

EVALUATING THE CUMULATIVE IMPACTS OF AIR POLLUTION
IN NORTHEAST BRITISH COLUMBIA

by

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ABSTRACT

This research examined the potential cumulative impacts of air pollution in northeast British Columbia (BC). It was part of a larger project to develop tools for assessing the cumulative impacts of development in BC's Treaty 8 traditional territory. Although this study was framed from a First Nations perspective, it has relevance to all residents of the region. The focus is on Criteria Air Contaminants (CAC); whose reporting in Canada is required based on contributions to acid rain, ozone and poor regional air quality. Air pollution in northeast BC is dominated by the upstream oil and gas (UOG) sector. An analysis of official emissions data and reporting policies showed that inventories severely underestimate UOG emission sources. Industry-based emission estimates were combined with a conventional government-based emissions inventory to give a more comprehensive dataset for the region. When CAC sources were considered inclusively and cumulatively across the region's landscape, emissions of the CAC sulphur dioxide (SO₂), nitrogen oxides (NO_x) and volatile organic compounds approximately doubled, reaching intensities comparable to urban areas. Due to the magnitude of SO₂ and NO_x emissions, and their known contribution to the acidification of ecosystems in parts of Canada, the Critical Loads of Acidity (CL(A)) were estimated for freshwater lakes in the region. A scarcity of detailed lake chemistry data pre-empted the development of empirical methods for estimating CL(A). Alkalinity and calcium measurements were available for a significant number of lakes and were consequently used as indicators of acidification sensitivity using relationships between these parameters and existing CL(A) estimation procedures. The resulting CL(A) were used alongside Ambient Air Quality Objectives (AAQO) and critical limits for various ecosystem elements, as thresholds for measuring potential air pollution effects. The AERMOD model, traditionally used for simulating the dispersion of UOG emissions from individual sources in BC, was used here to predict ambient concentrations and surface deposition of both SO₂ and NO_x from numerous emission sources in an area of both cultural significance and high source density. Results predicted potential threshold exceedances that may have implications for ecosystems, human health and First Nations Treaty rights.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAQO – Ambient Air Quality Objectives
AERMOD – American Meteorological Society (AMS) / United States Environmental Protection Agency (EPA) Regulatory Model Improvement Committee’s Regulatory Model
BC – British Columbia
BC-CAC – British Columbia’s year 2000 CAC emissions inventory
boe·d⁻¹ – barrel of oil equivalents per day
CAC – Criteria Air Contaminants
CAPMoN – Canadian Air and Precipitation Monitoring Network
CAPP – Canadian Association of Petroleum Producers and their year 2000 CAC emissions inventory
CH₄ – Methane
CL(A) – Critical Loads of Acidity
CL(EX) – Critical Load Exceedance
CLRTAP – Convention on Long-Range Transboundary Air Pollution
CMAQ – Community Multi-scale Air Quality Model
CO₂ – Carbon Dioxide
EMPR – BC’s Ministry of Energy Mines and Petroleum Resources
ERCB – Alberta’s Energy resources and Conservation Board
keq – H⁺ kiloequivalents = the acidification capacity of 1000 free protons
NO_x – Nitrogen oxides: may be NO, NO₂ or NO₃ in neutral or ionic form
N₂O – Nitrous Oxide
NORM – Naturally Occurring Radioactive Materials
NPRI – Canada’s National Pollutant Release Inventory
OGC – Oil and Gas Commission of British Columbia
PM – Particulate Matter
SCC – Source Classification Code
SO_x – Sulphur Oxides: may be SO₂, SO₃ or SO₄ in neutral or ionic form
SO₂ – Sulphur Dioxide
SO₃⁻ – Dry Sulphate
SO₄²⁻ – Wet Sulphate
UNECE-CLRTAP – United Nations Economic Commission for Europe – Convention on Long-range Transboundary Air Pollution
UOG – Upstream Oil and Gas
US-EPA – United States Environmental Protection Agency
VOC – Volatile Organic Compounds

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To my loving mother

Jane

(1943-2005)

CO-AUTHORSHIP STATEMENT

Chapter 3 (Paper 2)

Title: Back to the basics: estimating freshwater sensitivity to acidification using traditional approaches”

Co-Author: John L. Innes.

Role of Co-Author: insights and discussion relating to manuscript development

1 INTRODUCTION: EMISSIONS, EFFECTS AND A WAR IN THE PEACE

1.1 Foreword

Air pollution effects are a reality across the globe. While we often associate air pollution with urban smog or industrializing nations, poor air quality may exist in some of the most remote regions of Canada. Presented here are issues, concepts and results that emerged from an assessment of the cumulative impacts from air pollution in northeast British Columbia (BC). The research was developed as part of a larger project initiated by the Treaty 8 signatory First Nations of British Columbia (BC); the overall purpose being to develop a practical tool based on scientific principles that may be used to assess cumulative impacts and guide future industrial development within Treaty 8 traditional territory. The research presented in the following thesis defines some of the barriers to, methods of, and results from, assessing cumulative effects as they pertain to atmospheric emissions in the region. While the whole-project end goal is yet to be achieved, the results and measures of change described in the following, can be used by communities to assess and monitor cumulative impacts in the region, ultimately aiding in land and treaty negotiations.

1.2 Peace Country

Appropriately named ‘the Peace’ after the river that runs through it, northeast BC is a land where mountains meet the Great Plains, forests meet tundra, and traditional cultures clash with industrialization. The area is situated primarily within the Boreal White and Black Spruce Biogeoclimatic zone and to a lesser extent, the Alpine Tundra, Spruce-Willow-Birch and Sub-boreal Spruce zones (Meidinger and Pojar, 1991). Forests are composed largely of white spruce (*Picea glauca*), jack pine (*Pinus banksiana*), birch (*Betula spp.*) and willow (*Salix spp.*). Poorly drained sites at lower elevations are characterized by black spruce (*Picea mariana*) and *Sphagnum spp.* dominated bog and fen (Valentine et al., 1978). Stands of trembling aspen (*Populus tremuloides*), dispersed with balsam poplar (*Populus balsamifera*) and lodgepole pine (*Pinus contorta*) may also be found in the region spanning northwards from Fort St. John

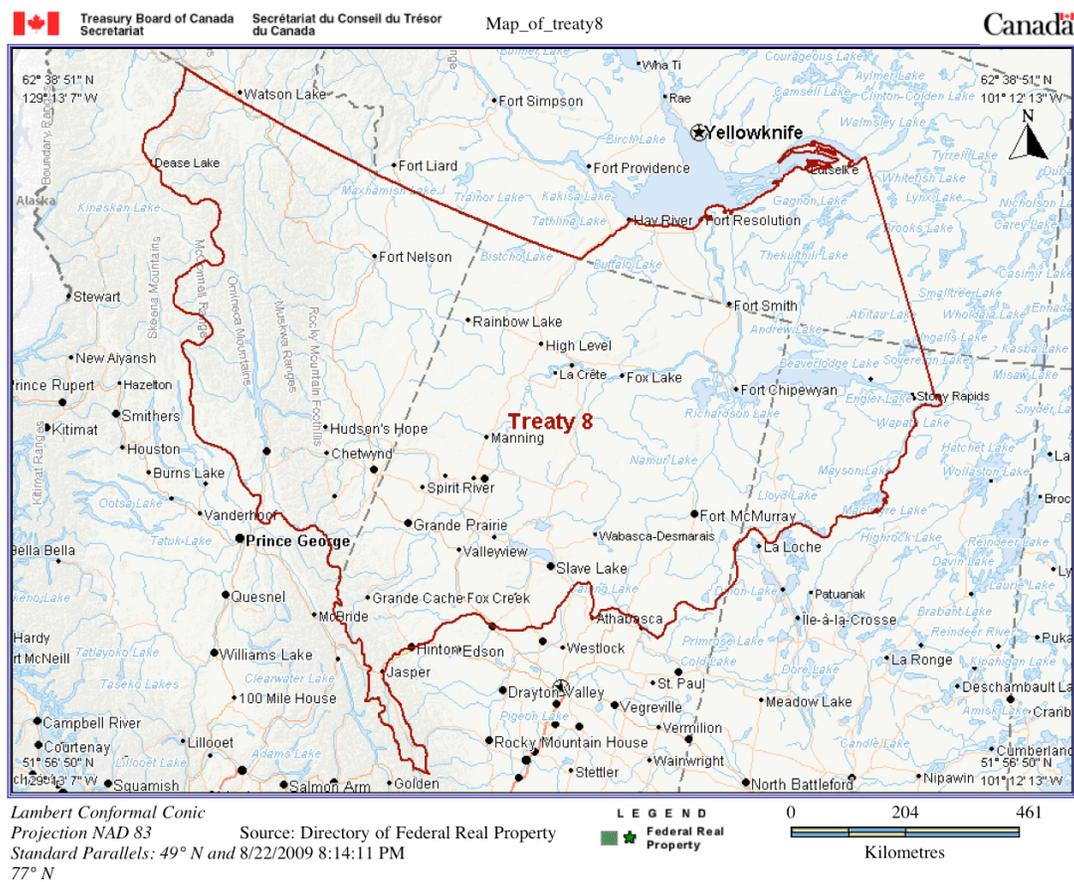
to Fort Nelson (Chen et al., 1998). Wildlife is abundant and the area provides habitat for bird, mammal, reptile, fish and mollusc species too numerous to name. However, specific organisms that are particularly sensitive to a form of air pollution injury (e.g. lichens), are considered threatened (e.g. caribou (*Rangifer tarandus*) or rare molluscs (*Physella wrighti*)), or have specific cultural relevance (e.g. moose (*Alces alces*)), are used as indicators of change as discussed in the following.

Geologically the region's sedimentary layers originate as crystalline Precambrian basement overlain by Cambrian to lower Jurassic sediments of chiefly marine origin (shale, evaporites and carbonates). These marine deposits are overlain by Upper Jurassic to Cretaceous period sediments composed predominantly of siliclastic minerals (sandstone, siltstone and shale) (BC Ministry of Energy, Mines and Petroleum Resources, 2003; Soil Landscapes of Canada Working Group, 2005). The Peace River Arch (PRA) – a large cratonic uplift of the Western Canada Sedimentary Basin (WCSB) – is responsible for the near-surface hydrocarbon reservoirs in the region (O'Connell, 1994). The surface layer shallows with distance northeast making hydrocarbon reservoirs more accessible. The region's geology varies in both hydrocarbon richness and ability to protect ecosystems from air pollution related injury, particularly “acid rain”.

Treaty 8 traditional territory (Figure 1-1) claims the entire northeast quarter of the province; it is within this territory that the following research was focused. Aboriginal people have inhabited northeast BC for tens of thousands of years (Carlson and Bona, 1996). The first European contact occurred sometime before Alexander Mackenzie arrived in 1789 (Bancroft, 1887). Following the consolidation of the fur trade in 1821, several outposts in the region came under the control of the Hudson's Bay Company (Asch, 1981). The first gold discoveries occurred in 1861, and by 1870 mining was seen as a way to populate what was believed to be a “boundless agricultural region” (Bancroft, 1887). It was not long before land-use conflicts developed between the foreign settlers and the land's native people; subsequently, a call for treaties arose. Treaty No. 8 was signed in 1899 and represents the largest (by area) of any Canadian

Treaty. The treaty promises signatory bands “the right to pursue their usual vocations of hunting, trapping and fishing” as well as the “encouragement of agriculture” if agriculture were the chosen way of life (Duhamel, 1966). It is these rights set by the dominion of Canada that are potentially threatened by current industrialization in the region; and it is these rights, particularly “the right to pursue”, on which the following impact assessment is focused.

Figure 1-1. The location of Treaty 8 traditional territory in western Canada. Source: Treasury Board of Canada Secretariat (2009).



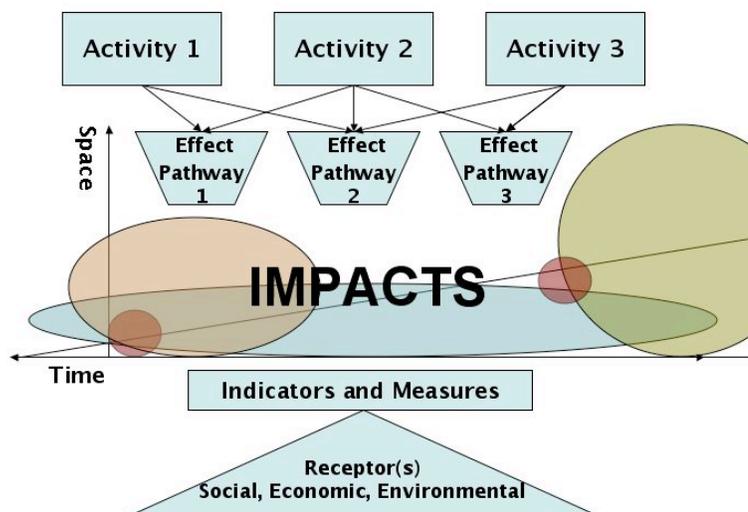
In the last 30 years, the Peace has experienced rapid development and changes in land-use arising primarily from forestry; upstream oil and gas (UOG); hydro-electric; agricultural land conversion; road creation; and tourism (AXYS Environmental Consulting Ltd. et al., 2003; BC Ministry of Sustainable Resource Management, 1997a; BC Ministry of Sustainable Resource Management, 1997b; BC Ministry

of Sustainable Resource Management, 1999). Oil and gas exploration began around Fort St. John in the late 1940s, but did not really boom until the mid-1990s (OGC, 2008a). The UOG sector is responsible for much of the region's recent development and lays claim to most of the region's atmospheric emissions of pollutants.

1.3 Cumulative Impacts

Human activities seldom occur in isolation and neither do the impacts that result from them. The terms “cumulative effects” and “cumulative impacts” are used interchangeably throughout this document. A well accepted definition of cumulative impacts is ‘impacts resulting from incremental changes as a result of past, present or reasonably foreseeable actions (Walker and Johnson, 1999)’ However, cumulative effects are more specifically defined for the purpose of this study (as in Chapter 4) as the outcomes of numerous actions along pathways of influence initiated by the interaction of multiple human activities in shared space and time. These outcomes may be positive or negative, additive or interactive and may have social, economic or environmental implications. The pathways of influence are referred to as “effect (or impact) pathways” and the resulting implication for a specified receptor as the “impact or effect” (Figure 1-2).

Figure 1-2. Schematic illustration of cumulative effects or impacts. Note the graphical overlap of impacts in space and time, their receipt by common receptors, and their measurement using common indicators.



In Canada recognition of cumulative effects entered legislation in the early nineties. Projects regulated by the *1992 Canadian Environment Assessment Act* (CEAA) must consider

“...any cumulative environmental effects that are likely to result from the project in combination with other projects or activities that have been or will be carried out;” (Canada, 1992).

This consideration of cumulative effects is only required for projects that have some sort of federal support, meaning that most projects in BC do not need to recognize cumulative effects. If they do, the assessment is based on the usually limited information available on projects already operating, or that have applied for approvals. Much of the information necessary to perform a realistic impact assessment is either proprietary or confidential, as we will see is the case for the UOG industry and the emissions it produces.

Air pollution has been approached from a cumulative impacts perspective in a number of regional on-going management activities such as the South Coast Air Quality Management District’s Cumulative Impacts Working Group (2004) in Diamond Bar, California and the Cumulative Effects Management Association’s (2009) work in Fort McMurray Alberta – where cumulative effects recognition is required under Alberta’s 1993 *Environmental Protection and Enhancement Act*. Although Canada has developed a Cumulative Effects Assessment Practitioners Guide (Hegmann et al., 1999) and northeast BC has seen the development of frameworks and indicators for cumulative effects assessment in the region (AXYS Environmental Consulting et al., 2003), there is little consensus among managers and practitioners, and no code of practice or legislation for cumulative effects analysis in BC. There is also a lack of First Nations consultation in the assessment process.

An ideal assessment of cumulative impacts would examine all potential impacts, their pathways and interactions – but this is rarely feasible and never the case. Some common elements of cumulative impact assessments include scoping to set priorities and determine project boundaries (ex. Schneider et al., 2003;

Callahan and Sexton, 2007); the use of indicators and measures of change to quantify effects (ex. Xue et al., 2004; Spies et al., 2007; Wilson and Stelfox, 2008); the use of specific ecosystem elements (or Valued Ecosystem Components (VEC)) whose particular effect thresholds define when undesirable impacts occur (e.g. AXYS Environmental Consulting et al., 2003; Xue et al., 2004; Halpern et al., 2008); the spatial modelling of present and future states such that effects may be mitigated (e.g. Schneider et al., 2003; Scrimgeour et al., 2008; Wilson and Stelfox, 2008); and continuous monitoring of systems and/or the effects they experience (Braat, 2001; Wilson and Stelfox, 2008). Each of these concepts is also briefly outlined in the 'Cumulative Effects Practitioner's Guide' (Hegmann et al., 1999), but only referred to on an individual project basis rather than at a landscape or regional level as recently proposed by Canadian Council of Ministers of the Environment (CCME) initiatives (CCME, 2009). Of the above assessment elements, only continuous monitoring was not incorporated into the research that follows. However, it is anticipated that one of the results from this work will be on-going monitoring of various indicators undertaken at a community or regional level.

1.4 Emissions

Atmospheric pollutants are boundless, and like other impact pathways, their effects combine and inter-mingle at the source and receptor level ultimately producing additive, multiplicative or synergistic effects. Nearly every human activity, from breathing to manufacturing, produces some form of atmospheric emissions. Nonanthropogenic sources of air pollution include plant and bacterial respiration, volcanic eruptions, lightning and sea spray. In northeast BC, typical sources of anthropogenic emissions are pulp and saw mills, open burning, mining operations and upstream oil and gas. The latter activity produces the majority of atmospheric emissions in the Peace and includes a wide variety of emission sources from pipeline leaks, to large gas processing plants and emergency or routine flares.

Flaring is a fairly common practice in the Peace largely for well (pressure) testing or as a way to 'safely' release gas during pressure build-up to avoid explosions or "blow-outs". Flaring is also used as a method

of “waste” disposal for solution-gas containing methane (CH₄); heavier hydrocarbons such as propane and butane; carbon dioxide (CO₂); and hydrogen sulphide (H₂S) – an unfortunately common constituent of “sour” gas and oil pools in the Peace. While there are energy conservation initiatives in BC (British Columbia, 2007) and abroad (Elvidge et al., 2007) to terminate the routine flaring of natural gas as waste, in 2007 over 4.5 million cubic metres of gas were approved to be flared in BC, predominantly in the northeast (OGC, 2008a). Additionally, flaring remains an attractive and widespread option to deal with “small volumes” of toxic H₂S (OGC, 2008b)

Typically the types of compounds emitted into the atmosphere have been classified into three categories: Criteria Air Contaminants (CAC), Greenhouse Gases (GHG) and other toxic substances – such as heavy metals and Persistent Organic Pollutants. There is some overlap between categories, for instance carbon monoxide is both a CAC and a GHG. Volatile Organic Compounds (VOC) are considered in their entirety as CAC, however many individual VOC such as xylene or benzene are also considered highly toxic and are also regulated individually. While all emissions of substances to air can have direct (acute toxicity, cellular damage, etc.), or indirect (climate change, acid rain, smog, etc.) effects on humans and the environment, here the focus is on CAC.

When this research was conducted Canada’s CAC class included: carbon monoxide (CO); ammonia (NH₃); nitrogen oxides (NO_x) usually reported as nitrogen dioxide (NO₂) equivalents; sulphur dioxide (SO₂); particulate matter of less than 2.5 microns (PM_{2.5}); particulate matter of less and 10 microns (PM₁₀); and volatile organic compounds (VOC). Although not considered a CAC, H₂S is also included in this research due to its prevalence in the study area, its importance to human and animal health, and its potential contribution to acid rain. In addition to the potential direct effects of each CAC substance, SO₂ and NO_x are responsible for the formation of acid rain (or acid deposition); NO_x and VOC react in sunlight to produce tropospheric ozone; NO_x and NH₃ can lead to nitrogen enrichment and eutrophication of ecosystems; and particulate matter can lead to reduced visibility or light levels and changes in

precipitation regimes. UOG operations emit all CAC but NH₃, which is produced predominantly through biological processes and anthropogenically by agricultural operations (Niemi et al. 2009). UOG sector CAC emissions are composed primarily of CO, SO₂, NO_x and VOC. Due to the known influences of SO₂ and NO_x emissions on ecological systems and human health in outdoor ambient environments, including their contributions to acidification, eutrophication and ozone formation, these two compounds are the focus of most of the effects research and are used as surrogate compounds for complex air pollution mixtures. SO₂ is commonly used as such an indicator pollutant of atmospheric contaminant mixtures (Scott et al. 2003).

In order for potential effects and fates of atmospheric emissions to be understood, they are usually estimated, reported, and held in databases for analysis, modelling or policy purposes. For these endeavours to be accurate and relevant, the emissions inventory itself must bear accurate and relevant characteristics. However, as presented in Chapter 2, this is often not the case. When this assessment first began the most recent emissions inventory for either Canada or BC was for the year 2000, released in 2004. At that time emissions reporting and data accumulation were carried out at the provincial level as described in Wakelin and Rensing (2004); and then compiled nationally as in Deslauriers and Niemi (2005). Briefly, inventory development was accomplished through permits and fees as required by BC's *Environmental Management Act – Waste Discharge Regulation* (British Columbia, 2004), replacing the *Waste Management Act of 1982*. For the upstream oil and gas sector, permitting requirements were (and continue to be) limited to “large” operations i.e. discharging greater than 30 tonnes of sulphur over a 15-day period. A year 2008 amendment of the regulation extends permitting requirements to activities emitting in excess of 4 tonnes of VOC over the same period.

Since 2002 CAC emissions reporting has been achieved federally through the NPRI (National Pollutant Release Inventory) as described in Canada (2007a; 2007b; 2008) and is no longer related to permit or fee requirements. Instead, reporting thresholds are unique to the NPRI, which has traditionally served more as a public rather than technical source of information. Reporting thresholds and requirements change

frequently. In the year 2006 NPRI reporting was specific to each industrial sector and related to activity thresholds. For instance the UOG industry was only required to report if a facility produced greater than 10 000 barrels of oil equivalents per day and had GHG emissions of greater than 1000 tonnes of CO₂ equivalents over the 2006 reporting year (Canada, 2007a). In 2007 reporting requirements were standardized to apply to all industry classifications (with some exceptions). New thresholds limited reporting to facilities characterised by at least 20 000 employee hours per year (approximately 10 full time workers) (Canada, 2007b). The 20 000 employee hours per year threshold remained in place for the 2008 and 2009 reporting years.

Both current NPRI reporting, and previous permit-based reporting, neglect to characterise the CACs emitted by thousands of small, often unmanned, point sources in the Peace region. Exclusively upstream oil and gas sector emission sources, the implications of excluding these sources from inventories are discussed in Chapter 2. Although, H₂S is not considered a CAC, it is reported to the NPRI (Environment Canada 2009). For reasons discussed in detail in Chapter 2, very few emission sources in the northeast meet reporting requirements, and most of the H₂S accounted for in the NPRI is in disposal and recycling (>99.9%), rather than air emissions.

1.5 Effects

Air pollution has known effects on human health, built structures, ecosystems and their function or elements. Due to the protection of the “right to pursue” offered by Treaty No. 8, this study focuses on the ecological effects that would influence the traditional vocations of hunting, fishing and trapping, as well as the practice of agriculture. Although framed from a First Nations’ perspective and focused on ecosystems, the effects approached in this study have relevance to the health and interests of all the northeast’s inhabitants.

An assessment of ecosystem impacts from air pollution is best achieved through a comparison of ecosystem sensitivity with the amount of pollutants that the ecosystem receives (UNECE-CLRTAP, 2004). This is generally accomplished by the use of thresholds or limits – pollutant magnitudes at which effects are known to occur. In air pollution science these are termed “critical levels” when referring to short-term ambient concentration thresholds causing direct effects; and “critical loads” when referring to the amount of a pollutant deposited on the surface over a longer period of time causing indirect (biotic) effects. The former are typically measured in parts per billion (ppb) or micrograms per cubic metre ($\mu\text{g}\cdot\text{m}^{-3}$) averaged over 1– 24 hours, and the latter are usually measured in kilograms per hectare per year ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$) or proton equivalents per hectare per year ($\text{eq}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$) for acidification. The notion of comparing receptor sensitivity to receptor receipt of pollutants can be applied to any receptor, not just ecosystems. Humans, crops, materials etc. have similar such critical limits, whereas as critical loads are applied solely to ecosystems.

Short and long-term ecosystem effects vary with ecosystem type, composition, placement and exposure extent or frequency. Since sulphur and nitrogen oxides are commonly emitted from upstream oil and gas sector sources; the Critical Loads of Acidity (CL(A)) were chosen as indicators/measures for this cumulative effects assessment. Dry or wet deposition of sulphur-, and to a lesser extent nitrogen-, oxides (“acid rain”) have been responsible for much of the freshwater lake and soil acidification experienced in eastern Canada (Henriksen et al., 2002; Ouimet et al., 2006) and Europe (Curtis et al., 2002; UN-ECE, 2004). Nutrient nitrogen critical loads are often calculated separately since nitrogen is first a growth promoting nutrient and can lead to aquatic or terrestrial eutrophication, but once a system becomes fully saturated with nitrogen, the nutrient becomes acidifying (UN-ECE, 2004; Henriksen and Posch, 2001). The accepted definition of critical loads today is: “a quantitative estimate of 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). Both aquatic acidification and eutrophication can lead to the eventual, and sometimes complete, loss of fish species (UNECE-CLRTAP,

2004) thereby affecting not only the treaty 8 defined “right to pursue” fishing, but also the recreational and subsistence angling of non-aboriginal people in the Peace.

The sensitivity to acidification (CL(A)) is estimated based on the ability of a system to neutralize incoming acids and thereby maintain a ‘normal’ pH through buffering. Usually some sort of steady state mass balance is assumed i.e. that inputs are equal to outputs and are constant in time. The ability of a system (ecological, agricultural, etc.) to neutralize acidity is based on the amount of incoming base cations. Base cation availability depends on both atmospheric base cation deposition, and the natural buffering capacity of the system – a function of the type of bedrock or parent material plus the rate of weathering of that material. If there is a low influx of base ions, then the CL(A) is low and the system is sensitive to acidification. If there are plentiful cations made available through weathering (or deposition) then the system will be resistant to acidification. The term “exceedance” is given to when the charge of incoming acid ions (most notably sulphate (SO_4^{2-})) exceeds the charge of available base cations – measured in proton (acid) equivalents. Exceedance is marked by acidification of the system.

There are several criteria used for evaluating acidification critical loads. A common soil indicator for acidification sensitivity is the base cation to aluminium (BC:Al) ratio (Ouimet et al., 2006). Excess acidity promotes the leaching of cations from the soil complex, thereby mobilizing aluminium, which is toxic to most plant and fish species in monomeric inorganic forms (Palmer and Driscoll, 2002). Evidence shows that mobile toxic Al species are responsible for much of the acidification injury to biota, rather than the change in pH itself (Henriksen and Posch, 2001). Although Al is the most common metal on Earth, other potentially toxic metals (such as Pb, Cu, Cd, Zn) may also be mobilised from soil complexes by acidification, if available in sufficient quantities (Bobbink et al. 2002). A freshwater threshold is commonly set for the minimum concentration of base cations available for buffering, known as the Acid Neutralizing Capacity Limit ($[\text{ANC}]_{\text{lim}}$), which is directly related to the pH of the freshwater system (also often used as a threshold). Freshwater lake CL(A) are assumed representative of the CL(A) for the entire

catchment (UN-ECE, 2004). As shown in Chapter 3, this project required the setting of rather conservative limits due to the high pH of many lakes in the Peace and the high level of ecological protection warranted by indigenous values.

The Nilsson and Grennfelt (1988) definition of a critical load can easily be extended to critical limits. Direct air pollution injury to forests was documented as early as 1350 AD in the Ore Mountains of Eastern Europe, where policy was drafted stressing protection of forests from further injury due to the mining, iron and coal industries (Smejkal, 2002). Sulphur dioxide, compared with other atmospheric pollutants, has a long and well-documented history of being injurious to vegetation (Mudd, 1975) and was the first pollutant documented as phytotoxic (Legge et al., 1995). Historically, SO₂ has been recorded at injurious levels in many parts of the world including urbanised parts of the United States, United Kingdom, Canada and Eastern Europe (Katz, 1939). In 1916 the first Canadian records of visible air pollution injury to forests were made surrounding a British Columbian smelter at Anyox on the northwest coast. Emissions from the smelter – comprised primarily of SO₂ – killed many forest trees (Miller and McBride, 1975).

Early research experiments began in the late 1920's to explore the relationship between SO₂ exposure and forest injury around the smelter operations at Trail, BC. The injury from the Anyox and Trail smelters showed a variety of conifers to be sensitive to SO₂ including: western redcedar (*Thuja plicata*), silver fir (*Abies amabilis*), sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), western Larch (*Larix occidentalis*), douglas-fir (*Pseudotsuga menziesii* ssp. *menziesii*), and western yellow pine (*Pinus ponderosa*). While these species are not native to the Peace region, white spruce (*Picea glauca*), subalpine fir (*Abies lasiocarpa*), jack pine (*Pinus banksiana*), black willow (*Salix nigra*), trembling aspen (*Populus tremuloides*), and other northeast tree species, have also displayed relative sensitivity to high concentrations of SO₂. Many culturally important species such as berries (e.g. *Rubus* and *Vaccinium* spp.) or moose forage (e.g. *Cornus stolonifera*) are also sensitive to SO₂ injury (Legge et al., 1998). Direct

vegetative injury from exposure to nitrogen oxides is less common but evident in parts of eastern Europe under extremely elevated concentrations near local sources such as fertiliser manufacturers (Bytnerowicz et al., 1998). Nitrogen oxides are also an ozone (O₃) precursor and O₃ has been shown to cause direct injury to many species of native plant around the globe (UNECE-CLRTAP, 2004).

In Canada and BC, Ambient Air Quality Objectives (AAQO) have been developed to protect human health and ecosystems from air pollution injury (see Table 1-1). AAQO exist for CAC and other primary (e.g. lead) and secondary (e.g. ozone) pollutants. The federal “maximum desirable” threshold corresponds to BC’s “Level A”, maximum acceptable” to BC’s “Level B” and “maximum tolerable” to BC’s “Level C”. In practice the objectives correspond to: long-term goals, adequate protection of environmental and human health, and levels that require immediate action, respectively. While these limits are neither species nor ecosystem specific, and were derived from crop fumigation experiments, they are essentially regulatory “critical limits” and were applied in Chapter 4 (along with critical loads and other “limits” from the literature) as thresholds for cumulative effects. However, in order to apply these various thresholds in a cumulative effects assessment, pollutant exposures must be known.

1.6 Modelling and Prediction

A wise man once said: “good modellers should never believe their results”. While most mathematical models of any sort are riddled with errors and assumptions, they are useful tools either in combination with measurements (i.e. to fill in gaps), or in place of measurements (i.e. where data are unavailable and uncollectible). Modelling is also the sole method by which researchers may examine future states, since the future cannot be measured directly. For this reason models are common tools for cumulative effects assessment (section 1.3), often requiring the consideration of past, present and future actions.

Table 1-1. Ambient Air Quality Objectives and Standards for BC and Canada. Source: BC Ministry of Environment (2009).

