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Steady-state critical loads of acidity for forest soils in the Georgia Basin, British Columbia

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ABSTRACT

There has been growing interest in acid rain research in western Canada where sulphur (S) and nitrogen (N) emissions are expected to increase during the next two decades. One region of concern is southern British Columbia, specifically the Georgia Basin, where emissions are expected to increase owing to the expansion of industry and urban centres (Vancouver and Victoria). In the current study, weathering rates and critical loads of acidity (S and N) for forest soils were estimated at nineteen sites located within the Georgia Basin. A base cation to aluminium ratio of 10 was selected as the critical chemical criterion associated with ecosystem damage. The majority of the sites (58%) had low base cation weathering rates (≤50 meq m^{-2} y^{-1}) based on the PROFILE model. Accordingly, mean critical load for the study sites, estimated using the steady-state mass balance model, ranged between 129–168 meq m^{-2} y^{-1}. Annual average total (wet and dry) S and N deposition during the period 2005–2006 (estimated by the Community Multiscale Air Quality model), exceeded critical load at five–nine of the study sites (mean exceedance = 32–46 meq m^{-2} y^{-1}). The high-elevation (>1000 m) study sites had shallow, acid sensitive, soils with low weathering rates; however, critical loads were predominantly exceeded at sites close to Vancouver under higher modelled deposition loads. The extent of exceedance is similar to other industrial regions in western and eastern Canada.

Key words: steady-state mass balance (SSMB) model, sulphur, nitrogen, exceedance, weathering rates, PROFILE, Canada

1. INTRODUCTION

Acid deposition has been a major environmental issue in eastern North America and Europe for decades, owing to the high levels of acid deposition and negative impacts on surface waters and forest soils. Recently there has been growing interest in western Canada where sulphur (S) and nitrogen (N) emissions are expected to increase. One region of concern is south-western British Columbia, specifically the Georgia Basin, where emissions are expected to increase owing to the expansion of industry and urban centres (Vancouver and Victoria) and the transportation sector (road vehicles and marine vessels; Fraser *et al*. 2006).

The critical load approach is used by policy makers in Europe to formulate emission reduction policies (Johansson *et al*. 2001). Critical loads are defined as a 'quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur, according to our present knowledge' (Nilsson & Grennfelt 1988). Critical loads link deposition to a chemical variable (the 'chemical criterion') in the soil, or soil solution, associated with ecosystem effects. The violation of a specific value (the 'critical limit') for the chemical criterion is associated with ecosystem damage (Hall *et al*. 2001a). The steady-state mass balance (SSMB) model is widely used for estimating critical loads of acidity for forest soils (Grennfelt *et al*. 2001; Ouimet *et al*. 2006; Whitfield *et al*. 2010, this issue). The most widely used soil chemical criterion is based on the ratio of base cations (Bc) and aluminium (Bc:Al) in soil solution. In eastern Canada, a critical limit of Bc:Al = 10 has been used to maintain soil base saturation (Ouimet *et al*. 2006).

The chemical weathering of soil minerals provides forest ecosystems with long-term buffering capacity against acidification (Warfvinge & Sverdrup 1992); as such (base cation) weathering is a key determinant of critical loads. Soils with low weathering rates are inherently sensitive to acid deposition. A number of different methods have been developed to calculate weathering rates (Melkreud *et al*. 2003; Whitfield *et al*. 2006); however, the most robust methods are based on soil mineralogy. PROFILE is a process-oriented soil chemical model that uses independent soil properties (including mineralogy) to calculate weathering rates (Warfvinge & Sverdrup 1992).

The Georgia Basin has long been recognised as highly sensitive to acid deposition because the region is dominated by base-poor geologies with poor weathering capacity (Wiens 1987). A recent survey of high-elevation lakes (n = 72) in the Georgia Basin suggested that approximately 20% received S deposition in excess of their critical load (Strang *et al*. 2010, this issue). The objective of this study was to assess the potential impacts of current S and N deposition on forest soils in the Georgia Basin. Base cation weathering rates and critical loads of acidity were estimated for nineteen study sites located across the Georgia Basin. Weather-

