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Acid deposition in the Athabasca Oil Sands Region: a policy perspective

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Abstract Industrial emissions of sulphur (S) and nitrogen (N) to the atmosphere associated with the oil sands industry in north-eastern Alberta are of interest as they represent the largest localized source in Canada (with potential for future growth) and the region features acid-sensitive upland terrain. Existing emission management policy for the Regional Municipality of Wood Buffalo, where the industry is located, is based on a time-to-effect approach that relies on dynamic model simulations of temporal changes in chemistry and features highly protective chemical criteria. In practice, the policy is difficult to implement and it is unlikely that a scientifically defensible estimate of acidification risk can be put forward due to the limitations primarily associated with issues of scale, chemical endpoint designation (selection of chemical limit for ecosystem protection from acidification) and data availability. A more implementable approach would use a steady-state critical load (CL) assessment approach to identify at-risk areas. The CL assessment would consider areas of elevated acid deposition associated with oil sands emissions rather than targeted political jurisdictions. Dynamic models should only be (strategically) used where acidification risk is identified via CL analysis, in order to characterize the potential for acidification-induced changes that can be detrimental to sensitive biota within the lifespan of the industry.

Keywords Acid · Atmospheric deposition · Base cations · Critical loads · Dynamic modelling · Policy · Soils

Introduction

Naturally occurring bitumen deposits underlie the boreal forest of northern Alberta, Canada, representing an important national fossil fuel reserve and one of the largest recoverable oil deposits in the world. Nearly 50 years ago, an industry formed to extract this unconventional source of oil, but production rates were low for much of the industry's history. The highly viscous bitumen is found in association with sand and clays in these deposits, thus the term 'oil sand' by which this fossil fuel is colloquially known, and must be separated from these materials as part of the recovery process. Recent advances in technology have led to rapid increases in production rates, and in the next 10 years, daily production level is forecast to more than double to 3.7 million barrels (Stringham 2012). Open pit mines are expected to be used to extract oil beneath 3 % of the approximately 140,000 km^2 of boreal forest overlying this reserve, while in situ (e.g. steam-assisted gravity

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drainage) techniques are being used elsewhere (Stringham 2012).

Large-scale landscape clearing for resource extraction is anticipated to reduce carbon (C) sequestration capacity through the loss of 2950 km^2 of peatlands, compounding potential effects of C emissions associated with mining and upgrading of the fossil fuel (Rooney et al. 2012). Atmospheric deposition of other pollutants generated from core industrial activities in the Athabasca Oil Sands Region (AOSR), including polycyclic aromatic compounds (Kelly et al. 2009) and metals (Kelly et al. 2010), occurs across a wide area. The history of industrial air pollution is well documented in lake sediments of the region (Curtis et al. 2010; Kurek et al. 2013). Nationally, emissions of the acid precursors associated with fossil fuel combustion (sulphur dioxide (SO_2) and nitrogen oxides (NO_x)) are highest in the province of Alberta (Environment Canada 2004). Remote sensing of SO_2 and nitrogen dioxide (NO_2) in the atmosphere indicates that these compounds are found at elevated concentrations across approximately 1500 km^2 of the AOSR, with NO_2 concentrations increasing during the 2005–2010 period coincident with increases in bitumen production (McLinden et al. 2012).

Elevated acid deposition in the AOSR is a concern, as this remote environment features extensive upland areas that are acid-sensitive owing to Precambrian bedrock geology with low buffering capacity (Shewchuk 1982). Buffering capacity of soil is determined primarily by the rate of release of base cations (BC: calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na)) via mineral weathering processes. Acid deposition leached from the soil rooting zone in the form of acid anions is accompanied by base cations (or other cations). Consequences can include lower soil pH, depletion of the base cation pool (reduction in base saturation) and a decrease in the ratio of nutrient base cations (Bc=Ca+Mg+K) to aluminium (Al) in soil solution (Bc:Al) (Reuss and Johnson 1985). Depression of Bc:Al below a critical threshold can impair root function and ultimately impact vegetation health (Cronan and Grigal 1995). Upland forest soils of the region feature extremely low weathering release of base cations, and have been identified as potentially at risk of acidifying due to elevated sulphur (S) deposition (Whitfield et al. 2010b). The majority of the land area in the AOSR, however, is comprised of peatlands and lakes which are relatively insensitive to acidic deposition (Whitfield et al. 2010a). Therefore, methods to assess sensitivity of uplands are important; the manner in which areal extent of acid-sensitive terrain is used can have important consequences for acid precursor emission management decisions. Where a targeted level of protection is based on total landscape area, large upland areas could acidify without the protection level being reached. In contrast, a protection level designated as a proportion of upland area would be more effective in preventing acidification of these sensitive ecosystem components.

As upland forests are the most acid-sensitive receptors in the region, this paper will focus on this terrain type. The oil sands industry forms an important part of Canada's economy, and consequently a unique policy has been established to evaluate the need for emission controls of S and nitrogen (N) in the region. The objectives of this contribution are (1) to describe the critical load concept that is widely used in acidification assessments, (2) to provide an overview of the current acid deposition management policy for north-eastern Alberta, (3) to highlight the main challenges associated with the policy, and (4) to discuss an alternate strategy for acid deposition management in the region.

