Environmental Reviews

OPEN ACCESS | Review

Wood ash amendments as a potential solution to widespread calcium decline in eastern Canadian forests

Natalie Kim[a], **Shaun A. Watmough**[b], **and Norman D. Yan**[a,c]

[a]Friends of the Muskoka Watershed, P.O. Box 416, Bracebridge, ON P1L 1T7, Canada; [b]School of the Environment, Trent University, Peterborough, ON K9J 7B8, Canada; [c]Department of Biology, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada

Corresponding author: **Natalie Kim** (email: ms.nataliekim@gmail.com)

Abstract

Decades of acidic deposition have depleted soil calcium (Ca) stocks over large areas of eastern Canada. The recovery of soil Ca levels has been limited despite substantial reductions in acidic deposition and will likely take many decades because rates of loss (owing to soil leaching, timber harvesting, and forest regeneration) may equal or exceed those of supply (via atmospheric input and natural mineral weathering). As low soil Ca levels may adversely affect local biota with relatively high Ca requirements, affected sites may benefit from supplementation with an alternative Ca source. A growing body of evidence suggests that the application of wood ash to Ca-deficient forest soils can help counteract the loss of Ca and other nutrients from the soil while boosting forest productivity. Yet the use of wood ash as a forest soil amendment is currently restricted in Canada, and the costs of obtaining permits and transporting/applying the ash make landfilling a more economically viable option. Here, we explore the potential of wood ash amendments in terms of their risks and benefits, dose and application frequency, time to see benefits, and longevity of benefits. After considering these topics in the context of Ca-deficient, acidified forest soils across eastern Canada, we propose that the potential benefits of ash amendments in these areas likely outweigh the risks. Future studies are needed to clarify both the short- and long-term effects of wood ash addition on different tree species in both natural and managed forests, as well as the potential benefits for carbon capture and implications for Ca-deficient aquatic ecosystems.

Key words: calcium decline, forest management, soil amendment, sugar maple, wood ash

Résumé

Des décennies de dépôts acides ont épuisé les stocks de calcium (Ca) du sol dans de vastes régions de l'est du Canada. Le rétablissement des niveaux de calcium du sol a été limité malgré les réductions substantielles des dépôts acides et il prendra probablement plusieurs décennies, car les taux de perte (en raison du lessivage du sol, de la récolte du bois et de la régénération forestière) peuvent égaler ou dépasser ceux de l'approvisionnement (par l'apport atmosphérique et la météorisation minérale naturelle). Puisque de faibles niveaux de Ca dans le sol peuvent exercer un effet négatif sur le biote local dont les besoins en Ca sont relativement élevés, les sites touchés peuvent bénéficier d'une supplémentation par une source alternative de Ca. De plus en plus de preuves suggèrent que l'application de cendres de bois sur des sols forestiers déficients en Ca peut aider à contrecarrer la perte de Ca et d'autres nutriments du sol tout en stimulant la productivité des forêts. Pourtant, l'utilisation des cendres de bois comme amendement des sols forestiers est actuellement restreinte au Canada, et les coûts d'obtention des permis et de transport/application des cendres font de l'enfouissement une option plus viable économiquement. Les auteurs explorent ici le potentiel des amendements à base de cendres de bois du point de vue des risques et des avantages, de la dose et de la fréquence d'application, du temps pour constater les avantages et de la durée des avantages. Après avoir examiné ces sujets dans le contexte des sols forestiers acidifiés et carencés en Ca dans l'est du Canada, les auteurs proposent que les avantages potentiels des amendements à base de cendres dans ces régions dépassent probablement les risques. Des études futures sont nécessaires pour clarifier les effets à court et à long terme de l'ajout de cendres sur différentes espèces d'arbres dans les forêts naturelles et aménagées, ainsi que les avantages potentiels pour la capture du carbone et les implications pour les écosystèmes aquatiques carencés en Ca.

Mots-clés : déclin du calcium, gestion forestière, amendement du sol, érable à sucre, cendre de bois

1 Introduction

Calcium (Ca) stocks in soils have been slowly declining around the world for millennia, but the downtrend has accelerated greatly over the past half century, especially in eastern North America and Europe (Leys et al. 2016). These regions have been subjected to decades of elevated acidic deposition, which caused the initial rapid leaching of Ca from the soil (Likens et al. 1998). Because Ca is essential for all life forms including prokaryotes, fungi, plants, and animals, dwindling supplies of this element have been detrimental to many organisms, particularly those with high Ca demands. In the United Kingdom, for example, low soil Ca availability has reduced the abundance, size, and diversity of terrestrial snails, which primarily require Ca for shell formation (Jubb et al. 2006). Declines in the abundance of snails across Europe owing to acidified, Ca-deficient soils have also been linked to eggshell defects in their avian predators (Graveland and van der Wal 1996). Additionally, low and (or) falling Ca has emerged as a major issue in the surface waters of eastern North America and western Europe (Jeffries et al. 2003; Skjelkvåle et al. 2005; Keller 2009). An examination of 43 100 aquatic sites across 57 countries revealed that 21% have Ca concentrations of $\leq$1.5 mg·L^{-1} (Weyhenmeyer et al. 2019)—a biologically critical threshold for many Ca-rich organisms (e.g., Ashforth and Yan 2008). Several workers have documented the direct damage imparted by Ca deficiencies to different *Daphnia* species (Jeziorski et al. 2008) and crayfish (Edwards et al. 2009; Hadley et al. 2015), as well as possible damage to molluscs and amphipods (Cairns and Yan 2009). Calcium deficiency may also exert indirect damage to pelagic food webs due to altered competitive (Jeziorski et al. 2015) and predatory interactions (Riessen et al. 2012).

In plants, Ca has various roles in cell functioning, which can be broadly categorized as structural (helping to uphold the cell wall and plasma membrane) or labile (acting as a messenger in cell signaling and allowing cells to detect and react to external stimuli) (Halman et al. 2008). Calcium is thus necessary for many plant processes including cell division, cell wall synthesis and functioning, cell membrane stability, protein synthesis, nuclear protein phosphorylation, freeze tolerance, and stomatal functioning (Monroy et al. 1993; McLaughlin and Wimmer 1999; Schaberg et al. 2001; Yoshioka and Moeder 2020). In trees, Ca limitation negatively affects wood formation and wound repair (McLaughlin and Wimmer 1999; Huggett et al. 2007), cold tolerance (McLaughlin and Wimmer 1999; Schaberg et al. 2001; Halman et al. 2008), and the ability of trees to withstand strong winds (McLaughlin and Wimmer 1999).

Our objectives in this review are twofold. First, we review the causes of Ca decline and explore the idea of supplementing soils affected by anthropogenic Ca declines in eastern Canada with an alternative Ca source. Second, we examine the evidence regarding the potential risks and benefits of Ca additions via wood ash to reverse the effects of Ca depletion in forest soils, especially as it applies to eastern Canada. Though the use of wood ash as a forest fertilizer is commonly recommended in many parts of the world, regulatory approval is required for the land application of wood ash in Canada owing to insufficient information on its effects (Hannam et al. 2018). We also discuss ash dose and application frequency, the time needed to see benefits in forests, and the longevity of such effects. We conclude that wood ash may be a suitable source of Ca as well as other essential elements like potassium (K), magnesium (Mg), and phosphorus (P); that the trace metal levels in ash derived from untreated wood likely pose minimal ecological risk; and that the application of wood ash may help advance restoration efforts for forests suffering the after-effects of acidification, logging, and Ca loss, especially in eastern Canada.

2 Causes of calcium decline

The soil base cation (BC) pool refers to the soil "bank" of BCs, mainly Ca, Mg, sodium (Na), and K ions. In most soils across eastern Canada, Ca is the dominant BC, accounting for between 50% and 70% of the exchangeable BC pool (Watmough et al. 2005). At forest sites with minimal human influence, Ca and other BCs enter the soil exchangeable pool via natural mineral weathering, atmospheric deposition, and biomass decomposition (Likens et al. 1998; McLaughlin and Wimmer 1999; Rosenstock et al. 2019). Atmospheric deposition and mineral weathering are net sources to the exchangeable pool, whereas decomposition and plant uptake are internal-cycling processes. Once Ca becomes mobile as a soluble cation, it enters the soil solution where it may be taken up by vegetation or microorganisms, bound to cation exchange sites on soil particles, or leached through the soil layers (Likens et al. 1998). Exchangeable Ca pools are usually considered to represent the Ca available to biota, although there is some evidence that ectomycorrhizae may "mine" Ca from minerals directly (Blum et al. 2002). In areas with shallow soils, the size of the exchangeable Ca pool is correlated with surface water Ca concentrations (Houle et al. 2006). Yet the natural bio-geochemical cycling of Ca has been disrupted by human activities to the extent that the rate of Ca loss in many regions now exceeds that of net Ca supply. Reduced atmospheric inputs of Ca (arising from stricter emission controls) contribute to the overall net loss of Ca from soil (Hedin et al. 1994; Likens et al. 1998; Yao et al. 2011; Smol 2019), but the two main drivers are acidic deposition and timber extraction.

Acidic deposition has affected large areas of eastern North America. At forest sites, the already low soil Ca concentrations were further reduced by decades of acidic deposition (Likens et al. 1998), which raised the concentration of H^+ ions and associated mobile anions in the soil solution while promoting the movement of Ca from the soil via uptake by vegetation or to surface waters through leaching (Reuss and Johnson 1986; Tomlinson 2003). The soils at seven catchments across the Muskoka–Haliburton region in central Ontario lost an estimated 10%–60% of their exchangeable Ca pool over a span of 17 years (Watmough and Dillon 2003). By contrast, no change in soil Ca has been seen over the past 15–20 years at the Turkey Lakes Watershed near Sault Ste. Marie, Ontario (Hazlett et al. 2011), which has deeper soils with higher weathering rates and is historically a lower acid deposition zone than more heavily affected regions in Ontario (e.g., Sudbury, Muskoka). Some forested sites across the northeastern USA and eastern Canada have begun showing signs of chemical recovery from acidification (Lawrence et al. 2015; Hazlett et al. 2020; Ott and Watmough 2022). However, the complete recovery of forest soils from Ca depletion to preindustrial levels may take centuries because of low BC-weathering rates (Huntington et al. 2000) and is unlikely with continued har-

 Environ. Rev. **00:** 1–16 (2022) | dx.doi.org/10.1139/er-2022-0017

vesting in managed forests (Ott and Watmough 2022). Surface water Ca levels also remain low, even with substantial reductions in acid deposition across Canada and the USA since the 1980s (Jeffries et al. 2003), and modeling studies suggest that lakewater Ca levels will continue to fall (Clair et al. 2007). Lakewater Ca concentrations likely rose during the early days of acidification owing to high soil leaching, but in nutrient-poor, noncalcareous soils, and areas underlain by weathering-resistant Precambrian granitic bedrock, the rate of Ca leaching greatly outpaced that of weathering, and soil Ca reserves decreased (reviewed in Duchesne et al. 2002; Smol 2019).

Environmental Ca declines are further aggravated by timber harvesting (Watmough and Aherne 2008), which directly removes the Ca from forest sites via wood tissues and bark. The harvesting of whole trees is especially harmful because Ca is highly concentrated in the stemwood and bark, but also present, to a lesser extent, in the foliage and branches (reviewed in Schaberg et al. 2001). Whole-tree removal may consequently result in a nutrient loss that is up to three times higher than that from the removal of stemwood alone (reviewed in Pitman 2006). The removal of foliage decreases the base saturation and pH of surface soils as well as foliar Ca concentrations in the regenerating stands (Achat et al. 2015). Moreover, multiple rotations of whole-tree harvesting can contribute to a net Ca loss that negatively affects tree growth in subsequent rotations (Proe et al. 1996; Walmsley et al. 2009) as regeneration creates further demand for Ca from soil (Likens et al. 1998; Watmough et al. 2003). In the eastern USA, multiple cycles of whole-tree harvesting have exported an estimated 20%–60% of the total site Ca (as well as 2%–10% of K, P, and Mg) over a span of 120 years, which is comparable to numbers reported for Sweden (reviewed in Pitman 2006). The short-term impacts of harvesting are varied and include the enhanced leaching of Ca from soil caused by higher nitrate leaching (Likens et al. 1998). Studies from south-central Ontario show that logging removes more Ca than that provided by deposition and mineral weathering combined (as does logging plus acid rain; Philips and Watmough 2012). Over the long-term, reductions in available soil Ca and continued harvesting will likely result in surface water Ca levels that are far below preindustrial values (Watmough et al. 2003; Reid and Watmough 2016).

