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

1. Establish a Critical Limit (Environmental Quality Standard)
2. Calculate the load that gives the Critical Limit at steady-state
3. Relate emissions and dispersal to loads
4. Use policy to control emissions

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

1) Sulphur and acidity

- Sulphur deposition
- Critical load
- Acidity and aluminium
- Base cations
- Sulphate

Sulphur deposition
Critical Loads and ecosystem damage

1) Sulphur and acidity

Sulphur deposition

Critical load

Acidity and aluminium
Base cations
Sulphate

?  ?
Critical Loads and ecosystem damage

1) Sulphur and acidity

Sulphur deposition

Acidity and aluminium
Base cations
Sulphate

Critical load

xxxx!

:(!

!!!
Critical Loads and ecosystem damage

1) Nitrogen and acidity
Critical Loads and ecosystem damage

1) Nitrogen and acidity

Nitrogen  Sulphur

Acidity and aluminium
Base cations
Sulphate
Nitrate

Critical load
Critical Loads and ecosystem damage

1) Nitrogen and acidity

Nitrogen  Sulphur

Acidity and aluminium  Base cations  Sulphate  Nitrate

Critical load
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…

\[
\text{CL}_{\text{max}}(S) = BC_{\text{dep}} - Cl_{\text{dep}} + BC_{w} - BC_{u} + (1.5 \times Ca_{le}/(Ca:Al)_{\text{crit}}) + Q^{2/3}(1.5 \times Ca_{le}/((Ca:Al)_{\text{crit}} \times K_{\text{Gibb}}))
\]
\[
\text{CL}_{\text{min}}(N) = N_{i} + N_{de} + N_{u}
\]
\[
\text{CL}_{\text{max}}(N) = \text{CL}_{\text{max}}(S) + \text{CL}_{\text{min}}(N)
\]
The critical load function

\[ \text{CL}_{\text{max}} S \]

CLF = acidity critical load

CL\text{min} \text{N} \quad \text{CL\text{max} N}

Sulphur deposition

Nitrogen deposition
UK 5th percentile Critical Loads for Acidity

CLmaxS

CLmaxN

keq ha⁻¹ year⁻¹

黑色 <= 0.2
红色 0.2 – 0.5
黄色 0.5 – 1.0
蓝色 > 2.0

keq ha⁻¹ year⁻¹

黑色 <= 0.2
红色 0.2 – 0.5
黄色 0.5 – 1.0
蓝色 > 2.0

1.0 – 2.0

European Critical Loads for Acidity
Critical Load Exceedance, UK

- **1970**
- **2001-2003**
- **2020**

keq ha⁻¹ year⁻¹:
- Blue: not exceeded
- Red: 1.0 – 2.0
- Green: <= 0.5
- Black: > 2.0
- Yellow: 0.5 – 1.0
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

Nitrogen

Critical load
Critical Loads and ecosystem damage

3) Nitrogen and biodiversity

Nitrogen

 Nitrate leaching

Critical load
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)*

\[ C_{\text{nut}}(N) = N_i + N_{\text{de}} + N_u + N_{\text{le(acc)}} \]

- **Critical Load**: 8-17 kg N/ha/yr
- **Sustainable long-term N immobilisation**: 1-4 kg N/ha/yr
- **Denitrification**: 1-4 kg N/ha/yr
- **Net uptake due to biomass removal**: 3-6 kg N/ha/yr
- **‘Acceptable’ NO₃ 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

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

- $C_{nut} N$ 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

1970

2001-2003

2020

kg N ha\(^{-1}\) year\(^{-1}\)

- Blue: not exceeded
- Black: > 14.0
- Red: 7.0 - 14.0
- Green: <= 2.8
- Yellow: 2.8 - 7.0
Critical load exceedances across Europe
2010 forecast