Contaminant	Averaging Period	Canada maximum desirable	Canada maximum acceptable	Canada maximum tolerable	B.C. level A	B.C. level B	B.C. level C
carbon monoxide	1 hour	15000	35000		14300	28000	35000
	8 hour	6000	15000	20000	5500	11000	14300
formaldehyde	1 hour				Action Level = 60 Episode Level = 370		
hydrogen sulphide	1 hour	1	15		7.5-14	28-45	42-45
	24 hour		5		4	6-7.5	7.5-8
lead	24 hour				4	4	6
	30 day geometric mean						
	quarterly annual geometric mean				2	2	3
nitrogen dioxide	1 hour		400	1000			
	24 hour		200	300			
	annual arithmetic mean	60	100				
ozone	1 hour	100	160	300			
	24 hour	30	50				
	annual arithmetic mean		30				
PM10	24 hour					50	
sulphur dioxide	1 hour	450	900		450	900	900-1300
	3 hour				375	665	
	24 hour	150	300	800	160	260	360
	annual arithmetic mean	30	60		25	50	80
total reduced sulphur	1 hour				7	28	
	24 hour				3	6	
total suspended particulate	24 hour		120	400	150	200	260
	annual geometric mean	60	70		60	70	75

Canada-wide Standards Established in 2000

PM2.5	24 hour	30 µg/m ³ *
ozone	8-hour daily max.	65 ppb **

based on annual 98th percentile value, averaged over 3 consecutive years; ** based on 4th highest annual value, averaged over 3 consecutive years

Ambient Air Quality Objectives Established in 2009

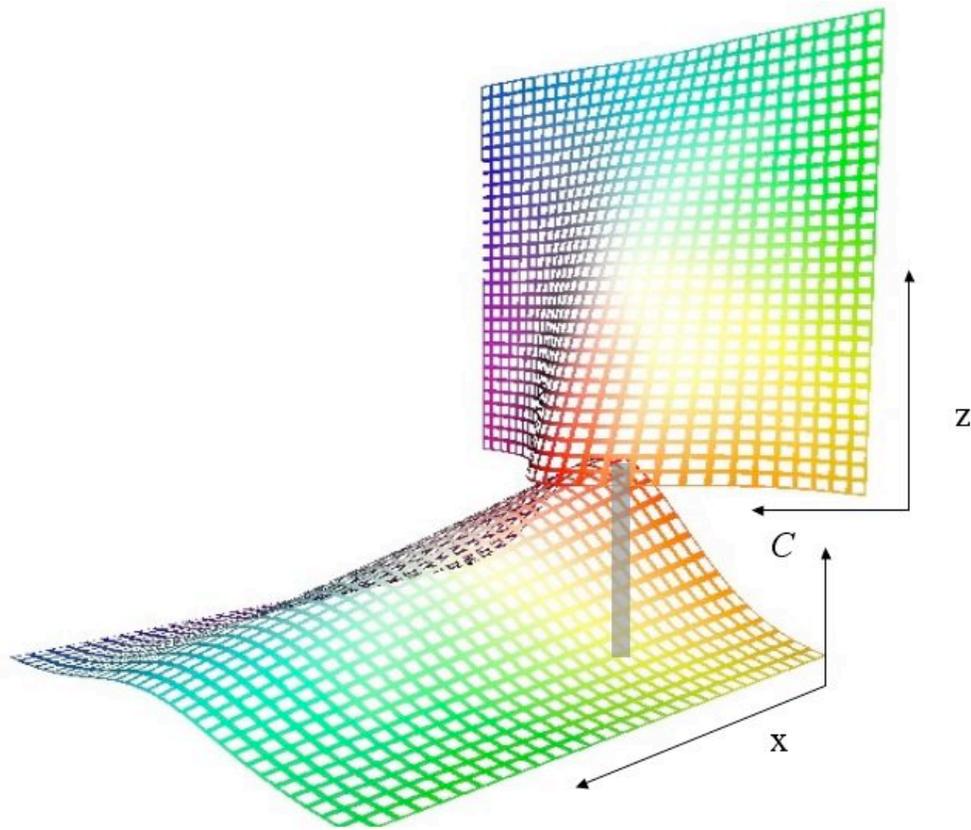
PM2.5	24 hour	Air Quality Objective: 25 µg/m ³ *
	annual arithmetic mean	Air Quality Objective: 8 µg/m ³
	annual arithmetic mean	Planning Goal : 6 µg/m ³

* based on annual 98th percentile value,

Models, employed as tools throughout this research, vary in complexity. A relatively simple model was used to estimate typical flare stack “pseudo” height and width parameters based on buoyancy and heat of radiation assumptions used to derive a flame size (Chapter 2). The Steady State Water Chemistry Model (SSWC) was used to estimate the critical loads of acidity (CL(A)) and derive even simpler linear models for estimating CL(A) based on individual lake chemistry measurements (Chapter 3). Although relatively simple for a dispersion model, the most complex model used as AERMOD – employed to estimate hourly concentrations and annual deposition for a small study area north of Fort St. John (Chapter 4).

The AERMOD model was designed through working group collaboration between the United States AMS (American Meteorological Society) and the EPA (Environmental Protection Agency), forming the AMS/EPA Regulatory Model Improvement Committee (AERMIC). AERMOD is a steady-state Gaussian plume model that uses a bi-Gaussian distribution developed by Willis and Deardorff (1981) to simulate vertical plume dispersion in a convective boundary layer (Figure 1-3). Recommended and accepted as a regulatory model in BC (British Columbia, 2008), AERMOD calculates plume rise and buoyancy; penetration into elevated inversions; vertical wind, temperature and turbulence profiles; and offers the treatment of surface, near-surface or elevated sources and receptors on differing terrain types. Estimates of pollutant concentration are expressed at a specified receptor as a weighted combination of both vertical and horizontal plume displacement (Cimorelli et al., 2004). In essence the model is used to estimate what concentrations and long-term loads of pollutants are being received at the ground surface. These values are then compared to chosen limits and thresholds at receptors (a grid or set of points). For instance vegetation located at some distance from the source, where a plume(s) intercepts the surface, would have the highest risk of direct (acute) pollutant injury. Depending on the prevailing winds and ‘typical’ meteorological conditions, this direct injury could become chronic if plume interception at the surface occurs in the same location for extended periods.

Figure 1-3 Illustration of pollutant concentration (C) with distance from source based on Gaussian plume dispersion in the (positive) x and z directions. Peak concentration occurs at the plume centre-line. Plume spread occurs similarly in the y direction. During convective conditions AERMOD uses a bi-Gaussian function which would be represented by a second x -axis curve upside-down above the existing normal distribution function i.e two plume centre-lines that grow further apart with increased distance.



The user can define monthly variations in surface characteristics for up to twelve upwind sectors (Cimorelli et al., 2004), which may aid in forecasting dispersion for future development and land-use scenarios. AERMOD's capabilities are limited by maximum transport lengths of 50 km, and a lack of multi-pollutant chemistry; but the model can simultaneously predict the dispersion of plumes from an unlimited number of point, area or volume sources. Lakes Environmental's AERMOD-View™ V 6.1.0 was used, providing a graphical user interface. The model's characteristics and user-defined parameters are discussed further in Chapter 4 where it is applied.

There are numerous air quality models that could have been used for assessing cumulative air pollution effects in northeast BC. A regional Eulerian air quality model such as CMAQ (Community Multiscale Air Quality Model) or AURAMS (A Unified Regional Air-quality Modeling System) would have been ideal for utilising the available annual emissions estimates, approaching multiple pollutant chemistry such as ozone formation, estimating concentration and deposition of for a domain the size of Treaty 8 BC's traditional territory (approximately 2.79×10^9 km²), and for predicting future growth and alternative policy scenarios. Unfortunately, these complex regional models lack a user interface and require extensive programming knowledge, sometimes in multiple 'languages'. CMAQ for instance is also very resource intensive and once operating properly would need to run a full year of meteorology (in real time) for annual deposition estimates on a multiple processor 'monster' computer. AERMOD View™ by Lakes Environmental allows non-programmers to take advantage of its dispersion capabilities on a laptop with annual runs completed in a few days, depending on the number of sources.

The reliability of any air quality model is determined by the accuracy of the emissions inventory, the validity of assumptions and the quality of the meteorological data (be it measured or modelled). Model results are never an accurate surrogate for measured values, but may be considered an acceptable tool for specific applications. Models such as CMAQ and AURAMS are utilized at the national and regional level for policy and compliance analysis, local air quality index forecasts and effects estimation. Models such as AERMOD are utilized at the provincial- and local-level for individual project permit applications and regulatory analysis. Here AERMOD modelling is applied to multiple projects and sources over a full year of meteorological data, permitting its effectiveness in carrying out some of the cumulative assessment purposes of more complex regional models.

1.7 Goals and Objectives

In the case presented here, the need for a cumulative impact assessment in northeast BC became apparent to local (aboriginal) communities a number of years ago. In 2003, the Treaty 8 Tribal Association of BC

expressed concern that the extent and rapidity of industrial (primarily resource sector) activity in the region, were affecting their treaty and constitutionally given rights to the land within their traditional territory (Figure 1-1). This concern gave rise to a cumulative impact assessment for northeast BC supported by the Sustainable Forest Management Network (a national network of centres of excellence). This work has been carried out by a team of researchers from the University of British Columbia's Department of Forest Resources Management led by Dr. John L. Innes and has involved collaboration with a number of provincial government and industry partners. In recent years the project has expanded to include researchers from the Universities of Calgary and Alberta and partnerships with aboriginal communities from Alberta - also signatories of *1899 Treaty No. 8*. The project in its entirety aims to determine if, and how, rights safeguarded by the treaty may be affected by development within the region it represents. These include the "right to pursue their usual vocations of hunting, trapping and fishing" and the "encouragement of agriculture" as declared in *Treaty No. 8 of 1899*, as well as the protection of these and other rights and freedoms as declared in Section 35 of the *Canadian Charter of Rights and Freedoms, Constitution Act of 1982*. Both BC's and Canada's Environmental Assessment Acts prescribe inclusion of aboriginal persons in the assessment process with respect to consultation, and impacts on tradition, resource- and land-use.

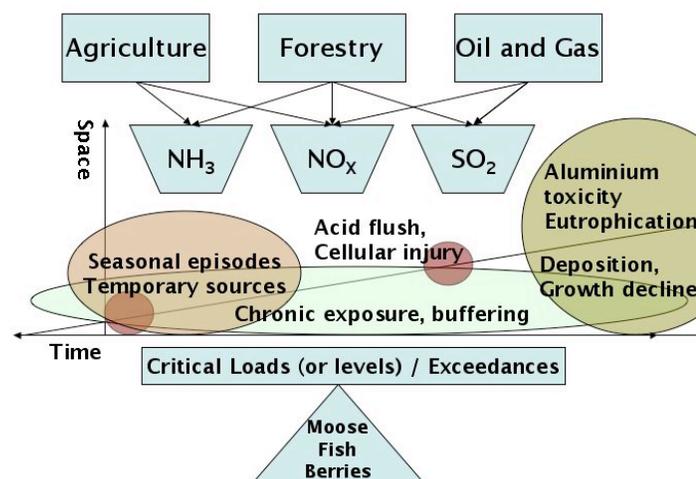
Community consultation took place at various project stages. A number of development-based concerns emerged from the initial consultation with First Nations communities including: 1) that air and water pollution are affecting human and ecosystem health; 2) that land-use and degradation are altering habitat and land resources; 3) that the ability to "pursue usual vocations", a right proclaimed in *Treaty No. 8*, is being threatened by current practices of natural resource development in the region. The work presented here specifically approaches air pollution and ecological effects, but acknowledges that this impact pathway is inextricably tied to water quality, the people, and the land base on which they depend. Results from community consultation (McGuigan, 2006) were used to define culturally relevant indicators, thresholds, foci and study area boundaries.

Four main research questions evolved through initial consultation and literature reviews. These are:

- 1) What are the main sources of emissions and what are their characteristics/levels?
- 2) How sensitive are ecosystems in northeast BC to these types of pollutants?
- 3) Are the levels of pollutants received by ecosystems capable of causing impacts?
- 4) How might the cumulative impacts from atmospheric pollutants translate into the compromising of aboriginal/treaty rights and interests of local First Nation communities?

The following chapters address (and answer) each of these research questions. Chapter 2 addresses research question 1. Chapter 3 addresses research question 2, and Chapter 4 addresses research question 3. All of the following chapters to some extent address First Nations rights and interests (question 4). The framing of cumulative impacts from a First Nations' perspective requires a unique approach that accommodates treaty rights and reflects indigenous values. Here the cumulative effects resulting from air pollution pathways provide the focus for such an assessment framework. The cumulative impact schematic given previously (Figure 1-2) can be substituted with examples from the natural resource sector and air pollution effect pathways (Figure 1-4) to illustrate the interactions and timeframes of impacts on ecosystem receptors.

Figure 1-4. Schematic of cumulative effects along air pollution pathways, using examples of natural resource sector activities and First Nations defined environmental receptors.



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2 THE IMPORTANCE OF POLICY IN EMISSIONS INVENTORY ACCURACY – A LESSON FROM BRITISH COLUMBIA, CANADA¹

2.1 Background

The first step in developing any regional air quality assessment programme is the preparation of an atmospheric emissions inventory. An emissions inventory is necessary for receptor-based modelling of dispersion and deposition; identifying dominant source areas or management zones; and in establishing appropriate policy guidelines or regulations. Once an emissions inventory has been developed, appropriate steps must be taken to assure its validity. Emission estimates are known sources of state uncertainty in studies of acidic deposition (Smith et al., 2001; Bouwman et al., 2002; Zhang et al., 2005), air quality (Russell and Dennis, 2000; Tao et al., 2004; Simon et al., 2008), and climate change (Winiwater et al., 2001; Jain, 2007; Mander et al., 2007), but this uncertainty is not always conveyed in public policy and may go far beyond choice of emission factors.

This particular example comes from Canada – a nation of ten provinces and 3 territories whose individual governments hold significant jurisdictional power over public goods such as health care, education and the environment. As such, provinces/territories also have jurisdiction to set their own atmospheric emission limits, standards, permitting, and reduction programs, usually through their ministries of Energy or Environment. As a result of these independent legislative measures, emissions reporting and estimation guidelines have historically been incongruent across provincial/territorial boundaries. Here the focus is on British Columbia (BC) where provincial emissions policy and legislation have allowed many pollutant sources to operate unnoticed by federal inventories.

In Canada during the year 2000 reporting period, atmospheric emissions data were maintained at two different jurisdictional levels; federal and provincial (or territorial). The National Emissions Inventory of

¹ A version of this chapter has been published. Krzyzanowski, J., 2009. The importance of policy in emissions inventory accuracy – a lesson from British Columbia, Canada. *Journal of the Air and Waste Management Association* 59: 430-439.

Criteria Air Contaminants was founded in 1970. By the mid-1980s this inventory evolved into a collaborative effort between the federal government, and the Environment and Energy Ministries of each province and territory (PDB/Canadian ORECH Environmental, 2004). A federal emissions inventory was compiled using individual inventories from provinces and territories. Each provincial inventory quantified annual emissions of compounds classified as Criteria Air Contaminants (CAC), namely carbon monoxide (CO), ammonia (NH₃), nitrogen oxides (NO_x), particulate matter ≤10µm in size (PM₁₀), particulate matter ≤2.5µm in size (PM_{2.5}), sulphur oxides (SO_x) and volatile organic compounds (VOC). These substances are known for their contributions to the formation of acid rain and smog, and for the role they play in urban air quality.

BC is not known for its poor air quality. As a result the province has not been included in federal SO_x and NO_x emission reduction programs. Some urbanised areas in southern BC have received attention regarding poor air quality, particularly in relation to elevated tropospheric ozone concentrations at higher altitudes in the Lower Fraser Valley downwind of the city of Vancouver (McKendry et al., 1997; Krzyzanowski et al., 2006). However, BC's northern and more remote locales have received less attention in terms of air quality monitoring and research. We focus here on northeastern BC where a recent boom in oil and gas extraction has created concern regarding the deterioration of local air quality.

In the northeast of the province there are currently four publicly operated particulate matter (PM) monitors and five industry-run SO₂ and/or H₂S monitors located near large gas plants, three of which are situated in the town of Chetwynd. Data for all of these sites are available through BC's Ministry of Environment's Air Resources Branch; however, these data are "unverified" and most concentration readings are zero (BC Ministry of Environment, 2009). In northeast BC the scarcity of monitoring data is not all that is limiting realistic air quality management. Many of the region's atmospheric emission sources are omitted from emissions inventories.

In BC, the year 2000 CAC emissions inventory (from now on referred to as BC-CAC) included emissions from sources operating under the authorization of the BC Ministry of Environment (formerly the Ministry of Water Land and Air Protection) through permits (fees) under the *Environmental Management Act – Permit Fees Regulation* (British Columbia, 1992). For the upstream oil and gas sector, these permits were required by sources such as large compressor engines. Additional emission estimates were made through the registration of individual sources that emit or remove 30 tonnes of sulphur or more over a 15-day period as prescribed by the (former) *Waste Management Act – Oil and Gas Waste Regulation* (British Columbia, 1996). The upstream oil and gas sector (UOG) is defined here as any facility or activity related to the exploration, extraction, production, compression and transport of crude oil or natural gas, and the processing of natural gas. UOG does not include oil refining or any other processes occurring after the product has been marketed, but does include pipelines. UOG emission permits are also administered by BC's Ministry of Environment for inter-provincial sources such as pipelines that are regulated by the National Energy Board (Canada, 1992).

Once complete, individual emissions inventories for the provinces and territories, were combined at the federal level into a national inventory and formatted for air quality and dispersion modelling. The Criteria Air Contaminants Division of Environment Canada subsequently filled in any perceived provincial data gaps (Wakelin and Rensing, 2004) as area sources using methods described in Canada's *2000 Criteria Contaminants Emissions Inventory Guidebook* (PDB/Canadian ORTECH Environmental, 2004). This national inventory was compiled every five years, the 2000 inventory being the most recent emissions dataset available at the time of this research. As of 2002 Canada's inventory has been conducted annually.

Since 2002 all CAC and other pollutant releases have been reported through the National Pollutant Release Inventory (NPRI) (Environment Canada, 2007; Deslauriers and Niemi, 2005). Under development of the OWNERS (One Window for Environmental Reporting System) launched by Environment Canada in 2005, emissions reporting in Canada is now central and standard across

jurisdictions and pollutants (Deslauriers and Niemi, 2005). Although NPRI reporting has always been mandated by the *Canadian Environmental Protection Act* (Canada, 1999), this database previously acted as a source of information for the public rather than a source of either scientific data or model-ready input (see http://www.ec.gc.ca/pdb/npri/npri_home_e.cfm). The NPRI is Canada's Pollutant Release and Transfer Register and has historically focused on larger industrial/commercial releases of over 300 chemical compounds and substances of concern. Information from the NPRI was used to fill gaps when preparing the year 2000 inventory of criteria air contaminants at the national level (PDB/Canadian ORTECH Environmental, 2004).

Detailed emissions inventories exist for specific industrial sectors or geographic regions. An example is 'A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H₂S) Emissions by the Upstream Oil and Gas Industry'. This inventory and its supporting documents were developed for the Canadian Association of Petroleum Producers by Clearstone Engineering, released in 2005, and included UOG sources exempt from year 2000 BC-CAC emissions reporting (sulphur inlet rate of <30 tonnes per 15 days). The year 2000, is the only year that any inventory of this detail existed for Canada's UOG industry. Because these UOG sector facilities are not regulated by the National Energy Board, provincially by the Ministry of Environment, or federally by the NPRI, many did not appear in the year 2000 BC-CAC for the northeast region as either point or area emission sources (as discussed below), and were not available for inventory inclusion until the CAPP inventory was released in the year 2005. This supplementary emissions inventory is referred to below simply as "CAPP".

In order to elucidate the effects of BC's permitting and reporting policies on CAC emissions inventories, emissions from the CAPP inventory for upstream oil and gas were combined with BC-CAC emissions from all sectors in the study area, to arrive at a more complete point source inventory for the region for the year 2000. This new combined inventory, whose creation, formatting and analysis are discussed

below, is starkly dissimilar to the official emission inventory estimates in the region for the year 2000. The potential consequences of this regulatory oversight are discussed, and in an effort to prevent the further development of unrealistic air quality management goals, policy recommendations are made.

2.2 Approach

2.2.1 Study Area

The emissions inventory represents all known year 2000 point- and area-source atmospheric releases from the 220 150km² area (Figure 2-1). The study area referred to here as ‘northeast BC’ is a region of plains and mountains just west of the petroleum-rich province of Alberta. Although BC consumes more crude oil than it produces, natural gas exports in 2000 were 14.7 million cubic metres per day or 55.3% of total production (Davies, 2004). British Columbia is now (and was in the year 2000) the second largest natural gas producer in Canada, and Canada is the third largest in the world (CAPP, 2007). Production and exploration have increased rapidly in recent years, illustrated by the continuing rise in new wells drilled annually (see Figure 2-2). The province intends to double year 2000 production volumes of both oil and gas by the year 2010 (EMPR, 2005). This increase in production, without the simultaneous implementation of available technological advances, will lead to increased atmospheric emissions from the upstream oil and gas sector. Environment Canada, the federal office responsible for national air quality standards and policy, predicts that UOG sector year 2015 emissions of SO_x, NO_x and VOC will increase above and beyond 1990 baselines (Environment Canada, 2007).

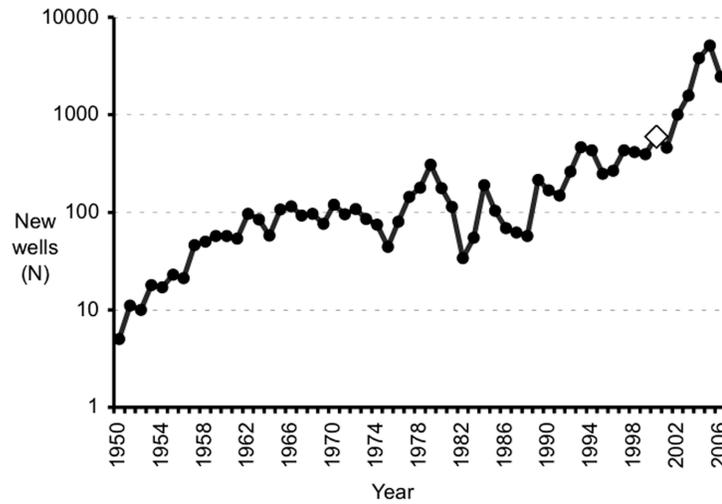
Figure 2-1. Map of Canada showing location of the study area (hatched), and Treaty 8 BC's traditional territory (white). The province of British Columbia includes both the white area and the dark grey area.



Current National CAC summaries for the year 2005 place upstream oil and gas sector contributions as responsible for more than half of the SO_x (36 286 tonnes per year or 57.4%) and NO_x (55 075 tonnes per year or 62.3%) emissions for the province of British Columbia (Environment Canada, 2007) most of which occurs in the northeast (the study area). Despite UOG sector dominance, other industries such as forestry, mining, and agriculture also contribute to atmospheric emissions, and add to the rapid modification of the landscape, impacting the people dependent on that landscape. This work is part of a Cumulative Effects Assessment for northeast British Columbia conducted on behalf of the Sustainable Forest Management Network (a Canadian Network of Centres of Excellence), at the request of the Treaty 8 Tribal Association of British Columbia, and represents work on behalf of six First Nations partners and two provincial government partners. The area outlined (hatched) in Figure 2-1 represents a substantial part of Treaty 8 First Nations traditional territory and approximately 98% of past and present UOG activity in British Columbia (OGC, 2007). This part of British Columbia is rural and largely remote. The

northeast's year 2000 population of 63 902 represented less than 2% of BC's (BCSTATS, 2008). Of those residing here about 13% consider themselves to be of aboriginal (or First Nations) descent.

Figure 2-2. Semi-logarithmic plot showing the number of new oil and gas wells drilled each year from 1950 – 2006 in the province of BC (note: the numbers are not cumulative). The diamond represents the number of new wells drilled in the 2000 reporting year. *Data source: OGC (2007).*



2.2.2 Data Collection

BC-CAC data for the 2000 reporting year were obtained, under an agreement of confidentiality, in Inventory Data Analyser (IDA) format from the Pollution Data Branch of the Criteria Air Contaminants Division of Environment Canada. The inventory had been prepared in accordance with the methodology described in methods manuals (PDB/Canadian ORTECH Environmental, 2004; Wakelin and Rensing, 2004), and was near ready for processing with the Sparse Matrix Operator Kernel Emissions (SMOKE) emissions processor, to be used with the Community Multi-scale Air Quality Model (CMAQ).

Clearstone Engineering Ltd. supplied the UOG specific inventory, under request from CAPP for whom it was developed. These data were not formatted for modelling purposes. The inventory was obtained in Microsoft Access© format and required rearranging, SCC (source classification code) assignment, and a variety of other technical modifications (discussed in the following). Both of the inventories lacked stack

parameters or temporal profiles and these were also created in order to better represent emissions specific to the region's upstream oil and gas industry. The CAPP point-source inventory estimated SO_x as sulphur dioxide (SO₂) and also contained emissions of hydrogen sulphide (H₂S) – a common component in the natural gas reservoirs of northeast BC.

The CAPP inventory's development is discussed in detail in Clearstone Engineering Ltd. (2005a). For the study area, most emission sources were estimated using non-confidential well and facility data from the BC's Oil and Gas Commission (OGC, 2007) and emission factors developed for Canada's UOG sector. However, for some facilities, actual emissions monitoring data was available, and for other sources such as glycol dehydrators and storage tanks, emission source simulation models were used to estimate CAC and H₂S releases.

2.2.3 Inventory Formatting – Source Classification and Stack Parameters

Both the BC-CAC and the CAPP inventories required formatting to make them comparable. To be used in SMOKE or other emissions processor, or to be used in combination with other more 'traditional' CAC inventories, each emission source from the CAPP inventory needed to be assigned a representative SCC (Source Classification Code) and SIC (Standard Industrial Classification). SCC were ascribed to emission sources based on 'Source Sector', 'Emission Category' and 'Emission Subcategory', as detailed in Appendix A. These classifications also enabled the analysis of emissions by source category (SCC). The assignment of SCC to upstream oil and gas sector point-source emissions was largely subjective. When doubt arose in the appropriateness of any given SCC in describing a point source in the CAPP inventory, any data inconsistencies, or missing spatial coordinates, Clearstone Engineering who developed the inventory for CAPP, were contacted for advice. All point-sources in the CAPP inventory were assigned SIC 1311 – 'Crude Petroleum and Natural Gas'. Note that recent changes have been made to the way industrial classifications are made in Canada: although the year 2000 BC-CAC and the national inventory were formatted to use SCC and SIC classifications, this is being replaced with the

NAICS (North American Industry Classification System) to standardise Canadian classifications with those of the United States and Mexico (Statistics Canada, 2006). SCC and SIC methods of source classification are utilised here for consistency with the year 2000 emission inventories.

Both the BC-CAC and the CAPP year 2000 emission inventories suffered from stack parameter scarcity. Emissions processing programs such as SMOKE interpret zero-filled fields as default values so that parameters such as stack temperature or exit velocity are entered using cross-reference tables provided with the program. However, SMOKE was developed in the USA and uses imperial units for stack parameters. Of the 590 point-sources in the BC-CAC, none had stack parameters and therefore the zero fields were in their place, resulting in the application of default stack parameters by any emissions processing system. In the process of converting from degrees Celsius in the Canadian data to degrees Fahrenheit for emissions processing, zero-filled temperature fields were replaced with values of -40 in the BC-CAC. This is below freezing temperature and is therefore an unlikely characteristic of any of the stacks that the value was assigned to in the CAC inventory for the province of British Columbia.

Default stack values provided with emission processing systems such as SMOKE, are unrepresentative of UOG point-source emissions – especially sour-gas flaring (a common practice in northeast British Columbia). The default stack parameters for ‘gas flares’ were reassigned using methods detailed in Appendix B. In addition, operating schedules were clarified with phone calls to local plants, mills, and industry experts, for all emission point sources in the northeast since temporal defaults were considered inappropriate. Individual operating schedules were allocated to the two coal mines, and two mills (one pulp and paper, the other ply- and stand-board) operating in the region in the year 2000. All UOG source emissions were temporally distributed based on monthly statistics from the BC Ministry of Energy, Mines and Petroleum Resources (EMPR, 2000) for wells drilled, gas plant receipts and disposition, and by-product production. All UOG point sources were assigned an operation schedule of 24 hours per day, 7

days per week within the monthly variations. The CAPP inventory also provided an H₂S (hydrogen sulphide) emissions field, discussed further in the following sections.

2.3 Findings

2.3.1 Contributions of Unreported Point-source Emissions

When unregulated UOG sector emissions are added to the BC-CAC for northeast British Columbia, total annual atmospheric emissions for the region increase dramatically. Table 2-1 gives the BC-CAC and CAPP emission totals of area and point source CAC for the study area. Annual totals of NO_x, SO_x and VOC emissions nearly double when unreported UOG emissions are included with BC-CAC estimates, increasing by 115.1, 89.9, and 109.5 percent, respectively. Conversely, CO and PM emission levels are dominated by saw-, pulp- and planing mills; these sources requires air release permits and are therefore included in the BC-CAC estimates.

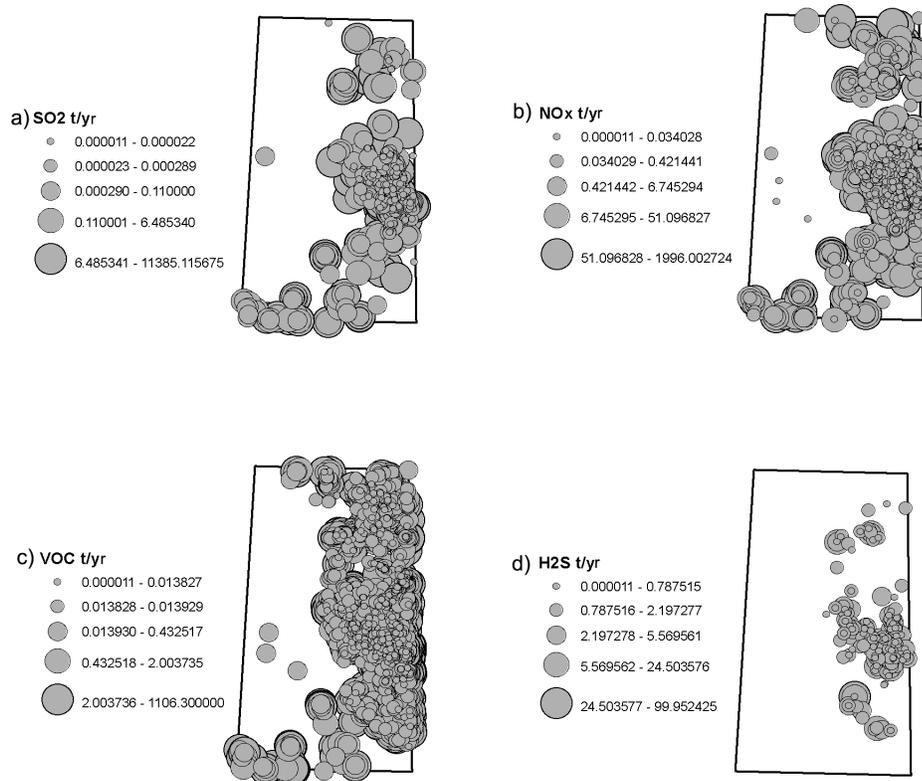
Table 2-1. Summary of CAC emission from stationary point and area sources. All values are in tonnes per year rounded to the nearest tonne.

N	source	CO	NH ₃	NO _x	PM ₁₀	PM _{2.5}	SO _x	VOC	H ₂ S
BC-CAC		140447	4656	32769	13451	9446	34825	23911	0
589	point	90014	1257	29706	8661	5327	22947	12881	0
140	area	50433	3399	3062	4790	4119	11879	11031	0
CAPP		44816	0	37704	980	977	31318	26183	644
10129	point	43297	0	33422	467	467	25214	15435	472
4	area	1519	0	4282	513	510	6104	10748	172
TOTAL		185263	4656	70473	14431	10423	66143	50095	644
729	point	133311	1257	63129	9128	5794	48161	28316	472
144	^a area	51952	3400	7344	5303	4629	17982	21779	172

Note: BC-CAC = British Columbia's Inventory of Criteria Air Contaminants; CAPP = The Canadian Association of Petroleum Producers supplementary inventory of unreported emissions for the UOG sector only; ^aMobile emissions are not included in the area source estimates.

The spatial extent of point sources is illustrated in Figures 2-3 a–d. The figures represent maps of the study area (outlined in Figure 2-1) and all point sources (N) by geographic location. Symbol size indicates source strength in tonnes per year for each a) SO_x (N=572), b) NO_x (N=1355), c) VOC (N=10425), d) H₂S (N=225), and breaks in source strength classifications are quartiles of the data ranges. All four CAC have emission sources grouped around the central-eastern region of the study area – also the area of most extensive UOG exploration and development. The southwest region contains some large emission sources at pulp- and saw-mills.

Figure 2-3 a–d. Map of study area (see Figure 2-1) showing locations and magnitudes of the CAC emission point sources from the combined BC-CAC and CAPP inventories for a) SO_x, b) NO_x, c) VOC, and d) H₂S. Symbol size ranges represent interquartile ranges.



The upper value in each of the figure legends represents the maximum point source emission level (tonnes per year) for that CAC in the year 2000. SO_x emissions from individual sources reach particularly high levels (11385.116 tonnes per year). The number of sources were especially high for VOC – 10425 or

97.3% of all point sources are estimated to emit some VOC, while only about 2.1% of all point sources in the inventory had emission fields for H₂S – not traditionally considered as a CAC or reported in CAC emissions inventories.

