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# Air pollution success stories in the United States: The value of long-term observations

Timothy J. Sullivan[a,*], Charles T. Driscoll[b], Colin M. Beier[c], Dallas Burtraw[d], Ivan J. Fernandez[e], James N. Galloway[f], David A. Gay[g], Christine L. Goodale[h], Gene E. Likens[i,j], Gary M. Lovett[i], Shaun A. Watmough[k]

[a] E&S Environmental Chemistry, Inc., P.O. Box 609, Corvallis, OR 97339, United States
[b] Civil & Environmental Engineering, Syracuse University, Syracuse, NY, United States
[c] Forest and Natural Resources Management, State University of New York College of Environmental Science and Forestry, Syracuse, NY, United States
[d] Resources for the Future, Washington, DC, United States
[e] School of Forest Resources & Climate Change Institute, University of Maine, Orono, ME, United States
[f] Department of Environmental Sciences, University of Virginia, Charlottesville, VA, United States
[g] Wisconsin State Laboratory of Hygiene, University of Wisconsin-Madison, Madison, WI, United States
[h] Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY, United States
[i] Cary Institute of Ecosystem Studies, Millbrook, NY, United States
[j] Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT, United States
[k] School of the Environment, Trent University, Peterborough, Ontario, Canada

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ABSTRACT

We summarize past examples of the use of science to document the effectiveness of policy in air quality management. Our goal is to inform public discourse amidst attempts to negate the relevance and value of scientific data and fact-based analysis in favor of partisan opinion and ideology. Although air quality is fundamental to environmental and human health, air pollution has degraded natural systems and reduced economic and cultural benefits and services. The quality of air and fresh water across much of the United States vastly improved in recent decades in response to the Clean Air and Clean Water Acts and other rules and policies. We point to recently observed decreases in air pollution and its effects attributable to policy that have been informed by environmental monitoring and research. Examples include decreased environmental lead contamination due to the elimination of tetraethyl lead from gasoline, decreases in tropospheric ozone, improved visibility from reduced airborne particulate matter, declines in atmospheric sulfur and nitrogen deposition that acidify the environment and declines in atmospheric mercury and subsequent bioaccumulation of toxic methyl mercury. Pollutant reductions have provided environmental, social, and economic benefits, highlighting the urgency to apply these lessons to address current critical environmental issues such as emissions of greenhouse gases. These examples underscore the important role of data from long-term research and monitoring as part of fact-based decision-making in environmental policy.

## 1. Introduction

Air and water quality have been long-standing concerns in the United States and elsewhere. However, evidence-based policy decisions and management have contributed to large improvements in environmental conditions over the recent past. Socio-economic, environmental, and public health benefits have been substantial. Across the United States, the quality of air and fresh water has vastly improved, mainly in response to the Clean Air and Clean Water Acts enacted nearly a half century ago. We have recently observed decreases in air pollution attributable to policy that have been informed by environmental monitoring and research. Examples illustrated here include decreased lead contamination due to the elimination of tetraethyl lead from gasoline, decreased ground-level (tropospheric) ozone, improved visibility and human health from reduced airborne particulate matter, declines in atmospheric sulfur and nitrogen deposition that acidify the environment, and declines in toxic mercury. None of these environmental stressors have been completely eliminated and further progress is needed, but all have been measurably reduced in the United States and elsewhere by evidence-based policy decisions. As we highlight here

* Corresponding author.
*E-mail address:* tim.sullivan@esenvironmental.com (T.J. Sullivan).