3 Calcium deficiency in trees

Tree species with relatively high Ca requirements like the sugar maple (*Acer saccharum* Marsh.) may have shown signs of Ca deficiency early on. Reports of sugar maple declines in Quebec and the northeastern USA date back to the 1960s (Mader and Thompson 1969). While the specific stressors responsible for such declines differ by site, multiple studies indicate that Ca availability plays a key role. In the early 1980s, the decline of sugar maples in northern Pennsylvania was linked to low soil pH and a soil Ca to aluminum (Al) ratio of ≤1, as well as declining BC levels in foliage (Drohan et al. 2002). Around that time, sugar bush operators in Ontario also began expressing concern about the perceptible decline in sugar maples, identifying acid precipitation as a possible cause (McLaughlin et al. 1985). Altered soil conditions following acidic deposition, including diminished soil Ca and increased Al concentrations, have since been linked to reduced sugar maple growth and population declines throughout eastern Canada (McLaughlin et al. 1987; Duchesne et al. 2002; Gradowski and Thomas 2006) and the USA (Schaberg et al. 2001; reviewed in Juice et al. 2006; Schaberg et al. 2006; Bishop et al. 2015). These declines likely resulted from the adverse effects of Ca deficiency on the growth of saplings (Kobe et al. 2002) and mature trees (Watmough 2002; Long et al. 2009), foliar nutrition (Miller and Watmough 2009), and the growth, survival, and regeneration of seedlings (Juice et al. 2006; Cleavitt et al. 2011; Sullivan et al. 2013).

Additionally, acidic deposition may induce the foliar leaching of Ca, possibly compromising the immune response of trees to stressors (e.g., drought, ultraviolet radiation, thermal stress, insect pests, pathogens, pollutants), which can slow growth and increase their susceptibility to decline (reviewed in Schaberg et al. 2001). Acid-induced changes in foliar Ca have been recorded in conifers such as the eastern white pine (*Pinus strobus* L.), eastern hemlock (*Tsuga canadensis* L.), and balsam fir [*Abies balsamea* (L.) Mill.] (Schaberg et al. 2001) and implicated in the decline of red spruce (*Picea rubens* Sarg.) (Schaberg and DeHayes 2000).

4 The need for calcium additions

Widespread environmental Ca declines have clearly been exacerbated by human activities. Compensatory fertilization of newly logged sites can help replace some of the Ca lost to logging, but this is not a common practice in Canada. And although naturally occurring wildfires can help return Ca to the soil, they do not add any new Ca to the watershed. Active restoration efforts may therefore be needed to slow and (or) reverse the loss of Ca from forest soils. Forests may benefit from soil amelioration with supplementary Ca. Schaberg et al. (2001) suggested that liming and (or) the addition of other forms of Ca to forest soils could reduce sugar maple decline arising from stressors such as freezing damage, drought, and defoliation by insects.

The benefits of Ca additions for forest health are perhaps the most evident in a series of Ca addition studies conducted at the Hubbard Brook Experimental Forest (HBEF) in northern New Hampshire. Likens et al. (1998) observed large declines in Ca concentrations and Ca flux in precipitation (from the years 1963 to 1975) and in stream water (from 1963 to 1985). Johnson et al. (2000) later reported that the Hubbard Brook watershed was losing Ca, likely due to losses from soil exchange sites and organic matter. Siccama et al. (2007) noted abnormally high rates of mortality in mature sugar maples in the HBEF during the late 1990s, as well as slow growth, which paved the way for their decline. A Ca addition study was thus initiated in one of the experimental watersheds in October 1999 to examine the responses of the forest ecosystem to wollastonite ($CaSiO_3$) supplementation (at a rate of 0.85 t Ca·ha^{-1}) and the anticipated ensuing recovery of pH and restoration of exchangeable soil Ca to preindustrial levels (Peters et al. 2004). In the fall of 2002, researchers noticed that sugar maple seed production was markedly high, and this led to the emergence of large numbers of sugar maple germinants the following year (Juice et al. 2006). Juice et al. (2006) confirmed that low Ca was indeed responsible for the dieback of sugar maples at HBEF, with wollastonite additions resulting in increases in soil pH, foliar chlorophyll, leaf and fine-root Ca concentrations, photosynthesis, transpiration, crown health of mature trees, seed production, seedling germination, and mycorrhizal colonization of seedling roots. When comparing the control and Ca-treated sites, they found clear differences in seedling density, survivorship, and growth (Juice et al. 2006). Cleavitt et al. (2011) also observed increased seedling survival in sugar maples at Ca-treated sites in HBEF. Over the course of 15 years, Battles et al. (2014) documented increases in tree biomass, aboveground net primary production, and photosynthetic surface area following the wollastonite addition, verifying that forest productivity can indeed be restored by replacing the lost Ca from acidic soils, following past anthropogenic activity. Green et al. (2013) found that wollastonite addition increased evapotranspiration rates and thereby altered local hydrology — an effect that lasted at least 3 years. In short, Ca additions at HBEF led to numerous benefits for the forest, which had long been suffering from Ca limitation.

Potential sources of Ca for soil amelioration include lime, alkaline residues, and biomass ashes. The most frequently applied buffering compounds in liming studies are calcite ($CaCO_3$; also known as limestone or calcium carbonate) and dolomite [$CaMg(CO_3)_2$], but others are wollastonite, calcium chloride ($CaCl_2$), calcium nitrate [$Ca(NO_3)_2$], and gypsum ($CaSO_4$) (Reid and Watmough 2014). However, Ca additions to watersheds and lakes through liming are unrealistic on a wide scale (Smol 2019), with high doses being potentially detrimental to forest ecosystems (Lawrence et al. 2016). Moreover, limestone is not always an ideal choice for soil amendment as it requires mining and transport to sites in need (Azan et al. 2019). These limitations also apply to wollastonite and other commonly used liming compounds. Alkaline residues are the by-products of activities such as steel production and coal-fired power generation (Royer-Tardif et al. 2019), the latter of which is being phased out in Canada (Government of Canada 2022). For the purposes of this review, we will focus on the solid residue produced from the combustion of the organic matter in biomass such as wood and woody biomass (Vassilev et al. 2013). Azan et al. (2019) recently proposed wood ash supplementation as a possible solution to the Ca decline problem in Ontario because wood ash contains reliably high amounts of Ca as well as other plant-essential nutrients (e.g., Mg, K, P), is usually locally available, and does not require mining, which translates to less environmental disturbance and lower shipping costs. The positive effects of wollastonite additions on forest productivity seen at the Hubbard Brook watershed may also apply to wood ash additions in Ca-deficient watersheds, even though the Ca is in a different form.

5 Wood ash amendment

5.1 Background

Ashes from the combustion of woody biomass and additional plant materials have been used for soil amelioration for hundreds of years (Vance 1996). Ash and biochar are major components of the highly fertile Anthropogenic Dark Earths in Amazonia (Glaser and Birk 2012), and they have also been used by indigenous groups across Africa and Asia to enrich agricultural soils (Fairhead et al. 2017). Wood ash has been used for decades as a soil ameliorant in some parts of the northeastern USA and Scandinavia (Pitman 2006), and ash addition is promoted across Europe to restore the nutrients lost to logging (Hannam et al. 2018). The production of waste ash has also been increasing recently in Scandinavia and Europe owing to the use of wood fuels in lieu of fossil fuels to produce heat and energy (Huotari et al. 2015). Similarly, the nutrient-rich waste ash generated from Canada's increasing adoption of forest fuels for power generation has unrealized value as a forest fertilizer (Hannam et al. 2018). But the addition of ash to forest soils is highly regulated in Canada, and the costs associated with obtaining approval and transporting and applying the ash often make landfilling a more economical option (Hannam et al. 2018). The estimated total cost of ash application to a forest site may be 15%–20% higher than that of landfilling (estimated median cost of $92 compared with $77 CAD per tonne of ash, respectively) (Hope et al. 2017). Still, the potential of wood ash to improve forest soil conditions, support sustainable forestry, and divert waste from landfills cannot be ignored, and numerous studies on these topics are ongoing across Canada through AshNet, a network of scientists, policymakers, and other stakeholders (Hannam et al. 2017). The potential long-term ecological benefits of ash amendments may outweigh the short-term financial costs when conscientiously applied.

5.2 Sources of wood ash

Wood-based ashes originating from industrial or nonindustrial sources may be used to amend forest soils. Industrial wood ash (IWA) is generated as a by-product of industrial processes like the manufacture of pulp and paper products (Azan et al. 2019) and can be further categorized as fly ash (the finer ash component that collects in the flue system) or bottom ash (the denser ash component that accumulates in the bottom of the combustion system) (Hannam et al. 2017). Nonindustrial wood ash (NIWA) refers to ash generated from people's homes (i.e., via wood-burning stoves used for heating) and other nonindustrial sources (Azan et al. 2019). The composition of NIWA may be more variable than that of ash from industrial sources because of the less consistent conditions under which the wood is combusted, as well as the multiple sources and wood fuels burned, and thus caution is needed to ensure prudent application (Deighton and Watmough 2020).

5.3 Composition of wood ash

Wood ash may be likened to a low-grade forest fertilizer because it contains all the macronutrients (Ca, Mg, K, P) and micronutrients (Fe, Mn, Zn, B, Cu, Mo) required by trees (Pitman 2006; Augusto et al. 2008). Ash amendments may benefit stands growing in mineral soils that are deficient in these nutrients (Pitman 2006; Augusto et al. 2008). For IWA (fly and bottom ashes) and NIWA from Canada, the nutrients occurring in the highest concentrations are Ca, K, Mg, and P, with NIWA having higher mean concentrations of Ca

 Environ. Rev. **00:** 1–16 (2022) | dx.doi.org/10.1139/er-2022-0017

and K than IWA and fly ash having higher mean nutrient concentrations than bottom ash (AshNet 2021). For example, the mean total Ca concentrations of NIWA, fly ash, and bottom ash are 303, 171, and 121 g·kg^{-1}, respectively (AshNet 2021). Detailed data on the composition of various types of wood ash from industrial and nonindustrial sources are available online at the Canadian Wood Ash Chemistry Database (AshNet 2021). Wood ash contains relatively high amounts of Ca, including the highly soluble Ca compounds calcium oxide (CaO) and portlandite [$Ca(OH)_2$], as well as less soluble compounds like calcite, calcium silicates, and calcium aluminum silicates (Steenari et al. 1999; Hansen et al. 2017). Samples of NIWA from central Ontario contain an average of 30% Ca dry mass, which is in agreement with NIWA values from Poland (Smołka–Danielowska and Jabłońska 2021), and most of it is sparingly soluble, meaning it would be released slowly when applied to land (Azan et al. 2019).

Wood ash contains very little nitrogen (N) (Huotari et al. 2015; AshNet 2021), which is mostly volatilized during the combustion process (Saarsalmi et al. 2001; Reid and Watmough 2014). In southern Sweden, wood ash additions have had positive effects on tree growth in mineral soils not limited by N (Emilsson 2006) because ash can stimulate the decomposition of soil organic matter, which releases N that can be taken up by tree roots (Augusto et al. 2008; Huotari et al. 2015; Hannam et al. 2018). In cases where N is overly abundant, active whole-tree harvesting combined with wood ash amendment can be used to help remove some of the excess N (Emilsson 2006). For mineral soils where N is the main limiting nutrient, the addition of wood ash may have no effect or even negatively affect tree growth in the short term (Augusto et al. 2008; Jacobson et al. 2014; Huotari et al. 2015). Most of the forest soils in eastern Canada have received elevated N deposition (Aherne and Posch 2013), however, and may thus respond favorably to wood ash amendment.

The final composition of wood ash depends on many factors. The proportion of Ca-rich bark included during combustion affects the Ca concentration of the resulting ash (Park et al. 2005; Pitman 2006). The tree species from which the ash was generated is also important. Because ash from hardwood species usually contains higher macronutrient concentrations and lower levels of silica (which, at high levels, can negatively affect ash granulation following combustion) than that from conifers, it is probably superior as a forest fertilizer (Pitman 2006). Combustion temperature also affects the composition of the resulting ash. Calcium carbonates and bicarbonates are typically generated at combustion temperatures below 500 °C, whereas calcium oxides and hydroxides are commonly formed at or above 1000 °C (Etiegni and Campbell 1991). Residential wood stoves typically have burn temperatures under 1200 °C, while commercial boilers often exceed 2000 °C (Pitman 2006). Overall, temperatures of 500–900 °C are best for nutrient retention and the minimization of possibly toxic metals like Al (Pitman 2006). The storage time of wood may also affect the composition of the resulting ash. Wood ash from fresh birch was found to have higher Ca, Na, Mg, P, Fe, and barium (Ba) concentrations than ash from seasoned birch, which tends to have a lower and highly variable moisture content depending on how long it has been stored in the open air (Smołka–Danielowska and Jabłońska 2021). Lastly, contamination of the wood with soil during logging may affect ash composition (Park et al. 2005).