The critical load concept

The critical load (CL) is defined as the highest load of acid deposition below which damage to sensitive biological components of the ecosystem will not occur over the long-term (Nilsson and Grennfelt 1988). The CL concept is the most widely used approach for assessing regional, national and international impacts of acid deposition (Environment Canada 2004; Forsius et al. 2010) and has been particularly successful in Europe (Hettelingh et al. 2007). Critical load assessments have also been used in areas where point sources are the main contributors to acid deposition, albeit less frequently (e.g. Moiseenko 1994; ESSA et al. 2014). Designation of acid precursor emission limits is typically informed by estimates of the CL for a region of interest, for example, with the end goal of achieving deposition levels that are lower than the CL for a pre-determined proportion of the landscape (e.g. 95 % protection). The Canada-Wide Acid Rain Strategy for Post-2000 (CCME 1998) operates on such a principle, with a long-term goal of maintaining acid deposition at or below the CL.

A CL reflects a long-term steady-state condition and is calculated such that ecosystem sinks and sources of acidity are balanced in order to maintain a critical chemical condition necessary for the protection of acid-sensitive biota. Alternately, a target load may be used to guide emission management. Where sustained acid deposition in excess of the CL has led to an adverse chemical condition, a target load can be established at a level lower than the CL to promote recovery to a desired chemical condition (e.g. above the critical chemical limit) within a prescribed timeframe. Likewise, where acid deposition has not yet exceeded the CL (exceedance results when acid deposition is greater than the CL), it is permissible to establish a target load that is temporarily higher than the CL, provided deposition is reduced to a level below the CL prior to chemical conditions reaching an unfavourable state (e.g. below the critical chemical limit). Dynamic hydrogeochemical models are used to assess these situations, as they provide the capacity to simulate chemical response to atmospheric deposition over long (multi-decade) time periods.

Acid deposition management in the Athabasca Oil Sands Region

In the province of Alberta, acid deposition is assessed using one degree (latitude by longitude) management units, with a goal of protecting 95 % of each management unit area. Where the provincial assessment indicates that acid deposition is greater than 90 % of the CL for a management unit, a regional emission management plan is required. An acid deposition management framework (ADMF) for the Regional Municipality of Wood Buffalo (RMWB; Fig. 1), which encompasses the AOSR (the AOSR has not been explicitly defined in a geographic sense, but rather is used to loosely describe the areas of industrial activity and their environs), was developed by regional stakeholders including industry, regulators, environmental non-governmental organizations and indigenous groups. Beyond the provincial requirement for acid deposition management, several other factors motivated development of the ADMF. It was recognized that the coarse spatial scale of the provincial assessments does not afford a robust assessment of acid sensitivity. Likewise, it was deemed necessary to consider future response of acid-sensitive ecosystems in the region due to rising S and N emissions. Additionally, because acid deposition in the region originates primarily from local sources associated with the oil sands industry that will have a defined lifespan owing to a finite resource, it was considered important to evaluate temporal (dynamic) chemical response of the surrounding ecosystems.

The central objective underlying the ADMF is to maintain chemical conditions such that adverse impacts on biota do not occur. Monitoring and dynamic hydrogeochemical modelling approaches are used in concert to assess soil chemical response to changes in atmospheric deposition. The monitoring program seeks to identify any realized long-term changes in soil chemistry at select monitoring sites (soil solution is not monitored, despite model simulations suggesting that solution chemistry will exhibit greater response to changes in atmospheric deposition than soil chemistry (Whitfield et al. 2009)). The dynamic Model of Acidification of Groundwater in Catchments (MAGIC; Cosby et al. 1985) is specified for use to both characterize a historical (pre-industrial) condition and simulate temporal (historical and future) change in soil and soil solution chemistry. A plot-scale MAGIC application procedure (Whitfield et al. 2009) is used to evaluate soil chemical response directly, as the traditional catchment-based approach is not well suited in this environment owing to contrasting sensitivities between uplands and surface waters draining the catchments (Whitfield et al. 2010a).

The ADMF is premised on a modelled time-to-effect approach. Under the time-to-effect approach, the management goal is for change in soil chemistry during a combined hindcast and 30-year forecast simulation period to be less than half of the difference between a modelled pre-industrial condition and a fixed endpoint. Fixed endpoint chemical criteria are analogous to critical chemical limits traditionally used to protect acid-sensitive biota. The calculated midpoint chemical condition is referred to herein as the management threshold. Both base saturation (BS) and Bc:Al are considered as chemical criteria, with fixed endpoints of 10 % and 2, respectively, used to identify the two management thresholds and assess relative change. Modelled soil chemical response to atmospheric deposition is evaluated at two spatial scales (e.g. Fig. 1), four by four floating blocks of townships (individual townships are approximately 100 km^2 and are the basis of the provincial surveying system) or the provincial one degree management unit. Floating blocks (each township is included in multiple blocks) are used to avoid the risk of overlooking acid-sensitive areas that might be distributed across several blocks (e.g. near the corners of several

