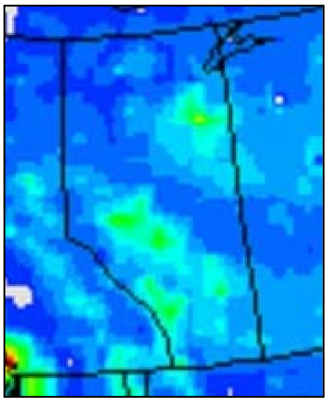
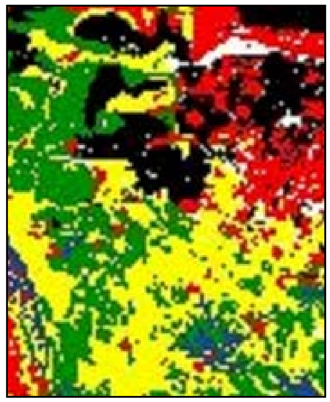
CALCULATING CRITICAL LOADS OF ACID DEPOSITION FOR FOREST SOILS IN ALBERTA

Final Report: Critical Load, Exceedance and Limitations

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PN 1408

February, 2008

Project Title: **Calculating Critical Loads of Acid Deposition for Forest Soils in Alberta (CLAB)**

Report Title: **Critical Load, Exceedance and Limitations (Final Report)**

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Report Citation: Aherne, J. Calculating Critical Loads of Acid Deposition for Forest Soils in Alberta: Critical Load, Exceedance and Limitations. Final Report. Canadian Council of Ministers of the Environment, 2008,14pp.

Preface

This report presents critical loads of acid (sulphur and nitrogen) deposition and exceedance estimates for upland forest soils in Alberta. The principal motivation for this work stems from the recent critical load mapping activity in eastern and western Canada through initiatives funded by the New England Governors-Eastern Canadian Premiers (NEG-ECP) and the Canadian Council of Ministers of the Environment. To date critical loads of acid deposition have been mapped for all provinces east of Alberta following guidelines established by the NEG-ECP. For consistency, the determination of critical loads and exceedances for forest soils in Alberta followed the NEG-ECP protocol. In addition, this report presents the first attempt at estimating regional critical loads using a soil point approach (based on soil observations) in contrast to the commonly used soil polygon approach (based on soil maps). While every attempt has been made to include the best available data, all modelling endeavours suffer from uncertainties and limitations in data and methods. The critical load and exceedance estimates will ultimately change as data and methods are revised; as such, the current estimates should be viewed as a starting point in the critical load process and not the end-point. While the 'science' of critical loads has developed rapidly in Canada in recent years, it is still in it's infancy compared to Europe, and there is considerable opportunity for improvement in methodologies and data.

Acknowledgements

This report has benefited from discussion with many individuals in relation to data sources and methodologies. Furthermore, many of these individuals represent organisations that contributed data. The following is an attempt to list individuals (and organisations) that have provided time, energy and data; their contribution is gratefully acknowledged.

Contributors: Mike Shaw, Bob Vet and Mike Moran (Environment Canada, Science and Technology Branch), Max Posch (Co-ordination Centre for Effects, The Netherlands), Brian Moneith (Agriculture and Agri-food Canada), Lawrence Cheng, Gary Byrtus and Preston McEachern (Alberta Environment), Cathy Jacques and Heather Evans (Alberta Sustainable Resource Development), Anthony Trofymow and Brian Titus (Canadian Forest Service, Victoria), Barbara Kishchuk and Cindy Shaw (Canadian Forest Service, Edmonton), Rock Ouimet (Quebec Ministère des Resources Naturelles) and Dave Fox and Markus Kellerhals (Environment Canada, Yellowknife).

Data sources: Agriculture and Agri-Food Canada (Soil Landscapes of Canada), Co-ordination Centre for Effects, The Netherlands (long-term precipitation, temperature and runoff), United States Geological Survey (North America Land Cover Characteristics Data Base), Environment Canada, Science and Technology Branch (mapped deposition fields and A Unified Regional Air-quality Modelling System data), Environment Canada, Yellowknife (Community Multiscale Air Quality model data), Alberta Environment (REgional Lagrangian Acid Deposition model data, Soil Metals Database and Long Term Soils Acidification Monitoring Program data), Cumulative Environmental Management Association (properties of sensitive soils) and the Canadian Forest Service (forest soil data from various national networks and projects: Canadian Intersite Decomposition Experiment, Soil Profile and Organic Carbon Database, ARNEWS, Forest Carbon Database).

Financial support from the Canadian Council of Ministers of the Environment is gratefully acknowledged, in addition to the time and energy contributed by Sara Davarbakhsh, Gwen Waedt and Sande Petkau under this contact.

Acronyms and abbreviations

AOSR	Athabasca Oil Sands Region
ARTG	Acid Rain Task Group
AURAMS	A Unified Regional Air quality Modelling System
Bc:Al	Base cation (calcium, magnesium and potassium) to aluminium ratio
CASA	Clean Air Strategic Alliance
CCME	Canadian Council of Ministers of the Environment
CL(S + N)	Critical load of sulphur and nitrogen
CMAQ	Community Multiscale Air Quality model
EC	Environment Canada
EXC	Exceedance
GEM	Global Environmental Multiscale
LUC	Land Use Categories
GIS	Geographical Information System
ICP M&M	International Co-operative Programme on Modelling and Mapping of Critical Loads (and Levels) and Air Pollution Effects, Risks and Trends
LRTAP	Long-Range Transboundary Air Pollution
N	Nitrogen
NEG-ECP	New England Governors-Eastern Canadian Premiers
Q	Precipitation surplus or runoff
RELAD	REgional Lagrangian Acid Deposition
S	Sulphur
SI	International System of Units (Système International d'Unités)
SIB	Simple Biosphere model
SLC	Soils Landscape of Canada
SSMB	Steady-State Mass Balance
UNECE	United Nations Economic Commission for Europe

Units. Where possible, data have been reported using the International System of Units. Critical load and exceedance data are reported using the unit of mol_c ha^{-1} yr^{-1} (note the subscript 'c' refers to moles of charge). A corresponding and somewhat archaic term still commonly used is equivalents (eq): eq = mol_c. The unit of mol_c ha^{-1} yr^{-1} are compatible with the critical load estimates for eastern Canada presented in the recent Canadian Acid Deposition Science Assessment (Environment Canada 2004).

Map projections. All maps are displayed using a Lambert Azimuthal Equal Area Projection. Parameters used for this projection are longitude of origin: 100 00 00 W and latitude of origin: 50 00 00 N. Maps were generated in raster format with a pixel size of 1000 meters.

Map legends. In a regional context, critical load data can span several orders of magnitude, higher values typically representing soils with greater buffering capacities. As such, critical load maps have been reported using unequal intervals with smaller category intervals for the lower (more acid sensitive) data values: < 250, 250–500, 500–1000, 1000–2000 and > 2000 mol_c ha^{-1} yr^{-1}.

Caveat emptor. The maps contained in this report represent a broad-scale regional assessment of critical loads of sulphur and nitrogen for upland forest soils and are not intended for site-specific assessments.

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Critical load. 'a quantitative estimate of exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge'.

