NADP Total Deposition Science Committee (TDep) Annual Report 2023

Contents

Introduction

The National Atmospheric Deposition Program's (NADP) Science Committees focus on key areas of atmospheric deposition, scientific interest and/or applications. They are approved by the NADP Executive Committee and must be dissolved or renewed every four years. The Total Deposition Science Committee (TDep) was established in 2011 and the charter was most recently renewed in 2020. The TDep mission is to improve estimates of atmospheric deposition by advancing the science of measuring and modeling atmospheric wet, dry, and total deposition. TDep provides a forum for the exchange of information on current and emerging issues among atmospheric scientists, ecosystem scientists, resource managers, and policy makers. The committee is open to anyone interested in contributing to the mission. The specific charges of TDep are:

- Support the national networks that monitor atmospheric deposition by providing information on emerging measurement techniques, model development, and uncertainties associated with these approaches;
- Identify and prioritize knowledge gaps in the field of measuring and modeling atmospheric deposition and advocate for research to bridge those gaps;
- Coordinate with NADP's Critical Loads of Atmospheric Deposition (CLAD) Science Committee and other groups to advocate for the use of the most scientifically defensible deposition estimates for critical loads and other environmental assessments;
- Provide expertise and advice on present and potential decisions and regulatory actions pertaining to the field of measuring and modeling atmospheric deposition; and
- Encourage greater communication and collaboration between groups from different disciplines and countries with interests in atmospheric deposition.

Additional information can be found on the TDep website (http://nadp.slh.wisc.edu/committees/tdep/).

TDep is currently directed by two **Co-chairs**, Amanda Cole (Environment Climate Change Canada; ECCC) and Colleen Baublitz (U.S. Environmental Protection Agency; EPA/Office of Air Quality Planning and Standards; OAQPS). Kristen Foley (EPA/Office of Research and Development; ORD) is the TDep **Secretary**. The TDep Steering Committee meets bi-monthly to establish meeting agendas, share information on upcoming opportunities for outreach, and identify project priorities. The **Steering Committee** is made up of past Co-chairs, Working Group leaders, EOS representatives, representatives of major NADP-funding agencies, and atmospheric and ecosystem scientists closely involved with the TDep mission. For 2023, the Steering Committee members included: Amanda Cole, Colleen Baublitz, Kristen Foley, Greg Beachley (EPA/Office of Air and Radiation; OAR), Mike Bell (National Park Service; NPS), Katie Benedict (Los Alamos National Laboratory), Ryan Fulgham (EPA/ORD), Selma Isil (WSP), Chris Rogers (WSP), Kristi Morris (NPS), Melissa Puchalski (EPA/OAR), Bret Schichtel (NPS), John Walker (EPA/ORD), Greg Wetherbee (U.S. Geological Survey; USGS), April Leytem (U.S. Department of Agriculture; USDA/Agricultural Research Service; ARS), Jeff Herrick (EPA/ORD), and Ian Rumsey (EPA/ORD).

TDep is organized into a workgroup format to provide structure and organization within the committee. This format helps to distribute workloads, provide more accessibility of projects and opportunities to committee members, and promote more collaborative work. Descriptions and updates from these workgroups are included herein.

This annual report serves as a summary and quick reference for the activity, progress, and accomplishments of TDep over the course of 2023. It contains links to the biannual meeting notes, updates from each of the TDep workgroups, and descriptions and status updates on TDep-related products and research.

Annual Summary of TDep Accomplishments

It was another productive year for TDep. Below is a snapshot of the 2023 accomplishments.

- **TDep MMF output for version 2023.01.** Version 2023.01 was made public in November 2023 and includes a new bias correction method that utilizes a five-year linear weighted moving average method. This method has the advantages of calculation of adjustment ratios that will consider multiple recent years, allowing for consistency to withstand reductions in site density while still preserving flexibility in annual trends and removing step changes due to seasonal grouping. The methodology and results of the method were presented at the Fall 2023 meeting.
- **Hosted a monitoring network optimization forum at Spring TDep meeting.** Facilitated by Melissa Puchalski (EPA) and Amanda Cole (ECCC), TDep created a forum for cross-agency discussion of the potential effects of site closures and how different monitoring networks approach this problem - methods and best practices in prioritization. Representatives from various agencies shared their work and perspectives, including Melissa Puchalski (EPA), Anthony Prenni (NPS), John Walker (EPA), David Gay (NADP Program Office), Amanda Cole (CAPMoN), and Greg Beachley (EPA).
- **Invited presenters to provide overviews of three different monitoring networks at Fall TDep meeting.** Network representatives included Sally Ng from the Atmospheric Science and Chemistry mEasurement NeTwork (ASCENT), Chris Florian from the National Ecological Observatory Network (NEON), and Dean Carpenter from the Albemarle-Pamlico National Estuary Partnership. Interacting with deposition monitoring networks is one of TDep's specific charges: "Support the national networks that monitor atmospheric deposition by providing information on emerging measurement techniques, model development, and uncertainties associated with these approaches."

