Cross Border Environmental Issues
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Transboundary Environmental Problems and U.S.–Canada Cooperation
by Terry J. Keating
Canada and the United States share the longest international border in the world, across which flows people, goods, materials, wastes, and air and water pollution. Canada and the United States also share a long history of working together to address transboundary environmental challenges, dating back to the Boundary Waters Treaty of 1907. To coincide with A&WMA’s 112th Annual Conference & Exhibition in Québec City later this month, this issue of EM includes a series of five articles that highlight some of the successes, challenges, and future directions of this Canada–United States cooperation.

25 Years of Tackling Transboundary Air and Hazardous Waste Issues in North America
by Orlando Cabrera, César Rafael Chávez, Nathalie Daoust, and Robert Maye

Mercury in the Great Lakes: New Insights into Deposition, Regulation, and Prognosis
by J.A. Perlinger, N.R. Urban, and H. Zhang

Wildfires Are Causing Extreme PM Concentrations in the Western United States
by James R. Laing and Daniel A. Jaffe

Ongoing U.S.–Canada Collaboration on Nitrogen and Sulfur Deposition
by Donna Schwede, Amanda Cole, Robert Vet, and Gary Lear

Pandora: Connecting in-situ and Satellite Monitoring in Support of the Canada–U.S. Air Quality Agreement

Spotlight on Waste
As a continuation of the March issue focus topic, this month and next, EM will feature a special spotlight on waste management with planned articles that will consider topics as varied as landfill leachate problems, zero waste as an achievable goal, food waste challenges and opportunities, and waste-to-biofuels conversion.

Landfill Leachate—Just ‘Evaporate’ the Problem
by David Greene

Zero Waste: A Fiction or an Achievable Goal?
by Chih C. Chao

Columns
EPA Research Highlights:
EPA Study Shows Combustion Emissions Influence Rate and Amount of PM from Vegetation
by Carrie Holz and Emily Smith

PM File: Revenue Recognition Is Different from Getting Paid
by David Elam

Departments
Message from the President:
Let’s ACE This!
by Michele E. Gehring, P.E.

In Memoriam: Thomas Maynard Merrifield (1950–2019)

Back In Time: June 2009
A look back at this month 10 years ago in EM Magazine.
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It’s time to get our ACE on! There are just three weeks until A&WMA’s Annual Conference & Exhibition (ACE) in Québec City and I couldn’t be more excited. The venue—awesome. The list of speakers—impressive. And the opportunity to see and interact with so many of our members—priceless!

This month’s EM highlights many of the topics we will be talking about in Québec and focuses on specific border issues that affect industries, regulatory programs, and residents on both sides of the line. I remember when we first started discussing the ACE in Québec in 2018. We had multiple conversations about how to drive cross-border participation and interest. And, as I look at the list of registrants right now, there is no doubt that our local host committee, board, councils, and volunteer force have succeeded in that effort.

As you’ll see when you step inside the door at the Centre des Congrès de Québec, we have strong participation not only from both sides of the border, but also from around the world. Approximately 50 percent of our abstract submissions come from U.S.-based authors, and another 30 percent from Canadian authors. The other 20 percent includes strong participation from Chile—home of the next UNFCC Conference of the Parties—France, Taiwan, China, Egypt, and 13 other countries from throughout the World. It is so exciting to see ACE embrace the international heart of our Association and still provide a concentrated focus on topics that are relevant to our core member base.

This year’s list of keynote speakers also reflects that cross-border feel. We’re honored to once again be joined by William Wehrum, Assistant Administrator for the U.S. Environmental Protection Agency’s Office of Air and Radiation. His take on U.S. air policy will be accompanied by a discussion on Canadian air initiatives from Benoit Charette, Minister of the Environment from Deux-Montagnes and Jean-Yves Benoit, Director of the Carbon Market for the Québec Ministry of Sustainable Development. The industrial side of the conversation, and another U.S. perspective, will be provided by George Minter, Regional Vice President for Southern California Gas Company. Last but not least, we will also get a different take on environmental issues from Dr. Francois Reeves, Cardiologist and Association Professor of Medicine from the University of Montréal, who will discuss the impact that environmental drivers have on cardiac health. It should be a spectacular keynote panel that provides many different perspectives on the environmental challenges that our members face.

Outside of the keynote and technical sessions, ACE is set to provide a host of networking and professional development opportunities. Our student and young professional (YP) program is loaded with opportunities to connect with colleagues and mentors, from the student welcome reception, to the YP mentor breakfast, and speed networking events. Also, attendees will have the opportunity to network and talk cross-border issues at the Opening Reception, where we get the chance to welcome you to Québec City in a grand fashion; the Honors and Awards Ceremony, where we recognize those that have excelled in their professional career and service to the Association; the Women’s Professional Development Luncheon; and the networking breaks and closing reception in the Exhibit Hall. And whether you’re a student, YP, or seasoned professional, make sure you set aside time to swing by the YP Hub, meet some of your Association leadership, take in some of our exhibitor product demonstrations, or just take a load off your feet.

And if you still have energy left at the end of our week, we are running a series of professional development courses on a variety of topics all day Friday.

As you page through this month’s EM, I hope your excitement for ACE grows and the little teaser that the articles in this issue provide leave you looking forward to a more extensive conversation in Québec. Last but not least, don’t forget the Annual Association Business meeting will be held at 5:45 p.m. on Tuesday, June 25th. Please join us then to hear the details on the Association’s business operations, and please take time throughout the week to pull me and the other A&WMA Board members aside to introduce yourself and share your thoughts on the Association. À Bientôt! em
Be a sponsor or exhibitor at ACE 2019 and showcase your products and services, build new relationships, and support the environmental industry. Discover your opportunities at www.awma.org/ACE2019.
Transboundary Environmental Problems and U.S.–Canada Cooperation

Canada and the United States share the longest international border in the world, across which flows people, goods, materials, wastes, and air and water pollution. Canada and the United States also share a long history of working together to address transboundary environmental challenges, dating back to the Boundary Waters Treaty of 1907. To coincide with A&WMA’s 112th Annual Conference & Exhibition in Québec City later this month, this issue of *EM* includes a series of five articles that highlight some of the successes, challenges, and future directions of this Canada–United States cooperation.
In the first article, “25 Years of Tackling Transboundary Air and Hazardous Waste Issues in North America,” Cabrera et al. describe some of the successes achieved under the North American Council on Environmental Cooperation, a unique international institution created in 1994 by a side-agreement to the North American Free Trade Agreement. The authors focus on the Commission for Environmental Cooperation’s (CEC) work on hazardous waste management and air pollution. As the three North American governments—United States, Canada, and Mexico—work to implement a new free-trade agreement, it is useful to take stock of the success achieved and lessons learned by the CEC over the past 25 years.

The second and third articles focus on two current pollution challenges facing Canada and the United States: mercury contamination in the Great Lakes and wildfire smoke in western North America, respectively. In “Mercury in the Great Lakes: New Insights into Deposition, Regulation, and Prognosis,” Perlinger et al. discuss the regional and global sources of mercury deposition in the Great Lakes and the impact of controls implemented due to Canadian and U.S. regulations and the global Minamata Convention. They explain the drivers of the persistently high mercury levels in Lake Superior and why fish consumption advisories in the Upper Great Lakes are not expected to go away any time soon.

Next, Laing and Jaffe discuss the growing impact of wildfires on particulate matter concentrations in western North America in “Wildfires Are Causing Extreme PM Concentrations in the Western United States.” They extend previous analyses looking at the influence of wildfires on air quality trends over the last several decades to explore the impacts of the devastating fire seasons in 2017 and 2018 and their implications for air quality management.

The final two articles describe two areas where Canadian and U.S. experts are working together to improve our understanding and tools for more effective management of transboundary air pollution. Building on a history of cooperation that began in the late 1970s, Schwede et al. discuss recent efforts to use measurement-model data fusion techniques to improve the characterization of atmospheric deposition of nitrogen and sulfur across Canada and the United States in “Ongoing U.S.–Canada Collaborations on Nitrogen and Sulfur Deposition.” The U.S. and Canadian efforts in this area are now being replicated in other regions of the world through cooperation under the World Meteorological Organization’s Global Atmospheric Watch Programme.

Last but not least, in “Pandora: Connecting in-situ and Satellite Monitoring in Support of the Canada–U.S. Air Quality Agreement,” Szykman et al. describe U.S. and Canadian cooperation to deploy a network of moderately-priced, ground-based spectrometers, known as Pandoras, to provide total column observations of atmospheric composition. The North American network is contributing to an emerging Pandonia Global Network that will provide ground-based information to complement a new constellation of geostationary satellites designed to observe air quality and atmospheric composition.

Building on a long history of cooperation, Canada and the United States continue to work together bilaterally and in multilateral forums to address evolving transboundary environmental problems along their shared border and around the world.

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Cover Story by Terry J. Keating

In Next Month’s Issue…

Reactive Nitrogen Deposition
The July issue will focus on the state of the science with respect to total nitrogen (N) deposition budgets in the United States and the research needed to improve these estimates.
A look at how two-plus decades of cooperation among the United States, Mexico, and Canada has been instrumental in tackling important transboundary air and waste management issues.
Since 1994, the North American Agreement for Environmental Cooperation (NAAEC; http://www.cec.org/sites/default/files/naaec.pdf) has been the environmental arm of the North American Free Trade Agreement (NAFTA). Through the NAAEC, Mexico, the United States, and Canada committed to accompany trade liberalization and economic growth with increasing cooperation to better conserve, protect, and enhance the environment. They recognized the interrelationship of the environment and understood the need to work together to ensure the quality and sustainable management of natural resources such as air and water. It was the first time an environmental agreement was signed in parallel with a trade agreement.

The Commission for Environmental Cooperation (CEC), an institution created by the NAAEC, still represents the only trilateral environmental organization that facilitates the protection of our shared North American environment. This article offers concrete examples of how cooperation has been instrumental in tackling important transboundary air and waste management issues.

The North American PRTR Initiative
Starting in the mid-1990s, the CEC led the way in addressing cross-border environmental issues through the North American Pollutant Release and Transfer Registers (PRTR) Initiative, supporting continued development and improvement of PRTR systems, mandatory and comparable pollutants reporting for all nations, and increased access to information about the sources and nature of industrial releases to support decision making relative to pollution prevention and reductions. This ongoing trinational effort set in motion the creation of a mandatory PRTR in Mexico.

Today, this CEC initiative integrates the data reported to Canada’s National Pollutant Release Inventory (NPRI), the U.S. Toxic Release Inventory (TRI), and Mexico’s Registro de Emisiones y Transferencia de Contaminantes (RETC), and provides value-added information on industrial pollution through the Taking Stock Report, and the Taking Stock Online website (http://www.cec.org/tools-and-resources/taking-stock/taking-stock-online-north-american-industrial-pollution), and facilitates cooperation amongst national PRTR programs in implementing the Action Plan to Enhance the Comparability of PRTRs in North America to address issues of data comparability, quality, and completeness. The Taking Stock Online database gives access to comparable data and information on more than 500 pollutants reported by nearly 30,000 North American facilities. This initiative has promoted trilateral information availability and usability, as well as transparency, accountability, and public/private sector participation. The success of the CEC’s PRTR has served as a model for countries worldwide.

CEC-Directed Studies
Other CEC studies were developed to examine air pollution issues and provide data and information to support government decision-making. Continental Pollutant Pathways (1997)\(^1\) was the first CEC report to highlight critical issues concerning the long-range transport of air pollutants in North America. It addressed public concerns over worsening air quality and transboundary pollution, and suggested opportunities for cooperation between the three countries relative to pollutant emissions reductions and monitoring.

