Contemporary Issues in Québec's Temperate Forest — Part 3: Air Pollutants

by Louis Duchesne,[1] Rock Ouimet[1], François Guillemette[1] and Steve Bédard[1]

ABSTRACT

This paper is the third in a series documenting contemporary issues in Québec's temperate forest. It addresses air pollutants, including the acidifying air pollutants that cause acid rain, as well as ground-level ozone and trace elements. It briefly discusses the anthropogenic sources of these pollutants, their current status, their impacts on forest ecosystems and the issues they cause for Québec's temperate forest. Most air pollutants come from combustion of fossil fuels for energy production or transportation. Since the mid-1990s, thanks to pollutant emission reduction programs implemented in Canada and the United States, emissions and ambient air concentrations of most pollutants have declined significantly. Sugar maple (*Acer saccharum* Marsh.), a dominant species in the northern temperate zone, is especially sensitive to air pollutants and their impacts for ecosystems. Previous chronic pollution of these forests has resulted in significant loss of ecosystem services. However, environmental monitoring is ongoing with a view to documenting ecosystem reactions in the wake of contemporary decreases in anthropogenic emissions of air pollutants in North America.

Keywords: air pollution, acid rain, acidifying emissions, air quality, heavy metals

RÉSUMÉ

Cet article est le troisième d'une série qui vise à documenter les enjeux contemporains en forêt tempérée au Québec. Nous y abordons plus spécifiquement les polluants atmosphériques, notamment les polluants atmosphériques acidifiants à l'origine du phénomène des pluies acides, l'ozone troposphérique et les éléments traces. Nous discutons brièvement des sources anthropiques de ces polluants, de l'état de la situation, de leurs effets sur les écosystèmes forestiers et des enjeux qui en découlent pour la forêt tempérée au Québec. Les polluants atmosphériques proviennent majoritairement de la combustion de combustibles fossiles pour la production d'énergie et pour le secteur des transports. Depuis le milieu des années 1990, grâce aux programmes de réduction des émissions de polluants atmosphériques mis en œuvre au Canada et aux États-Unis, les émissions et les concentrations dans l'air ambiant de la plupart des polluants ont baissé significativement. L'érable à sucre (*Acer saccharum* Marsh.), une essence dominante dans la zone tempérée nordique, s'avère particulièrement sensible aux polluants atmosphériques et à leurs effets sur les écosystèmes. La pollution chronique historique de ces forêts engendre donc une perte de services écosystémiques importante. Des suivis environnementaux des écosystèmes forestiers se poursuivent afin de documenter la réaction des écosystèmes forestiers à la baisse contemporaine des émissions anthropiques de polluants atmosphériques en Amérique du Nord.

Mots-clés : pollution atmosphérique, pluies acides, émissions acidifiantes, qualité de l'air, métaux lourds

1 Direction de la recherche forestière, Ministère des Ressources naturelles et des Forêts du Québec, 2700, rue Einstein, Québec (Québec) G1P 3W8, Canada

*Corresponding author: francois.guillemette@mrnf.gouv.qc.ca

Introduction

Other than carbon monoxide (CO) which, once in the atmosphere, is converted into carbon dioxide (CO_2) and plays a major role in climate change[2], there are several air pollutants that are harmful to forest ecosystems. They include the acidifying pollutants that cause acid rain (most notably sulphur dioxide [SO_2] and the nitrogen oxides [NO_x]), as well as tropospheric or ground-level ozone and trace elements.

In this third paper of a series on contemporary issues in Québec's temperate forests (see Part 1: Duchesne *et al.* (*In press*) for a definition of the area under study), we synthesize the existing literature on the anthropogenic sources of these pollutants, along with their current status, their impacts on forest ecosystems and the issues to which they give rise in Québec.

Acidifying air pollutants

Acidifying air pollutants (SO_2 and NO_x) are created mainly by fossil fuel combustion for energy production. In North America, the main SO_2 emitters are the petroleum and gas industry, the coal-fired energy sector and the non-ferrous metal smelting and refining industries. As for NO_x, the transportation sector is the main source, followed by the petroleum and gas industry and the coal-fired energy sector (ECCC 2023a). When these pollutants come into contact with atmospheric water vapour, they are converted respectively into sulphuric acid (H_2SO_4) and nitric acid (HNO_3), both of which can be transported over long distances by dominant winds before falling to earth in wet or dry form. These pollutants are the main causes of "acid rain", a phenomenon that has been shown to be harmful to terrestrial and aquatic ecosystems and infrastructures.

In recent decades, Canada and the provinces have entered into a series of national and international agreements aimed at reducing air pollutant emissions. They include: the *United Nations Economic Commission for Europe's*, initiated in 1979, and followed by the *Canada-US Air Quality Agreement* in 1991, the *Canada-Wide Acid Rain Strategy for Post-2000*, ratified in 1998, and the *Acid Rain Action Plan* adopted by the New England Governors and Eastern Canada Premiers, also in 1998. Various measures, including in the electrical energy sector, have been introduced since then and have resulted in a major reduction in air emissions and SO_2 and NO_x deposits in both Canada and the United States (ECCC 2023a). Measurements carried out by atmospheric precipitation chemistry monitoring networks showed a subsequent reduction of roughly 60% in sulphate deposits (SO_4), and 30% in nitrate deposits (NO_3) in eastern North America between 1990 and 2019 (Fig. 1, Cheng *et al.* 2022). Measurements taken at three stations operated by the Forest Ecosystem Research and Monitoring Network (RESEF) confirm these trends in Québec, with a significant reduction in SO_2 and NO_3 concentrations and an increase in precipitation pH values (see Fig. 2 showing trends at the station located in the northern temperate zone). Although the situation has improved, however, acidifying pollutants continue to cause concern and are responsible for significant environmental impacts, according to the conclusions of the last status report on the Air Quality Agreement published in 2023 (ECCC 2023a).

Acid rain damages the foliar organs of trees and disturbs the activities of enzymes, micro-organisms and mycorrhizal fungi (Zhang *et al.* 2023). It also impoverishes and acidifies forest ecosystem soils, increasing the availability of toxic metals in acid soils, and can cause nutrient deficiencies for trees, threatening long-term forest productivity (Likens *et al.* 1996; Houle *et al.* 1997; Driscoll *et al.* 2001; Duchesne and Houle 2006, 2008; Johnson *et al.* 2008; Zhang *et al.* 2023). The effects of acidification depend on the soil's pH, which determines its buffering capacity, and the Ca/Al ratio is a good indicator of aluminum toxicity, which, in large quantities, harms root cell division and is only minimally translocated within the plant.

The phenomenon is especially concerning for sugar maple, a species that is eminently sensitive to soil acidity and the availability of calcium (Ca) and magnesium (Mg) cations. This sensitivity has been shown in numerous studies linking growth, abundance, nutritional status, mortality, survival, photosynthesis and dieback symptoms in sugar maple to soil fertility and basic cation availability (Table 1). The impacts of soil fertility on the species' performance parameters have also been proved on several occasions by experiments in the forests and in controlled environments (Table 1). Some of these studies have shown that American beech is much less sensitive to soil fertility and basic cation availability than sugar maple (Table 1). Based on this, acid rain has been identified as one of the factors in the emergence of maple dieback in the early 1980s and the proliferation of American beech in declining maple stands.

Using the critical load for ecosystem acidity – i.e. the acidity load that an ecosystem can absorb over the long term without being damaged – the scientific community has been able to quantify the occurrence and severity of acid deposit effects in the forest ecosystems of eastern North America (Ouimet *et al.* 2001, 2006; Burns *et al.* 2008; Clark *et al.* 2018; Cathcart *et al.* 2024). The margin by which the critical load for ecosystem acidity has been exceeded has declined significantly since the early 2000s in line with the contemporary reduction in precipitation acidity (Cheng *et al.* 2022), and signs of improved soil fertility are beginning to appear (Lawrence *et al.* 2015; Hazlett *et al.* 2020; Lawrence and Bailey 2021). However, it is likely to be many decades before soil fertility is back to its pre-anthropogenic acidification level (Caputo *et al.* 2016; Watmough *et al.* 2016). At equilibrium with atmospheric CO_2, uncontaminated rain has a slightly acidic pH of approximately 5.6. Although the situation has improved, atmospheric inputs of nitrogen are still of concern (Pardo *et al.* 2019). While nitrogen is essential to plant growth, chronic inputs to forest ecosystems can saturate soils, leading to runoff and impoverishment of cations. Long-term experiments with chronic nitrogen inputs have shown that maple stands are especially sensitive (Moore and Houle 2023), while boreal forests appear to be extremely resilient (Houle *et al.* 2024a, 2024b).

Given the dominance of sugar maple in northeastern North America's temperate zone and the size of the area characterized by soils with low buffer capacity, past chronic pollution of the forests by acidifying air pollutants has caused significant loss of ecosystem services. For example, even in the early 1980s, it was estimated that two million tapholes (roughly 15% of the total

[2] Duchesne, L., F. Guillemette, S., Bédard and R. Ouimet. (Under review). Contemporary Issues in Québec's Temperate Forest — Part 4: Climate changes. Submitted to For. Chron.