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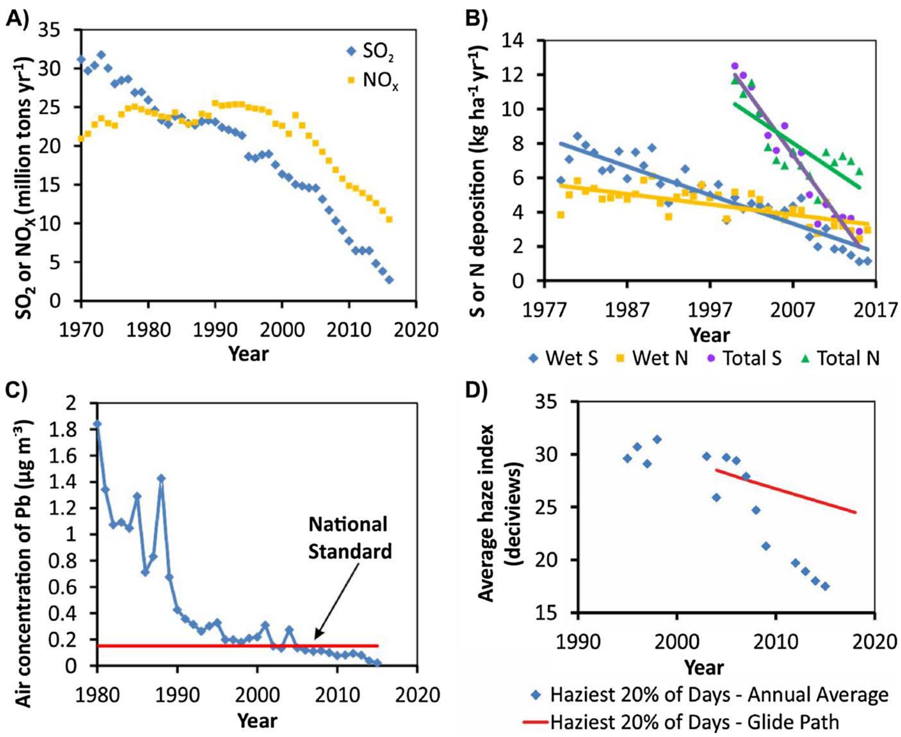


**Fig. 1.** Example time series trends in air pollution levels.
A) National emissions of oxidized nitrogen ($NO_x$) and sulfur dioxide ($SO_2$) throughout the U.S. from U.S. EPA's National Emissions Inventory.
B) Annual wet deposition of sulfur (S) and nitrogen (N) since 1979 as measured by the National Atmospheric Deposition Program at Huntington Forest, NY and total (wet plus dry) deposition estimated by Schwede and Lear (2014) since 2000 at Big Moose Lake, NY.
C) Mean air concentration of lead (Pb) measured at eight United States monitoring sites from 1980 to 2015. Data are annual maximum 3-month averages from U.S. EPA (https://www.epa.gov/air-trends/lead-trends).
D) Annual average haze index on the haziest 20% of days at Shining Rock Wilderness, NC, since 1995, plus the glide path of continuous improvement needed to meet the Regional Haze Rule requirement of zero human-caused haze by the year 2064. Data source: https://webcam.srs.fs.fed.us/graphs/vis/index.php?wilderness=shinin.

using examples across different regions and pollutants, substantial ecological and human health improvements and economic benefits to society have been realized. Many other examples are available, including regional measurements and model simulations that represent responses at dozens or hundreds of locations (cf., U.S. EPA 2013; Fakhraei et al., 2014; Driscoll et al., 2016; Fakhraei et al., 2016; Holmes and Likens, 2016; Sullivan, 2017). Evaluation of air pollution control policies and thresholds has been guided by advances in process science, monitoring data, and model development and application. Long-term measurements such as are reported here capture the accrued benefits of advances in science and technology that have supported the development of evidence-based regulations and public policy.

## 2. Analysis

### *2.1. Emissions and atmospheric deposition of oxides of sulfur and nitrogen*

There have been pronounced decreases in emissions and atmospheric deposition of sulfur and nitrogen oxide pollutants since the 1970s, especially throughout the eastern United States (Fig. 1A and B), although legacy damages have been observed. Some pollutants are not readily sequestered, and chemical recovery can take many decades or longer. Sulfur and nitrogen forms of acidifying air pollution are typically lower in the western states, with notable exceptions where nitrogen emissions and associated tropospheric ozone remain high, such as in parts of southern California. Higher air pollution impacts in the eastern United States are driven, in part, by the human population density and use of fossil fuels for energy and transportation in eastern and midwestern states and the dominant west to east direction of prevailing winds across the continent (U.S. EPA, 2009a).