Another CEC study, Destination Sustainability (2011)\(^2\) examined freight transportation activities linking Canada, Mexico, and the United States. It stressed the important connection between environmental sustainability and an efficient, competitive and secure North American freight transportation system. The report made recommendations to decision-makers about policies and actions to reduce carbon dioxide emissions and improving energy efficiency of the transportation sector (see Figure 1).

The CEC also worked on the North America expansion of the AirNow—International system. This system provides a consistent set of tools to manage, share, and publicly disseminate information on air quality conditions. This
effort has allowed Canada, Mexico, and the United States to share air quality monitoring data in real-time, leading to greater efficiency and effectiveness in air quality management decisions at the domestic level. For example, the implementation of AirNow—International in Monterrey, Nuevo Leon, Mexico, resulted in improved data quality as well as an 80-percent reduction in the time spent data processing.

Improving emissions accounting is another issue that benefited from trilateral cooperation, to support air quality management and climate change mitigation efforts. Two reports, the Assessment of the Comparability of Greenhouse Gas and Black Carbon Emissions Inventories in North America (2012), and the North American Black Carbon Emissions: Recommended Methods for Estimating Black Carbon Emissions (2015), represent trilaterally-coordinated actions to improve estimates of black carbon and co-pollutants emissions. Based on recommendations from these reports, in 2018, the CEC carried out a data collection campaign on small-scale biomass combustion to address gaps in black carbon inventories in the three countries.

Air emissions from the maritime transportation sector are also a major source of pollution, impacting coastal and inland air quality, public health, and the environment. Since 2015, the three North American countries have collaborated to apply consistent environmental requirements and share best practices for ships and ports operations across the region. Part of this collaboration includes supporting Mexico’s efforts to establish an Emission Control Area (ECA) for ships under the International Maritime Organization akin to those in Canada and the United States. The creation of a Mexican ECA will result in substantial human health and environmental benefits, consistent and harmonized fuel and emissions requirements for marine transport in Canada, Mexico, and the United States, and a level playing field for the shipping industry.

Regarding transboundary hazardous waste concerns, in 2013 the CEC conducted a study on transboundary spent lead-acid battery (SLABs) recycling, which examined the SLABs trade (as represented in Figure 2) and its legal framework in North America. The study addressed reported changes in trade between countries and noted discrepancies in the environmental and public health protection levels for lead.

Building on the 2013 SLABs report, the CEC developed technical guidelines on environmentally sound management practices for secondary lead smelters and other facilities that process these batteries. This included best practices and technologies for collecting and recycling in a manner that protects the environment, as well as, the health and safety of workers and the public. The report led to the development of a Mexican regulation establishing emission limits in the secondary lead smelting process.

To crack down on illegal shipments of hazardous waste, the CEC trained more than 600 environmental and customs officials to identify and interdict at the border illegal shipments of environmentally regulated materials, such as ozone-depleting substances and hazardous waste materials. CEC’s efforts led agencies to connect electronically and authorize legal shipments of hazardous waste and recyclable materials based on electronic records. This project also resulted in the modification of Annex III of the La Paz Agreement between the United States and Mexico.

The residents of North America have also played an active role in bringing to light the ineffective enforcement of environmental laws as it relates to air and hazardous waste. Through its submissions process, the CEC receives complaints from the public regarding a country’s alleged failure to effectively enforce its environmental laws. This process can lead to the development of a factual record by the Secretariat.

For example, in a submission filed by both U.S. and Canadian NGOs, the submitters asserted that Devils Lake, North Dakota, is polluted with biological pollutants (e.g., algae species and fish parasites) that unlawfully cross the
U.S.–Canada border and flow into Lake Winnipeg and other Canadian waters. The submitters contended that both Canada and the United States failed to divert and prevent cross-border pollution, contrary to 1909 International Boundary Waters Treaty. Although the Secretariat dismissed the submission and no factual record was prepared, the submission raised awareness about cross-border water pollution within the context of the environmental side agreement of NAFTA.

In another submission *Metales y Derivados*, filed by both Mexican and U.S. NGOs, the Secretariat did publish a factual record on the assertion that Mexico was not effectively enforcing its hazardous waste laws with respect to an abandoned lead smelter, previously operated by a Mexican subsidiary of a U.S. company, in Tijuana, Baja, Mexico. Subsequently, the abandoned smelter was cleaned-up under a landmark cleanup agreement with the Mexican government and the formation of a bi-national, community/government working group, resulting in a victory for cross-border environmental justice and public health.

The CEC projects discussed here are but a few examples of how the Commission is achieving long-term results through coordinated efforts. The CEC has been instrumental in building substantial environmental capacity, largely in Mexico but also in the United States and Canada. In doing so, it has helped to ensure a level-playing field in the enforcement of environmental law across all three countries.

**New Agreement on Environmental Cooperation**

Over the past 25 years, the CEC has proven to be a unique, innovative, and crucial institution. It has been able to create official linkages between countries that were at different stages of environmental development. With its commitment to meaningfully involving all sectors of society and with its development of innovative and creative tools and techniques, the CEC has been able to address many important transnational environmental issues and concerns. Moreover, it has demonstrated a proven ability to adapt to changing governments and shifting national priorities.

With the increasing number of commitments made by the three countries at the international level, Canada, Mexico, and the United States have come to view the CEC not only as a tool to address shared environmental issues, but also as a way of meeting their international commitments.

On November 30, 2018, Canada, Mexico, and the United States signed a new trade agreement updating and modernizing NAFTA. The new trade agreement includes an environment chapter that recognizes the CEC and its important work. At the same time, the countries announced the completion of negotiations of a new Agreement on Environmental Cooperation (https://www.epa.gov/international-cooperation/2018-agreement-environmental-cooperation-among-governments-united-states) that is expected to replace the NAAEC and provide a framework to modernize and enhance the effectiveness of environmental cooperation among the three countries.

The CEC understands that the environment knows no borders. By addressing pressing environmental issues as a whole, the three countries are better able to address the environment's evolving needs. em

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**References**

Mercury (Hg) pollution of the Laurentian Great Lakes region of the United States has led to fish consumption advisories not only for the Great Lakes themselves, but also for inland lakes in the Great Lakes region. These policies are of considerable concern to First Nation and American Indian communities and others who remain heavily reliant on fish consumption. Advice to restrict fish consumption results from human emissions of Hg into the atmosphere, Hg transport through the atmosphere, and eventual deposition some distance downwind. In this article, we first relate how atmospheric Hg, or rather its toxic form methylmercury (MeHg), ends up in fish we consume, then discuss how Hg environmental cycling is influenced by differing landscapes and examine how Hg regulations affect Hg deposition differently within the upper and lower Great Lakes and their inland water bodies.
Mercury enters the environment through natural sources, such as volcanoes and volatilization from rocks and soils with elevated Hg content (see Figure 1). An increasing amount of Hg also enters the environment through human activities, including fossil fuel combustion, metal refining, and artisanal small-scale gold mining. Once in the environment, the volatile form of mercury, Hg(0), can be transported through the atmosphere to far distant locales, because of the long atmospheric residence time (3–12 months) due to the combination of its moderately high air–water exchange coefficient and its relatively low octanol-water partition coefficient.\(^1,2\) Some oxidized Hg, Hg(2), also is emitted, but this form is rapidly scavenged from the air and deposited relatively close to its source in dry and wet deposition. Hg(0) can also be re-emitted from land and water, forming so-called “secondary emissions”. The form of Hg of most concern is methyl mercury (MeHg), which is formed in low-oxygen environments. Although it may be present at low concentrations in surface waters, MeHg bioaccumulates millions of times in aquatic food webs such that it reaches toxic concentrations in top predator fish in lakes.

**The Role of the Landscape in Hg Cycling**

The landscape itself influences Hg deposition from the atmosphere. Both particulate and gaseous Hg(2) are scavenged more effectively by vegetation than by water surfaces; in models, this phenomenon is expressed as higher deposition velocities to vegetation than to lakes or oceans. Additionally, Hg(0) passively enters the stomata of plants, becomes fixed within the leaves and contributes Hg to the watershed when the leaves fall and decompose.\(^3\) Consequently, Hg dry deposition is greater (~10-fold) to watersheds than to lakes, especially to large lakes (see Figure 2). Dry deposition is notoriously difficult to measure; careful examination of field measurements is required to determine appropriate mathematical parameterizations\(^4\) that may subsequently be incorporated into models to improve model accuracy in predicting deposition.

It has long been known that some fraction of atmospherically deposited Hg is revolatilized to the atmosphere, but the magnitude of these secondary emissions has been poorly quantified. A recent compilation of measurements of Hg emission fluxes\(^5\) yielded a rate of 5 µg m\(^{-2}\) yr\(^{-1}\) or 28% of deposition for the Great Lakes region. However, this value underestimates the total secondary emissions from the Great Lakes area because of the functioning of lakes within the landscape. Some fraction (1–30%) of atmospherically deposited Hg runs off of catchments into lakes. Some of this Hg runoff is buried in lake sediments, but a significant fraction is reduced and revolatilized back to the atmosphere as Hg(0). Estimates for watersheds ranging in size from those of small lakes (a few km\(^2\)) to that of Lake Superior (128,000 km\(^2\)) suggest that lakes increase secondary emissions of Hg(0) by 5–30% over that from the terrestrial landscape.

Another important influence of the landscape on Hg cycling is regulation of the efficiency with which atmospherically deposited Hg is methylated. Methylation, conducted by a variety of microbial types, occurs in low oxygen environments such as in the deep waters of productive lakes, as well as in waterlogged soils such as in wetlands and lake sediments. The more abundant are wetlands and low oxygen lakes in the landscape, the more efficiently is Hg deposition converted to the toxic and bioaccumulative MeHg. The distribution of these sensitive...
landscapes is reflected in the distribution of statewide fish consumption advisories due to Hg. States bordering Canada from Washington to Maine (including all Great Lakes states), have statewide fish consumption advisories. In Michigan’s Upper Peninsula, nearly 80% of lakes have fish Hg above the U.S. Environmental Protection Agency’s (EPA) water quality limit of 0.3 µg g⁻¹ because of the particularly high capability of this landscape to methylate Hg.

Greater Upwind U.S. Emissions in Lower Great Lakes Region, Greater Impact of Regulation on Deposition

The propensity of landscapes for runoff and MeHg formation, and their proximity to upwind primary emitters, as well as policies regulating those emissions determine the spatial distribution of Hg contamination in lakes. Mercury emissions in the United States and Canada were estimated to contribute ~22% and ~12%, respectively, to the total deposition to the Great Lakes. The emissions sources leading to Hg deposition in the entire Great Lakes region are estimated through modeling simulations to be dominated by oceanic secondary emissions (a component of global emissions) and emissions within the Great Lakes region (see Figure 3; in References 6 and 8, the Great Lakes region was defined as bounded by 40° and 50° N latitude and by 73° to 95° W longitude, which includes a part of Canada). Local and regional Hg emissions, primarily U.S. coal-fired power plants in the Great Lakes area, are greater in the vicinity of the lower Great Lakes (Lakes Erie and Ontario), but are smaller in the airsheds of the upper Great Lakes (Lakes Superior, Michigan, and Huron). Therefore, it is mainly global emissions through long-range atmospheric transport and deposition that impact the upper Great Lakes region, and the amount of Hg deposition is predicted and observed to be less to the upper Great Lakes as compared to the lower Great Lakes. For example, the present-day deposition to Michigan’s Upper Peninsula (located on the southern shore of Lake Superior) is estimated to be 24%
less than the deposition to the Adirondack region in upper New York (located to the east of Lake Ontario).