2.3.2 Contributions by Source-type

In northeast BC, anthropogenic NO_x, SO_x, VOC and H₂S emissions are dominated by the UOG sector.

Figure 2-4 shows the contributions of various source sectors (SIC) to each of these CAC and includes both area and point sources from the combined inventory. SIC contributing to <1.0% of the total annual emissions of any compound are classified as “other”. The extraction of either crude oil or natural gas, are the main sources of NO_x (74%), SO_x (92%) and VOC (57%), and natural gas transmission the second most important source of NO_x (19%), and SO_x (15%). Saw- and pulp- mills make a significant contribution (36%) to VOC, and they are also the main sources of CO, NH₃, and PM emissions in the region.

Figure 2-4 a–c. Contributions by SIC to a) SO_x, b) NO_x and c) VOC emissions in northeast British Columbia for the year 2000. Includes both point and area stationary source contributions.

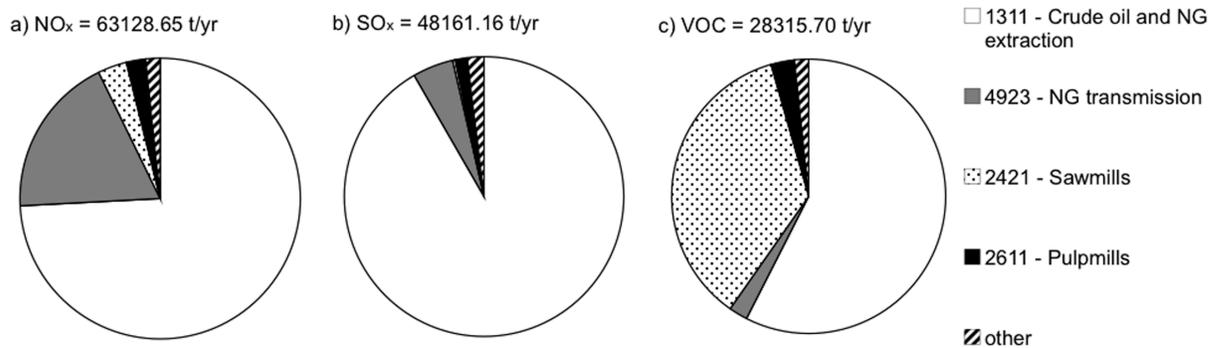


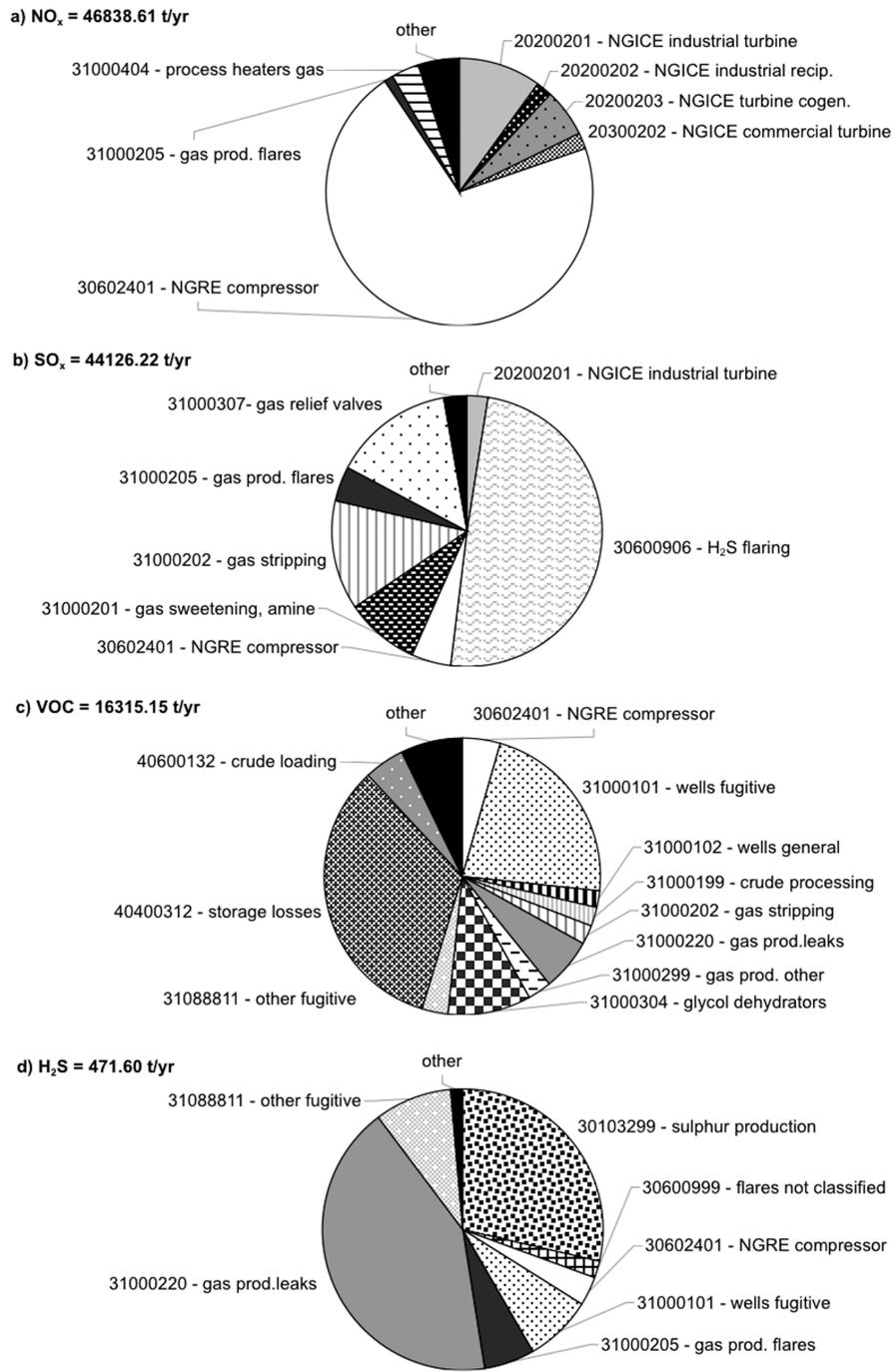
Figure 2-5 shows the makeup of annual NO_x, SO_x, VOC and H₂S emissions for SIC 1311 (crude oil and natural gas extraction) by SCC. Again the category “other” includes all source sectors contributing <1% of the annual emissions (and varies between compounds). Within the “extraction” sector, there is no single source type that dominates all CAC emissions. Instead, each compound has a unique set of sources

responsible for its release into the atmosphere. Nitrogen oxides are primarily a product of natural gas combustion. Natural gas is used as a fuel source in a number of processes including compressors and pump engines. Additional NO_x is emitted by the flaring of natural gas during production activities (mainly well tests and pressure relief). While natural gas (CH_4) is only flared when absolutely necessary, flaring is a common method used to dispose of H_2S in 'sour gas' streams – accounting for 48% of the SO_x produced in the region. Another 37% of the SO_x emitted arises from sources other than flaring during the processing of sour gas including, stripping (separating H_2S from the CH_4), amine sweetening (liberation of H_2S or CO_2 acid gases from a gas stream using amine-based solvents), and via pressure relief valves. VOC emissions are predominantly fugitive (as leaks and evaporative losses), or are vented as off-gas from glycol dehydrators. H_2S emissions are mainly attributed to equipment leaks (59%), the rest being primarily elemental sulphur production (sequestered from H_2S) or incomplete combustion at the flare stack.

2.3.3 H_2S Contribution

The CAPP inventory included estimates of annual H_2S emissions from UOG sources that fall below BC permitting thresholds. It is unknown what the H_2S emissions would be from larger point or area sources in the region as H_2S is not considered as a CAC, but is now included in NPRI reporting guidelines. H_2S emissions for the study area in the CAPP inventory were estimated to total 643.74 tonnes per year – typically as “fugitive” emissions (see Figure 2-5d). H_2S is oxidised in the atmosphere (primarily by OH) into SO_2 with a lifetime of approximately 70 hours. Assuming that all of the estimated 643.74 tonnes of H_2S were oxidised into SO_2 in the atmosphere in the year 2000, it contributed approximately 1209.60 tonnes of additional SO_x (as SO_2) to the atmosphere in northeast British Columbia. This represents only a 1.83% increase over the SO_x emissions reported here, and it is likely that H_2S is more important as a primary pollutant in terms of human and ecosystem health, than as a chemical precursor for atmospheric SO_2 production.

Figure 2-5 a–d. Year 2000 UOG (SIC 1311) contributions by SCC to a) SO_x, b) NO_x c) VOC and d) H₂S emissions in northeast British Columbia. NGICE = Natural gas-fired internal combustion engine, NGRE = Natural gas-fired reciprocating engine, gas = natural gas, crude = crude oil, and prod. = production.



2.4 Discussion

Large quantities of atmospheric emissions in northeast BC go unreported and without permits – a result of activity threshold exemptions. The exempt emission sources are primarily those of the upstream oil and gas sector. It is worth mentioning that the year 2000 BC-CAC includes estimates (as area sources) of bakeries (SCC 2302050000) and human breathing (SCC 9900000100), giving an air of comprehensiveness. However, thousands of UOG sources are excluded as area sources. For the entire study area, BC-CAC SO_x area-source emissions totalled ≈ 11878 tonnes per year, representing approximately 38% of total point-source SO_x emissions from the CAPP inventory ($\approx 31\,318\text{ t}\cdot\text{yr}^{-1}$). While there may be some overlap between the BC-CAC area sources and CAPP point sources, it is difficult to determine the extent due to the nature of area source emission estimates. Fugitive emissions, other than those from coal piles, are also excluded from the year 2000 BC-CAC. However, these emissions from log-sort yards, waste-water treatment etc. are likely to be small, due to low source densities, when compared with the UOG sources focused on here. The discrepancies between actual emissions and emissions inventories have far-reaching implications, from international conventions and transboundary issues to local air quality management and treaty negotiations. The following discussion is however, limited to uncertainty, policy and how we may reshape our atmospheric future.

2.4.1 Unknown Uncertainty

The uncertainty range in BC-CAC / national emission estimates are not described in either the British Columbia inventory methods manual (Wakelin and Rensing, 2004), or in the 2000 CAC Emissions Inventory Guidebook (PDB/Canadian ORTECH Environmental, 2004). However, these guides provide reference to methodologies used in determining emissions from various source sectors, each having their own unique error and uncertainty characteristics – many of which may be found through the US-EPA's Technology Transfer Network (US-EPA, 2007). The CAPP inventory compendium gives the upper and lower uncertainty within 95% confidence limits for each individual emission factor ($\text{kg}\cdot\text{hr}^{-1}$) used in the UOG emission inventory (Clearstone Engineering Ltd., 2005b). Uncertainties in emission estimates

range from: 100% for assumptions in facility equipment layouts; 25% for most emission factors, H₂S concentration or sulphur recovery efficiency; to as low as 10% for speciation profiles, molecular weight and heating value data. Despite high uncertainty, these factors are appropriate in estimating the total emissions within northeast BC because of the large source population. Errors associated with these uncertainties become more significant if factors are used for more local (smaller) source populations.

The uncertainty of the data presented here does not end with the emission factors. While only 2.1% of the point sources here had fields of H₂S, 43.28% of raw streams to all non-confidential oil and gas wells drilled in the area up to July of 2007, had some H₂S content (OGC, 2007). When only CAPP point sources are considered, only 2.2% of sources have H₂S emission fields, implying that there remain discrepancies between emissions inventory data and ‘the real world’. H₂S is not traditionally reported in BC-CAC and its sources are still under-estimated by the supplementary CAPP inventory.

Despite how ‘uncertain’ a particular emission estimate may be, as long as its uncertainty is disclosed and accurately represented, the appropriate policy and management decisions can be made by accounting for this uncertainty (or numerous potentials). If the uncertainties surrounding emissions are unknown or undisclosed (as in the case of the BC-CAC emission inventory in northeast BC) neither policy nor management decisions can be made appropriately. For example, the government of BC’s decision to double year 2000 UOG activity by 2010, without developing stricter industrial emission standards or reporting guidelines, may have been influenced by the low levels of emissions reported at the time.

2.4.2 Provincial Policy

The BC Energy Plan – A Vision for Clean Energy Leadership (British Columbia, 2007), promises to “reduce air emissions”; ensure “sound environmental land and resources management”; and “eliminate all routine flaring” at wells and oil and gas production facilities by 2016. It also plans to encourage development of “new technologies” and “conventional and unconventional resources”. Although

northeast British Columbia is home to many emerging new UOG technologies (such as solar-powered injection pumps for pipelines, acid gas (CO₂ or H₂S) sequestration, and benzene reductions from glycol dehydrators) these advances have largely been initiated by industry. While some innovations may be publicly funded (British Columbia, 2007), there is no legislative incentive for their application and still no sulphur (or CO₂) recovery required for facilities falling below the reporting thresholds.

The emission inventory presented here contains 10128 point source processes that are unregulated and therefore not included in the BC-CAC (346 of which represent flaring at oil and gas producing wells and facilities). “Routine flaring” traditionally refers to “associated” natural gas produced as a by-product at a well or facility whose purpose is crude oil production. 226 of the 346 year 2000 flares in the northeast BC inventory were associated with crude oil production (SCC 31000160), the rest being associated with H₂S flaring and emergency or well-test situations. Associated gas flares however, made no significant contribution to CAC. These sources are pure natural gas (CH₄) flames that under optimal conditions will produce some NO_x from combustion, but primarily release CO₂ and H₂O – these greenhouse gases are not discussed here. However, conditions are rarely optimal and even natural gas flares may produce a variety of volatile organic compounds through incomplete combustion processes brought on by high winds (Leahey and Preston, 2001).

2.4.3 National Policy

When the atmospheric CAC emissions from thousands of ‘small’ and unregulated UOG sector sources in northeast BC were summarised cumulatively, they became as significant to local, regional, national and global air quality issues as the reported emissions from large facilities. In the 2000 reporting year, “petroleum refining, heavy oil upgrading, oilsands mining, extraction and upgrading and natural gas distribution” were also exempt from emissions reporting to Canada’s NPRI, regardless of the production capacity or man-hours of labour (Canada, 2001; PDB/Canadian ORTECH Environmental, 2004). These types of sources are responsible for the most of the emission inventory underestimates discussed here.

Recent changes to federal policy related to the *Canadian Environmental Protection Act, 1999* include *Bill C-30* (Canada's "*Clean Air Act*") and a "Notice with respect to reporting of information on air pollutants, greenhouse gases and other substances for the 2006 reporting year" (referred to here on in as "the Notice") (Canada, 2007). *Bill C-30*, on its release in October 2006, received criticism from environmental groups and the public media. Now on the back pages, *Bill C-30* remains riddled with vague terms such as "any reasonable things that may be necessary", allows federal or provincial environment ministers to change reporting and monitoring guidelines when they "believe" it is justified, and includes provisions so that the "person making the report under subsection (1) may request their identity and any information that could reasonably reveal their identity not be released". Words such as "reasonable" and "believe" hinder enforcement and are open to numerous legal interpretations. Furthermore, allowances of confidentiality and reporting exemptions are not in the best interest of public health or transparency anywhere in Canada.

The Notice, while leaving less to interpretation, has more reporting exemptions. It reassigns reporting thresholds by substance and industry for the 2006 reporting year and mandates reporting CAC emissions as well as greenhouse gases under the *Canadian Environmental Protection Act, 1999* (to the NPRI). In Schedule 19 requirements specific to the upstream oil and gas sector have been changed to "total average production ... equal to or greater than 10000 boe·d⁻¹ (barrels of oil equivalent per day)" and "total greenhouse gas emissions are equal to or exceeded a release threshold of 1000 tonnes". The first condition greatly relaxes reporting requirements for UOG. Using monthly production data from BC's Oil and Gas Commission (OGC, 2007) for all "non-confidential wells" in the province during 2006, and converting to boe·d⁻¹, none of the 1277 producing wells in British Columbia exceeded the oil and gas production threshold of 10000 boe·d⁻¹ and none were required to report year 2006 CAC or GHG emissions under the Notice. This exemption includes most of the flaring and fugitive sources emissions that contributed extensively to the emissions quantified here. Only eight non-confidential facilities have

daily average production output exceeding 10000 boe·d⁻¹ (OGC, 2007), with the outputs from “confidential” sources completely unknown.

Assuming that both of the conditions are met and emissions reporting required, only those substances released above and beyond new substance thresholds are reported. Although these thresholds are quite conservative – 20 tonnes per year of SO₂, the same for NO_x and only 10 tonnes per year for VOC – as the previous discussion of exempt sources has shown, numerous seemingly insignificant emission sources become significant when considered cumulatively. But while emission reporting requirements are becoming less and less stringent, the rate of new UOG exploration and development is increasing (Figure 2-2). The Notice contains similar federal reporting thresholds for other industries, such as aluminium, metal smelting, potash, cement and chemical manufacture. However, this discussion is limited to the UOG sector as it by far dominates northeast BC.

2.4.4 International Policy

Canada is a member of a number of international conventions relating to CAC emissions and reporting. In 1979, the UNECE (United Nations Economic Commission for Europe) adopted the Convention on Long-Range Transboundary Air Pollution (CLRTAP) after surface water acidification occurred in much of North America and Europe. CLRTAP was ratified by Canada in 1981 and came into force in 1983. The *1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, formed under CLRTAP, requires emissions ceilings be set for oxides of sulphur and nitrogen, ammonia and volatile organic compounds using 1990 as a base year, and mandates emission reporting in a complete and transparent manner including those from oil and gas extraction (CORINAIR/SNAP Classification 01 05) (United Nations Economic Commission, 2003a), and UOG fugitive emissions (United Nations Economic Commission, 2003b). The Protocol only allows for confidentiality within emissions reports under provisions of the Protocol. Neither the year 2000 nor the present Canadian reporting scenarios appear to be in compliance with these conventions. Reporting confidentiality was, and is, permitted for sources that

apply for it, and many UOG sector sources were, and remain, exempt. The *1999 Gothenburg Protocol* does however allow ceilings to be set for designated ‘Pollutant Emissions Management Areas (PEMA). A Sulphur Oxide Management Area (SOMA) has been designated for Canada but extends only as far west as the border between Ontario and Manitoba. At the time this was written, there were no emission caps or reduction programs, for atmospheric sulphur- and nitrogen-oxides generated in western Canada (the energy producing provinces).

The *Canada-United States Air Quality Agreement* represents a collaborative North American ratification of the CLRTAP convention, signed by both parties in 1991. The Agreement addresses acid rain by requiring that signatories reduce their emissions of sulphur and nitrogen oxides and set ceilings for the emission of these compounds. For Canada, initial limits (1994 and 1995–1999) were set at 2.3 million tonnes per year (SO_x) for the “seven easternmost provinces”, excluding the northern territories and oil and gas rich Alberta and BC. Nationwide year 2000 caps were set at 3.2 million tonnes per year, and that same year Canada reported national SO_x emissions of less 2.3 million tonnes per year (Environment Canada 2007) using the methodology discussed for the national inventory. As part of this agreement, year 2000 and predicted future-year CAC emissions for Canada, are available from the United States Environmental Protection Agency’s Technology Transfer, but only in either post-SMOKE-processing CMAQ-ready format or as provincial and/or source sector summaries (US-EPA, 2007). In these formats, it is impossible to check, change or add emission fields, stack parameters or source information. The release of processed gridded emission fields, rather than raw point source data is to protect privacy issues, but unfortunately this practice limits the extent of analysis that may be done on the emissions dataset (especially when addressing management objectives). As indicated above, data may be both comprehensive and useful without revealing sensitive information. Additionally, emissions data from the USA and Mexico are available as geographic point source fields with individual source parameters (US-EPA, 2007). The lack of availability of Canadian data in a similar format, limits the extent of comparison

or modelling that can be done on the combined datasets in North American transboundary air pollution studies.

2.5 Conclusions and Recommendations

The analyses undertaken here reveal that emissions of NO_x, SO_x and VOC have been systematically underestimated in northeast British Columbia. With small-scale UOG sources exempt from either registration or permitting (British Columbia, 2004b), the actual emissions of each of these pollutants are almost double the figures that are reported. Use of incomplete data for modelling, effects assessment, or policy development, will yield unrepresentative results and conclusions. These underestimates put human and ecosystem health at risk of inadequate protection.

Recent changes and federal harmonisation in reporting requirements will not solve the problem of under-reporting, and may even exacerbate the problem. Bill C-30 and an associated “Notice” still contain limits on what must be reported, together with provisions that allow for confidentiality of pollutant emissions from specific sources (Canada, 2007). The rapid expansion of the upstream oil and gas sector in northeast BC, means that the data presented here represent only a portion of emissions discharged when this was written (Figure 2-2). Unless there are changes to policy, these emissions will continue to increase and will remain unreported.

The northeast corner of British Columbia provides an example of where jurisdictional contradictions and conflicts of interest have driven policy attention away from meeting the public good. Based on the above analysis of Canada’s emissions permitting and reporting requirements, the following recommendations are made to ensure a more complete representation of atmospheric emissions such that ecological and human/animal health values are protected at both local and global scales.

- 1) Standardise Canadian CAC emissions reporting requirements across sectors to eliminate inconsistencies that misguide any policy or management program stemming from them.
- 2) Remove reporting exemptions and thresholds such that inventories reflect actual emissions.
- 3) Develop source- and area-specific emission ceilings for British Columbia based on existing science, and develop incentives for the technology needed to meet these requirements.
- 4) Offer complete inventories with more transparency to institutions, private organisations and the public in a way that does not affect the privacy of industry or government (for example coded or numbered point-source facility names).
- 5) Adhere to the policy and guidelines of international agreements and conventions, or otherwise withdraw from those conventions.

Atmospheric emissions inventories were developed as a legislative tool for determining and limiting the threats that particular pollutants pose to humans, ecosystems, agriculture, and built structures. They are used in air quality and dispersion models to predict concentration and deposition values in areas where ambient monitoring is not feasible either economically or geographically. Through successive emissions inventories, the success of technological advancements and emissions reductions may be evaluated on local to global scales. Despite the numerous emission reduction programs already in effect, SO_x and NO_x emissions are increasing in western Canada – released by a thriving upstream oil and gas sector.

Rural areas such as northeast BC with economies based on energy production rather than consumption do not experience beneficial improvements in air quality when energy prices increase, as occurs in urban centres (Wettstad, 1997). Instead, their emissions increase due to increased activity. Energy extraction dominated communities around the world are experiencing a similar fate. Northeast BC is remote. The region does not have particularly high particulate matter emissions (see Table 2-1), a particularly large population (currently less than 70, 000 (BCSTATS, 2008)), or other problems associated with "urban air quality". However, the region's year 2000 emission intensity of SO_x for instance, is over 0.3 t · yr⁻¹ · km⁻²

(or $0.0008 \text{ t} \cdot \text{yr}^{-1} \cdot \text{km}^{-2}$) – comparable to that of heavily urbanised areas, and increasing. Although remote, the protection of northeast BC's vast boreal forests, muskeg, agricultural lands, traditional cultures and human health, depends on the accurate reporting of atmospheric emissions such that the state of air quality may be known. These emission inventories require policy to drive them, so that policy in turn may evolve from their guidance.

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3 BACK TO THE BASICS – ESTIMATING THE SENSITIVITY OF FRESHWATER TO ACIDIFICATION USING TRADITIONAL APPROACHES²

3.1 Introduction

Northeast British Columbia (BC) and the task of assessing the sensitivity of its surface waters to acidification, are unique in Canada for a number of reasons. The area is diverse in ecosystems, enterprise, language and culture, and has a history of traditional land use dating back thousands of years. European settlers arrived in the late 18th century, and today it is an economic hub of natural resource activity. Forestry, hydroelectric, mining, and upstream oil and gas (UOG) developments not only physically displace local people and disrupt the land-base, but release atmospheric pollutants. Of particular interest are sulphur- (S) and nitrogen- (N) oxides (primarily from the UOG sector) that can lead to the acidification of soil and surface water, and represent the majority of Criteria Air Contaminants (CAC) emitted in northeast BC (Krzyzanowski, 2009).

This study represents a portion of a larger project aimed at assessing the cumulative effects of development on the Aboriginal and treaty rights of First Nations in the region. Accordingly, this research addresses both ecological sensitivity to acidification, and the indirect effects of acidification on traditional land-use rights and interests of First Nations within the traditional territory of Treaty 8. Ecological indicators and thresholds of change were defined through collaboration with self-selected First Nations communities as outlined in McGuigan (2006). Aboriginal perspectives are applied here in assessing freshwater sensitivity to acidification, and in the development of measures (tools) by which communities can do the same.

During the 1980s, in response to acidification in parts of North America and Europe, Canadian researchers and policy makers conceptualised a means of quantifying ecosystem vulnerability to

² A version of this chapter has been published. Krzyzanowski, J., and Innes, J.L., 2010. Back to the basics – estimating the critical loads of acidity using traditional approaches. *Journal of Environmental Management* 91: 1227-1236.

acidification and determining damage thresholds (Gorham et al., 1984). This approach, now known as ‘critical loads’, has since evolved both conceptually and methodologically. Critical load(s) estimation and mapping is an essential component of the United Nations Economic Commission for Europe (UNECE) *1999 Gothenberg Protocol to Abate Acidification and Ground Level Ozone*, of which Canada is a signatory. Critical loads have also become a widely accepted method for quantifying both terrestrial and aquatic ecosystem sensitivity to acidification in North America (e.g., Dupont et al., 2005; Whitfield et al., 2006), Europe (e.g., Curtis et al., 2002; Posch, 2002) and Asia (e.g., Duan et al., 2000). The currently accepted definition of a critical load is “a quantitative estimate of 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).

Around the same time that critical loads were conceived, preliminary and somewhat preventative studies of freshwater sensitivity to acidification were beginning in western Canada. In the 1980s, BC lake surveys were conducted to assign sensitivity classes to lakes based on chemical characteristics: namely, pH, alkalinity, calcium, magnesium or aluminium concentrations (SRC, 1982; Swain, 1987). Results showed that many lakes, particularly those in northeast BC, were alkaline and at little risk of acidification from the low levels of SO₂ and NO_x deposition. However, since then, there has been substantial progress in both acidification science and industrial development. In light of these changes, we revisit the idea that freshwater lakes in the region may be sensitive to acidification under current or future emission scenarios.

Utilising all available datasets and a variety of methods, we evaluated lake sensitivity to acidification in northeast BC. The Steady State Water Chemistry (SSWC) model (Henriksen and Posch, 2001) and regression analyses between critical loads and individual lake parameters were used to develop a revised ‘back to the basics’ approach for estimating surface water sensitivity. The method is simple, and was applied to lakes lacking the detailed chemical data required by either steady-state or dynamic models. The

relationships detailed below hold promise as regional indicators for community-based cumulative effects management.

3.2 Materials and Methods

3.2.1 Study Area

Northeast BC, dominated by muskeg and boreal forest, hosts four primary biogeoclimatic zones: the Boreal White and Black spruce (BWBS), Spruce-Willow-Birch (SWB), Alpine Tundra (AT), and Engelmann spruce – Subalpine fir (ESSF) zones. The region's four main soil orders (and great groups) include the Luvisolic (Gray), Brunisolic (Dystric), Crysollic (Organic) and Gleysolic (Luvic) soils. Part of the Western Canada Sedimentary Basin, sediments vary widely in chemistry and may exhibit acidic neutral, alkaline or calcareous characteristics (Valentine et al., 1978, Soil Landscapes of Canada Working Group, 2005).

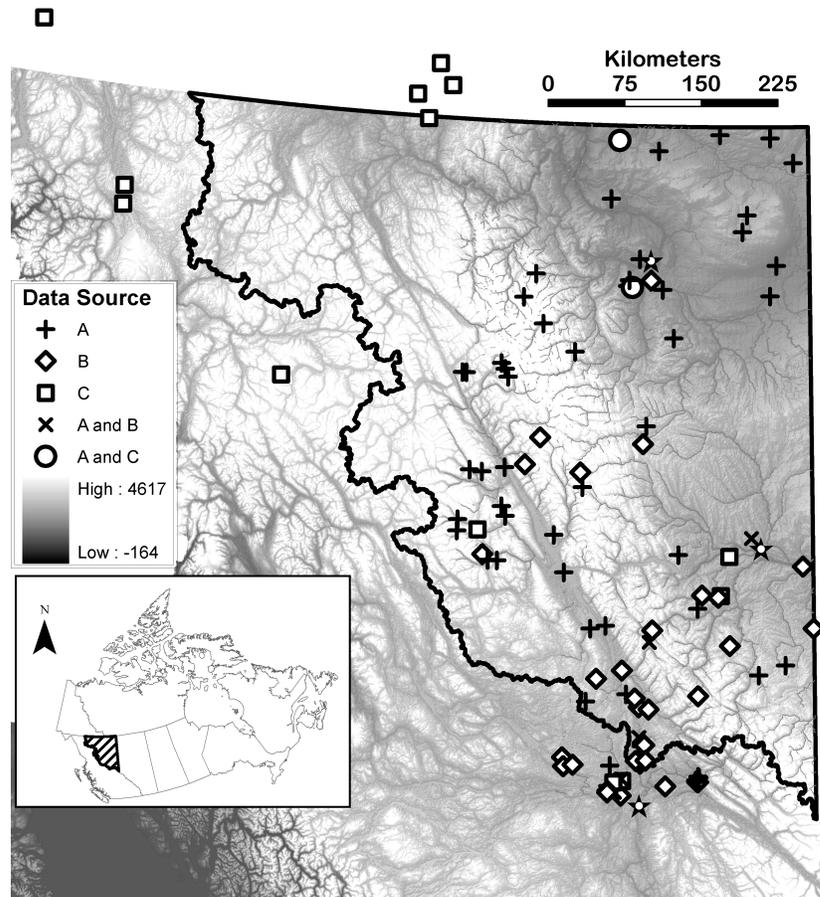
3.2.2 Surface Water Data

Three sources of data were used, constituting all available sources of lake chemistry for the region (Figure 3-1). A total of 131 lake records were compiled, representing 120 unique lakes after overlaps between datasets were averaged. Of the 120 lakes, 94 had water quality data for chemical parameters other than pH, representing <1% of all lakes in the study area.

Data from Swain (1987) (source A in Figure 3-1) included 69 lakes – those further north were sampled via float plane, while southern lakes were visited by plane, helicopter or road access. Swain's (1987) data represent one-time grab sample measurements of lake pH, alkalinity and calcium (Ca) concentrations, collected between 1977 and 1986, primarily in the winter months. pH measurements were taken from 67 lakes, Ca from 49 and alkalinity from 47, while 46 of the 69 lakes included measurements of all three chemical parameters. Samples were analysed by Ministry of Environment (MOE) staff following guidelines described in BC-MOE (1983) for pH and alkalinity. Calcium ion concentrations were

determined using either Inductively Coupled Plasma Emission Spectroscopy (ICP) or by Atomic Absorption (AA), as described in BC-MOE (1989).

Figure 3-1. Map showing the location of the study area in Canada (inset) and locations of various lake data-sources represented by symbols (see legend). The boundary of BC's Treaty 8 traditional territory (study area) is given by the black outline. Black stars with white centres mark major municipalities from south to north being Prince George, Fort Nelson and Fort St. John.



Environmental Monitoring System (EMS) data (source B in Figure 3-1) include information on lake pH and Ca concentrations taken between 1974 and 2003. The EMS dataset included 47 lakes in the study area, 40 with pH measurements, 41 with dissolved calcium concentrations and 34 with records of both pH and Ca. Some lakes have more than one station, and some stations made multiple measurements over many years. Four large lakes from source B had data spanning from the mid-1970s to the mid-1990s and

nine more had data collected through the mid-1980s and mid-1990s. Other lakes had measurements from a single day or year; no lakes had data from both before and after 1997 – around the time when increasing UOG emissions (Krzyzanowski, 2009) may have begun to change lake chemistry in the region. For all lakes with multiple measurements, data were averaged for each sampling site and then again for the entire lake so that each monitoring location was weighted equally. The Ministry of Environment (MOE), formerly known as the Ministry of Water, Land and Air Protection (WLAP), is responsible for EMS data. EMS samples are collected by either ministry staff or permittees and then analysed in public or private sector laboratories according to WLAP (2003) procedures.

The third source of data (source C in Figure 3-1) was collected in association with a trumpeter swan (*Cygnus buccinator*) survey conducted in spring and fall of 1981 and 1982 by Rick McKelvey – then of the Canadian Wildlife Service. Water chemistry measurements for 27 lakes in northern British Columbia and southern Yukon Territory were included in the dataset. These more detailed lake chemistry measurements included concentrations of dissolved ions (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , SO_4^{2-} , NO_3^-) as well as pH, conductivity and alkalinity measurements. However, only 16 of these 27 lakes could be identified geographically and of the 10 lakes located within the study area, all had measurements of pH and alkalinity, but only 7 included measurements of conductivity and dissolved ions. Samples were analysed using methods described in Committee on Analytical Methods (1979).