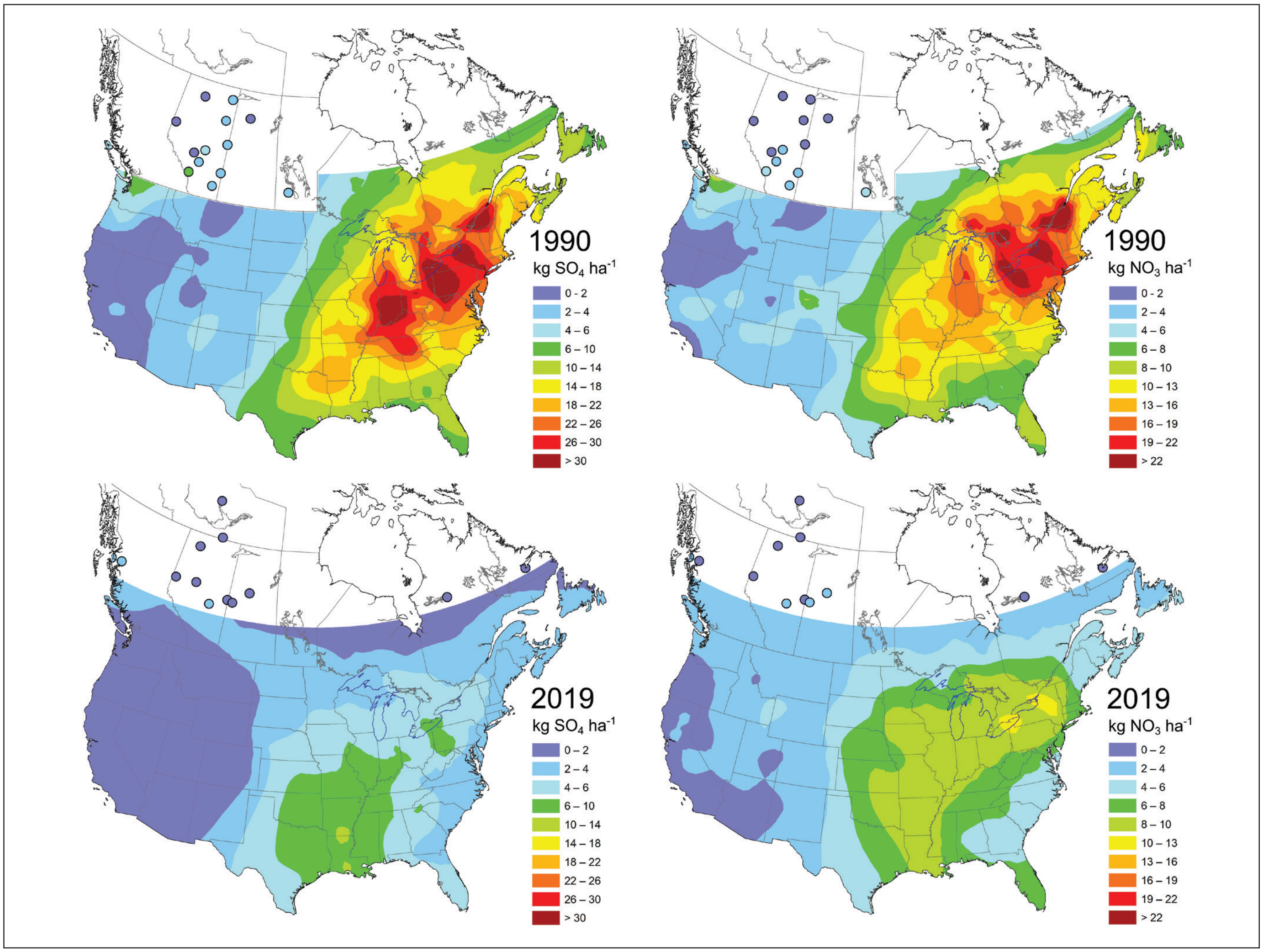

Fig. 1. Evolution of annual wet deposition of non-sea-salt sulphates (SO_4, left-hand column) and nitrates (NO_3, right-hand column) in North America from 1990 (top row) to 2019 (bottom row). Source: Air Quality Research Division, Environment and Climate Change Canada, Wet Deposition Maps – ECCC Data Catalogue.

Table 1. Examples of research documenting relationships between growth, abundance, nutritional status, mortality, survival, photosynthetic activity, sugar maple dieback symptoms and soil fertility, as well as sugar maple sensitivity to soil fertility, through experiments conducted in forests and controlled environments.

Study type	**References (in ascending chronological order)**
Relationship study for sugar maple	Bernier et Brazeau 1988a, 1988b, 1988c; Bernier *et al.* 1989; Ouimet et Camiré 1995, Ouimet *et al.* 1995; Wilmot *et al.* 1995; van Breemen *et al.* 1997; Horsley *et al.* 2000; McLaughlin *et al.* 2000; Arii *et al.* 2002, 2005; Drohan *et al.* 2002; Duchesne *et al.* 2002; Watmough 2002; St. Clair *et al.* 2005; Hallett *et al.* 2006; Kogelmann *et al.* 2006; Schaberg *et al.* 2006; Houle *et al.* 2007; Zaccherio *et al.* 2007; Page et Mitchell 2008; Long *et al.* 2009; Park et Yanai 2009; Bilodeau-Gauthier *et al.* 2011; Watmough et al. 2010; Sullivan *et al.* 2013; Pitel *et al.* 2014; Bishop *et al.* 2015; Cleavitt *et al.* 2018; Fernando *et al.* 2016; Lawrence *et al.* 2018; Soubeyrand *et al.* 2024
Experiments for sugar maple	Hendershot 1991; Ouimet et Fortin 1992; Paré *et al.* 1993; Ouimet *et al.* 1996a, 1996b; Wilmot *et al.* 1996; Long *et al.* 1997; Burke *et al.* 1998; Moore *et al.* 2000, 2008, 2012; Kobe *et al.* 2002; Wargo *et al.* 2002; Bailey *et al.* 2004; Juice *et al.* 2006; Moore et Ouimet 2006, 2014, 2021; Bigelow et Canham 2007; Huggett *et al.* 2007; Gradowski et Thomas 2008; Ouimet *et al.* 2008, 2017; Minocha *et al.* 2010; Cleavitt *et al.* 2011; Long *et al.* 2011; Duchesne *et al.* 2013; Halman *et al.* 2013, 2015; Battles *et al.* 2014; Marlow et Peart 2014; Long *et al.* 2015; Momen *et al.* 2015; Nolet *et al.* 2015; Collin *et al.* 2017, 2018; Bognounou *et al.* 2023
Comparison of the sensitivity of sugar maple and American beech	Long *et al.* 1997; van Breemen *et al.* 1997; Arii *et al.* 2002, 2005; Kobe *et al.* 2002; Bigelow et Canham 2007; Page et Mitchell 2008; Moore *et al.* 2008; Park et Yanai 2009; Minocha *et al.* 2010; Long *et al.* 2011; Duchesne *et al.* 2013; Marlow et Peart 2014; Battles *et al.* 2014; Halman *et al.* 2015; Nolet *et al.* 2015; Ouimet *et al.* 2017; Cleavitt *et al.* 2018; Lawrence *et al.* 2018; Bognounou *et al.* 2023; Tourville *et al.* 2023
Discussions and literature reviews	Jones et Hendershot 1989; St. Clair *et al.* 2008; Bal *et al.* 2015; West *et al.* 2023

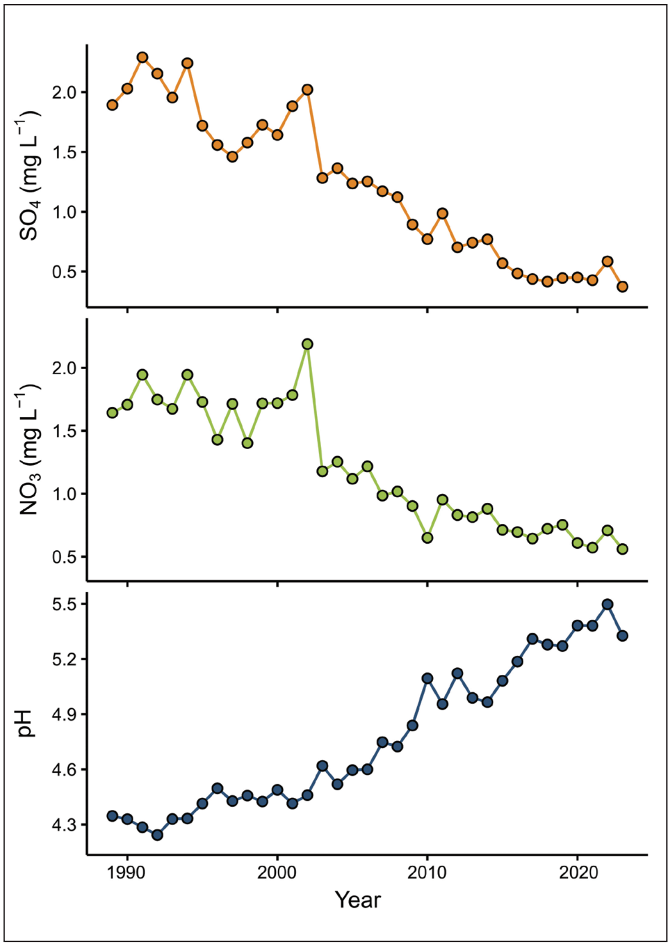

Fig. 2. Evolution in average annual concentrations of sulphates (SO_4) and nitrates (NO_3) and precipitation pH, measured at the Lac Clair station (Station touristique Duchesnay, Québec, Canada) by Québec's Forest Ecosystem Monitoring and Research Network for the period 1989–2023.

number of tapholes in Québec at the time) were lost due to sugar maple dieback, generating financial losses of tens of millions of dollars for maple syrup producers (Jones and Hendershot 1998). In the Adirondacks, deciduous forests damaged by acidity provide only half the potential benefits of forests on moderately to well-buffered soils (i.e., non-acidified soils) due to lost net present value for wood products, maple syrup, carbon sequestration and visual quality (Beier *et al.* 2017). In addition, the impacts of acid rain on the region's forest ecosystems limit the possibilities for sustainable ecosystem management and consequently reduce their potential economic and cultural value for present and future generations (Caputo *et al.* 2016). Among other things, although appropriate silviculture may be able to regenerate sugar maple trees on well-buffered soils, it is very unlikely that new natural maple cohorts will become established on acidified soils (Caputo *et al.* 2016). This suggests that the maple stands currently growing on acidified soils are an ecological legacy. Depending on the harvesting scenarios chosen, sugar maple is therefore likely to be replaced in the medium or longer term by species such as red maple and American beech. Given that poorly-buffered soils will take decades to recover completely from acidification, the change in composition will be a long-lasting legacy of acid rain (Caputo *et al.* 2016).

Tropospheric or ground-level ozone

Tropospheric or ground-level ozone (O_3) is not emitted as a pollutant but is what is referred to as a "secondary" pollutant that forms as a result of photochemical reactions between NO_x, volatile organic compounds (VOCs) and other pollutants present in the air. Triggered by ultraviolet rays, nitrogen dioxide (NO_2) reacts with the oxygen in the air to produce O_3. However, nitrogen monoxide (NO) reacts quickly with O_3, temporarily reducing O_3 concentrations. Because of this, O_3 concentrations are usually lower near urban areas due to the presence of traffic, and higher in rural areas and remote forests located far from NO emission points (Ainsworth *et al.* 2012; MELCCFP 2023, 2024).

The transportation sector is the main source of O_3 precursor pollutants, followed by industrial activity, residential heating, energy production and liquid fuel/solvent evaporation (ECCC 2023a). Thanks to the air pollutant emission reduction programs implemented in Canada and the United States, ambient air precursor pollutant concentrations and maximum O_3 values have tended to decline in the Canada-United States border zone since the mid-1990s (ECCC 2023a). In Québec, however, O_3 concentrations have increased in urban areas over the last decade but are stable or slightly lower in rural and forest stations (MELCCFP 2023). Data for Québec show that O_3 concentrations have not exceeded the eight-hour Canadian Ambient Air Quality Standard (CAAQS) of 62 ppb (parts per billion) since 2012-2014 but are very close to that level at numerous air quality measuring stations (MELCCFP 2024). However, there were 327 occurrences of levels exceeding the eight-hour O_3 standard (64 ppb) set out in the provincial *Clean Air Regulation* (CAR) at Québec's 48 air quality monitoring stations in 2021 (MELCCFP 2023). This is the highest number since the CAR came into force in 2012. It is due, among other things, to weather conditions conducive to O_3 accumulations, including high temperatures, that have affected both the northeastern United States and southern portions of Ontario and Québec. It is important to note that the apparent contradiction between compliance with the federal and provincial standards is due to the different statistical forms used. While the provincial standard refers to the average concentrations over an 8-hour period, the Canadian standard refers to the three-year average of the annual fourth highest of the daily maximum 8-hour average ozone concentrations.