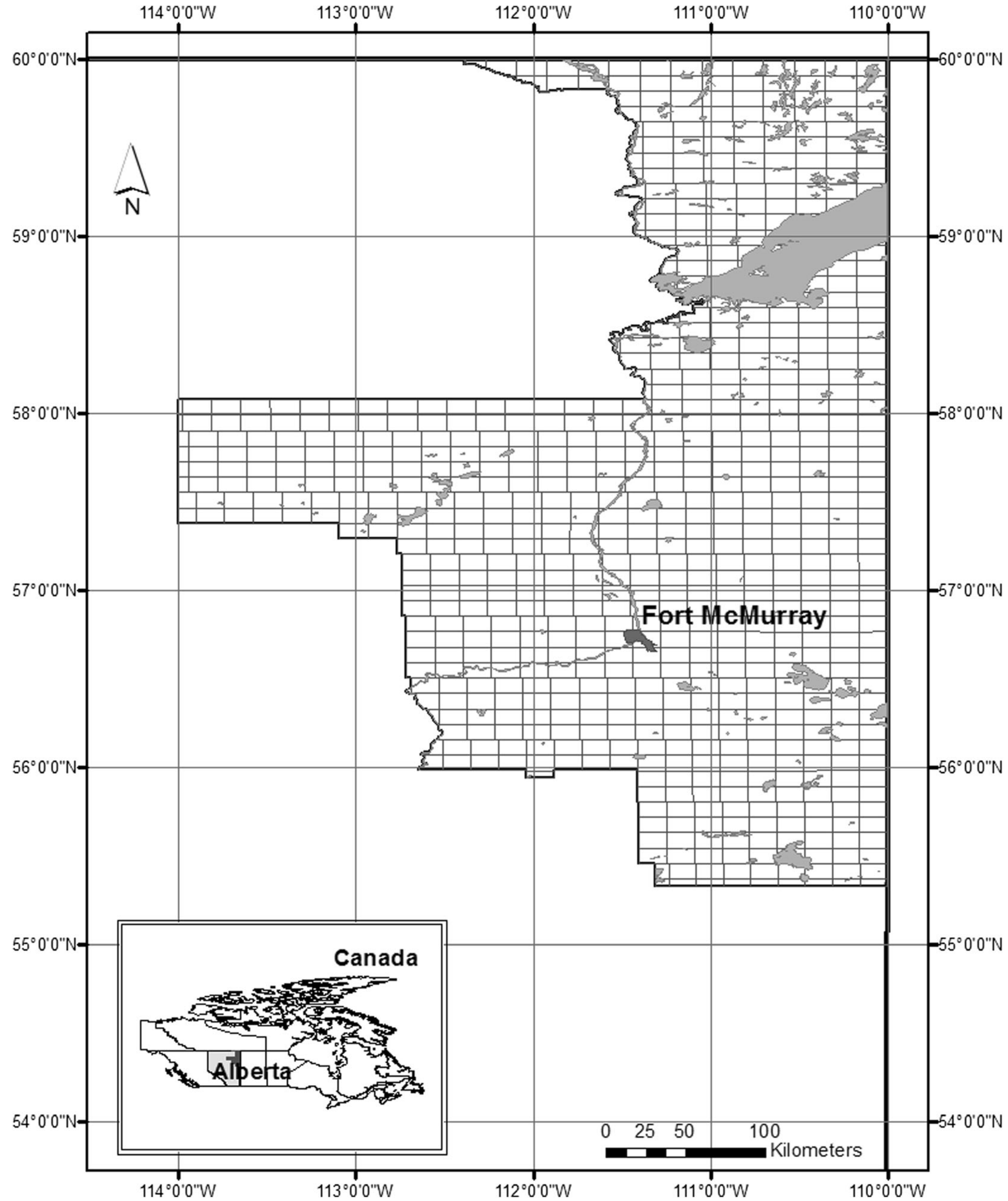

Fig. 1 The Regional Municipality of Wood Buffalo (RMWB) in northeastern Alberta, Canada, where the Athabasca Oil Sands industry is located near the community of Fort McMurray (*dark grey polygon*). *Gridlines* within the RMWB delineate townships surveyed according to provincial system. Surface waters (*light grey polygons*) are also shown

fixed blocks). Where soil area of greater than 100 km^2 within a township block (~6 % by area) or greater than 5 % by area of a provincial management unit exhibit a response beyond the management thresholds identified above, an emission management action would be triggered (Table 1, Fig. 2).

The ADMF outlines three emission management options, with each linked to a different response timeframe (Table 1). Where the management thresholds are not predicted to be reached within 30 years, and soil monitoring observations do not detect chemical change (e.g. no response), the industry will continue to use the

Table 1 Overview of chemical criteria (base saturation (BS); molar nutrient base cation to aluminium ratio (Bc:Al)), calculated management thresholds and management actions associated with timeframe of chemical response to the management threshold

Chemical criterion	Management threshold	Timeframe (years)	Action
BS	> half of change from historical condition to 10 %	>30	None
BS	> half of change from historical condition to 10 %	15–30	Cap emissions
BS	> half of change from historical condition to 10 %	<15	Reduce emissions
Bc:Al	> half of change from historical condition to 2	>30	None
Bc:Al	> half of change from historical condition to 2	15–30	Cap emissions
Bc:Al	> half of change from historical condition to 2	<15	Reduce emissions

emission control technologies that are currently in operation. In the event that model predictions indicate either management threshold (BS or Bc:Al) will be reached for an area greater than permitted at either spatial scale within 30 years, emissions from the industry will be capped. Similarly, if BS or Bc:Al is simulated to be depressed below the respective threshold within a shorter 15-year forecast window, actions will be taken to reduce emissions of acid precursors contributing to the soil chemical response. The latter two scenarios would likely require an investment in enhanced S and/or N emission control infrastructure.

Challenges to implementing the ADMF

There are numerous challenges to successful implementation of the ADMF owing to its structure as well as uncertainties around key environmental data. The most important practical limitations to implementing the ADMF are described herein, including issues of scale, chemical endpoint designation and data availability.