General Updates

Kristen Foley was elected as TDep secretary at the Fall 2023 TDep meeting. Colleen Baublitz was promoted to TDep Co-chair.

The Deposition Uncertainty Workgroup merged with the Measurement-Model Fusion Workgroup by unanimous vote at the Spring 2023 TDep meeting.

The Urban Deposition Workgroup (CityDep) merged with the Measurements Workgroup by unanimous vote at the Spring 2023 TDep meeting.

TDep Workgroup Updates

In 2019, TDep adopted and organized into a Workgroup structure to promote collaborative work. It is hoped that the new format will help to distribute workloads, make projects more accessible to a broader audience, and advance research between the spring and fall meetings.

The current workgroups include:

- Stakeholder Workgroup (Lead: Ian Rumsey)
- Measurement Model Fusion (MMF) Workgroup (Lead: Greg Beachley)
- Measurement Workgroup (Lead: Bret Schichtel)

Stakeholder Workgroup

Lead: Ian Rumsey, EPA (rumsey.ian@epa.gov)

Workgroup Objectives:

- Increase communication across scientific communities (i.e., atmospheric chemistry, ecology).
- Create new opportunities for collaborative research by promoting the inclusion of deposition science in grant programs.
- Advance the integration of TDep science needs into existing research programs across stakeholder groups.
- Facilitate communication among program managers within stakeholder Agencies and user groups.

Examples of Current Projects (Project descriptions listed in TDep Project Tracker):

- Participation in USDA North Central Regional Association Project developed by Richard Grant (Purdue University), Timothy Griffis (University of Minnesota – Twin Cities) and colleagues: 'NCDC1213 Sources and Fate of NH_3 Across the Landscape'. An annual meeting was held virtually on December 7th 2022. Project leads discussed research activities, research interests and potential collaborative activities. The participants are planning to meet again soon, potentially before the spring NADP meeting.

- Planning for Agricultural Stakeholder Forum in 2024.

Measurement Model Fusion Workgroup

Lead: Greg Beachley, EPA (beachley.gregory@epa.gov)

The objective of this workgroup is to be the caretakers of the TDep MMF model and manage product outputs (https://nadp.slh.wisc.edu/committees/tdep/). Workgroup members will conduct research and have discussions to ensure that the TDep MMF stays current with the state of deposition science. The group will respond to any questions and requests involving the TDep MMF products.

The workgroup is tasked with the following TDep MMF sub-projects: Annual products and Outreach, Model development and improvements, and Deposition Uncertainty assessment. The Annual Products and Outreach will focus on annual version updates, quality assurance/quality control of the products, and availability of those products and descriptions on the TDep Total Deposition maps website. The Model Development and Improvement will focus on incorporating improvements to the TDep MMF and helping to keep the TDep MMF current with the state of the science. The Deposition Uncertainty assessment inherits a portion of the work from the Deposition Uncertainty Workgroup and is focused on understanding the uncertainty that exists in measurements and models used to estimate the deposition of nitrogen (N) and sulfur (S). This group will coordinate with the Critical Loads of Atmospheric Deposition committee to further understand how uncertainty in deposition flux will impact critical load development and critical load exceedance.

Examples of Current Projects:

- Implementing updates including the incorporation of CMAQ wet deposition data into the next TDep version (2024.01) and subsequent QA for planned Fall 2024 release.
- A publication focusing on TDep MMF trends using the most current version and a comparison with past versions.
- Development of a protocol for replacement of missing observation data using spatial and temporal statistical analyses of past trends.
- Testing methods to incorporate weekly or monthly grids of CrIS satellite NH3 observations as a weighting tool in TDep MMF.
- Development of general approach and specific methods to estimate the uncertainty of deposition fluxes, building on the past work from the Deposition Uncertainty Workgroup (see 2022 TDep Annual Report).