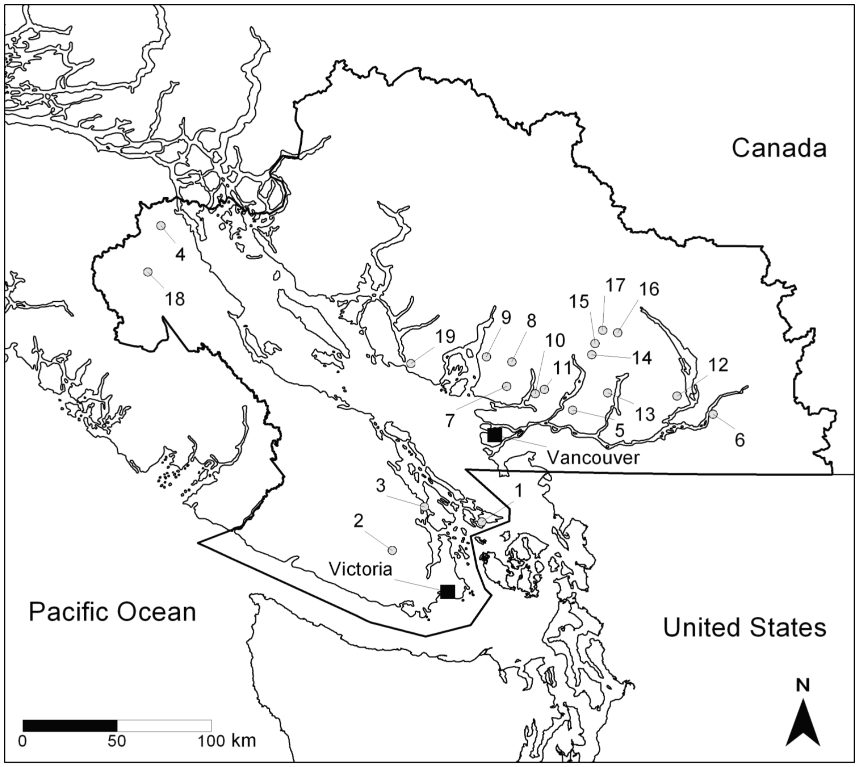

Fig. 1. Location of study sites (circles; n = 19) within the Georgia Basin (thick black line). Cities are also shown (black squares). The site ID (numeric descriptors) are described in table 1.

ing rates were estimated using the PROFILE model, and critical loads were estimated using the SSMB model following the approach used in eastern Canada (Ouimet *et al*. 2006).

2. METHODS

2.1. Study area

The Georgia Basin, which covers an area of approximately 48,000 km^2 in south-western, British Columbia (Fig. 1), is part of a larger basin under the jurisdiction of Canada (Georgia Basin) and the United States of America (Puget Sound). The Basin is ringed by the Olympic mountains, Vancouver island ranges, Coast ranges and the Cascades which trap air masses and lead to the build up of air borne pollutants. The air quality in the Lower Fraser valley in the Georgia Basin regularly exceeds national guidelines (Fraser et al. 2006). The basin encompasses seven biogeoclimatic ecosystem classification (BEC) zones: coastal Douglas fir (CDF), coastal western hemlock (CWH), mountain hemlock (MH), interior Douglas fir, montane spruce, Engelmann spruce-subalpine fir and the alpine tundra zones (Meidinger & Pojar 1991).

Base cation weathering rates and critical loads of acidity (S and N) were estimated for forest soils at nineteen sites across the Georgia Basin (Fig. 1 & Tab. 1). Eleven of the study sites were forest plots within the former Acid Rain National Early Warning System (ARNEWS) program, six of the sites were high-elevation lake catchments surveyed by Environment Canada for water quality (Strang *et al*. 2010, this issue), and the remaining two sites were long-term intensive research catchments (Malcolm Knapp Research Forest (Feller 2010, this issue) and Roberts Creek). Exceedance, defined as the amount of S and N deposition in excess of the critical load, was determined for each study site. Annual average total (wet and dry) S and N deposition for the period 2005–2006 was obtained from the Community Multiscale Air Quality (CMAQ: di Cenzo & Lepage 2003) model at a 4 km by 4 km grid resolution.

2.2. Soil data

Soils were sampled during July 2006, with at least one soil pit dug down to the C horizon or to the bedrock at each study site; more than one soil pit (two–five) was dug at the high-elevation sites, Malcolm Knapp Research Forest and Roberts Creek, to provide a better representation of soils in these catchments. The forest floor (litter, fribic and humic (LFH) layers) was sampled using a 0.25 m^2 quadrate. Mineral soil (~100 g) was sampled by horizon for chemical analysis. The depth of each soil horizon, including the LFH, was measured and percent stone content visually estimated for each pit. In the laboratory, mineral soils were air dried and sieved through a 2 mm mesh. The LFH samples were dried, ground using a Wiley mill, and weighed.

Exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) were measured by atomic absorption spectrometry

Tab. 1. Site ID, name, location (longitude, latitude), altitude, soil pit depth, pH, loss-on-ignition (LOI), cation excange capacity (CEC), base saturation (BS), gibbsite equilibrium constant (site-specific K_{gibb}), percent clay content, biogeoclimatic ecosystem classification (BEC) zone and data source or network (SRC) for the nineteen study sites in the Georgia Basin, British Columbia. ARN (Acid Rain National Early Warning System), EC (Environment Canada), CFS (Canadian Forest Service) and FBC (Ministry of Forestry, British Columbia).

ID	Site name	Longitude	Latitude	Alt.	Depth	pH	LOI	CEC	BS	K_{gibb}	Clay	BEC	SRC
		decimal degrees		m	m	H_2O	%	meq kg^{-1}	%	log	%	zone	
1	Saturna Island	–123.14	48.77	150	0.81	5.68	5.3	55.6	40.4	12.0	4.4	CDF	ARN
2	Shawnigan Lake	–123.72	48.63	366	0.63	5.22	7.1	72.2	26.4	10.8	9.2	CWH	ARN
3	Salt Spring	–123.52	48.83	122	0.46	5.39	10.6	92.4	37.0	10.3	7.9	CDF	ARN
4	Campbell River	–125.35	50.04	191	0.18	4.80	6.7	72.6	23.5	9.1	3.4	CWH	ARN
5	Malcolm Knapp	–122.56	49.28	366	0.47	4.79	14.2	83.0	10.4	8.9	4.7	CWH	ARN
6	Chilliwack	–121.63	49.27	489	0.27	4.18	24.1	135.8	14.4	6.1	2.4	CWH	ARN
7	Seymour E	–123.00	49.38	135	0.53	4.38	20.0	79.0	11.4	7.5	3.6	CWH	ARN
8	Seymour M-L	–122.97	49.49	342	0.67	4.72	17.8	82.4	5.7	8.6	2.7	CWH	ARN
9	Capilano	–123.14	49.51	100	0.51	4.36	21.3	88.5	5.1	7.6	2.3	CWH	ARN
10	Coquitlam W	–122.81	49.35	223	0.39	4.81	12.2	94.1	18.6	8.0	2.4	CWH	ARN
11	Coquitlam 110	–122.75	49.37	382	0.48	4.54	20.7	123.3	14.4	7.7	3.6	CWH	ARN
12	Weaver lake	–121.87	49.35	509	0.23	4.61	13.4	120.1	20.2	7.9	8.9	CWH	EC
13	Florence Lake	–122.33	49.36	416	0.49	4.83	17.6	117.4	8.3	8.9	4.0	CWH	EC
14	Tingle Lake	–122.44	49.53	1006	0.18	4.38	27.2	158.0	12.1	6.1	0.9	MH	EC
15	Thomas Lake	–122.42	49.58	1014	0.11	4.36	18.8	187.7	9.3	6.2	1.9	MH	EC
16	Tretheway Lake	–122.27	49.63	1370	0.29	4.72	23.4	131.8	3.9	8.5	2.7	MH	EC
17	Kinnear Lake	–122.37	49.64	1210	0.26	4.63	18.1	126.9	7.5	7.9	3.1	MH	EC
18	MASS	–125.42	49.83	701	0.34	4.58	40.6	97.2	29.8	7.6	10.1	CWH	CFS
19	Roberts Creek	–123.64	49.47	461	0.35	5.14	5.4	38.7	10.1	9.8	3.8	CWH	FBC
	Average			503	0.40	4.74	17.1	103.0	16.2	8.4	4.0		

(Varian AA 240FS) after extraction with a 1.0 M NH_4Cl solution. Total cation exchange capacity (CEC) was measured by colourimetery (Pulse Autoanalyzer System) following subsequent extraction with a 2.0 M NaCl solution. Base saturation (BS) was estimated as the percentage of cation exchange sites occupied by base cations. The pH was measured in distilled water with a glass electrode Oakton pH/MVC meter. Soil samples for the B horizons, or composites of A and B horizons (where A horizon was significant), representing the rooting zone were analysed for quantitative soil mineralogy by X-ray diffraction using a Siemens (Bruker) D5000 Bragg-Brentano diffractometer. Particle size analysis (sand, silt and clay) was measured using a Horiba Partica LA-950 and used to calculate soil surface area following Warfvinge & Sverdrup (1992). Loss-on-ignition (LOI) was determined by igniting samples in a muffle furnace at 450 °C for 8 hours. Soil bulk density (BD) was estimated from LOI according to Siltanen *et al*. (1997: BD = 0.075 + 1.301 × exp(–0.06 × LOI)). Average soil physico-chemical data for each study site were weighted by depth and bulk density according to Helliwell *et al*. (1998).