Assessment scale

National- to continental-scale assessments of acid sensitivity have been most successfully applied in Europe, using large (2500 km^2) grid cells and the CL approach, with a grid cell designated as exceeded when ≥5 % of the grid cell receives acid deposition in excess of the CL. Regional assessments of this nature are most readily conducted when numerous acid precursor emitters are distributed across the area leading to large areas of elevated acid deposition. When assessing potential acidification associated with a single source (e.g. the AOSR where acid emitters are concentrated in a small area), the issue of scale is paramount.

The smallest assessment scale designated in the ADMF is approximately 1600 km^2 (block of 16 townships); however, near the centre of the AOSR, atmospheric deposition levels change rapidly with distance from major emitters (Watmough et al. 2014). Accordingly, the scale at which acidification is assessed will dramatically influence whether an assessment unit is defined as at risk of acidification. An assessment approach that captures the deposition pattern will provide the most appropriate results, and using assessment blocks in this region where deposition declines logarithmically from the source is challenging, as large deposition gradients occur across relatively small scales (Fig. 3).

In practice, implementation of the ADMF is also time consuming since it requires that two spatial scales (smaller township blocks, larger latitude/longitude units) are simultaneously considered. The appropriate scale for MAGIC application in assessing soil response is a modelling unit that represents a single soil type and receives a uniform level of atmospheric deposition across its area. Thus, for the AOSR, where deposition gradients occur across short distances, the model should be applied at a finer resolution than either of the assessment scales outlined in the framework. Where deposition is homogenous across larger areas, the model can be applied at a coarser scale. In any case, upscaling of results from (finer-scale) individual modelling units where MAGIC is applied to the two larger spatial scales is necessary as part of the ADMF. This requires extensive analysis, however, as the boundaries for the two scales are inconsistent (Fig. 1). Consideration of multiple scales in this manner is rather cumbersome and ultimately could yield scale-dependent conclusions about the potential for acidification in the region. Instead, the model should be applied at an appropriate scale (above) and the results interpreted in accordance with a single defined level of protection.