Existing policies affecting Hg deposition to the Great Lakes include Canada-wide standards (CWS) on emissions from coal-fired power plants, Ontario regulations on emissions from coal-fired power plants, the Binational Program’s Zero Discharge Demonstration Program (ZDDP; Lake Superior only), the U.S. Mercury and Air Toxics Standards (MATS), and the Minamata Convention (MC). When only the last three of these policies were considered, deposition was predicted to decrease by 20% from the present to 2050, and of that 20%, the contribution of the MATS was 85% whereas the MC and ZDDP accounted for 14% and 1%, respectively. Also, the U.S. MATS were predicted to cause the Adirondacks to receive 21% less deposition than Michigan’s Upper Peninsula in 2050 (see Figure 4). Therefore, although the entire Great Lakes region was predicted to be most affected by MATS (relative to the MC and ZDDP policies) in 2050, local landscape sensitivity and lesser impact of the MATS in Michigan’s Upper Peninsula suggest that Hg deposition will be both greater and have a greater impact in Michigan’s Upper Peninsula than in the Adirondacks.

**No Short-Term Fixes in Remote Areas of Great Lakes**

The wheels of policy creation and implementation turn slowly. Fully 22 years elapsed between authorization by U.S. Congressional amendments to the U.S. Clean Air Act (1990) and EPA’s release of the MATS (2012); this timeline will be extended further if the current U.S. administration revokes the MATS. In contrast, Ontario banned power generation from coal and its associated Hg emissions in 2015. Awareness of Hg as an international problem led to the first International Conference on Mercury as a Global Pollutant in 1990. Efforts within the UN Environment Program date back to at least 2001 when a global assessment of Hg was initiated. These efforts culminated in 2013 with the signing of the Minamata Convention that entered into force in 2017 after being ratified by 50 countries. Because of the voluntary nature of the Convention, implementation of all articles will require additional decades.

The timescale for recovery of ecosystems following reduction of inputs is highly variable. Because of the lag between regulation and impacts, it is important to implement regulations quickly. One of the biggest unknowns regarding recovery times is how long the inventories in soils and wetlands of historically deposited Hg will continue to bleed into streams and lakes. Among the Great Lakes, Lake Superior has the highest concentrations of Hg in lake trout although it receives the lowest input from atmospheric deposition; this “anomaly” may reflect the high potential for MeHg formation in the catchment. Model simulations suggest that because Lake Superior receives a greater proportion of Hg inputs from global rather than regional sources, it will respond most slowly to current regulations.
The combination of high geologic potential for MeHg formation combined with low inputs from local sources suggest that Lake Superior will not experience a rapid decline in fish Hg in the coming decades. For fish-reliant communities, the heavy burden of health risk is likely to persist for at least another generation.

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References
Wildfires and PM Concentrations in the Western United States by James R. Laing and Daniel A. Jaffe

How increases in wildfire smoke have impacted air quality in the western United States.
Fires are a natural occurrence, but the past decade has seen a dramatic increase in the number and extent of wildfires in the western United States. This increase is due to a combination of factors including past forest management, an increase in human-caused ignitions (e.g., campfires, power lines, and vehicles), and climate change. Fires emit large amounts of primary fine particulate matter (PM$_{2.5}$; particles with diameter < 2.5 µm) and volatile organic compounds (VOCs) that are precursors for additional PM$_{2.5}$ formation. Due to its small size, PM$_{2.5}$ can travel deep into the respiratory system and is a well-documented health hazard that is regulated by the U.S. Clean Air Act (CAA).

In large part because of the CAA, anthropogenic emissions of primary PM$_{2.5}$ and its precursors (e.g., emissions from power plants, industrial sources, and cars and trucks) have declined substantially over the past four decades and air quality in most parts of the United States has improved dramatically. But the recent increase in wildfires is changing this picture for the western states. Wildfires in 2017 and 2018 resulted in the largest daily mean PM$_{2.5}$ concentrations ever measured at regulatory monitoring sites in the United States and exposed millions of people to unhealthy air.

In the United States, widespread observations of PM$_{2.5}$ began in the late 1990s. Because of the emission reductions, concentrations have steadily declined, but at the same time, the air quality standard has become increasingly tighter due to better information on the health impacts. The current standard for PM$_{2.5}$ includes both a daily standard (98th percentile < 35 µg/m$^3$, averaged over 3 years) and an annual standard (12 µg/m$^3$, averaged over 3 years). But despite the progress in improving air quality, approximately 30 million people in the United States live where the PM$_{2.5}$ standard is not met.

While prescribed burns and wildfires have always been around, their influence on air quality is increasing. Since the 1980s, the frequency and duration of large wildfires and the total area burned have increased in the Northwest United States. This increase in wildfires has been strongly linked with increased temperatures, enhanced fuel aridity, the earlier arrival of spring, and longer fire seasons. Past forest management practices also play an important role in explaining the current fire regime.

Projections into the future predict that the area burned in the western United States will continue to increase. A confluence...
Wildfires and PM Concentrations in the Western United States by James R. Laing and Daniel A. Jaffe

The increase in the western United States was shown to be due to PM$_{2.5}$ from wildfires.

**Wildfires in 2017 and 2018 and Extreme PM**

According to the National Interagency Fire Center, wildfires in 2017 and 2018 burned 10 and 8.8 million acres in the United States, respectively, mostly in western states. Both years are higher than the 10-year average of 7.0 million acres burned. In British Columbia, Canada, 2017 and 2018 were the largest fire seasons on record. In both years, wildfires burned over 3 million acres. For comparison, the third largest year was 1958 with 2.1 million acres burned, and from 1970–2015 there was no year with more than 1 million acres burned. The amount of smoke produced by these large fires was extensive. As an example, Figure 1 shows a large number of wildfires and extensive smoke in the Pacific Northwest United States and British Columbia on September 6, 2017.

We typically associate high pollution with industrial sources. Looking at air pollution data from the U.S. Environmental Protection Agency’s (EPA) Air Quality System (AQS) monitoring network going back 20 years, we find that PM$_{2.5}$ concentrations in a few polluted urban areas could reach up to ~100 µg/m$^3$, typically in winter, when strong inversions trap urban and industrial emissions. The fires in 2017 and 2018 led to unprecedented levels of PM$_{2.5}$ at sites throughout the western United States, exceeding all previous observations. From 1999 to 2016, there were 23 sites that had at least one day where PM$_{2.5}$ exceeded 200 µg/m$^3$. In 2017 alone, there were 26 sites with days that exceeded 200 µg/m$^3$ and many more in 2018 (AQS data for 2018 were not complete at the time this article was written).

For context, EPA defines PM$_{2.5} > 150$ µg/m$^3$ as very unhealthy and PM$_{2.5} > 250$ µg/m$^3$ as hazardous. In Table 1, we document some of the most extreme cases in 2017 and 2018, including the highest PM$_{2.5}$ concentrations ever recorded by a regulatory monitor in the United States (642 µg/m$^3$). The list of extreme cases in Table 1 is by no means exhaustive, as many other sites in the western states experienced PM$_{2.5}$ concentrations over 100 µg/m$^3$.

**PM Trends across the United States**

EPA’s AQS monitoring network compiles ambient air pollution data collected by EPA and state, local, and tribal air pollution control agencies from thousands of monitors across the United States. A trend analysis of the PM$_{2.5}$ measurements from AQS for 2006–2017 shows a decrease in the annual 98th percentile PM$_{2.5}$ for much of the country, but an increase at many sites in the western United States (see Figure 2). The 98th percentile represents the top 2% of days corresponding to high pollution events.

Figure 2. Ten-year trends (2006–2017) of yearly 98th percentile PM$_{2.5}$. Of the 699 sites shown, 458 had statistically significant trends (13 positive, 445 negative). Source: EPA’s Air Quality System (AQS) monitoring network data.
Wildfires and PM Concentrations in the Western United States by James R. Laing and Daniel A. Jaffe

Seattle the top 10 most polluted days ever recorded were from wildfire smoke in 2017 or 2018 (measurements going back to 1999).

Implications
The recent occurrence of extreme PM$_{2.5}$ in the United States due to wildfires has many implications and leads to several questions, including:

1. If a natural event causes a region to go out of compliance with the air quality standard, a state can petition EPA to exclude these data from regulatory use under the “exceptional events” policy. However, the process is cumbersome and can consume significant resources for the state agency. As the air quality standards have become tighter and large wildfires have become more common, states have requested that EPA streamline this process, especially when the source of elevated PM$_{2.5}$ is obvious. How could this process be improved?

2. Many studies have estimated an increase in the number and size of wildfires in future decades associated with climate change. But these predictions are complicated by the role that human ignition and past forest management has played on the recent increase in area burned. How can we identify the role of each factor (human ignition, forest management, and climate change) on data from the past decades, so that we can improve our forecast for future smoke conditions?

### Table 1. Extreme U.S. PM$_{2.5}$ events in 2017 and 2018.

<table>
<thead>
<tr>
<th>Location</th>
<th>Extreme PM$_{2.5}$ Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seeley Lake, Montana</td>
<td>Highest daily PM$<em>{2.5}$ on record (642 µg/m$^3$ on 9/6/2017). In August and September 2017, there were 35 days with PM$</em>{2.5}$ &gt; 150 µg/m$^3$ and 18 days with PM$_{2.5}$ &gt; 250 µg/m$^3$.</td>
</tr>
<tr>
<td>Ventura, California</td>
<td>Extremely high PM$_{2.5}$ (557 µg/m$^3$) measured on 12/6/2017, with a two-week average concentration of 165 µg/m$^3$.</td>
</tr>
<tr>
<td>Trinity County, California</td>
<td>Five consecutive days of PM$_{2.5}$ &gt; 200 µg/m$^3$, with a maximum daily value of 498 µg/m$^3$ (9/1/2017 to 9/5/2017).</td>
</tr>
<tr>
<td>San Francisco, California</td>
<td>Highest daily PM$<em>{2.5}$ ever recorded in San Francisco (177 µg/m$^3$ on 11/16/2018). Twelve consecutive days in November 2018 with PM$</em>{2.5}$ &gt; 50 µg/m$^3$.</td>
</tr>
<tr>
<td>Sacramento, California</td>
<td>Ten days with PM$<em>{2.5}$ &gt; 100 µg/m$^3$ (11/10/2018 to 11/20/2018), with highest daily PM$</em>{2.5}$ of 263 µg/m$^3$ on 11/15/2018.</td>
</tr>
<tr>
<td>Seattle, Washington</td>
<td>Highest daily PM$_{2.5}$ ever recorded in Seattle (110 µg/m$^3$ on 8/21/2018).</td>
</tr>
<tr>
<td>Medford, Oregon</td>
<td>Eight days over 100 µg/m$^3$ in 2017, with highest daily PM$_{2.5}$ of 268 µg/m$^3$ on 9/6/2017.</td>
</tr>
</tbody>
</table>

with the highest PM$_{2.5}$ concentrations and is the basis for the daily standard. At many sites, an increase in the number of days that exceed the daily standard (35 µg/m$^3$) is also seen. Regions with significant increasing PM$_{2.5}$ include Montana, Idaho, Oregon, and eastern Washington.

In addition to the poor air quality, there was a tremendous loss of lives and property in 2017 and 2018, especially in California. In the past two years, California witnessed the two largest fires in its history (Thomas Fire, December 2017; Mendocino Complex Fire, August 2018), and its most deadly and destructive fire ever (Camp Fire, November 2018).
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Figure 3. Time series plots of PM$_{2.5}$ in Seattle, WA (AQS site number: 530330080), Portland, OR (AQS site number: 410510080), and San Francisco, CA (AQS site number: 060750005). The blue lines are the daily mean PM$_{2.5}$, and the black lines are the 25th, 50th, 75th, 90th, and 98th yearly percentile regression slopes. Days with smoke overhead are indicated with red dots, and the grey bars are the months August–October. The plot covers the period from January 1, 2010 through December 31, 2018.

