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RESEARCH ARTICLE

Restoring soil and tree nutrition through non-industrial wood ash additions to sugarbushes

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Nutrient losses from forest soils caused by decades of acid deposition have affected tree growth and depleted soils of essential nutrients in eastern North America. Non-industrial wood ash (NIWA) is rich in macronutrients and may be a potential remediation strategy to restore lost nutrients as a forest soil amendment. We evaluated the effects of a single NIWA application on forest soils and Sugar maple (*Acer saccharum* Marsh) foliage at three sugar bush stands in Muskoka, Ontario, Canada. Soil pH and calcium (Ca) increased in the treatment plots (4 and 8 Mg/ha) 1 year after application and remained elevated into year 2. Soil potassium and magnesium concentrations also increased in the treatment plots; however, changes varied in intensity depending on the element, site, and time following application. Changes in soil metal concentrations after application were restricted to the organic soil horizons increasing in the litter in year 1 followed by a decrease in year 2 that was accompanied by increases in the fibrous-humic layer in year 2. Base cation concentrations increased significantly in sapling and mature sugar maple foliage particularly in the mature foliage in year 2. Despite changes in soil metals, changes in foliar metal concentrations were generally not significant. Foliar Diagnosis and Recommendation Integrated System indices indicated deficiencies in Ca and nitrogen (N) suggesting Ca benefits take longer to appear and that supplementing with N additions on acidic soils exhibiting foliar deficiencies might prevent further imbalances from occurring while facilitating tree recovery.

Key words: forest soil amendments, non-industrial wood ash, restoration, soil metals, soil nutrients, sugar maple

Implications for Practice

- Wood ash is nutrient rich (calcium, potassium, and magnesium) and should be considered by land managers as a restoration strategy for base-poor temperate forests in Ontario.
- Ontario policy makers should reclassify wood ash from a hazardous waste to a soil amendment to reduce material going to landfill. This would greatly reduce barriers and provide an effective treatment for temperate forest soils historically affected by acid deposition.
- Further research may focus on supplementing wood ash with N to prevent nutrient imbalances.
- A moderate dose of 4 Mg/ha NIWA is recommended to increase soil base status while limiting metal exposure and potential nutritional imbalances.
- Local environmental initiatives should consider developing a NIWA recycling program to foster community engagement and emphasize the principles of a circular economy.

Introduction

Decades of acidic deposition combined with timber harvesting have degraded forest soils across North America (Johnson et al. 1985; Driscoll et al. 2001). Losses of soil nutrients, especially calcium (Ca), have been linked to declines in tree health in the hardwood forests of eastern North America (Drohan et al. 2002; Duchesne et al. 2002). Though acidic deposition rates have decreased substantially, recovery in soil nutrients is projected to take centuries (Ott & Watmough 2022). This loss of soil nutrients has been connected to Sugar maple (*Acer saccharum* Marsh.) decline in the eastern United States (Miller et al. 1989) and Canada (Payette et al. 1996; McLaughlin 1998), a serious concern given the dominance of sugar maple in hardwood forests in these regions and its economic value in lumber and syrup production. Canadian maple product exports were valued at approximately $716 million in 2024 (Agriculture and Agri-Food Canada 2025).

One approach to restore nutrients lost from the soil is the application of wood ash (Pitman 2006; Augusto et al. 2008; Conquer et al. 2023), the residue from the combustion of wood and wood by-products (Pitman 2006; Hannam et al. 2018).

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Wood ash has a high alkalinity due to its large concentrations of base cations, especially Ca, usually in the form of oxides, hydroxides, and carbonates (Demeyer et al. 2001; James et al. 2014). Wood ash application decreases soil acidity and increases base saturation (Augusto et al. 2008), stimulates microbial activity and the enzymatic breakdown of recalcitrant organic matter (OM) on acidic sites thereby increasing nitrogen (N) availability (Mortensen et al. 2019), and decreases exchangeable Al concentrations through a reduction in solubility in soils (Saarsalmi et al. 2001). However, levels of potentially phytotoxic metals (e.g. chromium [Cr], nickel [Ni], copper [Cu], cadmium [Cd] and zinc [Zn]) naturally present in the ash may increase within the upper soil horizons (Ozolinčius & Varnagirytė 2005).

Although industrial wood ash (IWA) has been used as a soil amendment for decades in Europe, its use in North America has been limited (Pitman 2006). Additionally, while research exists on the chemical composition and effects of IWA (Elliott & Mahmood 2006; Deighton et al. 2021) little is known of the chemistry and effects of non-industrial wood ash (NIWA). In Ontario, Canada, approximately 18,000 t of NIWA are produced annually (Azan et al. 2019). Deighton and Watmough (2020) reported that NIWA generated from individual tree species contains on average 15%–25% Ca by weight, but Ca content tends to be much higher when ash is generated from several mixed temperate species (Syeda et al. 2024). Therefore, assuming homogenized NIWA is approximately 27%–30% Ca by weight (Conquer et al. 2023; Syeda et al. 2024), 2 Mg/ha is the minimum dose necessary to replace Ca that has been lost historically (Kim et al. 2022). However, because wood ash is classified as a hazardous waste material under the Non-Aqueous, Non-Agricultural Source Materials (NASM) Regulation 267/03 of Ontario's Nutrient Management Act, most of it is diverted to landfill (Government of Ontario 2002; Hannam et al. 2018). Application of NIWA is restricted based on limits of its metal concentrations (CM1 and CM2) making the approval process cumbersome, even though metal concentrations are most often well below the restricted CM2 limits, especially when homogenized from various sources (Syeda et al. 2024).