5.4 Potential risks

5.4.1 Trace metals and other contaminants

The main concern regarding wood ash amendments is the presence of trace metals in the ash (Aronsson and Ekelund 2004; Pitman 2006; Huotari et al. 2015; Hannam et al. 2018; Azan et al. 2019). Wood ash contains the toxic metals arsenic (As), Ba, cadmium (Cd), Cu, lead (Pb), mercury (Hg), nickel (Ni), and Zn at various concentrations, but it tends to have higher levels of Cu and Zn and lower levels of Cd and Hg (Smołka–Danielowska and Jabłońska 2021). Although Cu and Zn are heavy metals, they are also important plant micronutrients, whereas Cd and Pb are toxic to plants and other biota in low concentrations (Huotari et al. 2015). Overall, the relatively minor amounts of heavy metals in wood-based ashes are unlikely to affect ecological functioning, but any potential threats can be minimized by avoiding the use of fly ash or even removing the metals during the combustion process (Pitman 2006). During combustion and cooling, trace metals can become concentrated in fly ash, which is more chemically reactive than bottom ash due to its higher surface-to-volume ratio (Hannam et al. 2017). Alternatively, ash doses can be adjusted according to the relevant metal concentrations of the ash and the soil conditions of the receiving site.

To qualify as a soil amendment by the Canadian government, the concentrations of 11 trace metals/metalloids — As, Cd, Cr, Co, Cu, Pb, Hg, Mo, Ni, Se, and Zn — in wood ash must fall below the upper limit for content of any of the regulated metal (CM) levels, CM1 and CM2 (Hannam et al. 2016). The measured concentrations of trace metals/metalloids in NIWA samples from Ontario were found to be below the acceptable CM2 ranges, indicating that NIWA can safely be used as a soil amendment (Azan et al. 2019). Though the amounts of Cu and Zn in NIWA from Ontario frequently exceeded the CM1 limit, these essential micronutrients can be readily taken up by organisms and are unlikely to produce toxic effects in biota at these quantities (Azan 2018). Moreover, metals are usually immobilized in soil owing to the neutralizing effect of wood ash on acidity; this has consistently been seen with the use of loose ash (Huotari et al. 2015). The concentrations of Cd, Cr, Co, Pb, Mo, Ni, Se, and Zn in IWA are typically higher than those found in NIWA (Azan et al. 2019; AshNet 2021).

Nevertheless, both NIWA and IWA produced in Canada from untreated wood (i.e., free of paint, glue, insecticides) appear to pose little ecological risk in terms of their metal contents when applied at moderate doses. In south-central Ontario, the addition of 6 t·ha^{-1} of NIWA to acidic forest soils led to increases in soil pH, exchangeable BC concentrations, and foliar BC concentrations in sugar maple seedlings, with minimal to no increase in soil metal concentrations (Deighton and Watmough 2020). Similarly, foliar metal concentrations in sugar maple seedlings treated with 4 and 8 t·ha^{-1} IWA (fly and bottom ash) did not differ significantly from those of reference seedlings, and no increases were seen in the mobility or availability of trace metals following the application of IWA (with trace metal concentrations within Canadian limits) to hardwood forests with acidic soils at doses under 8 t·ha^{-1} (Deighton et al. 2021*a*).

To minimize the risks of metal contamination, ash from tree species with lower metal contents may be applied to soil. NIWA resulting from yellow birch (*Betula alleghaniensis* Britton.) contains higher levels of heavy metals than sugar maple and white pine, and its use as a soil amendment led to marked increases in the heavy metal concentrations of sugar maple seedling roots and shoots (Deighton and Watmough 2020). Additionally, trees growing in acidic soils like those of the Canadian Shield may be prone to higher metal accumulation than trees growing in nonacidic soils (Deighton and Watmough 2020). But because the atmospheric deposition of many metals such as Pb, Cd, Zn, and Hg was generally higher a few decades ago than it is today, the wood from which today's ash originated may have been accrued during a time of peak metal deposition, and the metal content of trees may decrease in the future.

Other concerns pertaining to wood ash amendments include the potential presence of polycyclic aromatic hydrocarbons, polychlorinated biphenyls, chlorobenzenes, and chlorophenols in the ash. However, these compounds are typically only found in negligible amounts and thus present little ecological risk (Someshwar 1996; Vance 1996). The small amounts of dioxins occasionally detected in wood-based ashes are also unlikely to be detrimental to ecological functioning (Pitman 2006). The risks may be minimized by considering the origin of the ash, analyzing the ash for contaminants of concern, and adjusting the ash dose as appropriate. For instance, ashes resulting from the burning of wood containing salt (e.g., lumber shipped via oceans) contain relatively high levels of dioxin (reviewed in Vance 1996), and thus may not be suitable as an amendment.

5.4.2 Effects on biota

The reported responses of biota to wood ash application have been mixed and vary depending on the study conditions. A mesocosm study showed that IWA (mixture of fly and bottom ashes) applied on top of soil has little effect on microbes in the deeper layers (Bang-Andreason et al. 2021). Some studies have reported impacts of wood ash addition on soil microbiological processes such as nitrification and denitrification (Odlare and Pell 2009; Björk et al. 2010), but such measurements are not often made in forest soils.

Wood ash is more reactive and soluble than ground limestone (Saunders 2018). Ash amendment is not recommended at sites with threatened plant species because it may drastically alter the existing vegetation (Huotari et al. 2015). Unsurprisingly, acidophilic organisms and communities are the most prone to negative effects from ash additions, especially bryophytes, soil bacteria, and ectomycorrhizal communities (Pitman 2006). Swedish studies have shown that the growth of mycelia and formation of fruit bodies by mycorrhizal fungi may suffer from soil amendment with 2–3 t·ha^{-1} of loose ash and that serious damage to Swedish mosses can occur with 2 t·ha^{-1} of loose ash, but soil fauna appear to tolerate the application of processed ash (reviewed in Nohrsted 2001). Thus, in Sweden, processing is recommended to stabilize the ash (i.e., form dense ash agglomerates and decrease solubility), increase homogeneity, facilitate spreading, and reduce dust and fine particles, thereby minimizing reactivity and harm to biota including the risk of alkaline shock to ground vegetation (Emilsson 2006).

The almost immediate increases in soil BCs following the application of unprocessed wood ash (Hansen et al. 2017; Bang-Andreasen et al. 2021) show that it is highly soluble, and the changes in plant chemistry that transpire within 1 year (e.g., Deighton and Watmough 2020) indicate that the elements (nutrients and metals) are readily available for uptake. However, some elements can actually become less soluble under certain conditions as the ash dissolves and soil pH rises. For example, in a pot experiment, IWA supplementation immobilized Cu, Zn, and Pb in the soil, which eliminated the stress of these trace metals on the earthworm *Eisenia foetida* and even supported its growth and reproduction (Pukalchik et al. 2018).

In studies conducted in Canada, the impacts of wood ash on soil biota have thus far been minimal. A recent metabarcoding study using soil samples from managed forests across Canada revealed little to no effects of adding up to 20 t·ha^{-1} wood ash on the bacterial, fungal, and arthropod communities (Smenderovac et al. 2022). Additionally, the community composition of soil microbes was largely unaffected by the addition of fly ash and bottom ash at doses of up to 5.8 t·ha^{-1} in field trials conducted in young boreal and mixed-age hardwood north-temperate forest soils in Ontario (Noyce et al. 2016). Adding fly and bottom ash at doses up to 8 t·ha^{-1} to the soils of a northern hardwood forest in central Ontario had no negative effects on abundances of the eastern red-backed salamander (*Plethodon cinereus* (Green, 1818)) 1 year later (Gorgolewski et al. 2016). However, the earthworm *Lumbricus terrestris* exhibited behavioral changes such as habitat avoidance and lower activity at the surface when exposed to 10 t·ha^{-1} of fly and bottom ash in the laboratory (McTavish et al. 2020).

5.4.3 Downstream effects

Currently, little information is available regarding the effects of wood ash additions on downstream surface waters and aquatic biota. Because ash amendments can help raise the pH and base saturation of soil, it is conceivable that they may subsequently raise the pH of surface waters and aid in their ecological recovery (reviewed in Hannam et al. 2018). Yet Deighton et al. (2021*b*) found only modest increases in soil water Ca following the addition of wood ash (4 and 8 t·ha^{-1}) in upstream areas of the Haliburton Forest in central Ontario, and the effects lasted only 2–3 years as most of the nutrients were retained in the soil and biomass. To our knowledge, very few studies have demonstrated a benefit of wood ash addition to lakes and streams, and this is likely due to a lack of ash addition field trials at the catchment scale. Additionally, Azan et al. (2019) investigated the short- and long-term effects of wood ash elutriate and sedimented wood ash, respectively, on the waterflea *Daphnia pulicaria*, concluding that wood ash applied to land is unlikely to be toxic to aquatic fauna. Thus, whether the effects of ash amendments extend to nearby surface waters and the magnitude of any effects likely depend on many factors such as the dose of ash applied, land area treated, and location of the treated site in relation to seasonal water inundation. These topics require further study.

5.4.4 Handling and other risks

Aside from the ecological risks, wood ash can pose practical hazards to handlers and property. It becomes highly alkaline when wet and can cause corrosive burns (Jackson and Odom 2021); thus, care must be taken to protect the skin if the ash is wet. Moreover, fly ash can be hazardous to the respiratory system and mucous membranes. Appropriate eye and respiratory protection should be used when handling should the ash become airborne. Wood ashes must also be thoroughly cooled and free of hot embers prior to collection, storage, and transport to reduce the risk of fire. An additional risk of promoting the use of wood-based ashes to combat Ca declines include inadvertently encouraging excessive tree harvesting or burning to produce wood pellets or NIWA. We do not recommend this practice.

5.5 Potential benefits

The amelioration of forest soils with wood ash can provide many ecological and economic benefits. The most frequently documented ecological benefits of ash amendments in acidic forest soils include improvements in soil conditions, tree growth, and foliar nutrition. The proven and anticipated benefits of ash amendments are depicted in Fig. 1.

Applying wood ash to forest soils can help restore the soil's acid-buffering capacity and replenish essential nutrients, including Ca, that may have been lost via leaching or biomass harvesting (Vance 1996; Pitman 2006; Augusto et al. 2008; Reid and Watmough 2014). The high pH values (often >11) of ash gives it a high acid-neutralizing capacity, such that the outcome of ash treatments on soil chemistry tends to mimic that of liming (Reid and Watmough 2014). Ash is typically applied to soils with pH values < 5, and it appears to be most beneficial when applied to soils with pH values < 4.5 (Reid and Watmough 2014). Decreasing soil acidity can positively affect P availability, base saturation, and the cation exchange capacity of soils (Pitman 2006; Augusto et al. 2008). According to a meta-analysis of European and North American studies, wood ash amendments are generally more effective than liming for increasing soil base saturation and tree growth, and vice versa for soil pH and foliar Ca (Reid and Watmough 2014). A recent study examining the effects of wood ash application (up to 20 $t{\cdot}ha^{-1}$) on various soil quality metrics at several sites across Canada found either slight improvements in soil quality or no effects (Joseph et al. 2022).