Emissions of sulfur, mainly from coal-burning power plants, and oxidized nitrogen, originating mainly from motor vehicles and power plants, have decreased continuously and substantially across the United States in recent decades (Fig. 1A). While changes in technology and the economy undoubtedly contribute to these trends, reductions in sulfur and nitrogen pollution have been primarily attributed to emissions controls associated with the Clean Air Act, its amendments, and other rules and legislation (U.S. EPA, 2009a).

The National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/) is an example of high quality environmental monitoring that informs evidence-based decision making. This program, and others, was established in response to enactment and requirements of the Clean Air Act. It includes 270 wet deposition monitoring locations across the United States. Multi-decadal precipitation chemistry trends at an example Adirondack Mountain, NY, lake monitoring site that has been used for research on the effects of acidic deposition have shown marked decreases in sulfur and nitrogen deposition (Fig. 1B) in response to decreases in sulfur dioxide and nitrogen oxide emissions. Dry deposition of air pollutants is more difficult to measure, and is often estimated from models based on monitored air quality and environmental parameters. Estimated total wet plus dry deposition of sulfur and nitrogen have decreased by more than half across much of the eastern United States since monitoring began in the 1970s (Fig. 1B).

### *2.2. Emissions and atmospheric deposition of mercury*

Mercury is emitted into the atmosphere from a variety of sources, particularly coal-fired power plants. Mercury emissions from power plants, incinerators, industry, mining, and biomass burning can travel long distances before being deposited to the surface of the earth. In the United States, mercury emissions and deposition decreased substantially from a peak in the 1980s (Drevnick et al., 2012; Zhang et al., 2016), while in many other countries mercury emissions have continued to increase (Pirrone et al., 2010).

### *2.3. Acidification*

Atmospheric deposition of nitrogen, and especially sulfur, contributes to acidification of soils and surface waters that can harm terrestrial and aquatic life. Nitrogen deposition also contributes to aquatic and terrestrial eutrophication. Key acidification metrics for lakes and streams include the sulfate concentration (largely from atmospheric deposition), the concentration of toxic dissolved inorganic aluminum (dissolved from soil), pH (or hydrogen ion concentration), and acid neutralizing capacity. For example, the acidity of precipitation at Hubbard Brook Experimental Forest, NH, as reflected by the hydrogen