Nilsson and Grennfelt, 1988

Executive summary

The critical loads of acid (sulphur and nitrogen) deposition have been determined and mapped for forest soils in Alberta. For consistency with existing critical load estimates in eastern and western Canada, the methodology followed the protocol and guidelines established by the New England Governors-Eastern Canadian Premiers (NEG-ECP). The key data inputs were base cation weathering rate, atmospheric base cation deposition and critical alkalinity leaching. The Soil Landscapes of Canada (SLC, version 2.1) was the principal database underlying the estimation of base cation weathering rate. Gridded (GEM grid: 35 km × 35 km) total (wet plus dry) atmospheric deposition data (including base cations) were provided by Environment Canada. Under the NEG-ECP protocol the critical alkalinity leaching was set to maintain soil base saturation at an acceptable level for forest health and productivity. In principal this should equate to a molar ratio of soil solution base cations to aluminium (Bc:Al) equal to 10. A Bc:Al ratio of 1 is the most common protection limit used in Europe.

The mean critical load for Alberta was 872 $mol_c\ ha^{-1}\ yr^{-1}$ under the NEG-ECP protocol. Using a Bc:Al ratio of 10 and 1, the mean critical load was 778 $mol_c\ ha^{-1}\ yr^{-1}$ and 1462 $mol_c\ ha^{-1}\ yr^{-1}$, respectively. The NEG-ECP protocol closely resembled a Bc:Al ratio of 10, although marginally less protective. In contrast, the commonly used Bc:Al ratio of 1 resulted in significantly higher critical loads. Mean annual total (wet plus dry) sulphur and nitrogen deposition for Alberta was 303 $mol_c\ ha^{-1}\ yr^{-1}$ during the period 1994–1998. Approximately 8.5 % of the mapped soils received acid deposition in excess of critical load. This increased to 11 % using a Bc:Al ratio of 10; in contrast, there was no exceedance under a Bc:Al ratio of 1.

The choice of critical chemical limit (receptor and level of protection) has a significant impact on the resultant critical load. Following the NEG-ECP protocol (consistent with eastern and western Canada), 8.5 % of the mapped soils were exceeded. However, much of these soils were classified as organic and their critical load is uncertain under the current protocol. Although the SLC is the highest resolution soil coverage available for Alberta, the scale is coarse (scale 1:1,000,000), with large regions classified entirely as 100 % organic soils. Removing these soil units, the mean critical load for Alberta was 1067 $mol_c\ ha^{-1}\ yr^{-1}$ under the NEG-ECP protocol. Furthermore, approximately 1.5 % of the mapped mineral soils received acid deposition in excess of critical load. However, in practice the organic soil units are a mosaic of mineral and organic soils. To address this uncertainty, critical loads for Alberta were further determined using a soil point approach based on soil observations rather than soil maps. Soil physio-chemical properties were collated for approximately 1200 mineral soil observation pits (from existing programs). Critical loads were estimated for each point following the NEG-ECP protocol and summarised on the GEM grid. Soil data were not available across the entire province, approximately 42 % of grids with forest soils had soil observations (227 out of a maximum of 546 grid squares); however, many of the grid squares (34 %) had only one soil observation (77 grid squares). Multiple observations within each grid were summarised using percentiles; the pentile critical load (5th percentile) is typically used as a regional target to account for uncertainties, but also to ensure a sufficient level of protection (95 % protection limit). The mean pentile critical load was 843 $mol_c\ ha^{-1}\ yr^{-1}$, which was close to the map-based estimate (872 $mol_c\ ha^{-1}\ yr^{-1}$); similarly, approximately 12 % of the grid squares received acid deposition in excess of critical load (27 grid squares) based solely on mineral soil physio-chemical observations.

1. Introduction

In October 1998, Canadian Energy and Environment Ministers signed The Canada-Wide Acid Rain Strategy for Post-2000, in which they committed to take steps over the long-term to manage the acid rain problem in eastern Canada and prevent one in western and northern Canada. The Strategy set a long-term goal of achieving the threshold of critical loads for acid deposition across Canada.

Critical loads have been determined and mapped for upland forest soils in eastern Canada (Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick, Quebec and Ontario) following guidelines established by the New England Governors-Eastern Canadian Premiers (NEG-ECP) Environmental Task Group on Forest Mapping (NEG-ECP 2001); reported in the 2004 Canadian Acid deposition Science Assessment (Environment Canada 2004). In western Canada, the Acid Rain Task Group (ARTG: mandated by the Air Management Committee of the Canadian Council of Ministers of the Environment (CCME)) have recently supported the determination of critical loads following the NEG-ECP protocol for upland forest soils in Manitoba and Saskatchewan (Aherne and Watmough 2006, Aherne 2008). In Alberta, a level 0[1] approach based on soil sensitivity has previously been used to estimate critical loads (Alberta Environment 1999, Foster et al. 2001). In addition, localised efforts have been carried out, e.g., in Provost-Esther, Alberta (Turchenek and Abboud 2001) and the Athabasca Oil Sands Region (AOSR: Abboud et al. 2002).

In June 2006, Trent University initiated a small project funded by the Canadian Council of Ministers of the Environment (CCME) to determine and map critical loads of acid deposition (and exceedances) for upland forest soils in Alberta. The work closely followed, and built upon, recent critical load assessments for Manitoba and Saskatchewan (Aherne and Watmough 2006, Aherne 2008). Details on the critical load methodology, applying the concept and the Steady-State Mass Balance (SSMB) model are described in Aherne and Watmough (2006).

2. Objective

The principal objective of this report was to describe the determination and mapping of critical load and exceedance of sulphur (S) and nitrogen (N) deposition for upland forest soils in Alberta. For consistency with eastern Canada, Manitoba and Saskatchewan, the methodology followed the protocol and guidelines established by the NEG-ECP. A secondary objective was to identify an alternative approach to determine and map critical loads based on mineral soil point observations.

The principal task was to generate or acquire spatial data-sets (base maps) of the input variables required to calculate critical loads for Alberta, following the protocol and guidelines established by the NEG-ECP. This report attempts to identify a framework for Canada-wide determination and mapping of critical loads (for acidity). Further, the report also recommends future research needs for Alberta.

3. Methodology

Critical load and exceedance of S and N have been estimated for forest soils in Alberta following the methodology and guidelines established by the NEG-ECP (NEG-ECP 2001, Ouimet 2005). The long-term critical load was estimated using the Steady-State Mass Balance (SSMB) model (see Appendix I and Aherne and Watmough 2006). The key spatial data-sets (or base maps) required as inputs for the SSMB model are atmospheric deposition, base cation weathering rate and critical alkalinity leaching. Critical loads estimated under this soil-map based approach are hereafter referred to as ‘vanilla’; critical loads estimated under the mineral soil-point approach, hereafter referred to as ‘neapolitan’, required observations of soil physio-chemical observations.

Atmospheric deposition. Average annual total (wet plus dry) atmospheric deposition data for Alberta during the period 1994–1998 were provided by Environment Canada on the Global

[1] Level 0 refers to semi-quantitative approaches as opposed to mass balance or level I approaches.

Environmental Multiscale (GEM) grid at a resolution of 35 km × 35 km (see Figure 1a and 1b for base cation, and sulphur and nitrogen deposition). These estimates represented an important contribution to the project and are consistent with the deposition fields recently developed for eastern Canada, Manitoba and Saskatchewan (see Appendix II for monitoring stations used to generate the deposition fields). Hereafter the deposition data are referred to as ECMAP. For further details on the deposition fields and a general description of uncertainty see Aherne and Watmough (2006).

