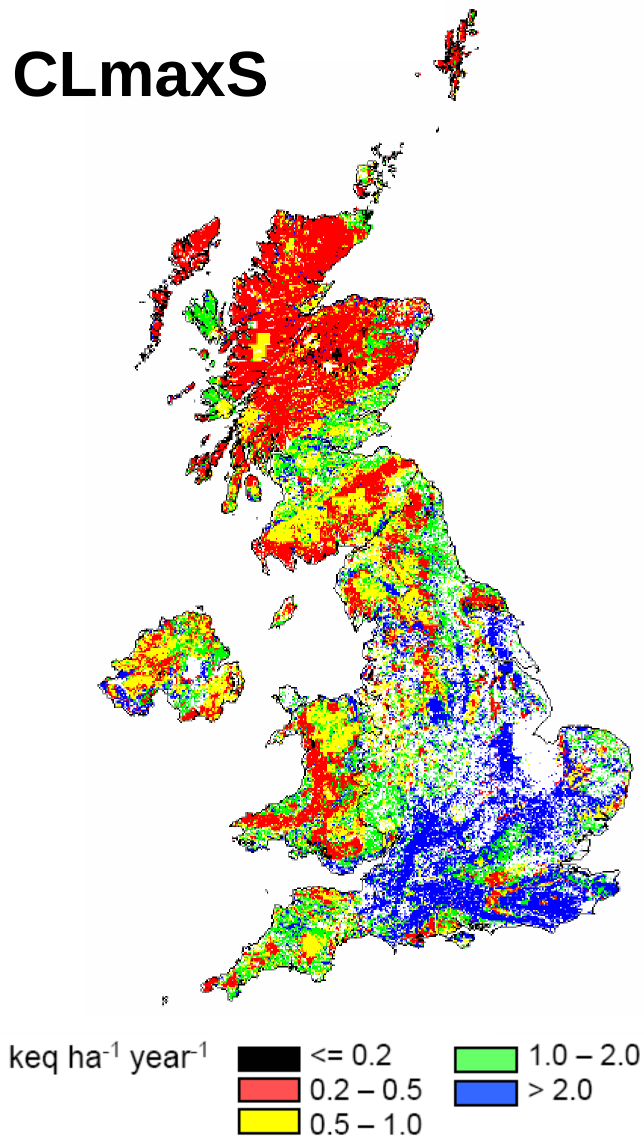
$CL_{max}(N) = CL_{max}(S) + CL_{min}(N)$