2.3. Base cation weathering rate

The soil base cation weathering rate for the rooting zone was estimated using the PROFILE model (Warfvinge & Sverdrup 1992), a steady-state soil chemistry model primarily driven by soil mineralogy, mineral surface area and moisture content (Warfvinge & Sverdrup 1992; Melkreud *et al*. 2003). The weathering rate is proportional to the exposed surface area of the mineral and the activity of the exposed mineral is dependent on soil moisture. Reactions only take place on wetted surfaces, with the degree of surface wetting proportional to the soil moisture saturation. PROFILE has been widely used in Europe and North America to estimate weathering rates (Barkman & Alveteg 2001; van der Salm 2001; Solberg *et al*. 2002; Melkreud *et al*. 2003; Ouimet & Duchesne 2005; Whitfield *et al*. 2006). The inputs for PROFILE were averaged for the A and B horizons and did not include the LFH layer (which is generally devoid of minerals). Moisture content was set using regional default values that ranged between 0.30 and 0.35 $m^3\ m^{-3}$.

A number of methods are available for estimating weathering rates (see Whitfield *et al*. 2006; Whitfield *et al*. 2010, this issue). While mineralogy-based approaches, such as PROFILE, are preferred, empirical-based approaches, such as soil texture approximation (STA; UBA 2004), have the appeal of being based on widely available data and being 'regionally applicable'. In the current study, the relationship between soil parameters (e.g., LOI, clay, pH, etc., Tab. 1) and PROFILE-based weathering rates was evaluated using simple multiple regression. All variables (dependent and independent) were log transformed prior to regression analysis to ensure normality and equal variance.

2.4. Steady-state mass balance model

The critical load of acidity (S and N) for each of the study sites was estimated using the SSMB model, which is a single layer model where the soil is treated as one homogeneous compartment. The model is based on balancing the inputs of acidity against sinks and outputs (UBA 2004):

$$CL\ (S+N) = BC_{dep} - Cl_{dep} + BC_w - Bc_u + N_i + N_u + N_{de} - ANC_{le(crit)} \qquad (1$$

where *BC* refers to base cations (BC = Bc + Na^+, $Bc = Ca^{2+} + Mg^{2+} + K^+$) and the subscripts *dep*, *w*, *u*, *i*, *de* and *le* refer to deposition, weathering, uptake, immobilisation, denitrification and leaching, respectively. Base cation and chloride (Cl^-) deposition were estimated using a polynomial regression model (Aherne *et al*. 2008, this issue). Base cation deposition was corrected for sea salt using theoretical sea salt ratios and assuming that all Cl^- in precipitation originated from sea salt (e.g., (eq) ratio for Ca^{2+}:Cl^- is 0.037:1; UBA 2004). It was assumed there was no forest harvesting (uptake removal), as such, N_u and Bc_u were set to zero. Default regional values for N_i and N_{de} were taken from literature: N_i = 4.8 meq m^{-2} y^{-1} and N_{de} = 2.5 meq m^{-2} y^{-1} (Feller & Kimmins 1984). $ANC_{le(crit)}$ is the critical (or acceptable) leaching of *ANC* (Acid Neutralizing Capacity) defined as:

$$ANC_{le(crit)} = -Q^{\frac{2}{3}} \cdot \left(1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit} \cdot K_{gibb}}\right)\right)^{\frac{1}{3}} - \qquad (2$$
$$-1.5 \cdot \left(\frac{Bc_w + Bc_{dep} - Bc_u}{(Bc:Al)_{crit}}\right)$$

where *Q* is the annual water flux (mm) through the soil at the bottom of the rooting zone (soil percolation), $(Bc{:}Al)_{crit}$ is the chemical criterion associated with ecosystem damage and K_{gibb} is the gibbsite equilibrium constant that describes the relationship between Al^{3+} and H^+ in soil solution. In the current study, soil percolation was determined from long-term (1961–1990) average monthly temperature, precipitation, and cloudiness derived from a 0.5° × 0.5° resolution global database (New *et al*. 1999). See Gibson *et al*. (2010, this issue) for further details. The $(Bc{:}Al)_{crit}$ was based on a default value of 10, which has been used in eastern and western Canada to protect soil base saturation (Ouimet *et al*. 2006). Critical loads of acidity were determined using a regional default K_{gibb} (log K_{gibb} = 9.0; Ouimet *et al*. 2006) and site-specific values estimated assuming that the exchange of base cations between soil and soil solution was in steady-state. The exchange equilibrium was described using the Gaines-Thomas equation assuming the selectivity coefficients for Ca^{2+} and Mg^{2+} were zero (UBA 2004).