Conquer et al. (2023) showed that NIWA application (6 Mg/ha) increased soil pH (1.4 and 1.1 units in the litter (L) and in the fibrous-humic [FH] layers, respectively) and base cations (Ca, magnesium [Mg], and potassium [K]) in as little as 1 year. Metal concentrations also increased in the litter layer but were expected to be immobile due to increased soil pH (Conquer et al. 2023). Potassium concentrations increased in mature sugar maple foliage, but no other foliar responses were found. Furthermore, Deighton and Watmough (2020) observed significant increases in foliar concentrations of base cations but recommended against using ash generated only from specific species (e.g. Yellow birch [*Betula alleghaniensis*]) to avoid increased metal concentrations in seedling roots and shoots.

Here our objective was to evaluate the short-term (2-year) response of two doses of mixed-species NIWA application (4 and 8 Mg/ha) in three sugar bushes in the District of Muskoka, Ontario to evaluate whether responses differ among doses and are consistent across sites. These doses were chosen to be consistent with common application rates and to determine whether increasing benefits would be observed while monitoring for associated risks. We hypothesized that NIWA application would: (1) increase soil pH and nutrient concentrations (Ca, Mg, and K) in the organic soil horizons 1 year after application with effects lasting into the following year; (2) increase metal concentrations in the organic horizons the first year after application, with effects subsiding in year 2; and (3) increase nutrient (Ca, Mg, and K) concentrations in both sapling and mature sugar maple foliage. Given its chemical makeup (Syeda et al. 2024), using NIWA as a soil amendment should have two benefits: (1) aid in the recovery of acidic, nutrient-depleted soils, and (2) the diversion of thousands of tons of waste from landfills each year.

Methods

The study was conducted at three sugar bushes in the Muskoka River Watershed in south-central Ontario, Canada. The region is located on the southern end of the Canadian Precambrian Shield, overlain with weakly developed podzols and brunisols (Soil Classification Working Group 1998). The soils are acidic with slow mineral weathering rates and receive low levels (<3 kg ha^{-1} yr^{-1}) of atmospheric Ca deposition (Watmough & Dillon 2003). Sixty-six percent of the region is forested, dominated by mixed hardwoods with some conifers (Reid & Watmough 2016). The mean annual temperature and precipitation (1981–2010), respectively, were 5.8°C and 985 mm (Environment and Climate Change Canada 2018).

Study Site I. Brooklands Farm

Study Site I is located on a 400-acre farm near Bracebridge, Ontario, at 304 m above sea level. The study site is a 60-acre sugar bush stand characterized by uneven terrain, several steep slopes and rocky outcrops, and is actively used for maple syrup production. The soils are Orthic Sombric brunisols (Soil Classification Working Group 1998). The mean thickness of the LFH layers was 3.05 cm. The mean mineral soil pH_{CaCl_2} (0–15 cm) was 3.83. The stand is uneven-aged; sugar maple is dominant (approximately 83% basal area [BA]) but species such as American beech (*Fagus grandifolia* Ehrh.) and Red maple (*Acer rubrum* L.) were also found. The BA was measured at 26 m^2/ha in 2019. A 2016 study found deficits of Ca and Mg in the sugar maple leaf tissue on this site (Riley 2017).

Study Site II. Wilf Creasor's Sugarbush

Study Site II is located near Huntsville, Ontario at 291 m above sea level. The area is an 83-acre mixed hardwood forest dominated by sugar maple. The study site has uneven terrain with gentle undulating slopes. The soils are coarse sandy loam, classified as Sombric Brunisols (Soil Classification Working Group 1998). The mean thickness of the LFH layers was 3.92 cm. The mean mineral soil pH_{CaCl_2} (0–15 cm) was 3.96. The stand is uneven-aged, and the BA was measured at 31 m^2/ha in 2019 with sugar maple (approximately 96% BA) the dominant species. The study area once produced maple syrup commercially but recently has shifted to private consumption.

Study Site III. Mark's Muskoka Maple Sugarbush

Study Site III is in Huntsville, Ontario at 291 m above sea level. It has relatively flat terrain and supports a 49-acre mixed hardwood forest. The soils are coarse sandy loam, classified as Sombric Brunisols (Soil Classification Working Group 1998). The mean mineral soil pH_{CaCl_2} (0–15 cm) was 3.88. The stand is uneven-aged, and the BA was measured at 26 m^2/ha in 2019 with sugar maple (approximately 98% BA) the dominant species. The sugar bush has been in active maple syrup production since 1980.

