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Introduction to the virtual special issue monitoring ecological responses to air quality and atmospheric deposition in the Athabasca Oil Sands region the wood Buffalo environmental Association's Forest health monitoring program

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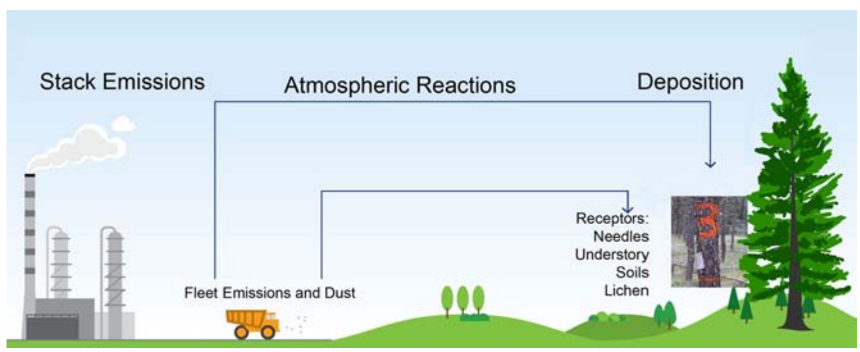
HIGHLIGHTS

- 20-Year, ecological monitoring program initiated by a multi-stakeholder committee
- Initiated prior to observed effects, focused on acid deposition based on emissions
- Integrated air, dispersion, deposition and ecological effects monitoring
- Monitoring activity increased in parallel with industrial expansion

GRAPHICAL ABSTRACT



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ABSTRACT

The expansion of oil sands resource development in the Athabasca Oil Sands Region in the early 1990's led to concerns regarding the potential ecological and health effects of increased emissions and deposition of acidic substances. Conditions attached to a 1994 approval for an oil sands facility expansion led to the creation of the Wood Buffalo Environmental Association, and its Terrestrial Environmental Effects Monitoring committee. This multi-stakeholder body was tasked with development and operation of an environmental (forest health) monitoring program for the detection of ecological responses to atmospheric emissions and deposition. Initially focused on acid deposition monitoring, jack pine forest, growing on sandy soils with limited acid buffering capacity, was selected as the receptor system. An initial set of 10 monitoring locations was established using the Canadian Acid Rain Network Early Warning System methodology (since increased to 27, with three lost to development). Ecological monitoring is on a 6-year cycle, with concurrent measures of soil, needle and lichen chemistry, and tree and understory condition, together with ongoing measurements of air quality and atmospheric deposition. Because jack pine forest edges facing the emissions sources were expected to be more exposed to acidic emissions, evaluation of stand edge monitoring locations began in 2008. Monitoring of a targeted suite of indicators began in 2012 at 25 jack pine stand edge monitoring sites. This special issue presents the results derived from biophysical sampling campaigns (1998 to 2013), coupled with ongoing ambient

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atmospheric, deposition and epiphytic lichen monitoring (data through 2017) and source apportionment studies, as well as papers contributed by others engaged in regional research and monitoring programs. The Forest Health Monitoring Program provides data supportive of regulatory and stakeholder evaluations of environmental quality, and is adaptive to new needs, extreme environmental events and technological development while providing continuity of monitoring.

1. Introduction

The heavy oil and bituminous oil sands deposits in northeastern Alberta, Canada represent over 10% of the world's recoverable oil reserves, and are the third largest in the world (166.3 billion barrels; 26.4 billion m^3; Natural Resources Canada, 2014). These reserves are contained within the Athabasca, Peace River and Cold Lake oil sands areas (Fig. 1), which are located within Alberta's boreal forest, a complex mosaic of upland forests and lowland wetlands that covers >50% of Alberta.

Commercial oil sands surface mining, extraction and upgrading operations began in northeastern Alberta in the late 1960's. Great Canadian Oil Sands (now Suncor Energy Inc.) began operation in 1967, followed by Syncrude Canada Ltd. in 1978. Surface mining, concentrated centrally within the Athabasca Oil Sands area (generally referred to as

Fig. 1. Alberta's bitumen reserves (Government of Alberta, 2018).

the Athabasca Oil Sands Region, or AOSR) where glacial till depths are relatively shallow, has since expanded. Between 1975 and 1985, several environmental research projects were undertaken under the Canada-Alberta Agreement for Alberta Oil Sands Environmental Research Program (AOSERP) to understand the potential effects of oil sands resource development on ambient air quality, and terrestrial and aquatic ecosystems (report series available at: https://era.library.ualberta.ca/collections/44558v340). In 1985, the Fort McKay First Nation expressed concerns about the impacts of oil sands development on the environment and on the ambient air quality in their community, located about 55 km north of Fort McMurray and north of Syncrude's (16 km) and Suncor's (22 km) main upgrader stacks. In 1993, work commenced on a long-term strategy for development of Alberta's oil sands, which considered the size of the resource, anticipated economic investments and returns, improvements in bitumen recovery and upgrading processes, secondary value-added processes (*e.g.*, metal extraction, hydrogen and nitrogen production facilities), and a pipeline network to link to markets to the south (Yildirim, 1995). In 1994, a regulatory decision for Syncrude's oil sands expansion project required that "…*the energy industry, working with the area stakeholders…assume a clearer leadership role in the collection of regional data designed to ensure that airshed-related impacts are properly measured and understood*" (Alberta Energy Resources Conservation Board, 1994). This led to the creation of the Wood Buffalo Environmental Association (WBEA) in 1997, a non-profit organization comprising representation from regional industrial corporations, government agencies, First Nation and Métis communities, and environmental non-government organizations (Wood Buffalo Environmental Association, 2018). An existing multi-stakeholder group convened under WBEA's predecessor organization (the Regional Air Quality Coordinating Committee) became the Terrestrial Environmental Effects Monitoring (TEEM) committee within WBEA and initiated the development of a Forest Health Monitoring (FHM) Program responsive to stakeholder and regulatory concerns and interests.

This paper, introductory to this special issue, presents the design, implementation and operation of the TEEM FHM Program from 1996 to present, and provides the context for the presentation of data and outcomes of the program's 20 years of ambient air, atmospheric deposition, and forest effects monitoring.

2. Oil sands resource development and population growth

Surface mining involves the stripping of overburden to expose the bitumen-containing ore body, a mixture of bitumen, sand, water and clay. Oil sands ore is moved from the mine pit to an extraction facility by one or a combination of heavy trucks and conveyor belt systems, where bitumen is extracted from the ore. Where the ore is deeper, *in situ* methods are used to extract the bitumen directly within the geologic formation, and the recovered bitumen is piped to a central facility where water and solids are removed. *In situ* methods are currently required in about 90% of the AOSR and throughout the Peace River and Cold Lake oil sands regions, and *in situ* technological advances are allowing oil sands development over a much larger area than was previously economically viable (Giacchetta et al., 2015). Although emission profiles differ between mining and *in situ* processes, both emit a range of substances into the air, with varying potentials for near-field and distant environmental effects (Berkowitz and Speight, 1975). Regardless of production method, the resultant heavy, sour (containing ~4.5% sulphur) bitumen is upgraded to a synthetic, light sweet (low-sulphur) crude oil at one of four upgraders in the AOSR (one is currently not operating) or transported to upgraders or heavy oil refiners elsewhere in Canada and the United States.

In the 1990's, several regulatory applications were filed with provincial and federal agencies for expansion of operating oil sands projects, and for new mining, upgrading, and *in situ* bitumen production projects. Many of these projects received approval and from 1998 to 2017, bitumen and synthetic crude oil production increased by factors of 6.6 and 2.7, respectively. As of 2017 bitumen production had reached 140 Mm^3/year, and synthetic crude oil production had reached 44 Mm^3/year (Fig. 2; Supplementary Information Tables S1 and S2). This industrial expansion resulted in significant population growth from 1999 to 2015, from 42,871 people (85% in Fort McMurray; Regional Municipality of Wood Buffalo, 1999) to 125,032 people (66% in Fort McMurray; Government of Alberta, 2015). The decrease in the regional proportion of Fort McMurray residents reflected the increased populations of workers in residential camps located near major industrial operations. The region also contains seven hamlets, is home to five First Nations, and a Métis population represented by six Métis locals. The size and rapid expansion of the oil sands industry has presented unique challenges, including measurement of atmospheric emissions and deposition and assessment of their effects on the environment and human health.