O_3 toxicity for trees, especially sugar maple, has long been of concern (Hibben 1969). Generally speaking, hardwood species are more sensitive to high O_3 concentrations than softwood species (Wittig *et al.* 2009; Lee *et al.* 2022). The impacts of high O_3 concentrations for trees include reduced growth and a significant decrease in respiration, foliar surface, Rubisco (a key enzyme in photosynthesis) and chlorophyll, which may have caused photosynthetic capacity to decrease significantly (Wittig *et al.* 2009). O_3 is a powerful oxidant; tissues that are more fragile and less protected by waxes or layers of protective cells are more susceptible to damage, particularly the organs involved in photosynthesis. However, the O_3 action mechanism has yet to be clarified (Dizengremel *et al.* 2001).

For sugar maple, experiments have shown that high O_3 concentrations may reduce growth (Topa *et al.* 2001, 2004; Gaucher *et al.* 2003, 2006; Karnosky *et al.* 2005; King *et al.* 2005); alter structure, speed up leaf senescence and reduce photosynthesis, CO_2 absorption and stomatal conductance (Carlson 1979; Reich and Amundson 1985; Reich *et al.* 1986; Tjoelker *et al.* 1995; Bäck *et al.* 1999; Ainsworth *et al.* 2012); hinder mycorrhiza development (Duckmanton and Widden

1994); reduce biological performance and alter the food preferences of defoliating insects, including the forest tent caterpillar (Fortin *et al.* 1997); and compromise the ability of seedlings to acclimatize to cold conditions (Bertrand *et al.* 1999). Some research has shown that sugar maple seedling response is influenced by the light environment (Tjoelker *et al.* 1993, 1995; Bäck *et al.* 1999; Topa *et al.* 2001, 2004), suggesting that seedlings growing in shade, under the canopy, and shade leaves, are more sensitive to O_3. However, other studies have suggested that the impact on sugar maple growth, biomass, photosynthesis, stomatal conductance and leaf or seedling senescence becomes weak or null after two to three years of exposure to high O_3 concentrations (Laurence *et al.* 1996; Rebbeck 1996; Rebbeck and Loats 1997; Pell *et al.* 1999) or have concluded that there is no evidence of O_3 being a factor in sugar maple decline (Hibben 1969; Manning 1989).

Sensitivity to high concentrations of O_3 has also been documented for other dominant species in Québec's northern temperate zone (red maple, yellow birch and American beech) (Jensen and Dochinger 1989; Davis and Skelly 1992; Schaub *et al.* 2003; Lee *et al.* 2022). Any generalization of observations concerning forest sensitivity to O_3 are complicated by the fact that it is dependent on tree development stage, microclimate, leaf phenology, in-species variations and other interactive stress factors. Tree sensitivity assessments are based on a limited number of species. In addition, most studies, whether carried out in natural or controlled environments, involve seedlings in non-competitive environments, and seedlings are not necessarily the best subjects for predicting mature tree reactions to O_3. Lastly, the scope and extent of the response also depend on numerous edaphic and climate-related factors, as well as on exposure duration and dynamics and the number of successive years of exposure (Lefohn *et al.* 1997; Chappelka and Samuelson 1998; Lee *et al.* 2022). Because of this complexity, researchers generally use modelling to assess the impacts of high O_3 concentrations on forest ecosystems (Cailleret *et al.* 2018). Some studies have found that O_3 has only negligible impacts on forest productivity in North America, among other things, because of the preponderant role of natural and anthropogenic disturbances in forest dynamics (Landry *et al.* 2013), and also because of changes to composition and community-level compensatory processes that mitigate the negative impacts at tree level (Wang *et al.* 2016). On the other hand, some studies have shown a decline in productivity due to high O_3 concentrations (Ollinger *et al.* 1997; Felzer *et al.* 2004; Yue and Unger 2014). In these models, however, there is uncertainty as to some of the hypotheses, and it will be necessary to measure the impacts of O_3 on mature forests before knowing whether or not the predictions are accurate (Ollinger *et al.* 1997; Cailleret *et al.* 2018). This lack of information, combined with the complexity of the influential factors and their interactions, are likely to have resulted in these apparently contradictory conclusions about the effects of O_3 on forest productivity (Cailleret *et al.* 2018). The effects of ground-level O_3 on tree growth and forest productivity is nevertheless an issue in the northern temperate zone's deciduous forest.

Trace elements

Anthropogenic emissions of trace elements into the environment have been of concern for decades due to their toxicity, their persistence in the environment and their biological accumulation. Lead (Pb), mercury (Hg) and cadmium (Cd), the documented harmful substances used as Canadian indicators of environmental sustainability, are all part the list of toxic substances in the *Canadian Environmental Protect Act* (1999) and in the CAR's air quality standards. The main sources of anthropogenic emissions of trace metals into the air include fossil fuels, the mining and metal processing industry and waste incineration, and there are significantly more anthropogenic emissions than natural emissions (Nriagu 1989; Pacyna and Pacyna 2001). Trace elements in the air are mainly concentrated in aerosols (or emitted as gases in the case of Hg), meaning that they can easily be transported over long distances (Simonetti *et al.* 2000).

Like acidifying pollutants and O_3 precursor pollutants, anthropogenic emissions of trace elements have declined considerably in North America in recent decades, thanks to the air pollutant emission reduction programs implemented in Canada and the United States. The removal of Pb from engine gasoline is just one of the measures contained in these programs (Dietrich and Filippelli 2023). In Canada, in the period from 1990 to 2021, emissions of Hg, Pb and Cd were reduced by 90%, 91% and 94%, respectively, (ECCC 2023b). In the case of Pb, lower emission levels have resulted in significantly better air quality (Fig. 3; Sullivan *et al.* 2018) and far fewer deposits (Dietrich and Filippelli 2023). These past trends in Pb emissions can be seen in tree growth rings, especially in sugar maple, where Pb concentrations increased in the first part of the 20th century and then decreased from the period 1970-1980 until today, to reach levels similar to or below those recorded at the beginning of the 20th century (Marty *et al.* 2024). Air quality measurements carried out at nine stations in Québec have shown that trace element detection frequency and measured concentrations are currently much lower at rural or forest stations than at urban stations. The rare cases in which levels exceeded CAR standards were observed at stations located close to known sources, such as factories or highways (MELCCFP 2023; Foucreault 2024).

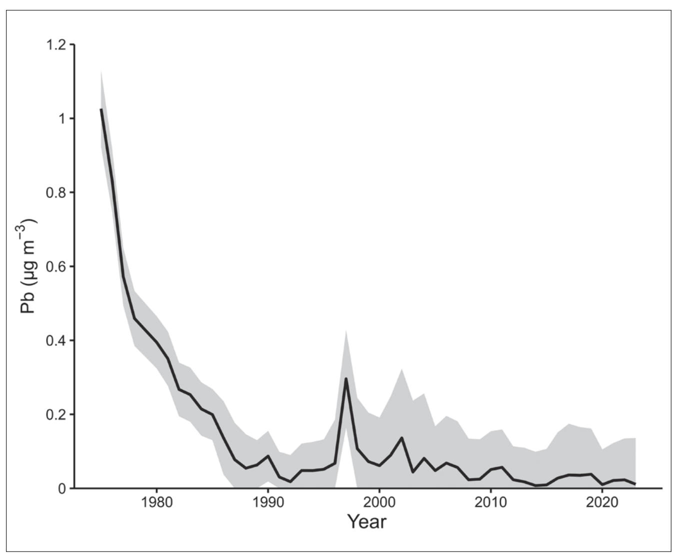

Fig. 3. Evolution of atmospheric lead (Pb) concentrations in Québec from 1975 to 2023. The data show the average annual median Pb concentration in total airborne particles measured at 107 stations by Québec's Air Quality Monitoring Network. The shaded portion shows the 95% confidence interval. Source: Direction de la qualité de l'air et du climat, Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs.

Trace metals enter the forest canopy via dry or wet deposition. Wet deposits include precipitation in the form of rain or snow, as well as fog and cloud droplets. Dry deposits include particle deposits and gas sorption. The portion of air deposits not intercepted by the forest canopy fall to the ground and are added to the elements generated by internal vegetation cycling, i.e., those absorbed by the roots and remobilized via trees (Bergkvist *et al.* 1989). Remobilization includes elements leached from various tree parts and those contained in forest litter and deadwood. Mobility within forest soils varies considerably among metals. Some trace metals form stable complexes with dissolved organic acids transported with percolating water when organic forest litter is mineralized (Bergkvist *et al.* 1989). As they percolate through the upper layer of mineral soil, organic acids become saturated in iron (Fe) and aluminum (Al) and end up being precipitated into the upper portion of the mineral horizons. Therefore, most of the mobilized trace metals accumulate in the upper part of the soil profile (Bergkvist *et al.* 1989; Watmough and Hutchinson 2004). The gradual release and increased concentration of trace metals from the mineral soil in the soil solution are influenced by soil acidity, which enhances their mobility (Watmough *et al.* 2005a). Metal mobility within the soil is also influenced by vegetation type, soil type and environmental variables influencing decomposition of organic matter (Bergkvist *et al.* 1989; Kaste *et al.* 2006).

Release and leaching of toxic trace metals have some major practical implications, in particular with respect to freshwater quality and community water supplies. Generally, trace metals are not particularly mobile and may be retained for years in the organic layer of forest soils and surface mineral horizons (Bergkvist *et al.* 1989; Watmough *et al.* 2005b). In the case of Pb, for example, organic horizons in forests in the northeastern United States can still contain up to 30 kg/ha of Pb derived from engine gasoline, despite legislation passed in the late 1970s which considerably reduced Pb emissions in North America (Kaste *et al.* 2006). Watmough and Hutchinson (2004) noted that roughly 90% of Pb pollution in a forest ecosystem in southern Ontario was situated in the upper layer (0–10 cm) of the mineral soil. Metal concentrations in forest ecosystem mineral horizons in northeastern North America are generally low, however, and are thought to be influenced more by soil properties and the geochemical composition of the rocks that form the soil parent material than by pollution from anthropogenic sources (Watmough 2008). Nevertheless, trace element pollution impacts biological activity and decomposition rates in organic forest litter, and this may negatively affect overall ecosystem productivity (Tyler 1972; Zwoliński 1994).