All of the lakes studied, save those in mountainous areas, were located at the end of first order streams and are therefore considered representative of the mean chemical status of the soils in their drainage basins (Chow et al. 1988). All data were assumed representative of annual mean values for the purpose of this analysis. This assumption is valid for those measurements made in the fall, due to turnover (Henriksen and Posch, 2001; Henriksen et al., 2002), or for those chemical values representing an average over multiple measurements, such as the EMS data. Spring sampling, which was conducted in June just after spring thaw and turnover, is considered representative of well-mixed near uniform chemical

conditions. However, due to snowmelt, spring measurements may reflect more dilute, more acidic, and less alkaline conditions than those following fall turnover (Schaefer et al., 1990). Some lakes were common between datasets and their measurements represent an average of two or more measurements made in various seasons. Surface water samples taken in the winter may not be representative of annual averages due to lake stratification – in such cases the above assumption may be invalid. Lakes with multiple measurements (of pH or Ca) over many years (from the EMS, source B data) generally showed no long-term trend. We therefore assumed historical data to be representative of current chemistry and measurements representative of steady-state conditions. Most of the surveys included large lakes due to sampling strategies (the need for a plane to be able to land and take-off on the lake, or proximity to a road). Lake sizes ranged from 0.3 – 388 ha with a median size of 180 ha for those 55 lakes with available size data.

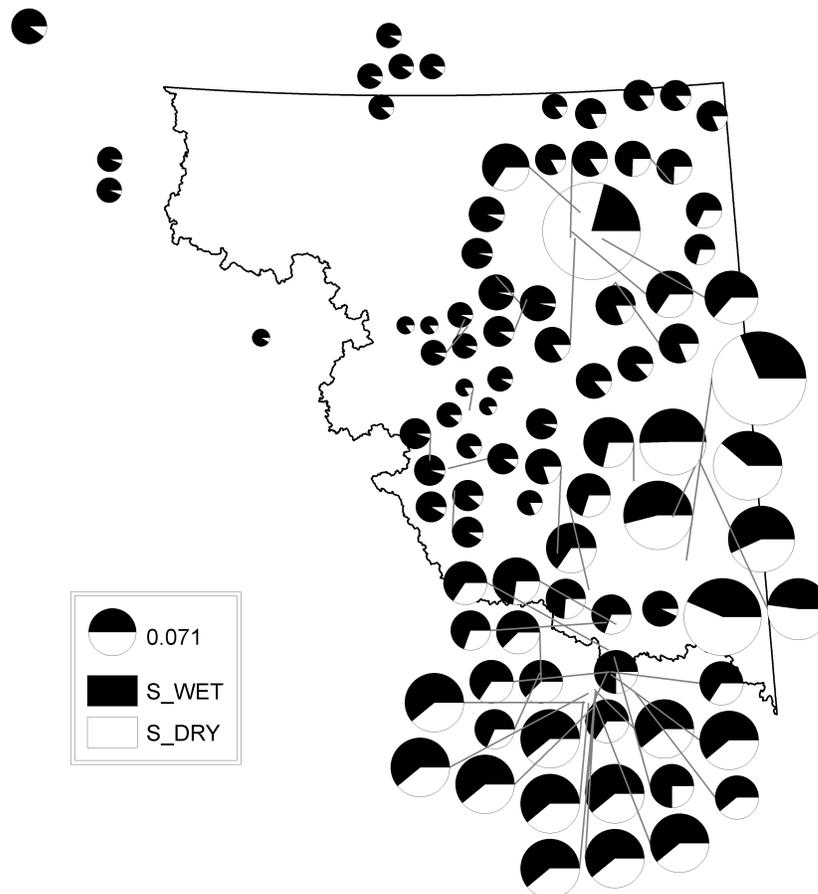
3.2.3 Deposition and Meteorological Data

Estimates of mean annual runoff, precipitation, temperature, and sulphur/nitrogen deposition (Table 3-2), were provided by Julian Aherne of Trent University (*Personal Communication* May 5, 2008). Runoff values originated from M. Posch, Co-ordination Centre of Effects, The Netherlands, using methods described in Federer (1982) and Prentice et al. (1993); i.e. subtracting modelled evapotranspiration from long-term precipitation measurements. Evapotranspiration, precipitation and temperature measurements were all simulated at a 0.5 degree resolution for the global grid (Mitchell et. al., 2004).

Estimated annual wet and dry deposition of sulphur and nitrogen at all 120 lakes originated from D. Fox, Environment Canada, Yellowknife, Northwest Territories. These values in $\text{eq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (the proton equivalency of hydronium ions per hectare per year) were modelled using CMAQ (Community Multiscale Air Quality Model v4.5) on a 36 km resolution grid over northwest North America. The CMAQ model is a state-of-the-art regulatory tool developed by the United States Environmental Protection Agency based on three-dimensional Eulerian transport and dispersion algorithms. This

simulation used Canada's year 2000 Emissions Inventory of Criteria Air Contaminants (CAC), year 2002 meteorological forecasts from MM5, the SMOKE (Sparse Matrix Operator Kernel Emissions v2.1) emissions processor, and the CB-IV (Carbon Bond 4) mechanism's gas-phase chemistry (D. Fox *Personal Communication* June 11, 2008). Wet and dry sulphur deposition estimates from CMAQ (Figure 3-2) were used in critical load exceedance calculations (discussed below). Total sulphur deposition and wet:dry deposition ratios show geographic variation. Deposition increases towards the southwest as local upstream oil and gas sources of emissions increase in density, as most sulphur is deposited near the emission source.

Figure 3-2. Estimates of wet (black) and dry (white) sulphur deposition at study lakes graduated by magnitude ranging from 0.0011 – 0.303 $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$.



3.2.4 Sensitivity Classes

Most of the available water data contained information limited to properties such as pH, alkalinity and/or calcium. In western Canada, lake sensitivity to acidic deposition has traditionally been assigned based on classes developed by the National Research Council of Canada (NRCC) (1981) and the Saskatchewan Research Council (SRC) (1982), as utilised by Swain (1987), Saffran and Trew (1996) and more recently by Foster et al. (2001). The methodology assigns a sensitivity rating to each lake of high, medium, or low based on the known chemical parameter(s). High, medium and low sensitivity classes correspond to critical loads of 0.25, 0.50 and 1.00 keq·ha⁻¹·yr⁻¹, respectively (Table 3-1). Sensitivity classes were assigned to lakes based on all and any chemical parameter data available for that lake (Table 3-2). If a particular lake had measurements of more than one chemical parameter (such as pH and alkalinity) that gave differing sensitivity classes (such as high and moderate sensitivity from Table 3-1), then the lowest sensitivity class (high sensitivity or CL(A) = 0.25) was chosen to offer more complete protection. This practice follows Swain (1987) and is in accordance with First Nations' priorities.

Table 3-1. Methodologies used for assigning acidification sensitivity classes based on single lake chemistry parameters. NRCC = National Research Council of Canada, SRC = Saskatchewan Research Council.

Freshwater Parameter	Sensitivity to Acid Deposition				Reference
	High	Moderate	Low	Least/No	
Alkalinity (mg/L CaCO ₃)	0 – 10	11 – 20	21 – 40	> 40	Saffran and Trew (1996), NRCC (1981)
Alkalinity (meq/L)	0 – 0.2	0.2 – 0.4	>0.4		Altshuller and McBean (1979)
***Alkalinity (mg/L CaCO ₃)	< 10	10 - 20	> 20		Swain (1997), SRC (1982)
pH	< 6.5	6.6 – 7	7.1 – 7.5	> 7.5	Saffran and Trew (1996)
***pH	< 6.6	6.6 – 7	> 7		Author
Ca (mg/L)	0 – 4	5 – 8	9 – 25	> 25	Saffran and Trew (1996)
Ca (mg/L)	< 4	5 – 8	> 8		Swain (1997), SRC (1982)
***Ca (mg/L)	< 4	4 – 8	> 8		NRCC (1981), Altshuller and McBean (1979)
HCO ₃ (mg/L)	1 – 12	12 – 14	>24		NRCC (1981)
HCO ₃ (mg/L)	1 – 12	12 – 24	>24		Altshuller and McBean (1979)
Conductance (µS/cm)	0 – 35	22 – 78	>60		NRCC (1981)
Conductance (µS/cm)	0 – 30	22 – 70	>60		Altshuller and McBean (1979)
***Conductance (µS/cm)	0 – 35	36 – 60	>60		Author
***CL(A) (keq H ⁺ /ha/y)	0.25	0.5	1		Foster et al. (2001), Schindler (1996)

*** used for this study

Table 3-2. Summary statistics for lake chemistry data utilised in this study.

Lake Parameter	pH -log ₁₀ H ⁺	Mg mg·L ⁻¹	Ca mg·L ⁻¹	ALK mg·L ⁻¹	COND μS·cm ⁻¹	NO ₂ +NO ₃ mg·L ⁻¹ N	ANC meq·L ⁻¹	TOC mg·L ⁻¹ C	Na:Cl	Q m·y ⁻¹
N	113	15	94	61	16	16	16	7	16.00	120
Minimum	5.50	0.0	2.0	2.07	26.6	0.001	173.2	2.9	0.93	0.062
5th percentile	6.49	1.5	3.0	18.1	52.3	0.001	530.4	3.9	1.39	0.074
95th percentile	8.40	21.9	43.6	164	384.5	0.043	3983.0	18.5	20.82	0.442
Maximum	8.58	23.4	55.0	207	386.0	0.043	4061.9	22.5	23.13	0.509
Mean	7.69	9.2	22.1	79.2	200.1	0.010	1895.0	7.1	7.23	0.250

3.2.5 SSWC Model

The SSWC model is just one example of a mass balance approach used to assess the critical loads for acidity using present day surface water chemistry. The model estimates weathering rate from the present day non-marine base cation flux and also employs an ‘F-factor’ to account for the leaching of base cations due to soil ion exchange processes. The SSWC model assumes that there is neither absorption nor retention of sulphate in the watershed and that SO₄²⁻ in runoff originates from weathering or as deposition from sea salt or anthropogenic emissions (Henriksen and Posch, 2001). It was used here to calculate the surface water critical loads for those 16 lakes with detailed chemical datasets and for which runoff estimates were available. The SSWC model is described in detail by Henriksen and Posch (2001), Henriksen et al. (2002) and UNECE-CLRTAP (2004) and follows the equation

$$1) \quad CL(A) = Q \times ([BC]_o - [ANC]_{lim})$$

where Q is runoff in m·y⁻¹, [BC]_o is the pre-acidification base cation concentration (not derived here) and [ANC]_{lim} is used as a chemical criterion to protect sensitive organisms.

Acid Neutralising Capacity (ANC) is defined as the difference between strong base cations (Ca²⁺, Mg²⁺, Na⁺, K⁺) and strong acid anions (SO₄²⁻, NO₃⁻, Cl⁻) (NAPAP, 1991; Henriksen and Posch, 2001) reflecting the freshwater system’s ability to neutralise acidity. In SSWC, CL(A) is estimated as the amount of

anthropogenic acidity (H^+) that can enter a system without reducing the ANC below a threshold level ($[ANC]_{lim}$) at which damage to sensitive aquatic ecosystem elements may occur (Henriksen et al., 1992). The $[ANC]_{lim}$ is either defined using a single fixed value or varies with catchment characteristics. Catchment-variable ANC exceeded the $50 \mu eq \cdot L^{-1}$ maximum at all lakes (Henriksen and Posch, 2001; Aherne and Curtis, 2003). The minimum calculated ANC was $173 \mu eq \cdot L^{-1}$ and since lakes contain unknown species assemblages, two fixed-value $[ANC]_{lim}$ were used for this study: $50 \mu eq \cdot L^{-1}$ and $100 \mu eq \cdot L^{-1}$.

Lakes in the study area are characteristically more alkaline than those in other parts of Canada where an $[ANC]_{lim}$ of $40 \mu eq \cdot L^{-1}$ has been used previously (Henriksen et al., 2002; Dupont et al., 2005). Higher values of $[ANC]_{lim}$ are recommended for less sensitive lakes in order to maintain their high levels of biodiversity (Henriksen and Posch, 2001), and an $[ANC]_{lim} > 100 \mu eq \cdot L^{-1}$ has been suggested for lakes with a Total Organic Carbon (TOC) $> 5 mg \cdot L^{-1}$ (Hesthagen et al., 2008); this was found for all but one of the lakes with TOC measurements (Table 3-2). A high level of protection, and the maintenance of biodiversity at all trophic levels, is in accordance with priorities held by local First Nations. We assumed that an $[ANC]_{lim} = 100 \mu eq \cdot L^{-1}$ would result in the full protection of fish (particularly Salmonidae such as bull trout (*Salvelinus confluentus*)) populations (Harriman et al., 1995) in brown water lakes (Hesthagen et al., 2008), and in protection of both pH-dependent phytoplankton biodiversity (Findlay, 2003) and calcium dependent invertebrates such as the region's BC red-listed mollusc *Physella wrighti*. The $[ANC]_{lim} = 50 \mu eq \cdot L^{-1}$ is used for purposes of comparison and conformity; it is also considered protective of fish populations (Henriksen and Posch, 2001; Moiseenko, 2002) and diatom assemblages in low TOC clear water lakes.

An $[S]$ value of $400 \mu eq m^{-2} \cdot yr^{-1}$ estimated for Norway by Brakke et al. (1990) is employed here, as in Russia (Moiseenko, 2002), Ontario (Henriksen et al., 2002; Watmough and Dillon, 2003), and Ireland (Aherne and Curtis, 2003). Results from Norway (Henriksen and Posch, 2001) were also used to estimate

pre-acidification sulphate concentrations from a linear regression with base cations. The pre-acidification nitrate concentration term $[\text{NO}_3]_0$ is assumed to be zero (Henriksen and Posch, 2001; UNECE-CLRTAP, 2004). While it is common practice in Canada and elsewhere to correct for marine-origin base cation concentrations in SSWC parameters (for example Moiseenko, 2002; Henriksen and Posch, 2001), calculations were performed without sea salt correction (such as in Henriksen et al., 2002). The Na:Cl ratios were all much higher than the 0.858 expected from marine sources (Table 3-2), indicating non-marine origins of sodium that would lead to base cation underestimates if sea salt corrections were used (UNECE-CLRTAP, 2004). Region-specific non-marine sources of Na^+ include Chernozem, Solodized Solonetz and Solod soils on lacustrine deposits underlain by marine shales (Valentine et al., 1978).

Statistical relationships between SSWC estimates of CL(A) and individual lake parameters were used to develop empirical models for estimating the acidification sensitivity of surface waters lacking adequate chemical data. Outcomes from this approach may be compared with acidic deposition estimates or measurements, in a similar manner to their steady-state counterparts (e.g., SSWC). Any “exceedances” of critical loads (EX(A)) were identified using:

$$2) \quad \text{EX(A)} = S_{\text{dep}} + N_{\text{leach}} - \text{CL(A)}$$

where S_{dep} is the total annual wet and dry deposition of sulphur ($\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and N_{leach} is the nitrogen leaching flux calculated as a product of nitrate (NO_3^-) and runoff (Q) for water bodies with nitrate data (all lacked NH_4^+ data). It was assumed that the area’s forests are managed, providing a long-term sink and removal process for excess nitrogen, even though much of the managed forest area has yet to be harvested. Lake nitrate concentrations were all quite low (Table 3-2) and N_{leach} made little contribution (<0.1%) to the exceedance calculations. In addition, total nitrogen deposition estimates discussed below (N_{dep} maximum = $1.07 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) are less than half the threshold conifer net uptake value of $2.94 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ used in the UK (UK National Focal Centre, 2003), and well below the $10\text{--}20 \text{ kg N}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ critical nitrogen load suggested for boreal forests by the UNECE’s Convention on Long-Range Transboundary Air Pollution (UNECE-CLRTAP, 2004). Therefore, the assumption that basins retain

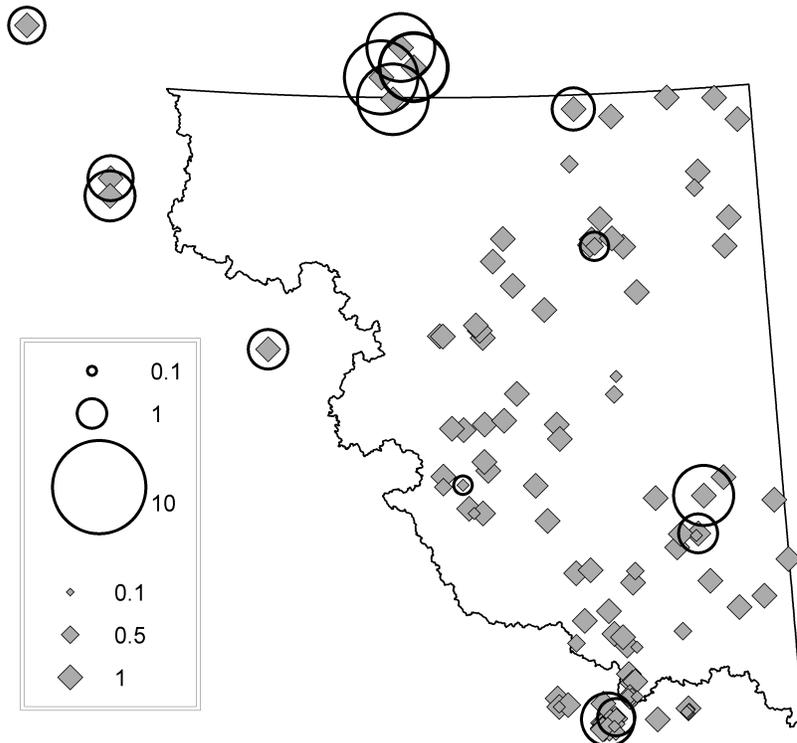
deposited NO_3^- appears valid and the term N_{leach} was set to zero in Equation 2. It follows that CL(A) and EX(A) may be regarded as the critical load of acidifying sulphur and the exceedance of the critical load of acidifying sulphur, respectively.

3.3 Results and Discussion

3.3.1 Lake Sensitivity using the NRCC/SRC Approach

Lake sensitivities to acidification estimated using conventional relationships (Table 3-1) were conservative (protective) in their sensitivity estimates when compared with modern mass-balance methodologies (Figure 3-3). For instance, the maximum critical load of acidity that can be achieved using this method is $1 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, which is lower than the maximum critical loads of acidity for lakes here and in other parts of the world, including Europe (Curtis et al., 2002; Posch, 2002) and eastern Canada (Whitfield et al., 2006; Henriksen et al., 2002). Although this class represents all $\text{CL(A)} > 1 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, the high alkalinity and ANC of most northeastern BC lakes, warrants some differentiation of higher CL(A) values. This compartmental approach also disregards the explicit nature of traditional knowledge (Nadasdy, 1999) and is too unspecific for establishing meaningful land-use agreements. The sensitivity classes assigned using this method were spatially variable and 14 lakes fell into each of the most sensitive ($< 0.25 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) and medium ($0.5 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) sensitivity classes, while the remaining 92 were not considered sensitive ($> 1.0 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$).

Figure 3-3. Map of lake sensitivity classifications (graduated diamonds) in $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ based on parameters in Table 3-1; and SSWC estimated CL(A) with an $[\text{ANC}]_{\text{lim}} = 50 \mu\text{eq}\cdot\text{L}^{-1}$ (graduated circles). Equal values would be represented by diamond corners flush with circle edges.



3.3.2 SSWC and Linear Regression

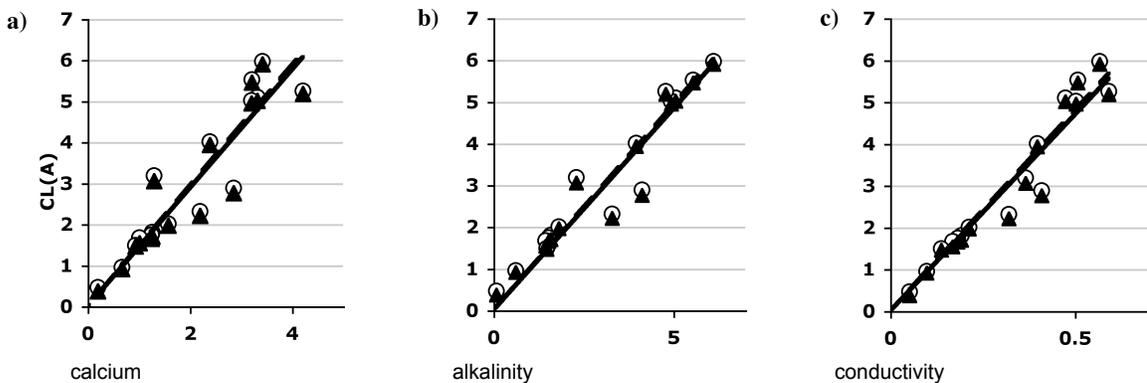
Freshwater CL(A) resulting from SSWC had a large range (first two columns Table 3-3) and showed high spatial variability (Figure 3-3). Because CL(A) values estimated using SSWC varied from those estimated using the empirical sensitivity classes described above, SSWC model results were plotted linearly against pH, alkalinity, calcium, magnesium and conductivity to examine which, if any, of these parameters offer a precise indication of CL(A). We expressed individual chemical characteristics as a product of concentration ($\text{eq}\cdot\text{L}^{-1}$) and runoff (Q) in $\text{m}\cdot\text{yr}^{-1}$, giving each parameter a value in $\text{eq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$; except conductivity with units of microsiemens per centimetre ($\mu\text{S}\cdot\text{cm}^{-1}$), which gave centisiemens per year ($\text{cS}\cdot\text{y}^{-1}$). Then with the same flux units as CL(A), parameters of pH (H^+ concentration), alkalinity (CaCO_3 equivalents) and elemental calcium and magnesium, were plotted against CL(A) to examine the predictive

capacity of these parameters in the absence of detailed chemical datasets. Linear relationships with a coefficient of determination (r^2) greater than 0.85, were deemed sufficient for indicator development (Figure 3-4).

Table 3-3. Summary statistics for CL(A) and CL(EX) calculated using SSWC and the equations derived here. Methods denoted “a” used an $[ANC]_{lim} = 50 \text{ meq}\cdot\text{L}^{-1}$ and “b” an $[ANC]_{lim} = 100 \text{ meq}\cdot\text{L}^{-1}$.

	Critical Loads / Acid Sensitivity - CL(A)						Deposition		Critical load exceedance - EX(A)					
	SSWC a	SSWC b	Eqn. 3a	Eqn.3b	Eqn. 4a	Eqn. 4b	$S^*_{dep.}$	N_{dep}	SSWC a	SSWC b	Eqn. 3a	Eqn. 3b	Eqn. 4a	Eqn. 4b
N	16	16	94	94	61	61	94	94	16	16	94	94	61	61
Minimum	0.486	0.386	0.307	0.301	0.0855	0.0838	0.011	0.023	-6.16	-6.08	-11.5	-11.2	-10.7	-10.5
5th Percentile	0.873	0.812	0.528	0.518	0.369	0.362	0.017	0.025	-5.80	-5.73	-9.26	-9.08	-9.42	-9.24
25th Percentile	1.82	1.71	1.58	1.55	1.09	1.07	0.026	0.029	-5.05	-4.98	-5.09	-4.99	-5.39	-5.29
50th Percentile	2.73	2.61	2.62	2.57	2.81	2.76	0.043	0.038	-2.39	-2.27	-2.57	-2.52	-2.89	-2.83
75th Percentile	5.30	5.22	5.11	5.01	4.62	4.54	0.093	0.062	-1.66	-1.55	-1.53	-1.50	-1.64	-1.61
95th Percentile	5.93	5.86	9.29	9.11	8.47	8.31	0.153	0.071	-0.810	-0.749	-0.490	-0.479	-0.681	-0.667
Maximum	6.28	6.21	11.52	11.30	9.80	9.61	0.303	0.077	-0.404	-0.305	-0.257	-0.249	-0.288	-0.282
Mean	3.25	3.16	3.55	3.48	3.20	3.14	0.064	0.045	-3.07	-2.98	-3.49	-3.42	-3.73	-3.66

Figure 3-4. ‘Best fit’ linear regression trend-lines for CL(A) (y) calculated using the SSWC model versus a) calcium; b) alkalinity; and c) conductivity (x) expressed as products of runoff (Q). All axes have units of $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (except conductivity (c) which is in $\text{cS}\cdot\text{y}^{-1}$). Circles represent CL(A) calculated with $[ANC]_{lim} = 50 \text{ }\mu\text{eq}\cdot\text{L}^{-1}$, and triangles $[ANC]_{lim} = 100 \text{ }\mu\text{eq}\cdot\text{L}^{-1}$. The trend-lines in a), b), and c) correspond to equations 3, 4 and 5, respectively.



The coefficient of determination for the power function calculated between CL(A) and pH (expressed as $H^+ \text{ eq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) was weak ($r^2 = 0.46$ and 0.48 for $[\text{ANC}]_{\text{lim}} 50$ and 100 respectively), but did increase slightly when multiplied by rainfall rather than runoff to achieve flux values ($r^2 = 0.54$ and 0.56). Although pH was the most commonly available parameter, those lakes having only pH data were subsequently removed from the dataset ($N = 19$) due to relatively weak relationships and complications caused by the nature of a power law function. Although pH is not a useful indicator of acidification sensitivity, it is the best indicator of acidification itself. Due to a relatively weak correlation ($r^2 = 0.673$) and a lack of measurements ($N=15$), Mg concentration was also abandoned as an indicator for estimating CL(A). The remaining lakes, with Ca ($N = 94$) and/or alkalinity ($N = 61$) measurements were used to estimate CL(A) – all lakes with alkalinity measurements also had Ca measurements. The linear plots shown in Figure 3-4 for a) calcium, and b) alkalinity, generated the following equations to estimate CL(A) for lakes with only calcium and/or alkalinity measurements:

$$(3a) \quad \text{CL(A)} = 1.55 \times ([\text{Ca}] \times \text{Q} \div 100) \quad r^2 = 0.854$$

$$(3b) \quad \text{CL(A)} = 1.52 \times ([\text{Ca}] \times \text{Q} \div 100) \quad r^2 = 0.855$$

$$(4a) \quad \text{CL(A)} = 1.04 \times ([\text{ALK}] \times \text{Q} \div 100) \quad r^2 = 0.919$$

$$(4b) \quad \text{CL(A)} = 1.02 \times ([\text{ALK}] \times \text{Q} \div 100) \quad r^2 = 0.922$$

where CL(A) is lake sensitivity to acidification in $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ estimated using SSWC (Figure 3-3), [Ca] is lake water calcium concentration ($\text{meq}\cdot\text{m}^{-3}$), [ALK] is lake water alkalinity measured as CaCO_3 ($\text{meq}\cdot\text{m}^{-3}$), Q is runoff ($\text{m}\cdot\text{yr}^{-1}$), and the factor of 100 is used to convert fluxes of either Ca or alkalinity into units of $\text{keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$. Equations labelled “a” used an $[\text{ANC}]_{\text{lim}} = 50 \mu\text{eq}\cdot\text{L}^{-1}$ and “b” an $[\text{ANC}]_{\text{lim}} = 100 \mu\text{eq}\cdot\text{L}^{-1}$. The CL(A) may then be used in Equation 2 to calculate critical load exceedances (EX(A)) caused by wet and dry deposition of sulphur (S_{dep}). A similar equation using conductivity measurements is:

$$(5a) \quad CL(A) = 10.10 \times ([COND] \times Q \div 100) \quad r^2 = 0.936$$

$$(5b) \quad CL(A) = 9.88 \times ([COND] \times Q \div 100) \quad r^2 = 0.931$$

where [COND] is conductivity measured in $\mu\text{S}\cdot\text{cm}^{-1}$ and the factor of 100 converts runoff and conductivity to give units of $\text{cS}\cdot\text{y}^{-1}$. Although not applied here since only source C (the detailed chemical dataset) had measurements, relationships between CL(A) and conductivity had the strongest correlation ($r^2 = 0.936$) and being simple to measure, should not be discarded as an indicator of acid sensitivity in Northeast BC, particularly in First Nations' assessment and monitoring programs.

3.3.3 Regression Statistics

The CL(A) standard error and sum of squared error were significantly lower for the alkalinity-derived regressions than for the calcium derived methods (Table 3-4). While both error margins were the lowest (and causality the strongest) for conductivity regressions, a lack of conductivity measurements meant that this method while promising, was not employed. Therefore, alkalinity was found to be the best single indicator of lake sensitivity to acidification, which is in agreement with past studies (Erickson, 1987; Saffran and Trew, 1996). The standard errors were high for all the relationships. However, residuals were $< 0.41 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ for all lakes with $CL(A) < 2 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. These more sensitive lakes are typically the only water bodies of interest in studies involving acidity critical loads, because $CL(A) > 2 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ are unlikely ever to be exceeded. Residuals were the highest at a pH between 8 – 8.3, which may be an artefact of the bicarbonate – carbonate equilibrium inflection point. The F-statistic was used to test whether the linear relationships were significant enough to predict the CL(A). All three regressions (Equations 3, 4, and 5) were significant at a 99.5% confidence level ($\alpha = 0.005$) (Table 4); these relationships are considered appropriate for cumulative effects assessment and management in northeast BC.

Table 3-4. Regression statistics including the correlation coefficient (r^2), standard error (SE), sum of squared error (SSE) and F statistic, for the three linear relationships found between CL(A) calculated using SSWC and lake chemistry parameters. Error values are in $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$.

Equation	r^2	SE	SSE	F ($\alpha=0.005$)	df
3a	0.854	0.726	7.92	87.48	15
3b	0.855	0.724	7.87	88.50	15
4a	0.919	0.539	4.36	171.0	15
4b	0.922	0.531	4.23	177.2	15
5a	0.936	0.478	3.43	221.3	15
5b	0.931	0.501	3.77	200.8	15

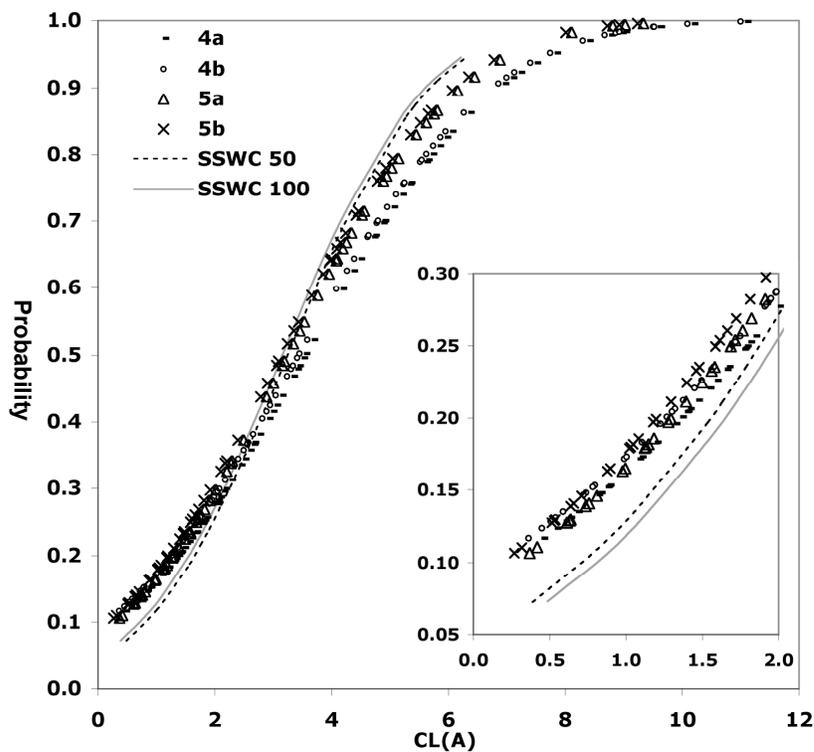
Predicted values of CL(A) (using SSWC) and their derived relationships were proportionally sensitive to changes in Q (runoff). The values of Q used here were calculated as the precipitation surplus after evapotranspiration. Limitations to these estimates have been shown through isotope analysis (Bennett et al., 2008); however, due to the absence of such data in northeast BC we assumed the precipitation surplus method to be sufficiently representative for our purposes. While CL(A) varies proportionally with Q, sensitivity to the chosen $[\text{ANC}]_{\text{lim}}$ depends on the base cation concentration – the more acid sensitive the lake, the more susceptible its CL(A) is to a change in $[\text{ANC}]_{\text{lim}}$. Sensitivity analysis showed CL(A) to be more responsive to the method used (Equation 3 or 4) than to the choice of $[\text{ANC}]_{\text{lim}}$ (Equation a or b) – both are discussed below.