Base cation weathering rate. Under the NEG-ECP protocol, weathering rates were estimated using a soil type–texture approximation method (Ouimet 2005). The approach estimates weathering rate from texture (clay content) and parent material class. This method was used in conjunction with the Soil Landscapes of Canada (SLC, version 2.1) map for Alberta to estimate province-wide base cation weathering rates. The SLC map is the best resolution database available for estimating regionally consistent base cation weathering for Alberta. Although more detailed soil databases (and maps) are available, they are generally confined to agricultural regions or spatially restricted surveys. The scale (1:1,000,000) is consistent with the critical load mapping carried out in Ontario, Manitoba and Saskatchewan.

Percent clay was vertically (all soil horizons excluding the C horizon) and spatially (component soil types within a mapping unit) weighted to derive a single average value for each mapping unit on the SLC map. The base cation weathering rate was estimated following Ouimet (2005). In addition, for consistency with Ontario, Manitoba and Saskatchewan, maximum soil depth was limited to 50 cm. For further details on the methodology see Aherne and Watmough (2006).

Critical alkalinity leaching. Alkalinity leaching is typically estimated from a critical molar base cation to aluminium (Bc:Al) ratio in soil solution and the gibbsite dissolution constant (K_{gibb}; see Appendix I). Under the NEG-ECP protocol, an alkalinity leaching function was developed that corresponds to a value of 10 for the Bc:Al ratio and 9 for log K_{gibb} (Rock Ouimet, personal communication). For consistency with eastern Canada, Manitoba and Saskatchewan, critical alkalinity leaching for Alberta was estimated following the protocol and guidelines established by the NEG-ECP. The choice of critical chemical limit (receptor and level of protection) has a significant impact on the resultant critical load. Critical loads of S and N deposition for forest soils was further estimated using a Bc:Al ratio of 10 (in principle equivalent the NEG-ECP protocol) and 1 to investigate uncertainty in exceedance based on the choice of critical chemical limit. A Bc:Al ratio of 1 is the most common protection limit used in support of the United Nations Economic Commission for Europe's (UNECE) Convention on Long-Range Transboundary Air Pollution.

Soil physio-chemical properties. The SLC is the only province-wide soil coverage available for Alberta. However in addition to the provincial map, soil physio-chemical properties are available for numerous soil pit observations through several monitoring programs or surveys in Alberta. Data are available for the Ecological Site Information plots, the Long Term Soil Acidification Monitoring Program and several networks operated by the Canadian Forest Service (ARNEWS and NFI). Much of these data have been summarised by Shaw et al. (2005) and Siltanen et al. (1997). Similar to the soil-polygon mapping procedure, critical loads of S and N deposition for forest soils may also be estimated for each soil observation point using the NEG-ECP protocol. Mineral soil physio-chemical properties (specifically site location, horizon depth, bulk density and percent clay) were collated for approximately 1200 observations throughout Alberta from five principal databases (Siltanen et al. 1997, Shaw et al. 2005, Alberta Sustainable Resource Development 2003, Cumulative Environmental Management Association 2005, Alberta Environment 2006).

4. Critical loads: Vanilla

Critical load and exceedance of S and N have been estimated for forest soils in Alberta following the methodology and guidelines established by the NEG-ECP. The SLC was the principal database underlying the estimation of weathering rate. The SLC mapping units contain one or more distinct soil types or components (mineral and organic); the location of these components within a polygon is not defined. The inclusion of organic soil components within these mapping units will decrease the area weighted critical load. In the current assessment, the base cation weathering rate represented only mineral soils within each mapping unit, i.e., organic soils were excluded. However, a minimal weathering rate was set for soil mapping units entirely composed of organic soils (250 $mol_c\ ha^{-1}\ yr^{-1}$). Furthermore, critical loads are only presented for forest soils. Forest cover was described using the Simple Biosphere (SIB) model, which is part of the 'North America Land Cover Characteristics Data Base' developed by the United States Geological Survey[2]. The SIB land cover was chosen to be consistent with the Land Use Categories (LUC) used by Environment Canada to determine dry deposition. Forest cover for Alberta was spatially defined from the three following LUC: (i) broadleaf deciduous trees, (ii) deciduous and evergreen trees, and (iii) evergreen needleleaf trees.

The mean critical load for Alberta was estimated at approximately 872 $mol_c\ ha^{-1}\ yr^{-1}$ (Figure 2a). The minimum critical load was estimated at 216 $mol_c\ ha^{-1}\ yr^{-1}$. The current estimates for critical load were consistent with other provinces in Canada (Table 1), with estimates for Alberta similar to British Columbia, Newfoundland and Labrador, Nova Scotia, Ontario and Quebec. Approximately 33 % of the mapped soils in Alberta had critical load less than 500 $mol_c\ ha^{-1}\ yr^{-1}$ (8.8 % less than 250 $mol_c\ ha^{-1}\ yr^{-1}$). The mean annual total (wet plus dry) S and N deposition for Alberta was 303 $mol_c\ ha^{-1}\ yr^{-1}$ during the period 1994–1998 (Figure 1b). Approximately 8.5 % of the mapped soils received acid deposition in excess of critical load (Figure 2d and Table 2). However, a considerable proportion of these soil mapping units were composed entirely of organic soils according to the SLC (Figure 2f).

Removing all mapping units classified entirely (100 %) as organic soils had a significant influence on the critical load and extent of exceedance. The mean critical load for Alberta was estimated at approximately 1067 $mol_c\ ha^{-1}\ yr^{-1}$ (Figure 3a and Tables 1). Approximately 1.5 % of the mapped soils received acid deposition in excess of critical load (Figure 3b and Table 3). However, mapping units classified entirely as organic are in practice composed of mineral and organic soils. Rather than completely remove these soil units, future studies should explore the use of digital elevation or wetland maps to delineate regions with organic soils.

Using a Bc:Al ratio of 10 and 1 under the UNECE protocol, the mean critical load for Alberta was 778 $mol_c\ ha^{-1}\ yr^{-1}$ and 1462 $mol_c\ ha^{-1}\ yr^{-1}$, respectively. The NEG-ECP protocol closely resembled a Bc:Al ratio of 10, although marginally less protective (Figure 2b and Table 2). In contrast, the commonly used Bc:Al ratio of 1 resulted in significantly higher critical loads (Figure 2c). Approximately 11 % of the mapped soils received acid deposition in excess of critical load using a Bc:Al ratio of 10 (Figure 2e); in contrast, there was no exceedance under a Bc:Al ratio of 1 (Table 2). To further investigate uncertainty in exceedance, a second deposition scenario (M4) was used to estimate critical load exceedance (Figure 1c). The M4 scenario is a multi-model scenario derived from the mean of four deposition fields available for Alberta (AURAMS, CMAQ, ECMAP and RELAD; see Aherne (2008) for further details). Exceedance estimates under the M4 scenario were considerably reduced, with a decrease for the NEG-ECP protocol (2 %) and the UNECE critical loads using a Bc:Al ratio of 10 (3.4 %, Table 2). Again, the majority of the exceeded soils are composed entirely of organic soils according to the SLC.

In contrast, approximately 2.4 % of the mapped soils received acid deposition in excess of critical load using a molar Bc:Al ratio of 10 for mineral soil only (all mapping units classified

[2] URL: edc2.usgs.gov/glcc/na_int.php

entirely as organic soils were removed; Table 3). There was no exceedance under a Bc:Al ratio of 1. Exceedance estimates under the M4 deposition scenario were similar (Table 3).