Pb accumulated in maple stand soils may be an issue for maple syrup production. Producers have made a considerable effort, among other things by modernizing their production equipment, to comply not only with California's drinking water standard, applicable to maple syrup, which allows for a maximum Pb level of 11 µg/L (Government of California 1986, also known as "Proposition 65"), but also with an agreement ratified by a judgment by consent handed down in 2014 by the California courts (Superior Court of the State of California 2014). The main goal of the agreement is to bring maple syrup production equipment up to standard, from tree to consumer, to ensure that there is no risk of Pb contamination in the process. For comparison, the Québec's Maple Syrup Marketing Agreement (PPAQ 2023) considers syrup to be contaminated when Pb levels are above 250 µg/L. The Health Canada threshold is 500 µg/L. Mobility of anthropogenically or naturally sourced Pb in maple stands may hinder efforts to reduce Pb concentrations in maple syrup. However, following sampling carried out in the spring of 1995 in 90 maple stands across six farming regions of Québec, Pb was found to be present in maple sap (> 0.1 µg/L) in only 18% of cases. Although the maximum detected level was 52 µg/L, concentrations were generally low (average: 1 µg/L; 95th percentile: 5 µg/L), and ten times less, on average, than the California standard (Dumont *et al.* 1996; Renaud 1998). In Connecticut, a similar average level (1.1 µg/L) was measured in maple sap harvested in uncontaminated plastic tanks (Stilwell and Musantec 1996). Robinson *et al.* (1989) obtained higher values ranging from 3 to 2090 µg/L, with an average of 80 µg/L in 27 sugar bushes in Québec, New Brunswick and Nova Scotia. The fact that the sampled sap had in fact come into contact with production equipment may explain these high concentrations (Dumont *et al.* 1996). Given that sap is concentrated roughly 40 times in order to obtain maple syrup, a concentration of 0.275 µg/L would, in theory, be sufficient to obtain 11 µg/L in the syrup if all the Pb in sap were to transfer to the maple syrup. However, a significant amount of the Pb from the sap precipitates out of solution as the sap is processed into syrup, and the solid containing the Pb can be eliminated during filtering (Robinson *et al.* 1989; Dumont *et al.* 1996; Stilwell and Musantec 1996). Pb in maple syrup therefore appears to be mainly of technological origin, probably deriving from tin/Pb welding in maple syrup conditioning systems, storage in galvanized steel tanks, metal pipes and the use of pumps with bronze gear systems to collect and transfer sap (Dumont *et al.* 1996; Stilwell and Musantec 1996; Greenough *et al.* 2010; Mohammed *et al.* 2022). In Québec, however, these contamination risks should have been eliminated with the additional Pb reduction measures recently implemented in the *Maple Syrup Marketing Agreement* (e.g., PPAQ 2023, Appendix N). Exceptionally, for reasons that are as yet unknown, high concentrations of Pb in maple sap may nevertheless still be an issue for some producers (Dumont *et al.* 1996; Renaud 1998).

Trace metal pollution not only causes nutritional deficiencies, it is also harmful to the health of sensitive tree species (Gawel *et al.* 1996). Soil acidification resulting from acid rain affects toxic metal mobility and availability, and also absorption by tree roots and internal circulation of metals within trees and ecosystems. It can therefore have major nutritional and toxicological consequences for trees (Bergkvist *et al.* 1989; Kahle 1993; Watmough 2002; Bilodeau-Gauthier *et al.* 2011). For example, foliar concentrations of metals in sugar maple may be higher in acidic soil conditions but bear no relationship to concentrations in mineral soil (Watmough 2008). This shows that the metal cycle is improved in acidic soil conditions. In sugar maple, manganese (Mn) concentrations in leaves are higher on acidic soils, and these high concentrations are associated with dieback and reduced photosynthesis (see St. Clair *et al.* 2008 for a literature review). Trace metal pollution, interacting with soil acidification through acid rain, is therefore an issue for sugar maple health and productivity. In addition to interactions with acidifying air pollutants, exposure to metals may enhance water stress for trees and cause loss of conductivity due to embolisms (in particular for sugar maple), making them more vulnerable to drought (de Silva *et al.* 2012; Tanentzap and Ryser 2015).

Regarding the impacts of forest management, it has been shown that whole tree cutting in deciduous forests in northeastern North America increases mobility of some trace metals along with leaching from forest soils to surface water (Scott *et al.* 2001). Conversely, phytoextraction of trace metals appears to offer potential for depollution of soils, especially when fast-growth tree species are used, for example willows or poplars, or species that collect large quantities of metals, such as birch (Gonzälez-Oreja *et al.* 2008; Munro and Courchesne 2019).

In addition to Pb, Hg ranks among the most concerning of the trace metals. Because it is emitted in gaseous form, it remains in the air for longer and is more mobile than other metals. It can therefore be transported globally and be deposited far from its source. Like Pb, Hg is a toxic pollutant with harmful effects for human health throughout the world (Zhang *et al.* 2021). In addition, it accumulates in food chains, impacts biodiversity and upsets biological balance, thereby endangering ecosystems (Eagles-Smith *et al.* 2016). In boreal forests, Hg preferentially accumulates in the humus rather than in the mineral soil (Lindqvist *et al.*, 1991). As for CO_2, trees can absorb large quantities of atmospheric Hg and act as sinks in the Hg cycle (Obrist *et al.* 2021; Zhou *et al.* 2021). In a changing environment, interactions between climate change, vegetation dynamics and the processes governing the global Hg cycle have become a major environmental issue. In concrete terms, scientists anticipate a 60% decline in the terrestrial Hg sink compared to the current situation, due to reduced stomatal conductance caused by an increase in atmospheric CO_2 (Yuan *et al.* 2024).

Conclusion

In the last few centuries, industrialization in North America has generated air pollutant emissions mostly from combustion of fossil fuels used to produce energy or for transportation. Research has focused mainly on the harmful impacts of acidifying pollutants (i.e., SO_2 and NO_x), pollutants implicated in the formation of ground-level ozone (i.e., NO_x and COV) and trace elements (heavy metals) on forest ecosystems. As awareness grew about the harmful effects of these air pollutants for human health, wildlife and vegetation, ecosystem functions and infrastructures, several national and international agreements aimed at reducing emissions. As a result, emissions and ambient air concentrations of most atmospheric pollutants have declined significantly since the mid-1990s.

Although the situation has improved, air pollutants continue to cause concern and continue to have major harmful effects for forest ecosystems, and in particular for soil fertility and tree physiology. The situation is of particular concern for the sugar maple, a species that is eminently sensitive to exchangeable cation availability, soil acidity and high ozone concentrations. Sugar maple stands growing on acidified soils encounter problems with natural regeneration, and the sugar maple trees that make up these stands tend to exhibit low vigour. As a long-term legacy of acid rain, these stands may well evolve toward different compositions over time. Environmental monitoring of forest ecosystems continues in order to see how these ecosystems are reacting to the lower levels of anthropogenic air pollutant emissions in contemporary North America.

References

Ainsworth, E.A., C.R. Yendrek, S. Sitch, W.J. Collins and L.D. Emberson. 2012. The effects of tropospheric ozone on net primary productivity and implications for climate change. Annu. Rev. Plant Biol. 63: 637–661. https://doi.org/10.1146/annurev-arplant-042110-103829

Arii, K. and M.J. Lechowicz. 2002. The influence of overstory trees and abiotic factors on the sapling community in an old-growth *Fagus-Acer* forest. Ecoscience 9(3): 386–396. https://doi.org/10.1080/11956860.2002.11682726

Arii, K., B.R. Hamel and M.J. Lechowicz. 2005. Environmental correlates of canopy composition at Mont St. Hilaire, Quebec, Canada. J. Torrey Bot. Soc. 132(1): 90–102. https://www.jstor.org/stable/20063748

Bäck, J., D.W. Vanderklein and M.A. Topa. 1999. Effects of elevated ozone on CO_2 uptake and leaf structure in sugar maple under two light environments. Plant, Cell Environ. 22(2): 137–147. https://doi.org/10.1046/j.1365-3040.1999.00393.x

Bailey, S.W., S.B. Horsley, R.P. Long and R.A. Hallett. 2004. Influence of Edaphic Factors on Sugar Maple Nutrition and Health on the Allegheny Plateau. Soil Sci. Soc. Am. J. 68(1): 243–252. https://doi.org/10.2136/sssaj2004.2430

Bal, T.L., A.J. Storer, M.F. Jurgensen, P.V. Doskey and M.C. Amacher. 2015. Nutrient stress predisposes and contributes to sugar maple dieback across its northern range: A review. Forestry 88(1): 64–83. https://doi.org/10.1093/forestry/cpu051

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

Beier, C.M., J. Caputo, G.B. Lawrence and T.J. Sullivan. 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. https://doi.org/10.1016/j.jenvman.2016.12.069

Bergkvist, B., L. Folkeson and D. Berggren. 1989. Fluxes of Cu, Zn, Pb, Cd, Cr, and Ni in temperate forest ecosystems. Water. Air. Soil Pollut. 47: 217–286. https://doi.org/10.1007/BF00279328

Bernier, B. and M. Brazeau. 1988a. Foliar nutrient status in relation to sugar maple dieback and decline in the Quebec Appalachians. Can. J. For. Res. 18(6): 754–761. https://doi.org/10.1139/x88-115

Bernier, B. and M. Brazeau. 1988b. Nutrient deficiency symptoms associated with sugar maple dieback and decline in the Quebec Appalachians. Can. J. For. Res. 18(6): 762–769. https://doi.org/10.1139/x88-116

Bernier, B. and M. Brazeau. 1988c. Magnesium deficiency symptoms associated with sugar maple dieback in a Lower Laurentians site in southeastern Quebec. Can. J. For. Res. 18(10): 1265–1269. https://doi.org/10.1139/x88-195

Bernier, B., D. Paré and M. Brazeau. 1989. Natural stresses, nutrient imbalances and forest decline in southeastern Quebec. Water. Air. Soil Pollut. 48: 239–250. https://doi.org/10.1007/BF00282381

Bertrand, A., G. Robitaille, P. Nadeau and Y. Castonguay. 1999. Influence of ozone on cold acclimation in sugar maple seedlings. Tree Physiol. 19(8): 527–534. https://doi.org/10.1093/treephys/19.8.527

Bigelow, S.W. and C.D. Canham. 2007. Nutrient limitation of juvenile trees in a northern hardwood forest: Calcium and nitrate are preeminent. For. Ecol. Manage. 243(2–3): 310–319. https://doi.org/10.1016/j.foreco.2007.03.027

Bilodeau-Gauthier, S., D. Houle, C. Gagnon, B. Côté and C. Messier. 2011. Assessment of sugar maple tree growth in relation to the partitioning of elements in xylem along a soil acidity gradient. For. Ecol. Manage. 261(1): 95–104. https://doi.org/10.1016/j.foreco.2010.09.035

Bishop, D.A., C.M. Beier, N. Pederson, G.B. Lawrence, J.C. Stella and T.J. Sullivan. 2015. Regional growth decline of sugar maple (*Acer saccharum*) and its potential causes. Ecosphere 6(10): 1–14. https://doi.org/10.1890/ES15-00260.1

Bognounou, F., D. Paré and J. Laganière. 2023. Changes in seedlings' composition and abundance following soil scarification and amendments in a northern hardwood forest. For. Ecol. Manage. 541: 121071. https://doi.org/10.1016/j.foreco.2023.121071

Burke, M.K. and D.J. Raynal. 1998. Liming influences growth and nutrient balances in sugar maple (Acer saccharum) seedlings on an acidic forest soil. Environ. Exp. Bot. 39(2): 105–116. https://doi.org/10.1016/S0098-8472(97)00029-4

Burns, D.A., T. Blett, R. Haeuber and L.H. Pardo. 2008. Critical loads as a policy tool for protecting ecosystems from the effects of air pollutants. Front. Ecol. Environ. 6(3): 156–159. https://doi.org/10.1890/070040

Cailleret, M., M. Ferretti, A. Gessler, A. Rigling and M. Schaub. 2018. Ozone effects on European forest growth — Towards an integrative approach. J. Ecol. 106(4): 1377–1389. https://doi.org/10.1111/1365-2745.12941

Caputo, J., C.M. Beier, T.J. Sullivan and G.B. Lawrence. 2016. Modeled effects of soil acidification on long-term ecological and economic outcomes for managed forests in the Adirondack region (USA). Sci. Total Environ. 565: 401–411. https://doi.org/10.1016/j.scitotenv.2016.04.008