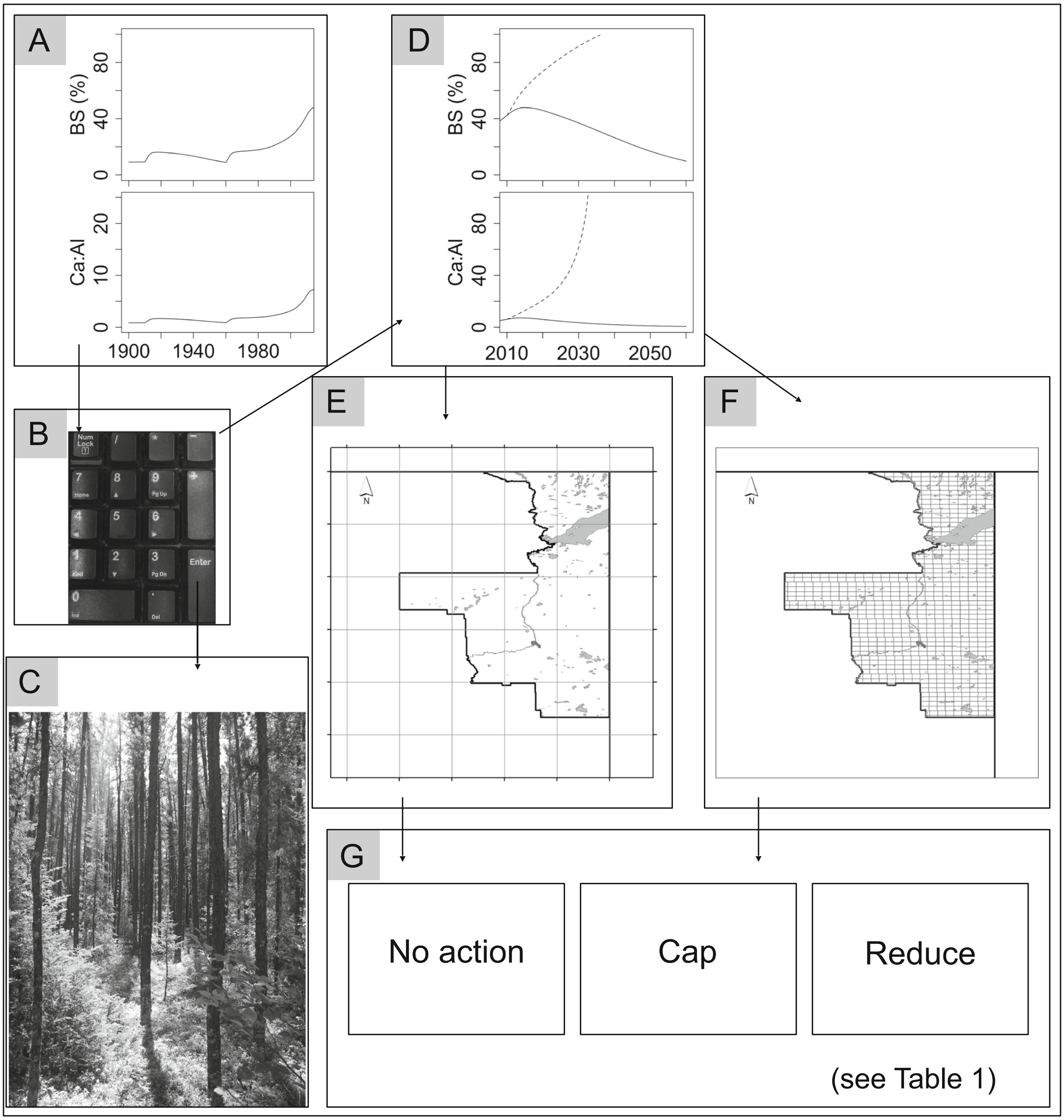

Fig. 2 Conceptual overview of the Acid Deposition Management Framework for the Regional Municipality of Wood Buffalo. **a** The Model of Acidification of Groundwater in Catchments (MAGIC) used to simulate historical chemical condition. **b** Management thresholds for base saturation and base cation-to-aluminium ratio calculated (see main text for explanation). **c** Base saturation monitored for change beyond the management thresholds at forest plots. **d** Forecast simulations of base saturation and base cation-to-aluminium ratio generated with MAGIC. **e**, **f** Potential for soil acidification assessed at two scales (latitude/longitude management units and township blocks). **g** Emission control action decision (according to Table 1)

Chemical endpoints

Most assessments of terrestrial acidification use a fixed chemical endpoint (e.g. critical chemical limit) specified to prevent damage to roots, for example, Ca:Al in soil solution is widely used (Cronan and Grigal 1995). Chemical conditions have rarely been linked to adverse biological responses of Canadian forest ecosystems.

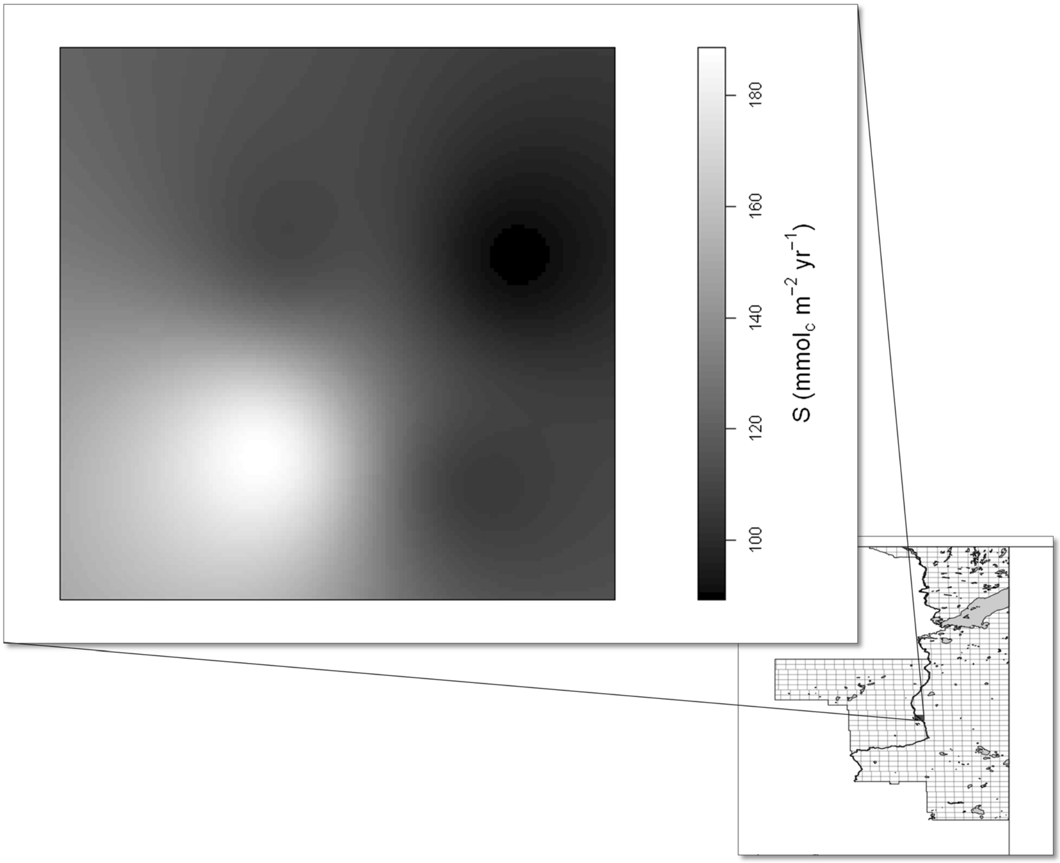

Fig. 3 Sulphur (S) deposition gradient (year 2010) within a township (nominally 10 km by 10 km) that features major regional S sources. Modelled deposition for four grid cell centroids lying within the township was inversely distance weighted to approximate the deposition between centroids of the deposition field. The location of the township near the centre of the AOSR is shown on the *inset map*

One exception is the identification of a Bc:Al ratio of 10, which is described as a limit necessary to maintain base saturation for forests on the boreal shield of eastern Canada (Ouimet et al. 2006). The ADMF uses a more complicated and conservative approach that is not linked to tree health. Instead the ADMF identifies the tolerance for change in soil (BS) and soil solution (Bc:Al) chemistry as half of the difference between a modelled pre-industrial condition and a fixed endpoint (the management threshold). While the fixed endpoint chemical criteria specified in the ADMF are generally consistent with those that have been used in other regions, it remains unknown if damage to vegetation should be expected at these levels in boreal Alberta. Furthermore, the management thresholds are calculated using a historical chemical condition, which can only be estimated (e.g. via dynamic modelling), and both the historical chemical conditions and calculated management thresholds are therefore subject to considerable uncertainty.