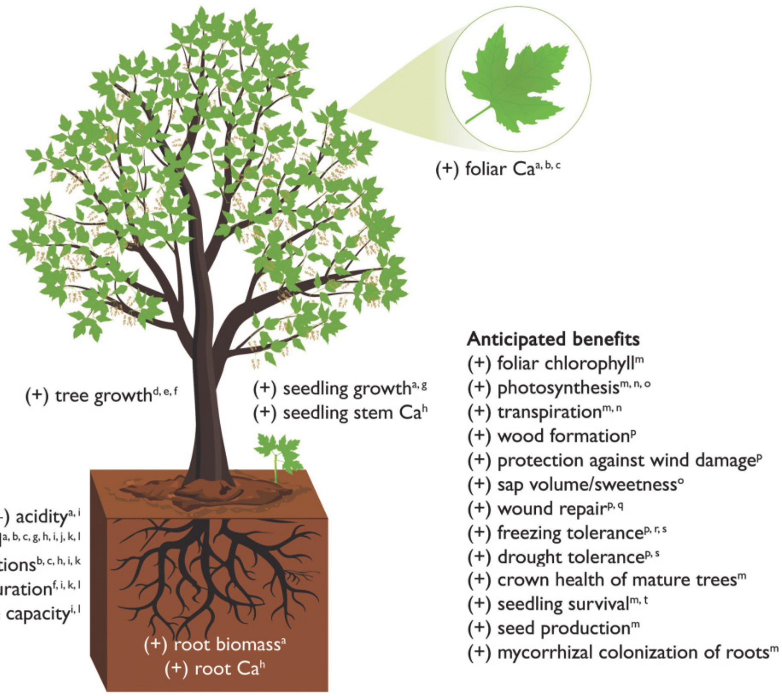
The growth response of trees may be species dependent. To date, most of the studies examining tree growth responses to ash addition have been conducted on conifers. Jack pine (*Pinus banksiana* Lamb.) growth increased as ash application rates increased, whereas mixed results were seen in hybrid larch (*Larix* × *marschlinsii*), and growth response was delayed in white spruce (*Picea glauca* (Moench) Voss) during field trials in northwestern Quebec (Bélanger et al. 2021). Thus, while species like jack pine may be well suited to treatment with wood ash, others like black spruce (*Picea mariana* Miller) may not be, as the latter exhibited a negative growth response to wood ash as application rates increased (Emilson et al. 2019). Such species-specific differences in growth response may reflect the diverse strategies used by different species to acquire and (or) store nutrients and is a topic requiring further study (Bélanger et al. 2021).

Because research on wood ash amendment of forest soils is still in its infancy in North America, evidence is lacking regarding the benefits for eastern hardwood species. However, wood ash additions may be more beneficial for hardwood species than conifers given that hardwoods typically require higher soil pH than conifers; have twice the Ca, Mg, and K requirements; and have a recommended nutrient ratio of 1:5:20:2.5 (P:K:Ca:Mg), which is unsurprisingly comparable to that of wood ash (1:7:45:2.5) (reviewed in Vance 1996). Species with particularly high Ca requirements, such as sugar maples, may benefit the most from Ca additions via wood ash. Over 30 years after the addition of dolomitic limestone at a load of 22.4 $t{\cdot}ha^{-1}$ to four hardwood stands in northern Pennsylvania, the basal area increment of sugar maples was more than twofold higher in limed than in unlimed plots (Long et al. 2021).

Improving the health and vigor of sugar maple stands, which have been disproportionately affected by acidification and Ca decline, also has substantial economic benefits given that maple syrup production is a major industry in eastern Canada. Nearly three-quarters of the world's "liquid gold" is produced on average each year in Quebec alone, representing almost $1 billion (CAD) of the country's gross domestic product (Producteurs et productrices acéricoles du Québec 2021). Wood ash addition and liming have been shown to increase sugar maple growth as the trees amass more woody tissue. In Quebec, amendment with IWA at a relatively high dose (20 $t{\cdot}ha^{-1}$) resulted in increased growth and basal area increment of mature sugar maples within 3 years (Arseneau et al. 2021). In other studies from Quebec, adding dolomite to a Ca-deficient sugar maple stand led to significant improvements in soil chemistry (Houle et al. 2002), and liming a base-poor sugar maple stand improved sap sweetness and yield over the long-term (Moore et al. 2020).

Isolating the Ca benefits of ash amendments is admittedly challenging. After all, increases in tree growth following ash additions have also been attributed to the increased availability of the essential nutrients K, P, and B (reviewed in Vance 1996), and the K in wood ash is more soluble than Ca (Reid and Watmough 2014). To objectively gauge the effectiveness of wood ash treatments for reversing Ca deficiency, a target of health is necessary but difficult to develop. Most of the contemporary data available from forests of relevance are inadequate for setting targets given that data collection has been conducted during a time of Ca depletion. Using space-for-time substitution may also be problematic because forest composition and factors that influence growth vary in space. Fur-

Fig. 1. Proven benefits of calcium addition via wood ash amendment on trees in acidified, calcium-deficient soils. Anticipated benefits listed on right refer to those documented in studies of calcium addition from non-wood ash sources. Superscripts for figure labels correspond to the following references: [(a)]An and Park 2021, [(b)]Arseneau et al. 2021, [(c)]Domes et al. 2018, [(d)]Emilsson 2006, [(e)]Ferm et al. 1992, [(f)]Reid and Watmough 2014, [(g)]Richard et al. 2018, [(h)]Deighton and Watmough 2020, [(i)]Bélanger et al. 2021, [(j)]Bang-Andreasen et al. 2021, [(k)]Brais et al. 2015, [(l)]Saarsalmi et al. 2001, [(m)]Juice et al. 2006, [(n)]Green et al. 2013, [(o)]Moore et al. 2020, [(p)]McLaughlin and Wimmer 1999, [(q)]Huggett et al. 2007, [(r)]Halman et al. 2008, [(s)]Schaberg et al. 2001, [(t)]Cleavitt et al. 2011.



ther complicating the selection of a health target and thus the isolation of the Ca benefits are the influences of other positive drivers (e.g., reduced acid precipitation) and negative drivers (e.g., climate change, drought, defoliators). One way to potentially estimate whether Ca is limiting is the diagnosis and recommendation integrated system (DRIS) approach (Beverly 1987), which involves comparing the ratio of observed nutrient concentrations in foliage with those known (or assumed) to maximize yields to obtain an estimated DRIS index, such that the limiting nutrients (i.e., the indices with the lowest values) may be identified (reviewed in Arseneau et al. 2021). Arseneau et al. (2021) found that the DRIS Ca index of sugar maple seedlings treated with 20 t·ha^{-1} IWA was higher than those of control seedlings after 3 years, indicating that foliar Ca deficiency was reduced with ash treatment. The DRIS approach is, however, limited in that it relies on known or assumed nutrient ratios. Though it may be difficult to clearly extrapolate the effects of Ca supplementation via wood ash to ecological benefits, isolating the Ca benefits may not be strictly necessary provided that overall forest health improves.

Another possible ecological benefit of wood ash amendments includes changes in the activity of ectomycorrhizal fungi. There is some evidence that wood ash additions may increase the ability of some ectomycorrhizal fungi to colonize tree roots and mobilize nutrients from the ash (van Breeman et al. 2000), but comprehensive studies on this topic are lacking (Reid and Watmough 2014).

Forest soil amendment with wood ash may also have implications for climate change mitigation. The Ca addition experiments at Hubbard Brook, which involved the land application of 3.44 t·ha^{-1} of wollastonite, resulted in a net carbon dioxide removal of 8.5–11.5 t CO_2·ha^{-1} over a span of 15 years (Taylor et al. 2021). Whether similar results can be achieved with wood ash has not been thoroughly explored, but in Finland, the application of wood ash to acidic forest soils led to higher C mineralization (the conversion of carbon dioxide into solid minerals such as carbonates) in the humus layer 2–7 years later (reviewed in Saarsalmi and Malkonen 2001). Mixing wood ash with biochar has been shown to enhance C fixation (Buss et al. 2019), and carbonated wood ash (which requires water for the reaction of CaO to Ca(OH)) has been suggested as a low-tech solution for C sequestration, potentially through addition to soils as a fertilizer (Koch et al. 2021). The effectiveness of wood ash amendments for C storage is thus a topic warranting further study.

5.6 Dose and application frequency

To minimize any potential ecological risks of wood ash additions, it is necessary to determine the minimum dose required to achieve the desired ecological outcome(s) (e.g.,

 Environ. Rev. **00:** 1–16 (2022) | dx.doi.org/10.1139/er-2022-0017

improve the soil, enhance tree health and growth, fertilize newly logged sites). In Finland, for example, wood ash is used to combat soil acidification and nutrient losses from leaching and logging (reviewed in Saarsalmi and Malkonen 2001) as well as boost tree productivity on peatlands, whereas in Sweden, ash amendments are typically a compensatory measure following biomass extraction from mineral soils (Emilsson 2006). In many Nordic countries, the maximum recommended dose ranges from 3 to 5 $t{\cdot}ha^{-1}$, which is generally sufficient for reducing acidity while increasing base saturation and nutrient (excluding N) content in the top 15 cm of soil (reviewed in Huotari et al. 2015). Many European countries also delineate the minimum Ca, Mg, K, and P contents of wood ash amendments to ensure that the nutrients lost through biomass extraction are replenished (Hannam et al. 2016). In Finland, the application dose is calculated based primarily on the P content of the ash, which should be at minimum 45 $kg{\cdot}ha^{-1}$ (reviewed in Hannam et al. 2018), as well as the Cd content. Given that the Cd concentrations in wood ash range from 4 to 20 $mg{\cdot}kg^{-1}$, the recommended maximum ash dose is generally 4 $t{\cdot}ha^{-1}$ (reviewed in Saarsalmi et al. 2001). In Lithuania, up to 6 $t{\cdot}ha^{-1}$ of ash is advised for sandy, nutrient-poor sites being afforested, whereas lower doses of approximately 2 $t{\cdot}ha^{-1}$ are recommended for less productive sites owing to the smaller quantity of nutrients removed via tree harvesting (reviewed in Hannam et al. 2018). In Sweden, the recommended doses according to the standardized dose calculation method (when information is lacking regarding past biomass extraction) differ by species, with birch and other species requiring slightly higher doses (1.2 $t{\cdot}ha^{-1}$) than spruce (1–2 $t{\cdot}ha^{-1}$) and pine (0.7–1.5 $t{\cdot}ha^{-1}$) (Emilsson 2006). The Swedish Forestry Act guidelines assert that a maximum of 3 $t{\cdot}ha^{-1}$ may be applied during a rotation period when compensatory fertilization is the goal; it also states that precautions are needed to ensure that N leaching and loss of added nutrients are minimal and that the total amount of contaminants (e.g., heavy metals) being added via the ash fall below the amount lost through biomass removal over the span of the rotation period (Emilsson 2006). Similarly in Denmark, up to 3 $t{\cdot}ha^{-1}$ of wood ash may be applied every 10 years for each 70-year growth cycle (Bang-Andreason et al. 2021).

In the eastern USA, Vance (1996) suggested that one 10 $t{\cdot}ha^{-1}$ application of wood ash would be adequate to replenish the soil Ca estimated to have been lost over 120 years from leaching plus one whole-tree harvest, and that up to 30 $t{\cdot}ha^{-1}$ was needed to replace the losses from leaching and three whole-tree harvests. According to the literature, however, relatively low doses of wood ash seem to produce the greatest benefits, with doses above 5 $t{\cdot}ha^{-1}$ possibly having negative repercussions on ground vegetation and woody shrubs at certain sites, and those exceeding 10 $t{\cdot}ha^{-1}$ potentially being toxic to many organisms (Pitman 2006). A South Korean study examining the effects of 0, 5, 10, and 20 $t{\cdot}ha^{-1}$ ash (from oak wood and bark) additions on Japanese elm (*Zelkova serrata*) seedlings across three soil types, with and without N, found that wood ash alone was most effective in acidic forest soils for increasing soil pH, organic matter, P availability, and exchangeable cation levels, as well as foliar Ca, K, and P concentrations (An and Park 2021). While doses of 5 and 10 $t{\cdot}ha^{-1}$ led to increased biomass production (leaves, stems, and roots), the authors suggested that higher doses (i.e., 20 $t{\cdot}ha^{-1}$) were likely detrimental to biota due to the short-term pH increase (An and Park 2021). While larger doses generally seem to have greater positive effects on tree growth than smaller doses, the possibility of negative effects also increases. Therefore, for soils severely deficient in Ca, repeated applications of low to moderate doses may be necessary, rather than one large dose.

In Canada, maximum wood ash dosage rates have not yet been established for forest soils, but they do exist for agricultural soils and are much higher than the European guidelines for forest soils (Hannam et al. 2018). In individual provinces where ash amendment of forest soils is sometimes performed (i.e., British Columbia, Quebec), required doses are usually determined by considering the trace metal contents of both the ash and the soil at the application site and (or) the liming needs of the soil (reviewed in Hannam et al. 2016). To assess the effects of IWA on forest productivity, the AshNet research network is currently conducting field trials across the country using doses of 0.5–20.0 $t{\cdot}ha^{-1}$ (Hannam et al. 2018), and their findings may provide additional valuable information on the doses required to see positive ecological benefits. The effects of different doses of wood ash (IWA and NIWA) on forest floor/soil parameters and trees in eastern North America are summarized in Table 1.

