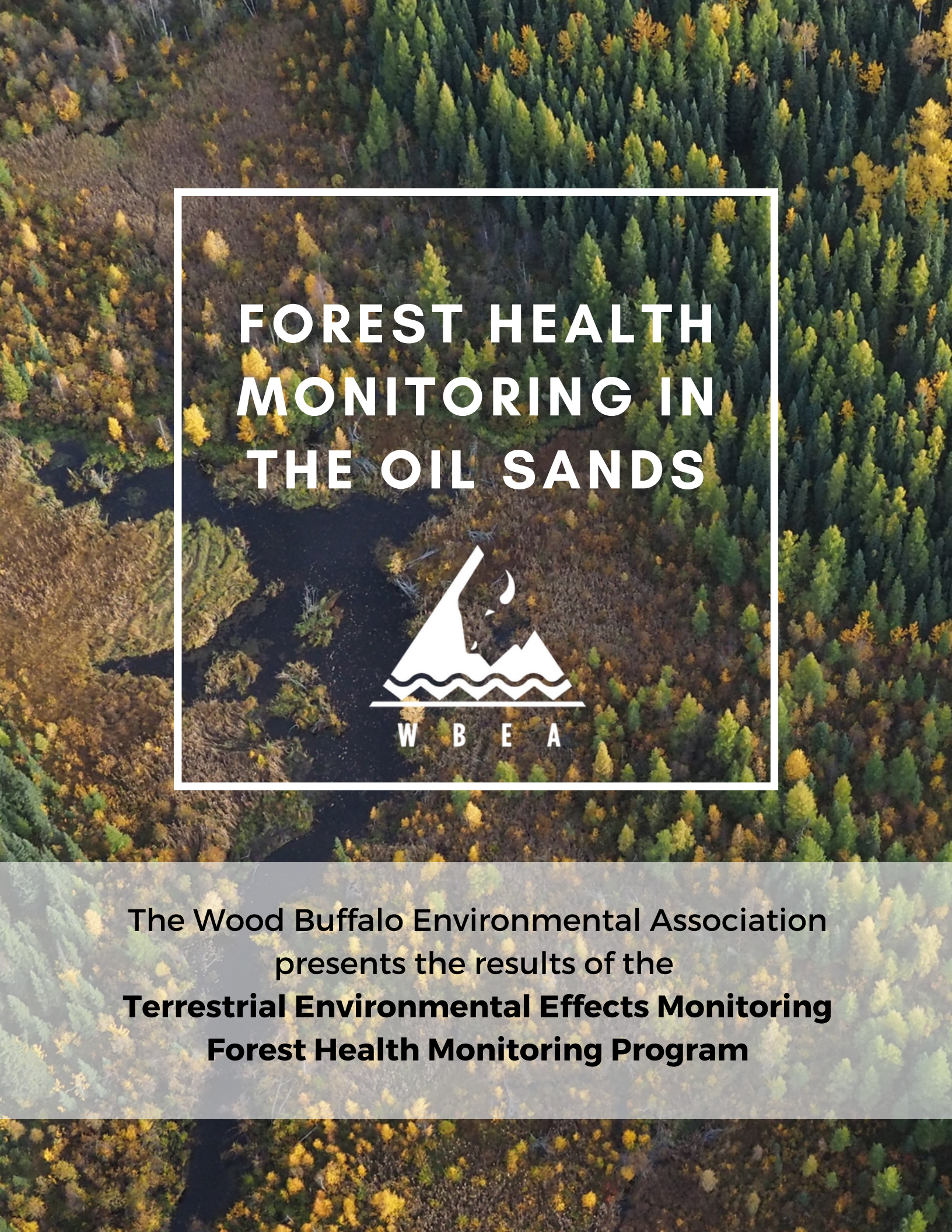


FOREST HEALTH MONITORING IN THE OIL SANDS

W B E A

The Wood Buffalo Environmental Association
presents the results of the
Terrestrial Environmental Effects Monitoring
Forest Health Monitoring Program

ABOUT THE Wood Buffalo Environmental Association

The Wood Buffalo Environmental Association (WBEA) is a multi-stakeholder non-profit organization that monitors the environment of the Regional Municipality of Wood Buffalo. Our environmental monitoring work is the most integrated and intensive focus on air and terrestrial monitoring in any one area, anywhere in Canada. The WBEA is committed to reporting accurate and timely high-quality data from our Ambient Air, Terrestrial, and Odour Monitoring programs to ensure regional stakeholders have the information they need to make informed environmental decisions.