Plot Setup and Study Design

Three replicate experiments were conducted by establishing eighteen 10 × 10-m plots at each sugar bush site in August 2019. Plots were selected to contain a minimum of two mature (>10 cm diameter at breast height [DBH]) sugar maple trees, and some sugar maple saplings (DBH <1–5 cm [mean saplings per plot ± SD (standard deviation) = 46 ± 49]). Plot locations were chosen with relatively flat topography to minimize runoff after ash application. A buffer area of 10 m was left between neighboring plots to minimize the risk of contamination.

Field Sampling and Ash Application

Wood ash was collected from Muskoka residents in monthly ash drives run by the Friends of the Muskoka Watershed and stored in galvanized metal bins. Before application, individual ash contributions were homogenized in three separate bulk mixtures using a cement mixer and distributed into containers for transport (description of the ash collection is provided in Syeda et al. 2024). Soil samples were collected prior to ash addition in August of 2019 and again in July–August of 2020 and 2021 after ash application. At the corners and middle of each plot, soil grab samples (10 × 10 cm) were taken for the L and FH horizons, and a Dutch auger was used for the mineral soil (0–15 cm). The five samples were combined per horizon per plot.

Wood ash was applied after leaf fall in 2019. Treatments were 0 (i.e. controls), 4 and 8 Mg/ha, each with six replicate plots. Site I was an exception with only five plots for the 8 Mg/ha treatment. Plots were assigned ash treatments at random. The NIWA was weighed out in the field and applied by hand (approximately 0.5 m) as evenly as possible using small jugs within each plot.

Foliage samples were collected from mature sugar maple trees and sugar maple saplings from each plot after ash application in 2020 and 2021. Samples from mature trees were collected from sun-exposed leaves in the mid canopy using extendable pole pruners. Sapling samples were collected by hand.

Laboratory Analyses

Non-Industrial Wood Ash Chemistry. The chemical properties of each treatment dose were similar despite the variability expected from household and small business collections. Once homogenized, the ash mixtures averaged a pH of 11.5–13.5, were high in macronutrients (29% Ca, 11% K, 2% Mg, and 1% phosphorus [P]), and low in heavy metal content (Table 1), consistent with other reports of NIWA (Azan et al. 2019; Conquer et al. 2023; Syeda et al. 2024). There were a few small differences among the three ash mixtures. For example, the pH of the ash mixture used in Mark's (III) sugarbush was significantly lower than the mixture applied at Brookland's (I) and Wilf's (II), although still very alkaline with a pH of 11.5. Ash mixture II had lower lead (Pb) concentrations than I or III, and lower iron (Fe) compared to I, while III had the lowest concentration of Cu (Table 1). Only Cu and Zn approached or were slightly above their CM1 limits but were still well below CM2. Nevertheless, as reported by an in-depth analysis of this homogenized ash in Syeda et al. (2024), all metal concentrations fell below the CM2 restricted levels as per provincial guidelines therefore qualifying it to be used for soil restoration (Table 1).

Soil Analyses. Soil samples were oven dried for 24 hours at 110°C. Once dried the L and FH samples were ground individually using a Wiley mill, while the mineral layer was sieved to 2 mm. Samples were analyzed for exchangeable cations, pH, loss-on-ignition (LOI; Ball 1964) to determine percent OM, and acid-extractable metal concentrations (aluminum [Al], arsenic [As], boron [B], Cd, Cu, Fe, manganese [Mn], Ni, Pb, and Zn). Soil pH was measured using an OAKTON pH 510 series multimeter. A 0.01 M Ca chloride slurry at a 1:5 ratio was shaken and rested each for 45 minutes before taking a reading. To determine OM, samples (5 g mineral soil, 2 g organic) were oven dried at 105°C for 24 hours, reweighed, and then ashed in a Fisher Scientific Isotemp Muffle Furnace at 450°C for 8 hours and then weighed again to calculate the difference. Acid-extractable metal concentrations were derived using a Perkin Elmer Optima 7000 DV inductively coupled plasma-optical emission spectrometry (ICP-OES) after hot digestion using concentrated trace metal grade nitric acid (HNO_3; 67–70% *w*/*w*). Approximately 0.2 g of soil were weighed into digiTUBEs (SCP Science, Quebec, Canada) with 2.5 mL HNO_3. Samples were digested for 8 hours at 100°C, then at room temperature for 8 hours until the entire sample dissolved. Solutions were filtered with Fisher P8 fast flow filter paper, diluted to 25 mL with B-pure water and refrigerated until analyses. Soil standards (EnviroMat SS-1) and blanks were used at the beginning, middle, and end to test for accuracy (80–100% recovery; Havlin & Soltanpour 1980).