3. Controlled burns are one approach to improving forest health and reducing human exposure to PM$_{2.5}$. But what are the emission factors and total emissions from controlled burns and under what conditions do these reduce human exposure to PM$_{2.5}$?

4. At present, most agencies advise people to stay indoors during periods of significant or prolonged smoke. This assumes that indoor concentrations will be lower than outdoor concentrations. However, many studies have found that indoor air concentrations reflect outdoor concentrations, depending on the air infiltration rate, which depends on the nature of the home or office building. While previous studies have examined indoor air for...
certain pollutants, like formaldehyde, little research has been conducted under heavily polluted situations, such as during wildfire smoke. Data from the authors suggests that in in older homes or some offices, indoor concentrations on smoky days can be equal to, or a substantial fraction of, the outdoor concentrations, and well above the health thresholds. What advice should we give in smoke-prone areas and how can individuals work to reduce their exposure to smoke? Further work is critically needed to identify optimal strategies for reducing smoke exposure, especially given that this problem is now exposing millions of people in the United States to unhealthy air.

References
Atmospheric deposition—both wet and dry—can be an important contributor to nitrogen and sulfur loading to ecosystems. Excessive deposition causes acidification and eutrophication, which can lead to harmful effects such as algal blooms, decreases in forest growth, loss of species richness, and shifts in species distribution. In more moderate amounts, atmospheric deposition can be a source of nutrients reducing the need for fertilization of agricultural areas. Quantifying the amount of atmospheric deposition is therefore a critical activity for both the United States and Canada.
The United States and Canada have a long history of collaborating to improve the understanding of the amount of deposition and the effects of deposition in both countries. Early efforts began in the late 1970s with the establishment of networks to monitor wet deposition of acidifying species (sulfate and nitrate) and other relevant components, with the National Atmospheric Deposition Program National Trends Network (NADP/NTN) in the United States in 1978, and the Canadian Network for Sampling Precipitation (CANSAP) in 1976, followed by the Canadian Air and Precipitation Monitoring Network (CAPMoN) in 1983.

Formal collaboration on the issue of acid rain between the two countries began with the 1986 Joint Report of the Special Envoys on Acid Rain and the 1991 U.S.–Canada Air Quality Agreement. Data from both networks have been used to generate interpolated maps of wet deposition across both countries and jointly report on reductions in nitrate and sulfate wet deposition under the 1991 Air Quality Agreement (e.g., progress reports 1996–2014, https://www.epa.gov/air-markets/us-canada-air-quality-agreement-progress-reports; and progress report 2016, https://www.canada.ca/en/environment-climate-change/services/air-pollution/publications/canada-united-states-air-quality-report-2016.html). Figure 1 shows an example of sulfate wet deposition changes similar to those in the joint reports. In addition, co-located NADP/NTN and CAPMoN sites in Pennsylvania, USA, and Québec, Canada, have been maintained since 1986 to quantify the long-term comparability of measurement and modeling approaches across the networks.$^1,2$

In addition to wet deposition monitored by precipitation networks, dry deposition is an important component of total deposition. Long-standing networks, CAPMoN in Canada and the Clean Air Status and Trends Network (CASTNET) in the United States, measure gas and particle species that contribute to nitrogen and sulfur dry deposition. Since neither network measures dry deposition directly, fluxes at the network sites are determined by multiplying the measured concentrations by modeled deposition velocities.

Scientists from the United States and Canada have collaborated on several studies using these data. For example, an extensive comparison of the inferential models used to determine the dry deposition velocities for the networks revealed important differences between the approaches.$^3$ In a follow-on study, concentration and meteorological data from the Borden forest site in

Figure 1. Annual non-sea-salt sulfate wet deposition interpolated using site measurements (dots) from U.S. and Canadian networks.
Canada were used to conduct an evaluation of the inferential models and other deposition approaches used by the U.S. Environmental Protection Agency (EPA) and Environment and Climate Change Canada (ECCC) in their regional air quality models (see Figure 2). These collaborative efforts have served to further model development in both countries as well as provide estimates of dry deposition uncertainty.

**Measurement–Model Fusion (MMF) Approaches**

Scientists from the United States and Canada are active participants in the National Atmospheric Deposition Program Total Deposition Science Committee (TDep; http://nadp.slh.wisc.edu/committees/tdep). The mission of this committee is to improve measurement and model estimates of dry, wet, and total deposition of sulfur and nitrogen. One of the efforts undertaken by this committee was the development of maps of total deposition to support critical loads assessments.

A new methodology was developed to produce the values of total deposition for the contiguous United States (CONUS) that uses both measured and modeled values. Measurement networks have a limited number of sites and dry deposition cannot be easily interpolated between sites due to its dependence on the underlying land use type. Additionally, not all chemical species that comprise important parts of the sulfur and nitrogen budgets are measured. Wet deposition values are typically representative of only inorganic species. At CASTNET sites, species such as NO, NO₂, N₂O₅, and organic N compounds are not measured. Chemical transport models (CTMs) provide complete spatial coverage across the modeling domain and a more robust estimation of the depositing species. However, concentration and deposition values predicted by CTMs are subject to uncertainties in emissions inputs, modeled meteorology, and atmospheric processes.

To adjust for these uncertainties, the measured concentrations of gas and particle species from CASTNET are used to adjust modeled values from EPA’s Community Multiscale Air Quality (CMAQ) modeling system using inverse distance weighting to calculate dry deposition values of measured species while CMAQ values for species not measured at network sites are used directly. Wet deposition values are developed from a fusion of measurements of precipitation and chemistry from NADP/NTN and precipitation from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; http://www.prism.oregonstate.edu/). The dry deposition and wet deposition values are combined to produce grids and maps of total deposition, which are available for download at https://nadp.slh.wisc.edu/committees/tdep/tdepmaps/.

A similar effort was undertaken by ECCC under the project Atmospheric Deposition Analysis Generated from optimal Interpolation from Observations (ADAGIO). Measured concentrations of nitrogen and sulfur species as gases, in particulate matter, and in precipitation from Canadian and U.S. networks are used to adjust predicted concentrations from ECCC’s GEM–MACH (Global Environmental Multiscale–Modelling Air quality and Chemistry) model using optimal interpolation techniques. Optimal interpolation is a statistical method for minimizing the differences between the model and measurements. These techniques have already been developed and used successfully to combine measured and modelled air concentrations of ozone, sulfur dioxide and nitrogen dioxide, and particulate matter in Canada. This process generates maps of nitrogen and sulfur species concentrations in air and precipitation at a 10-km horizontal resolution. A similar method is used to generate precipitation amounts. These are then combined with modelled dry deposition velocities to yield total deposition.
A primary goal under the U.S.–Canada Air Quality Agreement is to combine the results from the two approaches to obtain one set of maps for North America. A detailed comparison of the two methods, species by species, is expected to be completed by 2020 and result in combined maps that are accepted by both countries. The measurement-model fusion approaches used by the United States and Canada are now leading the way for the use of measurement-model fusion on a global scale as part of an effort sponsored by the World Meteorological Organization (WMO; https://library.wmo.int/index.php?lvl=notice_display&id=19885#). Two workshops have been held to work toward developing an implementation plan that would result in measurement-model fusion total deposition values globally.

**Future Plans to Improve Deposition Estimates**

Building on this long history of joint deposition activities, new collaborative projects using satellite data and model intercomparisons are also planned. For example, ECCC provided satellite-derived ammonia (NH₃) estimates for EPA scientists to evaluate bidirectional (emission and deposition) NH₃ exchange in the CMAQ model. In turn, EPA will provide ECCC with dry deposition measurements that can be used to help evaluate satellite-derived dry deposition of NH₃ and NO₂ over North America. Both Canada and the United States are participating in the

**Figure 3.** Total (wet and dry) sulfur deposition for 2010 produced by the ADAGIO (Canada) and TDep (U.S.) methods.
Phase 4 of the Air Quality Modelling Evaluation International Initiative (http://aqmeei.jrc.ec.europa.eu/phase4.html), which is focused on atmospheric deposition. Goals of this study include quantifying the performance and variability of deposition fields predicted by regional air quality models, documenting deposition schemes, and analyzing model outputs to understand differences in model predictions. With continued collaboration between the measurement, modeling, satellite, and measurement-model fusion communities in both countries, our ability to provide nitrogen and sulfur deposition estimates will continue to improve.

References


Figure 4. Total (wet and dry) nitrogen deposition for 2010 produced by the ADAGIO (Canada) and TDep (U.S.) methods.
Pandora
Connecting in-situ and Satellite Monitoring in Support of the Canada–U.S. Air Quality Agreement


A look at how the NASA Pandora Project is being used in support of the Canada–United States Air Quality Agreement.
Evaluating progress on transboundary air issues, in support of the Canada–United States Air Quality Agreement, requires scientifically credible methods that can span the 8,900-km border. Progress has been tracked by a combination of in-situ deposition sampling, source monitoring (e.g., Continuous Emission Monitoring System), and atmospheric modeling. There is recognition that low-earth orbit UV/visible measurements and soon-to-be launched geostationary-orbit UV/Vis spectrometers can be an important tool for monitoring air pollutant abundance and transport. To enhance the integrity of using satellite data products for interpreting impacts on surface air quality, there is a need to develop an integrated air quality monitoring and satellite validation network.

The technology and science underpinning the ability to retrieve trace gas column abundance from satellite-based spectrometers have matured over the past several decades, resulting in higher resolution data (e.g. GOME-2 40 x 40 km resolution, OMI with nominal 13 x 24-km resolution vs. Sentinel 5P TROPOMI with nominal 7 x 7-km resolution; see Figure 1).

While satellites in low-earth orbit provide once-a-day observations of an area of interest at best, remotely sensed air quality research and monitoring is on the cusp of a new era with the launch of a series of geostationary air quality instruments from 2020 to 2023: Korea–GEMS (Geostationary Environment Monitoring Spectrometer), NASA–TEMPO (Tropospheric Emissions: Monitoring Pollution), and European Space Agency (ESA) Sentinel-4.

As geostationary weather satellites have revolutionized mesoscale weather forecasting, this next generation of geostationary air quality instruments has the potential to revolutionize how air quality and pollutant transport is monitored. However, with these advancements, a new set of challenges associated with validation of their hourly measurements and data products arises. Monitoring air quality from space is a strategic research area within both the United States and Canada, and is a focus area for technical cooperation under the agreement. While there have been efforts to evaluate and validate satellite-based trace gas data products, routine and

Figure 1. NO₂ measured by TROPOMI (a) and OMI (b) on April 9, 2018, over the surface mines of the Alberta Oil Sands Region (w/NW winds). Averages (March–May, 2018) with an averaging radius of 5 km and 16 km were used for TROPOMI (c) and OMI (d), respectively. The black line traces the borders of the individual mining operations.
systematic validation of the geophysical parameters uncertainty and representativeness in space and time on a large scale is rare, with cost and technology being the main limiting factors.

**Pandora Ground-Based Spectrometer**

In 2005, NASA initiated an effort at Goddard Space Flight Center (GFSC) to address the gap in validation measurements through the development of cost-effective, easy-to-deploy, ground-based spectrometer called Pandora. Pandora is a compact, modestly-priced sun/sky/lunar passive UV/Visible grating spectrometer system. Over the past decade, the NASA Pandora Project together with the ESA Pandonia project, have endeavored to mature and refine the Pandora spectrometer system.

When the spectrometer and head assembly are carefully calibrated, Pandora provides high-quality spectrally resolved direct sun/lunar or sky scan radiance measurements in the UV and visible wavelengths. The Pandora radiance measurements combined with trace gas spectral fitting routines, and (in the case of sky-scan measurements) radiative transfer modeling provide real-time data of key air quality relevant pollutants, which can be compared to similar measurements from satellites. These observations include total column ozone (O₃), nitrogen dioxide (NO₂), formaldehyde (HCHO), sulfur dioxide (SO₂) and bromine oxide (BrO). Figure 2 shows the various components of the Pandora system, and their installation in different configurations, while Table 1 provides technical details on the components and measurement quality.