The critical load function

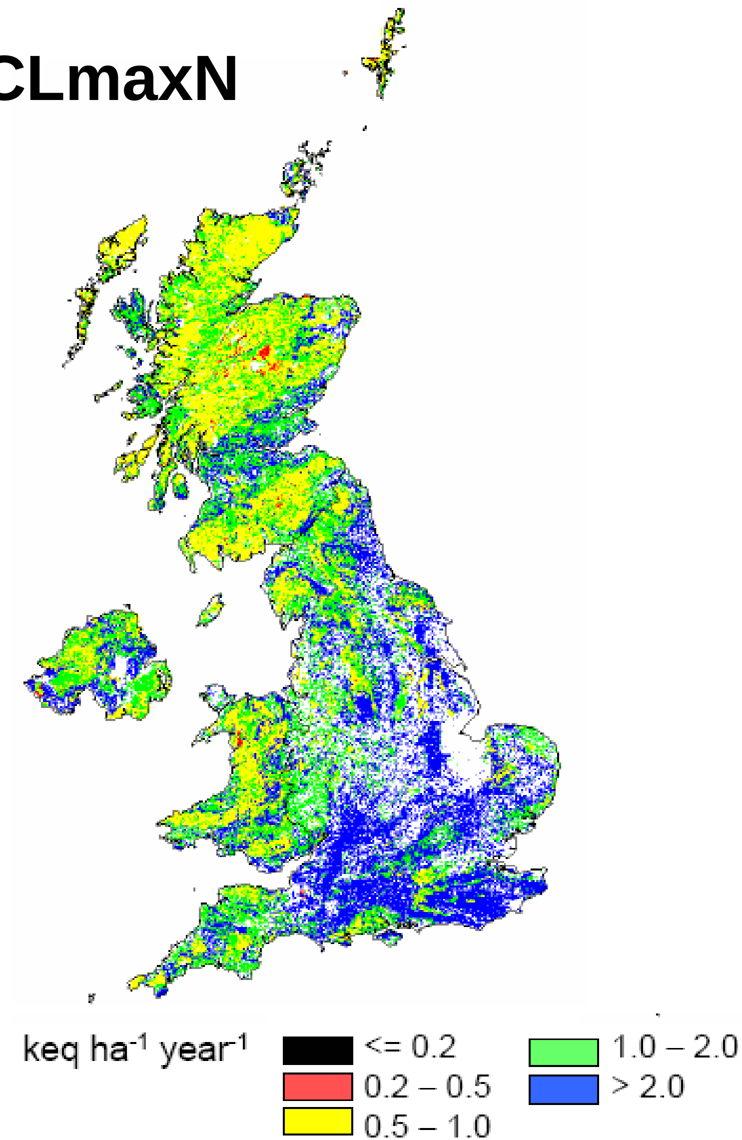


UK 5th percentile Critical Loads for Acidity

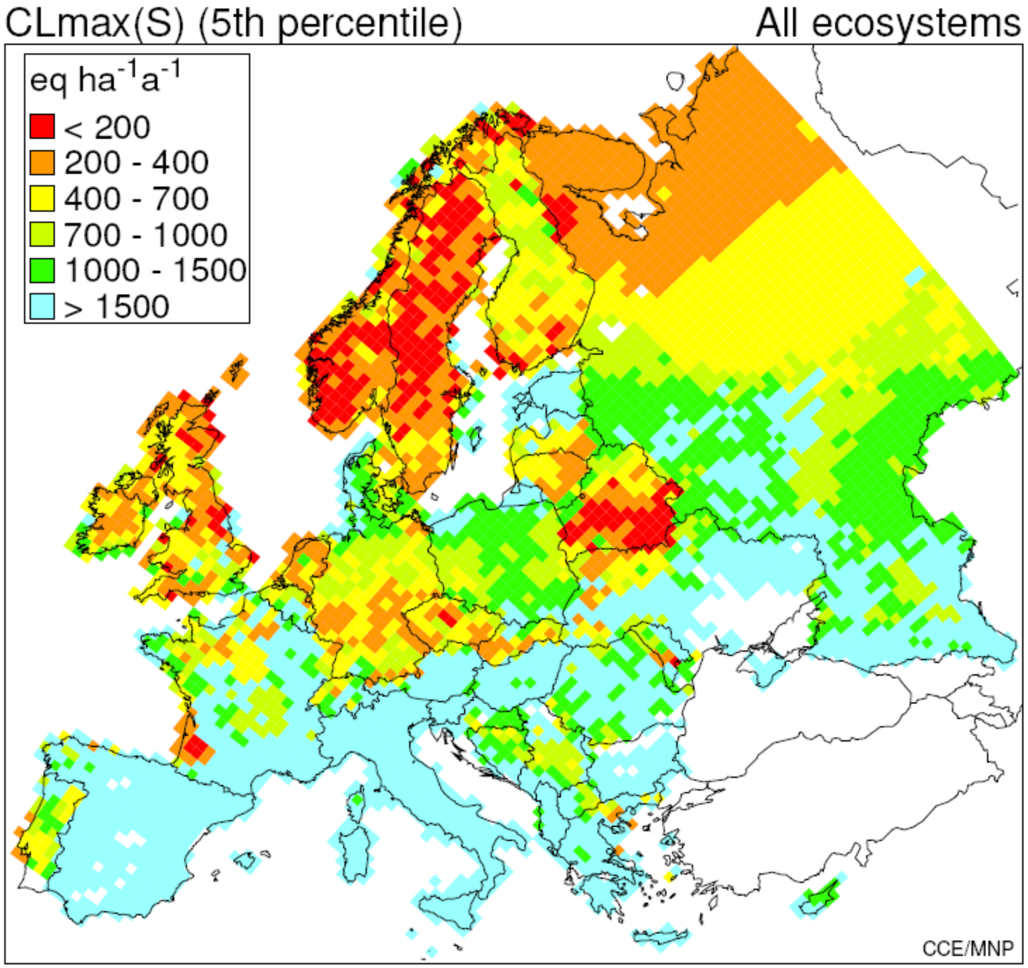
CLmaxS



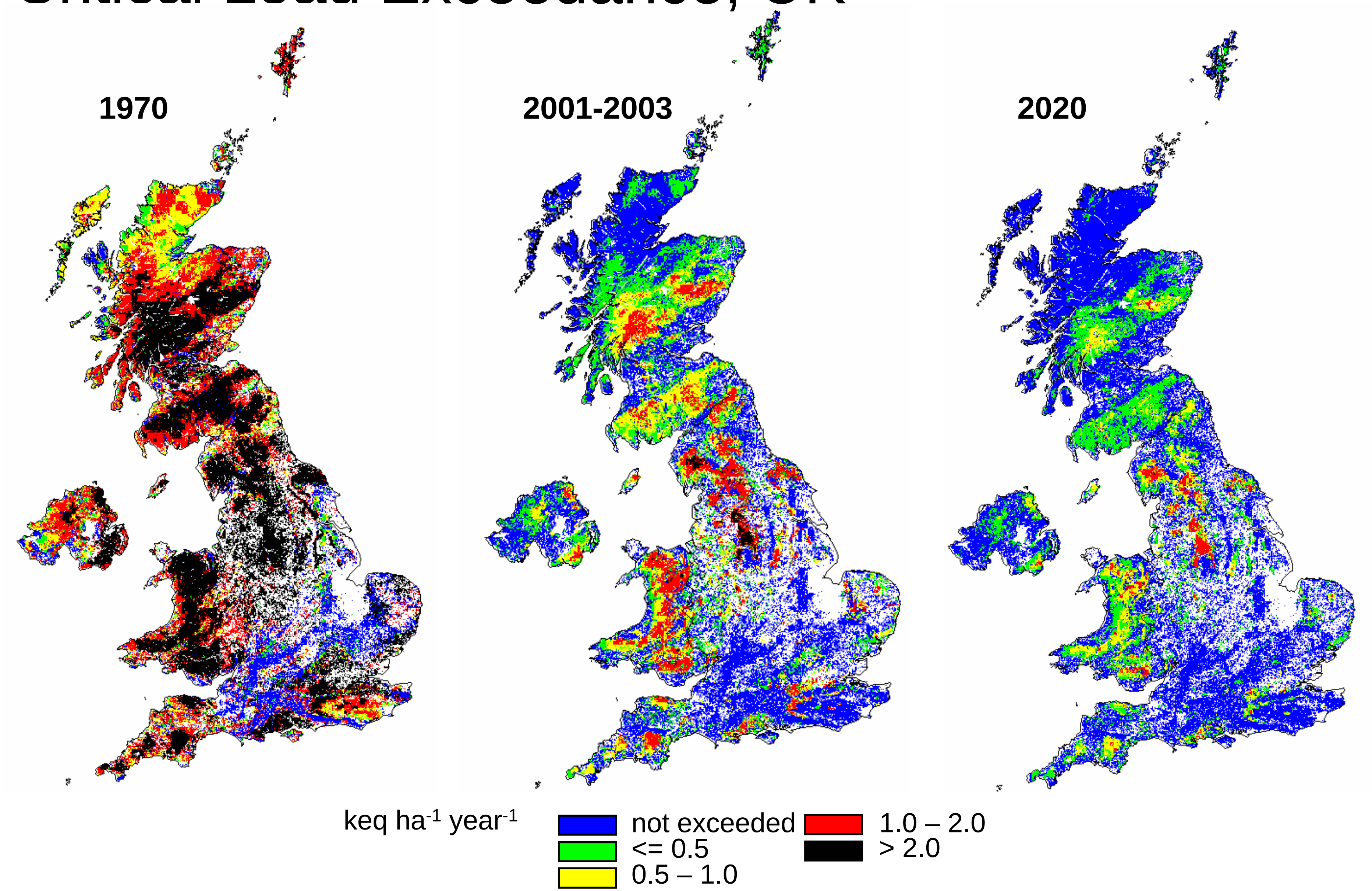
CLmaxN



European Critical Loads for Acidity

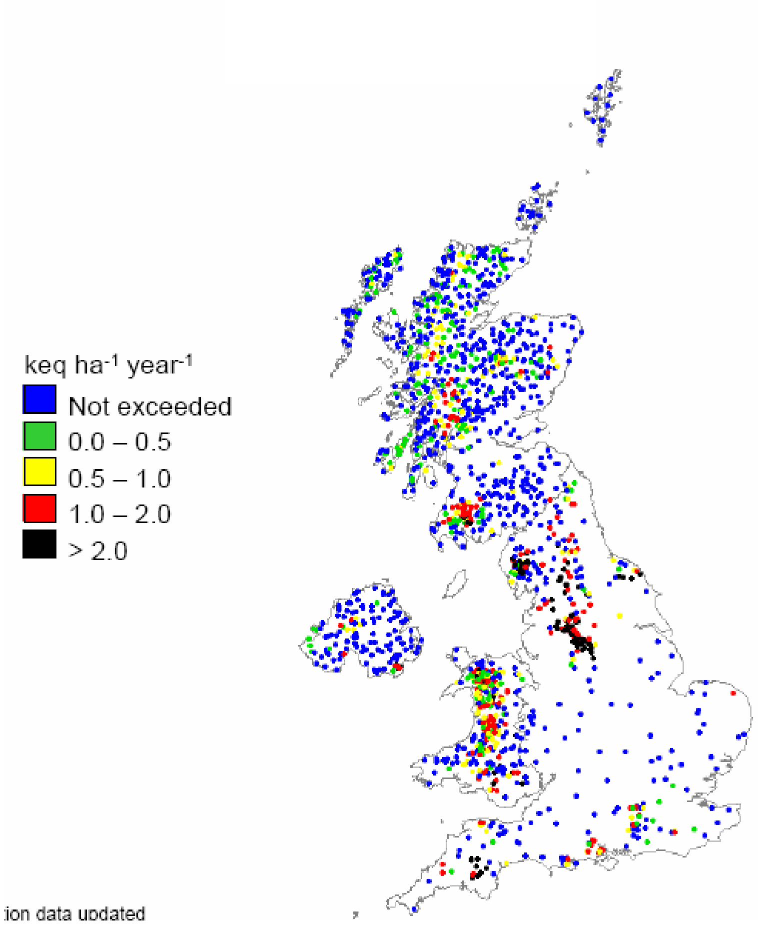


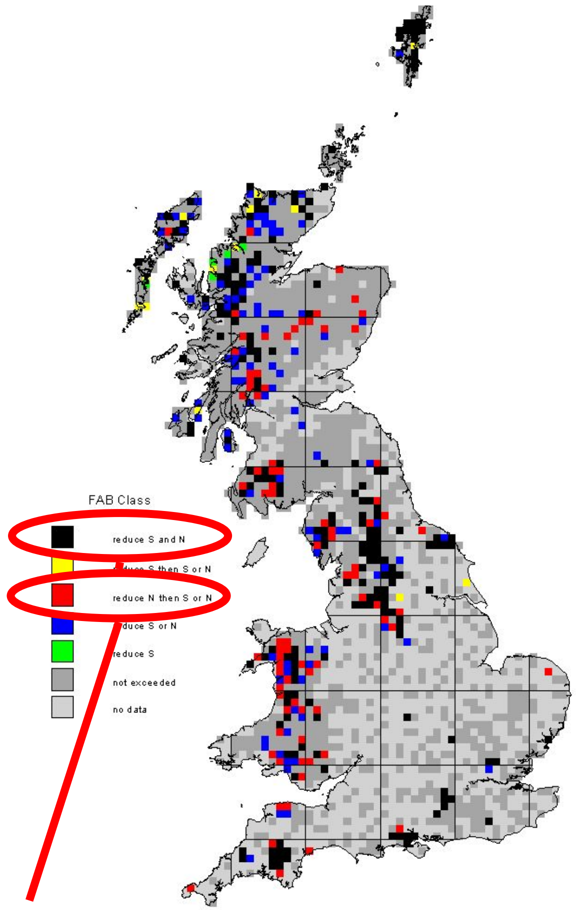
Critical Load Exceedance, UK



Critical Load exceedance in UK surface waters:

What needs to be done to reduce exceedance?





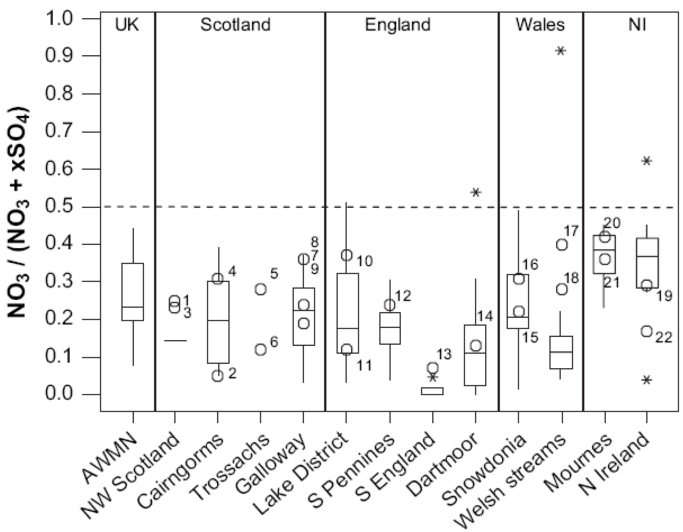
It will only be possible to remove critical load exceedance in these areas by reducing N deposition

Time lags between exceedance and damage

- For S deposition, exceedance of critical loads may lead to relatively rapid damage
- Delays occur due to:
  - Base cation buffering
  - S adsorption (mainly in unglaciated soils)
  - S reduction (mainly in wetlands)
- For N deposition, lags between critical load exceedance and damage may be much longer.
- Delays are primarily due to soil N immobilisation

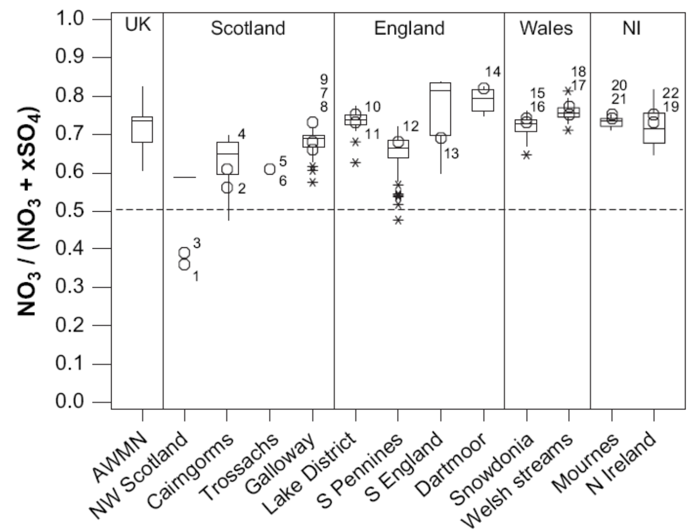
Significance of lags in N leaching

Now



Predicted steady state

(given 2010 deposition)



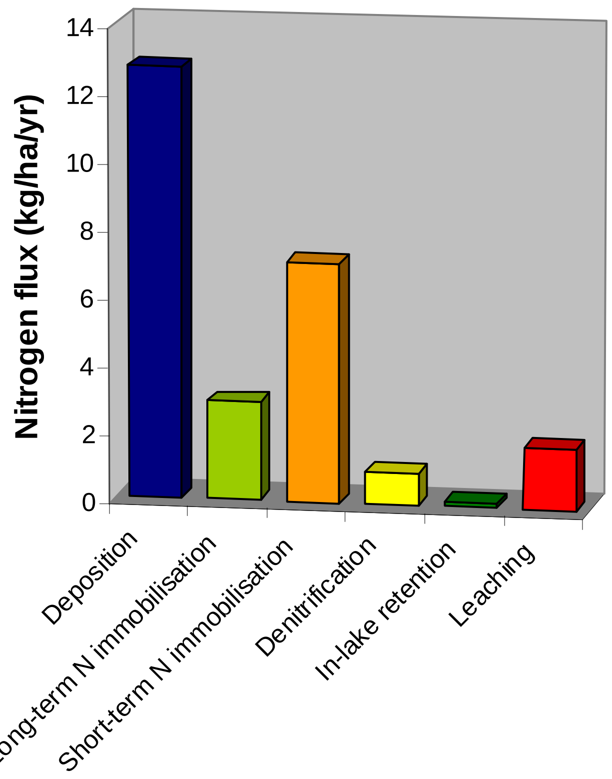
Curtis et al., Environmental Pollution (2005)

- Critical loads models generally predict a much higher level of steady-state N leaching than is currently observed
- Lag times appear to be long
- But if NO_3 leaching does reach predicted levels, future acidification could be as bad, or worse, than the 1970s-80s.

Significance of lags in N leaching

Nitrogen sources and sinks at Llyn Llagi, Wales

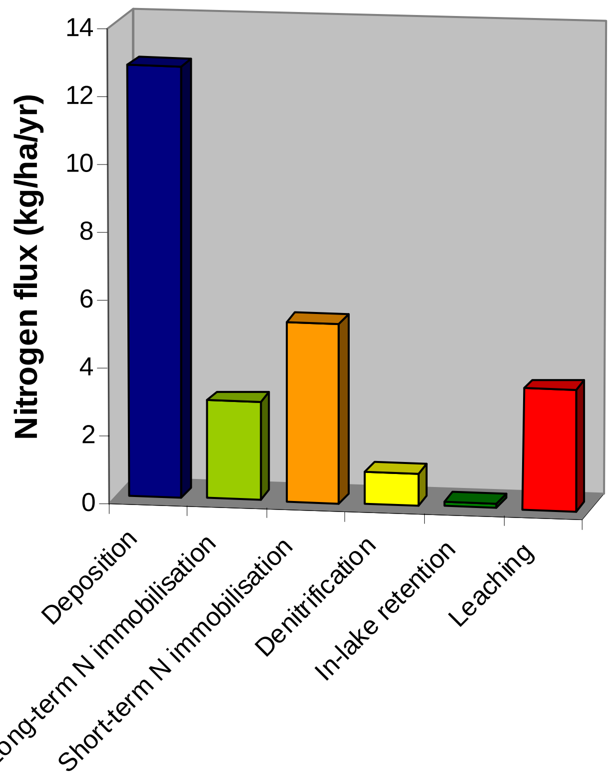
1. Present day



Significance of lags in N leaching

Nitrogen sources and sinks at Llyn Llagi, Wales

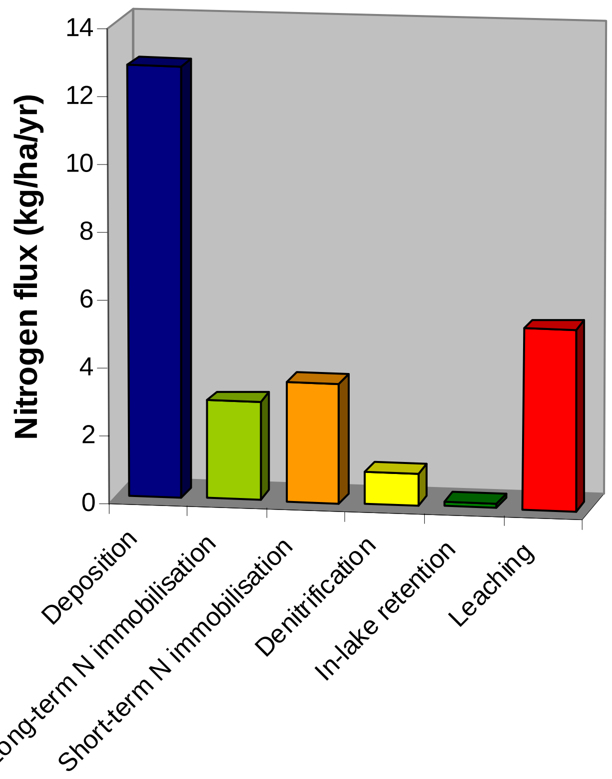
2. Future (1)