3.3.4 Lake Sensitivities and Critical Loads

We used Equations 3 and 4 to estimate acidification sensitivities of lakes in northeast BC. While these specific models may be less applicable to other regions, in northeast British Columbia they allowed us to estimate acidification sensitivity for 78 more lakes than if limited to SSWC. Most lakes in the region have relatively high predicted CL(A) (Table 3-3). The large size of most sampled lakes limited the dataset to less sensitive freshwater systems. Nonetheless, cumulative distribution functions (Figure 3-5) show that for lakes with $\text{CL(A)} < 2 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$, equations 3a and 4a produce similar distributions, as do equations 3b and 4b. Both equations 3 and 4 predict lower CL(A) (higher sensitivities) than SSWC. At higher

critical loads ($CL(A) > 2 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$) SSWC predicts the lowest $CL(A)$, followed by equation 4 and then 3. An $[ANC]_{lim} = 100 \text{ }\mu\text{eq}\cdot\text{L}^{-1}$ is more protective of lakes despite the method used. In southern Ontario where many lakes are now recovering from past acidification, critical loads calculated using SSWC have been found to range from -0.003 to $15.6 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ (Henriksen et al., 2002). The critical loads (or their equivalents) presented here are well within these ranges (Table 3-3 and Figure 3-5).

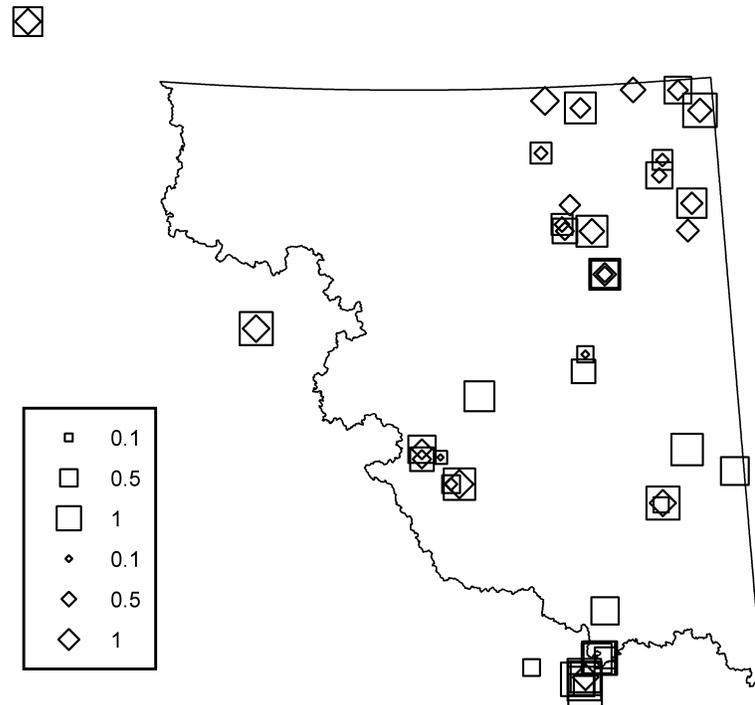
Figure 3-5. Cumulative distribution functions for $CL(A)$ calculated using equations 3 a), 3 b), 4 a), 4 b), and SSWC using $[ANC]_{lim} = 50$ and $100 \text{ }\mu\text{eq}\cdot\text{L}^{-1}$.



The seven most sensitive lakes (smallest symbols in Figure 3-6) were located at low–middle elevations on either side of the Rocky Mountain Range. Four of the thirteen lakes for which Equation 3b estimated $CL(A)$ to be $< 1.00 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ are located on Grey luvisol soils underlain by glaciolacustrine deposits with calcareous or saline calcareous properties (Soil Landscapes of Canada Working Group, 2005) and were of undocumented size. Despite typically alkaline conditions, $CL(A) < 0.25 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ were found using Equation 4 b) at two lakes: one characterised by Grey luvisols the other Humic gleysols (Soil Landscapes of Canada Working Group, 2005), both on fine-grained siliclastic parent material (Massey et

al., 2005). Sensitive ‘Jackpine’ and ‘Mason’ lakes had CL(A) that varied widely between methodologies. Jackpine’s CL(A) was 0.301 and 0.0838 $\text{keq}\cdot\text{ha}^{-1}\text{ yr}^{-1}$ from equations 3 b) and 4 b) respectively; and Mason’s CL(A) was 0.452 and 0.136 $\text{keq}\cdot\text{ha}^{-1}\text{ yr}^{-1}$ by equations 3 b) and 4 b), respectively. Both of these lakes are located on silicate (rather than carbonate) slow-weathering acid sensitive (UNECE-CLRTAP, 2004) bedrock comprised of quartz-based sandstone, or feldspar- and mica-based siltstone and shale (Massey et al., 2005).

Figure 3-6. Map of all lakes having $\text{CL(A)} < 2 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ calculated using regression equations 3b (proportional squares) and 4b (proportional diamonds). Tightly fitting symbols indicate similar results between equations and thick lines represent multiple lakes nearby.



The calcium method (equation 3) enabled the inclusion of more lakes than the alkalinity method (equation 4) due to data availability (Table 2-2). However, equation 3 may overestimate CL(A), underestimating lake sensitivity to acidification, especially where non-carbonate mineral sources of Ca^{2+} such as feldspar or mica dominate. While these minerals may supply Ca^{2+} , K^+ , Mg^{2+} or Na^+ contributing to ion exchange in

the soil and lake sediment complexes, they do not buffer the lake water directly unless in association with carbonate or hydroxyl ions. Therefore, CL(A) may be overestimated in non-carbonate systems when using equations 3 a) or b), or when using the SSWC model. Additionally, inorganic free Al^{3+} made available from the chemical weathering of feldspar or mica, is responsible for the toxic effects of acidification on aquatic and terrestrial organisms (UNECE-CLRTAP, 2004). While these factors are taken into account by dynamic models such as MAGIC (Cosby et al., 1985) these tools are too complex and data intensive to be used efficiently in community-based cumulative effects management. Equations 4 and 5, based on alkalinity and conductivity, respectively, are free from the cation assumptions that may lead to critical load underestimates.

3.3.5 Deposition and Exceedance

No lakes had critical load exceedances ($\text{EX(A)} > 0$) based on year-2000 CMAQ deposition estimates and therefore maps of exceedances are not given since they are similar to those of CL(A) (Figure 3-6).

Localised sulphur deposition (Figure 3-2) near emission sources is evident in particular for one receptor lake in the north where total sulphur deposition is $0.303 \text{ keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$ ($0.240 \text{ keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$ dry and $0.0631 \text{ keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$ wet, equivalent to a total of $14.6 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ of wet sulphate (SO_4^{2-})). The minimum CL(A) was 0.301 and $0.0838 \text{ keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$ predicted using equations 3b and 4b, respectively, and the highest predicted deposition was $0.303 \text{ keq}\cdot\text{ha}^{-1} \text{ yr}^{-1}$. The lack of exceedance seems due to geographic fate; an artefact of geological links between buffering capacity and hydrocarbon reserves. It is possible that lakes in the area not included here may be at risk of critical load exceedance – especially smaller lakes at higher elevations (Curtis et al., 2002), but more data are required before this can be substantiated.

If one were to accept a single representative critical load, protective of the most sensitive organisms for all of the BC Treaty 8 traditional territory (such as the proposed national-scope secondary standards in the United States (US Environmental Protection Agency, 2008)), then there would be exceedances. In

addition, deposition estimates reported here are severely underestimated due to emission reporting exemptions, and may have doubled since the year 2000 (Krzyzanowski, 2009).

The central eastern portion of the study area just north of Fort St. John (where we lacked any lake data) is the most densely developed in terms of the upstream oil and gas activity (Clearstone Engineering Ltd., 2005); and may be more at risk of acidification than other parts of the northeast due to dominating Luvisolic soils and fine grained siliclastic parent material discussed above, as well as agricultural activity that may be leading to nitrogen deposition. Dissolved lake nitrate data were available only for dataset C (see Figure 3-1). However, it is possible that higher nitrate levels exist in other study area lakes – such as in agricultural areas, or parks and protected areas with unmanaged forests. Under these land-use regimes, nitrogen saturation and leaching may occur, calling for the inclusion of nitrate deposition in the exceedance calculation (Equation 2). Although at this time we cannot verify when or where these conditions may exist in northeast BC, wet and dry nitrate deposition is included in Table 3-3 as total nitrogen in $\text{keq}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$.

3.4 Conclusion

The critical loads of acidity ($\text{CL}(\text{A})$ in $\text{keq}\cdot\text{ha}^{-1}\text{ yr}^{-1}$) were estimated using six different methods: the sensitivity class method (Table 1); the SSWC model (Henriksen and Posch, 2001); and four linear regression relationships derived using SSWC (Equations 3a through 4b), each employing two different biological limits ($[\text{ANC}]_{\text{lim}} = 50\ \mu\text{eq}\cdot\text{L}^{-1}$; and $[\text{ANC}]_{\text{lim}} = 100\ \mu\text{eq}\cdot\text{L}^{-1}$). Due to the result-based limitations of the sensitivity class method, and data limitations in the calculation of SSWC, we sought alternatives for assigning acid sensitivity thresholds that have minimal data requirements, can be employed as a tool by the region's First Nations' communities, and fit within the local traditional knowledge and values systems. By definition, critical loads are set to protect chosen organisms over others and prescribe a level of change (or damage). While these notions may seem at odds with fundamental aboriginal values, the use

of high chemical limits ($[ANC]_{lim} = 100 \mu\text{eq}\cdot\text{L}^{-1}$) bridges the gaps between holistic traditional viewpoints and the necessarily reductionist approach of critical loads.

Alkalinity and conductivity proved the most useful indicators of acidification sensitivity in northeast BC. However, care should be taken in applying the conductivity indicator in isolation from other methods, since acid ions (H^+) positively affect conductivity measurements. Where possible, both conductivity and alkalinity should be used in combination. Due to ease of measurement in the field, both parameters (especially conductivity) are practical and efficient indicators (in combination with runoff maps) by which First Nations' communities can expand this lake sensitivity dataset, and monitor freshwater ecosystem change within their traditional territories. To augment this monitoring, in situ measurements of pH should be made. Through community participation, these empirical models can be refined, tested, made more relevant to specific ecosystems, and applied in regional community-based cumulative effects management.

3.5 References

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4 APPROACHING CUMULATIVE EFFECTS THROUGH AIR POLLUTION MODELLING ³

4.1 Introduction

In Canada recognition of cumulative effects entered legislation in the early 1990s. Projects regulated by the *1992 Canadian Environmental Assessment Act (CEAA)* must consider any potential cumulative effects likely to result from an individual project's interaction with any past, present or future activities. This consideration is only achieved on a project-by-project basis; and the province of British Columbia (BC) is yet to append any provincial requirements for cumulative effects to its own *2002 Environmental Assessment Act (BCEAA)*. Projects in BC that are not federally espoused, located on federal lands, or requiring federal approval, need not approach cumulative effects in their environmental assessment certificate applications.

For the purpose of this study, the terms “effects” and “impacts” are used interchangeably (in accordance with existing literature). Cumulative Impacts (or Cumulative Effects) are defined for the purpose of this study as: the outcomes of numerous pathways of influence initiated by the interactions between multiple human activities in shared space and time. These outcomes may be positive or negative, additive or interactive and may have social, economic or environmental implications. The case study presented here is part of a project that was initiated by the Treaty 8 First Nations in northeast British Columbia. Therefore the focus, while primarily environmental, is on outcomes that are directly relevant to the social and economic rights or interests of local First Nations. The analysis and results however, are also relevant to non-aboriginal communities.

Cumulative effects can occur through a variety of ‘effect (or impact) pathways’. Surface change is an

³ A version of this chapter has been accepted for publication. Krzyzanowski, J., 2010. Approaching Cumulative Effects through Air Pollution Modelling. Water, Air and Soil Pollution. *In Press*.

obvious effect pathway of any development activity (road development, forestry, Upstream Oil and Gas (UOG), etc.). Air pollution is another pathway that is common to every development activity at some stage, but perhaps not as commonly approached by cumulative impact assessments. The air pollution effect pathway is the focus of this assessment and begins at the source of emissions. British Columbia's air emission permitting requirements have been shown to be both exclusive and inadequate (Krzyzanowski, 2009); and like other (non-air pollution) impact pathways, project approvals occur on a site-by-site basis (BC's 2004 *Environmental Management Act*). This approach to emissions regulation and to both traditional and cumulative environmental impact assessment, ignores the interactions and accumulation of multiple sources or activities in shared space and time.

When pollutant mixtures are emitted from a myriad of sources into a mutual atmosphere over time, they may interact through chemical, physical and biological response-based pathways to produce more complex and synergistic effects. For example, ambient concentrations of sulphur dioxide (SO₂) have been reported to reach levels capable of injuring vegetation in the provinces of BC (Katz et al., 1939; Legge et al., 1998), and Alberta (Legge et al., 1998; Krupa and Legge, 1999). Oxides of nitrogen (NO_x), although less toxic to vegetation, are emitted more prolifically and have shown similar effects on foliage at high concentrations in eastern Europe (Bytnerowicz et al., 1998). Oxides of sulphur, and to a lesser degree oxides of nitrogen, are also responsible for the acidification of freshwater lakes (Henriksen et al., 2002; Clair et al., 2003; Findlay et al., 2003) and forest soils (Arp et al., 1996; Ouimet et al., 2006) in eastern Canada. Atmospheric deposition also plays a role in nitrogen enrichment and subsequent saturation, leaching and eutrophication in natural systems (Fenn et al., 2003; Fenn et al., 2008). Nitrogen oxides undergo photo-mediated reactions with volatile organic compounds (VOCs) forming tropospheric ozone (O₃) – capable of causing injury to natural and cultivated vegetation (Krupa and Kickert, 1997; Krupa et al., 1998; McLaughlin, 1998), such as downwind of urban centres (Arbaugh et al., 2003). In addition to these individual pathways, pollutant co-occurrence can intensify individual effects (Krupa and Legge, 1999) and pollutant mixtures have been shown to cause injury to vegetation at levels below individual

pollutant exposure thresholds (Menser and Heggstad, 1966; Dueck and Elderson, 1992; Krupa and Legge 1999).

In addition to environmental impacts that ultimately have indirect effects on human health, the primary and secondary pollutants named above can cause direct impacts to human health. Exposure to elevated SO₂ and NO₂ is related to cardiopulmonary mortality, respiratory diseases and increased sensitivity to allergies and asthmatic attacks (Bernstein et al. 2004; Yang and Omaye 2009). Human O₃ exposure has been linked to respiratory diseases such as chronic pneumonia, increased mortality and morbidity (Mauzerall et al., 2005), pulmonary inflammation and asthma (Bernstein et al., 2004). Both SO₂ and NO_x also undergo reactions with other atmospheric constituents (such as ammonia) to produce fine particulate matter that can cause lung damage (Burtraw et al., 2003), and pulmonary inflammation (Bernstein, et al. 2004). Each of these pollutants, and their mixtures, may aggravate existing respiratory problems and cause oxidative damage to lung tissue. There is also increasing evidence of relationships between fossil fuel combustion sourced air pollutants, and lung cancer and cardiopulmonary diseases (Yang and Omaye 2009). Canada- and province-wide objectives (concentration limits) for SO₂, NO_x, O₃, and other air contaminants have been set to protect human health and the environment (see <http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/reg-eng.php#a3>). However, indirect environmental effects, such as those caused by sulphur or nitrogen deposition loads, are more complex and spatially variable. These “secondary” standards are yet to be incorporated within either national or provincial regulatory frameworks.

This study elucidates some of direct and indirect effects of multiple atmospheric emission sources in shared space and time. Using customary dispersion modelling tools and indicators and thresholds relevant to First Nations, the cumulative impacts of multiple point and area sources are assessed. A study area in Northeastern BC is used to illustrate how concepts of potential cumulative effects can be applied feasibly to air quality and airshed management to limit negative impacts on local residents, ecosystems and forest-

dependent First Nations communities.

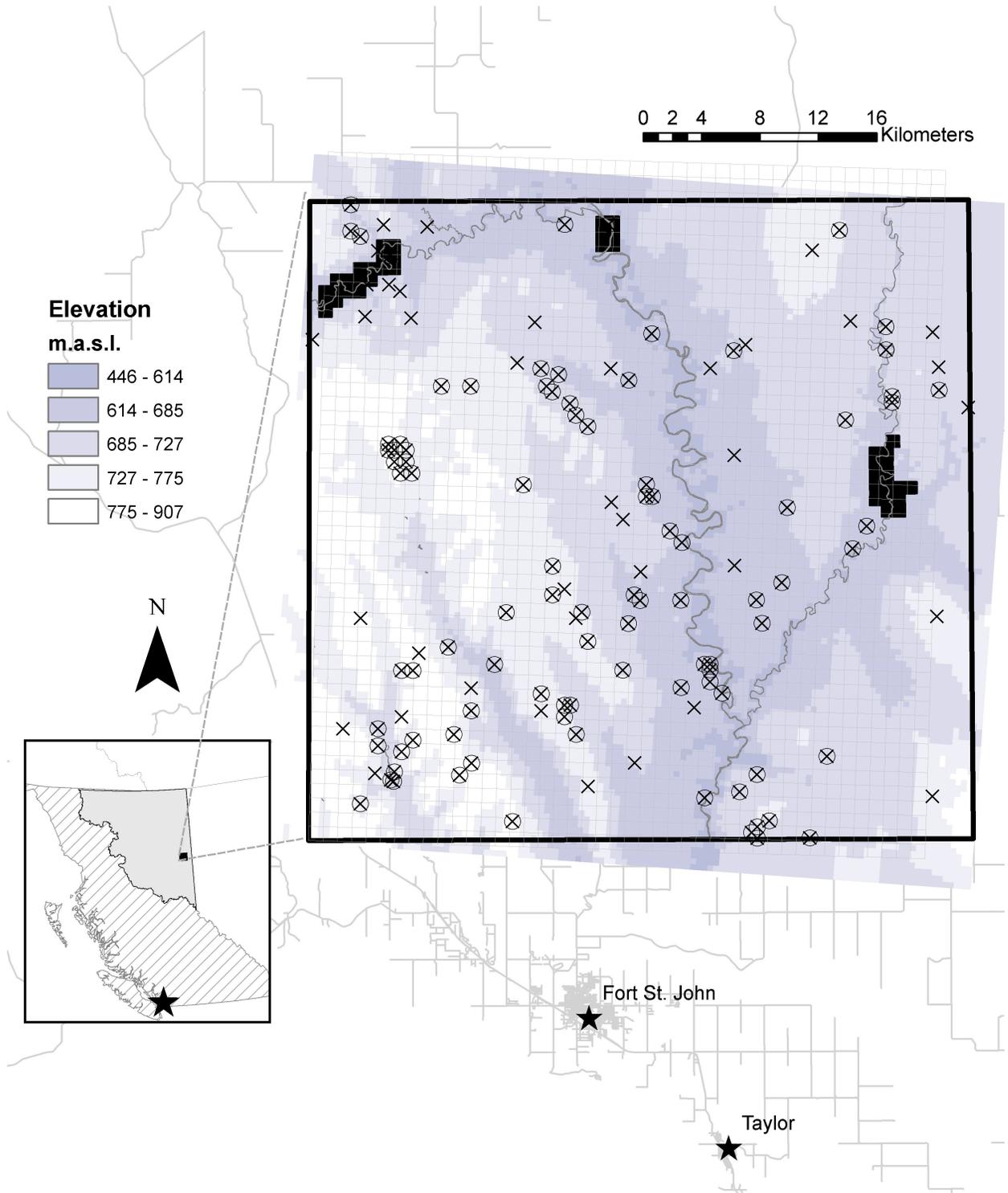
4.2 Methods

4.2.1 Background and Study Area

A broader assessment of cumulative impacts was commissioned by the Treaty 8 signatory First Nations of BC, whose traditional territory makes up most (approximately 278 710 km²) of the province's northeast (Figure 4-1). The federal Treaty 8 area (844 584 km²) also includes northern Alberta, northwest Saskatchewan, and a southern portion of the Northwest Territories. Although treaties originated as agreements between aboriginal groups and the Dominion of Canada, treaty negotiations and First Nations consultation is now (with some exceptions) carried out at the provincial level. Rights proclaimed in Treaty No. 8 of 1899 include the pursuit of "hunting, fishing and trapping" and the "encouragement of agriculture" (Duhamel, 1966) and are protected by Section 35 of the *Canadian Charter of Rights and Freedoms, Constitution Act of 1982*. The air pollution pathway examined here is just one of a number of impact pathways associated with economic development in the northeast of British Columbia.

For this dispersion-based assessment, a study area of 2156 km² was chosen 12 km north of Fort St. John (Figure 1). This area was chosen because of 1) the importance of this area for local aboriginal communities (i.e. locations of Blueberry River, Beatton River and Doig River reservations); 2) the high density of emission sources; 3) the relatively flat terrain; 4) the proximity to Fort St. John's airport (for meteorological data validation); 5) the 50km size limitation associated with AERMOD's prediction accuracy; and 6) community concerns regarding poor air quality in this region (L. Rhodes of Treaty 8 BC, *Personal Communication* October 30, 2008).

Figure 4-1. Map of study area used for dispersion modelling with AERMOD in relation to BC and the province's Treaty 8 traditional territory (inset). Locations of the municipalities of Vancouver (inset), Taylor and Fort St. John are marked by stars. The Blueberry River, Beatton River and Doig River Reservations (clockwise from left) are given by black blocks located on their respectively named streams. SO₂ sources are marked by (O) and NO_x by (X). The domain was extended to the north and south by 2.5 km for the purposes of modelling.



The study area is marked by the forested slopes of the Beatton River valley running from north to south down the centre, and its confluences with the Doig and Blueberry Rivers. Contained within the Boreal White and Black Spruce biogeoclimatic zone (Meidinger and Pojar, 1991), it features Regosol, Luvisol and Solod soils (Soil Landscapes of Canada Working Group, 2005) and hydrocarbon-rich coarse-grained clastic sedimentary rocks, with fine-grained sedimentary mudstones and shales in the eastern most quarter and along the southern segments of the Beatton and Doig Rivers (BC Ministry of Energy, Mines and Petroleum Resources, 2005a). The area is characterised by agricultural fields in the west, coniferous forest in the east, contains 1249 lakes, and boasts an even greater number of UOG sector emission sources (discussed below).

4.2.2 Dispersion Modelling

The dispersion and deposition of SO₂ and NO_x were modelled to predict effects related to air pollution. Lakes Environmental's AERMOD View™ version 6.1.0 was chosen for this purpose. The software combines the United States Environmental Protection Agency's (US-EPA) AERMOD model, the AERMAP terrain processor, the AERMET meteorological processor, and other user-friendly components including the functionality of a user interface. Meteorology was supplied by Lakes Environmental in MM5 format for the Fort St. John airport prior to processing with AERMET. AERMOD is a Gaussian plume model that uses a skewed bi-Gaussian probability density function (as in Willis and Deardorff (1981)) under convective conditions when vertical plume dispersion is non-Gaussian (Perry et al., 1994). More information on AERMOD and AERMOD View™ 6.1.0 including algorithms and background science can be obtained from the US-EPA (http://www.epa.gov/scram001/dispersion_prefrec.htm) and from Lakes Environmental (<http://www.weblakes.com>), respectively.

AERMOD is suggested for use in multi-source pollutant dispersion studies by both the federal and provincial governments (Environment Canada, 2009; BC Ministry of Environment, 2008). User-defined surface parameters for concentration modelling were obtained from BC's modelling guidelines (BC

Ministry of Environment, 2008). A number of additional user-defined parameters are required for wet and dry deposition estimates in AERMOD. The parameters used are given in Table 4-1 and are assumed equal for all sources in the model run, even though they may vary with temperature or source. ‘Method 2’ was chosen for particle fraction deposition due to unknown particle size distributions. Rural and elevated options were chosen for the uniform 1 km 46 x 49 Cartesian grid with a lower left (SW) corner of 56.35°N, 121.15°W. The AERMOD model requires user-defined land-use types for each 10° radial ‘wind sector’ division. The western and southernmost wind sectors were designated as agricultural land (135°–175° and 185°–355°), the eastern portion forest (5°–135°) and the middle (355°–5° and 175°–185°) open water to represent the Beaton River. These categories were based on crude estimates of dominant land uses (i.e. >60% of the wind sector area) and do not represent the only land surface types within a sector; there are forest and open water surfaces throughout the study area. These land-use designations are used by AERMOD in combination with user-defined parameters (Table 4-1) to estimate the deposition velocities of particles and gases.

Table 4-1. Parameters used for modelling the deposition of sulphur and nitrogen using AERMOD View™. All parameters represent conditions at standard temperature and pressure.

Module	Parameter	units	SO ₂	NO _x
Gas Deposition	Diffusivity in Air	cm ² ·s ⁻¹	0.1089 ^a	0.1361 ^a
	Diffusivity in Water*	cm ² ·s ⁻¹	1.541 x 10 ^{-5b}	1.879 x 10 ^{-5b}
	Cuticular Resistance	s·cm ⁻¹	20 ^{c,d}	0.1 ^e
	Henry's Law Constant*	Pa·m ³ ·mol ⁻¹	81.7 ^f	3070.4 ^f
Particle Deposition	Percent fine particles	%	0.99 ^g	0.99 ^g
	Mean size fine particles	microns	1 ^g	1 ^g

* calculated or averaged from the given source

^aMassman 1998

^bReible 1998

^cZhang et al. 2003

^dWesely 2007

^eErisman et al. 1994

^fSander 1999

^gJudy Chow Pers. Comm. April 2009

In addition to AERMOD domain extent restrictions, limits were set on the pollutants and impacts of focus

in order to keep the assessment manageable and relevant. Oxides of sulphur and nitrogen were chosen as ‘indicator’ pollutants as they, along with VOCs, are the most prolific of all Criteria Air Contaminants (CACs) within BC’s Treaty 8 traditional territory (Krzyzanowski, 2009). There is also a wealth of information available on the direct and indirect impact mechanisms for sulphur and nitrogen oxides. VOCs were not modelled due to unknown chemical speciation of the source emissions and the resulting difficulty in relating the subsequent chemical species to the effects-based focus of this study.

Summary statistics for point and area source emissions, derived using methods described in Krzyzanowski (2009), are shown in Table 4-2. Annual emission totals were converted to units of $\text{g}\cdot\text{s}^{-1}$ for input into AERMOD View™. The inventory represents a union of the official year 2000 CAC emission inventory and a supplementary inventory developed federally on behalf of the Canadian Association of Petroleum Producers. Area source emissions were modelled for those Source Classification Codes (SCC) whose emissions represented 1% or greater of the particular CAC’s emissions for the study area. Area source emissions were allocated using 12km grid outputs from the MIMS spatial allocator (Science Applications International Corporation, 2004) for all of northeast BC, giving a total of 25 adjacent rectangular sources for each area-source SCC. Source surrogates for input to MIMS were defined using BC Ministry of Environment’s Air Contaminant Emissions (ACE) system for the year 2000 (M. Rensing of BC Government, *Personal Communication*, November 20, 2005); all SO_2 and NO_x area emissions representing more than 1% of the study area’s annual total were represented by either gas production (BGASPRODN) or open burning (BPBURN) spatial surrogates.

Stack parameters were absent from all sources and instead defaults used by the US-EPA Models-3 community (see <http://www.cmascenter.org/>) were assigned based on Standard Industrial Classification (SIC) and SCC. An exception was made for flare sources, whose “pseudo-stack” parameters were assigned based on industry consultation and calculations (Briggs, 1969; BC Ministry of Environment, 2008) that employ heat of release ($\text{MJ}\cdot\text{s}^{-1}$) to calculate a buoyancy flux assuming a radiation loss of 25%

(Guigard et al., 2000), and combustion efficiencies as calculated in ERCB (2006) (see Appendix B). The resulting parameters are given by source input type in Table 4-3, where “sour” flares are those that emit SO₂ formed from the combustion of “sour gas” or hydrogen sulphide (H₂S); and NO_x emitting flares (without SO₂ emissions) are assumed to be “sweet”, burning only natural gas (CH₄) and associated liquids. Sweet flares are generally taller than sour flares and affiliated with larger facilities and flow rates (R. Kemp of Levelton Engineering, *Personal Communication* July 19, 2005). All area emissions were given a “stack height” of 3 m to represent fugitive emissions from oil or gas: pipelines, wells, or transport, and the effective release height of NO_x emissions from open burning.

Table 4-2. Total point, flare and area source CAC emissions for the study area in the year 2000. The dispersion of NO_x and SO₂ (grey) was simulated using AERMOD View™. All values are in tonnes per year.

Source	Statistic	Criteria Air Contaminant						
		CO	NH ₃	NO _x	PM ₁₀	PM _{2.5}	SO ₂	VOC
2000 - point	N	158	0	167	152	153	99	1766
	min	2.79E-06	0	2.05E-05	5.90E-07	5.90E-07	5.00E-08	4.60E-07
	mean	2.008	0	26.589	0.102	0.100	1.197	2.125
	max	23.760	0	644.493	2.775	2.775	57.860	778.475
	total	317.286	0	4440.280	15.478	15.270	118.482	3752.640
2000 - flare	N	82	0	82	82	82	4	82
	min	0.010	0	0.002	0.004	0.004	0.151	0.001
	mean	1.898	0	0.438	0.855	0.855	15.328	0.334
	max	8.559	0	3.875	7.564	7.564	18.195	2.959
	total	155.616	0	35.902	70.083	70.083	34.207	27.418
2000 - area N (SCC)		26	32	27	38	37	20	42
	min	1.841E-05	1.026E-06	1.841E-05	1.84E-05	7.36E-07	2.785E-06	1.288E-06
	mean	18.357	12.894	51.198	4.430	3.579	218.221	95.808
	max	280.707	168.388	791.554	94.790	94.247	3230.088	1966.186
	total	477.283	412.610	1382.342	168.350	132.414	4364.428	4023.954
Study Area	total	950.186	412.610	5858.524	253.911	217.766	4517.117	7804.013

The year 2000 was the last emissions inventory of its kind to be developed. Emission reporting in Canada is now accomplished through the National Pollutant Release Inventory (NPRI; see <http://www.ec.gc.ca/inrp-npri/>) whose requirements are characterized by numerous exceptions and exemptions (Canada, 2007a; Canada, 2007b; Krzyzanowski, 2009). The year 2007 NPRI, for example, included only 5 individual SO₂ and 22 NO_x point and flare sources in the study area, totalling annual emissions of 31.8 and 21.3 t·y⁻¹ respectively; compared with 103 SO₂, and 249 NO_x sources included here (Table 4-2) totalling 152.7 and 4476.2 t·y⁻¹ respectively. The NPRI was therefore used only as a source of guidance in this assessment. The resulting AERMOD output was averaged over 1-hour, 3-hour, 24-hour and annual periods to be compared with impact threshold timescales of interest.

Table 4-3. Stack parameters assigned to point sources used in AERMOD View™. SCC 31000160 and 31000205 (flares) are given psuedo (rather than actual) values of stack height and width to account for flame size and buoyancy. NG = Natural Gas; SIC 1311= crude petroleum and natural gas; SIC 4923 = natural gas transmissoin and distribution.