3. TEEM'S forest health monitoring program design & evolution

3.1. History of WBEA and TEEM

The founding of the multi-stakeholder, consensus-based TEEM committee and the development and implementation of a regional effects-based monitoring satisfied the conditions in Syncrude's ERCB approval (Percy et al., 2012). All parties agreed that the goal of a monitoring program would be detection of environmental change early enough to allow for regulatory adjustment of emission limits. Program development began in 1995 with a year-long process to define a program objective, which by consensus was stated as: "*To develop and operate a long-term program to detect and characterize the effects of oil sands emissions on terrestrial and aquatic ecosystems, and on traditional resources and hence on traditional resource users.*" Although aquatic systems were included in the objective statement, other initiatives in the AOSR in the late 1990's included aquatic monitoring, and the TEEM committee focused its efforts on monitoring in the terrestrial environment. The TEEM committee's 1996 objective statement also expressed the importance of considering the needs and expectations of local Indigenous communities in the development and execution of the program.

Based on preliminary work from AOSERP and the nature of air emissions from the Suncor and Syncrude facilities, stakeholders agreed that a primary concern was the emission, atmospheric deposition and environmental effects of acidifying substances, primarily sulphur and nitrogen, to the surrounding boreal forest. The specific question posed was whether regional, upland forests were receiving acid deposition at levels that were or would be harmful to forest health.

In the 1970s, recognition of the potential impacts due to acid deposition resulted in 11 European countries initiating intensive daily monitoring between 1973 and 1975 (Likens et al., 1972, 1979). Forest decline in Europe during the 1990's was attributed to long-term acidic deposition, thought to be the consequence of lowered soil pH, increased leaching of base cations (BC; Ca^2, Mg^2, K) and mobilization of phytotoxic Al^3 (Joslin and Wolfe, 1988). Molar soil solution Ca:Al (Cronan and Grigal, 1995) or BC:Al (Sverdrup and De Vries, 1994) ratios of 1:1 were suggested as thresholds below which tree growth and health would be impaired. Growing international and North American concern prompted the Canadian Forest Service to develop the Canadian Acid Rain Network Early Warning System in 1984 (D'Eon et al., 1994). This was followed by the northeastern United States and Canadian initiatives North American Maple Project in 1988 (Allen et al., 1999) and the Ecological Monitoring and Assessment Network in 1994 (Vaughan et al., 2001). These initiatives established long term monitoring networks with interdisciplinary research to identify and understand the potential impacts of acid and base cation deposition. Regions of high acid deposition were identified that included impacts to trees (reduced growth and signs of damage), soils (loss of essential nutrients) and indirect consequences on surrounding surface water systems (Driscoll et al., 2001). Having recognized regional risks due to acid deposition, the New

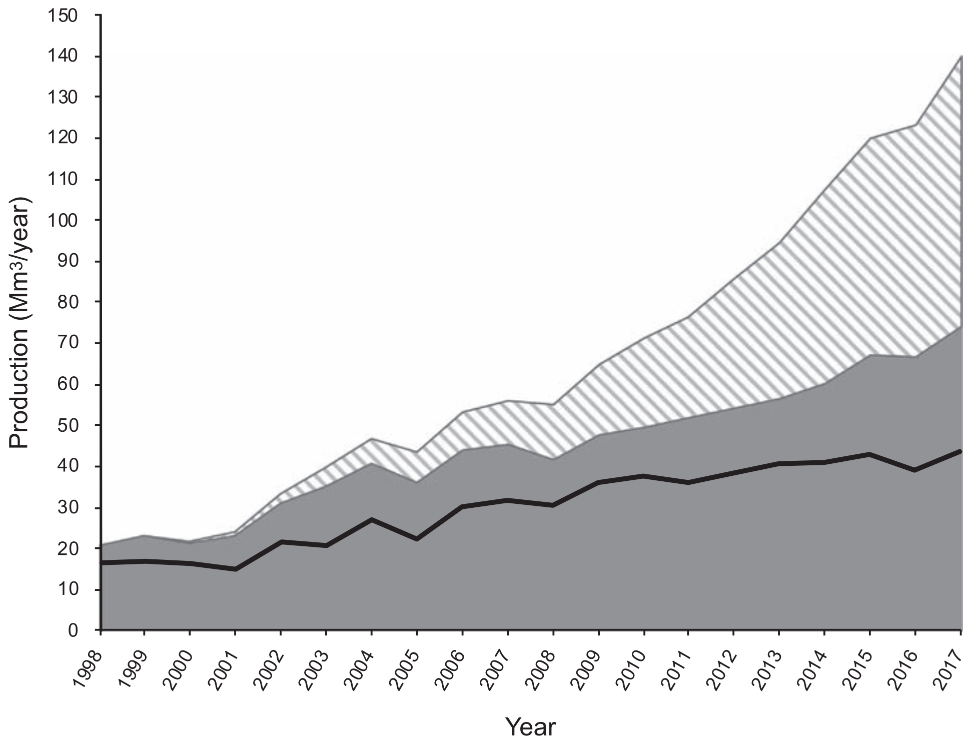


Fig. 2. Bitumen production from mining (solid) and *in situ* (hatched) processes, and synthetic sweet crude production (solid line), in the AOSR from 1998 to 2017. Compiled from the Alberta Energy Regulator database (https://www.aer.ca/providing-information/data-and-reports/statistical-reports).

England Governors and Eastern Canadian Premiers established the Acid Rain Action Plan in 1998, which was followed by the creation of The Canada-Wide Acid Rain Strategy for Post-2000 (Federal/Provincial/Territorial Ministers of Energy and Environment, 1998). Steady state simple mass balance models that incorporated considerations of harvesting, forest fires, nutrient cycling, soil weathering, decomposition and leaching as parameters affecting responses to acid deposition (Bhatti et al., 1998; Moayeri et al., 2001; Ouimet et al., 2006) were developed in parallel with and following the implementation of Canada-Wide strategy.

These studies guided program design, providing data and information supportive of a management system that would avoid a similar trajectory towards boreal forest decline in the oil sands region. The Cumulative Environmental Management Association (CEMA; active from 2000 through 2016), also a regional multi-stakeholder organization, developed a critical loads-based regional Acid Deposition Management Framework to support the evaluation of deposition levels and effects, and if warranted, support emission reduction requirements (Cumulative Environmental Management Association, 2004). A provincial framework (also based on the critical loads concept) that encompasses the AOSR was also developed (Clean Air Strategic Alliance and Alberta Environment, 1999; Foster et al., 2001; Government of Alberta, 2008), and has since been updated (Government of Alberta, 2008). The FHM Program provides data supportive of both the provincial and regional frameworks.

3.2. Monitoring program design considerations

An environmental effects monitoring program should reflect the nature of environmental stressors, the complexity and sensitivity of environmental receptors, and be based on clear statements of the program's long-term goals and objectives; indicators should be easily measured, have a known and sensitive response to acidic atmospheric deposition stress, be responsive in predictable ways, predict changes that may be averted by management action, and have a low variability in response (Bockstaller and Girardin, 2003; Dale and Beyeler, 2001). Clear, tractable questions based on a conceptual response model, consistent leadership and funding, data integrity, and frequent data use and preferably, peer-reviewed publication are key characteristics of successful long-term monitoring programs (Cronmiller and Noble, 2018; Lindenmayer and Likens, 2010). Lindenmayer and Likens (2009) promoted an adaptive monitoring paradigm that allows for iterative question-setting, evolution of program design and execution, and updating of analyses that continue to involve a diversity of participants, while at the same time rightly cautioning that any changes need to be implemented in a manner that preserves the integrity of the long-term dataset.

The FHM Program meets these criteria. The consensus-based, multi-stakeholder processes used to design the program included: (1) derivation of a clear objective statement and initial question, (2) identification of acid deposition as the most likely causal agent of ecological change, (3) construction of a conceptual response model (Fig. 3) to guide sampling and measurement, (4) selection of the most sensitive ecological system (acid-sensitive and nutrient-poor pine forest) based on the state of knowledge at the time, and (5) support for environmental management decision-making. Since its inception, the FHM Program has been overseen by the multi-stakeholder TEEM committee, with modifications to the program implemented after review and discussion between TEEM committee stakeholders and subject matter experts brought into the discussion to provide up-to-date scientific input. The FHM Program is adaptive, having increased its spatial coverage and added monitoring components in response to the industrial and environmental changes that have occurred over the period of monitoring, while maintaining its core ability to detect change due to acidic deposition.