Significance of lags in N leaching

Nitrogen sources and sinks at Llyn Llagi, Wales

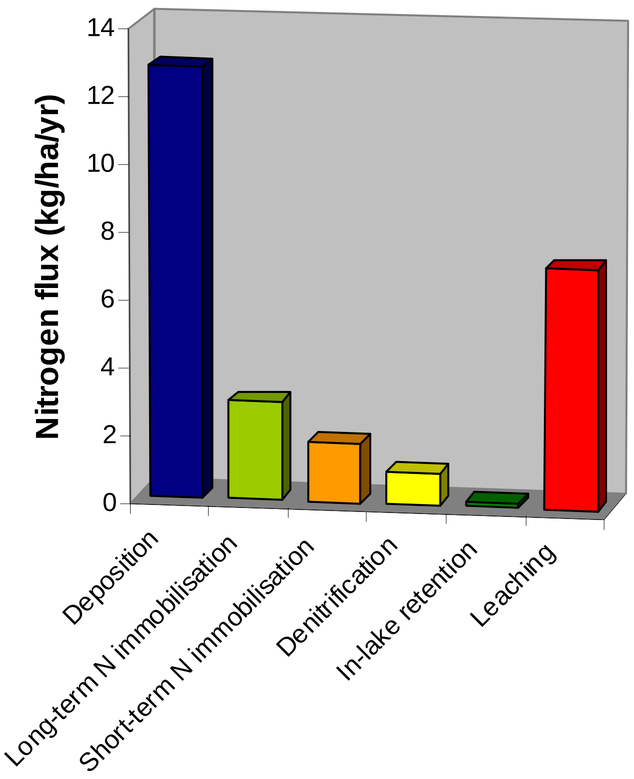
2. Future (2)



Significance of lags in N leaching

Nitrogen sources and sinks at Llyn Llagi, Wales

2. Future (3)



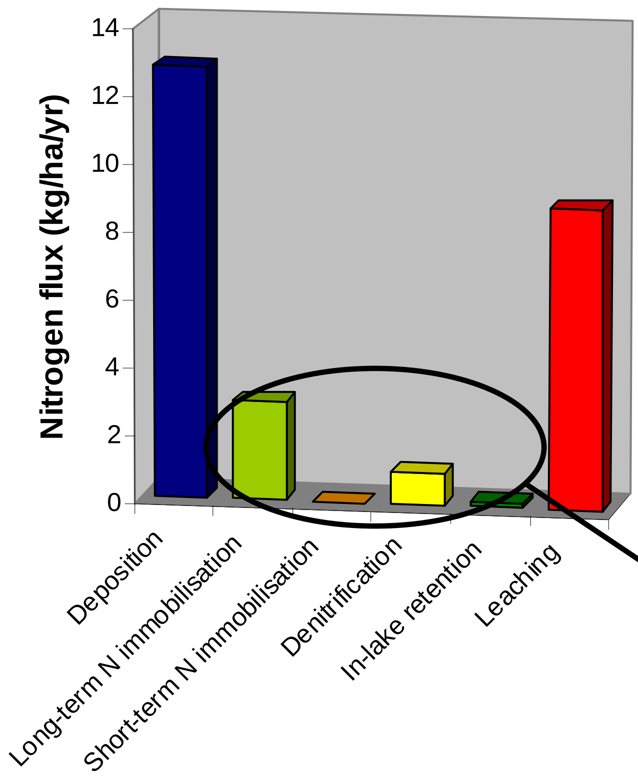
Significance of lags in N leaching

Nitrogen sources and sinks at Llyn Llagi, Wales

3. Steady State

But not all sites like this – some parts of Europe leaching most or all of incoming N already

In a managed forest, N uptake may reduce N leaching (but, N deposition may be higher)



Critical load for N only considers the sinks still operating at steady state

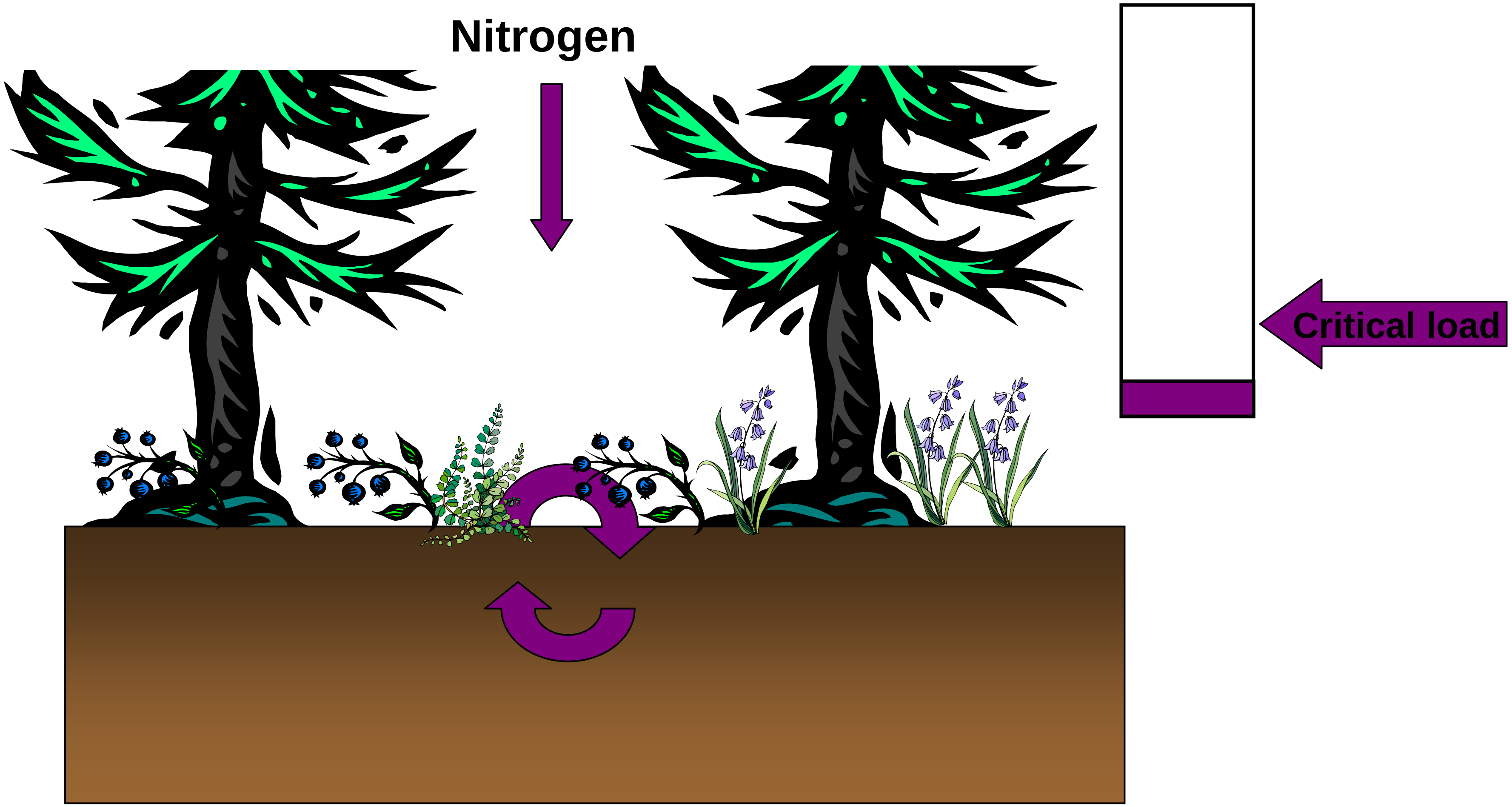
3. Critical Loads for Nitrogen as a Nutrient

Nitrogen as a nutrient

- Nitrogen is a major nutrient required by all plants, and the limiting nutrient in most northern ecosystems
- Many natural habitats are characterised by slow-growing species adapted for low-N conditions.
- With increased N deposition, these species are out-competed by faster-growing species more able to exploit increased N availability
- The results is a loss of biodiversity, or of characteristic plant species.