Our Vision

People are empowered to make informed decisions to ensure a safe and healthy environment.

Our Mission

The Wood Buffalo Environmental Association is a multi-stakeholder, consensus-based organization that leads in state-of-the-art environmental monitoring to enable informed decision-making.

Our Values

We are scientifically independent
We recognize, respect, and use traditional knowledge
We are transparent and timely in communication accurate and accessible data
We are dedicated to using best available practices and technology
We support diverse stakeholder participation to achieve consensus-based decisions

INTRODUCING THE WBEA'S Forest Health Monitoring Program

In 1997, Terrestrial Environmental Effects Monitoring (TEEM) became a formal program within the WBEA. The objective of the TEEM program is:

"To develop and operate a long-term program to detect, characterize and quantify the impact that air emissions have had or may have, in the longer term, on terrestrial and aquatic ecosystems and on traditional land resources."

and

"To implement an approach for establishing/determining cause-effect relationships between air pollutants and forest ecosystem health in the Oil Sands Region."

The WBEA, through TEEM, operates a long-term forest health monitoring (FHM) program to detect possible impacts of air contaminants on forest health. The FHM program is funded through the Oil Sands Monitoring Program (OSM) and aligns with the OSM objective to conduct comprehensive and inclusive monitoring to track impacts from oil sands development. The WBEA monitors jack pine forest sites that are sensitive to acid deposition to assess whether there are changes to biological, physical, and chemical indicators through a sampling campaign of vegetation, soils, and lichen, every 6 years. Monitoring includes measurements of air quality (using passive and active air quality samplers) and deposition (using ion exchange resins), and a suite of receptors (lichens and vegetation) for evaluation of a broad set of compounds (particulate matter, organic compounds, metals). Data from these programs has informed source apportionment studies that characterized the specific contributions of regional and international source types to deposition within the Wood Buffalo region.

The WBEA recently analyzed the forest health dataset, and using these data, prepared nine manuscripts for open access publication in a Virtual Special Issue entitled "Relationships Between Air Pollutants and Forest Ecosystem Health in the Oil Sands Region, AB, Canada" within the journal Science of the Total Environment.

Key messages from each of the nine manuscripts are summarized on the following pages.

Introduction to the Virtual Special Issue - Monitoring Ecological Response to Air Quality and Atmospheric Deposition in the AOSR: The WBEA's Forest Health Monitoring Program

Kenneth R. Foster, Carla Davidson, Rajiv Neal Tanna, David Spink

- The Wood Buffalo Environmental Association (WBEA), and its Terrestrial Environmental Effects Monitoring Committee (TEEM) were created in the 1990s as a response to Indigenous and stakeholder concerns about potential ecological and health effects of increased emissions and deposition of acidic substances in the Athabasca Oil Sands Region (AOSR).
- Jack pine forest stands were chosen as the acid-sensitive receptor system due to the limited buffering capacity of the sandy soils.
- Since 1990, mined bitumen production in the AOSR has increased 5-fold and in-situ production has increased nearly 10-fold.
- Ongoing measurements of air quality and atmospheric deposition are collected at the same locations where forest health indicators (soil, needle and lichen chemistry, and tree and understory condition) are assessed on a 6-year cycle. The program has expanded to include lichen sampling over a broad area, more compounds beyond acidifying substances, and source identification studies.

Ambient Concentrations and Total Deposition of Inorganic Sulfur, Inorganic Nitrogen, and Base Cations in the AOSR

Eric S. Edgerton, Yu-Mei Hsu, Emily M. White, Matthew S. Landis, Mark E. Fenn

- Trace gas, particulate matter, and deposition data collected from 2000-2017 in the AOSR were analyzed to evaluate variability across the region and through time.
- Ambient sulphur dioxide concentrations have generally declined, by roughly 40%, since 2000.
- Ambient nitrogen dioxide concentrations showed few significant trends, which contrasted with earlier studies. Nitrogen dioxide data suggest increasing concentrations region-wide from 2000 to ~2008, followed by a plateau or slight decrease through 2017.
- Deposition of sulphur, nitrogen, and base cations decreased rapidly with distance from emissions sources; near background levels were found within 50km. Since deposition changes so quickly between 10-50km from oil sands operations; it would be beneficial to add more monitoring sites in these areas.
- Estimated potential acid input ranged from 0.1 to 0.2 keq/ha/yr across the AOSR, except in three areas near industrial operations – in two of these areas, estimated acid deposition was high (0.8 keq/ha/yr), and deposition in the other area was dominated by base cations (0.6 keq/ha/yr).
- Data from passive measurements of sulphur dioxide, nitrogen dioxide, and nitric acid are robust enough to reveal trends, however, passive measurement of ammonia may require some improvement.