3.3. Emissions and ambient air quality monitoring in the AOSR

Emissions from the AOSR represent about 10% of total Alberta SO_2 emissions and 5% of provincial NO_x emissions, and 1% to 3% of each of total Canadian SO_2 and NO_x emissions, respectively (Table 1; Davidson and Spink, 2018; Government of Canada, 2018; Vijayaraghavan et al.,

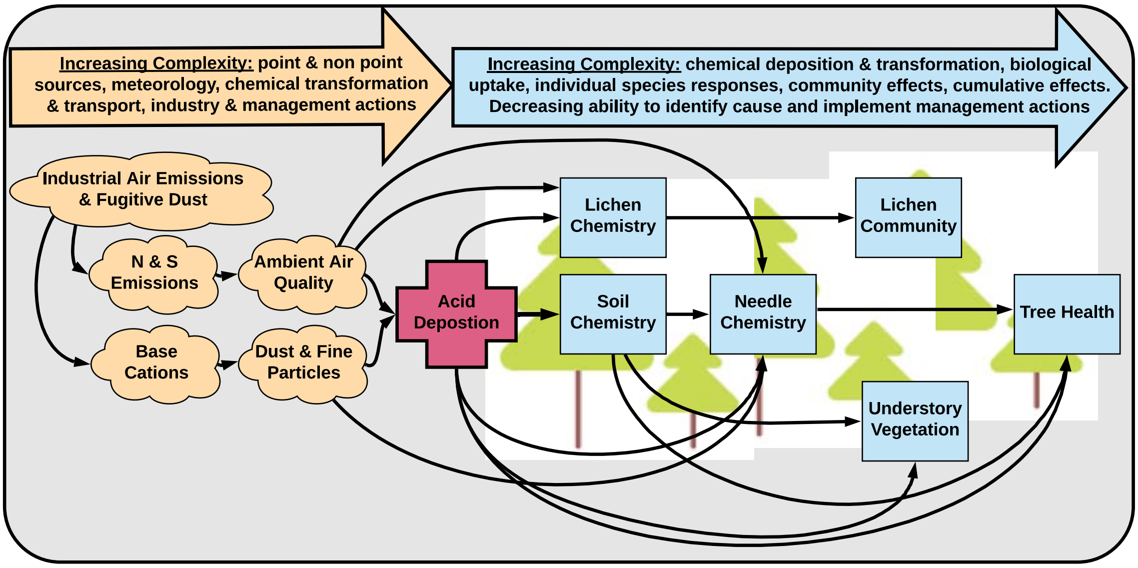


Fig. 3. Forest Health Monitoring Program conceptual model developed during program design. Light orange = acid deposition precursors and processes; red = stressor (acid deposition), and blue = ecological responses. In each of the precursor and processor and ecological response categories, system complexity increases from left to right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2016). SO_2 emissions have been decreasing since 1995 in the AOSR, and at provincial and national scales. While NO_x emissions have decreased nationally since 1995, and have remained relatively stable provincially, they have increased in the AOSR.

In 1996, as stakeholders were beginning FHM Program design, SO_2 was the dominant acidifying emission and 98% of regional SO_2 emissions originated north of Fort McMurray (Table 1). The fluctuations in SO_2 emissions since that time reflect both production increases and implementation of improved emissions control technologies. While oil sands development has increased in the AOSR in the past two decades, SO_2 emissions from the upgrader stacks north of Fort McMurray continue to represent 67% (in 2015) of regional SO_2 emissions. Initially considered a minor contribution to potential acidic input, NO_x emissions have steadily increased since 1995 (Table 1), partly due to increased bitumen production, but also due the replacement of draglines, bucketwheels, and conveyor belts with truck-and-shovel mining techniques (Oil Sands Magazine, 2016), which are a significant source of oil sands NO_x emissions (Cho et al., 2017; Davidson and Spink, 2018). In 2015, NO_x emissions exceeded SO_2 emissions, and are projected to increase through 2040. Cho et al. (2017) estimated that, on average, 60% of deposited nitrogen contributes to environmental acidification in the AOSR.

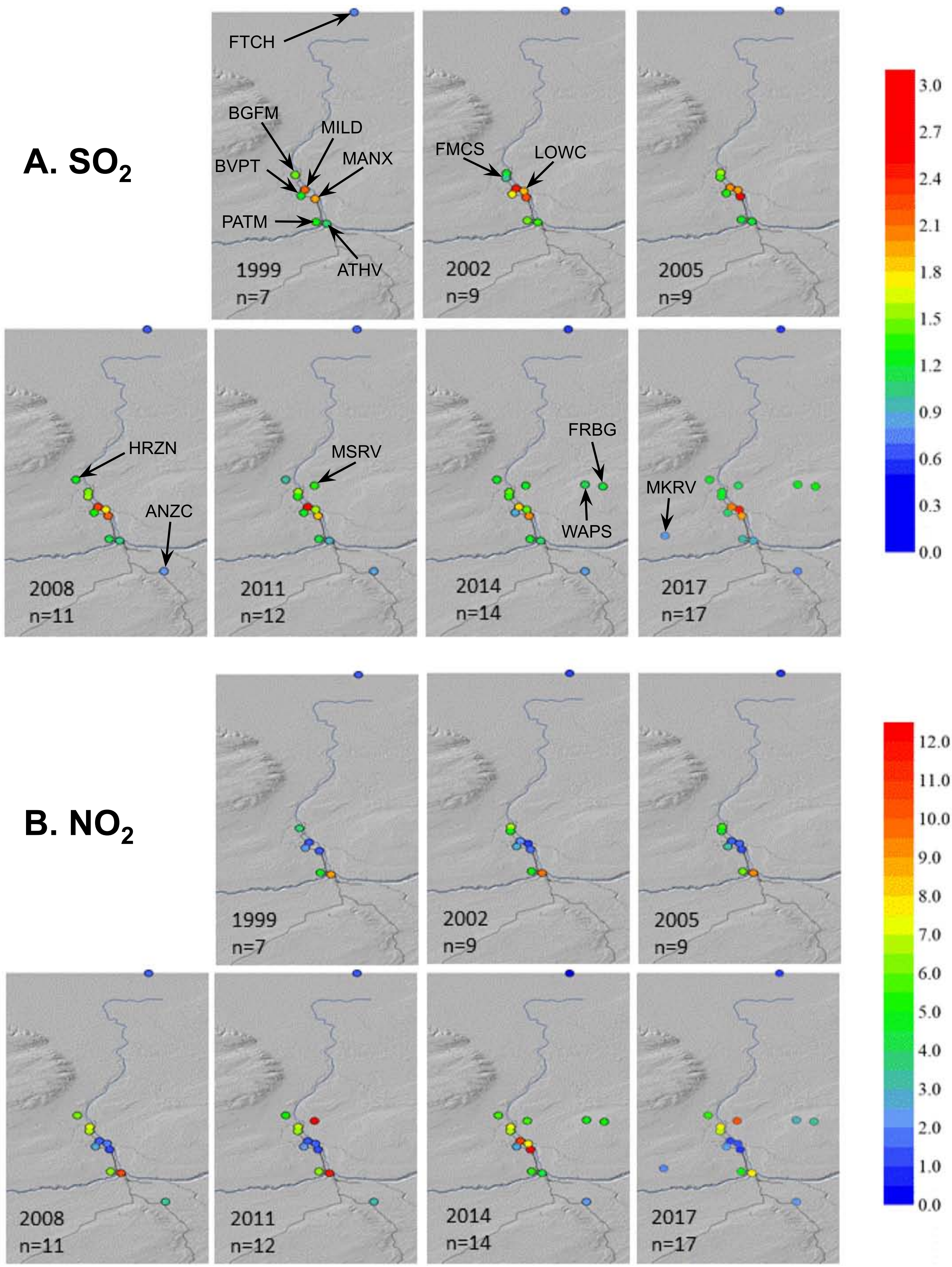
In parallel with the development of the FHM Program, WBEA developed a network of continuous, integrated ambient air monitoring stations throughout the AOSR, including within local communities (Supplementary Information Table S3; Edgerton et al., 2019). Measurements at these stations illustrate the changes in ambient air quality from the late 1990s to 2017 (Figs. 4 and 5). Average annual SO_2 and NO_2 concentrations at the most northerly, Fort Chipewyan (FTCH) air monitoring station have remained constant, providing a reliable measure of background levels (<0.6 ppb SO_2; <2 ppb NO_2). A general trend of increasing ambient air annual average concentrations of SO_2 from 1999 (up to 5 ppb) through 2011 (up to 12 ppb) is apparent in the core of the oil sands surface mining area north of Fort McMurray (Figs. 4A and 5A). Ambient air NO_2 levels gradually increased over the period 1999 to 2014 (peaking at up to 12 ppb), then decreasing in and around the mining centre and Fort McMurray in 2017 (Figs. 4B and 5B). While SO_2 and NO_2 are monitored at almost of the WBEA continuous monitoring stations, and which likely contribute most to environmental acidification, other substances (particulate matter, ozone, total reduced sulphur compounds, hydrogen sulfide, total hydrocarbons, non-methane hydrocarbons, carbon monoxide) are measured at a subset of the continuous ambient monitoring stations (station information and data available from www.wbea.org).