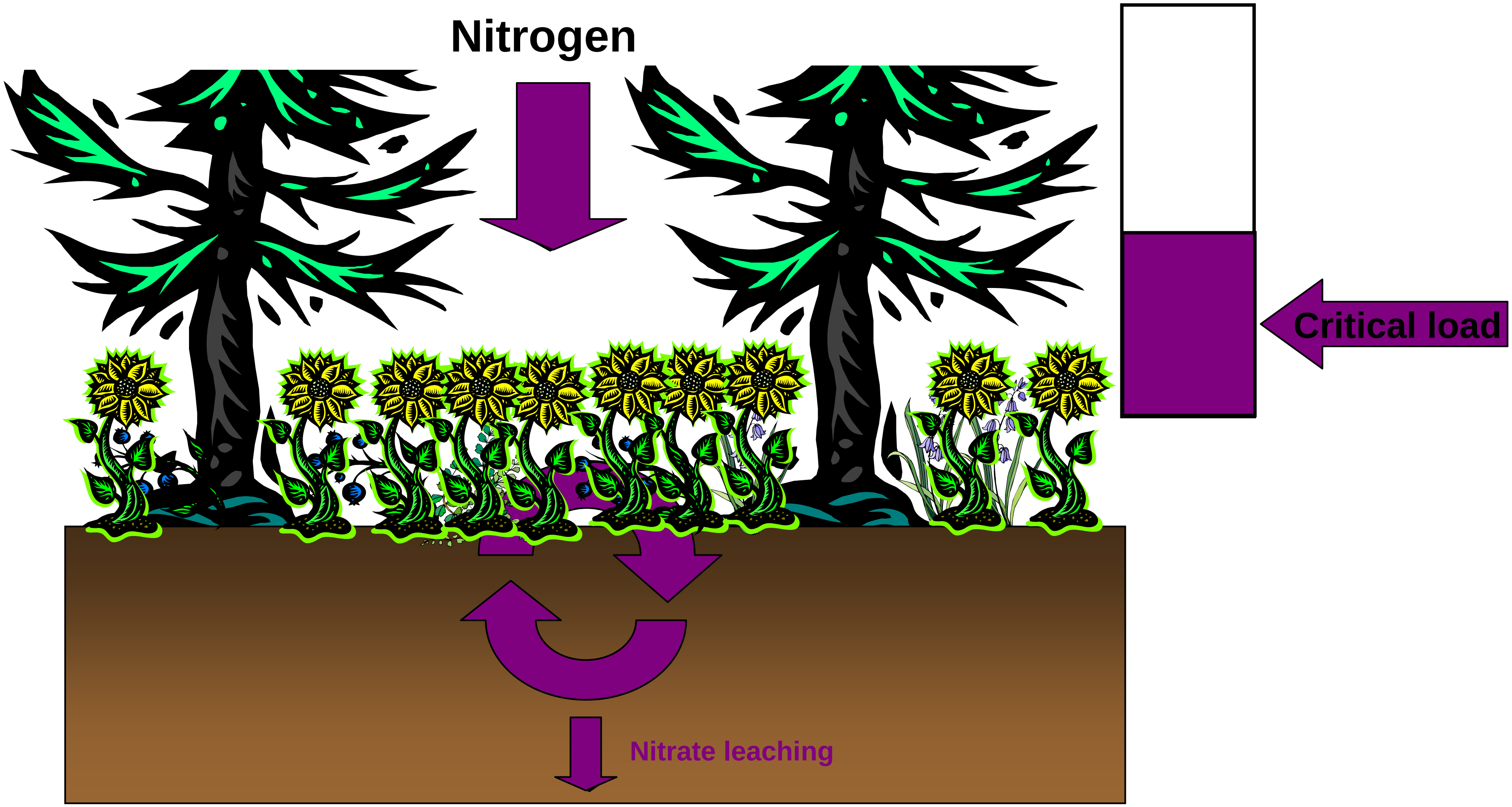
Critical Loads and ecosystem damage

3) Nitrogen and biodiversity

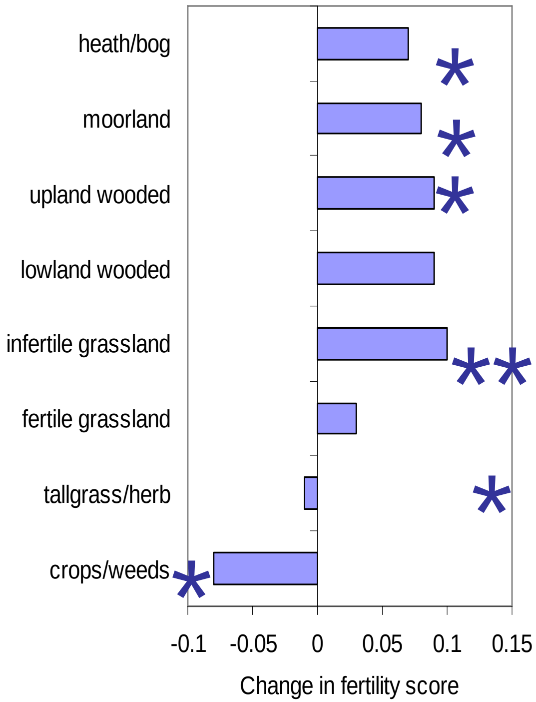


Critical Loads and ecosystem damage

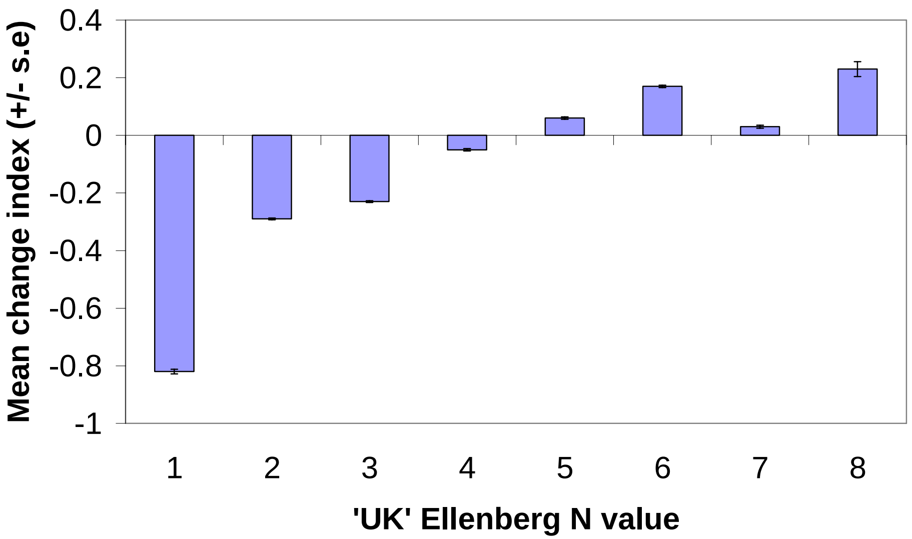
3) Nitrogen and biodiversity



Evidence that N deposition is causing eutrophication of UK ecosystems



Countryside Survey, changes between 1990 and 1998

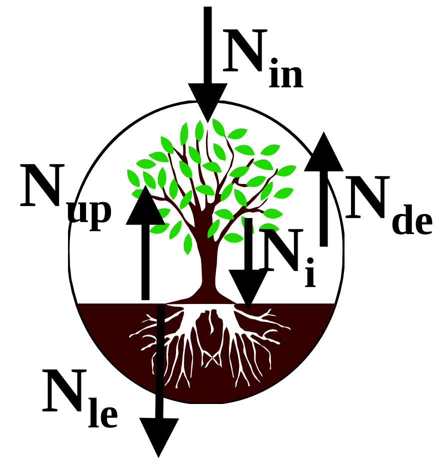


Plant Atlas, changes between 1930-69 and 1987-99

Critical Loads for N as a nutrient

Mass balance equation

(used for UK managed forests)



$$Cl_{nut}(N) = N_i + N_{de} + N_u + N_{le(acc)}$$

Critical Load

8-17

Sustainable long-term N immobilisation

1-3

Denitrification

1-4

Net uptake due to biomass removal

3-6

'Acceptable' NO_3 leaching

3-4

kg N/ha/yr

Critical Loads for Nitrogen as a nutrient

Empirical critical loads

(Used for other UK ecosystems)

- Based on experimental/field evidence of thresholds for change in species composition, plant vitality or soil processes
- Focused on communities likely to be sensitive to N deposition, of conservation value and with a reasonably wide distribution
- European ranges defined at a workshop in Berne, 2002
- Reliant on a large amount of scientific data, and a certain amount of expert judgement
- Countries decide which communities to protect, and where within the range to set their critical loads

Berne empirical critical loads, and their application in the UK

(a) Ecosystem (with corresponding EUNIS class, where used)	(b) 2001 UK mapping value	(c) Critical load range in 1996 Mapping Manual	(d) Critical load range from Berne workshop	(e) Revised UK mapping value
Grasslands				
Dry acid and neutral closed grassland (E1.7)	25	20-30 #	10-20 #	15
Calcareous grassland (E1.26)	25(1)	15-35 #	15-25 ##	20
Montane grassland	12	10-15 (#)		
Hay meadows (E2.2)			20-30 (#)	-
Montane hay meadows (E2.3)			10-20 (#)	-
Arctic/sub-alpine grass			10-15 (#)	-
Moist/wet oligotrophic grass (E3.5)			10-20 #	15
Molinia meadows (E3.51)			15-25 (#)	-
Nardus stricta swards (E3.52)			10-20 #	15
Moss/lichen mountain summits (E4.2)			5-10 #	7
Inland dune pioneer grass (E1.94)			10-20 (#)	-
Inland dune silicaceous grass (E1.95)			10-20 (#)	-
Heathland/moorland				
Lowland dry heaths (F4.2)	17	15-20 ##	10-20 ##	12
Lowland *Erica* wet heaths (F4.11)		17-22 #	10-25 #	15
Upland *Calluna* wet heaths (F4.11)	15	10-20 (#)	10-20 (#)	15
Arctic/alpine heaths (F2)	7.5	5-15 (#)	5-15 (#)	-
Tundra (F1)			5-10 #	-
Coastal habitats				
Coastal stable dune grasslands (B1.4)		20-30 #	10-20 #	15
Shifting coastal dunes (B1.3)			10-20 #	15
Coastal dune heaths (B1.5)			10-20 (#)	-
Moist-wet dune slacks (B1.8)			10-25 (#)	-
Dune slack pools (C1.16)			10-20 (#)	-
Salt marshes (A2.64 & A2.65)			30-40 (#)	-
Softwater oligotophic lakes				
Permanent oligotrophic lakes (C1.1)		5-10 ##	5-10 ##	-
Bogs, mires and fens				
Ombrotrophic and raised bogs (D1)	10	5-10 #	5-10 ##	10
Poor fens (D2.2)			10-20 #	15
Rich fens (D4.1)			15-25 (#)	-
Montane rich fens (D4.2)			15-25 (#)	-

Examples of evidence under-pinning Berne empirical CLs

1) Boreal forest

   10-20 kg N/ha/yr, '*quite reliable*'

- Onset of NO_3 leaching, N mineralisation
  - *forest surveys, fertilisation experiments*
- N/P and N/Mg imbalances in trees
  - *forest surveys, fertilisation experiments*
- Ground vegetation change
  - *fertilisation experiments (e.g. displacement of Vaccinium myrtillus by Deschampsia flexuosa at > 5 kg N/ha/yr in N. Sweden)*

Examples of evidence under-pinning Berne empirical CLs

2) Tundra

5-10 kg N/ha/yr, '*quite reliable*'

- Vegetation change
  - *One set of fertilisation experiments receiving 10 kg N/ha/yr, Svalbard, showing changes in species composition of moss layer, decrease in lichens.*

Examples of evidence under-pinning Berne empirical CLs

3) Alpine grasslands

10-15 kg N/ha/yr, '*expert judgement*'

- Vegetation change
  - *One experiment in Switzerland showing biomass increase after 4 years addition of 20 kg N/ha/yr*
- Extrapolation from (better studied) lowland grasslands

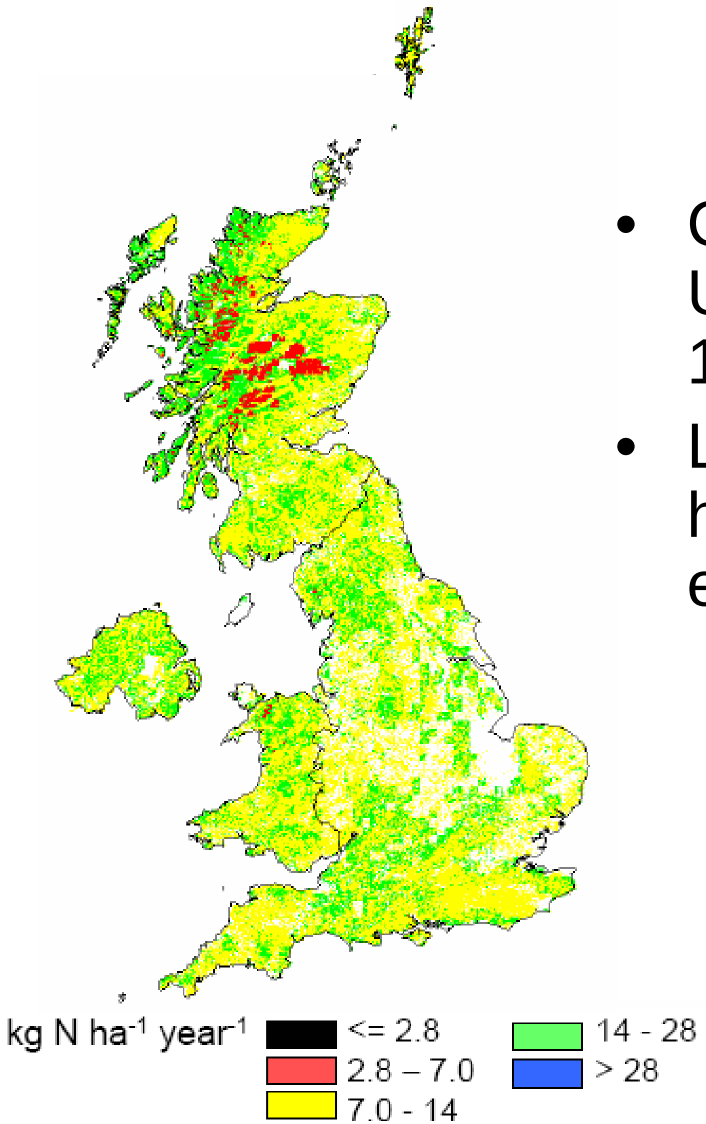
Examples of evidence under-pinning Berne empirical CLs

4) Blanket bogs

5-10 kg N/ha/yr, ‘*reliable*’