Atmospheric Sulfur and Nitrogen Deposition in the AOSR is Correlated with Foliar Nutrient Levels and Soil Chemical Properties

M. Derek MacKenzie and Sebastian T. Dietrich

- Soil properties and foliage nutrient levels from 2011 sampling were examined in the context of measured and modeled (estimated) acid deposition.
- Sulphur in the soil near the surface (0-5cm) had no significant relationship to sulphur deposition. However, a relationship in deeper soil (5-15cm, 15-30cm) suggests that sulphur does accumulate in soil and moves through the soil column.
- High nitrogen deposition was correlated with higher nitrogen levels in foliage, but not in soil. This suggests either rapid uptake of nitrogen from soil through the roots, or direct uptake through the foliage.
- Potential acid input was not correlated to the soil pH. However, there was a correlation between the pH of the organic layer and dry ammonia deposition, which requires further investigation.
- Adding more Forest Health Monitoring sites in the high and medium deposition range and assessing soil weathering rates to evaluate the risk of acidification in areas of high deposition is recommended.

The Impact of Atmospheric Acid Deposition on Tree Growth and Forest Understory Vegetation in the AOSR

Samuel F. Bartels and S. Ellen McDonald

- The authors evaluated the relationship between the health of forest understory vegetation and (i) modeled deposition of nitrogen, sulphur, base cation, and (ii) potential acid input from surface mining. They also tested the relationship between this atmospheric deposition and radial growth of jack pine, both prior to (1957-1966) and during (2001-2010) active oil sands development in the AOSR.
- Jack pine growth was greater in areas in close proximity to oil sands surface mining operations both prior to and after oil sands development. This likely means there were differences in the environmental conditions between the sites, that are not only related to deposition. This relationship was less pronounced in the later time period.
- Measures of understory vegetation (plant cover, species richness, and abundance) increased with estimated nitrogen and sulphur deposition, suggesting that deposition of these compounds have a fertilization effect.
- No evidence of acidification effects of oil sands production on tree growth or forest understory vegetation was found.

Use of an Epiphytic Lichen and a Novel Geostatistical Approach to Evaluate Spatial and Temporal Changes in Atmospheric Deposition in the AOSR, Alberta, Canada

Matthew S. Landis, Shanti D. Berryman, Emily M. White, Joseph R. Graney, Eric S. Edgerton, William B. Studabaker

- Concentrations of eight elements that serve as tracers for oil sands emissions sources (sulphur, nitrogen, aluminum, calcium, iron, nickel, strontium, vanadium) were evaluated within a 150km radius of major emission sources using lichen samples collected from 2002-2017, time series analysis, and geostatistical models.
- Lichen sulphur concentrations significantly increased in close proximity to oil sands operations, while nitrogen concentrations slightly decreased.
- The extent of dust-borne element deposition generally increased over time, with significantly higher deposition of petroleum combustion elements (vanadium, nickel) and earth crust elements (aluminum, iron) at sites within 25km of surface oil sands operations. Lichens at sites further from development generally had lower concentrations and fewer significant trends of accumulation over time.
- The Lichen *Hypogymnia physodes*, an epiphytic (tree-dwelling) species, was an effective biological indicator of both wet and dry atmospheric deposition in the AOSR as they get all their water and nutrients directly from the air.
- The many lichen samples throughout the region complement the WBEA passive and active deposition monitoring sites in assessing atmospheric deposition patterns over space and time. It also complements the jack pine monitoring network in the AOSR. Lichen sampling is effective and inexpensive, so continuing to sample is recommended to clarify the trends and monitor new changes.