Regional emissions and ambient ground-level concentrations measured at the Bertha Ganter-Fort McKay (BGFM) continuous air monitoring station in Fort McKay are significantly correlated for NO_2, but not for SO_2 (Davidson and Spink, 2018). This may be due to one or more of (i) upgrader stack emission heights and thermal buoyancy of the exhaust plumes leading to enhanced dispersion, (ii) the stratification of vertical atmospheric stability layers, such as nocturnal inversions formed by nighttime radiative cooling decoupling the ground-level mixing layer from the upper level free troposphere into which the stacks emit during these conditions (Husar et al., 1978; Stull, 1988), and (iii) local Athabasca River valley drainage flow into the north-south topographic depression which can occur in the absence of a dominant regional dispersion meteorological pattern (Davies, 2012; Hsu, 2013; Landis et al., 2017).

Table 1
Historic (1990 to 2015) and Projected (2025 to 2045) SO_2 and NO_x Emissions (t/d) from the Athabasca Oil Sands Region, Alberta and Canada.[a]

Substance	Year	Athabasca Oil Sands		Alberta	Canada
		North of Fort McMurray	Entire Region		
SO_2	1990	400	418	4246	25,207
	1995	443	453	4716	21,077
	2000	261	257	4044	19,730
	2005	305	343	3791	12,293
	2010	272	315	2945	11,255
	2015	126	188	2110	8903
	2025/30	nd	289	nd	nd
	2035/40	nd	311	nd	nd
NO_x	1990	41	164	5312	19,780
	1995	60	198	6022	21,358
	2000	98	217	6823	23,924
	2005	145	198	5763	17,866
	2010	187	243	5976	17,551
	2015	217	310	5475	15,452
	2025/30	nd	501	nd	nd
	2035/40	nd	547	nd	nd

nd = not determined.
[a] Davidson and Spink (2018), Government of Canada (2018), Vijayaraghavan et al. (2016).


A. SO2
FTCH
BGFM
MILD
BVPT
MANX
PATM
ATHV
1999
n=7
FMCS
LOWC
2002
n=9
2005
n=9
HRZN
ANZC
2008
n=11
MSRV
2011
n=12
FRBG
WAPS
2014
n=14
MKRV
2017
n=17
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
B. NO2
1999
n=7
2002
n=9
2005
n=9
2008
n=11
2011
n=12
2014
n=14
2017
n=17
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

Limestone aggregates are produced from Devonian bedrock exposed at the base of oil sands mines and from independent quarry operations in the core of the oil sands development. Aggregates are distributed and used in flue-gas desulphurization processes, and as construction material throughout the region. Quarrying, crushing, transport, and use of limestone aggregates (*e.g.*, as mine haul road construction material) result in emissions and deposition of calcium carbonate particulates (Wang et al., 2015b), a base cation source that has the capacity to both neutralize acidic input and function as a plant nutrient. This is a relatively recent activity, and dust emissions and deposition and the effects of substances entrained in coarse and fine particulate matter are an emerging issue that is the basis for recommendations for monitoring enhancements in the FHM Program (Davidson et al., 2019; Edgerton et al., 2019; Landis et al., 2019a; MacKenzie and Dietrich, 2019).

3.4. Forest health monitoring program development

3.4.1. Forest health monitoring site selection

In the late 1990s, the rapid pace of industrial growth, the absence of a comprehensive regional emissions database, and limitations in regional meteorological datasets and modelling tools resulted in a high degree of uncertainty in atmospheric deposition estimates and predicted associated ecological impacts. Rather than spending time compiling these datasets, deriving estimates or predictions of emissions, or constructing comprehensive predictive models, the TEEM committee took an effects-based approach, designing a monitoring program to detect changes in acid-sensitive systems, coupled with measurement of atmospheric deposition.

The jack pine (*Pinus banksiana* Lamb.) a1 ecosite phase (Beckingham and Archibald, 1996) growing on coarse-grained Eluviated Dystric Brunisol soils was selected as the acid-sensitive ecological system based on European (Abrahamsen and Miller, 1984; Sverdrup and Warfinge, 1993), Alberta (Holowaychuk and Fessenden, 1987) and AOSR (Turchenek et al., 1988) soil sensitivity research. This early understanding of acid sensitivity of jack pine forests growing on sandy soils has since been validated (Abboud et al., 2002; Jung et al., 2013; Jung and Chang, 2013; Jung et al., 2011; Whitfield et al., 2009; Whitfield et al., 2010). A conceptual response model was developed (Fig. 3), wherein deposited acidic substances were first expected to alter soil chemistry (decreased pH, BC:Al and base saturation) and lichen chemical content. Changes in soil chemistry changes were expected to affect tree growth, and potentially alter competitive relationships among plant species, resulting in changes in plant community composition (Shevtsova and Neuvonen, 1997).

The screening-level ADEPT2 model (Dixon, 1989) was used to predict acid deposition in the AOSR, divided into areas of presumptively higher (≥0.3 kmol H /ha/yr) and lower (≤0.2 kmol H /ha/yr) deposition levels (Bovar Environmental et al., 1997). Model inputs included 1996 SO_2 emissions from the Suncor and Syncrude upgrader stacks and meteorological data from WBEA's Mannix (MANX) monitoring station. NO_x emissions were not included because of their relatively low emission quantities and contributions to total potential acidifying emissions, at that time. The model calculated the conversion of SO_2 to SO_4^{2-}, then total sulphur deposition based on wet and dry deposition using precipitation chemistry and quantity and an estimated deposition velocity, respectively. Effective acidity, the acidity associated with dry deposition and acidity associated with wet deposition to account for acid processing was then derived (Cheng et al., 1995).

In 1996, ten a1 ecosite phase and ecologically-similar jack pine stands, five in each of the predicted high and low deposition zones, were selected as long-term, stand-interior, monitoring sites. Five additional stand-interior monitoring sites were established in 2001–2004, and 16 in 2011–2013 to increase spatial coverage in the region and to replace two sites lost due to expansion of industrial operations. The ecological criteria established for site selection are presented in Table 2.

A substantive challenge to the long-term FHM Program is the loss of sites due to fire. The 2011 Richardson Backcountry Wildfire (Bytnerowicz et al., 2016) burned the forests at five monitoring sites, one site was burned in a small forest fire in 2015, and the Horse River Wildfire in 2016 burned the forest at five additional stand-interior sites. There are currently 13 stand-interior sites that have remained unaffected by fire or industrial activity (Fig. 6). The distribution of these 13 sites continues to provide for monitoring of changes over time along the acid deposition gradient in the AOSR. Fire-affected sites remain in the monitoring program, and methods to monitor vegetative recovery as it relates to air quality and deposition are currently in development.