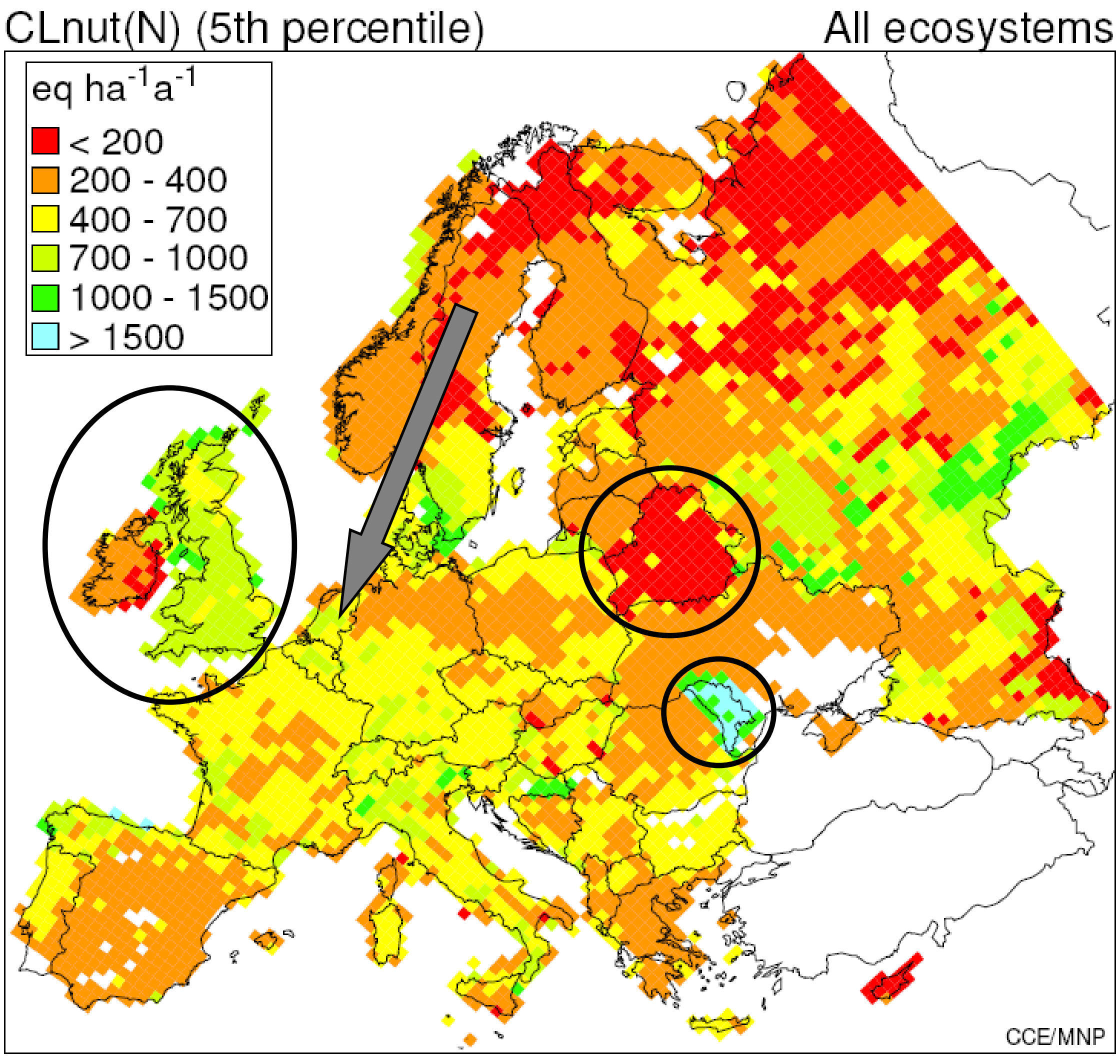
- Increased N in peat and peat water
  - *Experiments, field surveys*
- Changes in moss growth and N content
  - Experiments, field surveys
- Increases in vascular plants over mosses
  - *Experiments, field surveys*

UK 5th percentile nutrient N critical loads

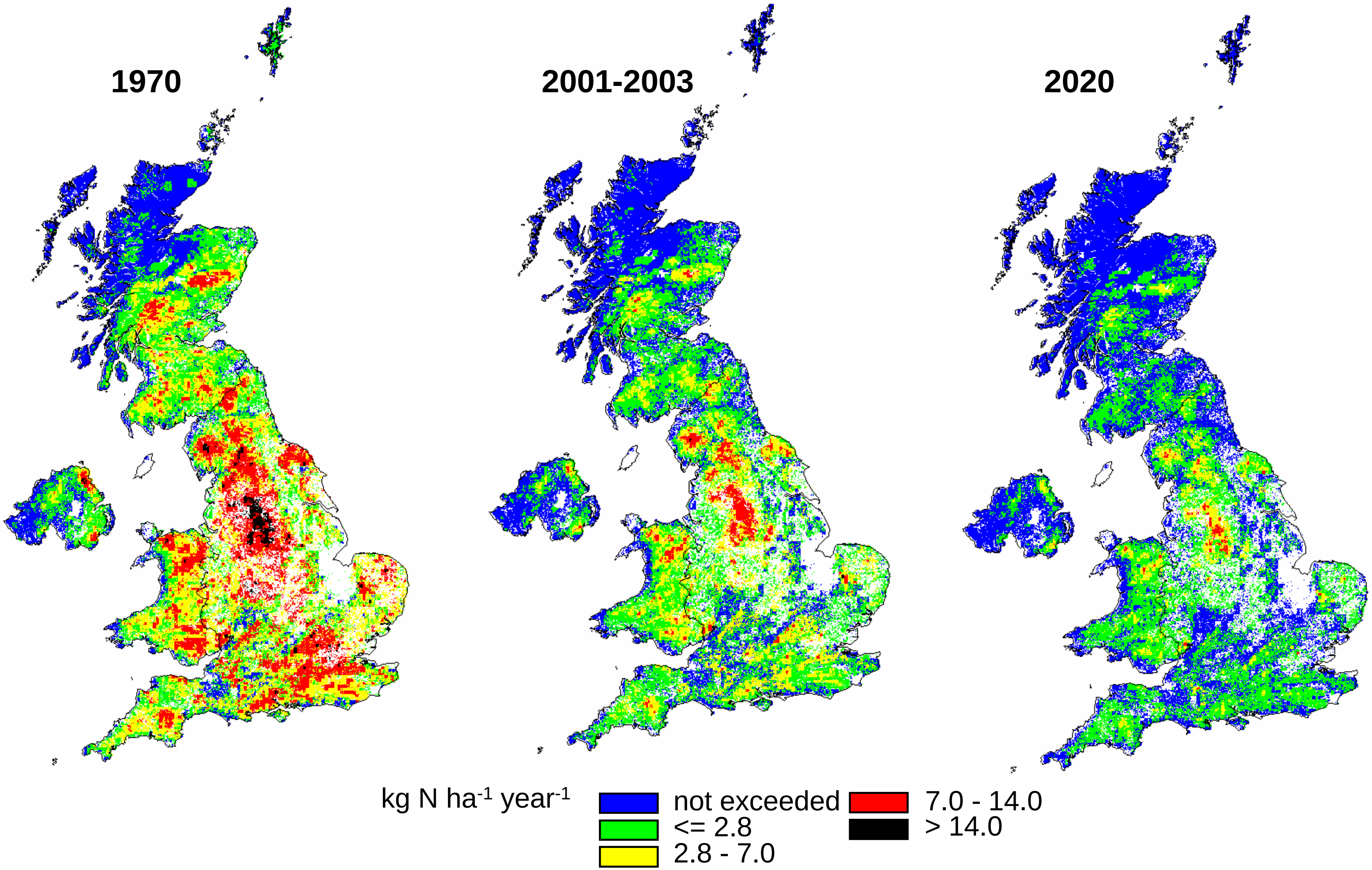


- $Cl_{nut}N$ for most of UK in the range 10-20 kg N/ha/yr
- Lower values for high mountain ecosystems

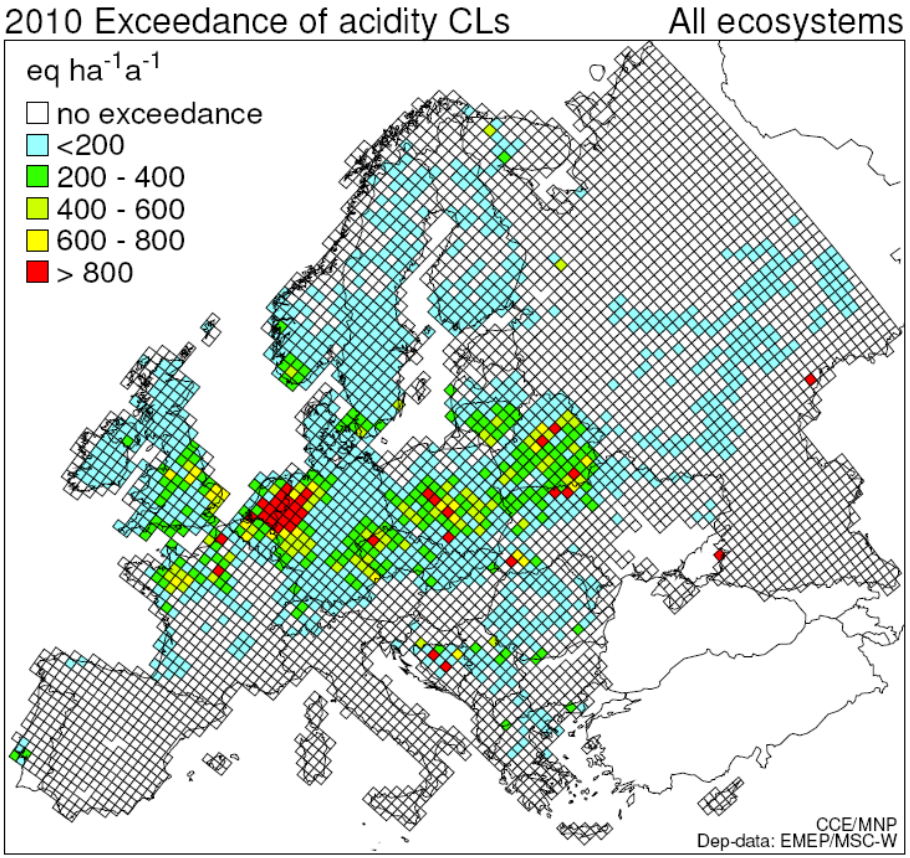
European 5th percentile nutrient N critical loads