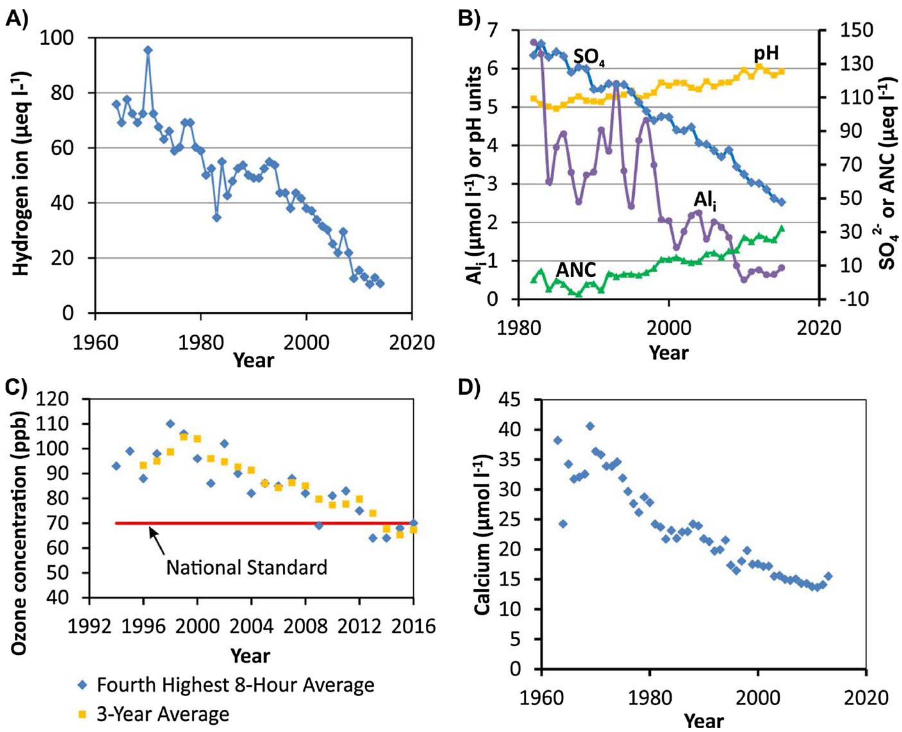


**Fig. 2.** Example time series trends in air pollution effects.
A) Decreasing concentrations of hydrogen ion in precipitation at Hubbard Brook Experimental Forest, NH over the period of available data. (Data source: Holmes and Likens 2016).
B) Water chemistry at Big Moose Lake, NY. Adverse impacts on aquatic life are generally associated with inorganic aluminum ($Al_i$) concentrations above 2 μM, pH below about 6.0, and acid neutralizing capacity (ANC) below 50 μeq $l^{-1}$ (U.S. EPA 2009a). Sulfate ($SO_4^{2-}$) is the major driver of effects. (Data source: Adirondack Lakes Survey Corporation [http://www.adirondacklakessurvey.org/]).
C) Atmospheric ozone concentration at Look Rock, Great Smoky Mountains National Park, TN, expressed as the fourth highest 8-hour annual average and three-year average concentration data. Note that ozone is considered as an “effect” because it forms in the atmosphere in response to emissions of its precursors nitrogen oxides and volatile organic compounds. Data source: https://www.epa.gov/outdoor-air-quality-data/monitor-values-report.
D) Decreasing concentration of calcium in streamwater at the Hubbard Brook Experimental Forest, NH, reference watershed, in part reflecting delayed recovery of the soil from acidification.

ion concentration, decreased by more than 60 μeq $l^{-1}$ since monitoring began in the 1960s (Fig. 2A). Recent improvements in water quality and acid-base chemistry have been documented for hundreds of montane surface waters such as Big Moose Lake in the Adirondack Park (Fig. 2B; Fakhraei et al., 2014; Driscoll et al., 2016), including decreasing trends in sulfate and inorganic aluminum concentrations, and increasing acid neutralizing capacity. Improvements in water quality in response to decreasing atmospheric sulfur and nitrogen deposition have also been reported for many other surface waters throughout the northeastern United States (Stoddard et al., 1999; Strock et al., 2014), along with the first evidence of improvements in soil chemistry (Lawrence et al., 2015). A critically important characteristic of environmental quality is that recovery processes are complex and vary in time. Improvements in the environment in response to improvements in air quality often unfold over years, decades and longer. Atmospheric sulfur and nitrogen deposition and associated effects data show clear improvements evident now. They represent the beginnings of processes of chemical and biological recovery that will continue to emerge over the next century.

### 2.4. Lead

One of the earliest air pollution abatement successes in the United States was the removal of lead-based fuel additives from gasoline, resulting in a > 95% decrease in the concentration of lead in the air (Fig. 1C). Lead causes neurological damage to children and cardiovascular effects in adults, with a strong linear correlation between levels in human blood and air (Thomas et al., 1999). Decreases in environmental lead contamination from atmospheric deposition have been documented in response to lead emissions regulation (Holmes and Likens, 2016), although lead can be strongly held in soil organic matter (Richardson et al., 2015). The redistribution of lead in ecosystems will remain a concern for decades (Kaste et al., 2006).