Forest edges may be more exposed to emissions and deposition (Hasselrot and Grennfelt, 1987; Legge et al., 1988; Lester et al., 1986) and offer the opportunity to detect increased deposition and the associated effects prior to these effects being observed at the monitoring locations within larger forest stands. From 2008 to 2013, 25 a1 ecosite phase monitoring locations were established at wetland-jack pine stand edges. Each edge monitoring site was located where the sandy soil-forest stand edge sharply abutted an open wetland complex, and where the stand of trees faced the larger regional oil sand production air emission sources. Of the 25 jack pine edge sites originally established, one has been lost due to industrial development and six were burned in the 2016 Horse River Wildfire. The distribution of jack pine monitoring sites, both interior to the forest stands and at jack pine stand edges, is shown in Fig. 7 (coordinates of the jack pine monitoring network are provided in Supplementary Information Table S4).

3.5. Jack pine forest monitoring

3.5.1. Soil and vegetation monitoring

The TEEM committee chose the Canadian Acid Rain Network Early Warning System (D'Eon et al., 1994) methodology as the basis of the FHM Program, with minor adjustments to accommodate regional stand characteristics. At interior stand monitoring locations, a permanent vegetation monitoring plot (10 m × 40 m) containing trees that best represented the stand was established. The vegetation plot was set a minimum of 50 m from the stand edge, cut-lines, roads, and other disturbances. Four soil monitoring plots (each 225 to 400 m^2; divided into four subplots of equal area) were placed at representative locations in the stand and located at least one tree height distance from the vegetation plot. A set of 10 off-plot trees, at least 5 m from the vegetation plot, having the same growth form and in an area of similar density as those in the vegetation plot were selected and tagged for destructive sampling (*e.g.*, needle sampling). Off-plot trees are replaced once sampling compromises canopy structure, or if the trees are showing signs of disease, insect infestation or physical damage at levels that diverge from those occurring across the stand. Interior jack pine site monitoring campaigns, including soil, vegetation, and epiphytic lichen sampling and analyses, tree growth measurements and vascular plant community composition were conducted in 1998, 2004 and 2011–2013 (the latter campaign was split over years due to safety and access constraints associated with the 2011 Richardson Wildfire).

The forest edge monitoring component of the TEEM FHM Program is in its early stages. The size of the vegetation plot at these edge sites was reduced (5 m × 20 m), as the transition between open wetland and interior upland forest was very narrow. Stand edge plots were oriented such that the long axis was parallel to the stand edge. A set of off-plot trees for destructive sampling was established adjacent to the plot. Measurements in these plots in 2011 to 2013 consisted of tree

Fig. 4. Mean annual ambient (A) SO_2 and (B) NO_2 concentrations (ppb) at the Anzac (ANZC), Athabasca Valley (ATHV), Bertha Ganter-Fort McKay (BGFM), Bison Viewpoint (BVPT), Horizon (HRZN), Firebag (FRBG), Fort Chipewyan (FTCH), Fort McKay South (FMCS), Lower Camp (LOWC), Mannix (MANX), MacKay River (MKRV), Mildred Lake (MILD), Muskeg River (MSRV), Patricia McInnes (PATM) and Wapasu (WAPS) WBEA continuous air quality monitoring stations.

Fig. 5. Yearly 25th, 50th, 75th, 90th and 98th percentiles of ambient A) SO_2 and B) NO_2 concentrations (ppb) at the continuous air monitoring stations in the WBEA network. Station names and abbreviations as in Fig. 4.

morphology and plant community composition, and sampling of needles and lichens for chemical analyses.

Soil and vegetation responses to acidic deposition are described in papers contained within this special issue (Bartels et al., 2019; MacKenzie and Dietrich, 2019).

3.5.2. Lichen monitoring

Biomonitoring using lichens is a well-established method for air quality and environmental quality monitoring, including in the evaluation of acidic deposition effects (Geiser et al., 2010), and use of lichens in deposition monitoring in the AOSR pre-dates the FHM Program (Addison, 1984; Addison and Puckett, 1980). In 2002, a lichen biomonitoring study was conducted to evaluate the sensitivity of lichen to atmospheric deposition in the AOSR and the utility of lichen to characterize regional patterns of deposition (Berryman et al., 2004). Results from this work showed that lichen, particularly epiphytic lichen, showed patterns of elemental enrichment close to oil sands development, and which decreased with distance from source. Regular sampling of epiphytic lichen was integrated into the FHM program starting in 2004 to document spatial and temporal changes in lichen chemistry across the AOSR.

Sampling and analyses for sulphur content in *Usnea* spp. were included in the jack pine site (1996) evaluation and the first intensive monitoring campaign (1998). Because *Hypogymnia physodes* and

Table 2
Jack pine stand interior monitoring site ecological criteria.

Ecological criteria	a1 Ecosite Phase[a] (Beckingham and Archibald, 1996)	1998, 2001 and 2004 Programs	2011/2012/2013 Program
Slope & position	2 to 30%, mid- to upper-slope, level, crest	Gentle, mid- to upper-slope, level, crest	Gentle, mid- to upper-slope, level, crest
Aspect	Any	Any	Any
Moisture regime	Subxeric, xeric (submesic)		
Nutrient regime	Poor to very poor	Poor	Poor
Soil drainage	Rapid to well	Rapid to well	Rapid to well
Parent material	Glaciofluvial, fluvial, eolian (morainal)	Glaciofluvial	Shallow calcareous bedrock, eolian, glaciofluvial
Organic horizon depth	≤5 cm (≤15 cm)		
Pinus banksiana:			
Stand characteristics	–	30 ha, 10 live trees/100 m^2	Large enough to maintain 3-tree height distance from plots to any transition zone to another forest type
Canopy cover	>20%	>20%	>20%
Tree age	–	40 to 70 years	–
Indicator species cover:			
Cladonia spp.[b]	>10%	20%	50%
Arctostaphylos uva-ursi	>20% (≤20%)	≤20%	≤5%
Vaccinium myrtilloides	≤20%	2% to 20%	≤5%
Vaccinium vitis-idaea	2% to 20%	5% to 10%	≤5%
Linnaea borealis	≤5%	≤5%	0%
Pleurozium schreberi	>5%	≤10%	≤10%
Dicranum polysetum	≤5%	–	2%
Ledum groenlandicum	≤5%	≤1%	0%
Maianthemum canadense	≤5%	≤8%	≤5%
Polytricium spp.	≤20%	≤10%	≤1%
Alnus crispa	≤20%	–	<1%
Cornus canadensis	–	≤2%	≤1%
Hudsonia tomentosa	≤2%	≤2%	–
Cladonia gracilis	≤5%	–	0%
Picea spp.	≤5%	–	0%
Rosa acicularis	≤2%	-≤ 2%	≤1%
Geocaulon lividum	≤5%	–	–
Peltigera aphthosa	≤2%	–	–
Betula spp.	≤20%	0%	0%
Populus spp.	–	–	0%
Sheperdia canadensis	–	–	≤1%
Juniperus spp.	≤10%	–	–
Salix spp.	–	–	0%

[a] The majority of TEEM monitoring sites are in the Boreal Mixedwood (BM) ecoregion; a few sites are in the Boreal Highlands and Canadian Shield ecoregions.
[b] Predominantly *Cladonia mitis*.

Evernia mesomorpha are more easily recognizable than *Usnea* spp. and are more abundant at the jack pine sites, these species were sampled in the 2004 and 2011–2013 campaigns, and analyzed for an expanded list of elements. In 2002, *Cladonia mitis*, *E. mesomorpha*, and *H. physodes* were sampled at distances from 5 to 120 km in each cardinal direction from the center-point of the oil sands development and analyzed for concentrations of metals and organic compounds.

As the TEEM lichen sampling program has evolved, the focus of lichen sampling has been refined to one lichen species, the epiphyte *H. physodes*. This species is common across the region, is very pollution tolerant and an excellent accumulator of atmospheric contaminants, and it is used world-wide as a biomonitoring tool for air quality (Garty, 2001), and its use facilitates comparisons between this program and those conducted by others (Jeran et al., 2002). In addition to sampling and analyses of *H. physodes* during the two recent jack pine sampling campaigns (2004, 2011–2013), regional lichen studies encompassing a large number of sites (extending to ~150 km from the main oil sands operations) were conducted in 2008 and 2014 (Landis et al., 2019a; Landis et al., 2012). A comprehensive source apportionment modelling assessment used *H. physodes* to identify emission sources contributing to lead deposition in the AOSR (Graney et al., 2019). Lichen sampling locations included in the FHM Program for one or more sampling campaigns are provided in Supplementary Information Table S5. Lichen contaminant loading may provide an independent means of evaluating the spatial and temporal deposition field estimates derived from ion exchange resin deposition collectors and passive monitoring devices (Edgerton et al., 2019).