A 1 M ammonium chloride (NH_4Cl) solution was used to determine the exchangeable cations for organic and mineral soils (Hendershot et al. 2008). Pulverized organic soils (1 g) and mineral soils (5 g) were shaken overnight (16 hours) with 25 mL NH_4Cl and rested (1 hour) before filtering with Fisher P8 filter paper using vacuum filtration. Samples were transferred using an additional 25 mL NH_4Cl, acidified to 2% HNO_3 and

Table 1. pH, loss-on-ignition (LOI), carbon, nitrogen, and sulfur (CNS), and nutrient and metal concentrations of three amalgamated non-industrial wood ash (NIWA) mixtures ($n = 10$ per mixture). Significant differences among the three amalgamated ash mixtures were determined by a Kruskal–Wallis test with a post hoc Dunn's test indicated with different letters. p Value significant at 0.05 (bolded within the table), BDL, below detection limit; S, detection limit—181 peak area, NA, not applicable; n.s., not significant.

	Amalgamated non-industrial wood ash chemistry													
	Mean	*SD*	*CV (%)*	*SE*	*Mean*	*SD*	*CV (%)*	*SE*	*Mean*	*SD*	*CV (%)*	*SE*	*p Value*	*NASM Limits (CM1, CM2)*
	Ash mixture I				Ash mixture II				Ash mixture III					
pH_{CaCl_2}	**13.5** ^{a}				**13.3** ^{a}				**11.5**^{b}				<0.001	
LOI	3.5	0.8	22.9	0.3	5.8	1	17.7	0.3	5.6	1	17.8	0.3	n.s.	
C (%)	11.6	4	34	1.3	8.8	0.8	9	0.3	9.1	0.9	9.8	0.3	n.s.	
N (%)	0.2	0.2	100	0.1	0.1	NA	NA	NA	0.1	NA	NA	NA	n.s.	
S (%)	BDL	NA	NA	NA	BDL	NA	NA	NA	BDL	NA	NA	NA	n.s.	
Ca (g/kg)	305	15.2	5	4.8	273	48.4	17.7	15.3	294	46.4	15.7	14.7	n.s.	
K (g/kg)	109	13	12	4.1	112	21.7	19.3	6.9	104	20.3	19.5	6.4	n.s.	
Mg (g/kg)	24.2	2.5	10.7	0.8	22.1	3.5	16	1.1	22.5	3.8	16.9	1.2	n.s.	
P (g/kg)	8.8	1.2	13.4	0.4	7.9	1.2	15.1	0.4	7.8	1.2	15	0.4	n.s.	
Al (mg/kg)	4076	1032	25.3	326	3045	1019	33.5	322	3933	1262	32.1	399	n.s.	
As (mg/kg)	3.9	6	153	1.9	3.1	7.4	237	2.3	3.7	5.7	153	1.8	n.s.	13, 170
B (mg/kg)	236	46	19.5	14.5	239	49.9	20.9	15.8	213	30.2	14.2	9.5	n.s.	
Cd (mg/kg)	2.7	0.4	14.4	0.1	2.5	0.6	24.7	0.2	2.6	0.4	15.2	0.1	n.s.	3, 34
Cu (mg/kg)	**140**^{a}	41.9	29.8	13.2	**154**^{a}	92.1	59.8	29.1	**106**^{b}	15.2	14.3	4.8	0.026	100, 1700
Fe (mg/kg)	**2793**^{a}	1150	41	364	**1322**^{b}	528	39.9	167	**1872**^{ab}	634	33.9	200	0.001	
Mn (mg/kg)	6306	683	10.8	216	6837	1023	15	324	6329	1215	19.2	384	n.s.	
Ni (mg/kg)	10.5	3	30.4	0.9	8.8	2	22.5	0.6	7.9	1.5	19.1	0.5	n.s.	62, 420
Pb (mg/kg)	**24.3**^{a}	17	71.8	5.4	**12.7**^{b}	3.8	30.3	1.2	**48.5**^{a}	64.2	132	20.3	0.015	150, 1,100
Zn (mg/kg)	523	109	20.9	34.5	516	151	29.3	47.8	439	61.5	14	19.4	n.s.	500, 4200

diluted 1:10 with B-pure. Soil standards, recoveries, and analyses were performed using the ICP-OES as described above.

Foliar Analyses. Foliage sample composites from mature trees and saplings from each plot were analyzed for carbon and nitrogen (CN) content and metals and macronutrients (metals as above, Ca, Mg, K, and P). Each sample was oven dried for 24 hours at 100°C then ground using a coffee grinder into a fine powder for analysis. An Elementar MAX Cube was used to determine CN content. Foliar metal and macronutrient content was analyzed using the acid digestion method outlined above.