### 2.5. Haze

Haze affects how far and how clearly we can see. Visibility can be degraded by light scattering and absorption caused by gasses and particles in the air. Throughout the eastern United States, the most important source of the resulting haze has been ammonium sulfate (http://vista.cira.colostate.edu/Improve/), which derives mainly from human-caused emissions of sulfur dioxide and ammonia. Haze impairs the value of the visitor experience in natural areas (Sullivan, 2017). Federal regulations, as reflected in the Regional Haze Rule, require that states develop plans to reduce haze to natural background by the year 2064 in highly protected national parks and wilderness areas designated as Class I areas. It also requires that states make reasonable progress by following a continuous reduction glide path to natural conditions on the 20% haziest days. Measurements at the Shining Rock Wilderness, NC, indicate that haze levels on the haziest days at this Class I site are decreasing at a rate faster than defined by the Regional Haze Rule (Fig. 1D). Similar observations have been documented at many eastern national parks (Sullivan, 2017), although smoke from forest fires has been an increasingly important component of haze in recent years in many parts of the western United States.

### 2.6. Ozone

Near ground level in the lowest layer of the atmosphere known as the troposphere, ozone is a gaseous component of smog, formed by atmospheric reactions between nitrogen oxides and volatile organic compounds in the presence of sunlight. Tropospheric ozone is a greenhouse gas and also harms the health of both humans and vegetation (U.S. EPA, 2013). Ozone concentrations are especially high in and downwind of urban areas and at many remote mountainous locations due to atmospheric transport of ozone precursors (Sullivan, 2017). The current National Ambient Air Quality Standard for ozone to protect human and environmental health is equivalent to 70 parts per billion, based on the annual fourth highest daily maximum 8-hour concentration and averaged over a 3-year period. Ozone concentrations at many Class I areas have decreased markedly in recent years (Fig. 2C; U.S. EPA, 2013; Sullivan, 2017).

### 2.7. Mercury bioaccumulation

Once deposited to soils and water bodies, mercury can be methylated and bioaccumulate in the food web, reaching toxic levels in fish.

Game fish, wildlife, and humans who consume contaminated fish can suffer neurological damage from high exposure. Consumption of tuna is the largest source of human mercury exposure in the United States (Sunderland, 2007). However, there is evidence that mercury bioaccumulation is decreasing. For example, concentrations of mercury in Atlantic bluefin tuna (*Thunnus thynnus*) have decreased markedly in recent years due to emission controls (Lee et al., 2016).

### *2.8. Ongoing challenges*

Despite these successes, we have not eliminated all health and welfare risks from these air pollutants, and others warrant action to evaluate trends in exposure, health, and welfare risk. For example, emissions and deposition of ammonia, which is not regulated in the United States and derives largely from agriculture and motor vehicles, have generally not decreased and in many areas have increased (Parker et al., 2009; Warner et al., 2017).

Some areas that historically received high sulfur and nitrogen deposition reflect a legacy of soil depletion of calcium and other important base cation nutrients, affecting the health and regeneration of calciphylic plants like sugar maple (Sullivan et al., 2013; Holmes and Likens, 2016). Even under much reduced levels, continued sulfur and nitrogen deposition have constrained the recovery of soil base nutrient status and tree growth. For example, at the Hubbard Brook Experimental Forest, soil calcium depletion caused by acidification left a legacy of damage that may take many decades or longer to reverse (Likens, 2013; Fig. 2D), and forest decline attributable partly to acidification was reversed by experimental calcium addition (Battles et al., 2014). Even with the improvements discussed here, additional emissions reductions and/or time may be needed for full recovery, particularly for sensitive components of ecosystems, at this experimental forest and at other locations across the country. Maintaining critical long-term monitoring and associated research will remain fundamental to developing informed evaluations and decisions that define cost-effective policies for the 21st century.

### *2.9. Effects on human well-being*

Globally, it has been estimated that air pollution contributes to the premature deaths of millions of people each year (U.S. EPA, 2009b; West et al., 2016; Landrigan et al., 2017). Air pollution that degrades ecosystem health has reduced the economic and cultural benefits and services that natural ecosystems provide (Beier et al., 2017). Examples include forestry, tourism, fisheries, greenhouse gas mitigation and others. Air quality is fundamental to human and ecosystem health. Outdoor exposure to polluted air contributes to a wide range of human ailments associated with asthma, other respiratory disease, cardiovascular disease, and lung cancer (Brook et al., 2010; Loomis et al., 2013). Improvements via the Clean Air Act over the period 1970 to 1990 provided the United States an estimated $22 trillion in cumulative human health and reduced mortality benefits, with about $0.5 trillion (1990 dollars) in implementation costs. The 1990 Clean Air Act Amendments are estimated to yield additional health and monetary benefits equal to $2 trillion in 2020, with compliance costs of approximately $65 billion in that year (U.S. EPA Office of Air and Radiation, 2011). Projected economic benefits are attributable to preventing about 230,000 cases of premature mortality in 2020; preventing morbidity, including acute myocardial infarctions and chronic bronchitis; and improving the quality of environmental resources, the largest component of which is willingness to pay for improved visibility.