Environment and Climate Change Canada (ECCC) and the U.S. Environmental Protection Agency (EPA) have partnered with NASA and ESA in the deployment of Pandora instruments across North America. While the spatial distribution of Pandora instruments in the field is not explicitly guided by issues of transboundary transport of air pollutants, data provided from the confederated network will be used to validate satellite data products of direct relevance to transboundary transport.

**Pandora Network**

Within the United States and Canada, measurements from Pandora instruments have demonstrated a new observational perspective of air quality. The O₃ and NO₂ products have been rigorously investigated over the course of a decade during a series of intensive field campaigns and also at long-term monitoring sites.

**The United States**

In the United States, NASA's Deriving Information on Surface conditions from COlumn and VERtically resolved observations relevant to Air Quality (DISCOVER-AQ) mission involved the deployment of Pandora spectrometers at local air quality sites in each study domain: Baltimore, MD (2011), San Joaquin Valley, CA (2013), Houston, TX (2013), and Denver, CO (2014). The local air quality sites, many of them either part of EPA’s State and Local Air Monitoring Stations (SLAMS) or Photochemical Assessment Monitoring Station (PAMS) networks, served as measurement anchor points for the coordinated 3D sampling strategy (airborne spirals, ground-, and aircraft-based remote sensing).

DISCOVER-AQ results highlighted both the ability and the importance of routinely monitoring factors affecting the 3D distribution of NO₂. NO₂ is a precursor of tropospheric O₃ production. Understanding its 3D distribution is thus important for understanding patterns of O₃ production, exposure, and transport.

Figure 3 demonstrates the power of adding Pandora (i.e., total NO₂ vertical column measurements) to a conventional air monitoring station for understanding the vertical distribution of NO₂. Pandora does not differentiate tropospheric NO₂ from stratospheric NO₂ columns, so we must make two assumptions. First, we assume that a stratospheric contribution to the total column is spatially uniform over all of Denver area and slowly increases through the day from 3.1 × 10¹⁵ molecule cm⁻² at 6:00 a.m. MST to 4.4 × 10¹⁵ molecule cm⁻².

![Figure 2](image-url)

**Figure 2.** (a) environmental enclosure housing instrument electronics (left), spectrometer on thermal electric cooler (right), computer (not shown), (b) sensor head with camera and enhanced sun tracker, (c) another configuration with sensor head installed on the roof of a trailer, and the spectrometer and computer located inside the trailer.
at 6:00 p.m. MST, consistent with previous climatological measurements. The second assumption is that the entire tropospheric NO₂ column is located within the boundary layer and that the boundary layer is well mixed, a reasonable approximation in urban environments near sources given the relatively short lifetime of NO₂ in the atmosphere.

With these assumptions, we are able to infer that the decrease of NO₂ surface concentration after 11:00 a.m. MST, as shown in Figure 3 relative to the Pandora NO₂ column reflects growth in the boundary layer mixing NO₂ higher in the atmosphere, or over a greater volume. This inference is supported by the temporal increase in the vertical extent of aerosol backscatter and increasing mixed layer height while the total NO₂ column remains relatively constant between 11:00 a.m. and 1:00 p.m. MST. The significance being that this behavior is not possible to observe with surface in-situ sensors alone.

Additional field campaigns, such as the 2016 NASA/NIER KORUS–AQ study: An International Cooperative Air Quality Field Study in Korea (https://www-air.larc.nasa.gov/missions/korus-aq/), the 2017 NASA/EPA Lake Michigan Ozone Study (https://www.ladco.org/technical/projects/lmos-2017/), the 2017 and 2018 Ozone Water Land Environmental Transition Study (OWLETS 1 & 2; http://pubs.awma.org/flip/EM-Aug-2016/crawford.pdf) and 2018 Long Island Sound Tropospheric Ozone Study (http://www.nescaum.org/documents/lists0), have effectively served as opportunities to continue the evaluation of the operational performance of the Pandora systems and to characterize column NO₂ diurnal patterns.

In 2015, EPA finalized changes to the PAMS Network, which included the addition of an Enhanced Monitoring Plan (EMP) for certain regions of the United States with persistent O₃ non-attainment issues. Informed by the use of Pandora spectrometers in multiple field campaigns to monitor column NO₂, recent EMP guidance provides the opportunity for state and local agencies to work with EPA and NASA to incorporate Pandora spectrometers into select monitoring sites as a component of the EMP. Under the new EMP monitoring requirements, Pandora column NO₂ combined with mixed-layer height measurements and surface in-situ measurements of true NO₂ will better aid in the characterization of NO₂ and allow for a direct comparison with satellite-based NO₂ column measurements.

Canada
In Canada, ECCC’s Pandora program is focused primarily on long-term monitoring. One of the first sites is Fort McKay (57.184°N, 111.64°W) in the Canadian oil sands region, where Pandora measurements began on August 15, 2013. Located in the province of Alberta, the oil sands region contains vast deposits of bitumen–oil mixed with sand, clay, and water. Environmental and health concerns associated with the oil sands operations, including air quality and acid deposition, are well known. The SO₂ emission sources in the oil sands region are among the largest in Canada, while NO₂ emissions are comparable to those from a small town. Due to the large area of the oil sands operations, satellite measurements are an appealing approach for air pollution monitoring in this region. Pandora was deployed to provide total column SO₂ measurements and validation of satellite NO₂ observations. Pandora SO₂ measurements compared with in-situ data during the “pollution events” at Fort McKay (see Figure 4) demonstrate Pandora’s capability for air quality monitoring.

ECCC deployed Pandora instruments at three sites in or north of the Greater Toronto Area between 2013 and 2018 to validate TROPOMI measurements at high spatial resolution. In 2018, an additional Pandora instrument was installed near Edmonton, AB, to study urban pollution, as well as

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**Table 1. Overview of Pandora Spectrometer.**

- System developed at NASA Goddard with a focus on satellite validation.
- Ground-based direct sun/moon and sky scanning remote sensing for air quality and atmospheric composition
  - 1-Spectrometer (1S) unit – spectral range 270–530 nm, resolution 0.6 nm
  - 2-Spectrometer (2S) unit: spectral range 400–900 nm, resolution 1 nm
- Initial measurement is a slant column
- NRT Standard Operational Products at high frequency (~ 2 mins): Total Column Ozone (+/-15 Dobson unit, ~5%); Total Column NO₂ (+/-0.05 Dobson unit, ~10%)
- Research products: HCHO; BrO, profile and near-surface NO₂, tropospheric and near-surface O₃.
- Two main parts to instrument: (1) sensor head and (2) spectrometer, thermoelectric cooler, electronics, computer contained with environmental housing case 23x16x39 inches or 8-inch rack mounted enclosure.
pollution from large coal-burning power plants located in the area. To withstand harsh winter conditions, all Canadian installations are configured with the sensor head placed outside, while the spectrometer and computer are indoors in a temperature-controlled environment.

Although scientific analyses have been published on both SO$_2$ and HCHO, these products and their associated algorithms are still undergoing review and require verification to ensure their integrity before becoming a standard data product. These focused studies, along with others in Europe, have provided opportunities to evaluate instrument operations and performance, which have resulted in engineering and software changes to increase operational reliability and long-term stability of the Pandora system.

The current distribution of Pandora instruments deployed in North America is depicted in Figure 5, with ECCC, NASA, and EPA instruments color coded separately. With the launch of TROPOMI (October 2017) and the future launch of the geostationary TEMPO instrument circa 2021, the Canada–U.S. Air Quality Agreement is providing a mechanism for scientific cooperation between ECCC, NASA and EPA to define a coordinated satellite validation strategy and measurement instrument suites at long-term sites, with these sites also being within a larger global network.

The Pandonia Global Network

NASA and ESA are collaborating to coordinate and facilitate an expanding global network of standardized, calibrated Pandora instruments focused on air quality and atmospheric
composition. The Pandora Global Network (PGN) endeavors to ensure systematic processing and dissemination of the data to the greater global community in support of in-situ and remotely sensed air quality monitoring. A major joint objective is to support the validation and verification of more than a dozen low-earth orbit and geostationary orbit based UV-visible sensors, most notably Sentinel 5P, TEMPO, GEMS, and Sentinel 4.

PGN participants are primarily comprised of governmental and academic researchers and technicians. The launch of the PGN in mid-2019 represents a programmatic shift by NASA and ESA toward establishing long-term fixed locations that are focused on providing long-term quality observations of total column and vertically resolved concentrations of a range of trace gases. PGN provides real-time, standardized, calibrated, and verified QA/QC air quality data. PGN also seeks to coordinate and implement network standards regarding common algorithms and data processing, instrument operating routines, quality control, real-time data processing, and data archiving.

**Conclusion**

The scientific cooperation and partnership between ECCC and NASA/EPA on the Pandora Spectrometer System will be beneficial to both countries with specific areas of collaboration focused on instrument development, standardization of deployment and operations, shared data processing techniques, and combined analysis of results. The cooperation on Pandora as a new routine and systematic monitoring

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**Figure 4.** SO$_2$ VCD (DU) measured by Pandora spectrometer (red dots) at Fort McKay and calculated from integrated aircraft SO$_2$ profile measurements (blue dots), as well as in-situ SO$_2$ concentration in parts per billion by volume (ppbv; green line).

**Figure 5.** The current distribution of deployed Pandora systems in Canada and the United States. Each site is color-coded to correspond to the agency owner of the Pandora with total numbers deployed indicated in the legend.
approach is expected to assist in providing an improved characterization and validation of satellite data, leading to greater use of satellite data to monitor and assess emissions and transport of air pollution over the vast areas that contribute to transboundary pollution. In addition, the PGN is expected to play a critical role through implementation of standards across the network, which will assist ECCC and EPA on the development of a common measurement platform.

J. Szykman, L. Valin, and D. Williams are with the U.S. Environmental Protection Agency (EPA); R.J. Swap and A. Kotsakis are with NASA Goddard Space Flight Center; B. Lefer is with NASA Headquarters; S.C. Lee, V. Fioletov, X. Zhao, and J. Davies are with Environment and Climate Change Canada (ECCC); N. Abuhassan, L. Shalaby, and J. Robinson are with the JET–UMBC NASA Goddard Space Flight Center; F. Santos, ESSIC, University of Maryland; and A. Cede, M. Tiefengraber, and M. Mueller are with the Laboratory of Atmospheric and Cryospheric Sciences, University of Innsbruck.

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References
In Québec, clean energy, innovation and the green economy are part of our nature

Québec is an innovative society
- A cleantech cluster
- A centre of excellence in ground transportation
- A world hub in artificial intelligence

Québec has efficient green industrial sectors

Electric transport
- 5,000 jobs
- More than 100 organizations, including 60 businesses and 30 research institutions

The environment and clean technologies
- 30,000 jobs
- $10.7 billion in revenues
- More than 1,000 organizations, including 500 businesses and 200 R&D organizations

Renewable electricity
- 24,000 direct jobs
- $4.6 billion in revenues

Québec is a source of clean, renewable energy
- One of the largest producers of hydroelectricity in the world
- 99% of its electricity is clean, renewable and affordable
- Abundant energy to meet our electrification needs

World leader in the fight against climate change, Québec is fertile ground for low-carbon solutions.
This article presents a novel technology that uses heat, generated by combusting methane-heavy landfill gas, to eliminate landfill leachate.
An environmental risk commonly associated with solid waste landfills is that posed by landfill leachate flowing off-site, potentially contaminating nearby ground or surface waters. Typically, landfill leachate—which is, ironically, a landfill’s own waste—must be treated, often at high cost, either off-site at a wastewater treatment plant or on-site via expensive biological or other types of treatment processes. What if landfill owners could use a freely available, high-potency greenhouse gas to eliminate the cost of managing this environmental liability?