Carlson, R.W. 1979. Reduction in the photosynthetic rate of *Acer*, *Quercus* and *Fraxinus* species caused by sulphur dioxide and ozone. Environ. Pollut. 18(2): 159–170. https://doi.org/10.1016/0013-9327(79)90091-0

Cathcart, H., J. Aherne, M.D. Moran, V. Savic-jovcic, P.A. Makar and A. Cole. 2024. Estimates of critical loads and exceedances of acidity and nutrient nitrogen for mineral soils in Canada for 2014–2016 average annual sulphur and nitrogen atmospheric deposition. EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2024-2371

Chappelka, A.H. and L.J. Samuelson. 1998. Ambient ozone effects on forest trees of the eastern United States: A review. New Phytol. 139(1): 91–108. https://doi.org/10.1046/j.1469-8137.1998.00166.x

Cheng, I., L. Zhang, Z. He, H. Cathcart, D. Houle, A. Cole, J. Feng, J. O'Brien, A.M. Macdonald *et al.* 2022. Long-term declines in atmospheric nitrogen and sulfur deposition reduce critical loads exceedances at multiple Canadian rural sites, 2000–2018. Atmos. Chem. Phys. 22(22): 14631–14656. https://doi.org/10.5194/acp-22-14631-2022

Clark, C.M., J. Phelan, P. Doraiswamy, J. Buckley, J.C. Cajka, R.L. Dennis, J. Lynch, C.G. Nolte and T.L. Spero. 2018. Atmospheric deposition and exceedances of critical loads from 1800–2025 for the conterminous United States. Ecol. Appl. 28(4): 978–1002. https://doi.org/10.1002/eap.1703

Cleavitt, N.L., T.J. Fahey and J.J. Battles. 2011. Regeneration ecology of sugar maple (*Acer saccharum*): Seedling survival in relation to nutrition, site factors, and damage by insects and pathogens. Can. J. For. Res. 41(2): 235–244. https://doi.org/10.1139/X10-210

Cleavitt, N.L., J.J. Battles, C.E. Johnson and T.J. Fahey. 2018. Long-term decline of sugar maple following forest harvest, Hubbard Brook Experimental Forest, New Hampshire. Can. J. For. Res. 48(1): 23–31. https://doi.org/10.1139/cjfr-2017-0233

Collin, A., C. Messier and N. Bélanger. 2017. Conifer presence may negatively affect sugar maple's ability to migrate into the boreal forest through reduced foliar nutritional status. Ecosystems 20: 701–716. https://doi.org/10.1007/s10021-016-0045-4

Collin, A., C. Messier, S.W. Kembel and N. Bélanger. 2018. Can sugar maple establish into the boreal forest? Insights from seedlings under various canopies in southern Quebec. Ecosphere 9(1): https://doi.org/10.1002/ecs2.2022

Davis, D.D. and J.M. Skelly. 1992. Foliar sensitivity of eight eastern hardwood tree species to ozone. Water, Air, Soil Pollut. 62: 269–277. https://doi.org/10.1007/BF00480261

de Silva, N.D.G., E. Cholewa and P. Ryser. 2012. Effects of combined drought and heavy metal stresses on xylem structure and hydraulic conductivity in red maple (*Acer rubrum* L.). J. Exp. Bot. 63(16): 5957–5966. https://doi.org/10.1093/jxb/ers241

Dietrich, M. and G.M. Filippelli. 2023. Positive outcomes from U.S. lead regulations, continued challenges, and lessons learned for regulating emerging contaminants. Environ. Sci. Pollut. Res. 30: 57178–57187. https://doi.org/10.1007/s11356-023-26319-4

Dizengremel, P. 2001. Effects of ozone on the carbon metabolism of forest trees. Plant Physiol. Biochem. 39(9): 729–742. https://doi.org/10.1016/S0981-9428(01)01291-8

Driscoll, C.T. G.B. Lawrence, A.J. Bulger, T.J. Butler, C.S. Cronan, C. Eagar, K.F. Lambert, G.E. Likens, J.L. Stoddard and K.C. Weathers. 2001. Acidic deposition in the northeastern United States: Sources and inputs, ecosystem effects, and management strategies. Bioscience 51(3): 180–198. https://doi.org/10.1641/0006-3568(2001)051[0180:ADITNU]2.0.CO;2

Drohan, P., S. Stout and G. Petersen. 2002. Sugar maple (*Acer saccharum* Marsh.) decline during 1979–1989 in northern Pennsylvania. For. Ecol. Manage. 170(1–3): 1–17. https://doi.org/10.1016/S0378-1127(01)00688-0

Duchesne, L. and D. Houle. 2006. Base cation cycling in a pristine watershed of the Canadian boreal forest. Biogeochemistry 78: 195–216. https://doi.org/10.1007/s10533-005-4174-7

Duchesne, L. and D. Houle. 2008. Impact of nutrient removal through harvesting on the sustainability of the boreal forest. Ecol. Appl. 18(7): 1642–1651. https://doi.org/10.1890/07-1035.1

Duchesne, L., R. Ouimet and D. Houle. 2002. Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. J. Environ. Qual. 31(5): 1676. https://doi.org/10.2134/jeq2002.1676

Duchesne, L., J.-D. Moore and R. Ouimet. 2013. Partitioning the effect of release and liming on growth of sugar maple and American beech saplings. North. J. Appl. For. 30(1): 28–36. https://doi.org/10.5849/njaf.12-012

Duchesne, L., F. Guillemette, S., Bédard and R. Ouimet. (*In press*). Contemporary Issues in Québec's Temperate Forest — Part 1: Profile of the forest. For. Chron.

Duckmanton, L. and P. Widden. 1994. Effect of ozone on the development of vesicular-arbuscular mycorrhizae in sugar maple saplings. Mycologia 86(2): 181–186. https://doi.org/10.1080/00275514.1994.12026392

Dumont, J., G. Allard, G. Paillard, G. Boudreault and É. Colpron. 1996. Intégrité des produits d'érable : identification des principaux contaminants potentiels, de leur teneur et des facteurs influençant cette teneur. Première partie : le plomb, le cadmium, le cuivre, le fer et le zinc : apport naturel et technologique dans la sève et le sirop. Projet de recherche : rapport final. Centre de recherche, de développement et de transfert technologique en acériculture (Le Centre ACER Inc.). St-Hyacinthe, 53 p. https://gestion.centreacer.qc.ca/fr/UserFiles/Publications/165_Fr.pdf

Eagles-Smith, C.A., J.G. Wiener, C.S. Eckley, J.J. Willacker, D.C. Evers, M. Marvin-DiPasquale, D. Obrist, J.A. Fleck, G.R. Aiken *et al.* 2016. Mercury in western North America: A synthesis of environmental contamination, fluxes, bioaccumulation, and risk to fish and wildlife. Sci. Total Environ. 568: 1213–1226. https://doi.org/10.1016/j.scitotenv.2016.05.094

ECCC. 2023a. [Environnement et Changement climatique Canada]. Accord sur la qualité de l'air. Rapport d'étape 2020–2022. 39 p. https://publications.gc.ca/collections/collection_2023/eccc/En85-1-2022-fra.pdf

ECCC. 2023b. [Environnement et Changement climatique Canada]. Indicateurs canadiens de durabilité de l'environnement : Émissions atmosphériques de substances nocives. 38 p. https://publications.gc.ca/collections/collection_2024/eccc/en4/En4-144-82-2023-fra.pdf

Felzer, B., D. Kicklighter, J. Melillo, C. Wang, Q. Zhuang and R. Prinn. 2004. Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. Tellus B 56(3): 230–248. https://doi.org/10.3402/tellusb.v56i3.16415

Fernando, D.R., A.T. Marshall and J.P. Lynch. 2016. Foliar nutrient distribution patterns in sympatric maple species reflect contrasting sensitivity to excess manganese. PLoS One 11(7): e0157702. https://doi.org/10.1371/journal.pone.0157702

Fortin, M., Y. Mauffette and P.J. Albert. 1997. The effects of ozone-exposed sugar maple seedlings on the biological performance and the feeding preference of the forest tent caterpillar (*Malacosoma disstria* Hbn.). Environ. Pollut. 97(3): 303–309. https://doi.org/10.1016/S0269-7491(97)00079-1

Foucreault, M.-A. 2024. Campagne quinquennale de mesure des concentrations de métaux dans l'air ambiant au Québec. Québec, ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, Direction de la surveillance de la qualité de l'air et du climat, 55 p. + 18 annexes.https://www.environnement.gouv.qc.ca/air/rapports-qualite-air/campagne-quinquennale-metaux-air.pdf

Gaucher, C., N. Costanzo, D. Afif, Y. Mauffette, N. Chevrier and P. Dizengremel. 2003. The impact of elevated ozone and carbon dioxide on young *Acer saccharum* seedlings. Physiol. Plant. 117(3): 392–402. https://doi.org/10.1034/j.1399-3054.2003.00046.x

Gaucher, C., N. Costanzo, P. Widden, J.-P. Renaud, P. Dizengremel, Y. Mauffette and N. Chevrier. 2006. Response to an ozone gradient of growth and enzymes implicated in tolerance to oxidative stress in *Acer saccharum* (Marsh.) seedlings. Ann. For. Sci. 63(4): 387–397. https://doi.org/10.1051/forest:2006019

Gawel, J.E., B.A. Ahner, A.J. Friedland and F.M.M. Morel. 1996. Role for heavy metals in forest decline indicated by phytochelatin measurements. Nature 381(6577): 64–65. https://doi.org/10.1038/381064a0

Gonzälez-Oreja, J.A., M. Rozas, I. Alkorta and C. Garbisu. 2008. Dendroremediation of heavy metal polluted soils. Rev. Environ. Health 23(3): 223–234: https://doi.org/10.1515/REVEH.2008.23.3.223

Government of California. 1986. Chapter 6.6. Safe Drinking Water and Toxic Enforcement Act of 1986 [25249.5–25249.14]. Health and safety code, Division 20, Miscellaneous health and safety provisions. https://leginfo.legislature.ca.gov/faces/codes_displayText.xhtml?lawCode=HSC&division=20.&title&part&chapter=6.6.&article

Gradowski, T. and S.C. Thomas. 2008. Responses of *Acer saccharum* canopy trees and saplings to P, K and lime additions under high N deposition. Tree Physiol. 28(2): 173–185. https://doi.org/10.1093/treephys/28.2.173

Greenough, J.D., B.J. Fryer and L. Mallory-Greenough. 2010. Trace element geochemistry of Nova Scotia (Canada) maple syrup. Can. J. Earth Sci. 47(8): 1093–1110. https://doi.org/10.1139/E10-055

Hallett, R.A., S.W. Bailey, S.B. Horsley and R.P. Long. 2006. Influence of nutrition and stress on sugar maple at a regional scale. Can. J. For. Res. 36(9): 2235–2246. https://doi.org/10.1139/X06-120

Halman, J.M., P.G. Schaberg, G.L. Hawley, L.H. Pardo and T.J. Fahey. 2013. Calcium and aluminum impacts on sugar maple physiology in a northern hardwood forest. Tree Physiol. 33(11): 1242–1251. https://doi.org/10.1093/treephys/tpt099

Halman, J.M., P.G. Schaberg, G.J. Hawley, C.F. Hansen and T.J. Fahey. 2015. Differential impacts of calcium and aluminum treatments on sugar maple and American beech growth dynamics. Can. J. For. Res. 45(1): 52–59. https://doi.org/10.1139/cjfr-2014-0250

Hazlett, P., C. Emilson, G. Lawrence, I. Fernandez, R. Ouimet and S. Bailey. 2020. Reversal of forest soil acidification in the northeastern United States and eastern Canada: Site and soil factors contributing to recovery. Soil Syst. 4(3): 54. https://doi.org/10.3390/soilsystems4030054

Hendershot, W.H. 1991. Fertilization of sugar maple showing dieback symptoms in the Quebec Appalachians, Canada. Fertil. Res. 27, 63–70. https://doi.org/10.1007/BF01048609

Hibben, C.R. 1969. Ozone toxicity to sugar maple. Phytopathology 59: 1423–1428.