2010 Exceedance of acidity CLs

2010 Exceedance of nutrient CLs

eq ha$^{-1}$a$^{-1}$

- no exceedance
- <200
- 200 - 400
- 400 - 600
- 600 - 800
- > 800

All ecosystems

Dep-data: EMEP/MSC-W

Dep-data: EMEP/MSC-W
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

Diagram showing nitrogen flux (kg/ha/yr) for different processes:
- Deposition
- Long-term N immobilisation
- Short-term N immobilisation
- Denitrification
- Intake retention
- Leaching

Axes:
- Y-axis: Nitrogen flux (kg/ha/yr)
- X-axis: Processes
Modelled lags in N leaching

*(Llyn Llagi again)*

MAGIC predicted 2100
Dynamic models suggest that many ecosystems are a long way (centuries?) from the steady state NO₃ 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
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+ relevées 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*

<table>
<thead>
<tr>
<th>Site</th>
<th>Time of vegetation response</th>
<th>Critical load deposition kg ha(^{-1})yr(^{-1})</th>
<th>Present deposition kg ha(^{-1})yr(^{-1})</th>
<th>Excess deposition kg ha(^{-1})yr(^{-1})</th>
<th>Required deposition reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Högbränna</td>
<td>1910</td>
<td>1.1</td>
<td>1.5</td>
<td>0.4</td>
<td>27</td>
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<tr>
<td>Brattfors</td>
<td>1890</td>
<td>0.9</td>
<td>2.0</td>
<td>1.1</td>
<td>55</td>
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<tr>
<td>Storulvsjön</td>
<td>1925</td>
<td>2.0</td>
<td>3.5</td>
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<td>Högskogen</td>
<td>1928</td>
<td>4.8</td>
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<td>Örlingen</td>
<td>1910</td>
<td>3.6</td>
<td>8.5</td>
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<td>Edeby</td>
<td>1918</td>
<td>3.9</td>
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<td>Blåbärskullen</td>
<td>1880</td>
<td>1.6</td>
<td>8.5</td>
<td>6.9</td>
<td>81</td>
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<td>Höka</td>
<td>1920</td>
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<td>8.9</td>
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<td>Hensbacka</td>
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<td>Fagerhult</td>
<td>1915</td>
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<td>19.4</td>
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<td>Vång</td>
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<td>9.2</td>
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<td>Västra Torup</td>
<td>1866</td>
<td>2.4</td>
<td>27.0</td>
<td>24.6</td>
<td>91</td>
</tr>
</tbody>
</table>
5. Critical Loads in Alberta
Alberta vs Europe: N deposition levels

1995-97 Total N deposition

kg N ha\(^{-1}\) year\(^{-1}\)

- Light gray: <= 7
- Light blue: 7 - 14
- Medium blue: 14 - 28
- Dark blue: 28 - 56
- Dark purple: >56

Wet Deposition of Nitrogen

- Fort Vermillion: 0.353
- Beaverlodge: 0.614
- Fort Chipewyan: 0.717
- Fort McMurray: 0.703
- Cold Lake: 1.072
- Royal Park: 3.302
- High Prairie: 0.646
- Edson: 1.048
- Whitecourt: 1.477
- Ellerslie: 1.954
- Red Deer: 2.048
- Coronation: 1.164
- Kananaskis: 1.346
- Calgary: 2.065
- Lethbridge: 1.513
- Suffield: 1.247
- Rocky Mt. House: 1.842
- Rocky Mt. House: 1.791
- Drayton Valley: 1.048
- Rocky Mt. House: 1.346
Alberta vs Europe: Acidity Critical Loads

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

  Net Acidifying Potential:

  \[
  \text{NAP} = ([\text{SO}_4^{2-}] - [\text{Ca}^{2+} + \text{Mg}^{2+}])_{\text{wet}} + [\text{NO}_3^-]_{\text{leached}}
  \]

  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 negotiations to reduce acidifying emissions in Europe
Critical loads have worked...

S deposition reductions

pH recovery, Llyn Llagi

Callitriche hamulata (water starwort)