A novel technology entails the use of heat, generated by combusting methane-heavy landfill gas (LFG), to eliminate most of the liquid portion of landfill leachate. Although using heat from LFG combustion to evaporate leachate is not completely cost-free and leachate management costs are not entirely eliminated, this technology proposes to accomplish something close. What is more, by combusting LFG to evaporate leachate, methane is converted to lower-potency carbon dioxide. With technologies for on-site evaporation of leachate now becoming available, landfill owners are actively considering this novel technology and the opportunity it offers for reducing operating expenses.

However, the planning process for obtaining the air permit required for LFG-fired leachate evaporation cannot be overlooked and can present a challenge. To successfully permit, the owner, operator, and regulator need to understand the technology and recognize how it can affect air permitting.

What Is Leachate?
Landfill leachate is produced when precipitation falling on the landfill, or moisture present within the waste, percolates through the waste mass, extracting and entraining dissolved and suspended contaminant matter. Leachate properties are influenced by factors such as the type of waste accepted, the age of waste, variations in precipitation, and operational practices. In addition to posing an environmental risk, leachate can impact operations and interfere with LFG extraction. Therefore, modern landfill design includes measures to prevent leachate from migrating beyond the lined portion of the landfill, as well as measures to collect and remove the leachate from the waste mass. Leachate collection and removal systems consist of collection piping, transport piping, cleanout access, and although typically gravity-driven, pumps and force mains are employed. Effective stormwater management practices are critical in reducing the volume of leachate generated.

After removal via the collection and removal system, and routing to storage tanks, ponds, or a lagoon, leachate is then treated through either on-site biological treatment systems, deep-well injection, discharge to natural wetlands, or more commonly trucked or piped to an off-site public wastewater treatment facility. A typical leachate storage lagoon is shown in Figure 1.

Important advances in leachate treatment have emerged, with industry, regulators, and environmental professionals having collaborated to produce such innovative approaches as LFG-fired evaporation, mechanically-induced evaporation, reverse osmosis, vegetative methods, among others. However, traditional treatment via hauling off-site to a publicly operated treatment plant (POTW) currently remains a common method.

Discharge of leachate to a POTW presents the landfill owner with considerable challenges: truck-hauling costs that can vary with the price of fuel; discharge fees at the POTW,

Figure 1. Landfill leachate lagoon. Photo courtesy of SCS Engineers.
over which the landfill owner exercises little control; limits on permissible levels of leachate contaminants; and POTWs that may be overstressed on capacity due to population growth. These service and cost uncertainties encourage landfill owners to seek alternatives. The combination of lower landfill gas prices and improved evaporation technologies makes LFG heat-assisted leachate evaporation more attractive to landfills challenged with high leachate disposal costs.

What Is LFG-Fired Leachate Evaporation?
This approach employs heat generated by onsite combustion of untreated LFG to evaporate the liquid portion of leachate, eliminating, or substantially reducing, the quantity of leachate that will need to be transported off-site, or otherwise treated. The process can be viewed as performing the same evaporative process that occurs naturally when a leachate pond or lagoon is used, only in a greatly accelerated manner regardless of weather conditions. Following evaporation, some residuals remain, typically containing only minimal water content, depending on the design of the evaporation system, and these can be disposed in the landfill. An example of an LFG-fired evaporator is shown in Figure 2.

Typically, this process uses an enclosed flare whose stack is mounted so as to discharge downward, somewhat similar to the childhood-fun practice of blowing through a straw downward into a drink to make bubbles. An example process diagram is shown in Figure 3. As commercial-scale technologies for leachate evaporation arrive on the market, many landfill owners are now exploring this option, especially given related economic drivers: prices for selling LFG as an energy fuel are dropping, while costs for conventional treatment of leachate are rising.

Permitting Challenges
Although operating an enclosed flare to control LFG is a long-established, conventional technology that is well-understood by air regulators, an enclosed flare combusting LFG to evaporate leachate is uncommon, presenting uncertainties for regulators. Accordingly, landfill owners pursuing LFG-fired evaporation should strive to understand regulator concerns, in addition to understanding applicable environmental regulations.

Federal and state air regulations govern LFG combustion, as well as volatile organic compounds (VOCs), products of combustion, and particulate matter (PM). For LFG-fired evaporation, air permitting can be more complex. For example, are regulated air pollutants emitted differently than in standard LFG combustion, as a consequence of evaporating the liquid fraction of the leachate? Do leachate constituents change due to the heat of combustion, inducing variation in air pollutant emissions? Will the products of LFG combustion in the leachate evaporation process be emitted at a high enough rate to push the landfill into the most complex level of air permitting (e.g., PSD permitting)?

Emissions and Air Permitting
LFG-fired leachate evaporators produce emissions in two general categories: emissions from the combustion of landfill gas and emissions related to leachate volatilization. Although most emissions in the evaporation category can be assumed to be water, there will normally be some emissions of regulatory concern in the form of VOCs and PM.

Based on decades of experience, LFG combustion emissions are well understood and have a widely accepted basis for quantification. As the design of the enclosed combustor used...
Landfill Leachate Evaporation by David Greene

in LFG-fired evaporation can differ from a conventional enclosed flare, the landfill owner should rely upon manufacturer emission guarantees when permitting. In calculating combustion emissions of sulfur dioxide, the assumed hydrogen sulfide concentration in the LFG should be representative of the particular landfill involved.

If dispersion modeling is required for permitting, note the maximum permissible LFG flow to the evaporator may be limited in the resulting air permit to the value used for modeling; therefore, a desire to increase LFG flow after permitting may require an additional dispersion modeling demonstration. For true potential-to-emit calculations of maximum emissions, the owner should assume the design maximum LFG flow rate. Alternatively, the owner can choose to accept a lower LFG flow rate limit and an associated monitoring condition to demonstrate compliance.

Considering emissions from leachate evaporation, quantifying the maximum VOC emissions associated with evaporation requires taking into account the VOC content of liquid leachate, and multiplying the associated emission rate by a reasonable safety factor. For conservative emissions estimates, calculations can assume complete volatilization during evaporation of the VOC compounds present in the leachate.

PM emissions are expected due to salts left after evaporation, and depending on the leachate constituents, one can assume that a portion of the particulate emissions is calculated as the PM10 and PM2.5 fractions. For anticipated relative quantities of each, owners should rely on manufacturer guarantees or guidance. Simply stated, a margin of safety can be a good practice in setting the stage for “livable” permit conditions, and for showing a good faith effort in working with a regulatory authority on a technology that may be unfamiliar in its jurisdiction.

**Key Air Regulations**

Besides the air permitting requirements discussed above, federal air regulations typically apply to devices combusting LFG. As combustors of untreated LFG, LFG-fired evaporators are considered a control device for LFG, and, if applicable to the landfill, are regulated as such. Per the related rule, combustors will need to be “designed and operated to reduce [emissions of Non-Methane Organic Compounds (NMOC) by]…98 weight

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**Figure 3. Evaporator process diagram. Diagram courtesy of Aptim.**
percent or... to less than 20 [ppm v], as stated in CFR 60.752 (Subpart WWW) and 60.762 (Subpart XXX).

Presuming the evaporator uses an enclosed combustion device, the rule also requires maintaining a minimum combustion temperature to ensure adequate control of NMOC emissions. To demonstrate required destruction efficiency, the evaporator combustor will be subject to an initial compliance test (per 60.752(b)(2)(iii)(B) or 60.762(b)(2)(iii)(B), as applicable). This test will also establish the minimum combustion temperature to be maintained (per 60.758(c)(1)(i) or 60.768(c)(1)(i)). Because the test is required for control of NMOC emissions from landfill gas combustion and not from leachate evaporation, a landfill owner can work with the state regulator to test LFG combustion only, not leachate evaporation.

For most sites, the evaporator’s enclosed flare heat source is part of the overall landfill gas collection and control system (GCCS) that also includes one or more primary control devices, such as candle stick flares or traditional enclosed LFG flares. The evaporator, when operated as part of the GCCS, can help reduce overall downtime that occurs when a primary control device goes offline for maintenance or due to a malfunction.

Additional air regulations may apply to LFG-fired leachate evaporators, including state-only or local jurisdictional rules.

**Conclusion**

LFG-fired leachate evaporation is a novel technology attracting the attention of landfill owners because it offers an operational win-win. The technology uses a readily available resource at landfills, LFG, to remove liquid from landfill leachate via evaporation, thus abating this environmental liability onsite, often at a lower cost than conventional leachate treatment options. In addition, combusting LFG to evaporate leachate converts methane, a highly potent greenhouse gas, to carbon dioxide, which reduces overall greenhouse gas emissions.

Landfill owners seeking to implement LFG-fired leachate evaporation must undergo the necessary air permitting and follow applicable emissions regulations. In this regard, air permitting and regulatory requirements for the combustion-related component of LFG-fired evaporation are similar to those applicable to conventional LFG flares. However, in addition, there are evaporation-related emissions that must be considered in permitting. As this is uncharted territory for regulators, it is important to work closely with the agency to ensure these technology-specific requirements are properly addressed.

With LFG prices generally low and leachate disposal costs rising, be on the lookout for LFG-fired leachate evaporation making an appearance at a landfill near you!
This article demonstrates how the zero waste concept can be made into an achievable goal.
The world is facing a mounting sustainability challenge, resulting from rapidly-increasing production, wasteful consumption, and excessive waste in many countries. Limited natural resources are being depleted at an ever-increasing rate; environmental quality in developing countries is being impaired to a level of risk concern; and many believe that climate change is now causing severe disruptions to the way of life across the globe.

All of this points to the fact that we need to make a fundamental change to our mindset. A key aspect of this mindset change is the “zero waste” concept, a sustainability goal, which in the ideal case means that we would no longer be generating waste that requires disposal. To achieve zero waste, several root changes are warranted, including doing more with less, changing from wasteful to green consumption, reorientation of environmental protection toward proactive conservation, and shifting the focus of waste management to resource/materials management. In principle, waste is simply a misallocated resource. Our job is to find the right place to put the recycled waste into rightful use, by applying appropriate technologies to convert it into value-added materials and products.

Zero waste generation is a difficult goal to reach in today’s society. However, the zero waste concept may be realized by stages and in various forms, such as zero waste to landfill, zero waste from production to consumption, zero waste generation, zero waste within a defined boundary, or zero waste at a local, national and regional level. Nevertheless, all these systems inherently have different complicating issues that need to be resolved to make implementation feasible. If not implemented properly, the zero waste approach could easily turn into a fiction. A key challenge for achieving any zero waste form is to demonstrate its economic viability. A sustainability index incorporating total value generated by the zero waste system on one hand, divided by the reduced environmental impact on the other, can best quantify the benefit of zero waste to the society.

A realistic strategy would be to take a step-wise approach, working toward the goal of zero waste goal in stages, starting with modest steps, then working through further measures in order of increasing complexity.

**Scope and Boundary of a Zero Waste System**

There is a hierarchy of zero waste systems. Their scopes, in order of increasing complexity, can be defined as follows:

- **Zero waste to landfill**: waste diversion from landfill by reducing the creation of waste in the first place (waste avoidance), recycling waste, and re-using waste beneficially (making energy or products from waste)
- **Zero waste from production to consumption**: waste avoidance throughout the production to consumption process
- **Zero waste generation**: waste is no longer generated at all—the ultimate goal

The boundary of the targeted zero waste system also needs to be defined, for example:

- **Zero waste within a defined boundary**: factory, zone, city, county, etc.
- **Large-scale zero waste**: state/provincial, regional, or national level

The chances of forming a zero waste system generally increase as the physical boundary expands, allowing beneficial collaborations among an increasing number of interested partners, such as product manufacturers, materials users, food producers and users, public-sector waste managers and policy setters, private waste management companies, and consumers.