Measurement Workgroup

Lead: Bret Schichtel, NPS (schichtel@cira.colostate.edu)

Workgroup Objectives:

- Support national networks relevant to atmospheric deposition by providing information on emerging measurement techniques and their uncertainties.
- Identify and prioritize knowledge gaps in current direct and indirect monitoring of atmospheric deposition and promote research to address those gaps, including monitoring in urban environments.
- Promote and support the incorporation of monitoring data into TDep products and workgroups and scientific and regulatory assessments.
- Facilitate communication between monitoring data generators and users.

Current Project:

- In 2023, the Workgroup began conversations about hosting a workshop on reactive nitrogen and phosphorus measurements. The workshop will be held on the first day of the spring 2024 meeting. The one-day workshop is to bring researchers together with the deposition monitoring community to discuss reactive nitrogen and phosphorous measurements, share information on

the state of the science, and determine how recent advances may be used to (1) fill monitoring gaps, (2) help routine networks evolve to address these monitoring gaps, and (3) improve total deposition estimates for critical loads assessments. The workshop will consist of two sessions of invited presentations followed by panel discussion. The morning session will focus on measurements of reduced nitrogen including talks on ground-based, satellite, process-level, and low-cost measurements. The afternoon session will focus on measurements of total, organic, and other forms of nitrogen, and phosphorus in wet and dry components of deposition.

TDep Project Tracker

TDep uses the annual report to communicate a "TDep Project Tracker". The objectives of the project tracker are to 1) allow TDep members to highlight research and products motivated by or relevant to the TDep mission and 2) log ideas that cannot be currently acted on so that they are not lost. The TDep Project Tracker will be included in each year's annual report and will be presented and discussed at biannual TDep meetings to solicit audience feedback and endorsement.

Current Research and products motivated by or relevant to the TDep mission

- **AMoN Flux Characterization Pilot Study update (John Walker, EPA)**

A project is currently underway (EPA/WSP) to develop a methodology to estimate net and component NH_3 fluxes using two-week integrated NH_3 concentrations at AMoN sites. Phase I measurements of micrometeorology, biogeochemistry, and canopy physical characteristics at three AMoN pilot sites: Duke Forest, NC; Bondville, IL; and Chiricahua National Monument, AZ are complete and results have been summarized in an EPA report currently in review. Phase II of the project is underway, in which a bidirectional NH_3 model is being used to assess seasonal and annual net and component NH3 fluxes across the AMoN network. Phase I measurements are used to parameterize the model and to assess sensitivities associated with the use of time-integrated concentration measurements, modeled versus measured meteorological inputs, and parameterizations of soil and vegetation emission potentials. A journal article led by Colleen Baublitz is expected to be completed in 2024.

This project directly addresses research gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper in applying a bidirectional ammonia air-surface exchange model at NADP AMoN sites (See White Paper section 3.2.1).

- **Reactive N flux measurements by eddy covariance (John Walker, EPA)**

Thermal and photolytic converter methods can be combined with fast nitric oxide chemiluminescence detection to quantify canopy-scale fluxes of reactive N by eddy covariance. A project is underway (EPA/WSP) to develop an inlet system for a two-channel chemiluminescence instrument for deployment at Duke Forest. The inlet system will include a photolytic converter for NO_2, a heated molybdenum converter for total NOy, and a heated stainless-steel converter for total

reactive N. By employing dual chemiluminescence reaction cells, fluxes can be measured in one of two modes for continuous concurrent flux measurements of (Mode 1) NO_2 and total NOy or (Mode 2) total NOy and total reactive N. This combination of fluxes allows for assessment of the contribution of NO_2 to total NOy fluxes and, by comparing total NOy and total reactive N, the relative fractions of reduced versus oxidized forms of reactive N dry deposition. The Total N, NOy, NO_2 converter/inlet system is undergoing laboratory testing at EPA with deployment at Duke Forest hardwood tower in Summer 2024.

This project directly addresses research gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper for process-level flux measurements (see White Paper Sections 3.1.1 and 3.1.1.1).