3. RESULTS AND DISCUSSION

3.1. Soil properties

There were broad similarities between the study sites as the majority were confined to two BEC zones: coastal western hemlock and mountain hemlock (Tab. 1). Similarly, soils at the majority of sites were podzolic with deep organic horizons, up to 30 cm at some sites (data not shown). Nonetheless, mineral soil depth to the C horizon (or bedrock) ranged from 0.11 m (Thomas Lake) to 0.81 m (Saturna Island) with a mean depth of 0.40 m (Tab. 1). The organic matter content (LOI) of the mineral soils ranged from 5–40% (mean 17%), with eleven sites >15%. The high organic matter content had a significant influence on soil properties, and was highly correlated to soil pH (r = 0.78 log LOI) and CEC (r = 0.65 log LOI). The soils were acidic (fifteen sites with pH <5), with the lowest weighted-average pH = 4.18 (Chilliwack). Similarly, the majority of the study sites had low base saturation; mean BS was 16%, ranging from 4% (Tretheway Lake) to 40% (Saturna Island). Thirteen sites had BS <20%, which is characteristic of acid sensitive soils (Tab. 1). In general, soil depth decreased with elevation (r = –0.59) and weighted-average LOI and CEC increased (r = 0.67).

The estimated site-specific log K_{gibb} ranged from 6.1 to 10.3 with a mean of 8.4, which is less than the regional default (log K_{gibb} = 9.0) used across eastern Canada (Ouimet *et al*. 2006). Site-specific K_{gibb} was highly related to pH and CEC (Figs 2a & 2b) reflecting the relationship to LOI (pH and CEC were highly correlated to LOI). Previous studies have related K_{gibb} to soil organic matter, suggesting log K_{gibb} = 7.6 for sites with 15–30% LOI (UBA 2004), which compared well with the current study. In general the soil properties of majority of the study sites (excluding Saturna Island and Campbell River) suggest that the soils in the Georgia Basin are inherently sensitive to soil acidification.

3.2. Weathering rates

Estimated (PROFILE) base cation weathering rates ranged from 19 to 351 meq m^{-2} y^{-1} (mean = 71 meq m^{-2} y^{-1}; Tab. 2) and were highly correlated to the mass of soil (soil depth × bulk density; r = 0.88) excluding one outlier, Campbell River (351 meq m^{-2} y^{-1}), which had the highest proportion of calcite (2.5%) an easily weatherable carbonate mineral. The high-elevation sites, Tingle Lake and Thomas Lake, had the lowest weathering rates (<30 meq m^{-2} y^{-1}) owing to their shallow soils (<0.30 m) and the relatively low or undetectable quantities of easily weatherable minerals. Further, the majority of the sites (58%) had base cation weathering rates ≤50 meq m^{-2} y^{-1}. Their mineralogy was dominated by quartz (mean = 41%) and plagioclase (mean = 35%), typical of acid sensitive soils (Tab. 2).

Base cation weathering rate was highly related to LOI and clay (Fig. 2c; relationship excludes Campbell River), consistent with other regions of Canada (Whitfield *et al*. 2010, this issue). This was not surprising as LOI was highly correlated to soil mass (r = 0.88) owing to the dependency of bulk density on LOI. Further, clay is strongly related to mineral surface area and is the basis for STA weathering methods (de Vries 1991; UBA 2004). In the current study, clay was correlated to plagioclase (r = –0.77) and chlorite (r = 0.78).