Horsley, S.B., R.P. Long, S.W. Bailey, R.A. Hallett and T.J. Hall. 2000. Factors associated with the decline disease of sugar maple on the Allegheny Plateau. Can. J. For. Res. 30(9): 1365–1378. https://doi.org/10.1139/x00-057

Houle, D., S. Tremblay and R. Ouimet. 2007. Foliar and wood chemistry of sugar maple along a gradient of soil acidity and stand health. Plant Soil 300: 173–183. https://doi.org/10.1007/s11104-007-9401-7

Houle, D., J.-D. Moore and M. Renaudin. 2024a. Eastern Canadian boreal forest soil and foliar chemistry show evidence of resilience to long-term nitrogen addition. Ecol. Appl. 34(3): e2958. https://doi.org/10.1002/eap.2958

Houle, D., M. Renaudin, L. Duchesne, J.-D. Moore and A. Benoist. 2024b. Soil solution chemistry weak response to long-term N addition points towards a strong resilience of northeastern American forests to past and future N deposition. Sci. Total Environ. 946: 174387. https://doi.org/10.1016/j.scitotenv.2024.174387

Houle, D., R. Paquin, C. Camiré, R. Ouimet and L. Duchesne. 1997. Response of the Lake Clair Watershed (Duchesnay, Quebec) to changes in precipitation chemistry (1988–1994). Can. J. For. Res. 27(11): 1813–1821. https://doi.org/10.1139/x97-143

Huggett, B.A., P.G. Schaberg, G.J. Hawley and C. Eagar. 2007. Long-term calcium addition increases growth release, wound closure, and health of sugar maple (*Acer saccharum*) trees at the Hubbard Brook Experimental Forest. Can. J. For. Res. 37(9): 1692–1700. https://doi.org/10.1139/X07-042

Jensen, K.F. and L.S. Dochinger. 1989. Response of eastern hardwood species to ozone, sulfur dioxide and acid precipitation. J. Air Pollut. Control Assoc. 39(6): 852–855. https://doi.org/10.1080/08940630.1989.10466572

Johnson, A.H., A. Moyer, J.E. Bedison, S.L. Richter and S.A. Willig. 2008. Seven decades of calcium depletion in organic horizons of Adirondack forest soils. Soil Sci. Soc. Am. J. 72(6): 1824–1830. https://doi.org/10.2136/sssaj2006.0407

Jones, A.R.C. and W. Hendershot. 1988. Le dépérissement des érables au Canada. Son développement et quelques pratiques correctives. Rev. For. Fr. 40(1): 20-27. https://doi.org/10.4267/2042/25859

Jones, A.R.C. and W.H. Hendershot. 1989. Maple decline in Quebec: A discussion of possible causes and the use of fertilizers to limit damage. For. Chron. 65(4): 280–287. https://doi.org/10.5558/tfc65280-4

Juice, S.M., T.J. Fahey, T.G. Siccama, C.T. Driscoll, E.G. Denny, C. Eagar, N.L. Cleavitt, R. Minocha and A.D. Richardson. 2006. Response of sugar maple to calcium addition to northern hardwood forest. Ecology 87(5): 1267–1280. https://doi.org/10.1890/0012-9658(2006)87[1267:ROSMTC]2.0.CO;2

Kahle, H. 1993. Response of roots of trees to heavy metals. Environ. Exp. Bot. 33(1): 99–119. https://doi.org/10.1016/0098-8472(93)90059-O

Karnosky, D.F., K.S. Pregitzer, D.R. Zak, M.E. Kubiske, G.R. Hendrey, D. Weinstein, M. Nosal and K.E. Percy. 2005. Scaling ozone responses of forest trees to the ecosystem level in a changing climate. Plant, Cell Environ. 28(8): 965–981. https://doi.org/10.1111/j.1365-3040.2005.01362.x

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

King, J.S., M.E. Kubiske, K.S. Pregitzer, G.R. Hendrey, E.P. McDonald, C.P. Giardina, V.S. Quinn and D.F. Karnosky. 2005. Corrigendum: Tropospheric O_3 compromises net primary production in young stands of trembling aspen, paper birch and sugar maple in response to elevated atmospheric CO_2. New Phytol. 168(3): 623–636. https://doi.org/10.1111/j.1469-8137.2005.01574.x

Kobe, R., G.E. Likens and C. Eagar. 2002. Tree seedling growth and mortality responses to manipulations of calcium and aluminum in a northern hardwood forest. Can. J. For. Res. 32(6): 954–966. https://doi.org/10.1139/X02-018

Kogelmann, W. 2006. Soil acidity and manganese in declining and nondeclining sugar maple stands in Pennsylvania. J. Environ. Qual. 35(2): 433–441. https://doi.org/10.2134/jeq2004.0347

Landry, J.-S., E.T. Neilson, W.A. Kurz and K.E. Percy. 2013. The impact of tropospheric ozone on landscape-level merchantable biomass and ecosystem carbon in Canadian forests. Eur. J. For. Res. 132: 71–81. https://doi.org/10.1007/s10342-012-0656-z

Laurence, J.A., R.J. Kohut, R.G. Amundson, D.A. Weinstein and D.C. MacLean. 1996. Response of sugar maple to multiple year exposures to ozone and simulated acidic precipitation. Environ. Pollut. 92(2): 119–126. https://doi.org/10.1016/0269-7491(95)00105-0

Lawrence, G.B. and S.W. Bailey. 2021. Recovery processes of acidic soils experiencing decreased acidic deposition. Soil Syst. 5(2): 36. https://doi.org/10.3390/soilsystems5020036

Lawrence, G.B., P.W. Hazlett, I.J. Fernandez, R. Ouimet, S.W. Bailey, W.C. Shortle, K.T. Smith and M.R. Antidormi. 2015. Declining acidic deposition begins reversal of forest-soil acidification in the northeastern U.S. and eastern Canada. Environ. Sci. Technol. 49(22): 13103–13111. https://doi.org/10.1021/acs.est.5b02904

Lawrence, G.B., T.C. McDonnell, T.J. Sullivan, M. Dovciak, S.W. Bailey, M.R. Antidormi and M.R. Zarfos. 2018. Soil base saturation combines with beech bark disease to influence composition and structure of sugar maple-beech forests in an acid rain-impacted region. Ecosystems 21: 795–810. https://doi.org/10.1007/s10021-017-0186-0

Lee, E.H., C.P. Andersen, P.A. Beedlow, D.T. Tingey, S. Koike, J.-J. Dubois, S.D. Kaylor, K. Novak, R. B. Rice, H.S. Neufeld, J.D. Herrick *et al.* 2022. Ozone exposure-response relationships parametrized for sixteen tree species with varying sensitivity in the United States. Atmos. Environ. 284: 119191. https://doi.org/10.1016/j.atmosenv.2022.119191

Lefohn, A.S., W. Jackson, D.S. Shadwick and H.P. Knudsen. 1997. Effect of surface ozone exposures on vegetation grown in the Southern Appalachian Mountains: Identification of possible areas of concern. Atmos. Environ. 31(11): 1695–1708. https://doi.org/10.1016/S1352-2310(96)00258-0

Lindqvist, O., K. Johansson, L. Bringmark, B. Timm, M. Aastrup, A. Andersson, G. Hovsenius, L. Håkanson, Å. Iverfeldt and M. Meili. 1991. Mercury in the Swedish environment — Recent research on causes, consequences and corrective methods. Water Air Soil Pollut. 55: xi–261. https://doi.org/10.1007/BF00542429

Likens, G.E., C.T. Driscoll and D.C. Buso. 1996. Long-term effects of acid rain: Response and recovery of a forest ecosystem. Science 272(5259): 244–246. https://doi.org/10.1126/science.272.5259.244

Long, R.P., S.B. Horsley and P.R. Lilja. 1997. Impact of forest liming on growth and crown vigor of sugar maple and associated hardwoods. Can. J. For. Res. 27(10): 1560–1573. https://doi.org/10.1139/x97-074

Long, R.P., S.B. Horsley, R.A. Hallett and S.W. Bailey. 2009. Sugar maple growth in relation to nutrition and stress in the northeastern United States. Ecol. Appl. 19(6): 1454–1466. https://doi.org/10.1890/08-1535.1

Long, R.P., S.B. Horsley and T.J. Hall. 2011. Long-term impact of liming on growth and vigor of northern hardwoods. Can. J. For. 41(6): 1295–1307. https://doi.org/10.1139/X11-049

Long, R.P., S.W. Bailey, S.B. Horsley, T.J. Hall, B.R. Swistock and D.R. DeWalle. 2015. Long-term effects of forest liming on soil, soil Leachate, and foliage chemistry in northern Pennsylvania. Soil Sci. Soc. Am. J. 79(4): 1223–1236. https://doi.org/10.2136/sssaj2014.11.0465

Manning, W.J. 1989. Effects of ozone and ozone-acidic precipitation interaction on forest trees in North America. Stud. Environ. Sci. 35: 239–249. https://doi.org/10.1016/S0166-1116(08)70592-2

Marlow, J. and D.R. Peart. 2014. Experimental reversal of soil acidification in a deciduous forest: Implications for seedling performance and changes in dominance of shade-tolerant species. For. Ecol. Manage. 313: 63–68. https://doi.org/10.1016/j.foreco.2013.10.036

Marty, C., D. Houle, S. Bilodeau-Gauthier and C. Gagnon. 2024. Using sugar maple tree rings to trace historic lead pollution in eastern Canada temperate forest. Appl. Geochemistry 160: 105855. https://doi.org/10.1016/j.apgeochem.2023.105855

McLaughlin, D.L., M. Chiu, D. Durigon and H. Liljalehto. 2000. The Ontario hardwood forest health survey: 1986–1998. For. Chron. 76(5): 783–791. https://doi.org/10.5558/tfc76783-5

MELCCFP. 2023. [Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs]. Bilan de la qualité de l'air au Québec 2021. Québec, ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, Direction de la qualité de l'air et du climat, 66 p. + 25 annexes https://environnement.gouv.qc.ca/air/bilan/qualite-air-quebec-2021.pdf

MELCCFP. 2024. [Ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs]. Rapport d'avancement 2023 par rapport aux normes canadiennes de la qualité de l'air ambiant. Québec, ministère de l'Environnement, de la Lutte contre les changements climatiques, de la Faune et des Parcs, Direction générale des politiques de l'air et du suivi de l'état de l'environnement, 21 p. https://www.environnement.gouv.qc.ca/air/rapports-qualite-air/normes-canadiennes/rapport2023.pdf