Critical load: Vanilla. Following the NEG-ECP protocol, approximately 8.5 % of the mapped soils received acid deposition in excess of critical load. Depending on the chosen critical chemical limit and the 'current' level of total deposition, exceedance will vary. However, much of the sensitive soils were classified as organic and their exceedance is uncertain under the current protocol. Although the SLC is the highest resolution soil coverage available for Alberta, the scale is coarse (scale 1:1,000,000) resulting in large regions classified entirely as 100 % organic soils. Removing these soil units, the mean critical load for Alberta was 1067 mol_c ha^{-1} yr^{-1} under the NEG-ECP protocol. Furthermore, approximately 1.5 % of the mapped mineral soils received acid deposition in excess of critical load. However, in practice these soil units are a mosaic of mineral and organic soils.

Previous studies in Alberta. Alberta Environment (1999) applied a 'Level 0' critical load assessment to the province of Alberta. The province was divided into cells measuring 1° × 1°, with each cell categorised as sensitive, moderately sensitive or of low sensitivity on the basis of the soil and water systems. Critical loads were set at 250, 500 and 1000 mol_c ha^{-1} yr^{-1}, respectively (Foster et al. 2001). The REgional Lagrangian Acid Deposition (RELAD: Cheng et al. 1995) model was used to estimate the amount of acid deposition in Alberta; no grid cells received acid deposition in excess of their assigned critical load. However, one cell spanning the southern part of Alberta-Saskatchewan border (Provost-Esther grid) was predicted to be at risk of exceedance (Turchenek and Abboud 2001). The current study applied a more sophisticated 'Level 1' or mass balance approach to determine critical loads for forest soils (Appendix I). The approach utilised newer data at a greater spatial disaggregation. It represents a significant advancement on the previous critical load assessments, and is consistent with procedures in eastern Canada, Manitoba and Saskatchewan. Since the Provost-Esther grid does not contain forest soils it is not included in the current assessment.

5. Critical loads: Neapolitan

Soil physio-chemical properties were collated for approximately 1200 mineral soil observation pits. A critical load was estimated for each point following the NEG-ECP protocol and summarised on the GEM (35 km × 35 km) mapping grid. For comparison, the map-based forest soil critical loads were also summarised on the GEM grid (Figure 4a). Approximately 42 % of grids containing forest soils had soil point observations (227 out of a maximum of 546 grid squares); however, many of the grid squares (34 %) had only one soil observation (77 grid squares). Multiple observations within each grid were summarised using percentiles; the pentile critical load (5th percentile) is typically used as a regional target to account for uncertainties, but also to ensure a sufficient level of protection (95 % protection limit). The pentile critical loads indicate somewhat of a similar pattern to the soil-map based approach; although, the low critical loads in north-western Alberta are absent and critical loads in the AOSR are lower (Figure 4b). However, the mean pentile critical load was 843 mol_c ha^{-1} yr^{-1}, which was close to the map-based estimate (872 mol_c ha^{-1} yr^{-1}). It is important to note that the soil point data were not randomly selected and do not cover all soil mapping units. Rather they were collated from existing programs and, as such, may be biased towards more sensitive soils.

The exceedance of critical load of S and N to upland forest soils was calculated as the current deposition flux of S plus N (Figure 1b) minus the pentile critical load (Figure 4b). Annual average total (wet plus dry) deposition during the period 1994–1998 was provided by Environment Canada on the GEM grid. Approximately 12 % of the grid squares (27 grids) received acid deposition in excess of critical load. Furthermore, a number of the exceeded grid squares (notably in the AOSR) had multiple soil observations (> 5) providing confidence in their exceedance state (Figure 4c). Unlike the map-based approach, the soil-point critical loads were based solely on mineral soil observations (the ~1200 soil pit observation data were for mineral soils only). Clearly this provides a more reliable estimate of critical load and exceedance for mineral forest soils compared to the map-based approach, which incorporated large mapping units categorised as entirely of organic soil or units composed of spatially undefined mixtures of mineral and organic soils.

Critical load: Neapolitan. The soil-point approach presents a promising alternative to the soil-map based approach for determining critical loads of S and N deposition. The approach directly utilises measured soil information and therefore provides greater confidence in the resulting critical loads. However, soil observations are limited in many regions (or grid squares) and the areal representatively of each point is unknown. Under the current 'preliminary' assessment, the Neapolitan approach is somewhat more pessimistic with lower critical loads and greater exceedance than the Vanilla approach. It was assumed that grid squares with multiple soil observations are more reliable; however, each soil point was given equal weighting within a grid. Nonetheless, it is recommended that the approach be further investigated and refined for future Canada-wide assessments.

Table 1. Summary statistics (mean, median, mode, minimum and maximum) for critical loads of sulphur and nitrogen for all Canadian provinces. Statistics are based on forest soil (mapped area in 1000 km^2) as defined by the Simple Biosphere model §§§.

Province	Mean	Median	Mode	Min.	Max.	Area 1000 km^2
Alberta	872	868	264	216	3421	409.9
Alberta §	1066	1101	818	259	3404	308.2
British Columbia §§	856	750	532	174	4026	697.2
Manitoba	1119	870	259	185	3240	317.6
New Brunswick	1361	1150	1267	178	6131	60.0
Newfoundland and Labrador	749	602	263	193	4635	87.9
Nova Scotia	950	805	405	220	5181	41.6
Ontario	775	525	250	213	4276	755.0
Prince Edward Island	1936	1950	2513	201	5930	1.5
Quebec	747	525	377	250	3219	619.8
Saskatchewan	539	354	303	208	2885	278.9

§ Critical loads for mineral soil polygons only; statistics for other provinces include organic soil polygons. §§ Preliminary estimates of critical load. §§§ URL: edc2.usgs.gov/glcc/na_int.php

Table 2. Comparison of critical load and exceedance estimates using three critical chemical limits (NEG-ECP protocol, UNECE SSMB Bc/Al = 10 and UNECE SSMB Bc/Al = 1). Two exceedance scenarios are presented: ECMAP and M4 total sulphur and nitrogen deposition.

Methodology	Critical load ($mol_c\ ha^{-1}\ yr^{-1}$)			Exceedance (% of mapped area §)	
	Mean	% area < 250	% area < 500	ECMAP	M4
NEG-ECP §§	871.9	8.75	33.36	8.45	2.06
SSMB (Bc:Al = 10)	778.3	16.64	34.90	11.35	3.37
SSMB (Bc:Al = 1)	1461.5	0.00	18.74	0.00	0.17

§ Mapped area is 409,857 km^2. §§ Based on a function equivalent to a Bc:Al ratio of 10.

Table 3. Comparison of critical load and exceedance estimates for mineral soils only using three critical chemical limits (NEG-ECP protocol, UNECE SSMB Bc/Al = 10 and UNECE SSMB Bc/Al = 1). Two exceedance scenarios: ECMAP and M4 total sulphur and nitrogen deposition.

Methodology	Critical load ($mol_c\ ha^{-1}\ yr^{-1}$)			Exceedance (% of mapped area §)	
	Mean	% area < 250	% area < 500	ECMAP	M4
NEG-ECP §§	1066.9	0.00	11.78	1.52	1.42
SSMB (Bc:Al = 10)	950.8	2.14	13.83	2.44	2.19
SSMB (Bc:Al = 1)	1782.9	0.00	2.79	0.00	0.23

§ Mapped area is 308,157 km^2. §§ Based on a function equivalent to a Bc:Al ratio of 10.