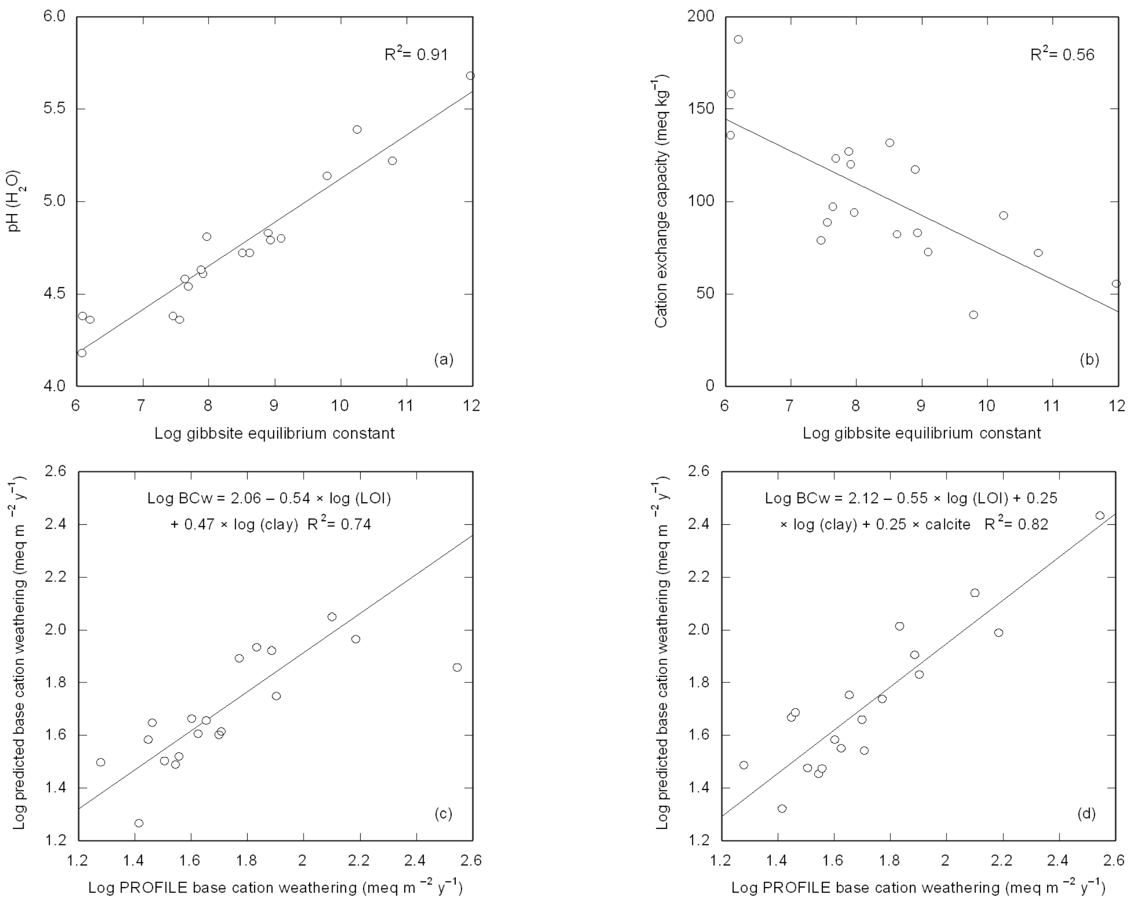

Fig. 2. Relationship between the (**a**) gibbsite equilibrium constant and pH, (**b**) gibbsite equilibrium constant and cation exchange capacity, (**c**) PROFILE estimated base cation weathering and predicted (based on loss-on-ignition and clay), and (**d**) PROFILE estimated base cation weathering and predicted (based on loss-on-ignition, clay and calcite) for the study sites (n = 19).

Tab. 2. Base cation weathering rate (BCw; meq m^{-2} y^{-1}) and mineralogy (%) for the study sites in the Georgia Basin, British Columbia. QUA (quartz), KFE (k-feldspar), PLA (plagioclase), HOR (hornblende), MUS (muscovite), CHL (chlorite) and CAL (calcite).