Application frequency should be determined on a case-by-case basis depending on factors such as whether harvesting occurs. One application of wood ash may be sufficient to replenish the nutrients lost following a clearcut (Pitman 2006). With clearcut systems, wood ash can be applied before replanting during the site preparation stage to lessen any risks to regenerating trees (reviewed in Hannam et al. 2018). Alternatively, ash may be applied once every crop rotation to conifer stands when growth is the most rapid (Pitman 2006). In Sweden, where compensatory fertilization is the main goal, up to 3 $t{\cdot}ha^{-1}$ of wood ash may be applied once every 10 years (reviewed in Hannam et al. 2018). Methods of application may vary depending on accessibility to and within the forest sites as well as budget constraints. In studies conducted in Canada, land application has been done using agricultural spreaders (Hannam et al. 2017) or manually. In Europe, ash is sometimes applied by helicopter, but this is not common due to the high cost (Emilsson 2006).

5.7 Time to see benefits and longevity of benefits

The time needed to detect the effects of wood ash additions depends on many factors (e.g., dose, type of ash, site conditions) and the parameter of interest. Whereas wood ash treatments induce very rapid changes in soil chemistry, their effects on tree growth may not become apparent until several years later. A recent mesocosm study showed that 3 and 9 $t{\cdot}ha^{-1}$ additions of wood ash (mixed bottom and fly ash from coniferous wood chips) resulted in an almost immediate (i.e., 1 day) increase in soil pH, which slowly decreased over a 1-year observation period, in the top 2 cm of soil (Bang-

Table 1. Effects of wood ash dose and type on acidic soils and tree species, as seen in field trials conducted in eastern North America.

Dose(s) and ash type	Forest floor/soil response	Tree species and response	Time (years)*	Study site, reference
1, 2, 4, 8 t·ha^{-1} loose fly ash (IWA)	(+) forest floor pH	Jack pine (*Pinus banksiana* Lamb.)		Northeastern Canada (Brais et al. 2015)
	(+) forest floor exchangeable base cation concentrations	(0) foliar nutrition	2	
	(+) forest floor base saturation	(0) growth	5	
		Black spruce (*Picea mariana* (Mill.) BSP) (−) growth at 8 t·ha^{-1}	5	
~11.2 t·ha^{-1} IWA in trenches (0–20.3 cm deep and 2.13 m apart) and ~1.4 t·ha^{-1} IWA across stands	(+) soil pH	Red pine (*Pinus resinosa* Ait.) (+) height in seedlings	2	Florence County, Wisconsin, USA (Richard et al. 2018)
		Jack pine (*Pinus banksiana* Lamb.) (+) diameter and height in seedlings	2	
6 t·ha^{-1} NIWA (from maple, white pine, and yellow birch)	(+) soil pH (+) soil Ca, Mg concentrations	Sugar maple (*Acer saccharum* Marsh.) (+) foliar Ca and K concentrations in seedlings (+) root and stem Ca, Mg, K concentrations in seedlings (+) root and stem metal concentrations in seedlings treated with yellow birch ash	1	Central Ontario, Canada (Deighton and Watmough 2020)
2.5, 7 t·ha^{-1} fly ash (IWA)	(+) forest floor pH (+) forest floor P, Ca, Mg, K, Na concentrations (+) forest floor base saturation (+) forest floor cation exchange capacity (−) forest floor acidity	Jack pine (*Pinus banksiana* Lamb.) (+) diameter and height	2	Northwestern Quebec, Canada (Bélanger et al. 2021)
		White spruce (*Picea glauca* (Moench) Voss) (+) height	8	
		Hybrid larch (*Larix × marschlinsii*) (−) mortality (−) height and diameter	8	

Table 1. Continued

Dose(s) and ash type	Forest floor/soil response	Tree species and response	Time (years)*	Study site, reference
4, 8 t·ha^{-1} fly and bottom ash (IWA)	(0) soil water metal concentrations	Sugar maple (*Acer saccharum* Marsh.) (0) foliar metal concentrations in seedlings (+) root Al, Fe, Zn, Pb, Ni, Sr concentrations in treated seedlings	4-year duration	Central Ontario, Canada (Deighton et al. 2021*a*)
5, 10, 20 t·ha^{-1} processed fly and bottom ash (IWA); crushed granules measuring 5–15 mm	(+) forest floor pH (+) forest floor P, Ca, Mg concentrations (+) soil pH (+) soil Ca, Mg concentrations	Sugar maple (*Acer saccharum* Marsh.) (+) foliar Ca concentration in seedlings at all doses	3	Southeastern Quebec, Canada (Arseneau et al. 2021)
		(+) foliar Ca concentration in seedlings and mature trees at 20 t·ha^{-1}	3	
		(+) basal area increment of mature trees at 20 t·ha^{-1}	1	

Note: The abbreviations "IWA" and "NIWA" refer to industrial wood ash and nonindustrial wood ash, respectively, whereas the notations (+), (−), and (0) refer to an increase, decrease, and no change, respectively.
*Time at which each tree response was seen.

Andreasen et al. 2021). The same study showed that the concentrations of exchangeable Ca, Mg, K, and Mn in the uppermost 1 and 5 cm of soil for ash additions of 3 and 9 t·ha^{-1}, respectively, were significantly higher than those of control soil when measured approximately 2 months after ash application (Hansen et al. 2017; Bang-Andreasen et al. 2021). Ash amendment at 5 t·ha^{-1} resulted in significant neutralization of acidic forest soils within 1 year under controlled conditions in South Korea, and positive effects on the growth of Japanese elm seedlings were detected after 20 weeks (An and Park 2021). When bottom ash was applied at a dose of 5 t·ha^{-1} at hybrid spruce (*Picea glauca* × *engelmannii* Parry × Engelm.) plantations in British Columbia, foliar Ca and S (as well as soil pH, Ca, and exchangeable BCs) increased within 1 year (Domes et al. 2018). For sugar maples in Quebec, Arseneau et al. (2021) observed increased foliar Ca in seedlings 3 years following ash additions at moderate doses (5 and 10 t·ha^{-1}) of IWA pellets and increased growth of mature trees after just 1 year at a higher dose (20 t·ha^{-1}). At Hubbard Brook, the experimental addition of Ca as wollastonite in 1999 resulted in markedly high sugar maple seed production 2 years later (Juice et al. 2006). In their meta-analysis, Reid and Watmough (2014) found that the greatest effects of ash addition on softwood growth were seen 10–54 years after treatment and noted that more long-term studies were needed to obtain a better understanding of the effects on tree growth. Finally, the type of ash used for soil amendment (e.g., fly ash, bottom ash, processed granules, pellets) affects nutrient release rates. Because crushed granules have relatively lower nutrient (e.g., Ca, K, Na) release rates than fly ash (Pitman 2006), the effects of the former on forest sites may take longer to manifest. Whether the ash is distributed on top of the leaf litter layer or incorporated into the soil will also affect how quickly its effects are seen.

The positive effects of Ca addition to forest sites through both wood ash amendment and liming are long-lasting. In Scandinavia, where the monitoring of some forest sites supplemented with wood ash has been ongoing for over 50 years, the positive effects of ash additions on soil acidity and trees have endured for decades (Huotari et al. 2015). Significant increases in forest soil pH, base saturation, and cation exchange capacity were still detected 16 years after application across many site types in Finland (Saarsalmi et al. 2001). On N-rich Finnish peatlands, the fertilizing effects of wood ash have lasted for at least 30 years, more than those of commercial fertilizers, with tree growth increasing by 2–4 m^3 per year following ash application at a dose of 4 t·ha^{-1} (Emilsson 2006). Thirteen years after application, the growth volume of young Scots pine (*Pinus sylvestris*) in Finland treated with 10 t·ha^{-1} of wood ash exceeded 70 m^3·ha^{-1} compared with 15 m^3·ha^{-1} in control plots (Ferm et al. 1992). Increases in foliar concentrations of Ca, K, and P following wood ash additions may also last for decades (Augusto et al. 2008; Reid and Watmough 2014). In Quebec, sugar maple sap was up to 20% sweeter 18 years following the addition of dolomitic lime (Moore et al. 2020). At the Hubbard Brook site, most of the originally added Ca (as wollastonite) remained within the watershed (44% of the exchangeable Ca stayed on cation exchange sites on the forest floor, while 54% was undissolved or taken up by plants within several years following treatment), suggesting that the added Ca would last for a few decades (Cho et al. 2012). Thus, the application of wood ash to acidic forest soils across eastern Canada to mitigate Ca decline and boost tree health may last for decades, especially with little to no logging.

5.8 Case study: Muskoka, Ontario

The Ca-depleted forest soils of eastern Canada may be particularly suited to wood ash amendment. Ash amendments may have negative effects on tree growth in alkaline or low-N soils (Pitman 2006), but forest soils in eastern Canada are characterized by low Ca and pH and high N. The Great Lakes–St. Lawrence Forest region, which includes central Ontario as well as parts of southern Quebec and eastern Canada, is prone to Ca limitation due to its history of acidic deposition and shallow soils underlain by granitic bedrock (Friends of the Muskoka Watershed 2021). For example, over 50% of lakes in the 2EB watershed in Muskoka have Ca concentrations below the critical biological level of 1.5 $mg{\cdot}L^{-1}$ (Azan 2017). Because lakes receive Ca from the surrounding watershed soils, Muskoka soils are likely also Ca deficient.

In areas of central Ontario affected by Ca decline, the estimated dose of loose NIWA needed to alleviate Ca deficiency in forest soils is roughly 2 $t{\cdot}ha^{-1}$. Assuming that 0.5 $t{\cdot}ha^{-1}$ of Ca has been lost from the soil (Watmough and Dillon 2004; Ott and Watmough 2022), the proportion of Ca in wood ash is approximately 30% (Azan et al. 2019), and the availability of that Ca is high (i.e., 90%), the ash dose needed to replace the lost exchangeable Ca may be calculated from: $Ca_{lost}/(Ca_{NIWA} \times Ca_{available})$, which is $0.5/(0.3 \times 0.9)$, or 1.85 $t{\cdot}ha^{-1}$ of ash. In the absence of biomass harvesting, a single 2 $t{\cdot}ha^{-1}$ dose of NIWA may be sufficient for restoring Ca to preacidification concentrations.

Currently, over 1100 Muskoka residents are participating in a pilot wood ash recycling program that encourages them to actively "garden the forest" to improve forest soil conditions, tree health and vigor, and thus the ecosystem services (e.g., oxygen generation, carbon sequestration, habitat) and products (e.g., biofuel, sap, lumber) that forests provide. The results of pending and future field trials examining the effects of wood ash on tree growth and forest productivity will provide valuable information on the efficacy and practicality of this approach on a broader scale.

Though the estimated annual NIWA production of Muskoka residents (i.e., 235 t) would not be enough to cover all the areas in central Ontario affected by Ca declines, an ash recycling program executed across the southern part of the province may generate sufficient amounts (Azan et al. 2019). Province-wide, approximately 18 000 t of NIWA was produced in 2017, with the majority originating from hardwood species such as maple (*Acer* spp.), beech (*Fagus* spp.), oak (*Quercus* spp.), birch (*Betula* spp.), ash (*Fraxinus* spp.), and cherry (*Prunus* spp.), and to a lesser extent, softwood species such as pine (*Pinus* spp.) and hemlock (*Tsuga* spp.) (Azan 2017). Alternatively, ash from industrial sources could be used to make up the deficit as it is readily available from local timber mills.

6 Conclusions

Forests today are at the mercy of multiple stressors such as nutrient-poor soils, insect pests, pathogens, and climate change, which—alone and interactively—can lead to decreased growth and regeneration and, ultimately, increased mortality. Human-induced Ca declines can threaten the health, structure, and functioning of forests, thereby negatively affecting the critical ecosystem services they offer including water filtration, oxygen production, and nutrient cycling (Schaberg et al. 2001). Wood ash from both industrial and nonindustrial sources has the potential to be used as a forest soil amendment to help combat deficiencies in Ca and other nutrients while reducing the amount of waste being added to landfills.