Data availability

In contrast to the CL approach, which can be applied more readily at landscape scales, the integration of a dynamic modelling approach in the ADMF is challenging owing to the much higher data requirement (Table 2). The RMWB is remote, with limited road access; most monitoring sites require aerial access. Soil data are primarily available from a collection of past surveys and are relatively sparse and span only some parts of the RMWB, and not all parameters of interest in the context of acidification response are available at each location. Acid-sensitive soils in the region are often almost pure sand, with limited release of base cations through weathering and low cation exchange

Table 2 Overview of (non-deposition) parameter data requirements for the Model of Acidification of Groundwater in Catchments (MAGIC) and the Simple Mass Balance (SMB) model used in terrestrial critical load assessments

Parameter	MAGIC	SMB
Sulphate adsorption half saturation	X	
Sulphate adsorption maximum	X	
Gibbsite dissolution coefficient	X	X
Porosity	X	
CO_2 partial pressure	X	
Temperature	X	
Runoff	X	X
Depth	X	X
Bulk density	X	
Cation exchange capacity	X	
Base saturation[a]	X	
Base cation weathering rate[a]	X	X
Base cation uptake[a]	X	X
Critical base cation to aluminium ratio		X
Dissolved organic carbon	X	
Nitrogen immobilization	X	X
Nitrogen uptake	X	X
Denitrification	X	X

Required parameters indicated with X

[a] Data specific to each base cation are required in MAGIC

capacity. For example, median rooting zone cation exchange capacity and base saturation for sandy brunisols in the region are 19 $\mathrm{mmol}_c \mathrm{kg}^{-1}$ and 54 %, respectively (n=140). Exchangeable base cation concentrations are very low, subject to analytical uncertainty, and therefore small changes in base cation pools translate to very large changes in base saturation. Base saturation is not a parameter that can be measured with confidence for these soils and therefore is not a good choice for monitoring purposes. Likewise, BS is used in plot-scale MAGIC calibration, and the variation in this parameter will lead to uncertain model predictions.

Whereas MAGIC is traditionally applied to sites with site-specific information, it can be applied regionally using uncertainty principles in an attempt to provide information despite the limitations of available data. Uncertainty-based regional MAGIC application has been undertaken in the RMWB, using mapped soil polygons as the modelling unit and characterizing each polygon according to available observations for soils of the same type across the region. This allows soil chemical response to the spatial atmospheric deposition pattern to be evaluated where observations are not directly available. Thousands of parameter sets were created for each mapped soil polygon as a means of representing collective uncertainty associated with each parameter. These parameter sets were processed through MAGIC, with the model results evaluated against (regional) observations of base saturation and pH for the corresponding soil type. Each simulation was classified as behavioural (simulations falling within the range of observations) or non-behavioural (simulations not in agreement with observations). The ensemble of behavioural simulations for each polygon was used to characterize individual polygon response.

This regional uncertainty-based MAGIC application approach was evaluated by comparison against an interactive calibration of MAGIC that featured site-specific deposition and soil solution chemistry observations in model parameterization (see Watmough et al. 2014 for details of site-specific application). Consistent with the nature of the sandy soils which demonstrate highly variable BS (and pH) among soil plots of the same soil type, model predictions based on regional data are highly uncertain (Fig. 4). One notable difference between model applications was the general pattern of simulated Ca:Al, which tended to be relatively unresponsive or decrease for the regional approach. This result contrasted the prominent increase in Ca:Al predicted for the site-specific application. Availability of higher quality data including BC deposition measurements that were an order of magnitude higher than the regional estimates afforded this improvement in prediction. Nonetheless, applications of MAGIC in the region suggest that soil solution (e.g. Bc:Al) is more responsive to changes in atmospheric deposition than is BS (Whitfield et al. 2009). Soil solution data, however, are not available regionally to screen model simulations, contributing to the model prediction uncertainty. Absence of soil solution chemistry from monitoring activities might also impede the ability of these programs to detect future responses.

Historical (pre-industrial) atmospheric deposition is characterized using a speculative approach, as data records offer little information for this period. Accordingly, dynamic hindcast simulations are invariably associated with some general uncertainty around the historical chemical condition. In the context of the ADMF, which relies on estimated historical chemical conditions to calculate the management thresholds, this