3.5.3. Passive air and acid deposition monitoring

Passive SO_2 and NO_2 monitoring devices were installed on towers above the canopy at ten forest sites in 1998 to acquire data to derive estimates of acidifying deposition (Hsu et al., 2016; Hsu, 2013). This

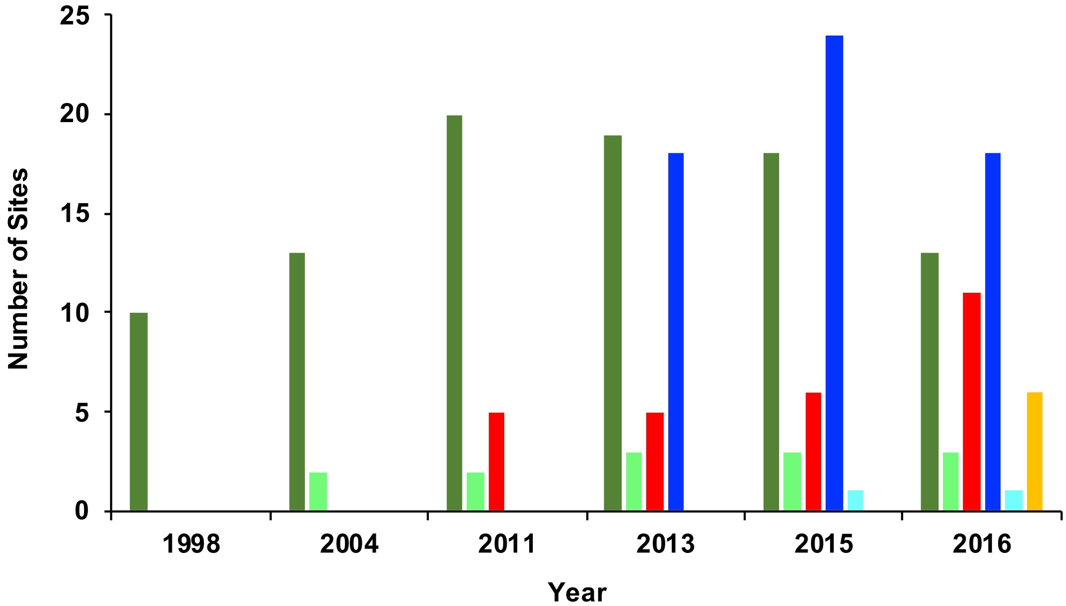


Fig. 6. The number of jack pine (a1 ecosite phase) interior stand monitoring sites (dark green = unaffected, light green = lost to industrial development, red = affected by forest fire) and jack pine stand edge monitoring sites (dark blue = unaffected, light blue = lost to development, yellow = affected by forest fire), from 1998 to 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

program has expanded, with towers being installed at an additional five forest sites, in non-forested wetlands at 15 locations, and at two WBEA air monitoring stations where they were co-located with powered air monitoring instrumentation. Passive monitoring devices for NH_3 and HNO_3 monitoring have been added to all towers, recognizing that increasing nitrogen emissions and deposition may contribute to soil acidification and/or increase nutrient availability, both of which may result in forest community responses.

Acidic deposition monitoring was initiated in 2007, and base cation deposition monitoring was tested in 2008 and implemented at a subset of sites in 2013, using ion exchange resins (Fenn et al., 2015). From the ion exchange resin data, model-derived spatially-resolved deposition fields have been generated, and data acquired from the passive monitoring program were used to improve these fields (Edgerton et al., 2019). The deposition fields were used to estimate relative acidic fluxes at each jack pine monitoring site and are the basis of the evaluation of deposition effects on soils and jack pine needle chemical composition (MacKenzie and Dietrich, 2019), and to tree growth and jack pine vegetation community composition (Bartels et al., 2019).

3.6. Traditional knowledge and berry monitoring

In 2010, Elders of the Fort McKay First Nation approached WBEA with their observations of changes in the quantity and quality of traditionally-used berries growing on their traditional lands. Fort McKay First Nation and WBEA jointly established a focus group to explore these concerns and consequently, the focus group implemented an integrated berry quality project comprising traditional knowledge, current methodological and ethical standards in the discipline of cultural anthropology, and scientific approaches including passive air quality and meteorological monitoring and laboratory analyses of berries for health-promoting constituents and trace element concentrations. This program directly links to the TEEM objective, which speaks to the need to evaluate environmental change related to air quality and deposition in relation to potential impacts to traditional resources and traditional resource users. The results of this ongoing study are discussed first within the Fort McKay First Nation community, and once complete, the data and outcomes will be made widely available.

4. Recent developments in environmental monitoring in the AOSR

The formation of the Joint Canada-Alberta Oil Sands Monitoring Program (Environment Canada and Alberta Environment, 2012) and renewed interest in the environmental impacts of oil sands development have led to increased attention on air emissions and deposition resulting from oil sands operations. Although acidic deposition remains a primary concern, the emissions, transport, transformation and deposition and effects of other substances, including nutrients, polycyclic aromatic compounds (PACs), metals and mercury have recently received increased attention in both scientific and public communities,

Whitfield et al. (2010) predicted that 34% to 62% of acid-sensitive soils in 333 study sites were at risk of acidification using a soil texture approximation method, the PROFILE model to estimate weathering rates, the Steady State Mass Balance Model to assess acidification loads, and an acidification threshold BC:Al ratio of 10:1, substantially more conservative (*i.e.*, intended to be more protective) than the 1:1 ratio suggested by Cronan and Grigal (1995) and Sverdrup and De Vries (1994). Laxton et al. (2010) found that nitrogen levels in jack pine needles and lichens (*H. phsysodes* and *E. mesomorpha*) sampled close to oil sands industrial activity were elevated, possibly indicating the early stages of nitrogen saturation. Zooplankton communities in Saskatchewan lakes (downwind of the AOSR) have shown some evidence of impact due to acidic and eutrophying deposition (Anas et al., 2017; Anas et al., 2014), although algal communities in lakes in this area may also be responding to climate change (Mushet et al., 2017).

Recent increased investment in air emission and atmospheric deposition research and monitoring is greatly increasing our understanding of deposition effects, including those resulting from oil-sands related compounds unrelated to acidic substances. PACs were quantified in snow-packs near and distant from oil sands operations in 2008 (Kelly et al., 2009), and have been better characterized more recently due to improved analytical methods (Manzano et al., 2017). PAC concentrations in ambient air (Schuster et al., 2015) and accumulated snow (Cho et al., 2014) declined exponentially with increasing distance from oil sands development, and deposition of organic substances including PACs has been attributed to entrainment within particles of wind-blown bitumen ore particles, petroleum coke (a solid, carbon-rich product of bitumen upgrading) and dry tailings deposits (Harner et al., 2018; Jautzy et al., 2013; Wang et al., 2014; Yassine and Dabek-