Minocha, R., S. Long, P. Thangavel, S.C. Minocha, C. Eagar and C.T. Driscoll. 2010. Elevation dependent sensitivity of northern hardwoods to Ca addition at Hubbard Brook Experimental Forest, NH, USA. For. Ecol. Manage. 260(12): 2115–2124. https://doi.org/10.1016/j.foreco.2010.09.002

Mohammed, F., P. Sibley, D. Guillaume and N. Abdulwali. 2022. Chemical composition and mineralogical residence of maple syrup: A comprehensive review. Food Chem. 374: 131817. https://doi.org/10.1016/j.foodchem.2021.131817

Momen, B., S.J. Behling, G.B. Lawrence and J.H. Sullivan. 2015. Photosynthetic and growth response of sugar maple (*Acer saccharum* Marsh.) mature trees and seedlings to calcium, magnesium, and nitrogen additions in the Catskill Mountains, NY, USA. PLoS One 10(8): e0136148. https://doi.org/10.1371/journal.pone.0136148

Moore, J.-D. and D. Houle. 2023. Chemistry of soil and foliage in declining sugar maple stands over 13 years of nitrogen addition. For. Ecol. Manage. 535: 120897. https://doi.org/10.1016/j.foreco.2023.120897

Moore, J.-D. and R. Ouimet. 2006. Ten-year effect of dolomitic lime on the nutrition, crown vigor, and growth of sugar maple. Can. J. For. Res. 36(7): 1834–1841. https://doi.org/10.1139/X06-081

Moore, J.-D. and R. Ouimet. 2014. Effects of two types of Ca fertilizer on sugar maple nutrition, vigor and growth after 7years. For. Ecol. Manage. 320: 1–5. https://doi.org/10.1016/j.foreco.2014.02.017

Moore, J.-D. and R. Ouimet. 2021. Liming still positively influences sugar maple nutrition, vigor and growth, 20 years after a single application. For. Ecol. Manage. 490: 119103. https://doi.org/10.1016/j.foreco.2021.119103

Moore, J.-D., C. Camiré and R. Ouimet. 2000. Effects of liming on the nutrition, vigor, and growth of sugar maple at the Lake Clair Watershed, Quebec, Canada. Can. J. For. 30(5): 725–732. https://doi.org/10.1139/x00-009

Moore, J.-D., L. Duchesne and R. Ouimet. 2008. Soil properties and maple–beech regeneration a decade after liming in a northern hardwood stand. For. Ecol. Manage. 255(8–9): 3460–3468. https://doi.org/10.1016/j.foreco.2008.02.026

Moore, J.-D., R. Ouimet and L. Duchesne. 2012. Soil and sugar maple response 15 years after dolomitic lime application. For. Ecol. Manage. 281: 130–139. https://doi.org/10.1016/j.foreco.2012.06.026

Munro, L. and F. Courchesne. 2019. Bioconcentration of Cd and Zn in the soils of an uncontaminated forest in the Quebec Laurentians. Biogeochemistry 143: 293–312. https://doi.org/10.1007/s10533-019-00562-9

Nolet, P., S. Delagrange, K. Bannon, C. Messier and D. Kneeshaw. 2015. Liming has a limited effect on sugar maple – American beech dynamics compared with beech sapling elimination and canopy opening. Can. J. For. Res. 45(10): 1376–1386. https://doi.org/10.1139/cjfr-2015-0010

Nriagu, J.O. 1989. A global assessment of natural sources of atmospheric trace metals. Nature 338: 47–49. https://doi.org/10.1038/338047a0

Obrist, D. E.M. Roy, J.L. Harrison, C.F. Kwong, J.W. Munger, H. Moosmüller, C.D. Romero, S. Sun, J. Zhou and R. Commane. 2021. Previously unaccounted atmospheric mercury deposition in a midlatitude deciduous forest. Proc. Natl. Acad. Sci. U. S. A. 118(29): e2105477118. https://doi.org/10.1073/pnas.2105477118

Ollinger, S. V., J.D. Aber, P.B. Reich. 1997. Simulating ozone effects on forest productivity: Interactions among leaf-, canopy, and stand-level processes. Ecol. Appl. 7(4): 1237–1251. https://doiorg/10.1890/1051-0761(1997)007[1237:SOEOFP]2.0.CO;2

Ouimet, R. and C. Camiré. 1995. Foliar deficiencies of sugar maple stands associated with soil cation imbalances in the Quebec Appalachians. Can. J. Soil Sci. 75(2): 169–175. https://doi.org/10.4141/cjss95-024

Ouimet, R. and J.-M. Fortin. 1992. Growth and foliar nutrient status of sugar maple: Incidence of forest decline and reaction to fertilization. Can. J. For. Res. 22(5): 699–706. https://doi.org/10.1139/x92-093

Ouimet, R., C. Camiré and V. Furlan. 1995. Endomycorrhizal status of sugar maple in relation to tree decline and foliar, fine-roots, and soil chemistry in the Beauce region, Quebec. Can. J. Bot. 73(8): 1168–1175. https://doi.org/10.1139/b95-126

Ouimet, R., C. Camiré and V. Furlan. 1996a. Effect of soil base saturation and endomycorrhization on growth and nutrient status of sugar maple seedlings. Can. J. Soil Sci. 76(2): 109–115. https://doi.org/10.4141/cjss96-017

Ouimet, R., C. Camiré and V. Furlan. 1996b. Effect of soil K, Ca and Mg saturation and endomycorrhization on growth and nutrient uptake of sugar maple seedlings. Plant Soil 179: 207–216. https://doi.org/10.1007/BF00009330

Ouimet, R., J.-D. Moore and L. Duchesne. 2008. Effects of experimental acidification and alkalinization on soil and growth and health of *Acer saccharum* Marsh. J. Plant Nutr. Soil Sci. 171: 858–871. https://doi.org/10.1002/jpln.200700197

Ouimet, R., L. Duchesne and J.-D. Moore. 2017. Response of northern hardwoods to experimental soil acidification and alkalinisation after 20 years. For. Ecol. Manage. 400: 600–606. https://doi.org/10.1016/j.foreco.2017.06.051

Ouimet, R., J.-D. Moore and L. Duchesne. 2008. Effects of experimental acidification and alkalinization on soil and growth and health of *Acer saccharum* Marsh. J. Plant Nutr. Soil Sci. 171: 858–871. https://doi.org/10.1002/jpln.200700197

Ouimet, R., L. Duchesne and J.-D. Moore. 2017. Response of northern hardwoods to experimental soil acidification and alkalinisation after 20 years. For. Ecol. Manage. 400: 600–606. https://doi.org/10.1016/j.foreco.2017.06.051

Ouimet, R., L. Duchesne, D. Houle and P.A. Arp. 2001. Critical loads and exceedances of acid deposition and associated forest growth in the northern hardwood and boreal coniferous forests in Québec, Canada. Water, Air, Soil Pollut. Focus 1: 119–134. https://doi.org/10.1023/A:1011544325004

Ouimet, R., P.A. Arp, S.A. Watmough, J. Aherne and I. DeMerchant. 2006. Determination and mapping critical loads of acidity and exceedances for upland forest soils in eastern Canada. Water. Air. Soil Pollut. 172: 57–66. https://doi.org/10.1007/s11270-005-9050-5

Pacyna, J.M. and E.G. Pacyna. 2001. An assessment of global and regional emissions of trace metals to the atmosphere from anthropogenic sources worldwide. Environ. Rev. 9(4): 269–298. https://doi.org/10.1139/er-9-4-269

Page, B.D. and M.J. Mitchell. 2008. Influences of a calcium gradient on soil inorganic nitrogen in the Adirondack Mountains, New York. Ecol. Appl. 18(7): 1604–1614.

Pardo, L.H., J.A. Coombs, M.J. Robin-Abbott, J.H. Pontius and A.W. D'Amato. 2019. Tree species at risk from nitrogen deposition in the northeastern United States: A geospatial analysis of effects of multiple stressors using exceedance of critical loads. For. Ecol. Manage. 454: 117528. https://doi.org/10.1016/j.foreco.2019.117528

Paré, D., W.L. Meyer and C. Camiré. 1993. Nutrient availability and foliar nutrient status of sugar maple saplings following