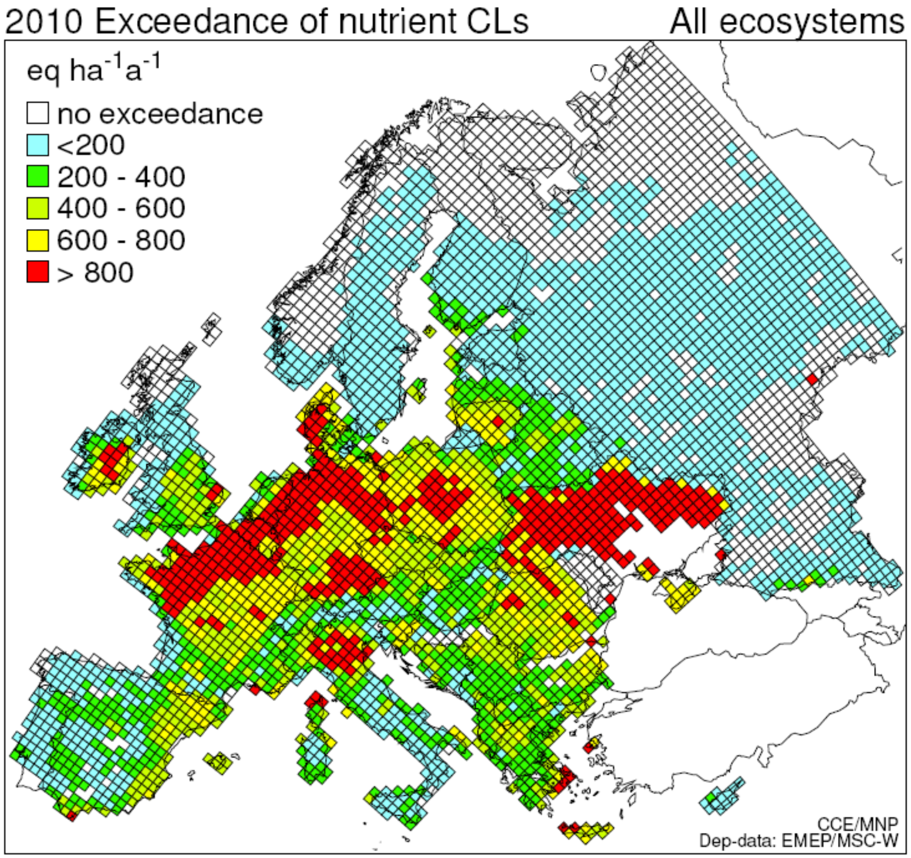


Exceedance of 5th percentile nutrient N critical loads

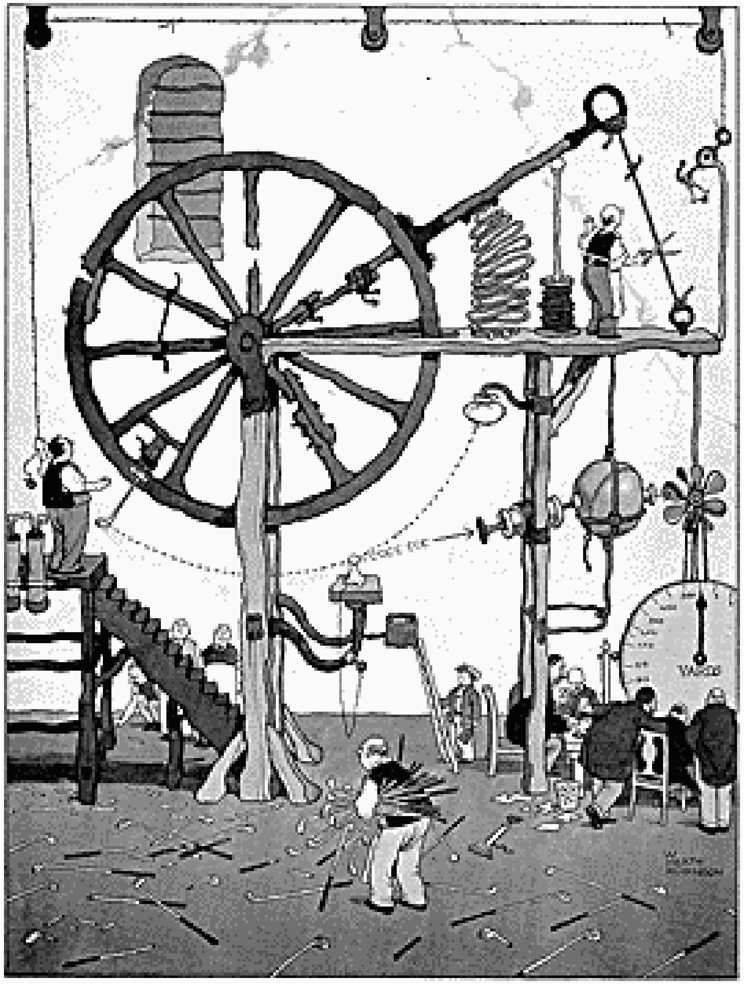


Critical load exceedances across Europe
2010 forecast





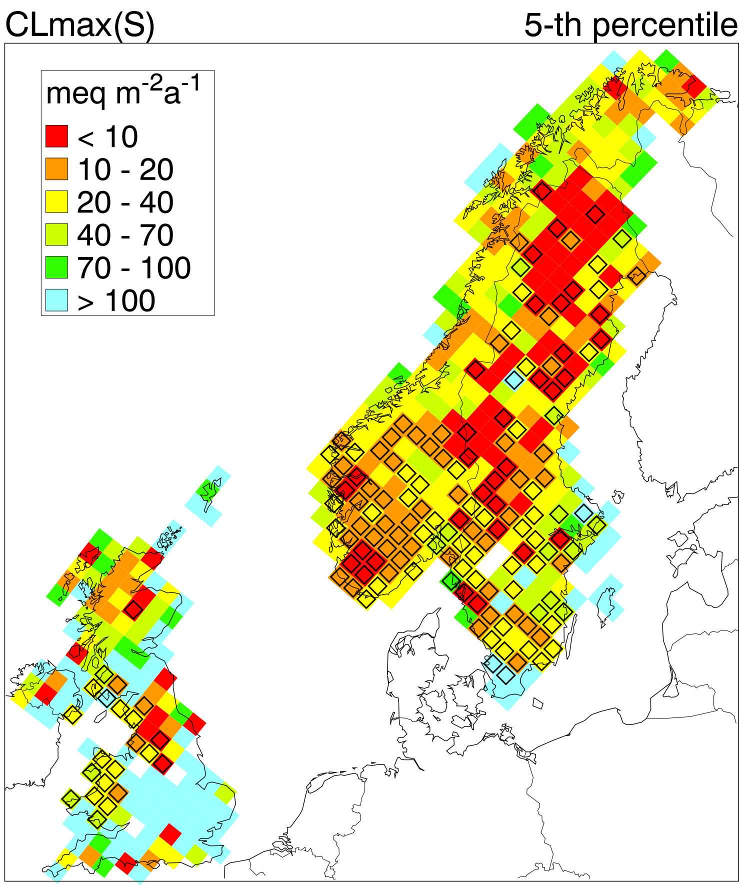
4. Dynamic Models



Dynamic Models

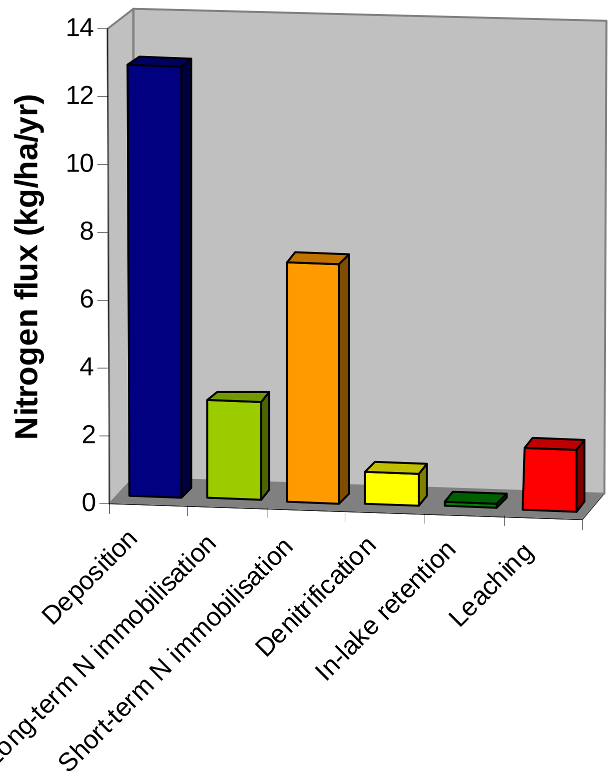
- Critical loads are essentially models of steady-state chemistry
- Dynamic models predict the *time* at which damage (or recovery) will occur
- Much current work in Europe is focused on modelling, in particular:
  - Setting ‘Target Loads’ - the target deposition required to achieve acceptable chemical status by a given target date
  - Modelling biodiversity impacts by relating vegetation status to soil chemical status

Target loads for acidity, N European surface waters



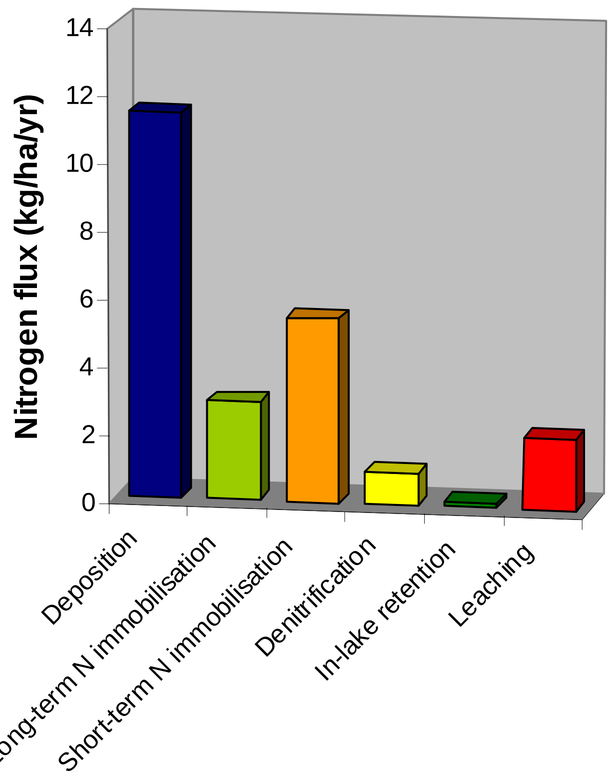
Modelled lags in N leaching
(Llyn Llagi again)

MAGIC calibrated present day



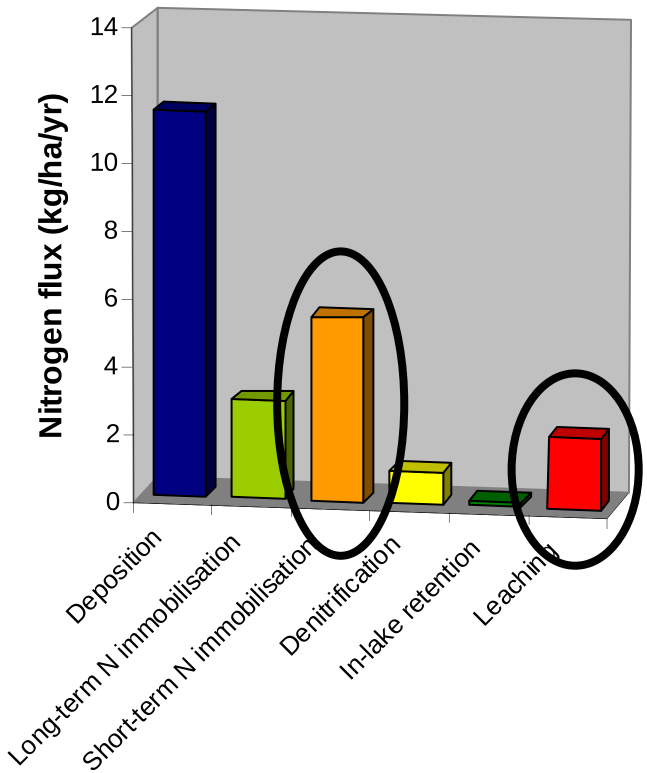
Modelled lags in N leaching
(Llyn Llagi again)

MAGIC predicted 2100

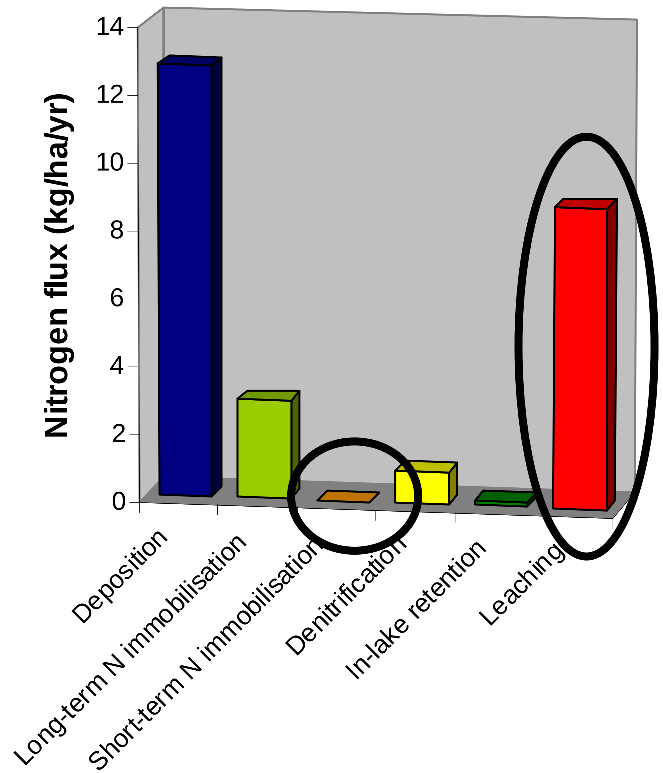


MAGIC modelling of lags in N leaching *(Llyn Llagi again)*

MAGIC predicted 2100

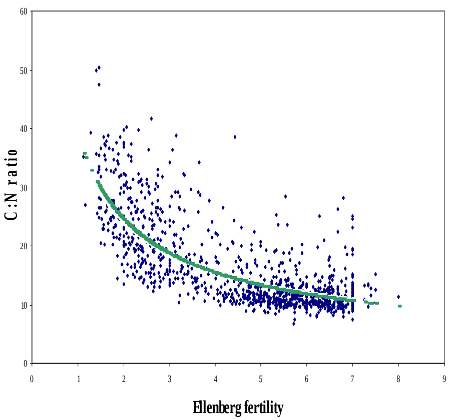


Predicted Steady State



Dynamic models suggest that many ecosystems are a long way (centuries?) from the steady state NO_3 leaching levels indicated by the steady state mass balance