Calcium limitation is currently not included in Canada's national agenda as a cause of forest decline (State of Canada's Forests 2020), but our review of the literature suggests that it should be. The idea of amending forest soils with wood ash to replenish Ca and other minerals lost to soil leaching and biomass harvesting has only emerged fairly recently in Canada. Our review of the relevant literature indicates that wood-based ashes can positively affect the growth rates and health of trees, especially sugar maples, which have relatively high Ca requirements and are important both ecologically and economically. Metal contamination via the ash is often the biggest concern, but the small amounts of toxic metals detected in wood ash from Ontario are within Canadian regulatory limits (e.g., Azan et al. 2019; Deighton et al. 2021*a*) and unlikely to have any considerable effects on forest ecosystems, especially when the ash is applied at low to moderate doses. Prior to land application, the anticipated benefits of wood ash amendment must be carefully weighed against the potential risks while considering factors such as the characteristics of the receiving soils, target tree species, existing flora and fauna, optimal doses, and whether biomass harvesting will occur. Moreover, the lowest dose needed to achieve the desired outcome (i.e., replacing the soil Ca lost to leaching and harvesting) should be used. In eastern Canada, where the main objective of ash amendment would be to replenish the soil Ca that has been lost to leaching and biomass extraction, one application at an appropriate dose (i.e., 2 $t{\cdot}ha^{-1}$ of NIWA) may suffice. Additionally, ash amendments are arguably the most needed in hardwood forests that are selectively harvested rather than in coniferous forests that are clearcut because the latter are farther north, have not been subject to acidic deposition, and have lower Ca requirements.

Overall, the use of wood ash as a forest soil amendment holds promise for mitigating Ca declines across eastern Canada and for supporting sustainable forest management. Areas of future research include verifying the efficacy of forest soil amendments with wood ash with respect to the anticipated benefits shown in Fig. 1, including the implications for C capture. Additionally, our knowledge regarding the potential effects of wood ash amendments on surface waters and aquatic biota is currently limited and requires further study. Extended field trials are also needed to ascertain the long-term (i.e., decades-long) effects of wood ash amendment on different tree species growing in acidic, Ca-deficient forest soils, with and without logging.

Acknowledgements

The authors thank Paul Grinnell for his artwork and Neil Hutchinson for his comments on an earlier version of this manuscript. They are also grateful to two anonymous reviewers for their detailed feedback, which helped improve the quality of the manuscript.

Article information

History dates

Received: 22 February 2022
Accepted: 14 April 2022
Version of record online: 29 August 2022

Data availability statement

No data were deposited into a public repository because no data were used in this manuscript.

Author information

Author ORCIDs

Natalie Kim https://orcid.org/0000-0001-9298-661X

Contributors' statement

NK contributed to the conceptualization and writing of the original draft, as well as the review and editing of the manuscript. SAW and NDY contributed to the conceptualization, review, and editing of the manuscript.

Competing interests

The authors declare there are no competing interests.

Funding statement

This project received funding support from the Ontario Trillium Foundation and the Ontario government.

References

Achat, D.L., Deleuze, C., Landmann, G., Pousse, N., Ranger, J., and Augusto, L. 2015. Quantifying consequences of removing harvesting residues on forest soils and tree growth—a meta-analysis. For. Ecol. Manage. **348**: 124–141. doi:10.1016/j.foreco.2015.03.042.

Aherne, A., and Posch, M. 2013. Impacts of nitrogen and sulphur deposition on forest ecosystem services in Canada. Curr. Opin. Environ. Sustain. **5**(1): 108–115. doi:10.1016/j.cosust.2013.02.005.

An, J.Y., and Park, B.B. 2021. Effects of wood ash and N fertilization on soil chemical properties and growth of *Zelkova serrata* across soil types. Sci. Rep. **11**: 14489. doi:10.1038/s41598-021-93805-5.

Aronsson, K.A., and Ekelund, N.G.A. 2004. Biological effects of wood ash application to forest and aquatic ecosystems. J. Environ. Qual. **33**: 1595–1605. doi:10.2134/jeq2004.1595.

Arseneau, J., Bélanger, N.B., Ouimet, R., Royer-Tardif, S., Bilodeau-Gauthier, S. Gendreau-Berthiaume, B., et al. 2021. Wood ash application in sugar maple stands rapidly improves nutritional status and growth at various developmental stages. For. Ecol. Manag. **489**: 119062. doi:10.1016/j.foreco.2021.119062.

Ashforth, D., and Yan, N.D. 2008. The interactive effects of calcium concentration and temperature on the survival and reproduction of *Daphnia pulex* at high and low food concentrations. Limnol. Oceanogr. **53**(2): 420–432. doi:10.4319/lo.2008.53.2.0420.

AshNet. 2021. Canadian wood ash chemistry database [online]. Available from http://nrcan.gc.ca/forests/research-centres/glfc/ashnet/20288 [accessed 22 January 2022].

Augusto, L., Bakker, M.R., and Meredieu, C. 2008. Wood ash applications to temperate forest ecosystems—potential benefits and drawbacks. Plant Soil. **306**(1/2): 181–198. doi:10.1007/s11104-008-9570-z.

Azan, S. 2017. Could a residential wood ash recycling programme help solve the calcium decline problem: insights from a Muskoka wood burner's questionnaire. Friends of the Muskoka Watershed. Available from: https://fotmw.org/2021/05/solving-the-calcium-decline-problem-insights-from-a-muskoka-wood-burners-questionnaire/ [accessed 21 January 2022].

Azan, S. 2018. Is residential wood ash safe to use to help solve the calcium decline problem in Muskoka? Friends of the Muskoka Watershed. Available from https://fotmw.org/2021/05/report-is-residential-wood-ash-safe-for-use-to-help-solve-the-calcium-decline-problem-in-muskoka/ [accessed 21 January 2022].

Azan, S., Yan, N.D., Celis-Salgado, M.P., Arnott, S.E., Rusak, J.A., and Sutey, P. 2019. Could a residential wood ash recycling programme be part of the solution to calcium decline in lakes and forests in Muskoka (Ontario, Canada)? FACETS **4**: 69–90. doi:10.1139/facets-2018-0026.

Bang-Andreasen, T., Peltre, M., Ellegaard-Jensen, L., Hansen, L.H., Ingerslev, M. Rønnz, R., et al. 2021. Application of wood ash leads to strong vertical gradients in soil pH changing prokaryotic community structure in forest top soil. Sci. Rep. **11**: 742. doi:10.1038/s41598-020-80732-0.

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

Bélanger, N., Ponce, G.P., and Brais, S. 2021. Contrasted growth response of hybrid larch (*Larix* × *marschlinsii*), jack pine (*Pinus banksiana*) and white spruce (*Picea glauca*) to wood ash application in northwestern Quebec. iForest - Biogeosciences and Forestry, **14**(2): 155–165. doi:10.3832/ifor3597-014.

Beverly, R.B. 1987. Comparison of DRIS and alternative nutrient diagnostic methods for soybean. J. Plant Nutr. **10**(8): 901–920. doi:10.1080/01904168709363619.

Bishop, D.A., Beier, C.M., Pederson, N., Lawrence, G.B., Stella, J.C., and Sullivan, T.J. 2015. Regional growth decline of sugar maple (*Acer saccharum*) and its potential causes. Ecosphere, **6**(10): 179. doi:10.1890/ES15-00260.1.

Björk, R.G., Ernfors, M., Sikström, U., Nilsson, M.B., Andersson, M.X. Rütting, T., et al. 2010. Contrasting effects of wood ash application on microbial community structure, biomass and processes in drained forested peatlands. FEMS Microbiol. Ecol. **73**(3): 550–562. doi:10.1111/j.1574-6941.2010.00911.x.

Blum, J., Klaue, A., Nezat, C., Driscoll, C.T., Johnson, C.E. Siccama, T.G., et al. 2002. Mycorrhizal weathering of apatite as an important calcium source in base-poor forest ecosystems. Nature, **417**: 729–731. doi:10.1038/nature00793.

Brais, S., Bélanger, N., and Guillemette, T. 2015. Wood ash and N fertilization in the Canadian boreal forest: soil properties and response of jack pine and black spruce. For. Ecol. Manag. **348**: 1–14. doi:10.1016/j.foreco.2015.03.021.

Buss, W., Jansson, S, Wurzer, C., and Masek, O. 2019. Synergies between BECCS and biochar—maximizing carbon sequestration potential by recycling wood ash. ACS Sustainable Chem. Eng. **7**(4): 4204–4209. doi:10.1021/acssuschemeng.8b05871.

Cairns, A., and Yan, N.D. 2009. A review of the influence of low ambient calcium concentrations on freshwater daphniids, gammarids, and crayfish. Environ. Rev. **17**: 67–79. doi:10.1139/A09-005.

Cho, Y., Driscoll, C.T., Johnson, C.E., Blum, J.D., and Fahey, T.J. 2012. Watershed level responses to calcium silicate treatment in a northern hardwood forest. Ecosystems, **15**(3): 416–434. doi:10.1007/s10021-012-9518-2.

Clair, T.A., Aherne, J., Dennis, I.F., Gilliss, M., Couture, S. McNicol, D., et al. 2007. Past and future changes to acidified eastern Canadian lakes: a geochemical modeling approach. Appl. Geochem. **22**: 1189–1195. doi:10.1016/j.apgeochem.2007.03.010.

Cleavitt, N.L., Fahey, T.J., and Battles, J.J. 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**: 235–244. doi:10.1139/X10-210.

Deighton, H.D., and Watmough, S.A. 2020. Effects of non-industrial wood ash (NIWA) applications on soil chemistry and sugar maple (*Acer saccharum*, Marsh.) seedling growth in an acidic sugar bush in Central Ontario. Forests, **11**(6): 693. doi:10.3390/f11060693.

Deighton, H.D., Reid, C., Basiliko, N., Hazlett, P.W., and Watmough, S.A. 2021*b*. Soil water responses to wood ash addition to acidic upland soils: implications for combatting calcium decline in lakes. Water Air Soil Pollut. **232**: 191. doi:10.1007/s11270-021-05146-8.

Deighton, H.D., Watmough, S.A., Basiliko, N., Hazlett, P.W., Reid, C.R., and Gorgolewski, A. 2021*a*. Trace metal biogeochemical responses following wood ash addition in a northern hardwood forest. Can. J. For. Res. **51**(6): 817–833. doi:10.1139/cjfr-2020-0320.

Domes, K.A., de Zeeuw, T., Massicotte, H.B., Elkin, C., McGill, W.B., Jull, M.J., et al. 2018. Short-term changes in spruce foliar nutrients and soil properties in response to wood ash application in the sub-boreal climate zone of British Columbia. Can. J. Soil Sci. **98**: 246–263. doi: http://dx.doi.org/10.1139/cjss-2017-0115

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

Duchesne, L., Ouimet, R., and Houle, D. 2002. Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. J. Environ. Qual. **31**: 1676–1683. doi:10.2134/jeq2002.1676.

Edwards, B.A., Jackson, D.A., and Somers, K.M. 2009. Multispecies crayfish declines in lakes: implications for species distributions and richness. J. North Am. Benthol. Soc. **28**(3): 719–732. doi:10.1899/08-148.1.

Emilson, C.E., Bélanger, N., Brais, S., Chisholm, C.E., Diochon, A. Joseph, R., et al. 2019. Short-term growth response of jack pine and spruce spp. to wood ash amendment across Canada. Glob. Change Biol. Bioenergy, **12**(2): 158–167. doi:10.1111/gcbb.12661.

Emilsson, E. 2006. From extraction of forest fuels to ash recycling: international handbook[online]. Available from https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=2363 [accessed 1 January 2022].

Etiegni, L., and Campbell, A.G. 1991. Physical and chemical characteristics of wood ash. Bioresour. Technol. **72**(2): 173–178. doi:10.1016/0960-8524(91)90207-Z.

Fairhead, J., Fraser, J.A., Amanor, K., Solomon, D., Lehmann, J., and Leach, M. 2017. Indigenous soil enrichment for food security and climate change in Africa and Asia: a review. *In* Indigenous Knowledge: Enhancing Contribution to Natural Resources Management. *Edited by* P. Sillitoe. CAB International, Wallingford, Oxfordshire, United Kingdom. doi:10.1079/9781780647050.0000.

Ferm, A., Hokkanen, T., Moilanen, M., and Issakainen, J. 1992. Effects of wood bark ash on the growth and nutrition of a Scots pine afforestation in central Finland. Plant Soil, **147**(2): 305–316. doi:10.1007/BF00029082.

Friends of the Muskoka Watershed. 2021. Residential wood ash recycling and forest soil amendment operations guide. 69pp.