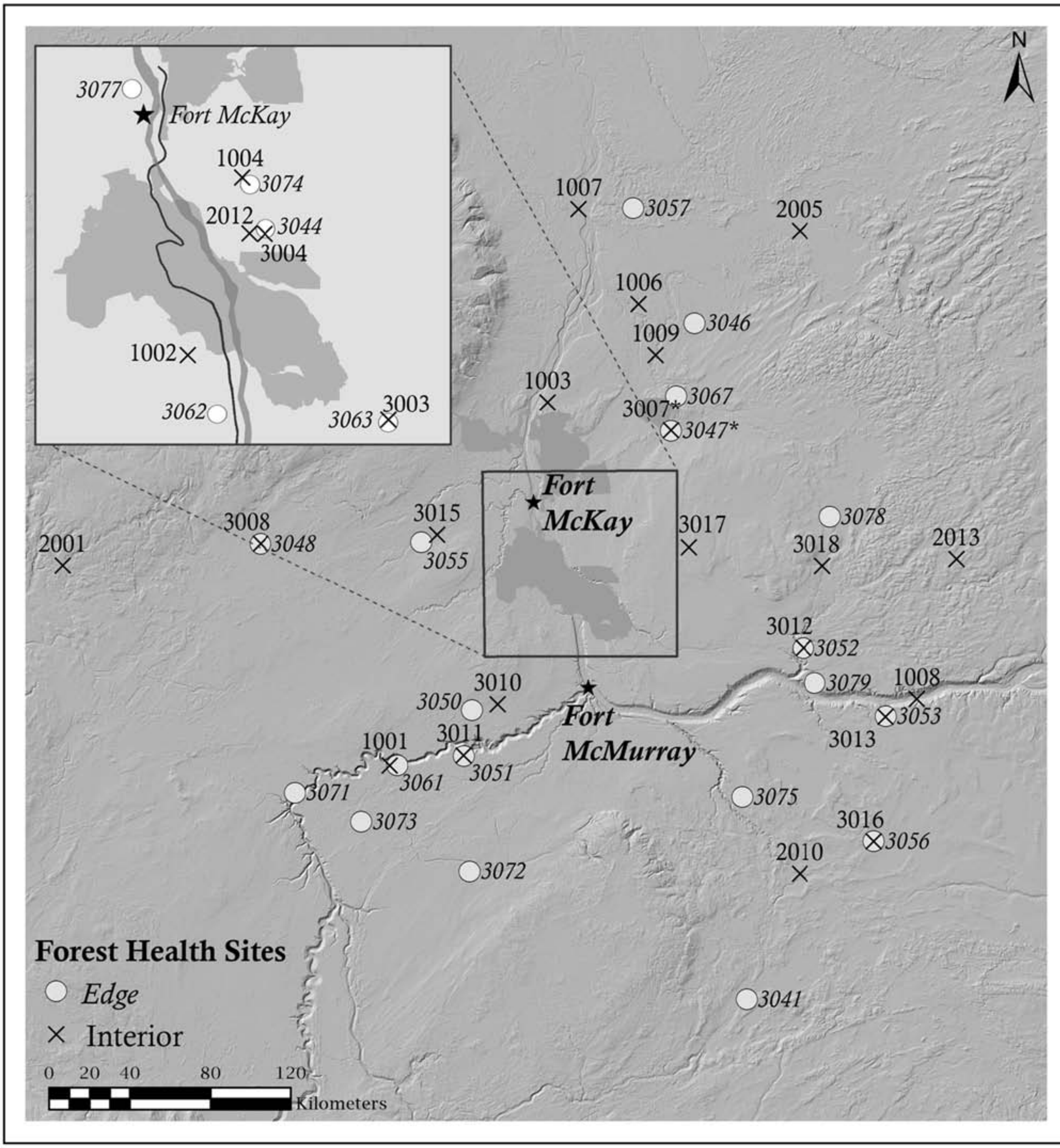


Fig. 7. Jack pine interior stand and edge monitoring sites in the WBEA Forest Health Monitoring Program. Oil sands development areas shown in solid grey.

Zlotorzynska, 2017; Zhang et al., 2016). Dust from oil sands operations was also identified as the primary source of deposited polycyclic aromatic hydrocarbons to the lichen *H. physodes* (Graney et al., 2017).

Similarly, atmospheric emissions and deposition of metals has received a great deal of attention. Understanding the sources, dispersion and deposition of metals is complex, with metals being emitted from tall stacks at upgraders, during ground disturbance associated with mining and road use, and from exposed dry tailings areas. Atmospheric metal deposition decreases with distance from industrial sources (Bari et al., 2014; Guéguen et al., 2016; Huang et al., 2016) and is characteristic of mineral dust released during land clearing, overburden removal, and other hauling operations (Lynam et al., 2015; Shotyk et al., 2017), as well as particulate matter generated during processing of the bitumen ore (Shotyk et al., 2014; Shotyk et al., 2016). Dust arising from bitumen processing is enriched in molybdenum, nickel and vanadium, and analyses of peat cores (Shotyk et al., 2017) and lake sediment cores (Cooke et al., 2017) have shown decreased deposition of these compounds over the past two decades. Using yttrium as an indicator of the source of dust deposited to berries within the AOSR, Stachiw et al. (2019) found that most dust contributing to metal levels on berries originated from crustal materials exposed and manipulated during industrial processes. The global phasing out of leaded gasoline is reflected in decreased regional lead deposition since the 1990s, however global lead sources continue to represent about 50% of the lead in ambient fine ($PM_{2.5}$) particulate matter, and 22% of the lead in *H. physodes* samples in the AOSR (Graney et al., 2019). In addition to global sources, AOSR sources contributed 20% of the lead in $PM_{2.5}$ and 32% of the lead in *H. physodes* samples collected in 2014. Similar to lead, global mercury sources have been identified as the key drivers of mercury deposition in the AOSR (Cooke et al., 2017), although elevated mercury and methyl mercury concentrations in snow samples within about 50 km of the oil sands mining and upgrading processes indicate the presence of local, industrial mercury atmospheric emission sources (Kirk et al., 2014; Willis et al., 2017).

Various modelling approaches have been used to understand links between emissions and deposition. In the decade after the initiation of the FHM Program, the CALPUFF (California Puff Model; Scire et al., 2000) and CMAQ (Community Multiscale Air Quality; https://www.epa.gov/cmaq) modelling systems were adopted for regional dispersion and deposition modelling, primarily for estimation of acidic deposition (Davies, 2012), replacing more rudimentary models like ADEPT2. Recent improvements in constraining the uncertainty in oil sands

Table 3
Primary concepts and conclusions arising from the TEEM Forest Health Monitoring Program.