## 3. Conclusions

Many of the air pollution issues highlighted here have common sources. Thus, cleaning up sources of one pollutant can yield co-benefits with respect to other pollutants. For example, mitigation of water and soil acidification through controls on sulfur emissions from electricity generating units reduces emissions of mercury, particulate matter, and ozone precursors, as well as acidifying compounds.

We increasingly hear public narratives that appear to be grounded in a post-truth world, where empirical evidence and science take a back seat to ideology. Perhaps nowhere is this disregard for facts more evident than in discourse on environmental policy. Environmental scientists are generally effective at analyzing data to assess risk, and communicating those findings through time-tested mechanisms of scientific peer review. We are less skilled at communicating successes and their scientific foundations to the public and policy-makers, despite many clear and cost-effective examples of success from local to global scales. Many of those successes are highlighted with concrete examples here. In a recent editorial, Lubchenco (2017) encouraged scientists to confront the new, and increasingly unsettling, post-truth world by demonstrating the value and relevance of science. We show here important examples of how environmental research and monitoring have informed air quality policy that has reduced adverse effects of pollutants on humans and ecosystems. Pollutant reductions provide environmental, social, and economic benefits. These examples show how we can sustain and enhance these improvements and highlight the urgency to apply these lessons to critical issues such as rising emissions of greenhouse gases. They underscore the importance of data and fact-based decision-making. Continued environmental monitoring and associated research will be even more essential in confronting the accelerating changes that lie ahead in order to track improvements, avoid reversals, and identify emerging threats.

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## References

Battles, J.J., Fahey, T.J., Driscoll, C.T., Blum, J.D., Johnson, C.E., 2014. Restoring soil calcium reverses forest decline. Environ. Sci. Technol. Lett. 1 (1), 15–19. http://dx.doi.org/10.1021/ez400033d.

Beier, C.M., Caputo, J., Lawrence, G.B., Sullivan, T.J., 2017. Loss of ecosystem services due to chronic pollution of forests and surface waters in the Adirondack region (USA). J. Environ. Manage. 191, 19–27. http://dx.doi.org/10.1016/j.jenvman.2016.12.069.

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L., Kaufman, J.D., 2010. Particulate matter air pollution and cardiovascular disease. Circulation 121 (21), 2331.

Drevnick, P.E., Engstrom, D.R., Driscoll, C.T., Swain, E.B., Balogh, S.J., Kamman, N.C., Long, D.T., Muir, D.G.C., Parsons, M.J., Rolfhus, K.R., Rossmann, R., 2012. Spatial and temporal patterns of mercury accumulation in lacustrine sediments across the Laurentian Great Lakes region. Environ. Pollut. 161, 252–260.

Driscoll, C.T., Driscoll, K.M., Fakhraei, H., Civerolo, K., 2016. Long-term temporal trends and spatial patterns in the acid-base chemistry of lakes in the Adirondack region of New York in response to decreases in acidic deposition. Atmos. Environ. 146, 5–14. http://dx.doi.org/10.1016/j.atmosenv.2016.08.034.

Fakhraei, H., Driscoll, C.T., Selvendiran, P., DePinto, J.V., Bloomfield, J., Quinn, S., Rowell, H.C., 2014. Development of a total maximum daily load (TMDL) for acid-impaired lakes in the Adirondack region of New York. Atmos. Environ. 95, 277–287. http://dx.doi.org/10.1016/j.atmosenv.2014.06.039.