Diagnosis and Recommendation Integrated System Calculations. The Diagnosis and Recommendation Integrated System (DRIS) provides an assessment of the nutrient deficiencies and excesses in plants relative to other nutrients (Walworth & Sumner 1987). DRIS indices were calculated for foliar Ca, Mg, K, P, and N, where,

$$A\,\text{index} = \frac{[f(A/B)+f(A/C)+f(A/D)+f(A/E)]}{z} \qquad (1)$$

where, when $A/B \geq a/b$,

$$F\left(\frac{A}{B}\right) = \left(\frac{(A/B)}{a/b} - 1\right) \times \frac{1000}{\mathrm{CV}} \qquad (2)$$

or where, when $A/B \leq a/b$,

$$F\left(\frac{A}{B}\right) = \left(1 - \frac{(a/b)}{(A/B)}\right) \times \frac{1000}{\mathrm{CV}} \qquad (3)$$

A is the foliar concentration (%) of the element for which the index is being calculated while B, C, D, and E are the foliar concentrations of the remaining elements. A/B is the value of the ratio of the two elements in the leaf tissue of the sugar maple foliar samples, while a/b is the optimum value or foliar ratio norms from Lozano and Huynh (1989), CV is the coefficient of variation associated with the norm, and z is the number of functions comprising the nutrient index. The sum of all indices equals zero so that they can be compared relative to one another (Walworth & Sumner 1987). Negative values indicate nutritional deficiency (<−20) such that higher values indicate the most limiting nutrient, while more positive value indicate excess (>+20) as compared to the other nutrients.

Statistical Analyses

To test the main effects of treatment and time, we ran linear mixed-effects models with treatment and year as fixed effects and site as a random intercept on soil pH, OM, and soil and foliar nutrient and metal concentrations, as well as sapling and mature foliar DRIS concentrations (*lmerTest* package). These results are reported in the main document. To explore whether site-specific responses were present, we also fit linear models with treatment, time, and site as fixed effects (*lme4* package). These results are included in Tables S1–S5. Where necessary, models of best fit were determined using Akaike's Information Criteria

(AIC; Akaike 1974), residual normality was evaluated using the Shapiro–Wilk normality test (*rstatix* package) and QQ plots (*ggpubr* package), and homogeneity of variances was tested using Levene's test (*car* package). If the dependent variable did not satisfy assumptions of normality of the residuals, logarithmic or square root transformations were applied. Post hoc comparisons were conducted when fixed effects were statistically significant, using estimated marginal means (EMM; *emmeans* package) for all treatment–year combinations, with a single Bonferroni adjustment across contrasts within each model to correct for multiple comparisons. Statistical analyses were conducted using R Statistical Software (v4.3.2; R Core Team 2023).

Results

Soil Response

Litter and FH horizon pH was 1.5–2.5 units higher in the ash-treated plots relative to the controls 1 year after treatment, and the response increased with dose with pH values above 7 in the 8 Mg/ha treatment (Fig. 1). Changes in soil chemical properties resembled a "wave," first with a large and rapid response in the litter layer, then subsequent changes in the lower horizons in year 2 as the ash weathered and components moved down the soil profile and fresh litter was added to the forest floor. For example, in the second year following application, pH values decreased in the litter relative to the year before but continued to increase in the FH layer in the treated plots, and higher pH values appeared in the mineral horizon (Fig. 1). It should be noted that such increases in the litter layer the first year are likely also caused in part by some residual ash remaining on the surface of the soil that was somewhat visible the first summer after application. Generally, significant differences were largely driven by treatment and time after application (Table S2).

Percent OM decreased in the 4 Mg/ha treatment compared with the controls, and even more so in the 8 Mg/ha treatment in the litter layer at all sites the first year following ash application (Table S1). In some cases, this decrease persisted in the higher treatment dose in the second year following application, but OM content returned to baseline and control levels in the litter layer the second year following application in the lower treatment dose (Table S1).

Changes in Ca, K, and Mg concentrations in the ash-treated plots were mostly evident the first year post-application, but the level and magnitude differed depending on the element, site, and time following application (Table S2; Figs. 2–4). The soil Ca response was similar to pH, with increases in the ash-treated plots most apparent in the organic horizons and sustained throughout the second year especially in the FH horizon and