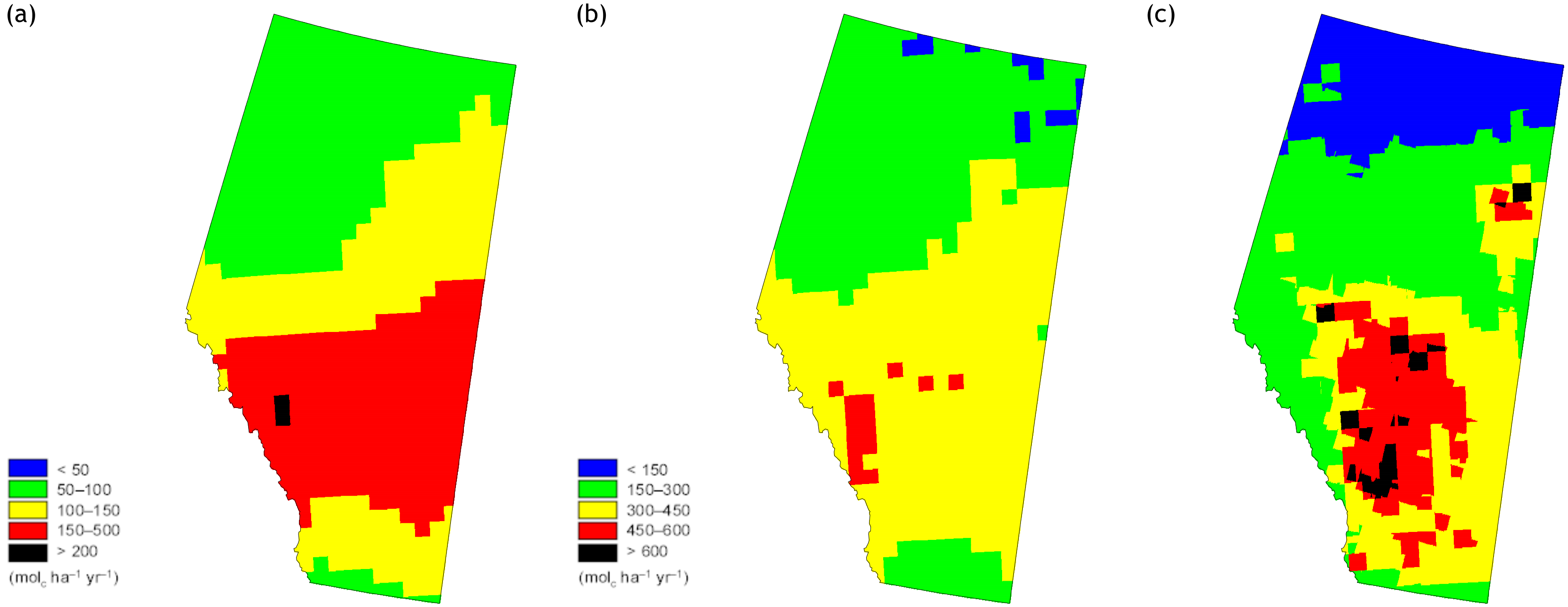

Figure 1. Atmospheric deposition to Alberta (a) ECMAP: Total (wet plus dry) base cation (calcium, magnesium, potassium and sodium) deposition interpolated from 1994-1998 observations (b) ECMAP: Total (wet plus dry) sulphur and nitrogen deposition interpolated from 1994-1998 observations. See Appendix II for monitoring used to generate the ECMAP deposition fields (c) M4: Total (wet plus dry) sulphur and nitrogen deposition derived from the average of four modelled and mapped deposition fields (AURAMS, CMAQ, ECMAP and RELAD; see Aherne (2008) for further details).

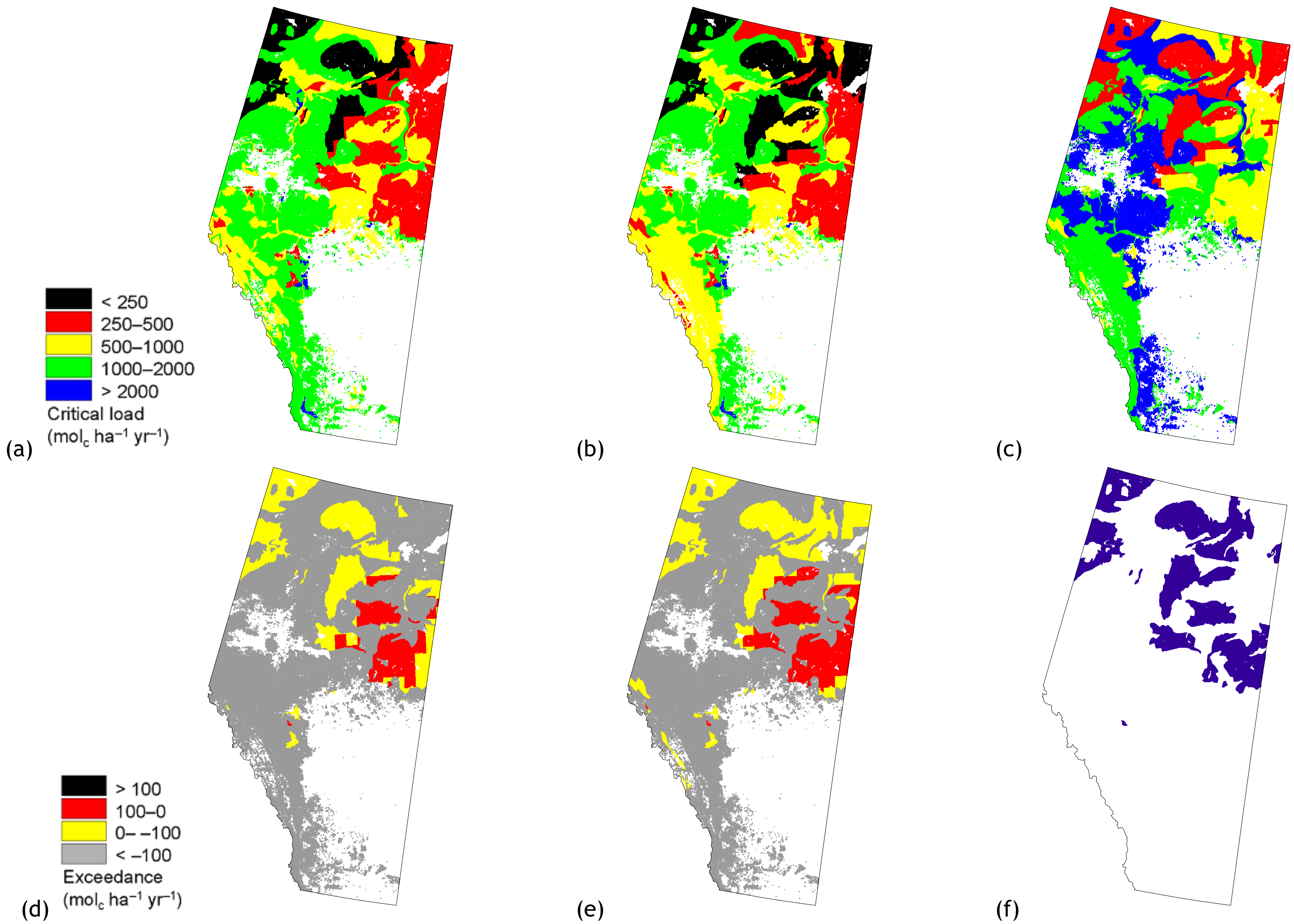

Figure 2. Critical load and exceedance of sulphur and nitrogen deposition for forest soils in Alberta. (a) Critical load based on the NEG-ECP protocol (b) Critical load based on the UNECE (SSMB Bc:Al = 10) protocol (c) Critical load based on the UNECE (SSMB Bc:Al = 1) protocol (d) Exceedance (red area) of NEG-ECP critical load (e) Exceedance (red area) of UNECE (SSMB Bc:Al = 10) critical load (f) Soil polygons comprised of 100 % organic soils.