Fakhraei, H., Driscoll, C.T., Renfro, J.R., Kulp, M.A., Blett, T.F., Brewer, P.F., Schwartz, J.S., 2016. Critical loads and exceedances for nitrogen and sulfur atmospheric deposition in Great Smoky Mountains National Park, United States. Ecosphere 7 (10), 1–28. http://dx.doi.org/10.1002/ecs2.1466.

Holmes, R.T., Likens, G.E., 2016. Hubbard Brook: The Story of a Forest Ecosystem. Yale University Press 271 pp.

Kaste, J.M., Bostick, B.C., Friedland, A.J., Schroth, A.W., Siccama, T.G., 2006. Fate and speciation of gasoline-derived lead in organic horizons of the Northeastern USA. Soil Sci. Soc. Am. J. 70 (5), 1688–1698. http://dx.doi.org/10.2136/sssaj2005.0321.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K.V., McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2017. The lancet commission on pollution and health. Lancet. http://dx.doi.org/10.1016/S0140-6736(17)32345-0.

Lawrence, G.B., Hazlett, P.W., Fernandez, I.J., Ouimet, R., Bailey, S.W., Shortle, W.C., Smith, K.T., Antidormi, M.R., 2015. Declining acidic deposition begins reversal of forest-soil acidification in the northeastern U.S. and eastern Canada. Environ. Sci. Technol. 49, 13103–13111.

Lee, C.-S., Lutcavage, M.E., Chandler, E., Madigan, D.J., Cerrato, R.M., Fisher, N.S., 2016. Declining mercury concentrations in bluefin tuna reflect reduced emissions to the North Atlantic Ocean. Environ. Sci. Technol. 50 (23), 12825–12830. http://dx.doi.org/10.1021/acs.est.6b04328.

Likens, G.E., 2013. Biogeochemistry of a Forested Ecosystem, 3rd ed. Springer, New York 208 pp.

Loomis, D., Grosse, Y., Lauby-Secretan, B., Ghissassi, F.E., Bouvard, V., Benbrahim-Tallaa, L., Guha, N., Baan, R., Mattock, H., Straif, K., 2013. The carcinogenicity of outdoor air pollution. Lancet Oncol. 14 (13), 1262–1263. http://dx.doi.org/10.1016/S1470-2045(13)70487-X.

Lubchenco, J., 2017. Environmental science in a post-truth world. Front. Ecol. Environ. 15 (1). http://dx.doi.org/10.1002/fee.1454. 3-3.

Parker, B.R., Schindler, D.W., Beaty, K.G., Stainton, M.P., Kasian, S.E.M., 2009. Long-term changes in climate, streamflow, and nutrient budgets for first-order catchments at the Experimental Lakes Area (Ontario, Canada). This paper is part of the series "Forty years of aquatic research at the experimental Lakes Area". Can. J. Fish. Aquat. Sci. 66 (11), 1848–1863. http://dx.doi.org/10.1139/F09-149.

Pirrone, N., Cinnirella, S., Feng, X., Finkelman, R.B., Friedli, H.R., Leaner, J., Mason, R., Mukherjee, A.B., Stracher, G.B., Streets, D.G., Telmer, K., 2010. Global mercury emissions to the atmosphere from anthropogenic and natural sources. Atmos. Chem. Phys. 10, 5951–5964.

Richardson, J.B., Donaldson, E.C., Kaste, J.M., Friedland, A.J., 2015. Forest floor lead, copper and zinc concentrations across the northeastern United States: synthesizing spatial and temporal responses. Sci. Total Environ. 505 (Supplement C), 851–859. http://dx.doi.org/10.1016/j.scitotenv.2014.10.023.

Schwede, D.B., Lear, G.G., 2014. A novel hybrid approach for estimating total deposition in the United States. Atmos. Environ. 92, 207–220. http://dx.doi.org/10.1016/j.atmosenv.2014.04.008.