SO ₂	NO _x	SIC	SCC	Height (m)	Diamet (m)	Exit Temp	Exit Vel.	Source Description
0	1	1311	10200601	19.2	1.2	474	23.5	NG-fired external combustion engine >100 Mill Btu/hr
2	2	1311	10500106	11.3	0.6	421	24.7	NG-fired external combustion boiler – space heater
0	4	1311	20200201	8.5	0.6	674	36.3	NG-fired, internal combustion turbine engine – industrial
0	5	4923	20200201	8.5	0.6	674	36.3	NG-fired, internal combustion turbine engine – industrial
87	87	1311	20201001	9.1	0.3	627	17.1	Propane – reciprocating engine
1	62	1311*	30602401	12.5	1.2	479	20.1	NG-fired reciprocating engine compressors
2	0	1311	31000160	25.8	2.1	1273	20.0	Crude production – flares (sour)
0	70	1311	31000160	45.5	4.2	1273	20.0	Crude production – flares (sweet)
0	1	1311	31000199	12.5	1.2	479	20.1	Crude production – processing not classified
2	0	1311	31000202	12.5	1.2	479	20.1	Natural gas production – gas stripping
2	0	4923	31000202	12.5	1.2	479	20.1	Natural gas transmission – gas stripping
1	1	1311	31000203	12.5	1.2	479	20.1	Natural gas production – compressors
2	0	1311	31000205	25.8	2.1	1273	20.0	Natural gas production – flares (sour)
0	12	1311	31000205	45.5	4.2	1273	20.0	Natural gas production – flares (sweet)
4	4	4923	31000299	12.5	1.2	479	20.1	Natural gas transmission – other not classified
0	1	1311	31000404	12.5	1.2	479	20.1	Oil and Gas production – NG-fired process heaters

Model output was also compared with monitoring data from the Taylor Townsite (56.15°N, 120.68°W), 18km to the southwest of the study area. This monitoring site represents the nearest of all air quality monitoring stations in the region, and is the only one of 17 ambient air quality monitoring stations north of the Rockies to have ever measured nitrogen oxides (NO and NO₂) and ozone (O₃) in addition to the more customary measurements of SO₂ and hydrogen sulphide (H₂S) (and for some stations particulate matter of <2.5 microns (PM_{2.5}) and/or <10 microns (PM₁₀)). As measurements of NO, NO₂ and O₃, were discontinued in January 2002, and this assessment utilised year 2000 emissions, the station data were examined for the period 1996–2001 (BC Ministry of Environment, 2009a). Due to the influence of local emission sources on the measurements made at this station (such as a large gas plant), and the unverified form of the data (BC Ministry of Environment 2009a), these concentrations were not used to assign background levels. In AERMOD View™ the background concentration is added to modelled concentrations after run completion; the effects of such a background concentration addition (or lack thereof) are discussed below.

4.2.3 Effects Limits and Thresholds

The impacts to be assessed were chosen based on the relevance of their end-points to local First Nations. Human health is undoubtedly a concern in terms of air quality and therefore provincial (when available) or federal Ambient Air Quality Objectives (AAQO) were used as concentration limits for sulphur and nitrogen oxides. Impacts to forest health and structure are also of importance to First Nations' communities who depend on a forest-based economy. Impacts that may occur to fish or aquatic systems, hunted animals, gathered foods or agricultural capacity, are in direct conflict with Treaty 8 designated rights, as they impair the ability of First Nations' members to exercise those rights. Similarly, pollutant exposures capable of causing adverse human health effects, either directly through inhalation, or indirectly through food quality, impede one's ability to continue a traditional way of life. When ambient air concentrations reach levels above (or near) those defined by environmental and health-based regulatory standards or biological limits for nitrogen (N) and sulphur (S) compounds, damaging effects

are anticipated. Exposure limits particularly relevant to the region and First Nations were chosen from the available literature and are given in Table 4-4. These thresholds or endpoints were compared with AERMOD output for the corresponding time scale to identify potential effects.

Table 4-4. Damage thresholds of S and N compounds for relevant study area components.

Receptors	Levels ($\mu\text{g}\cdot\text{m}^{-3}$)						Loads ($\text{kg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$)	
	SO_2				NO_x		S	N
	1-hr	3-hr	24-hr	annual	1-hr	24-hr	annual	annual
Human health / environment	450 ^a	375 ^a	160 ^a	25 ^a	400 ^b	200 ^b	60 ^c , 100 ^b	
Vegetation (all)						75 ^d	30 ^d	
Boreal Forest				20 ^d				10 – 20 ^{d,e}
Lichens				10 ^d				10 – 15 ^{d,e}
Crops				30 ^d				
Freshwater lakes								1.4 – 5.4 ^f 5 – 10 ^{d,e}
Soil								3.2 ^d
Soil*								1001 – 8000 ^{g*}

*combined S + N soil acidification load in $\text{H}^+\text{eq}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$

^aBC Ministry of Environment 2009b – BC Level A

^bBC Ministry of Environment 2009b – Canada Max. Acceptable

^cBC Ministry of Environment 2009b – Canada Max. Desirable

^dUNECE-LRTAP 2004

^eBobbink et al. 2002

^fKrzyzanowski and Innes 2010

^gCarou et al. 2008

A “critical load” is defined as “a quantitative estimate of 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). The term “level” is commonly used to denote ambient concentration limits, and “load” applied to surface deposition limits of a pollutant (UNECE-CLRTAP, 2004). Where a range is given for loads or levels in the literature, the lower estimate was used to offer higher protection in accordance with First Nations values. Deposition is expressed as elemental S or N in $\text{kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ due to the unknown chemical makeup of dry/wet deposited species – AERMOD simulates deposition as SO_2 and NO_x (as NO_2) whereas deposition commonly occurs, and is expressed, as SO_4^{2-} and

NO₃⁻.

The soil (acidification) critical load was estimated using the empirical methods described in UNECE-CLRTAP (2004). The slow weathering of shale- and mudstone-derived feldspars, micas and quartz puts these soils in the high sensitivity (or low critical load) class (<200 eq·ha⁻¹·yr⁻¹). Being characterised by moderately well-drained soils and coniferous forest makes this area more sensitive to acidification; while moderately fine soil texture and slopes of less than 15% (Soil Landscapes of Canada Working Group 2005) increase the base cation weathering ability and therefore the critical load. Due to the unknown nitrogen status of these soils the acidification critical load is expressed as S (in kg·ha⁻¹·yr⁻¹). (i.e. they are assumed unsaturated and therefore N has fertilising rather than acidifying effects (UNECE-CLRTAP, 2004)). However, the Carou et al. (2008) soil acidification critical load assumes N saturation and therefore includes both S- and N-deposition in the exceedance calculation and needs to be expressed in acid (or hydronium ion) equivalents (H⁺eq·ha⁻¹·y⁻¹) due to the different atomic weights of sulphur and nitrogen.

4.2.4 Prediction of Future State

Predictive capacity can be the downfall of resource sector cumulative impact assessments. The realism associated with predicted future states is often clouded by unforeseeable events and economic or political influences. While mathematics, through observations of the past, can be used to predict future outcomes through extrapolation, this is unfortunately not the case for UOG's atmospheric emissions in northeast BC. While the province has claimed that year 2000 production levels will be doubled by 2010 (BC Ministry of Energy, Mines and Petroleum Resources, 2005b), production data for the 2000–2008 period suggest otherwise (OGC, 2008). Oil production in northeast BC has been steadily decreasing since a boom in the late 1960s. Natural gas, which experienced a small secondary production peak in the mid-1990s, has been decreasing progressively since then (Figure 4-2a). This does not mean that UOG activity is decreasing. The number of new (mainly exploratory) wells drilled in the northeast has been increasing

logarithmically since the 1990s boom (OGC, 2008), with a downward trend only recently in 2006 and 2007, with 2008 showing a slight recovery in activity over the two previous years.

It is hard to predict the future or long-term nature of these trends or to translate them into emissions.

While the amount of gas flared and the maximum H₂S content of the stream both show steady increases since the mid-1990s, the last few years have seen decreases in both of these, and there is no trend in average H₂S content (Figure 4-2b). From these data it is not apparent whether the downward trend is simply a small fluctuation or whether it will continue in the long-term. While an ideal cumulative impact assessment would include a modelling scenario featuring future emission estimates, these estimates would be based on conjecture and source locations could only be propagated randomly (with known pools as constraints), lacking the spatial explicitness that is desired by Treaty 8 First Nations. Therefore, the year 2000 maps are discussed in terms of future emission and management scenarios rather than the modelling of speculative emissions

4.3 Results

4.3.1 Predicted Concentrations/Levels

Maximum value concentrations and deposition estimates for specified AERMOD averaging times are given in Table 4-5. Predicted SO₂ concentrations across all four averaging periods were highest in river and topographical valleys near larger emission sources (Figures 4-3a-d). Maximum 1- and 3-hour concentrations occurred during the winter months (January, February and December) with no preference for time of day. The highest 3-hour concentrations all occurred in February in a night-time stable boundary layer with light winds (1 – 4 m·s⁻¹). The highest 24-hour maxima all occurred in late December when easterly winds between 4 – 7 m·s⁻¹ dominated a persistently shallow and stable winter boundary layer. Predicted 1-hour (Figure 4-3a), 3-hour (Figure 4-3b), and 24-hour (Figure 4-3c) maximum concentrations did not exceed any of the chosen SO₂ limits (Table 4-5) anywhere in the study area (Table 4-5). However, predicted annual average concentrations (Figure 4-3d) exceeded the 10 µg·m⁻³ threshold

for lichens in three areas: on an east-facing slope of the Beatton River valley and at the northwest and southeast domain corners, the latter receiving the highest annual average concentration. These areas were also subject to higher 1-hour, 3-hour and 24-hour mean exposures.

Figure 4-2. Plot of oil production (m^3), gas production (km^3) and number of new wells drilled from 1950–2007 using data from OGC (2008) a); and temporal variation in the maximum and average H_2S fractions of produced oil and gas with the total annual flared gas volume over the same period b). Trend-lines represent moving averages and there were no records of flaring in the province prior to 1993.

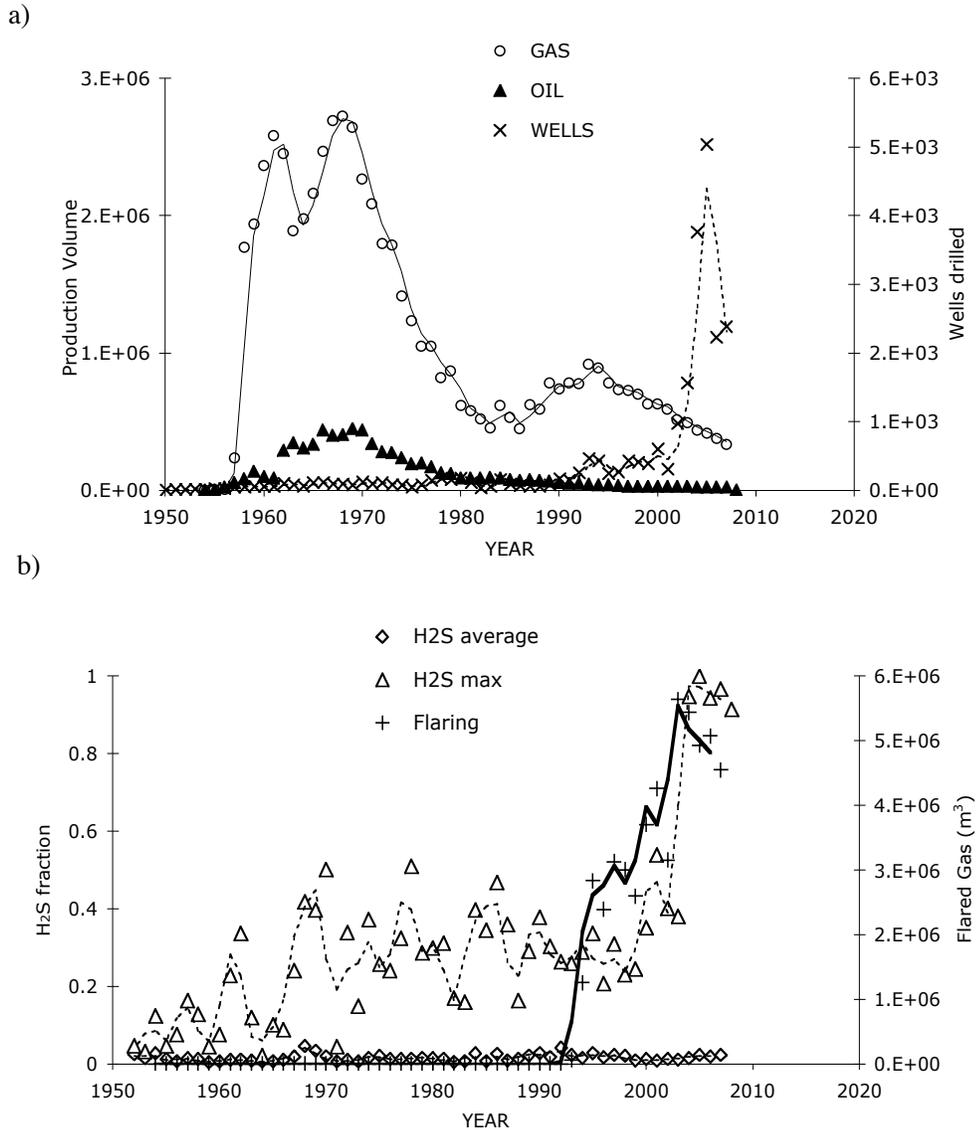
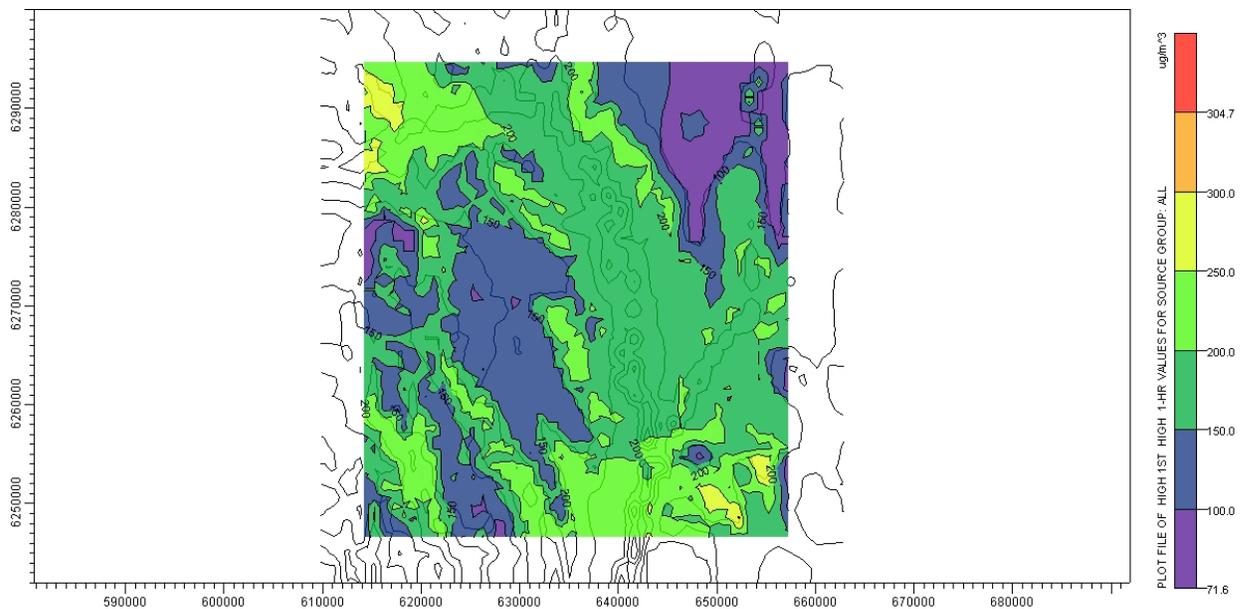


Table 4-5. AERMOD View™ predicted maximum concentrations over averaging times of interest and total annual deposition estimates as a sum of wet and dry fractions. Bold values represent exceedances of chosen thresholds (Table 4). There was no 3-hr NO_x threshold chosen; this averaging period is shown for comparison.

pollutant	Concentration (µg·m ³)				Deposition (kg·ha ⁻¹ ·y ⁻¹)	
	1-hr	3-hr	24-hr	annual	S	N
SO ₂	304.7	288.8	123.6	14.0	0.98	1.94
NO _x	532.5	384.3	159.6	8.15		

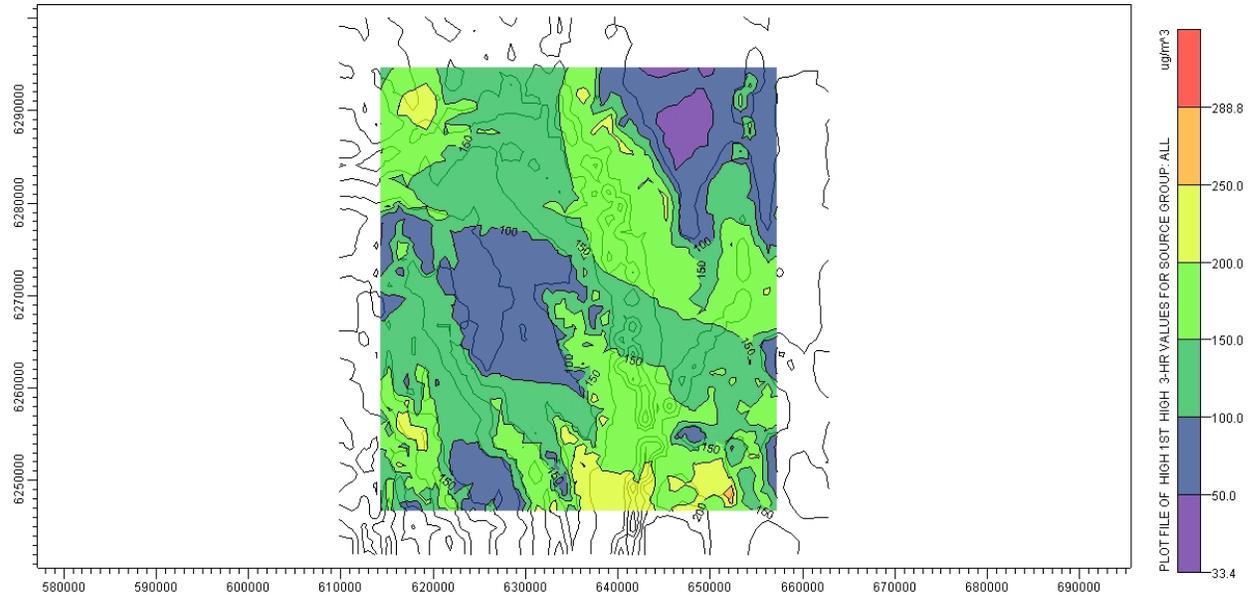
Figure 4-3. Predicted 1-hour a); 3-hour b); 24-hour c); and annual d), maximum SO₂ concentration contours. Scale axes represent NAD 1983 UTM zone 10N coordinates in metres.

a)

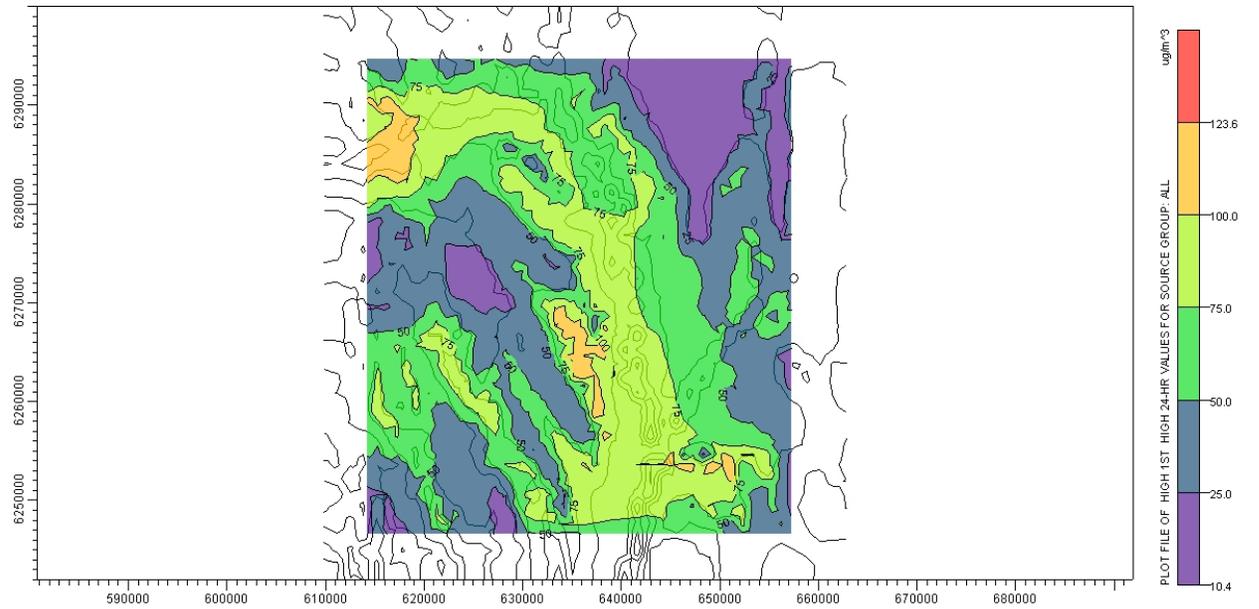


(continued)

b)

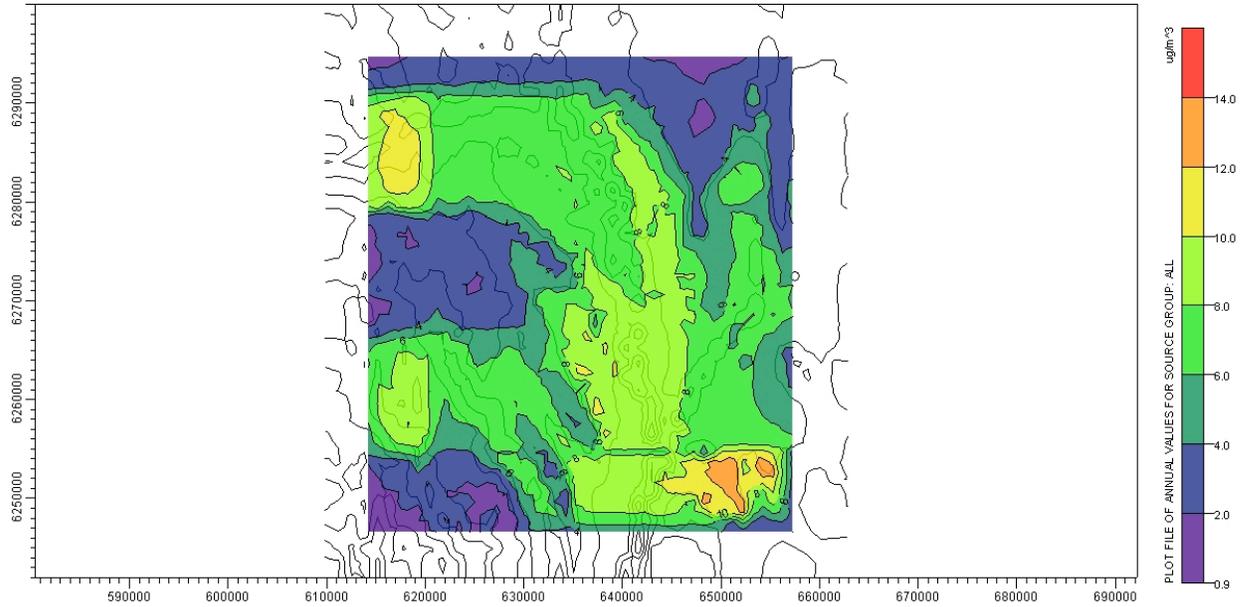


c)



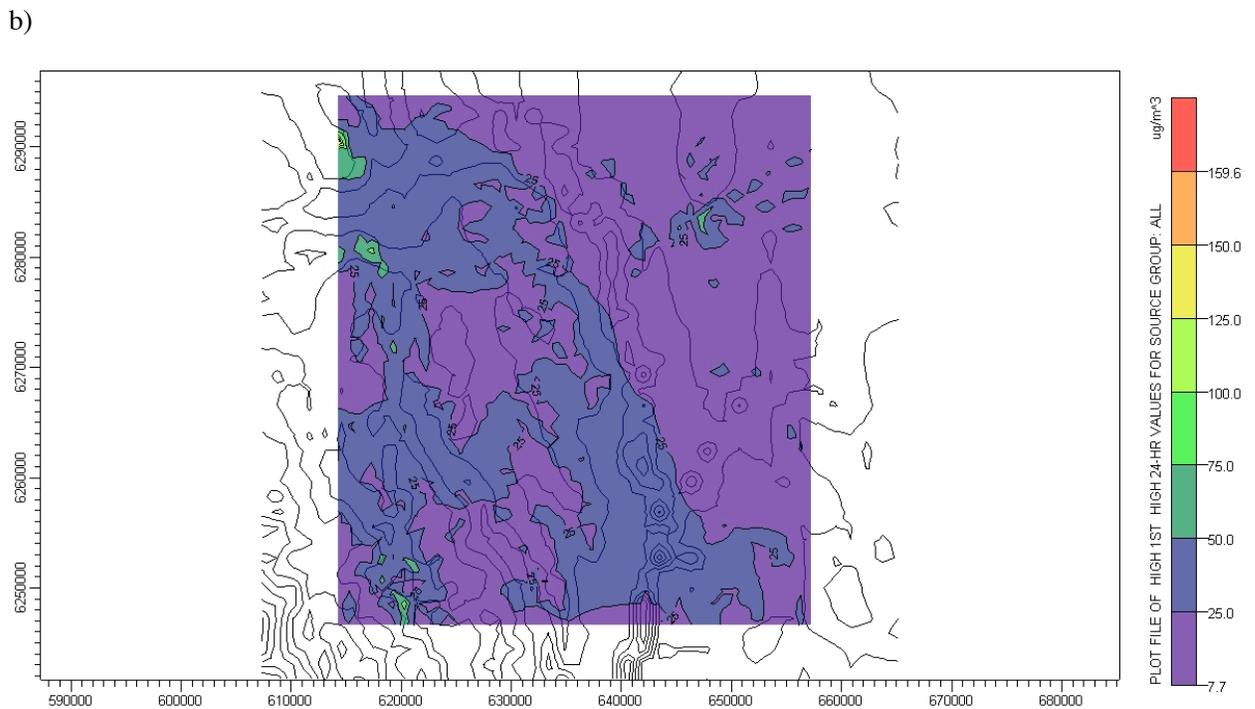
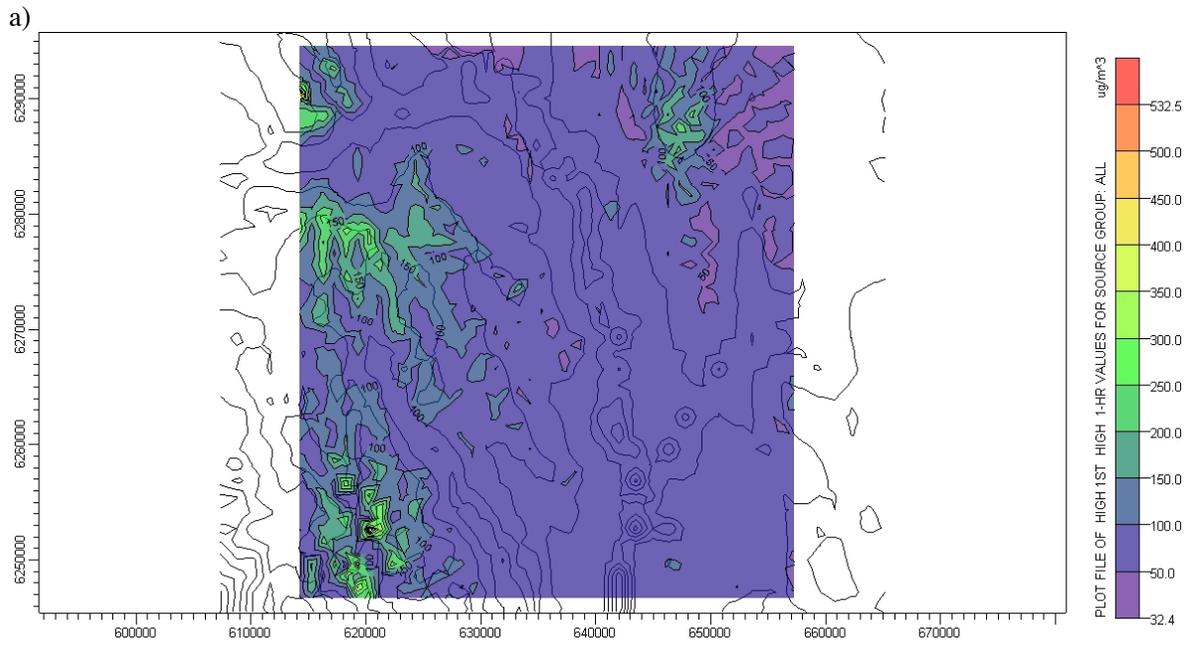
(continued)

d)



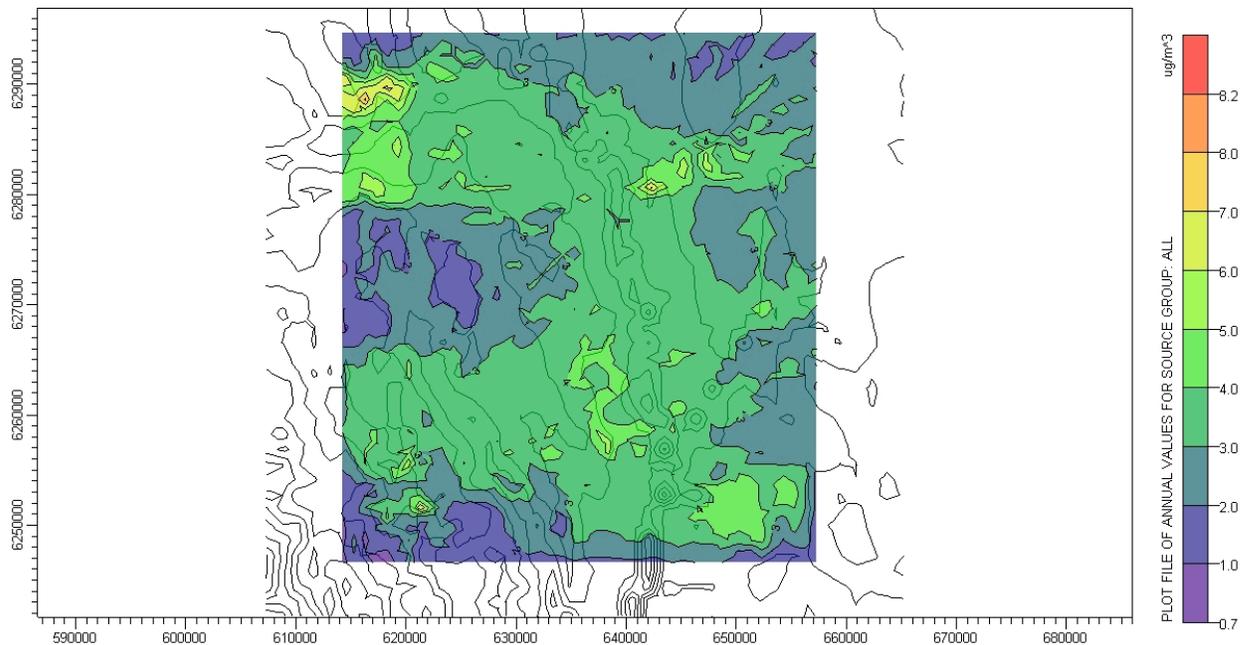
Predicted 1-hour maximum NO_x concentrations exceeded Canada's maximum acceptable level on 17 distinct winter occasions (December to February) in small isolated patches along topographic ridges in the southwestern portion of the modelling domain (Figure 4-4a), with no time-of-day preference. Maximum 24-hour average concentrations exceeded thresholds at one location near the northwest margin of the study area (Figure 4-4b) in December and February. Predicted 1- and 24-hr NO_x exceedances occurred on slopes near point sources when light winds ($1 - 4 \text{ m}\cdot\text{s}^{-1}$) and a shallow stable winter boundary limited convective and turbulent mixing. Annual average NO_x concentrations (Figure 4-4c) did not exceed thresholds anywhere in the study area.

Figure 4-4. Predicted 1-hour a); 24-hour b); and annual c) maximum NO_x concentration contours. Scale axes represent NAD 1983 UTM zone 10N coordinates in metres.