Site name	BCw	QUA	KFE	PLA	HOR	MUS	CHL	CAL
Saturna Island	153	37.70	10.16	34.61	3.88	6.42	2.59	0.43
Shawnigan Lake	126	44.43	4.41	28.32	6.22	2.95	5.47	0.98
Salt Spring	77	42.25	6.89	32.60	2.62	4.51	8.49	0.50
Campbell River	351	28.24	4.67	42.93	8.67	–	8.40	2.54
Malcolm Knapp	80	44.54	8.28	32.35	8.57	–	1.48	0.71
Chilliwack	35	35.41	9.36	38.58	8.27	1.96	1.16	–
Seymour E	51	24.72	7.21	34.33	3.24	4.06	9.31	–
Seymour M-L	28	50.94	7.06	32.83	2.35	0.69	1.93	0.51
Capilano	32	40.54	5.87	36.15	12.79	–	1.35	–
Coquitlam W	29	49.69	7.03	32.30	4.74	–	1.30	0.28
Coquitlam 110	50	40.66	7.54	31.54	11.85	–	0.70	0.51
Weaver Lake	59	41.61	11.8	12.96	1.36	–	22.25	–
Florence Lake	40	36.41	4.82	39.81	13.23	–	1.22	–
Tingle Lake	26	45.04	4.09	40.41	6.78	–	–	–
Thomas Lake	19	42.78	8.75	39.03	6.60	–	0.53	–
Tretheway Lake	36	32.52	5.87	35.37	16.07	–	1.22	–
Kinnear Lake	42	32.96	4.28	37.65	18.49	–	–	–
MASS	45	42.07	–	20.70	5.84	–	19.38	1.08
Roberts Creek	68	40.60	9.25	42.50	2.04	2.11	1.26	0.60
Average	71	39.64	6.70	33.95	7.56	1.19	4.63	0.43

Tab. 3. Modelled total (wet and dry) sulphur (S) and nitrogen (N) deposition, critical loads of acidity (S + N) based on a regional default K_{gibb} (A) and site-specific values (B; see Tab. 1), and exceedance for the study sites. Units are meq m^{-2} y^{-1}.

Site name	Deposition		Critical loads		Exceedance	
	Sulphur	Nitrogen	A	B	A	B
Saturna Island	10	11	210	193		
Shawnigan Lake	13	25	175	163		
Salt Spring	14	31	113	105		
Campbell River	22	17	455	453		
Malcolm Knapp	47	114	150	149	12	13
Chilliwack	29	88	73	212	44	
Seymour E	85	137	123	191	99	31
Seymour M-L	40	74	94	103	20	11
Capilano	34	59	103	158		
Coquitlam W	50	107	93	124	64	33
Coquitlam 110	82	161	118	169	125	74
Weaver Lake	10	56	111	145		
Florence Lake	19	79	99	101		
Tingle Lake	30	79	75	261	33	
Thomas Lake	23	60	65	218	18	
Tretheway Lake	24	64	83	94	4	
Kinnear Lake	17	47	93	128		
MASS	11	24	86	116		
Roberts Creek	36	42	129	117		
Average	31	67	129	168	46	32

The relationship with PROFILE weathering rate was improved by incorporating calcite (Fig. 2d) as a classifier for sites with higher weathering potential.

3.3. Deposition, critical load and exceedance

Modelled annual average total (wet and dry) anthropogenic S deposition for the period 2005–2006 ranged from 10 to 85 meq m^{-2} y^{-1} (mean = 31 meq m^{-2} y^{-1}), compared with 11–162 meq m^{-2} y^{-1} (mean = 67 meq m^{-2} y^{-1}) for total reduced and oxidised N deposition (Tab. 3). Sulphur deposition was approximately half that of N; moreover, N deposition was dominant at all study sites except Campbell River.

Critical loads of acidity (S + N) for forest soils were estimated using a regional default (log) K_{gibb} (= 9.0) and estimated site-specific values (Tab. 1). Critical loads based on the default K_{gibb} ranged from 65 to 455 meq m^{-2} y^{-1} (mean = 129 meq m^{-2} y^{-1}, Tab. 3) with a large proportion of the sites <100 meq m^{-2} y^{-1} (n = 9). Tingle Lake, Thomas Lake and Chilliwack had the lowest critical loads owing to their relatively low weathering rates. Deposition exceeded critical loads at nine sites (mean = 46 meq m^{-2} y^{-1}); dominated by the high-elevation catchments (Tingle Lake, Thomas Lake and Tretheway Lake) and sites close to Vancouver (Chilliwack, Seymour, Coquitlam and Malcolm Knapp) under high deposition.

Critical loads based on site-specific K_{gibb} values ranged from 94 to 453 meq m^{-2} y^{-1} (mean = 1689 meq m^{-2} y^{-1}, Tab. 3), with only one site <100 meq m^{-2} y^{-1}. The site-specific K_{gibb} values resulted in significant changes in critical loads at some sites, e.g., Tingle Lake, Thomas Lake and Chilliwack shifted from the lowest to the highest critical loads owing to the very low site-specific K_{gibb} (log K_{gibb} ~6), which resulted in high critical leaching (Eqn 2). Deposition exceeded critical loads at five sites (mean = 32 meq m^{-2} y^{-1}) predominantly receiving the highest deposition loads (Tab. 3).