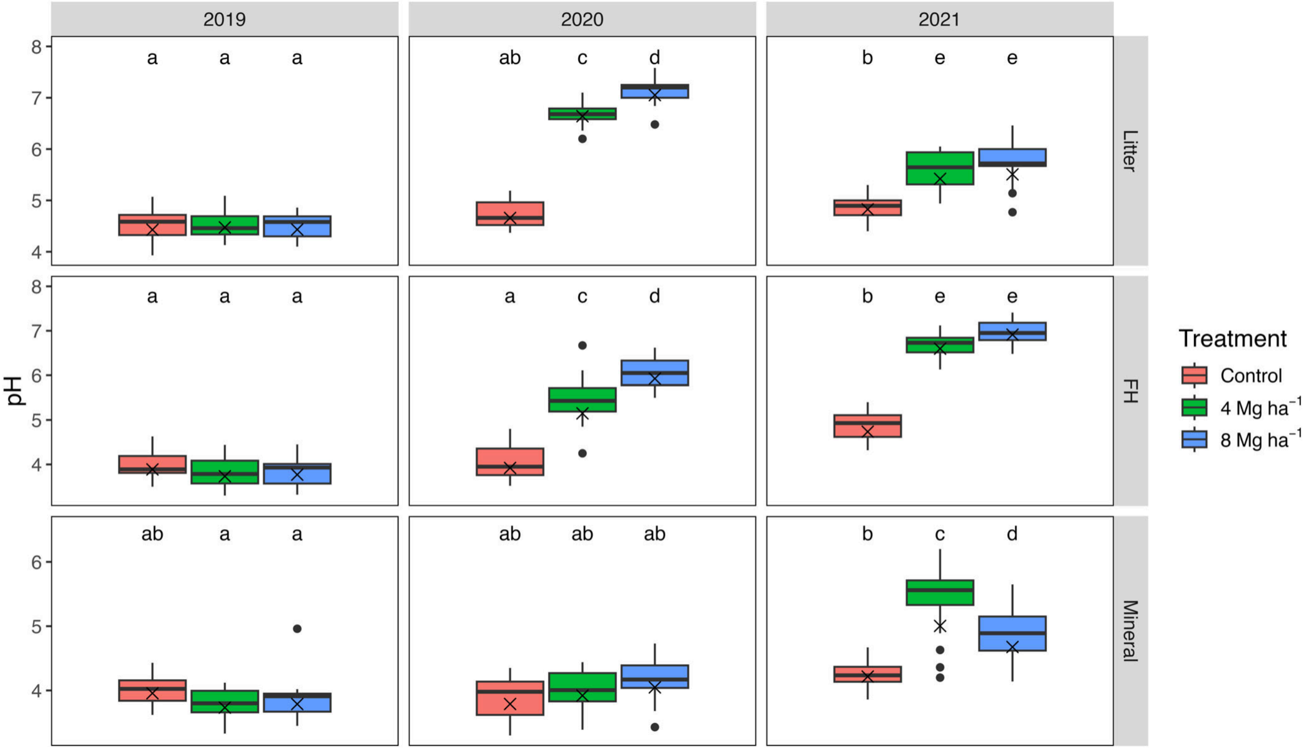

Figure 1. Litter, FH, and upper mineral (0–10 cm) soil pH 1 year before (2019), 1 (2020) and 2 (2021) years after 4 and 8 Mg/ha non-industrial wood ash (NIWA) application averaged across the three experimental sites in Muskoka, Ontario. Black X's indicate mean pH (calculated on [H^+] concentrations), and letters indicate statistically significant differences ($p < 0.05$) among all treatment–year combinations within each horizon. Statistical differences were determined using linear mixed-effects models with treatment and year as fixed effects and site as a random intercept. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment.