Glaser, B., and Birk, J.J. 2012. State of the scientific knowledge on properties and genesis of anthropogenic dark earths in central Amazonia (*terra preta de Í ndio*). Geochim. Cosmochim. Acta **82**: 39–51. doi:10.1016/j.gca.2010.11.029.

Gorgolewski, A., Caspersen, J., Hazlett, P., Jones, T., Tran, H., and Basiliko, N. 2016. Responses of Eastern Red-backed salamander (*Plethodon cinereus*) abundance 1 year after application of wood ash in a northern hardwood forest. Can. J. For. Res. **46**(3): 402–409. doi:10.1139/cjfr-2015-0230.

Government of Canada. 2022. Coal phase-out: the Powering Past Coal Alliance[website]. Available from https://www.canada.ca/en/services/environment/weather/climatechange/canada-international-action/coal-phase-out.html#toc1 [accessed 21 January 2022].

Gradowski, T., and Thomas, S.C. 2006. Phosphorus limitation of sugar maple growth in central Ontario. For. Ecol. Manag. **226**: 104–109. doi:10.1016/j.foreco.2005.12.062.

Graveland, J., and van der Wal, R. 1996. Decline in snail abundance due to soil acidification causes eggshell defects in forest passerines. Oecologia, **105**(3): 351–360. doi:10.1007/BF00328738.

Green, M.B., Bailey, A.S., Bailey, S.W., Battles, J.J., Campbell, J.L. Driscoll, C.T., et al. 2013. Decreased water flowing from a forest amended with calcium silicate. Proc. Natl. Acad. Sci. U.S.A., **110**: 5999–6003. doi:10.1073/pnas.1302445110.

Hadley, K.R., Paterson, A.M., Reid, R.A., Rusak, J.A., Somers, K.M. Ingram, R., et al. 2015. Altered pH and reduced calcium levels drive near extirpation of native crayfish, Cambarus bartonii, in Algonquin Park, Ontario, Canada. Freshw. Sci. **34**(3): 918–932. doi:10.1086/681910.

Halman, J.M., Schaberg, P.G., Hawley, G.J., and Eagar, C. 2008. Calcium addition at the Hubbard Brook experimental forest increases sugar storage, antioxidant activity and cold tolerance in native red spruce (*Picea rubens*). Tree Physiol. **28**(6): 855–862. doi:10.1093/treephys/28.6.855.

Hannam, K.D., Deschamps, C., Kwiaton, M., Venier, L., and Hazlett, P.W. 2016. Regulations and guidelines for the use of wood ash as a soil amendment in Canadian forests. Can. For. Serv. Inf. Rep. GLC-X-18. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ont. Available from http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/37781.pdf [accessed 14 January 2022].

Hannam, K.D., Venier, L., Allen, D., Deschamps, C., Hope, E. Jull, M., et al. 2018. Wood ash as a soil amendment in Canadian forests: what are the barriers to utilization? Can. J. For. Res. **48**(4): 442–450. doi:10.1139/cjfr-2017-0351.

Hannam, K.D., Venier, L., Hope, E., McKenney, D., Allen, D., and Hazlett, P.W. 2017. AshNet: facilitating the use of wood ash as a forest soil amendment in Canada. For. Chron. **93**(1): 17–20. doi:10.5558/tfc2017-006.

Hansen, M., Bang-Andreasen, T., Sørensen, H., and Ingerslev, M. 2017. Micro vertical changes in soil pH and base cations over time after application of wood ash on forest soil. For. Ecol. Manag. **406**: 274–280. doi:10.1016/j.foreco.2017.09.069.

Hazlett, P.J., Emilson, C., Lawrence, G., Fernandez, I., Ouimet, R., and Bailey, S. 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. doi:10.3390/soilsystems4030054.

Hazlett, P.W., Curry, J.M., and Weldon, T.P. 2011. Assessing decadal change in mineral soil cation chemistry at the Turkey Lakes Watershed. Soil Sci. Soc. Am. J. **75**: 287–305. doi:10.2136/sssaj2010.0090.

Hedin, L., Granat, L., Likens, G., Buishand, T.A., Galloway, J.N., and Butler, T.J., 1994. Steep declines in atmospheric base cations in regions of Europe and North America. Nature **367**: 351–354. doi:10.1038/367351a0.

Hope, E.S., McKenney, D.W., Allen, D.J., and Pedlar, J.H. 2017. A cost analysis of bioenergy-generated ash disposal options in Canada. Can. J. For. Res. **47**(9): 1222–1231. doi:10.1139/cjfr-2016-0524.

Houle, D., Duchesne, L., Moore, J.D., Laflèche, M.R., and Ouimet, R. 2002. Soil and tree-ring chemistry response to liming in a sugar maple stand. J. Environ. Qual. **31**(6): 1993–2000. doi:10.2134/jeq2002.1993.

Houle, D., Ouimet, R., Couture, S., and Gagnon, C. 2006. Base cation reservoirs in soil control the buffering capacity of lakes in forested catchments. Can. J. Fish Aquat. Sci. **63**(3): 471–474. doi:10.1139/F06-007.

Huggett, B.A., Schaberg, P.G., Hawley, G.J., and Eagar, C. 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. doi:10.1139/X07-042.

Huntington, T.G., Hooper, R.P., Johnson, C.E., Aulenbach, B.T., Cappellato, R., and Blum, A.E. 2000. Calcium depletion in a Southeastern United States forest ecosystem. Soil Sci. Soc. Am. J. **64**: 1845–1858. doi:10.2136/sssaj2000.6451845x.

Huotari, N., Tillman-Sutela, E., Moilanen, M., and Laiho, R. 2015. Recycling of ash—for the good of the environment? For. Ecol. Manage. **348**: 226–240. doi:10.1016/j.foreco.2015.03.008.

Jackson, A., and Odom, C. 2021. Wood ash and water: cause of superficial alkaline burns in a toddler. Pediatr. Dermatol. **38**: 973–974. doi:10.1111/pde.14645.

Jacobson, S., Lundström, H., Nordlund, S., Sikström, U., and Pettersson, F. 2014. Is tree growth in boreal coniferous stands on mineral soils affected by the addition of wood ash? Scand. J. For. Res. **29**(7): 675–685. doi:10.1080/02827581.2014.959995.

Jeffries, D.S., Clair, T.A., Couture, S., Dillon, P.J., Dupont, J. Keller, W., et al. 2003. Assessing the recovery of lakes in southeastern Canada from the effects of acidic deposition. Ambio, **32**(3): 176–182. doi:10.1579/0044-7447-32.3.176.

Jeziorski, A., Tanentzap, A.J., Yan, N.D., Paterson, A.M., Palmer, M.E. Korosi, J.B., et al. 2015. The jellification of north temperate lakes. Proc. Biol. Sci. **282**(1798): 20142449. doi:10.1098/rspb.2014.2449.

Jeziorski, A., Yan, N.D., Paterson, A.M., DeSellas, A.M., Turner, M.A. Jeffries, D.S., et al. 2008. The widespread threat of calcium decline in fresh waters. Science, **322**: 1374–1377. doi:10.1126/science.1164949.

Johnson, C.E., Driscoll, C.T., Siccama, T.G., and Likens, G.E. 2000. Element fluxes and landscape position in a northern hardwood forest watershed ecosystem. Ecosystems, **3**(2): 159–184. doi:10.1007/s100210000017.

Joseph, R., Diochon, A., Morris, D., Venier, L., Emilson, C.E. Basiliko, N., et al. 2022. Limited effect of wood ash application on soil quality as indicated by a multisite assessment of soil organic matter attributes. GCB Bioenergy, **00**: 1–22. doi:10.1111/gcbb.12928.

Jubb, M.R., Wilkin, T.A., and Gosler, A.G. 2006. Eggshell-pigmentation, soil calcium and the local abundance, distribution and diversity of woodland snails (Mollusca). Ardea, **94**(1): 59–70.

Juice, S.M., Fahey, T.J., Siccama, T.G., Driscoll, C.T., Denny, E.G. Eagar, C., et al. 2006. Response of sugar maple to calcium addition to northern hardwood forest. Ecology, **87**(5): 1267–1280. doi:10.1890/0012-9658(2006)87[1267:ROSMTC]2.0.CO;2.

Keller, W. 2009. Limnology in northeastern Ontario: from acidification to multiple stressors. Can. J. Fish. Aquat. Sci. **66**(7): 1189–1198. doi:10.1139/F09-080.

Kobe, R.K., Likens, G.E., and Eagar, C. 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. doi:10.1139/x02-018.

Koch, R., Sailer, G., Paczkowski, S., Pelz, S., Poetsch, J., and Müller, J. 2021. Lab-scale carbonation of wood ash for CO_2-Sequestration. Energies, **14**(21): 7371. doi:10.3390/en14217371.

Lawrence, G.B., Burns, D.A., and Riva-Murray, K. 2016. A new look at liming as an approach to accelerate recovery from acidic deposition effects. Sci. Total Environ. **562**: 35–46. doi:10.1016/j.scitotenv.2016.03.176.

Lawrence, G.B., Hazlett, P.W., Fernandez, I.J., Ouimet, R., Bailey, S.W. Shortle, W.C., et al. 2015. Declining acidic deposition begins reversal of forest soil acidification in the northeastern U.S. and eastern Canada. Environ. Sci. Technol. **49**: 13103–13111. doi:10.1021/acs.est.5b02904.

Leys, B.A., Likens, G.E., Johnson, C.E., Craine, J.M., Lacroix, B., and McLauchlan, K.K. 2016. Calcium depletion in a northern forest ecosystem. Proc. Natl. Acad. Sci. U.S.A., **113**(25): 6934–6938. doi:10.1073/pnas.1604909113.

Likens, G.E., Driscoll, C.T., Buso, D.C., Siccama, T.G., Johnson, C.E. Lovett, G.M., et al. 1998. The biogeochemistry of calcium at Hubbard Brook. Biogeochem. **41**(2): 89–173. doi:10.1023/A:1005984620681.

Long, R.P, Bailey, S.W., Horsley, S.B., and Hall, T.J. 2021. Thirty-year effects of liming on soil and foliage chemistry and growth of northern hardwoods in Pennsylvania, USA. Can. J. For. Res. **52**(4): 539–552. doi:dx.doi.org/10.1139/cjfr-2021-0246.

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

Mader, D.L., and Thompson, B.W. 1969. Foliar and soil nutrients in relation to sugar maple decline. Soil Sci. Soc. Am. Proc. **33**: 794–800. doi:10.2136/sssaj1969.03615995003300050046x.

McLaughlin, D.L., Linzon, S.N., Dima, D.E., and McIlveen, W.L 1985. Sugar maple decline in Ontario. Ont. Min. Environ., Toronto, Ont. Rep. No. ARB-144-85-Phyto A.P.I.O.S. #026/85. 18 p.

McLaughlin, D.L., Linzon, S.N., Dimma, D.E., and McIlveen, W.D. 1987. Sugar maple decline in Ontario. *In* Effects of Atmospheric Pollutants in Forests, Wetlands, and Agricultural Ecosystems. *Edited by* T.C. Hutchinson, and K.M. Meema. Springer-Verlag, New York, NY, USA, pp. 101–116.

McLaughlin, S.B., and Wimmer, R. 1999. Calcium physiology and terrestrial ecosystem processes. New Phytol. **142**: 373–417. doi:10.1046/j.1469-8137.1999.00420.x.

McTavish, M.J., Gorgolewski, A., Murphy, S.D., and Basiliko, N. 2020. Field and laboratory responses of earthworms to use of wood ash as a forest soil amendment. For. Ecol. Manag. **474**: 118376. doi:10.1016/j.foreco.2020.118376.

Miller, D.E., and Watmough, S.A. 2009. Air pollution, climate, soil acidity, and indicators of forest health in Ontario's sugar maple forests. Can. J. For. Res. **39**(11): 2065–2079. doi:10.1139/X09-124.

Monroy, A.F., Sarhan, F., and Dhindsa, R.S. 1993. Cold-induced changes in freezing tolerance, protein phosphorylation, and gene expression (evidence for a role of calcium). Plant Physiol. **102**(4): 1227–1235. doi:10.1104/pp.102.4.1227.

Moore, J.D., Duchesne, L., Ouimet, R., and Deschênes, M.L. 2020. Liming improves sap characteristics of sugar maple over the long term. For. Ecol. Manag. **464**: 118044. doi:10.1016/j.foreco.2020.118044.