- **Low-cost dry deposition system (John Walker, EPA)**

Datasets of dry deposition of reactive nitrogen are lacking due to the cost and complexity of online micrometeorological flux measurements. A low-cost dry deposition measurement system suitable for routine network operation is needed. In collaboration with USDA, EPA has constructed and is testing a conditional time-averaged gradient (COTAG) system for measurement of speciated dry deposition of NH3 on weekly to monthly time-scales. Two systems are currently deployed in southern Idaho. A design package for the EPA COTAG, including mechanical drawings, wiring schematics, field and lab SOPs, has also been completed. WSP is building the EPA COTAG system with expected delivery by the end of 2024.

This research project directly addresses research gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper in 3.1 Measured total Nr deposition budgets, particularly for 3.1.2.4. Low-cost method for routine monitoring of air-surface exchange of Nr compounds.

- **Water soluble organic nitrogen (WSON) aerosol pilot study status (John Walker, EPA)**

EPA and WSP conducted a special study using samples collected from five CASTNET sites: Great Smoky Mountains National Park, TN; Kickapoo Tribe in Kansas, KS; Rocky Mountain National Park, CO; Salamonie Reservoir, IN; and Washington Crossing State Park, NJ. The study involved analyzing the Teflon filter extracts (the 1st stage in the CASTNET filter pack which captures particles) for total nitrogen. Precision and detection limits for total N and total water soluble organic nitrogen (WSON), calculated as the difference between a Shimadzu combustion/chemiluminescence total nitrogen measurement and the particulate NO_3^- (ion chromatography) and NH_4^+ (colorimetry) measured using standard CASTNET methods were assessed.

In early 2021, a 12-week study of more comprehensive testing of sample handling and storage effects on WSON was conducted. Split samples were analyzed from a test site in Gainesville and co-located filter packs from Mackville, KY (MCK131/231). The results indicated that further testing was needed to reduce the blank values and improve precision. To this end, WSP acquired a Seal Analytical colorimetric autoanalyzer for the total N and NH_4^+ measurements. Use of colorimetry for both Total N and NH_4^+ reduces instrument cross-calibration requirements and aligns with the WSLH SNiPiT method for Total N in precipitation. A 12-month study, analyzing filters from 27 CASTNet sites (25 locations), began in winter 2022 following WSP's acquisition of SEAL analyzer. Analysis of final datasets is underway with a draft journal article anticipated in early 2025.

This project directly addresses research gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper, which include development of routine methods to quantify organic nitrogen in (See White Paper section 3.1, particularly subsections 3.1.2.5 and 3.1.2.4). This project will also advance the science of routine ON measurements (See White Paper section 3.4 specifically subsection 3.4.1).

- **Testing of the NADP total N / total P wet deposition sampler (WSLH)**

The Wisconsin State Laboratory of Hygiene (WSLH) is developing a collector and analytical methods for measurement of organic nitrogen (N) and phosphorus (P) in precipitation. The prototype collector (SNiPiT) fits on the outside of the NTN bucket and is pre-charged with acid to avoid microbial processing and sorption of N and P. Chris Worley presented on the status of this project at the 2021 Fall TDep meeting, finding on average organic N and organic P accounted for 13% and <10% of total N and total P, respectively, during the pilot study in Madison, WI. However, sample acidities were too high (i.e. low pH) and interfered with instrumental analysis when sample volumes were low (<50 mL). The addition of buffer solution to the acid pre-charge eliminated these issues for organic nitrogen but seem to cause a contamination issue with the P measurements. Experiments are ongoing to address P measurements in low sample volumes. Katie Blaydes will present on this work at the 2024 Spring TDep meeting.

This research project directly addresses gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper to develop routine methods to quantify organic nitrogen in 3.1 Measured total Nr deposition budgets, particularly for 3.1.1.1 'Measurements of air-surface exchange of Nr in natural ecosystems across North America' and 3.1.2.5 'Characterization of organic nitrogen in air and precipitation'. This also addresses knowledge gaps for routine organic nitrogen (ON) measurements identified in 3.4 'Spatial and Temporal Patterns of total Nr deposition', specifically for subsection 3.4.1 'Relationship of long-term Nr trends in emission and deposition'.