(continued)

c)



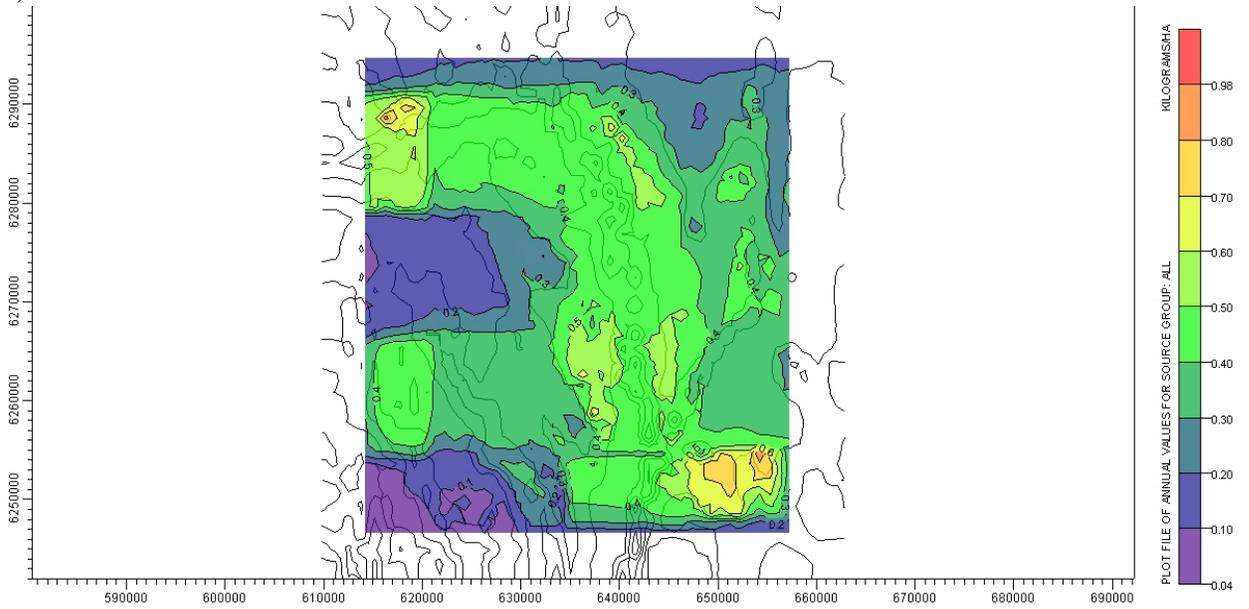
4.3.2 Predicted Deposition/Loads

Neither sulphur nor nitrogen deposition (critical) loads were exceeded by simulated annual wet and dry deposition estimates (Table 4-4). Sulphur deposition reached levels only 70% of the most protective threshold (Figure 4-5a) and nitrogen deposition about 40% of its most conservative load (Figure 4-5b).

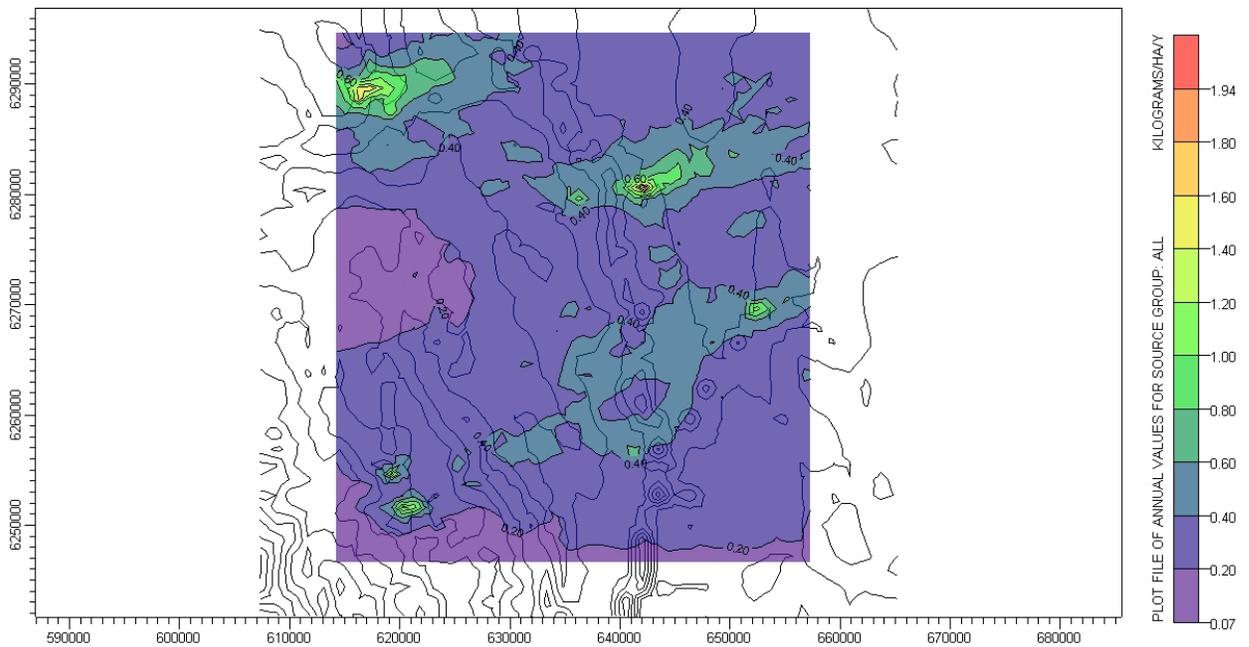
The combined sulphur and nitrogen deposition at the dominant point of receipt (i.e. in the northwest near Blueberry River First Nation) was $73.5 \text{ eq}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$; much lower than the federally derived critical load for the area (Table 4-3). While AERMOD was used to model both wet and dry deposition of sulphur and nitrogen, dry deposition made up more than 99% of the predicted deposition fields; therefore, only total deposition is presented.

Figure 4-5. Estimates of total annual sulphur a) and nitrogen b) deposition. Scale axes represent NAD 1983 UTM zone 10N coordinates in metres.

a)



b)



4.4 Discussion

4.4.1 Reliability of Results

Fort St. John has a relatively dry climate and in 2000 received a total of 383.4 mm of precipitation as rain and snow equivalents (Meteorological Service of Canada, 2009). The MM5 data over-predicted annual precipitation, estimating it at 511.6 mm for the year 2000; the estimates for wet deposition were nonetheless very low. The MM5 data are considered reasonable in all other fields when compared with measurements from the Fort St. John airport (Meteorological Service of Canada, 2009). MM5 has been shown to be valuable in short-range AERMOD pollution forecasts (Isakov et al., 2007) and while not well tested for deposition estimates, much of the meteorological station data – such as precipitation – was available only as daily value tables, making MM5 the only available hourly meteorological data for the region to be used as input in this assessment. The meteorological data from Taylor’s ambient air quality monitoring station were too sparse for the study year to warrant their use.

Predicted SO₂ concentrations were well within the range of values measured in Taylor for the year 2000. Maximum 1-hour averages were 378.0 and 304.7 µg·m⁻³, for measured and predicted concentrations, respectively. This difference is likely reflective of a source event near the Taylor monitoring station, since 98th percentile 1-hour maxima were higher when modelled (84.47 µg·m⁻³) than when measured (37.0 µg·m⁻³). Some larger SO₂ point sources exist near the Taylor ambient air quality monitoring station (such as a sour gas plant emitting over 1.5 M t·y⁻¹ in 2008 (Environment Canada 2008)), whereas sources are more numerous in the study area leading to consistently higher concentrations, rather than the wind direction dominated episodes in Taylor. The Taylor 99th percentile (51 µg·m⁻³) was similar to the modelled 95th percentile (51.3 µg·m⁻³) due to differences in summarising one monitoring location versus the many receptor locations in the study area.

Predicted maximum NO_x concentrations were in accordance with NO₂ winter maxima measured at the Taylor site in the year 2000. Measured versus predicted 98th percentile 1-hour concentrations in the year

2000 were 66.9 and $65.4 \mu\text{g}\cdot\text{m}^{-3}$, respectively. Though the study area is 18 km north of Taylor, and both are strongly affected by localised UOG sources, this 98th percentile agreement supports the use of AERMOD in the region as a tool for cumulative source effects management. There were discrepancies in the prediction of maximum values ($133 \mu\text{g}\cdot\text{m}^{-3}$ measured at Taylor versus $532.5 \mu\text{g}\cdot\text{m}^{-3}$ predicted). However, Taylor measurements speciate NO_x into both NO and NO_2 contributions, the former of which reached $391.7 \mu\text{g}\cdot\text{m}^{-3}$ in 2000. The Taylor station is at an elevation of 480 m, lower than the ridges where hourly exceedances were predicted. The absence of background concentrations may have led to underestimates of SO_2 and NO_x maximum concentrations – others have illustrated AERMOD's tendency to underestimate concentration maxima despite the use of background concentrations (e.g., Hanna et al., 2001; Hurley et al., 2005; Kumar et al., 2006).

The AERMOD concentration estimates are considered acceptable for the assessment of potential cumulative effects, due to the general agreement between estimates and nearby measurements, and the current utilisation of AEMROD as a regulatory tool to predict the effects of individual sources (BC Ministry of the Environment, 2008). While the time and place of maxima may be variable, the high concentrations predicted are likely to occur sometime over the modelling period and somewhere within the domain (BC Ministry of Environment, 2008). The annual deposition estimates however, are less reliable. Although BC's Air Quality Modelling Guide (BC Ministry of Environment, 2008) suggests the use of AERMOD for the modelling of both concentration and deposition of pollutants, this model and other Gaussian plume models such as BPIP of ISCST3 may not be suitable for simulating deposition because they fail to take into account chemical transformations in the gas and liquid phases (such as the oxidation of SO_2 and NO_x into their acidic forms) that determine aspects such as deposition velocity and uptake by clouds that are key to the realistic determination of deposition rates (Tonnesen et al., 2007). From a biological perspective data on the speciation of compounds are required due to different uptake rates and responses of vegetation, water or soil surfaces to differing sulphur (SO_2 , SO_3^- , SO_4^{2-} , HSO_3^- , H_2SO_4 , etc.) or nitrogen (NO , NO_2 , NO_3^- , HNO_3 , etc.) compounds (Legge, 1990).

Gas and particle phase estimates are based on user-defined source-specific parameters and particle-size distributions, respectively (see Table 4-1). Both gas and particle deposition velocities will vary with land-cover, vegetation, the pH of surface moisture, atmospheric pressure, temperature etc., and it might be more appropriate if AERMOD deposition characteristics were defined on a receptor-, rather than source-, specific basis; or ideally, calculated by the model itself using input meteorology and base maps. However, as with all Gaussian plume models designed for simulating dispersion rather than deposition, this is not the case and is likely a source of much error in deposition estimates. AERMOD View™ runs for both SO₂ and NO_x deposition were very sensitive to the choice in parameters, particularly cuticular resistance and Henry's Law coefficients, which when chosen within accepted value ranges altered deposition estimates by an order of magnitude. In addition, because the AERMOD deposition algorithm relies on cuticular resistance and other canopy-based parameters such as leaf area index (US-EPA, 2004), the method may not be suitable for the estimation of deposition to soil or water surfaces (as required by critical loads estimates). When land-use type was changed to open water, predicted deposition did not increase as expected to account for an absence of resistance to surface transport (Wesely, 2007). In addition, surface deposition of both sulphur and nitrogen was much lower than reported nearby in the study using CMAQ and an incomplete emissions inventory (Krzyzanowski and Innes, 2009).

While use in deposition studies is limited due to fairly recent implementation of deposition algorithms, AERMOD has been found to underestimate dry deposition of ammonia (Philips et al., 2004; Bajwa et al., 2008). Due to its infancy with deposition estimates, together with the factors outlined above, AERMOD View™ is not recommended for use in estimating the annual deposition of sulphur and nitrogen. Instead, deposition estimates from a more complex regional model such as AURAMS (Zhang et al., 2003) or CMAQ (Byun and Schere, 2006) should be used with a complete inventory and appropriate stack parameters to get realistic estimates of sulphur and nitrogen in the region. Direct and indirect measurements of wet and dry deposition, respectively, would of course be optimal.

In addition to uniformly allocated deposition parameters (Table 4-1), stack parameters (Table 4-3) were assigned based uniformly across source types using regulatory defaults and expert opinion. The uniformity with which these parameters were applied does not accurately reflect the diversity of emission sources. There is a need to record actual stack and source specifications along with emissions, in order to gain a realistic understanding of cumulative or even individual effects. Unfortunately this information was not (and is not usually) available. Additionally, emissions are reported as total annual releases ($t \cdot y^{-1}$). When these cumulative values are used to derive emission rates in $g \cdot s^{-1}$, the model cannot identify unique acute exposure events that may occur during emergencies, well-testing or sour gas flaring events at oil or gas facilities – such as those that may have caused the high SO_2 concentrations at the Taylor monitoring site.

Gas-plant flares are discontinuous intermittent point-sources that may emit large amounts of SO_2 and NO_x for relatively brief periods of time (Lundgren, 2003). Such events have been known to cause direct SO_2 injury to natural vegetation in northeast BC and Alberta (Legge, 1995, Legge et al., 1998), and may make up the majority of sulphur emissions from the four flare sources. When annual totals were converted to units of $m \cdot s^{-1}$ the resulting emission rates and corresponding exit velocities were reduced to values too small to be achieved by realistic flare stacks (Appendix B); instead flaring emissions likely occurred at much higher intensities, over shorter time periods. Events, locations, frequency and emission intensity in a single regional database would greatly aid this sort of cumulative effects modelling and significantly enhance the assessment's veracity. Although estimated flaring volumes and gas composition are currently obtainable through the OGC (2008); flaring duration, stack parameters and exact location are often unknown, limiting the use of these data for effects management purposes.

Restricting the assessment to oxides of sulphur and nitrogen, and utilising AERMOD, which does not account for atmospheric chemistry, meant that the impacts of other pollutants were not accounted for.

This is of particular importance for secondary pollutants such as peroxyacetyl nitrate (PAN) and ozone (O_3) – both damaging to forest vegetation (Karnosky and Thakur, 2004) – the presence of which can be inferred from the elevated levels of NO_x and other precursors in the region. The maximum one-hour average O_3 concentration measured at the Taylor town-site in 2000 reached $121.7 \mu\text{g}\cdot\text{m}^{-3}$, with a 24-hr average of $100.7 \mu\text{g}\cdot\text{m}^{-3}$, exceeding Canada's 24-hr AAQO of $50 \mu\text{g}\cdot\text{m}^{-3}$ by a factor of 2, on April 19th, 2000. Maximum ozone concentrations occurred in the spring of each year from 1996–2001, and may be the result of stratospheric intrusion. Springtime ozone maxima have been reported frequently in parts of the Northern Hemisphere; however, the origin of this phenomenon remains a source of debate (Monks, 2000; Vingarzan, 2004). The accuracy of simulating nitrogen deposition with AERMOD would also be affected by the amount of nitrogen in various stages of oxidation. While AERMOD allows simulation of $NO_x \rightarrow NO_2$ using ozone concentrations and scavenging ratios, O_3 formation is not treated and the contribution of this chemistry to potential misestimates is unknown.

Additional discrepancies between the results and the 'real world' may occur as a result of using year 2000 data. Although this dataset was the most recent inventory of sufficient detail available to warrant such a study, some emission sources and strengths may have changed since the inventory was developed. It was not realistic to attempt the creation of future emission scenarios. While simple multiplicative factors based on scatter-plots of production over time could have been used to predict future emission scenarios, they would not represent the true complexity of variation in upstream oil and gas source emissions in northeast BC. These variations are due to a variety economic, geologic and technologic unknowns. It should also be noted that only one year of meteorology was used in this analysis. Inter-annual variation in weather and climate, especially in light of climatic change, may warrant the use of larger meteorological datasets (of 5 – 10 years duration) in the evaluation of pollutant deposition and exposure (BC Ministry of Environment, 2008) from multiple point and area sources.

4.4.2 Associated Impacts

The predicted exceedance of the annual lichen SO₂ threshold suggests that the east-facing slope of the Beaton River valley and at the northwest and southeast domain corners (Figure 3d) may expect shifts in lichen community composition and a disappearance of sensitive foliose cyanobacterial species (UNECE-LRTAP 2004) – such as *Peltigera* spp., *Leptogium* spp., and *Lobaria* spp. (Goward, 1999) – in areas of potential maximum annual concentrations (Figure 3d). Lichens are important for ungulate winter forage such as the fruticose algal *Cladonia* spp. (Tallis, 1964) and *Byoria* spp. (Holopainen and Karenlampi, 1984) and are also very sensitive to SO₂ exposure. Impacts to the *Cladonia* genus were suggested as early as 1970 around Alaskan oil and gas extraction areas (Schofield and Hamilton, 1970) and may be expected in northeast BC. Research in The Netherlands found the abundance of most epiphytic lichen species to be sensitive to both SO₂ and NO₂ concentrations (van Dobben et al., 2001).

Although temporal variations were not applied to the model emissions, predicted concentrations of both SO₂ and NO_x reached their highest levels in winter months (December to February – due to weak pressure gradients and local transport – also when UOG activity and emissions from well testing or construction peak due to the ease of access to frozen and otherwise swampy terrain. While not a significant component of the emissions inventory used here, these sources may contribute to localised winter air quality issues. Since the maximum concentrations of both SO₂ and NO_x occurred in the winter when most vegetation is dormant, lichens – some of which can photosynthesize at subzero temperatures (Atanasiu, 1971; Kappen, 1989) – are the most at risk of effects from uptake of either sulphur or nitrogen oxides during peak concentrations. At the predicted NO_x and SO₂ levels, winter lichen forage may become limited for the red-listed caribou (*Rangifer tarandus*) whose winter range historically includes roughly 75% of the modelling domain (Massey et al., 2005).

Concentrations of SO₂ and NO_x may also reach elevated levels in the summer especially when high release episodes are taken into account. Some species of vascular plant are known to be particularly

sensitive to SO₂, and have a specific relevance to First Nations. Examples include raspberries (*Rubus* spp.), blueberries (*Vaccinium* spp.) and Red osier dogwood (*Cornus stolonifera*) (Legge et al., 1998) – the two former providing direct food sources, the latter winter forage for moose (*Alces alces*), which are a staple of the northeast traditional diet (McGuigan, 2006). In Alberta, Krupa and Legge (1999) found saskatoon berry (*Amelanchier alnifolia*), another important indigenous food source, to be sensitive to relatively very low SO₂ concentrations, particularly in combination with other phytotoxic pollutants such as ozone. While individual plant and lichen species were not assigned specific damage thresholds, it is assumed that their sensitivities and tolerances are represented by the Canada's maximum acceptable 1-hr, 24-hr, and annual thresholds (Table 4-3). The same is assumed for the protection of human health.

The predicted exceedances of Canada's 1-hour NO_x AAQO and the UNECE-CLRTAP (2004) 24-hour NO_x vegetation threshold, suggest that both human and forest health may be at risk in the region from acute exposures. Experimental animal studies have shown the potential for a variety of pulmonary effects at intermittent concentrations between 75.2 – 940 µg·m⁻³ (Kagawa 1985); the maximum concentrations predicted here are within those ranges. Kagawa and Komizo (1981) found significant decreases in airway conductance following a 2-hr human exposure to NO₂ levels of 564 µg·m⁻³, only marginally higher than those predicted for the study area. Additionally, acute exposure to NO₂ concentrations as low as 188 µg·m⁻³ for 30 min. has been shown to cause reduced bacterial resistance in healthy lungs (Voisin et al., 1977). Some individuals may experience adverse health effects from NO_x concentrations predicted here (Kagawa, 1985). High potential pollutant exposures occur in areas traditionally utilised for hunting, trapping and gathering by local First Nations. Perpetual exposures to these potential levels over sustained periods can lead to numerous chronic health effects (Yang and Omaye, 2009). The highest predicted concentrations of both SO₂ and NO_x occurred in the winter only hours apart, indicating the potential for combined health effects during this time of year. Exposure to multiple pollutants can lead to human health effects at levels below air quality objectives (Bernstein et al., 2004; Yang and Omaye, 2009). There are no combined pollutant indices for either human or environmental health, further limiting the assessment

of cumulative effects from air pollution.

Nonetheless studies conducted under ambient conditions of pollutant mixtures have shown forest effects. Growth reductions in black spruce (*Picea mariana*) from ambient NO_x and SO₂ exposure have been reported in association with Canadian smelter emissions (Aznar et al., 2009) and injury to green foliage may occur from NO_x concentrations of 300 µg·m⁻³ (Bytnerowicz et al., 1998) or lower when in the presence of SO₂ and O₃ (Nihlgard, 1990). Pollutant mixtures have the potential to greatly increase the likelihood of injury to any plant species (Krupa and Legge, 1999) and at concentrations below damage thresholds, air pollution may have invisible effects on plant species' biochemical functions including, growth, resistance to disease or environmental stress (Nihlgard, 1990; Bytnerowicz et al., 1998) and competitive ability (Dueck and Elderson, 1992). While the potentially high pollutant exposures predicted here are of short duration and only affect a very small portion of the study area, they are just as likely elsewhere in northeast BC. It remains a decision of local communities as to whether or not these changes and levels of protection are considered acceptable culturally or otherwise (McGuigan, 2006).

The north-western portion of the study area received some of the highest predicted pollutant levels, experienced all estimated exceedances, and is the location of the Blueberry River First Nations reserve. This community may, due to geographical location, be more susceptible to air pollution impacts than the neighbouring communities of Doig River and Beatton River. The cumulative effects of pollutants in the northwest of corner of the study area may have broad implications for the Blueberry River First Nations community members that reside there.

4.4.3 Future Directions

The majority of sources were small (i.e. propane-fired reciprocating engines) some releasing less than 1x10⁻⁷ t·y⁻¹ of SO₂ and 1x10⁻⁴ t·y⁻¹ of NO_x (Table 4-2). These emissions are not expected to decrease in the near future since these sources are associated with small individual well sites and batteries. Releases from

large facilities may decline if production continues to follow the downward trend shown in Figure 4-2. Such facilities report to the NPRI and the reductions would therefore be captured by federal inventories, unlike the increases from smaller sources. Flaring (and venting) are expected to increase with increased exploration and drilling, due to increased well testing. Recent voluntary measures to contain well-testing within pipelines (BC Ministry of Energy, Mines and Petroleum Resources, 2009) are unlikely result in significant emission reductions unless these measures are enforced. While it is assumed that associated gas flaring (natural gas produced as a by-product of crude oil) will be eliminated entirely by 2020 as an energy conservation measure (British Columbia, 2007; BC Ministry of Energy, Mines and Petroleum Resources, 2009), no specific SO₂ or NO_x emissions reduction programs are predicted between 2000 and 2020 for the region.

Whichever direction that future upstream oil gas activity and associated emissions take, two recommendations can be proposed: 1) to carry out emissions permit modelling on a cumulative basis so that emission sources in a shared atmosphere can be incorporated; and 2) to conduct modelling over longer time periods to identify potential long-term threshold violations and chronic exposures while accounting for year-to-year meteorological variations. While this will require the transparent provision of more complete emissions data, the recommendations are in line with emerging cumulative effects assessments and regional management approaches (CCME, 2009).

4.5 Conclusions

The isolation of facilities and events for current atmospheric release permits (and traditional environmental impacts assessments) ignores the potential cumulative impacts of multiple emission sources (or activities) in shared space and time. While individual plants and “small” UOG emission sources may appear benign, when considered cumulatively, even over a relatively small study area, their plumes have the potential to intersect and exceedances of ambient air concentration standards for SO₂ and NO_x are likely to occur. Episodically high concentrations occur under conditions of a stable boundary

layer with light winds and little convective or turbulent mixing. The elevated concentrations of these pollutants in combination with increased levels of other atmospheric constituents such as O₃ can have deleterious effects on human health and boreal forest species – particularly the diverse lichen communities of northeast BC. Lichen effects may in turn affect species at risk, such as caribou, which if in ill health or decline, further impact the health and traditional vocations of First Nations' communities in the region. Emission sources cannot be treated in isolation if human health, ecosystem diversity and First Nations rights are to be protected. However, in order to treat emissions data and modelling cumulatively from a regulatory perspective, many of the current barriers to emissions transparency – such as well confidentially or proprietary datasets – need to be addressed. In addition, the development of multi-pollutant exposure indices would further the practices of both assessment and impact prevention.

4.6 References

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5 CONCLUSION: SEEING THE FOREST FOR STACKS

5.1 Overview

The cumulative impacts from air pollution can be received by communities in BC's northeast through numerous impact pathways: either directly through the air, or indirectly through water, soil, plants and animals. Each of these channels has end-points that may affect the health of all residents, as well as First Nations' ability to succeed in, or sustain, a traditional forest-based economy. It follows that the "right to pursue the usual vocations of hunting, trapping and fishing throughout the tract" as defined in Treaty No. 8, may be threatened by the past, present and/or future levels of CAC emissions occurring within the territory.

Chapter 2 illustrated that the vast majority of these emissions are from UOG sector sources, primarily in the form of SO₂, NO_x and VOC, that are largely unreported, routinely unregulated, and not reduced or further considered by new reporting regulations. Oxides of sulphur and nitrogen are known to be acidifying and Chapter 3 explored the vulnerability of freshwater ecosystems, and therefore their watersheds, to acidification. This analysis showed that while much of the region's geology lends itself to acid neutralisation abilities, there are some lakes and basins within the area that are relatively sensitive to atmospheric acid deposition (i.e. of sulphur and/or nitrogen compounds). While available deposition data did not show loads capable of reaching acidification thresholds, Chapter 4 used the more complete emissions data set derived in Chapter 2 to simulate deposition and concentration of SO₂ and NO_x within a small but socially significant portion of the study area. Results showed the potential for direct human health and vegetative effects.

5.2 Limitations

As with any undertaking of this magnitude, there are many associated limitations. Some of these are deliberate; necessitated by constraints to financial, temporal or cognitive resources. An example would be the use of AERMOD View™ over CMAQ. The former does not carry out pollutant chemistry nor handle domains of ≥ 50 km in size, but neither does it require a supercomputer, a year to run, or programming capabilities, as does the latter.

The uncertainties associated with mathematical modelling of any sort cannot be over-stressed. Models were used throughout this work and generate compounded errors: from the emissions factors and methods used to create the inventory discussed in Chapter 2, to the SSWC model used to derive critical loads of acidity in Chapter 3, and finally AERMOD View™ used to estimate the concentration and deposition of sulphur and nitrogen oxides for comparison with distantly measured values in Chapter 4. The choice of AERMOD View™ meant that only a small portion of northeast BC had its emissions simulated, whereas distinct situations may occur elsewhere in Treaty 8 traditional territory. The diversity of topography, emissions, climate variables, land-cover and species compositions, means that extrapolation of the modelled results to elsewhere in the ‘Peace’ is unrealistic. However, at the modelling domain level, despite a high level of uncertainty (10 – 40%), the predicted maximum concentrations can be expected to occur somewhere within the domain over the specified modelling period (BC Ministry of Environment, 2008).

From a cumulative impact perspective, this assessment did not account for all emitted pollutants in the region, nor all of the potential impacts of sulphur and nitrogen oxides and their associated chemical by-products. In addition, there was no assessment of pollutant chemistry or the interactions amongst sulphur and nitrogen in either the ambient or biological atmospheres of pollutant receipt. These synergistic impacts are however discussed in a following section (5.4), and while not the focus, these synergies were described briefly in the preceding chapters. Unlike an “ideal” cumulative impact assessment, the work

presented here did not explicitly predict future impacts. For instance steady state CL(A) models such as SSWC do not account for when acidification will occur, as do their dynamic counterparts for which data was lacking. In addition, unclear trends in oil and gas production, hydrocarbon composition and reservoir availability limited the extent to which future (or even current) CAC levels in northeast BC could be assessed (Chapter 4). These difficulties were furthered by a lack of political will and environmental policy to keep data accurate and current.

A common theme throughout each chapter was a lack of available data. Perhaps the greatest limitation of this research was that it lacked any direct field measurements carried out for the purpose of answering the research questions proposed in Chapter 1. An ideal assessment would have used a combination of monitoring (pollutant concentration, deposition and/or effects) and modelling. However due primarily to financial constraints, the work was forced to rely on existing data. These data were sometimes dated, of unknown accuracy, and scarce.

The inaccessibility of comprehensive datasets riddled this work – such as the emission-poor CMAQ runs used to calculate CL(EX) in Chapter 3, or unverified data used to compare to modelled data in Chapter 4. Perhaps more importantly, effects limits such as critical loads or concentrations thresholds, were not specific to ecosystems and species encountered in northeast BC. While BC's Ambient Air Quality standards were used in Chapter 4, these standards were developed from a largely agricultural rather than ecological or human health perspective. Although Treaty No. 8 supports agricultural endeavours, farming is not practiced by the majority of First Nations in the north.

European experiments were used for both critical limits (such as that for sulphur on lichens which was exceeded) and in calculating critical loads. This study did however, approach limits for ANC and vegetation doses from other than purely regulatory perspectives. For instance the ANC_{lim} was set to protect freshwater biodiversity at all trophic levels (rather than just sport fish) and lichens were chosen as

an important ecosystem element, since they are essential ungulate winter forage (Braune et al., 1999; Ferguson and Elkie, 2004; Serrouya and D'Eon, 2008) and hold a variety of traditional uses (Marles, 1999). A lack of site- or even region-specific effects threshold data is unfortunately not unique to this assessment. Canada-wide CL(A) are generally estimated using biological thresholds developed in Europe. For instance brown trout (*Salmo trutta*) sensitivity data from Europe is often used in Canadian studies (Tri-Star Environmental Consulting, 2009); although this species stocked in some sport lakes, it is not a native fish species to Canada and is less sensitive to acidification than other lake-fish species (Dupont et al., 2005).

Despite these limitations, the results show a clear potential for negative impacts from air pollution in the Peace region. The larger cumulative impacts project that this study is a part of, aimed to develop a useful tool by which First Nations can assess and manage cumulative effects within their traditional territory. Ideally this tool would be a model with a simple user-interface that uses inputs from various land-use and development scenarios, to give output of likely ecological outcomes. Despite associated errors and unknowns, through the development of freshwater indicators and the elucidation of potential air pollution effects and emission oversights, the results presented here contribute to such a tool.

5.3 Implications

5.3.1 Wildlife

Air pollution can have either direct or indirect effects on wildlife. Indirect effects can occur through changes to forest species such as reductions in important forage or overall changes in community structure and growth. The most definitive prediction of was for lichen species - from the modelling in Chapter 4.

Caribou (*Rangifer tarandus*) now a red-listed species, were once a staple of the north, and are dependent on pollutant sensitive lichens as winter forage (Braune et al., 1999; Monks, 200; Ferguson and Elkie,

2004). Lichen disappearance or reduction would increase the threat to already vulnerable populations in northeast BC. Lichens represent an important food source for other mammals as well, including mule deer (*Odocoileus hemionus*) (Serrouya and D'Eon, 2008), and smaller moles, voles and squirrels (Hagar et al., 2007). Although moose (*Alces alces*) do not rely quite as heavily on lichens for winter survival as other ungulates, lichens are still an important moose food source (State of Alaska Department of Fish and Game, 1986), and moose were the most valued ecosystem component specified by local First Nations in the northeast (McGuigan, 2006).

5.3.2 *First Nations*

Ecosystem health is directly linked to human health through ecosystem services. These are functions provided by natural systems without human intervention, but which without humans could not survive (Costanza et al. 1997; Forget and Lebel, 2001). The links between ecosystems and human health are particularly strong for First Nations' communities in northeast BC whom rely on directly natural systems for food, water, and spiritual or ceremonial practice (McGuigan, 2006). However, non-aboriginal residents of the northeast are also directly and indirectly affected by atmospheric pollution in the Peace.

According to Canada's *Constitution Act, 1982, Canadian Charter of Rights and Freedoms* "Everyone has the right to life, liberty and security of the person and the right not to be deprived thereof except in accordance with the principles of fundamental justice" (Part.2 s.7.). The Charter also states that "existing aboriginal and treaty rights of the aboriginal peoples of Canada are (hereby) recognized and affirmed" (Part 3 S.35 (1)). By negatively affecting the forests in which the "usual vocations of hunting, fishing and trapping" as protected by Treaty No. 8, are carried out, air pollution indirectly impacts both of these rights in northeast BC. The Charter provides further that "anyone whose rights or freedoms, as guaranteed by this Charter, have been infringed or denied may apply to a court of competent jurisdiction to obtain such remedy ... (Part 3 S.24(1))". This right to apply to a court is impeded by barriers to information such as actual CAC emissions. The lack of fair and transparent access to information of all affected parties is an obstruction to presenting factual evidence in such a proceeding.

Here, direct effects were examined through concentrations and exposures to ambient levels or threshold concentrations. The AERMOD model was used to detect biologically harmful levels of SO₂ and NO_x in the atmosphere over a co-chosen segment of Treaty 8 traditional territory (Chapter 3). Exceedances of federal health and environmental protection limits (i.e. AAQO) especially at the Blueberry River Reservation, in addition to exceedances of vegetative thresholds (UNECE-CLRTAP, 2004), suggest the potential for both direct and indirect CAC effects on human health in the region. Potential health outcomes, both indirect and direct, result from combinations of social and environmental factors. For example Hu et al. (2008) found that air pollution effects combined with factors such as low income and reduced “greenness” (proximity to green spaces such as parks) significantly increased mortality rates associated with strokes.