The next questions to consider in implementing a zero waste system are:

1. Ways and means to achieve the set goal of zero waste?
2. Mechanism to implement a zero waste system?
3. Necessary and sufficient conditions to fulfill the set goal of zero waste?
4. Compatibility of regulatory systems with the zero waste initiative?
5. Incentives for the intended zero waste program?
6. Public awareness of zero waste implications?

Addressing these considerations requires a multidisciplinary, multi-stakeholder collaboration among interested parties. Factors that can mean failure or success should be assessed collectively, and corresponding strategy should be mapped out right at the beginning, to better ensure a successful implementation of the planned zero waste system.

**Mindset Change Required**

To work toward the zero waste goal, a fundamental change in our mindset is necessary. Rule number one in this changed mindset: there is no longer such a thing as waste; it is simply a misallocated resource. Correspondingly, we must change the concept of waste management and shift it to resource management (see Figure 1).

For example, if the goal is zero waste to landfill, achieving this would require far more aggressive recycling and reuse of materials. During the production of goods and their consumption, unwanted materials are generated which we...
normally view as waste. These unwanted materials generally contain a mix of various components which make them unusable. Our job is to make them usable again through a series of operations, including sorting, separation, purification, upgrading, and/or remanufacturing. The regenerated products are then put into the market for rightful use, with an added value. This recycling framework will likely involve a network of waste or secondary resource collection, processing, regeneration, and product distribution. Stakeholders may include collectors, recyclers, communities, governments, industries, market distributors, product users, academia, the research sector, financing institutions, and NGOs.

Collective Actions Approach
Achieving zero waste to landfill would be a major step forward in sustainability. However, to aspire to even higher goals such as zero waste from production to consumption, and ultimately, zero waste generation, this will require further fundamental changes in our way of life and thinking. These fundamental changes include:

- **Change the economic drive from unlimited use of resources to “doing more with less.”**
  Revisit the production and consumption processes in a continuing effort to make them more efficient by reducing the material and energy uses, while achieving an equivalent or higher functionality. Examples include forming value-added materials and energy synergistic systems within industrial parks; supplying the information technology-related manufacturing industry with the high-value nano-grade electromagnetic materials it requires, which are recovered from steelmaking spent liquor; and innovating a virtual keyboard and monitor system to replace the computer hardware.

- **Change our life pattern from wasteful to green consumption.**
  Educate ourselves to be material, energy, and safety conscientious while purchasing needed products and/or services. For consumers, this could mean opting for goods having better sustainability attributes, such as recycled components, recycling potential, higher energy-efficiency, longer durability, or less toxicity. For those with policy-level interests, this could mean forming a consumer coalition to demand manufacturers practice green production and provide sustainable goods.

- **Change our environmental management practices from passive protection to proactive conservation.**
  Restructure the environmental management system to adopt a resource conservation approach instead of the
conventional end-of-pipe protection practice. Examples include amending the tax code and regulatory framework to encourage green production and value-added recycling; and setting corporate goals of minimizing material and energy consumption, while seeking toxicity reduction.²

**Sustainability Index**

In the process of implementing a targeted zero waste system, questions will be raised among stakeholders regarding its economic viability and environmental soundness. An appropriate index for evaluating the sustainability of the proposed zero waste system is needed to prove its worthiness to those stakeholders and to the public. Such a sustainability index would calculate the total value generated by the zero waste system divided by the reduced environmental impact. This index, which can best quantify the sustainability benefit of a given zero waste system to society, is as follows:

\[
\text{Green Competitiveness} = \frac{\sum \text{Value of Products and Services}}{\sum \text{Reduced Impact to Environment}}
\]

In this sustainability index, the numerator is the summation of the total value of the products and services generated by the subject zero waste system, and the denominator is the summation of the impact that the subject system imposes on the environment. Depending on the characteristics of the particular zero waste system and the priority concerns of the stakeholders, the indicators of the environmental impact can be expressed as materials consumption, water usage, energy use, carbon dioxide emissions, toxicity accumulation, and other indicators. In pursuit of a viable zero waste system, the value of the numerator is expected to become higher than that of the existing system of production, while the value of the denominator is expected to be lower than the current system, hence an increasing green competitiveness.

**Sufficient Conditions for Achieving Zero Waste Goal**

Having workable technologies to produce valuable materials and products out of waste is a first step toward developing a targeted zero waste system. However, there are many barriers that lie ahead to implementing such a system. The following factors constitute the sufficient conditions for achieving zero waste goals:

- Coherent governmental regulations and permitting requirements;
- Clear definitions of what constitutes a waste vs. a recyclable resource;
- Standards and certification system of recycled products;
- Market acceptability of recycled products;
- Achieving economies of scale for resource recovery;
- Mechanism to finance hopeful innovators for start-ups;
- Incentives for zero waste participants and programs; and
- Technology breakthroughs for creating added value for recycled products.

**Multi-Stakeholder Partnership**

The development of a zero waste system is a community or regional effort, hence requiring multiple involved stakeholders to work together as a team. The government/industry/research-community partnership must work collectively to:

- Resolve the legal and administrative issues of shifting from waste disposal to zero waste systems;
- Select a champion region(s) and demonstrate the feasibility of developing and operating zero waste systems;
- Educate the public about how an individual can participate effectively in sorting, separation, collection, and delivering sorted wastes and recyclables to designated locations; and
- Align multiple resources in science and technology research, as well as venture capital, to accelerate the necessary innovations to business practices.

**Zero Waste in Practice**

While zero waste is presently a goal and not yet a reality, economies around the world are making substantial progress toward achieving the first step, zero waste to landfill.

**The Netherlands**

The zero waste initiative forms the backbone of the circular economy. Waste is generally considered a commodity encouraged to be used and traded between the generator and the user. Governmental agencies monitor the status of the commercial contracts signed between the two parties, to ensure they are properly executed.

In the Netherlands, the benefits already realized from its circular economy are reported as follows:²

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural resources conserved</td>
<td>7.3 billion Euro/yr</td>
</tr>
<tr>
<td>Employment created</td>
<td>54 thousand jobs</td>
</tr>
<tr>
<td>Carbon emissions reduced</td>
<td>17 million tonnes/yr</td>
</tr>
<tr>
<td>Use of natural resources reduced</td>
<td>0.1 billion tonnes/yr</td>
</tr>
<tr>
<td>Use of water and land reduced</td>
<td>2,180 km²</td>
</tr>
</tbody>
</table>

**Taiwan**

Taiwan’s Four-in-One Recycling Program is based on the “extended producer responsibility” concept that obligates manufacturers and importers of new products to fund recycling.¹ This program requires manufacturers and importers to pay a recycling fee to a government fund, which is then used to subsidize waste collection and recycling by private sector enterprises. The program entails a necessary collaboration
among participants: communities, their residents, recycling industries, local governments, and the recycling fund administration. Respective responsibilities are:

- **Community network**: sort, separate, and deliver the wastes and recyclables to designated collection points or recycling facilities (see Figure 2).

- **Local government**: collect the sorted wastes and recyclables at designated locations and transport them to recycling industries.

- **Recycling industry**: process the sorted wastes and recyclables, sell and distribute the regenerated products to the market users.

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**Figure 2.** Schematics of waste sorting and separation.¹

**Figure 3.** Taiwan’s Four-in-One Recycling Program – Materials and Cash Flow.¹
Zero Waste: Fiction or an Achievable Goal? by Chih C. Chao

Recycling fund administration: collect recycling fees from sold goods and waste generators; allocate funding to community, recycling, and local government partners.

Taiwan's Four-in-One Recycling Program has been very effective, reducing the nation's annual waste disposal by 20 percent (or 1.76 million tonnes) since 1998. The material and cash flows for the program are illustrated in Figure 3. It helps to relieve the disposal burden on the landfills, which has enabled the shutdown of many public landfill sites, in turn, reducing landfill-related environmental burdens. Owing to this program and other recycling programs undertaken in Taiwan, the national recycling rate for municipal waste has reached an impressive 60 percent, making Taiwan a sustainability leader in efforts to reach the goal of zero waste to landfill.

City of Edmonton, Alberta, Canada

The City of Edmonton is often cited as a model of sustainable waste management for other municipalities to emulate. The city's comprehensive approach to pursuing zero waste to landfill, as well as more detailed information on the innovative, green fuels conversion technology, are described more fully in an article that appeared in the May 2019 issue of Em.

The Way Forward

Realistically, achieving the ultimate goal of zero waste generation will need to be reached in steps over time. A major initial accomplishment would be to achieve zero waste to landfill via reducing the creation of waste in the first place (waste avoidance), recycling waste, and re-using waste beneficially. A number of countries and cities in Europe, Asia, and North America are already making impressive progress toward achieving this goal.

Looking ahead, to fully achieve the zero waste goal, we must make a concerted effort to implement the necessary building blocks. These include stable and systematic policy, coherent regulations, and economic incentives, as well as a certification program for secondary materials and products, innovation in business models and markets, and the cultivation of green jobs and talent.

References

EPA Study Shows Combustion Emissions Influence Rate and Amount of PM from Vegetation

by Carrie Holz and Emily Smith

Results from a study that examined how atmospheric oxidation from vegetation influences the formation of fine particulate matter.

Recent research led by the U.S. Environmental Protection Agency (EPA) examined how the rate of atmospheric oxidation of volatile organic compounds (VOCs) influences the formation of fine particulate matter (PM$_{2.5}$). The team’s research included laboratory experiments, atmospheric observations, and model calculations, and found that when nitrogen oxides (NOx)—which is dominantly man-made and comes from combustion activities—is reduced, there is a corresponding reduction in how quickly VOCs from vegetation form PM$_{2.5}$. This, in turn, reduces the amount of PM$_{2.5}$ in that region.

The research estimates that a quarter of the decreases in organic PM$_{2.5}$ seen over the past 20 years in the southeastern United States are likely due to reductions in NOx emissions. This means that air quality mitigation strategies targeting reductions in ozone and inorganic PM$_{2.5}$ formation have also led to decreases in organic PM$_{2.5}$ formation.

The study, published in the Proceedings of the National Academy of Sciences (PNAS), focuses on a class of compounds from vegetation called monoterpenes, which are chemicals emitted from certain types of plants. Monoterpenes all have the same chemical formula, but can have different structures. This study focused specifically on the “alpha-pinene” structure, which is one of the major species emitted from pine trees that gives rise to their pine scent. Prior research showed that monolopene chemistry is responsible for most of the organic component of PM$_{2.5}$ in the southeastern United States.

“Since monoterpenes are emitted in the gas phase, chemistry is required to process them into lower-volatility forms that can enter PM$_{2.5}$,” said Havala Pye, EPA scientist and lead author of the study. “This study was unique, in that it focused on the mechanism by which NOx affect PM$_{2.5}$ and was able to verify the mechanism with experimental data.”
The research team used datasets developed from laboratory environmental chamber experiments to understand the chemical interactions taking place. Pye noted that the study was motivated by concern about a “NOx penalty” that could potentially increase PM$_{2.5}$ as NOx emissions are reduced.

“Monoterpenes are known to undergo a unique type of reaction called autoxidation, which leads to efficient PM$_{2.5}$ formation,” she explained. “Autoxidation exhibits a NOx penalty in terms of PM$_{2.5}$ yield when NOx emissions decline, since NOx generally acts to suppress autoxidation reactions.”