- **WMO Measurement-Model Fusion for Global Total Atmospheric Deposition Initiative (Amanda Cole; Measurement Model Fusion workgroup)**

TDep members Amanda Cole and Greg Beachley are members of a steering committee for the WMO's MMF-GTAD initiative. The long-term goal of this initiative is to produce high-quality maps and estimates of fluxes of atmospheric pollutants on a global scale in a semi-operational manner, drawing from the methods and expertise of TDep and other regional MMF deposition products. In 2023, a paper was published describing global N and S deposition from combining the 2010 HTAP multi-model mean with available deposition data (ACP - Global nitrogen and sulfur deposition mapping using a measurement–model fusion approach (copernicus.org). A project to evaluate global operational model output for deposition was initiated and will continue in 2024 and beyond. Also, a contract was signed to generate a harmonized global wet deposition dataset in 2024 for this evaluation and other MMF applications.

- **Measurements of NH_3 and other reactive N dry deposition fluxes in Rocky Mountain National Park (RMNP)**

A project funded through an EPA Regional Applied Research Effort (RARE) grant, with additional funding from the National Park Service, is now in its second year. This collaborative project between EPA ORD, EPA Region 8, NPS and Colorado State University (CSU) seeks to measure NH_3 and other reactive N dry deposition fluxes in RMNP and along the NH_3 transport path from agricultural sources on the Front Range to the Park. The first set of flux measurements was collected during the summer of 2021 over an evergreen forest in RMNP. During 2022, flux measurements were collected at a grassland site (NOAA Table Mountain facility) near Boulder, CO. In addition to direct flux measurements, seasonal and annual NH_3 fluxes will be modeled using measurements of NH_3 air concentrations, micrometeorology, and soil and vegetation emission potentials. A final report has been submitted to EPA and a draft journal article is under development, led by CSU.

This research project directly addresses research gaps presented in the TDep Reactive Nitrogen (Nr) deposition White Paper for 3.4 'Spatial and Temporal Patterns of total Nr deposition', specifically for 3.4.2 'Spatial variability of ammonia in agricultural regions'.

- **Sensitivity of critical loads to modeled deposition estimates (Mike Bell, NPS; Measurement Model Fusion Workgroup)**

This project was a collaboration between the NPS (Mike Bell), US Forest Service (Mark Fenn), and San Francisco State University (Leora Nanus) to compare measured values of N and S throughfall to TDep model outputs from corresponding years. The initial phase of the study compared deposition measurements from IER columns to modeled data in the western US. Researchers looked for consistencies in differences between measurements and modeled outputs, but did not find any correlations that could inform model uncertainty. The timing of exposures, different ecosystems, lack of data on tree type all played into the lack of informative results. An organized project focused on a few forest types and known deposition gradients would be more effective at tackling this question.

This research project will address research gaps presented in the TDep Reactive Nitrogen deposition White paper (see sections 3.1.1.3 and 3.2.4).

- **Using epiphytic lichen tissue nitrogen content to understand TDep uncertainty in the Pacific Northwest (Measurement Model Fusion Workgroup)**

This is an on-going project with the NPS (Mike Bell), US Forest Service (Linda Geiser), and Washington State University (Dave Evans/Meaghan Petix) using tissue nitrogen concentrations from epiphytic lichen species as bioindicators of deposition. Correlation of tissue N, tissue isotopic concentration, and deposition values will be evaluated to assess consistency of tissue to model values and better understand deposition patterns on a fine scale. An early analysis has been completed and should be wrapped up by Summer 2024.

This research project will address research gaps presented in the TDep Reactive Nitrogen deposition White paper (see sections 3.2.4).

- **Using disaggregated N deposition model estimates to evaluate critical loads (Measurement Model Fusion workgroup)**

A continuing project with the NPS (Mike Bell) and the EPA/ORD (Jesse Bash/John Walker) assesses differences in critical load exceedances based on the scale at which deposition is modeled. Phase I

of this project will use land-use specific dry deposition estimates at a 500m scale developed for the Chesapeake Bay to assess changes to critical loads exceedances at Shenandoah National Park and the Otter Creek Wilderness. Exceedances will be compared to CMAQ and TDep total N estimates.

This research project will address research gaps presented in the TDep Reactive Nitrogen deposition White paper (see sections 3.2.4).