Stoddard, J.L., Jeffries, D.S., Lükewille, A., Clair, T.A., Dillon, P.J., Driscoll, C.T., Forsius, M., Johannessen, M., Kahl, J.S., Kellogg, J.H., Kemp, A., Mannio, J., Monteith, D.T., Murdoch, P.S., Patrick, S., Rebsdorf, A., Skjelkvale, B.L., Stainton, M.P., Traaen, T., Van Dam, H., Webster, K.E., Wieting, J., Wilander, A., 1999. Regional trends in aquatic recovery from acidification in North America and Europe. Nature 401, 575–578.

Strock, K.E., Nelson, S.J., Kahl, J.S., Saros, J.E., McDowell, W.H., 2014. Decadal trends reveal recent acceleration in the rate of recovery from acidification in the northeastern U.S. Environ. Sci. Technol. 48 (9), 4681–4689. http://dx.doi.org/10.1021/es404772n.

Sullivan, T.J., Lawrence, G.B., Bailey, S.W., McDonnell, T.C., Beier, C.M., Weathers, K.C., McPherson, G.T., Bishop, D.A., 2013. Effects of acidic deposition and soil acidification on sugar maple in the Adirondack Mountains, New York. Environ. Sci. Technol. 47, 12687–12694. http://dx.doi.org/10.1021/es401864w.

Sullivan, T.J., 2017. Air Pollution and Its Impacts on U.S. National Parks. CRC Press, Boca Raton, FL 638 pp.

Sunderland, E.M., 2007. Mercury exposure from domestic and imported estuarine and marine fish in the U.S. seafood market. Environ. Health Perspect. 115 (2), 235–242. http://dx.doi.org/10.1289/ehp.9377.

Thomas, V.M., Socolow, R.H., Fanelli, J.J., Spiro, T.G., 1999. Effects of reducing lead in gasoline: an analysis of the international experience. Environ. Sci. Technol. 33 (22), 3942–3948. http://dx.doi.org/10.1021/es990231+.

U.S. Environmental Protection Agency, 2009a. Risk and Exposure Assessment for Review of the Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Oxides of Sulfur: Final. EPA-452/R-09-008a. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division, Research Triangle Park, NC.

U.S. Environmental Protection Agency, 2009b. Integrated Science Assessment for Particulate Matter (Final Report). EPA/600/R-08/139F. U.S. Environmental Protection Agency, Washington, DC Available at: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=216546.

U.S. Environmental Protection Agency, 2013. Integrated Science Assessment for Ozone and Related Photochemical Oxidants. EPA 600/R-10/076F. Office of Research and Development, National Center for Environmental Assessment-RTP Division, Research Triangle Park, NC.

U.S. Environmental Protection Agency Office of Air and Radiation, 2011. The Benefits and Costs of the Clean Air Act from 1990 to 2020. Final Report – Rev. A (April). Available at: https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf. .

Warner, J.X., Dickerson, R.R., Wei, Z., Strow, L.L., Wang, Y., Liang, Q., 2017. Increased atmospheric ammonia over the world's major agricultural areas detected from space. Geophys. Res. Lett. 44 (6). http://dx.doi.org/10.1002/2016GL072305. 2016GL072305.

West, J.J., Cohen, A., Dentener, F., Brunekreef, B., Zhu, T., Armstrong, B., Bell, M.L., Brauer, M., Carmichael, G., Costa, D.L., Dockery, D.W., Kleeman, M., Krzyzanowski, M., Künzli, N., Liousse, C., Lung, S.-C.C., Martin, R.V., Pöschl, U., Pope, C.A., Roberts, J.M., Russell, A.G., Wiedinmyer, C., 2016. What we breathe impacts our health: improving understanding of the link between air pollution and health. Environ. Sci. Technol. 50 (10), 4895–4904. http://dx.doi.org/10.1021/acs.est.5b03827.

Zhang, Y., Jacob, D.J., Horowitz, H.M., Chen, L., Amos, H.M., Krabbenhoft, D.P., Slemr, F., St. Louis, V.L., Sunderland, E.M., 2016. Observed decrease in atmospheric mercury explained by global decline in anthropogenic emissions. Proc. Nat. Acad. Sci. 113 (3), 526–531. http://dx.doi.org/10.1073/pnas.1516312113.