Nohrstedt, H. 2001. Response of coniferous forest ecosystems on mineral soils to nutrient additions: a review of Swedish experiences. Scand. J. For. Res. **16**: 555–573. doi:10.1080/02827580152699385.

Noyce, G.L., Fulthorpe, R., Gorgolewski, A., Hazlett, P., Tran, H., and Basiliko, N. 2016. Soil microbial responses to wood ash addition and forest fire in managed Ontario forests. Appl. Soil Ecol. **107**: 368–380. doi:10.1016/j.apsoil.2016.07.006.

Odlare, M., and Pell, M. 2009. Effect of wood fly ash and compost on nitrification and denitrification in agricultural soil. Appl. Energy, **86**(1): 74–80. doi:10.1016/j.apenergy.2008.04.004.

Ott, N.F.J., and Watmough, S.A. 2021. Does forest tree species composition impact modelled soil recovery from acidic deposition? Can. J. For. Res. **52**(3): 372–384. doi:10.1139/cjfr-2021-0170.

Park, B.B., Yanai, R.D., Sahm, J.M., Lee, D.K., and Abrahamson, L.P. 2005. Wood ash effects on plant and soil in a willow bioenergy plantation. Biomass Bioenerg. **28**(4): 355–365. doi:10.1016/j.biombioe.2004.09.001.

Peters, S.C., Blum, J.D., Driscoll, C.T., and Likens, G.E. 2004. Dissolution of wollastonite during the experimental manipulation of Hubbard brook watershed 1. Biogeochem. **67**(3): 309–329. doi:10.1023/B:BIOG.0000015787.44175.3f.

Phllips, T., and Watmough, S.A. 2012. A nutrient budget for a selection harvest: implications for long-term sustainability. Can. J. For. Res. **42**(12): 2064–2077. doi:10.1139/cjfr-2012-0224.

Pitman, R.M. 2006. Wood ash use in forestry—a review of the environmental impacts. Forestry, **79**: 563–588. doi:10.1016/j.foreco.2015.03.008.

Producteurs et productrices acéricoles du Québec. 2021. The maple syrup reserve: serving its purpose in a time of high demand[webpage]. Available from https://ppaq.ca/en/communiques/la-reserve-de-sirop-derable-un-outil-strategique-pour-repondre-a-la-forte-demande/ [accessed 14 January 2022].

Proe, M.F., Cameron, A.D., Dutch, J., and Christodoulou, X.C. 1996. The effect of whole-tree harvesting on the growth of second rotation Sitka spruce. Forestry, **69**(4): 389–401. doi:10.1093/forestry/69.4.389.

Pukalchik, M., Mercl, F., Terekhova, V., and Tlustoš, P. 2018. Biochar, wood ash and humic substances mitigating trace elements stress in contaminated sandy loam soil: evidence from an integrative approach. Chemosphere, **203**: 228–238. doi:10.1016/j.chemosphere.2018.03.181.

Reid, C., and Watmough, S.A. 2014. Evaluating the effects of liming and wood ash treatment on forest ecosystems through systematic meta-analysis. Can. J. For. Res. **44**: 867–885. doi:10.1139/cjfr-2013-0488.

Reid, C., and Watmough, S.A. 2016. Spatial patterns, trends, and the potential long-term impacts of tree harvesting on lake calcium levels in the Muskoka River watershed, Ontario, Canada. Can. J. Fish Aquat. Sci. **73**(2): 382–393. doi:10.1139/cjfas-2015-0231.

Reuss, J.O., and Johnson, D.W. 1986. Acid deposition and the acidification of soils and waters. Springer-Verlag, New York, NY. 119pp.

Richard, R.P., Potvin, L.R., Kane, E.S., Handler, S.D., Smith, P.J., and Peterson, D. 2018. Biochar and wood ash amendments for forestry in the lake states: field report and initial results. J. For. **116**(3): 222–227. doi:10.5849/jof.2016-060R2.

Riessen, H.P., Linley, R.D., Altshuler, I., Rabus, M., Sollradl, T. Clausen-Schaumann, H., et al. 2012. Changes in water chemistry can disable plankton prey defenses. Proc. Natl Acad. Sci. U.S.A. **109**: 15377–15382. doi:10.1073/pnas.1209938109.

Rosenstock, N.P., Stendahl, J., van der Heijden, G., Lundin, L., McGivney, E. Bishop, K., et al. 2019. Base cations in the soil bank: non-exchangeable pools may sustain centuries of net loss to forestry and leaching. SOIL, **5**: 351–366. doi:10.5194/soil-5-351-2019.

Royer-Tardif, S., Whalen, J., and Rivest, D. 2019. Can alkaline residuals from the pulp and paper industry neutralize acidity in forest soils without increasing greenhouse gas emissions? Sci. Total Environ. **663**: 537–547. doi:10.1016/j.scitotenv.2019.01.337.

Saarsalmi, A., and Mälkönen, E. 2001. Forest fertilization research in Finland: a literature review. Scand. J. For. Res. **16**: 514–535. doi:10.1080/02827580152699358.

Saarsalmi, A., Mälkönen, E., and Piirainen, S. 2001. Effects of wood ash fertilization on forest soil chemical properties. Silva Fennica, **35**(3): 355–368. doi:10.1080/02827580410024124.

Saunders, O. 2018. Guide to using wood ash as an agricultural soil amendment[online]. Available from https://extension.unh.edu/sites/default/files/migrated_unmanaged_files/Resource004042_Rep5718.pdf [accessed 11 April 2022].

Schaberg, P.G., and DeHayes, D.H. 2000. Physiological and environmental causes of freezing injury in red spruce. *In* Responses of Northern U.S. Forests to Environmental Change. *Edited by* R.A. Mickler, R.A. Birdsey, and J. Hom. Ecological Studies (Analysis and Synthesis) vol. 139. Springer, New York, NY. doi:10.1007/978-1-4612-1256-0_6.

Schaberg, P.G., DeHayes, D.H., and Hawley, G.J. 2001. Anthropogenic calcium depletion: a unique threat to forest ecosystem health? Ecosyst. Health, **7**(4): 214–228. doi:10.1046/j.1526-0992.2001.01046.x.

Schaberg, P.G., Tilley, J.W., Hawley, G.J., DeHayes, D.H., and Bailey, S.W. 2006. Associations of calcium and aluminum with the growth and health of sugar maple trees in Vermont. For. Ecol. Manag. **223**(1–3): 159–169. doi:10.1016/j.foreco.2005.10.067.

Siccama, T.G., Fahey, T.J., Johnson, C.E., Sherry, T.W., Denny, E.G. Girdler, E.B., et al. 2007. Population and biomass dynamics of trees in a northern hardwood forest at Hubbard Brook. Can. J. For. Res. **37**(4): 737–749. doi:10.1139/X06-261.

Skjelkvåle, B.L., Stoddard, J.L., Jeffries, D.S., Tørseth, K., Høgåsen, T. Bowman, J., et al. 2005. Regional scale evidence for improvements in surface water chemistry 1990–2001. Environ. Pollut. **137**(1): 165–176. doi:10.1016/j.envpol.2004.12.023.

Smenderovac, E., Emilson, C., Porter, T., Morris, D., Hazlett, P Diochon, A., et al. 2022. Forest soil biotic communities show few responses to wood ash applications at multiple sites across Canada. Sci. Rep. **12**(1): 4171. doi:10.1038/s41598-022-07670-x.

Smol, J.P. 2019. Under the radar: long-term perspectives on ecological changes in lakes. Proc. R. Soc. B **286**: 20190834. doi:10.1098/rspb.2019.0834.

Smołka-Danielowska, D., and Jabłońska, M. 2022. Chemical and mineral composition of ashes from wood biomass combustion in domestic wood-fired furnaces. Int. J. Environ. Sci. Technol. **19**: 5359–5372. doi:10.1007/s13762-021-03506-9.

Someshwar, A.V. 1996. Wood ash and combination wood-fired boiler ash characterization. J. Environ. Qual. **25**: 962–972. doi:10.2134/jeq1996.00472425002500050006x.

Steenari, B.M., Karlsson, L.G., and Lindqvist, O. 1999. Evaluation of the leaching characteristics of wood ash and the influence of ash agglomeration. Biomass Bioenerg. **16**(2): 119–136. doi:10.1016/S0961-9534(98)00070-1.

Sullivan, T.J., Lawrence, G.B., Bailey, S.W., McDonnell, T.C., Beier, C.M. Weathers, K.C., et al. 2013. Effects of acidic deposition and soil acidification on sugar maple trees in the Adirondack Mountains, New York. Environ. Sci. Tech. **47**(22): 12687–12694. doi:10.1021/es401864wes401864w.

Taylor, L.L., Driscoll, C.T., Groffman, P.M., Rau, G.H., Blum, J.D., and Beerling, D.J. 2021. Increased carbon capture by a silicate-treated forested watershed affected by acid deposition. Biogeosciences, **18**: 169–188. doi:10.5194/bg-18-169-2021.

The State of Canada's Forests Annual Report 2020. 2020. Natural Resources Canada, Canadian Forest Service, Ottawa. 88p. Available from https://cfs.nrcan.gc.ca/publications?id=40219&lang=en_CA [accessed 30 January 2022].

Tomlinson, G.H. 2003. Acidic deposition, nutrient leaching and forest growth. Biogeochem. **65**: 51–81. doi:10.1023/A:1026069927380.

van Breemen, N., Finlay, R., and Lundström, U. 2000. Mycorrhizal weathering: a true case of mineral plant nutrition? Biogeochem. **49**: 53–67. doi:10.1023/A:1006256231670.

Vance, E.D. 1996. Land application of wood-fired and combination boiler ashes: an overview. J. Environ. Qual. **25**(5): 937–944. doi:10.2134/jeq1996.00472425002500050002x.

Vassilev, S.V., Baxter, D., Andersen, L.K., and Vassileva, C.G. 2013. An overview of the composition and application of biomass ash. Part 1. Phase–mineral and chemical composition and classification. Fuel, **105**: 40–76. doi:10.1016/j.fuel.2012.09.041.

Walmsley, J.D., Jones, D.L., Reynolds, B., Price, M.H., and Healey, J.R. 2009. Whole tree harvesting can reduce second rotation forest productivity. For. Ecol. Manag. **257**(3): 1104–1111. doi:10.1016/j.foreco.2008.11.015.

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

Watmough, S.A., Aherne, J., Alewell, C., Arp, P., Bailey, S. Clair, T., et al. 2005. Sulphate, nitrogen and base cation budgets at 21 forested catchments in Canada, the United States and Europe. Environ. Monit. Assess. **109**(1–3): 1–36. doi:10.1007/s10661-005-4336-z.

Watmough, S.A., Aherne, J., and Dillon, P.J. 2003. Potential impact of forest harvesting on lake chemistry in south-central Ontario at current levels of acid deposition. Can. J. Fish. Aquat. Sci. **60**: 1095–1103. doi:10.1139/f03-093.

Watmough, S.A., and Aherne, J. 2008. Estimating calcium weathering rates and future lake calcium concentrations in the Muskoka–Haliburton region of Ontario. Can. J. Fish Aquat. Sci. **65**(5): 821–833. doi:10.1139/f07-196.

Watmough, S.A., and Dillon, P.J. 2003. Base cation and nitrogen budgets for seven forested catchments in central Ontario, 1983–1999. For. Ecol. Manag. **177**(1–3): 155–177. doi:10.1016/S0378-1127(02)00320-1.

Watmough, S.A., and Dillon, P.J. 2004. Major element fluxes from a coniferous catchment in central Ontario, 1983-1999. Biogeochem. **67**(3): 369–398. doi:10.1023/B:BIOG.0000015792.42624.57.

Weyhenmeyer, G.A., Hartmann, J., Hessen, D.O., Kopáček, J, Hejzlar, J. Jacquet, S., et al. 2019. Widespread diminishing anthropogenic effects on calcium in freshwaters. Sci. Rep. **9**: 10450. doi:10.1038/s41598-019-46838-w.

Yao, H., McConnell, C., Somers, K.M., Yan, N.D., Watmough, S.A., and Scheider, W. 2011. Nearshore human interventions reverse patterns of decline in lake calcium budgets in central Ontario as demonstrated by mass-balance analyses. Water Resour. Res. **47**(6): W06521. doi:10.1029/2010WR010159.

Yoshioka, K., and Moeder, W. 2020. Calcium channel in plants helps shut the door on intruders. Nature, **585**(7826): 507–508. doi:10.1038/d41586-020-02504-0.