The most obvious indirect health impact pathway is through food – either a change in the quality or quantity of food available for consumption. Moose and berries are staple food sources for First Nations in northeast BC (McGuigan, 2006). In addition to potential direct injury to moose forage and sensitive berry species, acute and chronic levels of pollutants, particularly ozone, can alter the nutritional value of ungulate forage (Sanz et al., 2005; Lin et al., 2007) and cultivated food crops (Pleijel et al., 1999). There is less research, and less reported nutritional effects from SO₂ or NO_x (Lin et al., 2007); however, ambient levels of these compounds may decrease the growth of sensitive species in favour of increased growth in S or N limited species. Natural selection for these ‘tolerant’ plants (Karnosky and Thakur, 2004) can replace other important food or forage species in the wild. The ability to cultivate and fish hunt or trap for food are rights protected by Treaty No. 8; these rights may be threatened by current (or year 2000) levels of pollutants in northeast BC. Other potential food vector effects are discussed in Section 5.4.

5.3.3 Policy

New federal reporting policy (Canada, 2008) includes exclusions for upstream oil and gas sources. These exemptions apply to all hydrocarbon rich regions, including BC, Alberta and Saskatchewan. Nationally the amount of unreported air pollutants under these guidelines, although not calculated here, would be substantial. As discussed in Chapter 2, policy steers reporting which is then used in assessments of human health and the environment to see if negative environmental impacts are likely to occur from the “business as usual” scenario (Niemi, 2005). If no effects are predicted then policy does not change and business continues as usual, as has historically been the case in western Canada (Environment Canada, 2005). If predictions are based on only a portion of reality, such as the year 2000 CAC emissions in northeast BC, then we risk the chance of allowing effects to occur and continue without management or mitigation.

Estimation of the critical loads of acidity in Northeast BC has shown that while much of the area is underlain by carbonate bedrock and is relatively insensitive, some lakes are relatively sensitive to acidification (i.e. $CL(A) < 0.5 \text{ keq}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$). Canada’s Acid Rain and CL(A) maps have traditionally focused on eastern Canada (Carou et al., 2008). The research presented here, along with that being carried out in the Georgia Basin of southern BC (e.g. Mongeon et al., 2010; Nasr et al., 2010) and parts of Alberta (e.g. Whitfield et al., 2010a; Whitfield et al., 2010b), has shown that western Canada deserves attention in terms of acidification sensitivity and critical load exceedances.

It is not sufficient to assess the impacts of emission sources in isolation. Permit and fee requirements for atmospheric emissions in BC are handled much like environmental impact assessments – on a project-by-project basis. However, as shown in Chapter 4, when the combined effects of these sources in a shared atmosphere are taken into account, concentrations reach levels that may become harmful to sensitive species and human health. In addition, the use of thresholds in the federal reporting of CAC underestimates emissions, and therefore leads to underestimates in concentration and deposition estimates

made by government-led modelling programs. Emission inventories are kept in order to track pollution, determine regulatory requirements, protect human health and the environment (CEPA, 1999) and adhere to international conventions (e.g. UNECE-CLRTAP (1979)) (Niemi, 2005). Underestimates can lead to inadequate protection of human and environmental health.

5.3.4 Industry

Upstream oil and gas industry faces an unknown future in BC. While exploration and drilling activity in the sector still appear to be growing, these factors do not necessarily translate into increases in production, pollution, or profit. Contrary to government plans of doubling production cited in Chapter 2 (from a document that “does not exist anymore” (D. Sun *Personal Communication* February 13th 2009)), production of both oil and gas are declining (Chapter 4). Whether the decline in production will equate to a reduction in emissions will depend on the success of future exploration, the chemical composition of fuel streams and whether new policy is put into place to either reduce or cap emissions. Although recently introduced voluntary measures aim to reduce flaring or venting associated with well testing by proposing in-pipe releases, with production figures down, it is unlikely that industry will be inclined to invest in better practices without regulatory or market-driven incentives.

In recent years BC’s forestry industry has also seen declines, from pine beetle outbreaks to international disputes – all of which have impacted the northeast. Several of the pulp and board mills included in the year 2000 emissions inventory in Chapter 2 have since closed their doors. While a detriment for local economies, local air quality tends to benefit substantially from these closures (D. Fudge *Personal Communication* September 8, 2009). Air pollution has been shown to have a variety of effects on forests (Dueck et al., 1992; Flager, 1998; Riggins et al., 2000; Enns, 2004; Bytnerowicz et al., 2007) and may further impact a suffering forest industry by affecting forest health, composition or stand growth, thereby influencing management-based decision-making and forest-based economies, whether aboriginal or otherwise.

5.4 Air Pollution Related Impacts

The focus here has been on CAC, mainly the cumulative impacts of NO_x and SO₂ emissions. However, these indicator pollutants and their sources are linked to other emissions whose effects were not discussed in detail. For instance VOC emissions were found, like NO_x and SO₂, to be both prolific and under-reported in northeast BC (Chapter 2). The emissions inventory sources did not speciate individual VOC compounds, which is unfortunate considering the vast number emitted from oil and gas sources. For instance under controlled conditions Stroscher (1996) found that a single natural gas flare can produce >60 different VOCs through pyrolytic reactions including large amounts of benzene – a known carcinogen (Atari and Luginaah, 2009), and VOCs such as ethyl-benzene, toluene and xylene – all considered harmful to human health even at low concentrations with prolonged exposure (Shojania et al., 1999). These compounds were some of 26 different VOCs found by You et al. (2008) in ambient air samples near UOG facilities in northeast BC. The estimation of emitted volumes and the effects of these potentially toxic organic compounds was beyond the scope of this work, but depending on their ambient levels and exposure frequencies, these VOCs may have long-term impacts on human and animal health.

Tropospheric ozone (O₃) is a secondary pollutant formed from the photolysis of NO₂ in the presence of sunlight, atomic oxygen and VOCs. Although AERMOD View™ lacks the ability to simulate its formation through photochemistry, O₃ measured in Taylor reached high ambient levels, particularly in the spring. Elevated O₃ levels may form further downwind (east) in northern Alberta where the plume may become further enriched with nitrogen oxides and UOG or boreal sources of VOCs. While emitted over a larger area, northeast BC's NO_x emissions are approximately one half those reported by the Greater Vancouver Regional District for the same period (GVRD, 2002) – a region known for episodic exceedances of O₃ AAQO in remote areas downwind of Vancouver (Krzyzanowski et al., 2006). Ozone has been shown to have negative effects on human health (Curtis et al., 2006), forest trees (Percy et al., 2003; Turnipseed et al., 2009), lichens (Zambrano et al., 2000), and berry (*Rubus* spp.) species (Chappelka et al., 1986) thereby both directly and indirectly impacting First Nations' health, livelihoods

and Treaty rights through the quantity and quality of available forest resources – including both food and fresh air.

Upstream oil and gas also produces a variety of other harmful wastes that may lead to effects through air-borne pathways. Naturally Occurring Radioactive Materials (NORM) are sometimes associated with UOG production water, equipment scale and to a lesser extent extracted fuel. Occurring most commonly in the form of radium and daughter products (Hamlat et al., 2001; Eriksen et al., 2005; Shakhawat et al., 2006) they emit ionizing beta (β) – from ^{228}Ra , or alpha (α) – from ^{226}Ra and ^{224}Ra particles, and gamma (γ) rays. Human and animal exposure to radioactive particles occurs through the ingestion of contaminated food (i.e. grown on contaminated soils) and water, or direct inhalation (Canadian NORM Working Group of the Federal Provincial Territorial Radiation Protection Committee, 2000). Gamma rays are produced throughout the uranium (ex. ^{226}Ra) and thorium (ex. ^{224}Ra and ^{228}Ra) decay series (Canadian NORM Working Group of the Federal Provincial Territorial Radiation Protection Committee, 2000) and are known to cause chromosomal mutations in plants and animals and contribute to cancer related effects in animals and humans (Petrucci and Harwood, 1993; Claxton and Woodall, 2007). Produced or disposed water in BC is not analysed for radium or other isotopes producing γ , β or α radiation (OGC, 2008). However, one study found ^{226}Ra as well as isotopes of lead (^{210}Pb) and radon (^{222}Rn) in gas streams, pipelines and equipment from a facility in northeast BC (van Netten et al., 1998). The authors cite no risk from occupational exposure; nonetheless α -emitting ^{222}Rn gas levels reported in output gas and some equipment were above limits specified by the Canadian NORM Working Group of the Federal Provincial Territorial Radiation Protection Committee (2000). First Nations' exposure to γ rays may occur near production or waste spreading areas, and to β or α through inhalation, drinking water, and wild food (e.g. berries grown on contaminated soils or moose fed on contaminated forage). Biochemistry in *Cladonia* spp. – important ungulate forage – is known to be altered by γ -ray exposure (Nifontova et al., 1995). Depending on geographic flow regimes, exposure may also occur through locally cultivated food. The related cumulative dose and risk estimates are not calculated here.

Saline water is also a common by-product of most oil and gas production facilities. Enns (2004) found that brine-spray released from upstream oil and gas operations in northeast BC caused damage to vegetation that was similar to that of acute air pollution injury. Much of the drilling fluid waste and produced water is stored on-site in ponds known as 'sumps'. Saline wastewater evaporates and leaves crystalline residue that attracts ungulates such as deer and moose as a salt lick. This salt in combination with the optimal forage species planted on well pads (such as wheatgrass (*Elymus* spp.)) (OGC, 2003), and pools of open 'water', attracts a variety of wild ungulates which then become exposed to localised sources of air pollution (particularly H₂S which is heavier than air and sinks to ground level), radioactivity, and liquid hydrocarbons.

Greenhouse gases (GHG) are emitted from the same pollutant sources examined in the preceding sections. These compounds (namely CO₂, CH₄ and N₂O) also have implications for provincial, federal, and global science and policy. Like the CAC emissions discussed in Chapter 2, many GHG sources are excluded and under-reported. While beyond the scope of this dissertation, annual GHG totals for northeast BC from the CAPP inventory for the year 2000, totalled over 1.6 megatonnes of CO₂ equivalents. For perspective, these omitted emissions represent only 2.4% of BC's total GHG emissions for the year 2000 (BC Ministry of Environment, 2009). Land-use and conversion practices in the region, are likely more pervasive to a changing climate through the alteration of energy and water balances, especially on a local or micrometeorological level. Future large developments in the region, such as the four proposed wind power projects with a combined capacity of 295 MW (an indirect effect of air pollution) and the Site C dam on the Peace River, will also likely impact local climate and in turn alter atmospheric dispersion and the transport of pollutants.

Climate change and greenhouse gases interact with pollutants on physical, chemical and biological levels. For instance a change in temperature or moisture characteristics, leads to changes in: pollutant reaction

rates; deposition velocities; and vegetative uptake, resistance, and sensitivity. Greenhouse gases in addition to increasing atmospheric temperatures and shifting moisture regimes, also directly alter atmospheric chemistry (Sellers and Schimel, 1993) and the way plants respond to air pollution (Karnosky and Thakur, 2004). An understanding of forest responses to these synergisms between air pollution and climate change is beginning to emerge (McLaughlin and Percy, 1999; Bytnerowicz et al., 2007), and the tackling of both problems in combination is considered economically and socially beneficial (IPCC, 2007). Nevertheless, climate change and its interactions with the air pollution effects pathway were considered outside the scope of this assessment.

Visibility, odour and noise pollution are additional effects not accounted for in the preceding assessment. Visibility and odour are direct results of air pollution. Noise may or may not be associated with the air pollution pathway but is often regulated in a similar manner (RWDI Air Inc., 2005). Each of these impacts is sometimes associated with being a nuisance, rather than an actual threat to human health and safety. However, noise, odour and visibility impacts one's 'sense of place' and perception of the natural environment. For forest-based cultures these factors may have large impacts on traditional occupations and community health. Noise, visibility and odour issues also reduce the ability to practice traditional tracking and hunting methods that require a keen eye, ear and nose. Odour in northeast BC originates from H₂S emissions, a toxic gas that contaminates some hydrocarbon streams. While perceptible at levels generally too low to cause harm (at higher levels the olfactory senses become paralysed (CAPP, 2003)) this particular scent has strong psychological and perhaps legitimate ties to unhealthy levels of air pollution. Noise originates from well-sites, batteries and gas plants distributed across the land throughout the northeast. Visibility can be altered or reduced by a number of air pollutants that scatter light in the atmosphere. These include, but are not limited to, primary pollutants such as NO₂, PM, and VOC, and secondary pollutants such as O₃ or SO₄²⁻ aerosols.

A comprehensive and complete cumulative impact assessment of air pollution in northeast BC, inclusive of the interactions with associated effects discussed above, would require a team of researchers and their budgets. The effects of air pollutants in combination are often greater than the sum of their individual effects (Menser and Heggstad, 1966, Dueck and Elderson, 1992). This is also true of the effects of air pollution in combination with other pathways such as climate change (Bytnerowicz et al., 2007). These synergisms and their related responses are often species specific. While the preceding research suggested impacts to sensitive lichen species, the combined effects of climatic warming, SO₂, NO_x and O₃ on lichens or less-sensitive species such as Red-osier dogwood (*Cornus stolonifera*) – an important moose forage – are unknown. NO₂ for instance inhibits complete stomatal closure by plants at night, thereby increasing the potential uptake and subsequent damage caused by SO₂ or O₃ (Amundson and MacLean, 1982). Such interactions and how they may effect forest ecosystems, their function, and forest-dependent communities in BC's northeast, can only be determined through research and monitoring programs.

5.5 Future Directions and Recommendations

5.5.1 First Nations

A key to the fruition of the objectives set out by the larger cumulative effects project, and the air pollution portion described here, is the continuation of First Nations engagement in cumulative effects monitoring. In Chapter 3, freshwater acid sensitivity indicators were developed that can easily and effectively be measured by First Nations' communities. In addition to these indicators other community biomonitoring projects could be established. Lichens in particular are a good indicator of SO₂ (Holopainen and Kärenlampi, 1985; Nash and Gries, 2002; Enns, 2004), NO_x (Holopainen and Kärenlampi, 1984), H₂S (Paoli and Loppi, 2008) and O₃ (Egger et al., 1994; Zambrano et al., 2000) concentrations, and the deposition of sulphur or nitrogen compounds (Fenn et al., 2003; Addison and Pucket, 1980). A simple record of the presence, absence or disappearance of a particularly sensitive lichen genus (e.g. *Peltigera spp.*, or *Cladonia spp.*) or group (ex. cyanobacterial, epiphytic, fruticose, etc.) within its known range and habitat, can indicate a great deal about the local air quality (DeWit, 1976; Rigina and Kozlov, 2000;

Kinnunen et al., 2003) – although not necessarily the type of air pollutant(s). Discolouration is also a good indicator of pollutant exposure for some lichen species (Paoli and Loppi, 2008). Since exceedance of the annual sulphur concentration threshold for lichens was predicted over a substantial portion of the modelling domain in Chapter 4, it is likely that changes in lichen communities will be seen throughout the Peace region.

Many species of tree and shrub are also good indicators and pollutant exposure (Kozlov et al. 2009). With the use of an injury guide, such as Flagler (1998) that includes examples of visible injury from vegetation in the region, skills can be developed by community members to recognise potential foliar injury from pollutants in the field. Since other factors may cause similar symptoms (such as drought or nutrient deficiency), circumstantial evidence of injury should be followed up with further monitoring and analysis. Tobacco, a ceremonial plant for aboriginal people, is also a powerful indicator of NO_x and O₃ and can be planted (or placed) in areas of air quality concern and monitored for the development of visible injury symptoms (Gombert et al., 2006). These observations or measurement in the case of freshwater indicators, can easily be made while carrying out one's usual vocations of hunting, trapping and fishing.

The ideal way for communities to monitor air pollution levels and make inferences about effects is through direct measurements. The Fort Nelson band has a small meteorology station and PM monitor. While PM is not considered a pollutant of concern in northeast BC as associated with UOG activity in the area, it is a favourite of provincial monitoring initiatives (see BC Ministry of Environment, 2009). Fort Nelson serves as an example of community involvement that could be achieved elsewhere in the territory if funding were available. Direct measurements of ambient air quality are expensive, and both active monitoring of its alternatives often require levels of skill and training that may not be readily available to these communities. This is also true of the microscopic and biochemical analyses (ex. Bussotti et al., 2003) that should follow any observed changes in community structure or foliage through lichen or vascular plant monitoring initiatives before any cause-effect conclusions may be drawn.

5.5.2 Science

Although largely dictated by social and political will, science is capable of filling the measurement gap for First Nations communities, and for society as a whole. Any sort of direct air concentration or deposition monitoring in the region, preferably for multiple substances, would assist in alleviating unknowns and filling in gaps. Multi-pollutant monitoring stations are expensive and in northeast BC are established and maintained by the oil and gas industry (see BC Ministry of Environment, 2009).

Unfortunately the data retrieved from these sites are unverified, prone to zero values, and discontinuous (BC Ministry of Environment, 2009). Most of the air pollution related research that has been conducted in northeast BC to date has been conducted or initiated by the local oil and gas sector such as Legge (1995) and Reid (2003), or funded by the OGC's SCEK (Science & Community Environmental Knowledge) fund, such as Enns (2004), which itself is funded through contributions from the oil and gas industry. Unfortunately, the SCEK has not been accepting unsolicited proposals since 2004, throwing doubt on its value as a source of independent and reliable research, while most industry reports remain internal and difficult to locate.

The cost of equipment can deter academic researchers from engaging in long-term monitoring programs, especially since monitoring is generally required at multiple locations. Passive samplers are economical and can be used in conjunction with a continuous monitor to provide better spatial resolution for monitoring studies (Bytnerowicz et al., 2005; Salem et al., 2009). While limited by their measurement of cumulative rather than hourly doses, long-term exposure indices (not applied here) can be used with passive samplers to assess potential vegetative dose (Krzyzanowski et al., 2006) and effects from multiple or individual pollutants. Lichens and certain species of indicator plants can aid in developing region-specific dose-response metrics.

There are currently no cumulative or short-term indices to assess the doses and effects of multiple pollutants – other than combined sulphur and nitrogen acidity critical loads discussed in Chapters 3 and 4. The development of multi-pollutant indices through a combination of laboratory and field measurements would provide valuable indicators in cumulative impact assessments in northeast BC and elsewhere around the globe. These indices would ideally be biologically relevant to the ecosystem in question – something lacking for most of the indices or thresholds used here and elsewhere in Canada. Because air pollutants can have a variety of effects on forests many of the criteria and indicators of sustainable forest management (Montréal Process, 1999) can also be used to assess the effects of various pollutants – for example lichen diversity or crown condition (Rennolls et al., 2007). The area of forest exposed to threshold levels of air pollutants is also an established indicator of forest health (Montréal Process, 1999).

Biologically and culturally relevant indicators and thresholds of change (i.e. measures) need to be developed for the correct application of critical loads. Those used here were derived from research conducted on various ecosystems throughout Canada and the globe, and modified to reflect First Nations' specific criteria. For instance, lichens were used as an indicator due to their sensitivity to relatively low levels of pollutants and their importance as ungulate winter forage; and the ANC_{lim} used in critical loads calculations was set much higher than customary to offer increased protection of aquatic ecosystems, because First Nations' communities do not consider the loss of any aquatic species an "acceptable" risk (Chief R. Wilson *Personal Communication* Oct. 20, 2008).

The relevance of CL(A) to assessments of impacts requires accurate measurements or estimates of S, N and base cation deposition. AERMOD was unable to provide reliable deposition estimates in Chapter 4 and those obtained using CMAQ from Environment Canada in Chapter 3 are limited by the use of an incomplete emissions inventory as outlined in Chapter 2. A number of methodologies exist for measuring deposition to surfaces. Rain collection and chemical analysis, or the use of resin tubes (Fenn et al., 2009) and other surface collectors (that can also measure base cations) (Chu et al., 2008) are relatively

inexpensive ways to measure wet and bulk deposition, respectively. Levels of S or N in lichen tissues (Carreras and Pignata, 2001) and conifer foliage (Innes, 1995; Enns, 2004) also correspond well to levels of atmospheric deposition. The most complex, but some argue the most accurate, way to examine deposition to forests and other vegetated or non-vegetated surfaces, is through the use of flux towers employing the techniques of eddy correlation (Stocker et al., 1995; Walton et al., 1997; Burkard et al., 2003). Flux measurements relate to actual uptake and would be useful in setting region-, ecosystem-, or species-specific exposure thresholds.

While there are directives approaching cumulative air pollution impacts elsewhere – such as: the South Coast Air Quality Management District (2004) in Diamond Bar, California and the Cumulative Effects Management Association(2008) in Fort McMurray Alberta; or the Environment Canada’s national modelling directives (Carou et al., 2008) – this is the first of such an assessment to frame impacts from a First Nations’ perspective; use a comprehensive emissions inventory; publish policy relevant results; or focus on British Columbia. As with cumulative effects research for any pathway, the methods employed are as unique and diverse as the impacts they consider.

Ideally, an assessment of cumulative impacts would examine all ‘likely’ impacts from past, present and future actions, on all species, and all systems within a predefined management area. However due to the resource limitations of any project, this practice is rarely feasible and boundaries must also be applied to temporal scales, types of activities, impact pathways, and outcomes of interest. This ‘scoping’ of the project’s boundaries can be especially difficult in air quality management due to the diverse, boundless and interactive nature of atmospheric contaminants, their receptors and the sources that produce them. Nevertheless these limitations can be overcome with regional and airshed level assessments.

Although science is capable of answering most of the unresolved questions from this research, such scientific assessments are often limited by the political will to provide support for such endeavours. For instance it remains a common assumption at various levels of BC’s government that all of the

freshwater systems in BC's northeast are so alkaline from carbonate bedrock, that they could never become acidified (Jesse Montes *Personal Communication* Mar 16, 2009; Dennis Fudge *Personal Communication* Sept. 8 2009). However, Chapter 3 showed that some lakes on siliclastic bedrock may be receiving their base cations from non-carbonate sources and therefore be quite sensitive to acidification. Extending federal Critical Loads programs by conducting water chemistry surveys of lakes in siliceous basins in the northeast of BC, would facilitate air pollution effects assessment and management.

In Canada CAPMoN stations have been monitoring precipitation chemistry, gaseous pollutants and/or meteorological variables across Canada since 1983 (CAPMoN, 2002a). Data from these stations provides the best description of acidifying sulphur/nitrogen and neutralising base cation deposition in the country. These sites however, are focused in eastern Canada. There is only one CAPMoN site in BC (Saturna Island), and one station in each Alberta (Esther) and Saskatchewan (Bratt's Lake). Ozone is the only variable currently measured at the Alberta site (CAPMoN, 2002b). The Meteorological Service of Canada is expanding the CAPMoN program, and while sites are being placed further left on the map to account for the west's UOG boom, it is unlikely that one will become located in northeast BC (Robert Vet *Personal Communication* April 28, 2009). The locations of new sites are still under debate; northeast BC or a downwind location in northwest Alberta is (and has been) strongly suggested. Measurement is the only way to obtain correct deposition data for the region.

International government initiatives are responsible for monitoring forest state and its relation to air pollution in Europe (ex. Lorenz et al., 2008; Ferretti and Chiarucci, 2003) and the United States (ex. Smith, 2002). In Canada a project entitled Forest Indicators of Global Change was established in 1998 comprising 26 permanent monitoring plots from Northern Ontario to New Brunswick where acidification critical loads and ozone critical levels are exceeded (Canada-United States Air Quality Agreement, 2002). These monitoring plots replace the previous 150 Acid Rain National Early Warning System (ARNEWS) sites that were also located in, or east of, Ontario (Canadian Forest Service, 2003). The eastern focus of

these projects neglects the dramatically increasing emissions in western Canada, and continuously decreasing emissions in the east (D. Niemi *Personal Communication* October 5, 2009; see Chapter 2). Some attention should be focused on forest health in western Canada in light of these CAC emission increases and the sensitivity of some western species such as Saskatoon berry (*Amelanchier alnifolia*). It would be beneficial for forest monitoring to spatially coincide with CAPMoN stations, and for activities to include similar biomonitoring programs using lichens and other sensitive species as indicators of air pollution injury; as suggested in the previous section (5.5.1) for First Nations.

5.5.3 Policy

Currently in BC the discharge of industrial waste via air, land, or water is regulated by the 2004 *Environmental Management Act – Waste Discharge Regulation*. This regulation limits the need for permits to only “large” UOG industry sources. BC’s former *Waste Management Act* of 1983 regulated the releases of all waste through air, land and water – there were no reporting thresholds. From a cumulative impact perspective the regulation of all emitters regardless of size provides a more accurate view of the actual substances entering into ecosystems via air, land, or water effects pathways. Although more costly than processing permits for only a fraction of potential emitters, it is within the mandate of environmental protection to regulate all emission sources no matter their size. Part of the permitting process requires the use of dispersion models to ensure that AAQO are not exceeded. As was shown in Chapter 4 the number and vicinity of sources warrants the modelling of emissions from multiple projects sharing an airshed. This can be accomplished using models already utilized for permitting requirements, such as AERMOD.

Recommendations for inclusiveness are also made for federal NPRI reporting. Canada-ratified international covenants such as CLRTAP and the *Canada-United States Air Quality Agreement* mandate comprehensive reporting (and reductions) of sulphur and nitrogen oxides. At the domestic and global levels emissions reporting serves as both a benchmark and measure of progress. Accurate reporting is also the only means of realistically predicting current and future pollutant loads using regional or plume-based

models. Once inclusiveness is achieved, regulatory caps or limits can be placed at any number of geographic scales to ensure adequate environmental protection and achievement of the federal mandate to “keep clean areas clean” (Carou, 2008).

Information regarding air pollution or reported emissions should be made freely available to interested parties. Data confidentiality is not in the best public interest and creates a barrier to effective cumulative impact assessments whether conducted by industry, First Nations, academia, or otherwise. This recommendation is made, despite the generally poor quality of available emissions or monitoring data. Transparency with emissions datasets and otherwise can aid in co-management and can ease conflicts arising during consultation or negotiation processes.

5.6 Conclusion

The air pollution impacts presented here were explored from a First Nations’ perspective, yet all issues and results reported are relevant beyond the realms of Treaty and aboriginal rights. Atmospheric pollutants know no political boundaries, and the underreporting of emissions has provincial, federal and global implications for pollution management and abatement strategies. Steeply increasing and unregulated atmospheric emissions can cause both direct and indirect effects to plants, animals and humans. For northeast BC potential ecological effects include: direct vegetative injury from foliar uptake; changes in lichen community composition; the loss of sensitive species; changes in forest structure; and the resulting indirect impacts on humans and animals depending on the extent forest effects. Human and animal health may be directly affected by current levels of pollution if National AAQO are frequently or persistently exceeded at a significant number of locations. If the emissions and their effects discussed above are allowed to continue at year 2000 levels, vegetation damage and forest community changes are expected in parts of northeast BC near emission sources or where pollutant build-up is favoured.

Combined with land-use pressures, climate change and other stressors, the cumulative impacts may be complex and extensive. For First Nations’ communities dependent on forest-based resources, this may

equate to a loss of health, livelihoods, and an infringement of Treaty given rights “to pursue their usual vocations of hunting, fishing and trapping”. The potential for agriculture is also impeded by high ambient pollutant concentrations.

The results presented in the preceding chapters have far-reaching implications that are political in nature. Inherent are ways in which Canada has not upheld either international (CLRTAP) or domestic treaties (Treaty No. 8). Although it is unclear how CAC emissions trends may proceed, it is unlikely that policy will catch up to impact progression. Since this work began in 2003 Canada’s emissions reporting policy has been standardised nationally and inventories made even less accessible or comprehensive (Canada 2007); BC (particularly its north) has been added to Canada’s National Acid Rain and Critical Loads Maps (Carou et al. 2008); and First Nations are using emissions summaries and reporting standards from Chapter 2 to negotiate with BC’s oil and gas industry. The results from this thesis have been (and are being) widely communicated to policy makers, government scientists, industry representatives, the media, First Nations and land-owners in the Peace. While successful in completing many of its original and evolved goals, there are still many unknowns and gaps to comprehending the cumulative impacts of air pollution in northeast BC. It is difficult if not impossible to accurately predict what the cumulative impacts of air pollution (or of this research) will be for the forests and forest-dependent communities of northeast BC. Time only knows who will win this war in the Peace: whether it will be the stacks, or if it will be the trees.

5.7 References

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APPENDICES

Appendix A

Table developed for assigning SCC to the CAPP inventory.

Symbol Legend	
Source Sector	
CO	Light / Medium Crude Oil
GP	Gas Production
GSW	Gas Processing - sweet
GSR	Gas Processing - flaring
GSS	Gas Processing - sulphur recovery
GSI	Gas Processing - injection
TP	Product Transportation
Emission Category	
COMB	Combustion
DEHY	Glycol Dehydrator Off-Gas - Unreported Venting
LEAK	Fugitive Equipment Leaks
LOAD	Loading and Unloading Losses
TANK	Storage Losses
VENT	Unreported Venting
Emission Sub Category	
PROP	Propane Fuel Use
FLARE	Gas Flaring
VENTED	Reported Venting
ACID GAS	Acid Gas Flaring
HVP LOAD	Loading and Unloading of High Vapour Pressure Gases
S POURING	Sulphur Pouring, Handling and Venting

(Clearstone Engineering Ltd. 2005)

(continued)

Source Sector	Emission Category	Emission SubCategory	SCC	SCC Description
CO	COMB	PROP	20201001	industrial reciprocating engine - propane
CO	COMB	FLARE	31000160	crude production - flares
CO	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
CO	DEHY	N/A	31000107	crude production - oil/gas/water separation
CO	LEAK	N/A	31000101	crude production - well fugitive
CO	LOAD	N/A	40600132	crude - submerged loading
CO	TANK	N/A	40400312	crude fixed roof - working, breathing and flashing
CO	VENT	VENTED	31000102	crude - misc. well general
CO	VENT	N/A	31000199	crude prod - processing operations not classified
GP	COMB	FLARE	31000205	gas production - flares
GP	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
GP	DEHY	N/A	31000304	ethylene glycol dehy general
GP	LEAK	N/A	31000220	gas production - fugitives all equipment
GP	VENT	VENTED	31000203	gas production - wells
GP	VENT	N/A	31000299	gas production - other not classified
GSW	COMB	FLARE	30600999	indust. processes, petrol - flares not classified
GSW	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
GSW	DEHY	N/A	31000304	ethylene glycol dehy general
GSW	LEAK	N/A	31088811	oil and gas production - fugitive emissions
GSW	LOAD	HVP LOAD	40600197	petrol / solvent evap - tank car / truck not classified
GSW	TANK	N/A	40400311	condensate fixed roof - working, breathing and flashing
GSW	VENT	N/A	31000299	gas production - other not classified
GSR	COMB	ACID GAS	30600906	indust. processes - H ₂ S flares
GSR	COMB	FLARE	30600999	indust. processes, petrol - flares not classified
GSR	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
GSR	DEHY	N/A	31000304	ethylene glycol dehydrator general
GSR	LEAK	N/A	31088811	oil and gas production - fugitive emissions
GSR	VENT	N/A	30603201	sour gas treating unit - general
GSR	LOAD	HVP LOAD	40600197	petrol / solvent evap - tank car / truck not classified
GSS	COMB	ACID GAS	30600906	indust. processes - H ₂ S flares
GSS	COMB	FLARE	30600999	indust. processes, petrol - flares not classified
GSS	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
GSS	DEHY	N/A	31000304	ethylene glycol dehydrator general
GSS	LEAK	N/A	31088811	oil and gas production - fugitive emissions
GSS	LOAD	HVP LOAD	40600197	petrol / solvent evap - tank car / truck not classified
GSS	VENT	N/A	31000208	gas production - S recovery unit
GSS	VENT	S POURING	30103299	elemental S production not classified
GSI	COMB	FLARE	31000205	gas production - flares
GSI	COMB	N/A	30602401	petrol. ind. - NG fired reciprocating engine compressor
GSI	DEHY	N/A	31000304	ethylene glycol dehy general
GSI	LEAK	N/A	31088811	oil and gas production - fugitive emissions
GSI	LOAD	HVP LOAD	40600197	petrol / solvent evap - tank car / truck not classified
GSI	VENT	N/A	30603201	sour gas treating unit - general
TP	COMB	FLARE	30600999	indust. processes, petrol - flares not classified

Appendix B

The development of flare stack parameters.

'Pseudo' stack values for height and diameter are needed for modelling flares as regular (pseudo) stacks that have the same buoyancy. Because the flame adds both height and width to the emission source (combustion products are released from the flame rather than from the stack), the pseudo' stack height (h_{pseudo}) and diameter (d_{pseudo}) need to be calculated from the actual flare height (h), diameter (d) using the flame's heat of release (H) and the sensible heat flux (Q_H)