- **Analysis of metals on nanoparticles from Urban deposition sites (NUANC) (Measurements Workgroup)**

James Ranville (Colorado School of Mines) and his students, Aaron Goodman and Carmen Villarruel, are analyzing the metals on nanoparticles obtained from NUANC site samples, especially from CO86. They conducted research on the Marshall Fire that destroyed 1,000 homes in a suburban community only a few kilometers from CO86 in 2021 and published the work in 2022.

This research project will address research gaps presented in the TDep Reactive Nitrogen deposition White paper (see section 3.1.1.4) in understanding deposition to urban areas and developing source apportionment methods (see section 3.3.1).

- **Investigation of phosphorus contributions from urban sources (Pamela Templer; Measurements Workgroup)**

Pamela Templer's group at Boston University published an article that investigated the effects of urbanization and climate change on phosphorus deposition.

- **Dry Deposition of P at NADP sites using samples collected with Aerochem Metrics Dry Side Inserts (DSIs) (Janice Brahney; Measurements Workgroup)**

A project led by Janice Brahney (Utah State University) is investigating dry deposition of P at NADP sites using samples collected with Aerochem Metrics Dry Side Inserts (DSIs) invented by the group.

The group has collected deposition samples from 30 sites, for a total of >1000 samples from NADP locations. Data on mass deposition, pH, metal chemistry (via XRF), charcoal, organic C and N, microbial composition on select samples, plastic and tire wear content, reachable nitrate and ammonium, as well as extractable phosphorus fractions (exchangeable, labile organic, Al/Fe associated, Ca associated, and recalcitrant) have been collected. Bioassays have also been conducted with the material collected.

Recent TDep Publications (submitted or published since 2023)

Published:

- Blake, K., and P.H. Templer, 2023. Interacting effects of urbanization and climate on atmospheric deposition of phosphorus around the globe: a meta-analysis. *Atmospheric Environment*, 309, 119940. 10.1016/j.atmosenv.2023.119940.

- Felix, J.D., A. Berner, G.A. Wetherbee, S.F. Murphy, R.C. Heindel, 2023. Nitrogen isotopes indicate vehicle emissions and biomass burning dominate ambient ammonia across Colorado's Front Range urban corridor. *Environmental Pollution*, 316, 120537. 10.1016/j.envpol.2022.120537.

- Feng, J., A. Cole, G. A. Wetherbee, and K. Banwait, 2023. Inter-comparison of measurements of inorganic chemical components in precipitation from NADP and CAPMoN at collocated sites in the USA and Canada during 1986–2019. *Environmental Monitoring and Assessment*, 195, 1333. 10.1007/s10661-023-11771-z.

- Goodman, A.J., A. Gundlach-Graham, S.G. Bevers, J.F. Ranville, 2022. Characterization of nano-scale mineral dust aerosols in snow by single particle inductively coupled plasma mass spectrometry. *Environmental Science: Nano*, 9, 2638-2652. 10.1039/D2EN00277A.

- Leytem, A.B., J.T. Walker, Z. Wu, K. Nouwakpo, C. Baublitz, J. Bash, G. Beachley, 2024. Spatial Distribution of Ammonia Concentrations and Modeled Dry Deposition in an Intensive Dairy Production Region. *Atmosphere*, 15, 15. 10.3390/atmos15010015.

- Walker, J.T., X. Chen, Z. Wu, D. Schwede, R. Daly, A. Djurkovic, A.C. Oishi, E. Edgerton, J. Bash, J. Knoepp, M. Puchalski, J. Iiames, C.F. Miniate, 2023. Atmospheric deposition of reactive nitrogen to a deciduous forest in the southern Appalachian Mountains, *Biogeosciences*, 20, 971-995. 10.5194/bg-20-971-2023.

- Wetherbee, G.A., 2023. Atmospheric Deposition of Inorganic Nitrogen at the Rocky Flats National Wildlife Refuge, 2017 – 2019, *U.S. Geological Survey Open-File Report*, 1027. 10.3133/ofr20231027.

In review:

- You, Y., J. O'Brien, A.S. Cole, L. Zhang, Z. He, Z., J. Feng, S. Pearson, 2024. Contribution of emissions from the oil sands activities in Alberta, Canada to atmospheric concentration and deposition of nitrogen and sulfur species at a downwind site. *Environmental Pollution*, under review.