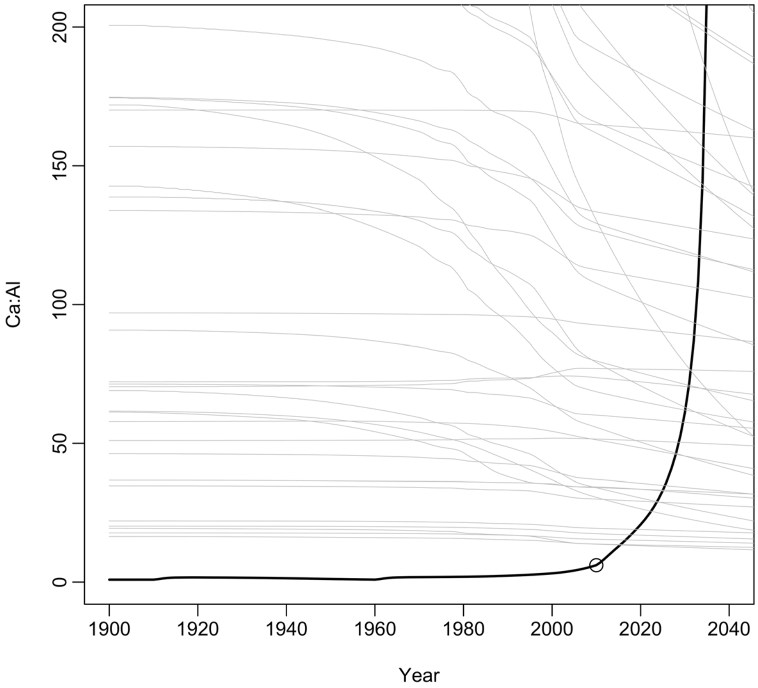

Fig. 4 Comparison of model simulations of calcium to aluminium ratio (Ca:Al) from an interactive application of MAGIC parameterized using site-specific data (*black line*) including calibration to soil solution chemistry, and uncertainty-based simulations for the same site with MAGIC parameterized using regional data for soils of the same type and calibrated to observations of soil pH and base saturation only (*grey lines*). The *open circle* indicates average soil solution Ca:Al from observations over a 3-year period

uncertain historical condition directly translates to uncertain management thresholds. While there is little that can be done to reduce this uncertainty, it can be viewed as an argument against the use of dynamic models to determine management thresholds.

Predicting response of upland forest ecosystems in the RMWB to changes in atmospheric deposition is also hampered by poor understanding of current deposition levels. In the context of acidification, uncertain N deposition is of low concern, as current evidence suggests that N deposition is largely retained in these upland systems (Laxton et al. 2012), with relatively frequent losses of N from above-ground pools via forest fires. Thus, N leaching is unlikely to contribute to soil acidification. The inputs of S and BC (Ca+Mg+K+Na) through atmospheric deposition, however, will be critical for determining acidification response. The most recent modelled S deposition estimates (from CALPUFF and CMAQ) vary by up to twofold, which constitutes a notable source of uncertainty. Likely more problematic is the uncertainty around BC deposition, as the nature of this source in the region is not well characterized and is linked largely to diffuse sources (Landis et al. 2012), with pervasive landscape disturbance a likely driver. Recent investigations at a site located adjacent to major mine sites in the region indicated that BC deposition was roughly equal to acid (S and N) deposition (Watmough et al. 2014). The magnitude of total measured (using ion exchange resins) Ca, Mg and Na deposition at this site was approximately ten times higher than regional deposition estimates (from RELAD), highlighting the need for updated regional BC deposition estimates. Modelled soil chemical response to changes in atmospheric deposition at this site, constituting the most robust assessment performed to date in the region (soil solution chemistry and deposition fluxes were both measured and used to parameterize MAGIC), suggests that BS and soil solution calcium to aluminium ratio will increase in the future (Watmough et al. 2014), owing to N retention and base cation deposition inputs in excess of S deposition. This contrasts earlier model simulations that suggested modest decreases in Bc:Al.

Sulphur and N emissions have long been known to reflect production levels of the oil sands industry, but estimates of deposition of these pollutants continue to range considerably. Further, in the absence of improved estimates of current base cation deposition for the region, dynamic simulations of soil chemical response can be expected to yield uncertain results. Understanding of the nature of base cation sources in the region is also necessary to quantify how this deposition flux will change in the future. It is clear that the capacity for reliable dynamic or steady-state assessments of the potential for soil acidification in the AOSR is currently limited in large part by poorly characterized atmospheric deposition. Efforts to reduce these uncertainties in future assessments should be a priority.

Alternate strategies for acid deposition management in north-eastern Alberta

At present, because of the reasons identified above, it is unlikely that a scientifically defensible assessment of the acidification impacts resulting from emissions of SO_2 and NO_x from the oil sands industry can be made. In recognition of the challenges associated with acid deposition management in the region, an alternate two-level acidification assessment approach is outlined below. The recommended approach, while general in nature, seeks to reduce the complexity of the assessment procedure and avoid some of the main limitations of the current ADMF.

The two-level assessment would use a combination of steady-state and dynamic approaches. The first level would feature a steady-state CL assessment to identify areas at risk of acidification. While there are uncertainties associated with the steady-state CL, in particular estimates of base cation weathering used in the calculation, previous assessments in the region employing a variety of methods indicate that weathering rates are consistently low (Watmough et al. 2014; Whitfield et al. 2011). Weathering rates were among the lowest rates reported for acid-sensitive soils in Canada and typically much less than inputs from deposition. Going forward, improved estimates of atmospheric deposition will be key to minimizing uncertainty associated with CL assessments, including CL exceedances. Additional assessment using dynamic models would be conducted (second level) for areas identified as at risk (CL exceedance), to quantify the potential for damage to sensitive biota.

Several decisions are paramount at the outset. It is necessary to (i) clearly identify the study area over which the assessment will be conducted, (ii) articulate the level of protection and whether this applies to upland mineral soil only or the entire landscape (including lakes and wetlands) and (iii) specify whether the level of protection should be maintained over the entire study area or also for smaller areas. Given recent evidence which suggests S and N deposition decline rapidly with distance from the centre of the oil sands industry (Watmough et al. 2014), the study area should ideally be selected to represent an area of elevated acid deposition, rather than the entire RMWB. Limiting the spatial focus in this way would greatly simplify the assessment procedure. One option would be to define for consideration an ‘effects domain’ as the zone with current (or future) modelled acid deposition originating from the oil sands industry above a specified level that could reasonably be expected to result in chemical change. This level would necessarily be higher than background levels of base cation deposition (~11 $\mathrm{mmol_c\,m^{-2}\,yr^{-1}}$), as acidification will not be realized where acid deposition is less than neutralizing inputs from base cations (in the absence of forest harvesting). In order to restrict focus to areas with a realized risk of CL exceedance, this geographic domain should be defined at the outset; however, the domain would not be static and would be expected to change as new industrial developments alter the spatial pattern and magnitude of acid deposition.