Source Apportionment of an Epiphytic Lichen Biomonitor to Elucidate the Sources and Spatial Distribution of Polycyclic Aromatic Hydrocarbons in the AOSR, Alberta, Canada

Matthew S. Landis, William B. Studabaker, J. Patrick Pancras, Joseph R. Graney, Keith Puckett, Emily M. White, Eric S. Edgerton

- Lichen samples (species *Hypogymnia physodes*) were collected in 2014 from 127 jack pine and black spruce dominated sites, within a 150km radius from the center of oil sands operations.
- A source apportionment model identified eight major source factors that contribute to the lichen concentration of polycyclic aromatic hydrocarbons, polycyclic aromatic compounds, and inorganic elements.
- The eight major sources were petroleum coke, haul road dust, stack emissions, raw oil sands, biomass combustion, mobile source, and two lichen biogeochemical factors.
- 63% of polycyclic aromatic hydrocarbons and polycyclic aromatic compounds in lichens were from petroleum coke particles and oil sands ore fugitive dust emissions. 90% of these were deposited within 25km of their emission sources.
- Use of a minimum distance to nearest emission source produces a more precise spatial representation of deposition compared to the historical method of using distance from an arbitrary location in the center of oil sands operations.

Source Apportionment of Ambient Fine and Coarse Particulate Matter Polycyclic Aromatic Hydrocarbons at the Bertha Ganter-Fort McKay Community Site in the Oil Sands Region of Alberta, Canada

Matthew S. Landis, William B. Studabaker, J. Patrick Pancras, Joseph R. Graney, Emily M. White, Eric S. Edgerton

- This study was designed to(i) measure ambient polycyclic aromatic hydrocarbon concentrations in aerosol, semi-volatile, and volatile phase concentrations in Fort McKay, and (ii) identify source contributions for the observed compounds using tracer species.
- Five sources were found to contribute to measured concentrations of fine particulate matter (PM2.5) in Fort McKay: biomass burning excluding wildfire (22%), fugitive dust (28%), stack emissions (21%) petrogenic (fuel burning) polycyclic aromatic hydrocarbons (18%), and transported aerosols (6%). It was found that that the pyrogenic (combustion) source factor did not contribute to particulate matter (PM2.5), but did contribute to polycyclic aromatic hydrocarbons.
- Sources of coarse particulate matter (PM10) mass were haul road dust (53%), mixed fugitive dust (32%), fugitive oil sands dust (10%), mobile sources (2%), and organic aerosol (1%). Only the organic aerosol source significantly contributed (86%) to the measured polycyclic aromatic hydrocarbons.
- Fugitive dust, haul road dust, and road salt were key sources of base cations in particulate matter (PM2.5 and PM10). Oil combustion and fugitive oil sands was a source of sulphur compounds in particulate matter, and biomass combustion (including wildfire) was a source of nitrogen compounds in particulate matter.

Using Pb Isotope Ratios of Particulate Matter and Epiphytic Lichens from the AOSR in Alberta, Canada to Quantify Local, Regional, and Global Pb Source Contributions

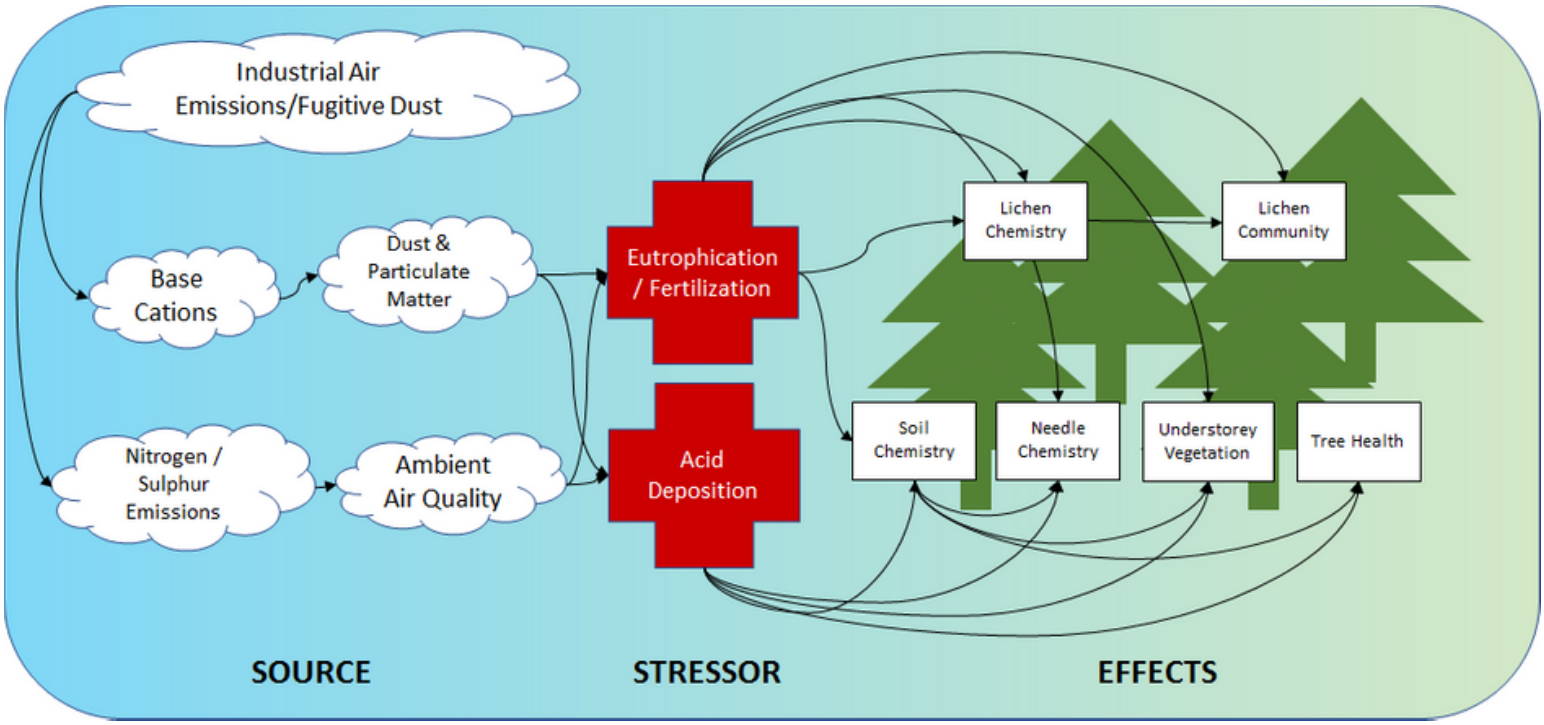
Joseph R. Graney, Eric S. Edgerton, Matthew S. Landis