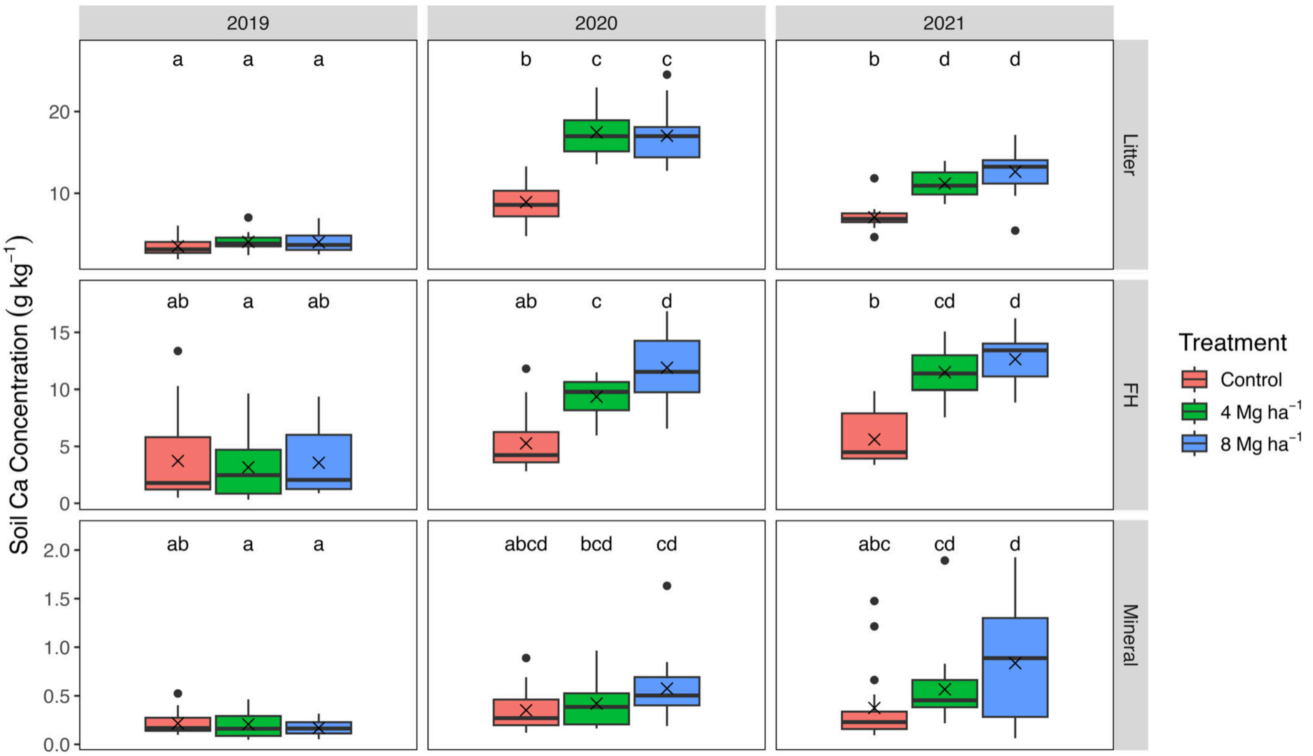

Figure 2. Soil Ca concentrations 1 year before (2019), and 1 (2020) and 2 (2021) years after 4 and 8 Mg/ha non-industrial wood ash (NIWA) application in the litter, FH, and upper mineral (0–10 cm) soil horizons averaged across the three experimental sites in Muskoka, Ontario. Black X's indicate mean Ca concentrations, and letters indicate statistically significant differences ($p < 0.05$) among all treatment–year combinations within each horizon. Statistical differences were determined using linear mixed-effects models with treatment and year as fixed effects and site as a random intercept. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment.

materializing in the upper mineral horizon (Fig. 2). Magnesium behaved similarly to Ca, but the Mg "wave" was more rapid with large increases in the mineral soil by year two and decreasing concentrations in the organic horizons between the first and second year after application (Fig. 3). Potassium exhibited a different response, as no significant increases in response to ash application were observed in the litter and increases in K in the FH were only observed 1 year after application (Fig. 4). The strongest response was observed in the upper mineral soil 1 year after application, with large increases in K concentration that were proportional to ash dose (Fig. 4). Generally, the treatment and time interactions were significant and showed that concentrations in base cations increased in the organic horizons up to 1 year following application, followed by subsequent decreases and then elevated concentrations in the mineral horizon that were often consistent with dose (Figs. 2–4).

Concentrations of most metals increased in the litter layer the first year following application (Table S1; Fig. 5). By the second year after treatment, litter metal concentrations decreased and were highest in the FH horizon (Fig. 5). Increases in metal concentrations in the treated plots in the soil organic horizons were generally proportional to dose, and most notable for B, Cu, Pb, Zn, and to some extent Mn, relative to the control plots both years (Table S1; Fig. 5). Though Al concentrations tended to be higher in the litter horizon, decreases were noted in Al in the FH and Al and Fe in the mineral horizon relative to the controls. Otherwise, very few differences were observed in metal concentrations in the mineral soil both years following application. In most cases the treatment and site interaction were not significant, and the significance of the treatment effect depended on time after application (Tables S1 & S2; Fig. 5).

Sugar Maple Foliar Response

Base cation and P concentrations increased in sugar maple foliage while some metal concentrations also changed after ash application, but the response varied among nutrients and metals and was more pronounced in the mature foliage in the second year after application (Fig. 6). Concentrations of Ca, K, Mg, and B were 50–100% higher in the sapling and mature foliage in both years following application. Increases in foliar P were only evident in the second year after application in both sapling and mature foliage (Table S3; Fig. 6). Foliar Zn concentrations increased in some cases, but only in the mature foliage and at the higher treatment dose in the first year after application (Table S3; Fig. 6). In contrast, 2 years after treatment, average sapling foliar Mn levels were 40–50% lower in the higher dose ash-treatment plots than in the controls (Table S3; Fig. 6).