After defining the scope of the assessment, terrestrial steady-state CLs would be calculated at a plot level using site-specific data, or for soil polygons using uncertainty-based methods (Wolniewicz and Aherne 2010) to identify acid sensitivity. Under a polygon-based approach, critical loads would be identified at a scale consistent with the modelled atmospheric deposition grid cells (currently 4 km by 4 km). Improved understanding of deposition is also required to conduct a CL assessment; this is particularly true for BC deposition which can strongly affect the CL calculation. Because current BC deposition is quite high compared to the level considered as a background, and may undergo additional change in the future, a useful modification to the CL calculations would be to include only background BC deposition in the Simple Mass Balance (Sverdrup and de Vries 1994) CL calculation:

$$\mathrm{CL_{S+N}} = \mathrm{BC}_w + \mathrm{BC}_{dep(bkg)} - \mathrm{Bc}_u - \mathrm{Cl}_{dep} + \mathrm{N}_i + \mathrm{N}_u + \mathrm{N}_{de} - ANC_{le(crit)} \quad (1)$$

where the subscripts w, u, dep, $dep(bkg)$, i and de refer to weathering, uptake, atmospheric deposition, background (pre-industrial, long-term) atmospheric deposition, immobilization and denitrification, respectively. The terms BC, Bc, Cl and N are base cations, nutrient base cations (excluding Na), chloride and nitrogen, respectively, and $ANC_{le(crit)}$ refers to the critical leaching (from the rooting zone) of acid neutralizing capacity required to protect against damage to fine roots due to low molar ratio of base cation to aluminium concentrations in soil solution (UBA 2004). By including only background deposition in the CL calculation, any base cation deposition in excess of the background amount ($BC_{dep(ex)}$) would necessarily be included when calculating exceedance:

$$Exc_{S+N} = S_{dep} + N_{dep} - BC_{dep(ex)} - CL_{S+N} \qquad (2)$$

where Exc_{S+N} is the CL exceedance and S_{dep} and N_{dep} are atmospheric deposition of S and N, respectively. The effect of these modifications would be to avoid setting the CL too high (low) for future scenarios where base cation deposition decreases (increases) from current levels, while maintaining an accurate calculation of Exc_{S+N}. Consequently, Exc_{S+N} may be re-calculated in the future without having to revise the CL (to account for changes in $BC_{dep(ex)}$). Accordingly, the principle of the CL, to describe the long-term (steady-state) condition, would be maintained in this region that is subject to dramatic fluctuations of acid and base cation deposition. Chloride deposition is not known to be similarly impacted by local sources; thus, a similar modification is not introduced here, although the same principle could be applied.

For locations where CL are exceeded or predicted to be exceeded in the future, the second level of assessment would be triggered. Monitoring would be conducted in these areas, with emphasis on soil solution chemistry, rather than base saturation. Dynamic acidification models would be applied to investigate potential temporal chemical changes using site-specific parameter information (e.g. atmospheric deposition) and calibrated using observations of soil and soil solution chemistry. This targeted approach, in comparison to the current plan for indiscriminate application of MAGIC across the entire region, coupled with greater emphasis on data collection in high-risk locations would help to reduce prediction uncertainty as it has been shown that where high-quality observations are available for model calibration, parameter convergence can nonetheless result for highly uncertain model parameters (MacDougall et al. 2009). Enhanced monitoring of at-risk locations, including observations of soil solution chemistry, would be particularly valuable, both because soil solution chemistry can be used in model calibration to improve confidence in model predictions and because soil solution is expected to show earlier evidence of change for these sandy soils than the soil exchange complex. In the event that dynamic model simulations indicate a reasonable risk of reaching an adverse soil chemical condition in violation of the designated protection level within the projected lifespan of the industry, target loads would be used to establish emission management actions (caps or reductions).

Conclusions

The potential impact that acid precursors emitted from Canada's oil sands industry in north-eastern Alberta have on acid-sensitive ecosystems in the region has been of interest for some time. Only recently has a more comprehensive picture of atmospheric deposition for the region begun to emerge. With base cation deposition higher than originally thought, previous assessments of soil acidification for the region are unlikely to accurately depict the potential for acidification. Now is an opportune time to revisit emission management policies for the region. Existing policies are difficult to implement and it is unlikely that a scientifically defensible estimate of acidification risk can be put forward due to several inherent limitations. Going forward, a simpler strategy is recommended. A revised policy would use steady-state CL assessments as the principal method for identifying at-risk areas. With this strategy, the area of focus would be limited to areas with elevated (current or future) acid deposition rather than be defined by political jurisdiction. This would greatly reduce the need for data. Long-term monitoring would be pursued in at-risk upland forests where CL exceedance is identified, emphasizing measurement of soil solution chemistry and atmospheric deposition. Dynamic modelling techniques would be pursued in these locations to investigate the timing of future acidification events. This integration of monitoring efforts with dynamic model applications is necessary to reduce temporal prediction uncertainty. The proposed two-level assessment procedure would eliminate reliance on modelled historical conditions and is anticipated to be of greater utility in identifying the need for controls on the industrial emission of S and N to the atmosphere in the region.

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