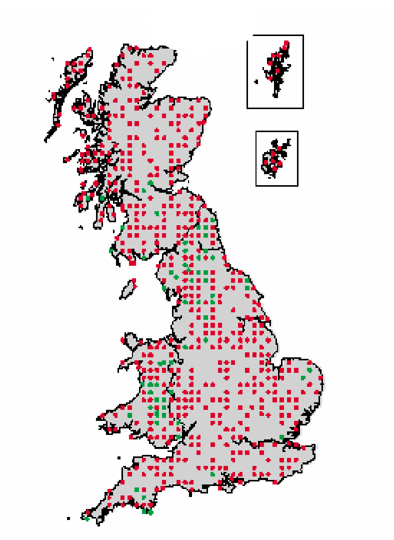
Predicting biodiversity change with dynamic models: MAGIC-GBMOVE

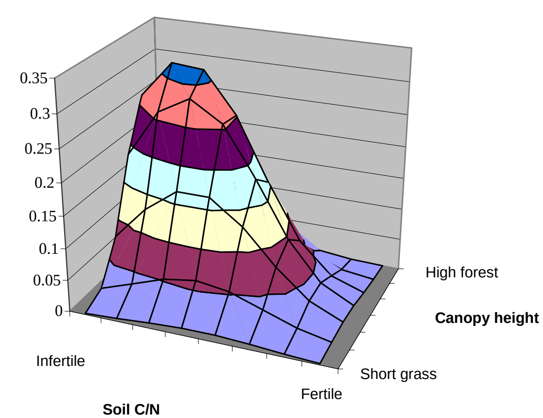


UK Countryside Survey: 16,691 vegetation survey plots. Species recorded, Ellenberg values for fertility (Eb N), acidity (Eb R) and moisture (Eb F) calculated

Subset of sites to relate Ellenberg values to abiotic conditions (soil pH, moisture, C/N ratio)

GBMOVE: Empirical relationships derived to predict probability of occurrence as a function of nitrogen, acidity and other environmental drivers





Predicting biodiversity change with dynamic models: MAGIC-GBMOVE

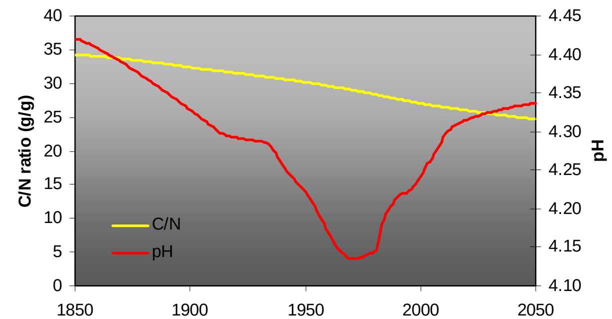
MAGIC: Prediction of soil pH and C/N change in response to changing S and N deposition

Other environmental data
e.g. moisture, temperature, grazing

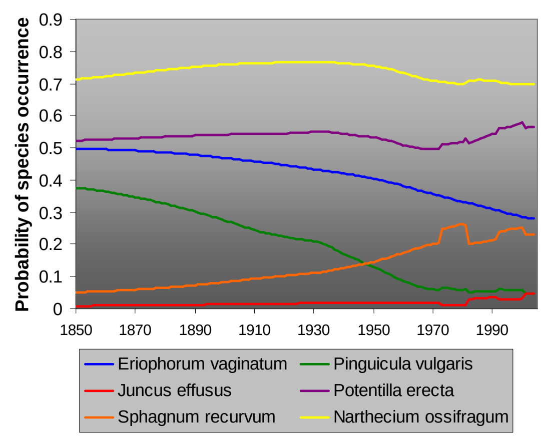
GBMOVE: Empirical relationships derived to predict probability of occurrence as a function of nitrogen, acidity and other environmental drivers

Note that GBMOVE does not assume a threshold

MAGIC simulation



GBMOVE predictions



Calculating critical loads with dynamic models: 1. Netherlands

Sensitive plant associations

139 plant associations important for biodiversity in NL

Minimum acceptable pH defined as 20th percentile Eb R

Maximum acceptable N availability defined as 80th percentile Eb N

Survey data

46000+ relevees used to define Ellenberg values for fertility, acidity and moisture

Subset of sites used to relate Ellenberg values to abiotic conditions

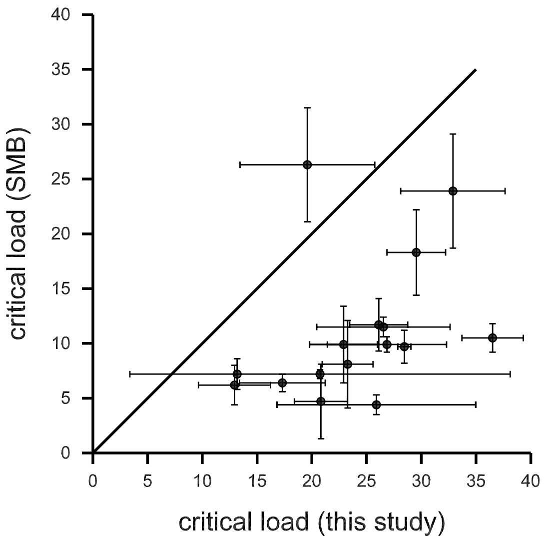
Dynamic modelling

Dynamic biogeochemical model SMART2 run in inverted mode to estimate steady-state N deposition giving rise to required pH and N availability

Critical Load

Van Dobben et al., Ecosystems (2006)

Calculating critical loads with dynamic models: 1. Netherlands

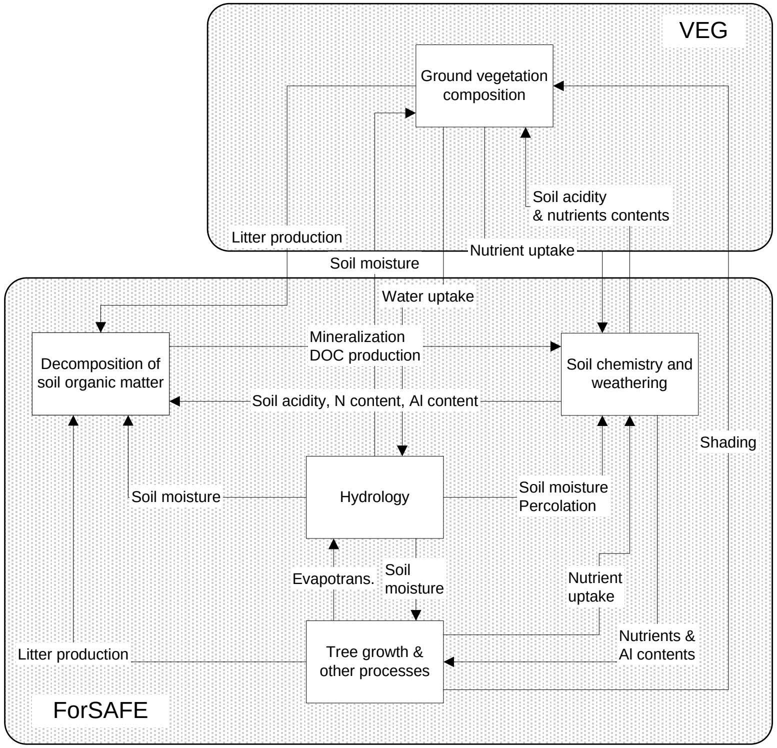


Comparison of critical loads estimated by the method of van Dobben et al. (2006) with those estimated by the Steady State Mass Balance

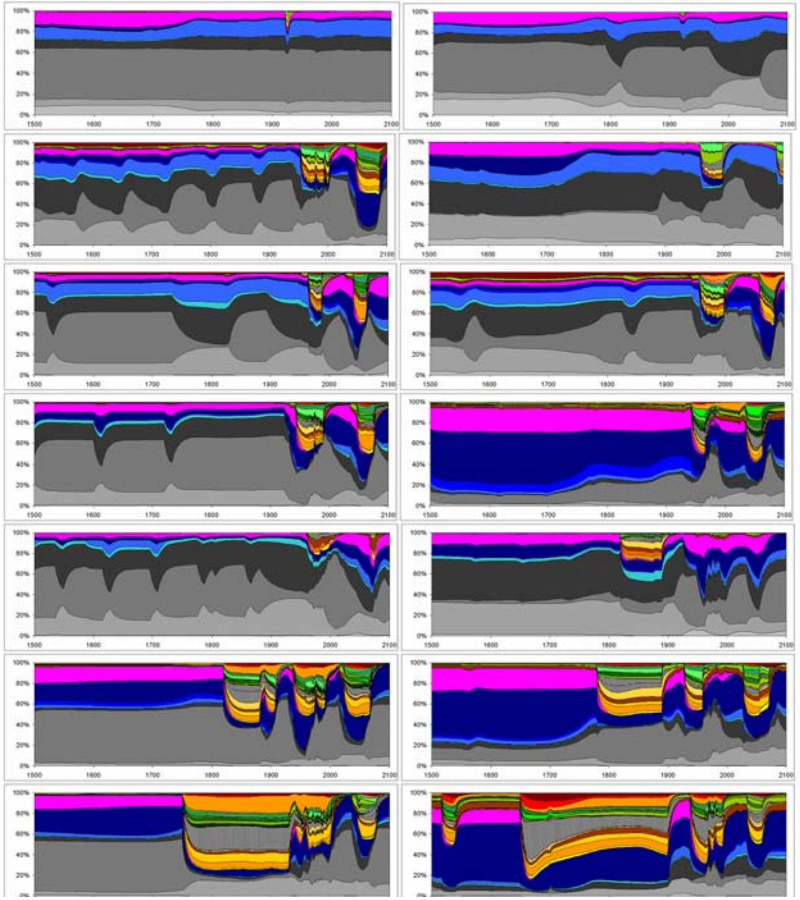
- Differences occur because:
  - The SMART model approach allows greater 'acceptable' N leaching than the DMB
  - Estimated N immobilisation is higher
- Compared to empirical critical loads, van Dobben approach gives similar range but no correlation for individual habitat types

Calculating critical loads with dynamic models: 2. Sweden

The ForSAFE Model

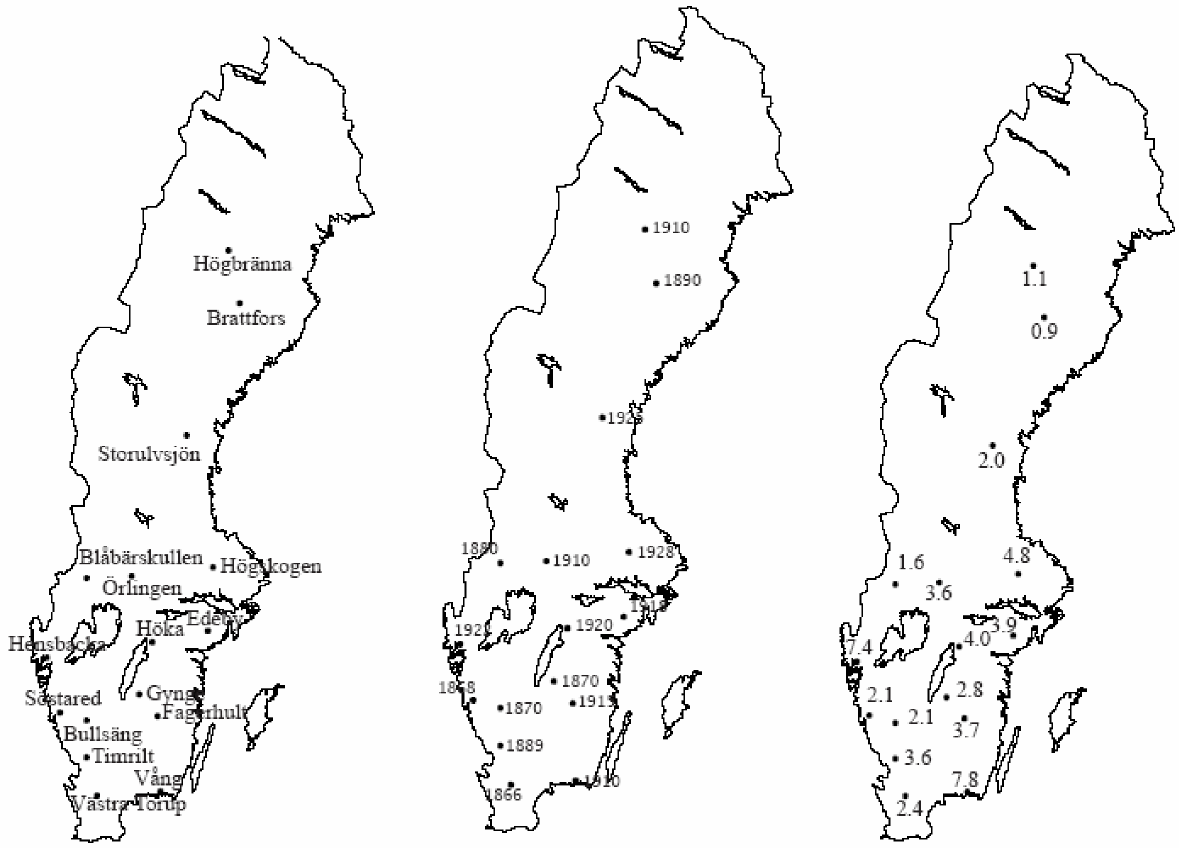


ForSAFE modelled vegetation change



Calculating critical loads with dynamic models: 2. Sweden

ForSAFE estimated critical loads based on the N deposition at which species composition changed by 5%