fertilization. Soil Sci. Soc. Am. J. 57(4): 1107–1114. https://doi.org/10.2136/sssaj1993.03615995005700040038x
Park, B.B. and R.D. Yanai. 2009. Nutrient concentrations in roots, leaves and wood of seedling and mature sugar maple and American beech at two contrasting sites. For. Ecol. Manage. 258(7): 1153–1160. https://doi.org/10.1016/j.foreco.2009.06.003
Pell, E.J., J.P. Sinn, B.W. Brendley, L. Samuelson, C. Vinten-Johansen, M. Tien and J. Skillman. 1999. Differential response of four tree species to ozone-induced acceleration of foliar senescence. Plant, Cell Environ. 22(7): 779–790. https://doi.org/10.1046/j.1365-3040.1999.00449.x
Pitel, N.E. and R.D. Yanai. 2014. Abiotic and biotic factors influencing sugar maple health: Soils, topography, climate, and defoliation. Soil Sci. Soc. Am. J. 78(6): 2061–2070. https://doi.org/10.2136/sssaj2014.06.0240
PPAQ. 2023. [Producteurs et productrices acéricoles du Québec]. Convention de mise en marché du sirop d'érable entre les Producteurs et productrices acéricoles du Québec et tous les acheteurs du produit visé par le plan conjoint des producteurs acéricoles du Québec, représentés par le Conseil de l'industrie de l'érable. Longueuil (Qc). 27 p. + 18 annexes. https://ppaq.ca/app/uploads/2023/03/2023-02-28_Convention_MEM_sirop_2023-2024_VF_Annexes_signee_FINALE.pdf
Rebbeck, J. 1996. Chronic ozone effects on three northeastern hardwood species: Growth and biomass. Can. J. For. Res. 26(10): 1788–1798. https://doi.org/10.1139/x26-203
Rebbeck, J. and K.V. Loats. 1997. Ozone effects on seedling sugar maple (*Acer saccharum*) and yellow-poplar (*Liriodendron tulipifera*): Gas exchange. Can. J. For. Res. 27(10): 1595–1605. https://doi.org/10.1139/x97-121
Reich, P.B. and R.G. Amundson. 1985. Ambient levels of ozone reduce net photosynthesis in tree and crop species. Science 230(4725): 566–570. https://doi.org/10.1126/science.230.4725.566
Reich, P.B., A.W. Schoettle and R.G. Amundson. 1986. Effects of O_3 and acidic rain on photosynthesis and growth in sugar maple and northern red oak seedlings. Environ. Pollution. Ser. A, Ecol. Biol. 40(1): 1–15. https://doi.org/10.1016/0143-1471(86)90054-1
Renaud, J.P. 1998. Étude des variations régionales en métaux lourds contenus dans l'eau d'érable en fonction de la période de récolte. Projet de recherche : rapport final. Centre de recherche, de développement et de transfert technologique en acériculture (Le Centre ACER Inc.). St-Hyacinthe, 10 p. https://gestion.centreacer.qc.ca/fr/UserFiles/Publications/19_Fr.pdf
Robinson, A.R., K.S. MacLean and H.M. MacConnell. 1989. Heavy metal, pH, and total solid content of maple sap and syrup produced in eastern Canada. J. Assoc. Off. Anal. Chem. 72(4): 674–9. https://doi.org/10.1093/jaoac/72.4.674
Schaberg, P.G., J.W. Tilley, G.J. Hawley, D.H. Dehayes and S.W. Bailey. 2006. Associations of calcium and aluminum with the growth and health of sugar maple trees in Vermont. For. Ecol. Manage. 223(1–3): 159–169. https://doi.org/10.1016/j.foreco.2005.10.067
Schaub, M., J.M. Skelly, K.C. Steiner, D.D. Davis, S.P. Pennypacker, J. Zhang, J.A. Ferdinand, J.E. Savage and R.E. Stevenson. 2003. Physiological and foliar injury responses of *Prunus serotina*, *Fraxinus americana*, and *Acer rubrum* seedlings to varying soil moisture and ozone. Environ. Pollut. 124(2): 307–320. https://doi.org/10.1016/S0269-7491(02)00462-1
Scott, N.A., G.E. Likens, J.S. Eaton and T.G. Siccama. 2001. Trace metal loss following whole-tree harvest of a northeastern deciduous forest, U.S.A. Biogeochem. 54(2): 197–217. https://doi.org/10.1023/A:1010624315658
Simonetti, A., C. Gariépy and J. Carignan. 2000. Pb and Sr isotopic evidence for sources of atmospheric heavy metals and their deposition budgets in northeastern North America. Geochim. Cosmochim. Acta 64(20): 3439–3452. https://doi.org/10.1016/S0016-7037(00)00446-4
Soubeyrand, M., P. Marchand, L. Duchesne, Y. Bergeron and F. Gennaretti. 2024. Interactions between climate, soil and competition drive tree growth in Quebec forests. For. Ecol. Manage. 555: 121731. https://doi.org/10.1016/j.foreco.2024.121731
St. Clair, S.B., J.E. Carlson and J.P Lynch. 2005. Evidence for oxidative stress in sugar maple stands growing on acidic, nutrient imbalanced forest soils. Oecologia 145(2): 257–268. https://doi.org/10.1007/s00442-005-0121-5
St. Clair, S.B., W.E. Sharpe and J.P Lynch. 2008. Key interactions between nutrient limitation and climatic factors in temperate forests: A synthesis of the sugar maple literature. Can. J. For. Res. 38(3): 401–414. https://doi.org/10.1139/X07-161
Stilwell, D.E. and C.L. Musante. 1996. Lead in maple syrup produced in Connecticut. J. Agric. Food Chem. 44(10): 3153–3158. https://doi.org/10.1021/jf9600869
Sullivan, T.J., G.B. Lawrence, S.W. Bailey, T.C. McDonnell, C.M. Beier, K.C. Weathers, G.T. McPherson and D.A. Bishop. 2013. Effects of acidic deposition and soil acidification on sugar maple trees in the Adirondack mountains, New York. Environ. Sci. Technol. 47(22): 12687–12694. https://doi.org/10.1021/es401864w
Sullivan, T.J., C.T. Driscoll, C.M. Beier, D. Burtraw, I.J. Fernandez, J.N. Galloway, D.A. Gay, C.L. Goodale, G.E. Likens, G.M. Lovett, S.A. Watmough *et al.* 2018. Air pollution success stories in the United States: The value of long-term observations. Environ. Sci. Policy 84(2): 69–73. https://doi.org/10.1016/j.envsci.2018.02.016
Superior Court of the State of California, 2014. Mateel Environmental Justice Foundation *vs* Anderson's Maple Syrup, Inc., *et al.* County of Humboldt, case No. DR-140469. https://oag.ca.gov/system/files/prop65/judgments/2014-00281J2359.pdf
Tanentzap, F.M. and P. Ryser. 2015. Decreased resistance to embolism in red maple (*Acer rubrum* L.) saplings within a heavy metal contaminated region. Environ. Exp. Bot. 109: 40–44. https://doi.org/10.1016/j.envexpbot.2014.07.019
Tjoelker, M.G., J.C. Volin, J. Oleksyn and P.B. Reich. 1993. Light environment alters response to ozone stress in seedlings of *Acer saccharum* Marsh, and hybrid *Populus* L. New Phytol. 124(4): 627–636. https://doi.org/10.1111/j.1469-8137.1993.tb03852.x
Tjoelker, M.G., J.C. Volin, J. Oleksyn and P.B. Reich. 1995. Interaction of ozone pollution and light effects on photosynthesis in a forest canopy experiment. Plant. Cell Environ. 18(8): 895–905. https://doi.org/10.1111/j.1365-3040.1995.tb00598.x
Topa, M.A., D.W. Vanderklein and A. Corbin. 2001. Effects of elevated ozone and low light on diurnal and seasonal carbon gain in sugar maple. Plant, Cell Environ. 24(7): 663–677. https://doi.org/10.1046/j.0016-8025.2001.00722.x
Topa, M.A., D.J. McDermitt, S.C. Yun and P.S. King. 2004. Do elevated ozone and variable light alter carbon transport to roots in sugar maple? New Phytol. 162(1): 173–186. https://doi.org/10.1111/j.1469-8137.2004.01014.x
Tourville, J.C., M.R. Zarfos, G.B. Lawrence, T.C. McDonnell, T.J. Sullivan and M. Dovčiak. 2023. Soil biotic and abiotic thresholds in sugar maple and American beech seedling establishment in forests of the northeastern United States. Plant Soil 491: 387–400. https://doi.org/10.1007/s11104-023-06123-2
Tyler, G. 1972. Heavy metals pollute nature, may reduce productivity. Ambio 1(2): 52–59.

van Breemen, N., A.C. Finzi and C.D. Canham. 1997. Canopy tree-soil interactions within temperate forests: Effects of soil elemental composition and texture on species distributions. Can. J. For. Res. 27(7): 1110–1116. https://doi.org/10.2307/2641084

Wang, B., H.H. Shugart, J.K. Shuman and M.T. Lerdau. 2016. Forests and ozone: Productivity, carbon storage, and feedbacks. Sci. Rep. 6: 22133. https://doi.org/10.1038/srep22133

Wargo, P.M., R. Minocha, B.L. Wong, R.P. Long, S.B. Horsley and T.J. Hall. 2002. Measuring changes in stress and vitality indicators in limed sugar maple on the Allegheny Plateau in north-central Pennsylvania. Can. J. For. Res. 32(4): 629–641. https://doi.org/10.1139/X02-008

Watmough, S.A. 2002. A dendrochemical survey of sugar maple (Acer saccharum Marsh) in south-central Ontario, Canada. Water, Air, & Soil Pollution 136: 165–187. https://doi.org/10.1023/A:1015231526980

Watmough, S.A. 2008. Element mobility and partitioning along a soil acidity gradient in central Ontario forests, Canada. Environ. Geochem. Health 30: 431–444. https://doi.org/10.1007/s10653-007-9127-8

Watmough, S.A. 2010. Assessment of the potential role of metals in sugar maple (Acer saccharum Marsh) decline in Ontario, Canada. Plant Soil 332: 463–474. https://doi.org/10.1007/s11104-010-0313-6

Watmough, S.A. and T.C. Hutchinson. 2004. The quantification and distribution of pollution Pb at a woodland in rural south central Ontario, Canada. Environ. Pollut. 128(3): 419–428. https://doi.org/10.1016/j.envpol.2003.09.007

Watmough, S.A., P.J. Dillon and E.N. Epova. 2005a. Metal partitioning and uptake in central Ontario forests. Environ. Pollut. 134(3): 493–502. https://doi.org/10.1016/j.envpol.2004.09.001

Watmough, S.A., T.C. Hutchinson and P.J. Dillon. 2005b. Lead dynamics in the forest floor and mineral soil in south-central Ontario. Biogeochemistry 71: 43–68. https://doi.org/10.1007/s10533-005-7661-y

Watmough, S.A., C. Eimers and S. Baker. 2016. Impediments to recovery from acid deposition. Atmos. Environ. 146: 15–27. https://doi.org/10.1016/j.atmosenv.2016.03.021

West, R.R., R.R. Lada and M.T. MacDonald. 2023. Nutrition and related factors affecting maple tree health and sap yield. Am. J. Plant Sci. 14: 125–149. https://doi.org/10.4236/ajps.2023.142011

Wilmot, T.R., D.S. Ellsworth and M.T. Tyree. 1995. Relationships among crown condition, growth, and stand nutrition in seven northern Vermont sugarbushes. Can. J. For. Res. 25(3): 386–397. https://doi.org/10.1139/x95-043

Wilmot, T.R., D.S. Ellsworth and M.T. Tyree. 1996. Base cation fertilization and liming effects on nutrition and growth of Vermont sugar maple stands. For. Ecol. Manage. 84(1–3): 123–134. https://doi.org/10.1016/0378-1127(96)03743-7

Wittig, V.E., E.A. Ainsworth, S.L. Naidu, D.E. Karnosky and S.P. Long. 2009. Quantifying the impact of current and future tropospheric ozone on tree biomass, growth, physiology and biochemistry: A quantitative meta-analysis. Glob. Change Biol. 15(2): 396–424. https://doi.org/10.1111/j.1365-2486.2008.01774.x

Yuan, T., S. Huang, P. Zhang, Z. Song, J. Ge, X. Miao, Y. Wang, Q. Pang, D. Peng *et al.* 2024. Potential decoupling of CO_2 and Hg uptake process by global vegetation in the 21st century. Nat. Commun. 15: 4490. https://doi.org/10.1038/s41467-024-48849-2

Yue, X. and N. Unger. 2014. Ozone vegetation damage effects on gross primary productivity in the United States. Atmos. Chem. Phys. 14(17): 9137–9153. https://doi.org/10.5194/acp-14-9137-2014

Zaccherio, M.T. and A.C. Finzi. 2007. Atmospheric deposition may affect northern hardwood forest composition by altering soil nutrient supply. Ecol. Appl. 17(7): 1929–1941. https://doi.org/10.1890/06-2067.1

Zhang, Y., Z. Song, S. Huang, P. Zhang, Y. Peng, P. Wu, J. Gu, S. Dutkiewicz, H. Zhang *et al.* 2021. Global health effects of future atmospheric mercury emissions. Nat. Commun. 12: 3035. https://doi.org/10.1038/s41467-021-23391-7

Zhang, Y., J. Li, J. Tan, W. Li, B. P. Singh, X. Yang, N. Bolan, X. Chen, S. Xu *et al.* 2023. An overview of the direct and indirect effects of acid rain on plants: Relationships among acid rain, soil, microorganisms, and plants. Sci. Total Environ. 873: 162388. https://doi.org/10.1016/j.scitotenv.2023.162388

Zhou, J., D. Obrist, A. Dastoor, M. Jiskra and A. Ryjkov. 2021. Vegetation uptake of mercury and impacts on global cycling. Nat. Rev. Earth Environ. 2: 269–284. https://doi.org/10.1038/s43017-021-00146-y

Zwoliński, J. 1994. Rates of organic matter decomposition in forests polluted with heavy metals. Ecol. Eng. 3(1): 17–26. https://doi.org/10.1016/0925-8574(94)90008-6