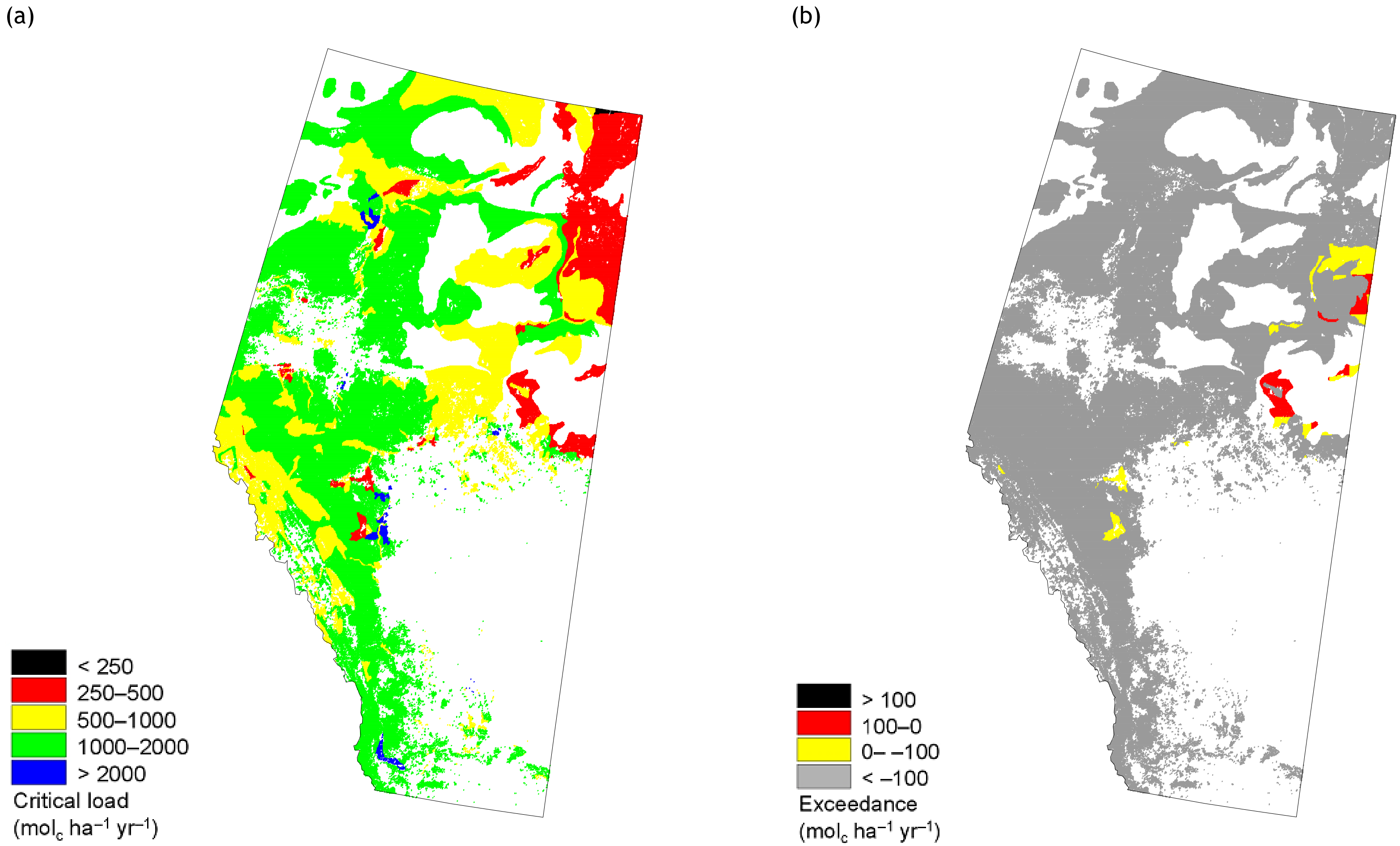

Figure 3. Critical load and exceedance of sulphur and nitrogen deposition for mineral forest soils in Alberta. (a) Critical load based on the NEG-ECP protocol (b) Exceedance (red area) of NEG-ECP critical load. Soil polygons comprised of 100 % organic soils have been removed (see Figure 2).