- Data from lichen collections from 2008, 2011, and 2014 in northeastern Alberta, combined with particulate matter collected in 2010-2011 from Ft. McKay, were examined for lead concentrations and isotope (different forms of a chemical element) composition.
- Lead in fine particulate matter (PM2.5) originated mostly from eastern Asia (47%), but also from local AOSR sources (20%), and other sources within Western Canada (19%).
- Lead in larger particulates (dust) originating in the AOSR comprised 27% of total lead in larger particulate matter (PM10) at Fort McKay.
- Lead content in lichen was from Western Canada (46%), AOSR (32%) and global (22%) sources.
- Most AOSR-produced particulate lead is deposited within 30km of emission sources.

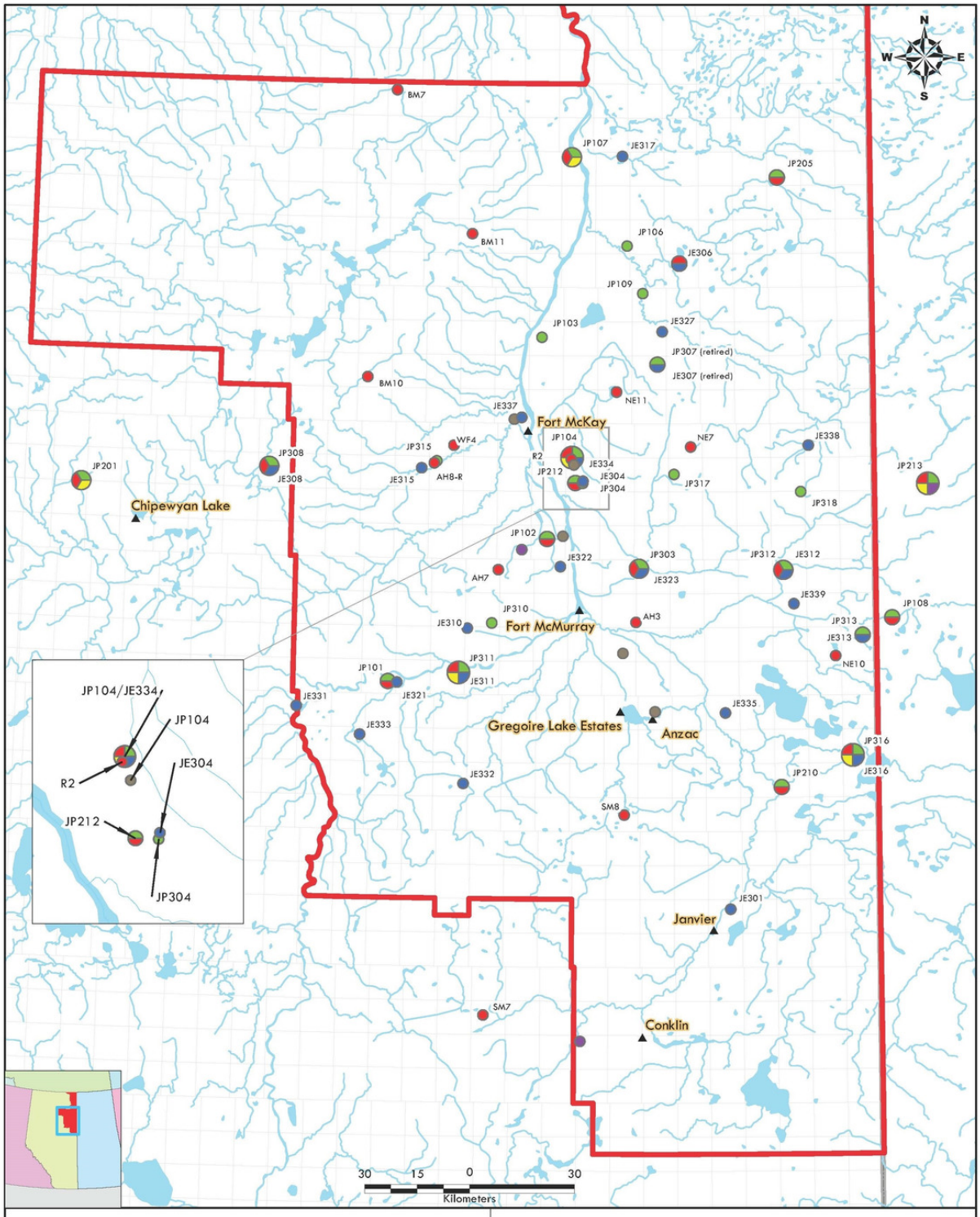
Forest Health Effects due to Atmospheric Deposition: Finds from Long-Term Forest Health Monitoring in the Athabasca Oil Sands Region