Depending on the approach, exceedance was estimated at five–nine (26–46%) of the study sites. Although based on only 19 sites, the results are in general agreement with regional assessments for the Georgia Basin (showing 32–42% exceedance: Nasr *et al.* 2010, this issue), Canada (Carou *et al.* 2008) and similar site-specific studies for the Athabasca Oil Sands Regions (34–62% exceedance: Whitfield *et al.* 2010; this issue).

3.4. Uncertainties

The effects-based critical load approach is well established and the SSMB model has been widely applied across Europe and North America. Nonetheless it is inevitable that there are uncertainties associated with any model application. These can be roughly grouped into two categories: (a) uncertainties owing to model structure, and (b) model parameters. Uncertainties in the SSMB model structure are beyond this study, and to some extent are implicitly axiomatic in a simplified mass balance approach. Uncertainties in SSMB model inputs have been widely discussed (e.g., see Hall *et al.* 2001b; Skeffington 2006; Li & McNulty 2007). The relationship between the critical chemical limit and the 'harmful effect' is one of the largest sources of uncertainty (see Løkke *et al.* 1996; Reinds *et al.* 2008). A Bc:Al = 1, considered to represent a 50:50 risk of negative impacts on tree growth or nutrition, is the default value commonly used in Europe (Cronan &

Gringal 1999, Hall *et al*. 2001a). However, to be consistent with previous studies in Canada, it was deemed that a Bc:Al = 10 (to preserve soil base saturation) was more appropriate for the Georgia Basin.

Uncertainties in critical load are also primarily associated with the base cation weathering rate (Skeffington 2006, Li & McNulty 2007). In the current study, weathering rates were estimated using the PROFILE model; the uncertainties and merits of PROFILE have been widely debated (Hosdon *et al.* 1996, 1997; Barkman & Alveteg 2001; Hodson 2002). PROFILE is sensitive to soil moisture content, soil mass and mineral surface area (Barkman & Alveteg 2001). In the current study, site-specific soil moisture was unavailable, instead default values ranged between 0.30 and 0.35 $m^3\ m^{-3}$ depending on the amount of site precipitation. Similarly, estimates of bulk density and surface area were based on limited observations of LOI and particle size analysis (respectively). Nonetheless, the estimated base cation weathering rates were in agreement with previous studies in Canada (Watmough *et al.* 2005, Whitfield *et al.* 2006); shallow soils with little or no weatherable minerals had the lowest weathering rates. Moreover, the PROFILE-based weathering rates showed the expected relationships with LOI and texture (clay).

There is considerable uncertainty on the long-term fate of N in forest catchments. In the current study, N input parameters were based on regional defaults owing to the limit observations. Nonetheless, the parameter values were consistent with widely used (and accepted) values (UBA 2004). In general, it is assumed that much of the deposited N will exceed ecosystem capacity and lead to increased N leaching and acidification (Galloway 1998). Moreover, N is the limiting nutrient for plant growth; as such, increased N deposition may result in changes in plant growth, inter-species relationships and soil-based processes. The eutrophying impact of N deposition is also evaluated using critical loads (UBA 2004). The estimated empirical critical loads for temperate forests are in the range 10–20 kg N $ha^{-1}\ y^{-1}$ (5–10 kg N $ha^{-1}\ y^{-1}$ in low deposition areas: Achermann & Bobbink 2003, UBA 2004). In the current study, eight sites received modelled total N deposition greater than 10 kg N $ha^{-1}\ y^{-1}$. In concert, a recent study in the Georgia Basin suggested that lichen communities in urban areas are affected by N deposition (Raymond *et al.* 2010, this issue).

4. CONCLUSION

Modelled annual average total S and N deposition exceeded critical load of acidity for forest soils at five–nine of the study sites (mean exceedance = 32–46 meq $m^{-2}\ y^{-1}$). Despite the limited number of sites (n = 19) and uncertainties inherent in the calculations, the extent of exceedance was similar to other acid sensitive regions in Canada. Moreover, it is clear that high-elevation sites with shallow, acid sensitive, soils and sites close to urban centres under high deposition loads are sensitive to soil acidification. In the current study, site-specific K_{gibb} values derived from Gaines-Thomas exchange equilibrium relationships were highly correlated to soil pH (and LOI) suggesting they better captured the natural variation in soil properties compared with a regional default value (log K_{gibb} = 9).

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