Wood Buffalo Environmental Association Terrestrial Environmental Effects Monitoring Forest Health Monitoring Program
To develop and operate a long-term program to detect and characterize the effects of oil sands emissions on terrestrial and aquatic ecosystems, and on traditional resources and hence on traditional resource users
Monitoring Ecological Responses to Air Quality and Atmospheric Deposition in the Athabasca Oil Sands Region The WBEA Forest Health Monitoring Program (this paper)
Sulphur emissions from an expanding oil sands industry increased from the 1990s through to the mid-2000s and have subsequently decreased, while nitrogen emissions have been steadily increasing
Stakeholder-driven, consensus-based acid deposition monitoring, based on ecological response model, in sensitive jack pine forest
The continuity of the 20-year monitoring program has been maintained while increasing the number of monitoring sites, enhancing air and deposition monitoring, and broadening the suite of measurement indicators
Ambient Concentrations and Total Deposition of Inorganic Sulphur, Inorganic Nitrogen and Base Cations in the AOSR (Edgerton et al., 2019)
Generally declining ambient SO_2 concentrations, by about 40% since 2000
No consistent trend in ambient NO_2 concentrations, since 2000
Deposition of S, N and base cations decreased rapidly with distance from sources, with near background levels occurring within 50 km
Potential acid input estimated from monitoring data ranged from 0.1 to 0.2 keq/ha/yr across the AOSR, except in three areas near industrial operations – two where deposition of up to 0.8 keq/ha/yr was estimated and one where deposition of −0.6 keq/ha/yr (base cation dominated) was estimated
Atmospheric Sulphur and Nitrogen Deposition in the Athabasca Oil Sands Region has Measurable Effects on Foliar Nutrient Levels and Soil Chemical Properties (MacKenzie and Dietrich, 2019)
Sulphur and nitrogen concentrations in jack pine needles correlated positively with potential acid input
Sulphur, but not nitrogen, levels in soil correlated positively with deposition
Potential acid input and dry NH_3 deposition correlated positively with the pH of the LFH layer
Jack Pine Tree Growth and Understory Plant Composition in the Athabasca Oil Sands (Bartels et al., 2019)
Jack pine radial growth was negatively related to distance from emission sources both before oil sands development and in recent years; this likely reflects differences in environmental conditions between sites near and distant from emissions sources, rather than being related solely to deposition
Increased understory cover and species richness correlated with increased S and N deposition, suggesting a fertilizer effect
Use of an Epiphytic Lichen and a Novel Geostatistical Approach to Evaluate Spatial and Temporal Changes in Atmospheric Deposition in the Athabasca Oil Sands Region (Landis et al., 2019a)
Epiphytic lichen concentrations of eight elements identified as tracers for the main oil sands atmospheric emissions sources were evaluated within a 150-km radius of major emission sources from 2004 to 2017
Empirical Bayesian kriging and cokriging of lichen concentrations with industrially-relevant influence variables, and derivation of gridded zonal means, indicated that S concentrations significantly increased in every grid cell in the domain, with the largest increases (44–88%) occurring in proximity to the major surface oil sand operations, while N, Ca and Sr concentrations remained unchanged or decreased
The areal extent of dust-borne element deposition generally increased, with significantly higher deposition (23–258%) of petrogenic (V, Ni) and crustal elements (Al, Fe) at sites within 25 km of surface oil sand operations, reflecting new and expanding surface mining activity. Lichens at distal sites had generally lower concentrations and fewer significant trends of accumulation over time
Source Apportionment of an Epiphytic Lichen Biomonitor to Elucidate the Sources and Spatial Distribution of Polycyclic Aromatic Hydrocarbons in the Athabasca Oil Sands Region, Alberta, Canada (Landis et al., 2019c)
63% of PAH PAC in lichens were derived from coarse particle petroleum coke and oil sand ore emissions, 90% of which were deposited within 25 km of emission sources
Use of a minimum distance to source yielded a more precise spatial representation of deposition compared to the use of a single point in the approximate centre of operations that has been used previously to represent the source of AOSR emissions
Source Apportionment of Ambient Fine and Coarse Particulate Matter Polycyclic Aromatic Hydrocarbons (PAHs) at the Bertha Ganter-Fort McKay Community Site in the Oil Sands Region of Alberta, Canada (Landis et al., 2019b)
From 2014 to 2015, measured concentrations of $PM_{2.5}$ in Fort McKay originated from biomass burning (40%), fugitive dust (28%), upgrader stacks (21%) petrogenic PAH (18%), and transported aerosols (6%); pyrogenic PAH did not contribute to $PM_{2.5}$ mass but accounted for 78% of the PAH measured
Predominant sources of $PM_{10-2.5}$ mass were haul road dust (53%), mixed dust (32%), oil sand dust (10%), mobile sources (2%), and organic aerosol (1%); only the organic aerosol source significantly contributed (86%) to the measured total PAH
Using Pb Isotope Ratios of Particulate Matter and Epiphytic Lichens from the Athabasca Oil Sands Region in Alberta, Canada to Quantify Local, Regional, and Global Pb Source Contributions (Graney et al., 2019)
Lead in $PM_{2.5}$ measured at Fort McKay in 2010 to 2011 originated from eastern Asia sources (47%), local AOSR sources (20%), and sources within Western Canada (19%)
Lead in larger particulates (dust) originating in the AOSR comprised 27% of total lead in $PM_{10-2.5}$ at Fort McKay
Lichen lead content originated from Western Canadian regional (46%), AOSR (32%) and global (22%) sources, with most AOSR-produced particulate lead deposited within 30 km of emission sources
Forest Health Effects due to Oil Sands Atmospheric Deposition: Findings from Long-Term Forest Health Monitoring in the Athabasca Oil Sands Region (Davidson et al., 2019)
There are no indications of widespread acidification effects in sensitive jack pine ecosystems in the AOSR, suggesting that from the Alberta, provincial-scale regulatory perspective, acid deposition is below the levels required for a regulatory or management response
Sulphur accumulation in soils may provide a sufficient rationale to initiate detailed time-to-effect dynamic modelling as described in the acid deposition management framework for the AOSR, to evaluate the potential for future acid deposition effects in areas where deposition of up to 0.8 keq/ha/yr has been estimated
Sulphur, nitrogen and base cation deposition effects appear to reflect nutrient inputs into a nutrient-deficient ecological system
Elemental accumulation in lichens, soils and vegetation and ecological responses are apparent within 50 km of emission sources, beyond which neither elemental accumulation nor ecological responses are apparent
Source apportionment studies indicate the important contribution of dusts to elemental deposition, while quantifying the contributions of organic and inorganic substances to deposition both locally (Fort McKay) and across the AOSR
The FHM Program is a credible, long-term ecological monitoring initiative, founded on scientific principles, transparent to stakeholders and regulators, and operated in an adaptive monitoring paradigm. Strengths, challenges and opportunities in program design and management that have been identified in the analyses presented in this special issue are described for consideration and by the WBEA TEEM committee that oversees program operations

emission inventories, including integration of the diversity of emission inventories into a single inventory (Environment and Climate Change Canada and Alberta Environment and Parks, 2016), have been used in the GEM-MACH (Global Environmental Multiscale-Modelling Air quality and CHemistry) modelling system (Zhang et al., 2018). New remote sensing approaches may provide the means to validate model predictions (Jiang et al., 2018). These improvements are important, as challenges in the application of the provincial acid deposition management framework to the AOSR region have been raised (Whitfield and Watmough, 2015). Modelling using the CMAQ model indicated a restricted area around the major oil sands operation receiving elevated acid deposition, with limited expansion of this area under two future emissions scenarios Cho et al. (2017). Exceedances of critical loads over an area of up to 330,000 km^2 have been predicted (through GEM-MACH modelling) due to AOSR-sourced emissions (Makar et al., 2018). Cho et al. (2019) described a downward trend in the pH and base saturation percentage in sandy soils at forested sites in the AOSR since 1981, although no overall trend was apparent in the BC:Al ratio. Small, but statistically-significant differences in pH, BC:Al and base saturation percentage were not necessarily linked with biological responses or effects.

Detailed chemical characterizations of atmospheric emissions from tall upgrader stacks, mine vehicles, haul road dust, oil sand ore dust, mixed source dust, and biomass combustion (Wang et al., 2016; Wang et al., 2015a; Wang et al., 2015b) are now supporting source apportionment analyses (Graney et al., 2019; Landis et al., 2012; Landis et al., 2017; Landis et al., 2019c; Phillips-Smith et al., 2017; Wang et al., 2015a), which speak to air quality and sources of deposited substances within the local community of Fort McKay. Challenges remain in characterizing and quantifying tailings ponds emissions, which are likely dominated by organic emissions (Galarneau et al., 2014; Parajulee and Wania, 2014; Qiu et al., 2018; Small et al., 2015). Recent work has shown that forest fire emissions are significant contributors to air quality and atmospheric deposition in the AOSR (Bytnerowicz et al., 2016; Landis et al., 2018).

5. Closing comments

Although the structure of WBEA has evolved from an organization directly funded by participating industrial corporations to one now funded and overseen by the Oil Sands Monitoring Program (http://environmentalmonitoring.alberta.ca/), WBEA retains its multi-stakeholder governance structure, and relies heavily upon the broad range of stakeholders participating in the program to guide the organizations monitoring and research programs. TEEM committee member have sought guidance from scientific specialists since the inception of the program, with some specialists interacting directly with the TEEM committee stakeholders on a routine basis and others brought in to evaluate and provide guidance and support on monitoring program design, implementation, and interpretation of results.

Over the 20 years of operation, the FHM Program has evolved in a manner consistent with an adaptive monitoring paradigm. Notable successes are the adjustment and enhancement of monitoring activities, identification of unexpected environmental change (*e.g.*, calcium deposition) and the creation of a continuous data record, within the original multi-stakeholder structure that provides all affected parties with full participation opportunities. Percy (2012) described the outcomes arising from the suite of WBEA monitoring and research programs, at a time when TEEM was expanding its vision beyond monitoring for the effects of acidic deposition. The FHM Program has evolved from its initial focus on monitoring soil, tree and lichen chemical and growth responses at ten sites to one that includes nearly 50 sites and has broadened to the examination of source apportionment of deposited acidifying, elemental and organic comounds. The longevity of the FHM Program and its continued contribution to the understanding of regional ecological effects in a region in which monitoring is both logistically and institutionally challenging (Cronmiller and Noble, 2018) is a notable success, with the next step in its evolution being enhanced integration with other initiatives in the AOSR (Wentworth and Zhang, 2018).

The results of the FHM Program are described in the papers in this special issue, the highlights of which are presented in Table 3. These papers provide regulators, stakeholders and environmental professionals with a collated presentation of TEEM's work and findings, which will hopefully inform the environmental assessment and management of oil sands developments, which was the purpose of establishing the FHM Program. These papers also provide the foundation for an evaluation of the strengths, weaknesses, and gaps within the FHM Program, which will be considered by the TEEM stakeholder members as part of ongoing evolution and program improvement (Davidson et al., 2019).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.05.353.

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