Carla Davidson, Ken R. Foster, Neal R. Tanna

- Deposition of sulphur, nitrogen, base cations, polycyclic aromatic hydrocarbons, and trace elements declined exponentially with distance from emission sources, reaching background levels at roughly 50km from the nearest emission source.
- There is limited evidence of acidification of forest soils, however, it will be important to continue monitoring, particularly where acid deposition rates have been estimated up to 0.8 keq/ha/yr.
- Particulate matter and dust deposit base cations which play a key role in neutralizing acidic deposition. Since they also deposit polycyclic aromatic hydrocarbons and metals, measures to control dust will upset the balance of deposition and may lead to more acidification.
- There was a detectable fertilization effect on soil, needles, and understory plant communities from steady and increasing sulphur and nitrogen deposition.
- Nitrogen and sulphur deposition for sites close to emissions sources exceed levels expected to change the environment and should be further assessed.
- The WBEA's Forest Health Monitoring Program is a credible, long-term ecological monitoring initiative, that was founded on scientific principles, transparent to stakeholders and regulators, and able to adapt its conceptual model to changing conditions.



The conceptual model for the TEEM Forest Health Monitoring Program. The top line identifies the different conceptual parts of the monitoring program from source (industrial emissions) to stressor, to effects (forest). Solid lines indicate cause-effect relationships. The FHM program monitors both the source and the effect.



Wood Buffalo Environmental Association
Terrestrial Monitoring Network

W B E A

Legend

- Community
- Regional Municipality of Wood Buffalo
- Forest Health Interior Plot
- Passive Monitor
- Meteorological Tower
- Forest Health Edge Plot
- Bog Site
- Portable Ozone Monitor

GLOSSARY

AOSR	Athabasca Oil Sands Region
Crustal Elements	Elements that make up the earth's crust
FHM	Forest Health Monitoring
keq/ha/yr	kiloequivalent per hectare per year; a measure of potential acid input (PAI)
N	Nitrogen
NH3	Ammonia
NO2	Nitrogen Dioxide
Petrogenic	Resulting from petroleum fuel combustion
Pb	Lead
Potential Acid Input (PAI)	Difference between deposited nitrogen/sulphur and base cations, expressed in hydrogen ion equivalents.
Pyrogenic	Resulting from combustion
S	Sulphur
SO2	Sulphur Dioxide
TEEM	Terrestrial Environmental Effects Monitoring

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Alberta

OIL SANDS MONITORING PROGRAM

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