To determine the atmospheric impact of NOx, researchers first showed that autoxidation reactions were the main driver of PM$_{2.5}$ for monoterpenes by building a chemical mechanism that would describe in detail what was taking place at each stage of the chemical reaction. The highly detailed mechanism, consisting of hundreds of reactions and products, was able to reproduce PM$_{2.5}$ concentrations observed in previous lab experiments.

Researchers then looked at the mechanism in the context of changing NOx emissions. “While the NOx yield penalty was indeed present, the mechanism indicated that oxidant abundance was actually more important for dictating the PM$_{2.5}$ from monoterpenes,” Pye said. “In fact, oxidant reductions due to decreasing NOx emissions can overcome the yield penalty from autoxidation.”

Models, including EPA’s Community Multiscale Air Quality Modeling (CMAQ; https://www.epa.gov/cmaq/learn-about-cmaq) System, and data from a 2013 Southeast Nexus (SENEX; https://www.esrl.noaa.gov/csd/projects/senex/) field study were also used to confirm the research team’s understanding of how PM$_{2.5}$ changes in the ambient environment.

During the SENEX study, an aircraft was flown in and out of the urban plume downwind of Atlanta, measuring the effects of NOx. Researchers noticed that inside the plume, NOx concentrations, ozone, organic PM, and monopente chem istry.

Researchers then looked at the mechanism in the context of changing NOx emissions. “While the NOx yield penalty was indeed present, the mechanism indicated that oxidant abundance was actually more important for dictating the PM$_{2.5}$ from monoterpenes,” Pye said. “In fact, oxidant reductions due to decreasing NOx emissions can overcome the yield penalty from autoxidation.”

According to Pye, research dating back to the 1990s has proposed that monoterpenes were important for PM$_{2.5}$ formation, but that science is only now beginning to reveal the nuances of this relationship. She says there’s still much work to be done before researchers will fully understand monopente chemistry.

“The abundance of monopente secondary organic aerosol and interaction with NOx is only now being elucidated and quantified,” Pye said. “Mechanisms offer a path forward to determine robust associations of biogenic VOCs with anthropogenic emissions and the resulting implications for air quality today, and in the future.”

**About the Collaborators**

EPA scientists collaborated on this study with scientists from the University of Washington; Pacific Northwest National Laboratory; National Oceanic and Atmospheric Administration; and University of Colorado, Boulder. The research was made possible by a Presidential Early Career Award for Scientists and Engineers (PECASE; https://obamawhitehouse.archives.gov/the-press-office/2017/01/09/president-obama-honors-federally-funded-early-career-scientists) award to Havala Pye. The PECASE award is the highest honor bestowed by the U.S. government on science and engineering professionals in the early stages of their independent research careers. The award comes with a financial stipend that allows investigators to pursue questions of high societal importance to protecting public health and the environment. Advances in this work provide the scientific underpinnings of future National Ambient Air Quality Standards and air quality management strategies to achieve them.

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**References**


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**Disclaimer:** The views and opinions expressed in this article are those of the authors and do not represent the official views of the U.S. Environmental Protection Agency (EPA).

**More Information**

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Revenue Recognition Is Different from Getting Paid

by David Elam

We discussed utilization and billing rates in the previous two editions of PM File, where the combination of these translates into revenue for the firm. This column explores revenue, building on information that was presented in my March 2014 column, “Managing Project Revenues Requires More than Managing Project Effort” (http://pubs.awma.org/flip/EM-Mar-2014/pmfile.pdf).

Environment, health, and safety (EH&S) consulting firms typically consider revenue in two ways: gross revenue and net service revenue.

1. **Gross Revenue (GR):** The gross income generated by the sale of services before any project expenses are deducted. Simply put, total gross revenue corresponds to the sum of invoices.

2. **Net Service Revenue (NSR):** The income generated by the firm after subcontract and pass-through project expenses are deducted from GR.

Both GR and NSR are important; however, most EH&S consulting firms will focus on NSR. The ratio of NSR to GR can vary widely in the EH&S consulting field. EH&S consulting firms providing extensive field services requiring travel and the use of subcontractors may find NSR to be 60–70% of GR. On the other hand, firms providing in-office services may find NSR is 90–95% of GR. Firms will typically markup direct project expenses; however, the markup can vary from project to project and from client to client. Because of the uncertainty in direct project costs and markups embedded in GR, EH&S consulting firms, particularly those with multiple practice areas, favor NSR for financial planning and evaluation purposes.

A discussion of revenue is more complicated than an allocation between gross and net service categories. We also need to understand revenue recognition. In other words, when can the firm count the money it has earned? If an EH&S consulting firm operated like a big box store where the services were paid for as they were received, the answer would be apparent at the end of the business day when the cash register receipts were totaled. But EH&S consulting firms typically work under contract
against a project budget and are paid at defined intervals or upon milestone or project completion. Firms need to be able to recognize revenue as it is earned, so that they can manage financial performance and credibly engage with investors, creditors, and vendors.

Francisco-Javier Rodriguez explains revenue recognition as follows: “Revenue recognition is the process of recording an item in the financial statements of the company when earned, regardless of when cash is received or paid out. This means that revenue recognition is independent of cash flow, even though revenue recognition could influence and be influenced by cash flow.”

There are two methods to recognize revenue: cash method and accrual method.

1. **Cash Method**: The determination of income and recognition of revenue is based on the collection of cash and payment of expenses.

2. **Accrual Method**: The recognition of revenue occurs when it is earned and when expenses are incurred without regard to the time of receipt or payment of cash.

Most EH&S consulting firms use the accrual method to recognize revenue, following the process outlined below:

1. The firm prepares a written proposal that describes the scope of work and assumptions, the basis for compensation, the contract value, the payment terms, and contract terms and conditions.
2. If necessary, the firm and the client negotiate revisions to the proposal.
3. The client formally authorizes the firm to perform the proposed work. Formal authorization requirements will vary from one consulting firm to another, but in general, a purchase order referencing the proposal, a signed contract, or a written notice-to-proceed are acceptable forms of authorization. Formal authorization of the work is an important step. Unless the authorization conforms to U.S. Generally Accepted Accounting Principles (GAAP), the revenue is at risk and can’t be counted.
4. The firm sets up a project number that is used to accrue posted labor and expenses. Labor and direct project expenses are posted to the project number. Revenue is recognized as costs are posted to the project number.
5. The client is billed for expenses posted to the project number.
6. The firm receives payment for contracted services, typically 45–90 days after they were provided.

Although the accrual method is important to the consulting firm in terms of revenue recognition, the cash method remains important for cash flow management and tax calculation purposes.

It is important for project managers to understand the differences in these two accounting systems, from both firm and client management perspectives. For example, some clients may press for invoices at the end of their fiscal year so that invoices can be paid and claimed as expenses for tax purposes.

Revenue for the EH&S consulting firm is more complicated than “payments received." Revenue is defined by accounting standards and contract agreements. EH&S project managers need to understand revenue and the principles that govern it to develop proposals, establish billing milestones, and invoice for services. While the technical work is important, these principles help shape the value of the project to both the client and the consulting firm. EH&S project managers demonstrate their full value when they manage revenue to the full benefit of both their firms and their clients.

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Reference
The air quality community mourns the loss of Thomas M. Merrifield, who passed away suddenly on March 9, 2019, at the age of 68. He is survived by his wife (Deborah) and daughter (Megan), as well as his mother (Barbara), brother (John), and sister (Carol).

An A&WMA member beginning in 1979, Merrifield was actively involved in the organization and logistics of the vendor exhibition for A&WMA’s Annual Conference & Exhibition, representing a variety of instrument manufacturers. He chaired the Exhibition Committee for the first A&WMA International Specialty Conference for PM$_{2.5}$, held during May 2010 in Xi’an, China and attracted over 400 international participants and vendors.

Merrifield was respected for his expertise in particulate matter measurement system and its application to quantifying community exposures. He was instrumental in the development and testing of size-selective inlets and sampling systems that have been incorporated into U.S. Environmental Protection Agency’s Federal Reference and Equivalent Methods to determine compliance with PM$_{2.5}$ National Ambient Air Quality Standards. These methods have been adopted worldwide. His experience in characterizing urban air quality and pollution sources, assessing visibility impairment, and developing state implementation plans was recognized through invitations to conferences and training workshops in Russia, India, Pakistan, Malaysia, Japan, China, Brazil, Columbia, and Mexico. In 2014, Merrifield received the certificate of Foreign Experts,” one of the highest honors recognized by the State Administration of Foreign Expert Affairs in Beijing, China.

Merrifield earned his Bachelor of Sciences degree in Environmental Sciences from the University of Kansas in 1973 and started as a field operator, then project manager at the Midwest Research Institute (Kansas City, MO) working on fugitive dust sampling. In 1978, he joined Andersen Samplers/Graseby Instruments (Smyrna, Georgia) as one of the first employees and partners, which led to his career in designing, developing, and testing aerosol instruments for the following 40-plus years. He later worked at MetOne Instruments and BGI Instruments before forming Merrifield & Associates in 2012.

Merrifield will be remembered for his dedication to air quality improvement, his contributions to the aerosol sampling instrumentation, his generosity for assisting colleagues worldwide, his polite demeanor, and his long-lasting “smiles.”

Editor’s Note: This memorial piece was prepared by Judith Chow, John Watson, Paul Solomon, John Tisch, and Annie Chen.
A look back at this month 10 years ago in EM Magazine: June 2009.

To coincide with A&WMA’s 102nd Annual Conference & Exhibition, which was held in Detroit, MI—The Motor City—the June 2009 issue of EM focused on emerging advanced transportation policies and technologies, including electric plug-in vehicles, hydrogen fuel cells, hybrids, and rapid mass transit, along with associated infrastructure issues and the status of vehicle greenhouse gas emissions in the United States a decade ago.

In the article, A Brief History of Technology-Forcing Motor Vehicle Regulations, authors Paul Miller and Matt Solomon traced the history of a “technology-forcing” approach to establishing motor vehicle tailpipe emission standards. This approach, which began in California in the 1960s, sought to advance vehicle pollution control technology by establishing future tailpipe emission limits even if no technologies existed to meet them at the time regulators set the standards.

Quoting from the article: “While technology-forcing approaches grew out of the failures of technology-following policies, efforts akin to technology-following have not entirely disappeared. In 1995, for example, the U.S. Environmental Protection Agency (EPA) proposed an alternative program, called National LEV, for states outside of California to adopt in lieu of the CA LEV program.”

In another article, Moving Toward Clean Vehicles and Fuels: A Global Overview, by Michael Walsh, the author described the growth of the world’s motor vehicle population since the end of World War II and its adverse effect on air quality, followed by the more recent movement toward cleaner vehicles.

Quoting from the article: “Increasing vehicle production and ownership creates continuing pressure to maintain and improve air quality in cities across the world. Compounding the adverse health effects of poor air quality is climate change, another global problem to which motor vehicles are major contributors. Necessary to address these challenges are new emissions control systems and vehicle propulsion advances beyond the conventional internal combustion engine. Another critically important lesson learned to date is that clean vehicles and high-quality fuels go hand in hand; they must be treated as a system.”

Elsewhere in this issue, Jennifer Dunn discussed the transportation sector’s contribution to worldwide greenhouse gas (GHG) emissions. The article, Reducing Transportation Sector Greenhouse Gas Emissions: Case Studies in Operational Strategies, illustrated three broad, interrelated techniques to reduce transportation sector emissions, each with an important role: technology advancements, policy measures, and operational strategies.

Quoting from the article: “Unmistakably, transportation of both freight and passengers is a significant source of GHG emissions. While technology and policy measures are pivotal resources in efforts to reduce emissions from this sector, strategy options that can increase the efficiency of goods and people movement are indispensable, can be near term without the delays inherent in technology and regulation development, and can bring financial benefits such as lower fuel costs for businesses and families.”

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