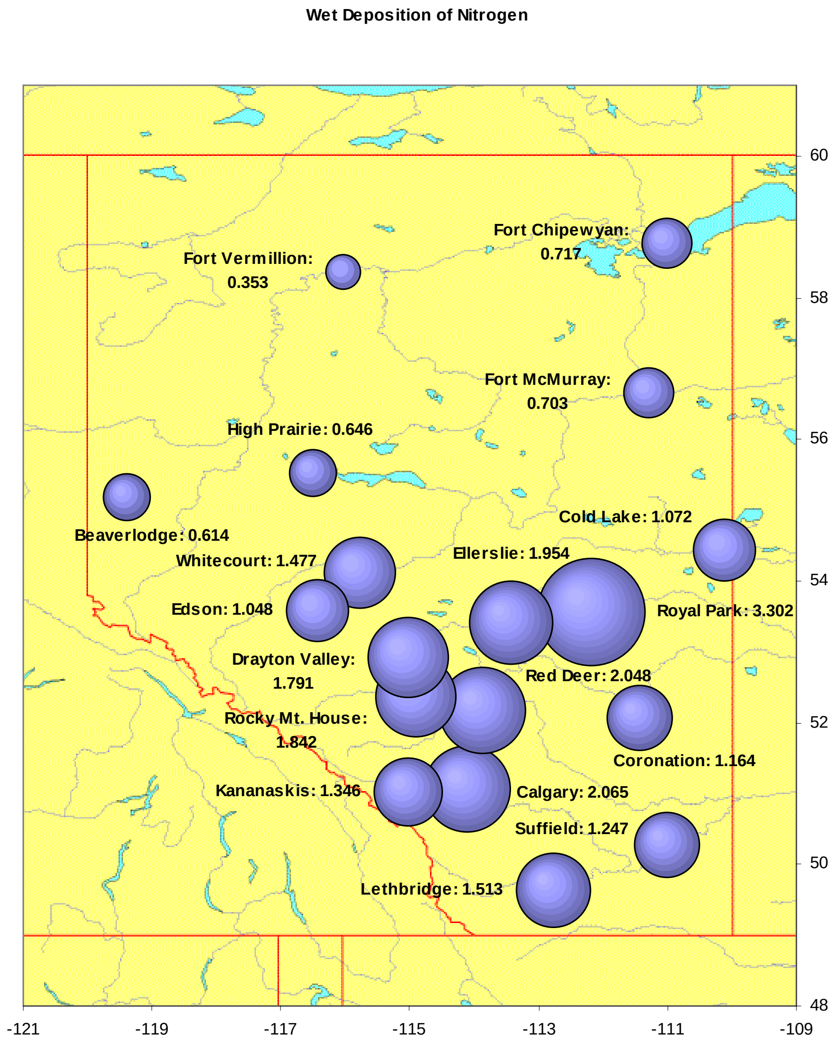
Calculating critical loads with dynamic models: 2. Sweden

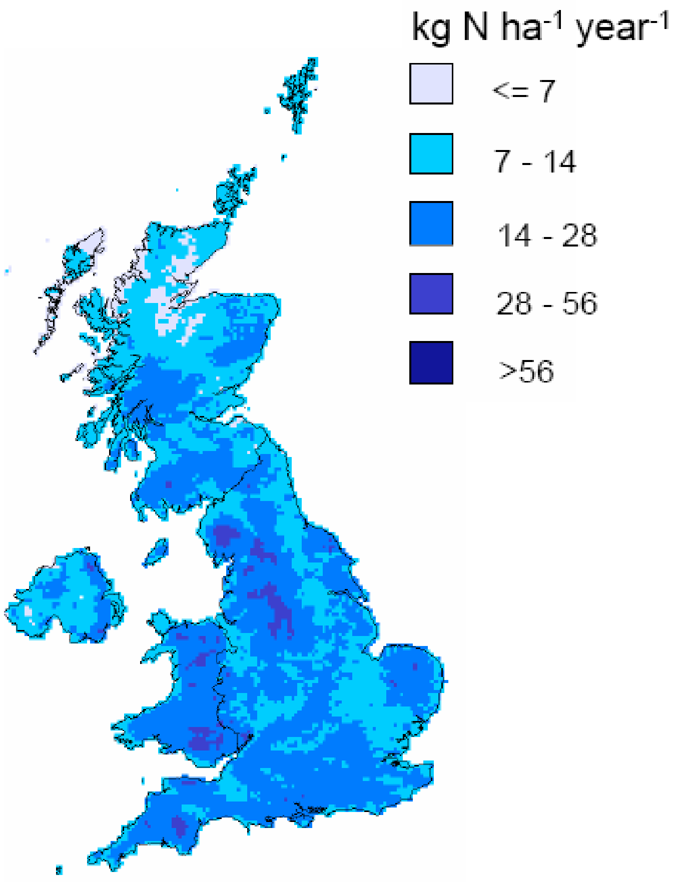
ForSAFE critical loads and exceedances for individual sites

Site	Time of vegetation response	Critical load deposition kg $ha^{-1}yr^{-1}$	Present deposition kg $ha^{-1}yr^{-1}$	Excess deposition kg $ha^{-1}yr^{-1}$	Required deposition reduction %
Högbränna	1910	1.1	1.5	0.4	27
Brattfors	1890	0.9	2.0	1.1	55
Storulvsjön	1925	2.0	3.5	1.5	43
Högskogen	1928	4.8	7.9	3.2	40
Örlingen	1910	3.6	8.5	3.9	52
Edeby	1918	3.9	7.8	3.9	50
Blåbärskullen	1880	1.6	8.5	6.9	81
Höka	1920	4.0	8.9	4.9	55
Hensbacka	1922	7.4	18.0	10.6	59
Söstared	1868	2.1	20.0	17.9	89
Gynge	1870	2.8	8.3	5.5	66
Fagerhult	1915	3.7	7.5	3.8	51
Bullsäng	1870	2.1	15.0	12.9	86
Timrilt	1889	3.6	23.0	19.4	84
Vång	1910	7.8	17.0	9.2	54
Västra Torup	1866	2.4	27.0	24.6	91

5. Critical Loads in Alberta

Alberta vs Europe: N deposition levels





1995-97 Total N deposition

Alberta vs Europe: Acidity Critical Loads

- Acidity critical loads applied to both
- Methods appear fundamentally similar:

Net Acidifying Potential:

$$NAP = ([SO_4^{2-}] - [Ca^{2+} + Mg^{2+}])_{wet} + [NO_3^-]_{leached}$$

ForSust model: Steady state mass balance approach

- 95% protection level, similar chemical thresholds used
- Range of acidity critical loads (0.25 to 1.0 keq/ha/yr) similar to Europe, but with lower maximum values

Alberta vs Europe: Damage vs Recovery

- In Europe, critical loads are, or have been, exceeded across much of the area, so emphasis is on reduction of CL exceedance and modelling timescales of recovery
- In Alberta, critical loads haven't been exceeded anywhere, so emphasis is on avoiding damage

European Target Loads:

The target deposition required to achieve recovery by a specified date at a currently exceeded site:
'Have to do more'

Albertan Target Loads:

Somewhere between current deposition and the critical load (~90%).

'Factor of safety'

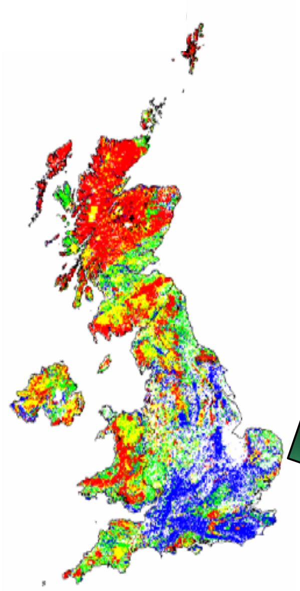
Alberta vs Europe: Eutrophication

- Critical loads for N as a nutrient have not yet been applied to Alberta
- Evidence from Europe is that ecosystems may be more sensitive to N deposition with regard to eutrophication than with regard to acidification
- One possibility is to adopt the critical loads for N as a nutrient developed in Europe
- But Albertan ecosystems and plant species differ significantly from those in Europe – need to ensure that sensitivity to N deposition is similar before applying European values.
- Ideally, a combination of experiments and linked soil-vegetation condition surveys are required to establish local species sensitivity to N deposition

Conclusions

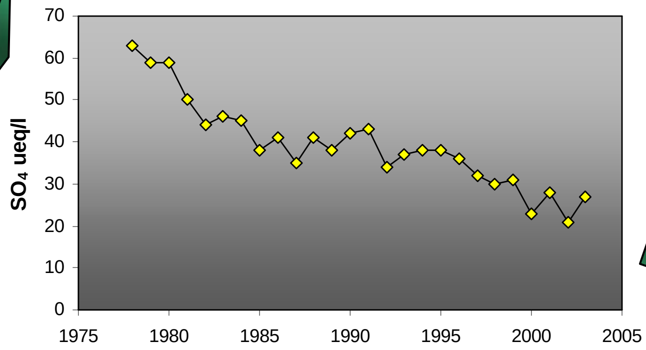
- Critical loads aren't perfect!
  - They do not consider timescales of change
  - They simplify complex ecosystem processes by which deposition impacts on environmental quality into 1 (or 2) numbers
  - Chemical criteria and damage thresholds are not always well defined or verified
  - Long-term sinks, particularly for N, are uncertain
  - They assume a threshold that might not really exist
- Dynamic models can address some of these limitations, but are unlikely to entirely replace critical loads
- And whatever their failings, critical loads have proven to be a highly effective means of translating science into policy, and take significant credit for the success of negotations to reduce acidifying emissions in Europe

Critical loads have worked…

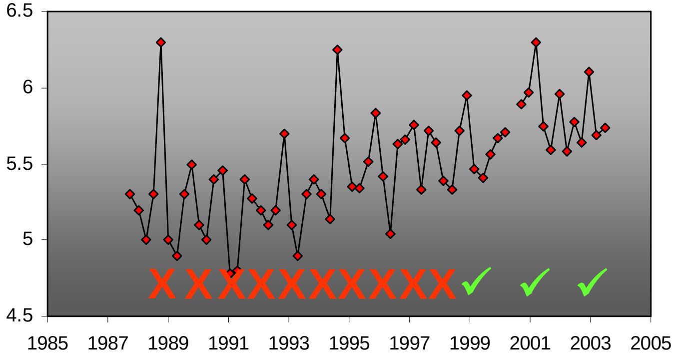


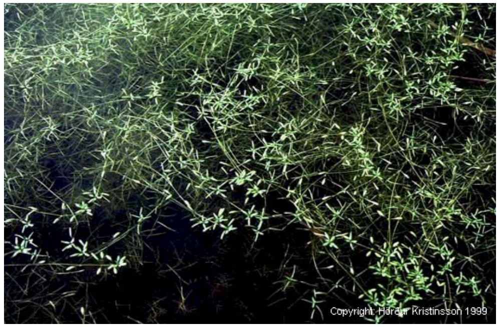
Critical Loads

S deposition reductions



pH recovery, Llyn Llagi





Callitriche hamulata (water starwort)