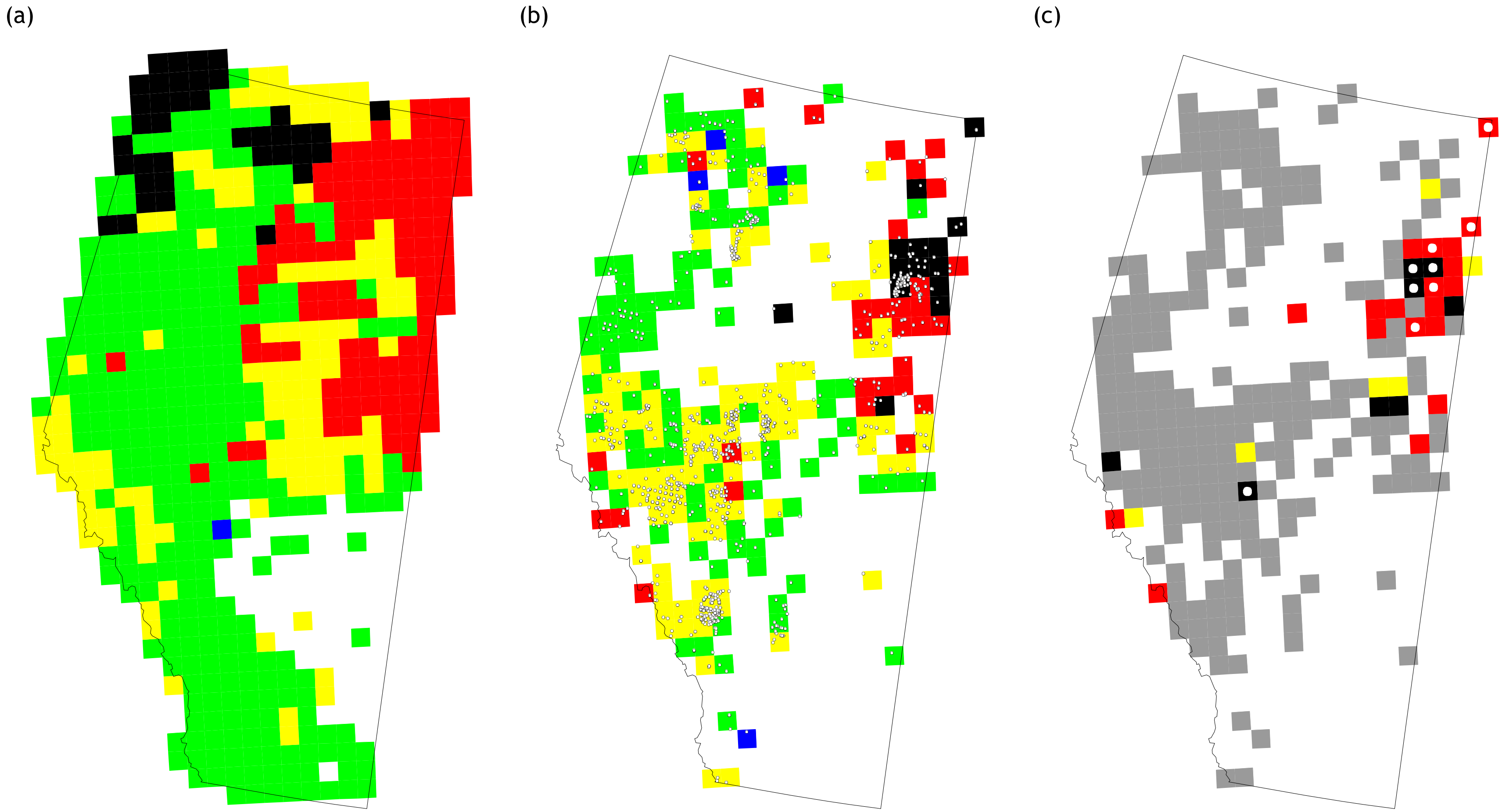

Figure 4. Critical load and exceedance for forest soils based on a soil point approach (a) Mean critical load of sulphur and nitrogen for forest soils in Alberta based on the NEG-ECP protocol (map-based approach, see Figure 2a) aggregated to the Global Environmental Multiscale (GEM) mapping grid used for the ECMAP deposition field (b) The 5th percentile critical loads estimated from point observations (approximately 1200 soil pits) aggregated to the GEM grid; soil observation points are also shown as open circles (c) Exceedance of the 5th percentile critical load under the ECMAP total sulphur and nitrogen deposition (1994–1998). Red (exceedance 0-100 $mol_c\ ha^{-1}\ yr^{-1}$) and black (> 100 $mol_c\ ha^{-1}\ yr^{-1}$) grid squares are exceeded; grid squares containing a white circle have five of more point observations (nine grid squares).

6. Conclusions

The mean critical load for Alberta was estimated at 872 $mol_c\ ha^{-1}\ yr^{-1}$; however, a significant proportion of the sensitive regions are associated with organic soils. Mean annual total S and N deposition was 303 $mol_c\ ha^{-1}\ yr^{-1}$ for Alberta during the period 1994–1998. Approximately 8.5 % of the mapped soils received acid deposition in excess of critical load, although much of these regions were again classified as entirely organic soils. Removing the organic soil units, approximately 1.5 % of the mapped mineral soils received acid deposition in excess of critical load. However, an alternative 'soil-point' approach based solely on mineral soil observations indicated levels of exceedance similar to the mapped soils approach that included organic soils.

Uncertainties. The determination and mapping of critical loads for Alberta builds upon works in Canada, specifically Manitoba and Saskatchewan. In general terms, the resultant maps for Alberta are consistent to those for other regions in Canada. However, the final maps should be viewed somewhat as a starting point in the critical load process and not the end-point. While every attempt has been made to include the best available data, all modelling endeavours suffer from uncertainties and limitations in data and methods. The current study suffers from many uncertainties, specifically related to: the resolution of the soils data, the choice of an appropriate critical limit, the treatment of nitrogen and the spatial resolution of deposition data. The critical load and exceedance estimates will ultimately change as data and methods are revised.

7. Future research

A number of future research needs are recommended to address data limitations or knowledge-gaps, and to provide more reliable or improved estimates of critical load and exceedance (see Aherne and Watmough 2006 for a more complete listing of recommendations).

It is recommended that the 'soil point' approach be further investigated (developed). The approach would allow for more comparable critical load estimates between provinces. The approach is consistent with critical load estimates for surface waters and would allow for a greater integration of both data sets. In addition, the approach will provide a structure for future dynamic modelling assessments.

It is recommended that nitrogen parameter values be reassessed. The proposed assessment should attempt to define (or recommend) parameter values for multiple receptor ecosystems. Similarly, it is also recommended that the fixed values used for the determination of the critical alkalinity leaching be reviewed and evaluated for multiple receptor ecosystems. The link between the chemical criterion and the biological indicator, i.e., the critical limit, requires further investigation and verification.

It is recommended that a technical working group be formed to discuss, co-ordinate and develop a framework for Canada-wide critical loads (aquatic and terrestrial). There is a need for a focused working group mandated to revise and extend the existing methodology and guidelines, and to integrate critical loads for terrestrial and aquatic ecosystems. It should be noted that a Canada-wide framework would not restrict greater detail at the provincial level but rather would ensure a more comparable and consistent base level approach between Canadian provinces. Ideally, the task group would also be a focal centre for co-operation with the United States and Europe on related critical load activities.

Finally it is highly recommended that the methodology behind the NEG-ECP protocol be reviewed and revised to be consistent with the ICP M&M protocol (UNECE).

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Appendix I. The Steady-State Mass Balance model

Long-term critical load of sulphur (S) and nitrogen (N) to forest soils may be estimated using the Steady-State Mass Balance (SSMB) model. The SSMB model assumes a simplified, steady state input-output description of the most important biogeochemical processes that affect soil acidification. Potential ecosystem inputs include atmospheric deposition of sulphate (SO_4^{2-}), N (nitrate and ammonium), chloride (Cl-), sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+), and soil base cation weathering rate. Ecosystem outputs and consumption include net removal of nutrients by forest harvesting, nutrient loss through soil leaching, denitrification and N immobilisation. The SSMB model, described in detailed by the ICP M&M (UBA 2004), estimates critical load of sulphur, CL(S), and nitrogen, CL(N):

(A.1) $$CL(S) + CL(N) = BC_{dep} - Cl_{dep} + BC_w - Bc_u + N_i + N_u + N_{de} - Alk_{le,crit}$$

where BC_{dep} = base cation (BC = Ca^{2+} + Mg^{2+} + K^+ + Na^+) deposition, Cl_{dep} = Cl^- deposition, BC_w = base cation weathering, Bc_u = net base cation (Bc = Ca^{2+} + Mg^{2+} + K^+) uptake by trees (harvesting removal), N_i = net N immobilisation rate in soil, N_u = net N uptake by trees, N_{de} = net denitrification rate, and $Alk_{le,crit}$ = critical alkalinity leaching rate. Units of $mol_c\ ha^{-1}\ yr^{-1}$. This formulation has been rewritten by the NEG-ECP to estimate the long-term critical loads of sulphur plus nitrogen CL(S+N):

(A.2) $$CL(S+N) = BC_{dep} - Cl_{dep} + BC_w - Bc_u + N_i + N_u + N_{de} - Alk_{le,crit}$$

Under the NEG-ECP protocol, harvesting removals were not considered; therefore, long-term net uptake of N and Bc were set to zero. The long-term net denitrification was considered negligible in well-drained upland forest ecosystems. Similarly, the net N immobilisation in soils was also assumed to be negligible in the long-term since this process can be negative or close to zero with stand dynamics and natural disturbances such as fire (NEG-ECP 2001). The final model under the NEG-ECP protocol can therefore be simplified to:

(A.3) $$CL(S+N) = BC_{dep} - Cl_{dep} + BC_w - Alk_{le,crit}$$

The critical alkalinity leaching rate for forest soils is estimated from a critical molar base cation to (inorganic) aluminium (Bc:Al) ratio in soil leachate and the gibbsite dissolution constant (K_{gibb}) which controls aluminium solubility in mineral soils (UBA 2004):

(A.4) $$Alk_{le,crit} = -Q^{2/3} \cdot \left(1.5 \cdot \frac{Bc_{dep} + Bc_w - Bc_u}{K_{gibb} \cdot (Bc:Al)_{crit}}\right)^{1/3} - 1.5 \cdot \frac{Bc_{dep} + Bc_w - Bc_u}{(Bc:Al)_{crit}}$$

where Q is soil runoff rate or precipitation surplus ($m^3\ ha^{-1}\ yr^{-1}$), The NEG-ECP protocol used a Bc:Al ratio of 10, a log K_{gibb} of 9.0 and Bc_u = 0 (as above); K_{gibb} is expressed as $m^6\ mol_c^{-2}$. In practice, the NEG-ECP protocol uses a function based on the total acid input to derive a critical chemical limit equivalent to a Bc:Al ratio of 10.

Exceedance (EXC) of steady-state critical load of S and N to upland forest soils, is calculated as the current total deposition flux of S plus N (nitrate plus ammonium) minus critical load:

(A.5) $$EXC = S_{dep} + N_{dep} - CL(S + N)$$

where S_{dep} = total (wet plus dry) S deposition and N_{dep} = total N deposition. Unit of $mol_c\ ha^{-1}\ yr^{-1}$; negative exceedance values represent regions that are 'not exceeded', i.e., soils will not acidify to a level where forest soil damage is expected.

Appendix II. Monitoring sites used to generate the ECMAP deposition fields

Sites used for Alberta-Saskatchewan-Manitoba deposition estimates

Data used: 1994–1998 except for CAPM (Cree Lake): 1991–1993 (Air concentration values of calcium and magnesium estimated using data from ELA), Alta-Cont: 1998–2002, TEEM: 1999–2003 and Sask-Pass: 2005.

		Dry										Wet							
		CA	CL	HNO3	K	MG	NA	NH4	NO3	SO2	nss SO4	CA	CL	K	MG	NA	NH4	NO3	nss SO4
Station	Network																		
B W Canoe Area	IMPR	*	*		*	*	*	*	*		*								
Badlands Nat Pk	IMPR	*	*		*	*	*	*	*		*								
Beaverlodge	ABPM											*	*	*	*	*	*	*	*
Big Springs Fish	NADP											*	*	*	*	*	*	*	*
Bridger Wildern	IMPR	*	*		*	*	*	*	*		*								
Brochet B	MAPN											*	*	*	*	*	*	*	*
Camp Ripley	NADP											*	*	*	*	*	*	*	*
Cedar Creek	NADP											*	*	*	*	*	*	*	*
Chassell	NADP											*	*	*	*	*	*	*	*
Clancy	NADP											*	*	*	*	*	*	*	*
Cold Lake	ABPM											*	*	*	*	*	*	*	*
Cottonwood	NADP											*	*	*	*	*	*	*	*
Cree Lake	CAPM	*	*	*	*	*	*	*	*		*	*	*	*	*	*	*	*	*
Drayton Valley	ABPM											*	*	*	*	*	*	*	*
ELA	CAPM	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Esther	CAPM	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Fernberg	NADP											*	*	*	*	*	*	*	*
Fond Du Lac	NADP											*	*	*	*	*	*	*	*
Fort Chipewyan	ABPM											*	*	*	*	*	*	*	*
	Alta-Cont									*									
Fort Mcmurray B	ABPM											*	*	*	*	*	*	*	*
Fort Vermillion	ABPM											*	*	*	*	*	*	*	*
Geraldton	APIC											*	*	*	*	*	*	*	*
Give Out Morgan	NADP											*	*	*	*	*	*	*	*
Glacier N.P.	CAST			*						*									
	IMPR	*	*		*	*	*	*	*		*								
	NADP											*	*	*	*	*	*	*	*
Grindstone Lake	NADP											*	*	*	*	*	*	*	*
Gypsum Creek	NADP											*	*	*	*	*	*	*	*
Havre Experiment	NADP											*	*	*	*	*	*	*	*
High Prairie	ABPM											*	*	*	*	*	*	*	*
Hovland	NADP											*	*	*	*	*	*	*	*
Huron Well Field	NADP											*	*	*	*	*	*	*	*
Icelandic	NADP											*	*	*	*	*	*	*	*
Island Lake	CAPM											*	*	*	*	*	*	*	*
Isle Royale B	NADP											*	*	*	*	*	*	*	*
Kananaskis	ABPM											*	*	*	*	*	*	*	*
Lake Dubay	NADP											*	*	*	*	*	*	*	*
Lamberton	NADP											*	*	*	*	*	*	*	*
Little Big Horn	NADP											*	*	*	*	*	*	*	*
Marcell	NADP											*	*	*	*	*	*	*	*
Mccreary	CAPM											*	*	*	*	*	*	*	*
Near 54.3N 109.1W (3 site)	Sask-Pass									*									
Near 55.3N 108.1W (4 site)	Sask-Pass									*									
Near 56.4N 106.4W (2 site)	Sask-Pass									*									
Near 56.5N 109.4W (1 site)	Sask-Pass									*									
Near 57.1N 111.5W (10 site)	TEEM									*									
Newcastle	NADP											*	*	*	*	*	*	*	*
Perkinstown	CAST			*					*	*	*	*	*	*	*	*	*	*	*
Pinedale	CAST			*					*	*	*								
	NADP											*	*	*	*	*	*	*	*
Point Du Bois	MAPN											*	*	*	*	*	*	*	*
Popple River	NADP											*	*	*	*	*	*	*	*
Red Deer	ABPM											*	*	*	*	*	*	*	*
Roosevelt N.P. B	NADP											*	*	*	*	*	*	*	*
Royal Park	ABPM											*	*	*	*	*	*	*	*
Sinks Canyon	NADP											*	*	*	*	*	*	*	*
Snare Rapids	CAPM											*	*	*	*	*	*	*	*
Snare Rapids-Dup	CAPM											*	*	*	*	*	*	*	*
Snare Rapids-Dup2	CAPM											*	*	*	*	*	*	*	*
South Pass City	NADP											*	*	*	*	*	*	*	*
Spooner	NADP											*	*	*	*	*	*	*	*
Suffield	ABPM											*	*	*	*	*	*	*	*
Suring-Nadp	NADP											*	*	*	*	*	*	*	*
Theodore Roosevelt N	CAST			*					*	*	*								
Trout Lake	NADP											*	*	*	*	*	*	*	*
Voyageurs N.P.	CAST			*					*	*	*								
Wildcat Mountain	NADP											*	*	*	*	*	*	*	*
Wolf Ridge	NADP											*	*	*	*	*	*	*	*
Woodworth	NADP											*	*	*	*	*	*	*	*
Yellowstone	NADP											*	*	*	*	*	*	*	*
Yellowstone N.P.	CAST			*															
	IMPR	*	*		*	*	*	*	*	*	*								