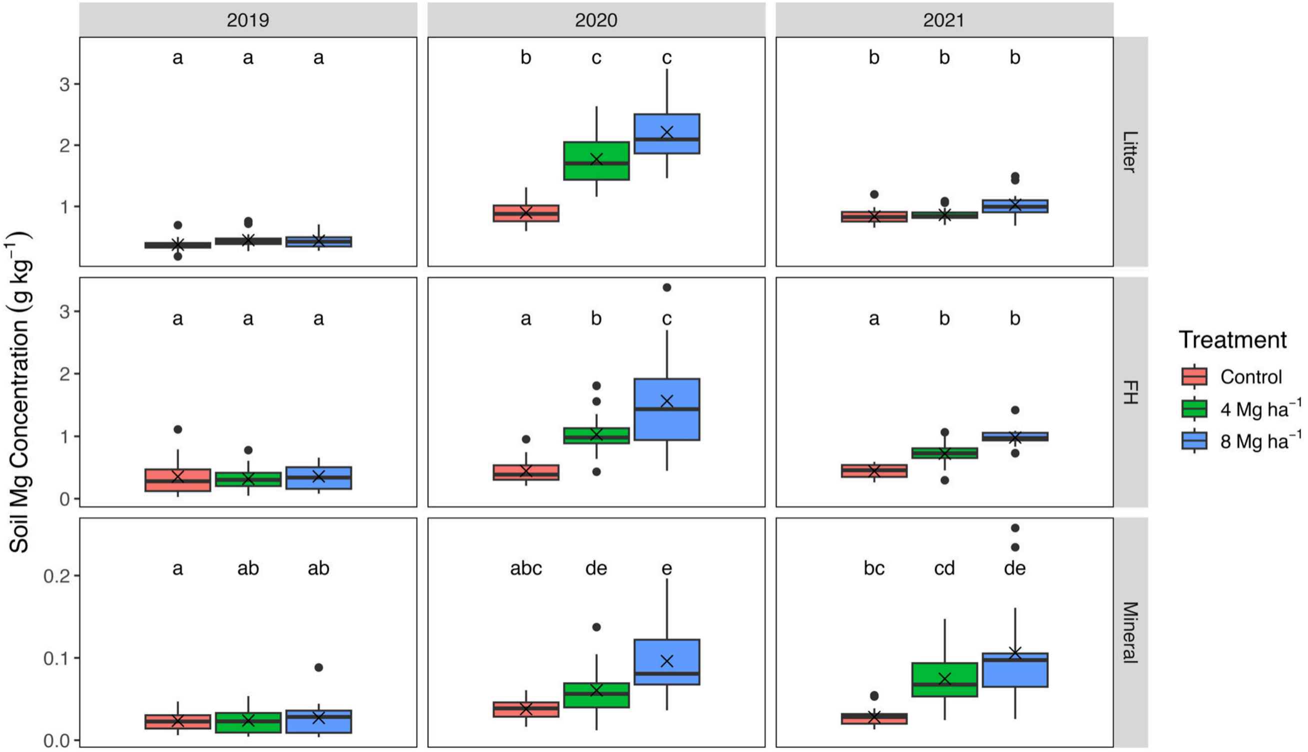

Figure 3. Soil Mg concentrations 1 year before (2019), and 1 (2020) and 2 (2021) years after 4 and 8 Mg/ha non-industrial wood ash (NIWA) application in the litter, FH, and upper mineral (0–10 cm) soil horizons averaged across the three experimental sites in Muskoka, Ontario. Black X's indicate mean Mg concentrations, and letters indicate statistically significant differences ($p < 0.05$) among all treatment–year combinations within each horizon. Statistical differences were determined using linear mixed-effects models with treatment and year as fixed effects and site as a random intercept. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment.

Changes in the concentrations of almost all other metals and N were small and insignificant (Table S3 & S4; Fig. 6).

Based on DRIS analysis, P appears to be available in excess in both mature and sapling foliage, and this tended to increase with treatment by the second year (Table 2) but overall concentrations remain within the critical foliar thresholds for sugar maple (0.8–1.8 g/kg; Table S3). Conversely, higher concentrations of other nutrients led to much lower, possibly deficient N DRIS values (<-20) in the treated plots particularly at the larger treatment dose (Table 2). Both K and Mg nutrition were generally better in the treated plots relative to the controls both years, while Ca DRIS values exhibited little change or tended to decrease, sometimes significantly, to values <-20 suggesting Ca was relatively more deficient (Table 2).

Discussion

Soil Response

The soil chemical response to NIWA additions resembled a "wave," with large and rapid increases initially in the litter layer that migrated to deeper soil horizons over time. Prior to application, organic and mineral soil pH averaged 3.5–4.5 at all sites. Following application, it increased significantly, averaging 6.5–7.5 in the litter and 5–6 in the FH in both ash treatments at all three sites. These results align with an average increase of 2.1 pH units observed previously (Augusto et al. 2008; Conquer et al. 2023) due to the oxide and carbonate compounds in the ash (Demeyer et al. 2001) as well as some residual ash remaining on the forest floor the first summer following application. Such large increases in pH may stress some components of the forest flora and microfauna, but most appear to fully recover in 1–3 years (Aronsson & Ekelund 2004; Augusto et al. 2008).

NIWA may also influence OM decomposition. Deighton and Watmough (2020) reported no effect of NIWA on percent OM, but others reported decreases following IWA (Saarsalmi et al. 2001) and NIWA (Conquer et al. 2023) application, consistent with the findings of this study. In some cases (e.g. shortly following application) this may result from ash remaining on the soil surface, but it could also reflect enhanced OM decomposition through increased microbial activity because of the higher soil pH (Bang-Andreasen et al. 2017; Neina 2019; Couch et al. 2021). Given that OM content returned to baseline and control levels by the second year at the lower treatment, this decrease appears to be a short-term effect influenced by the initial treatment dose. This supports the use of more moderate treatment doses (e.g. 2–4 Mg/ha) of NIWA.

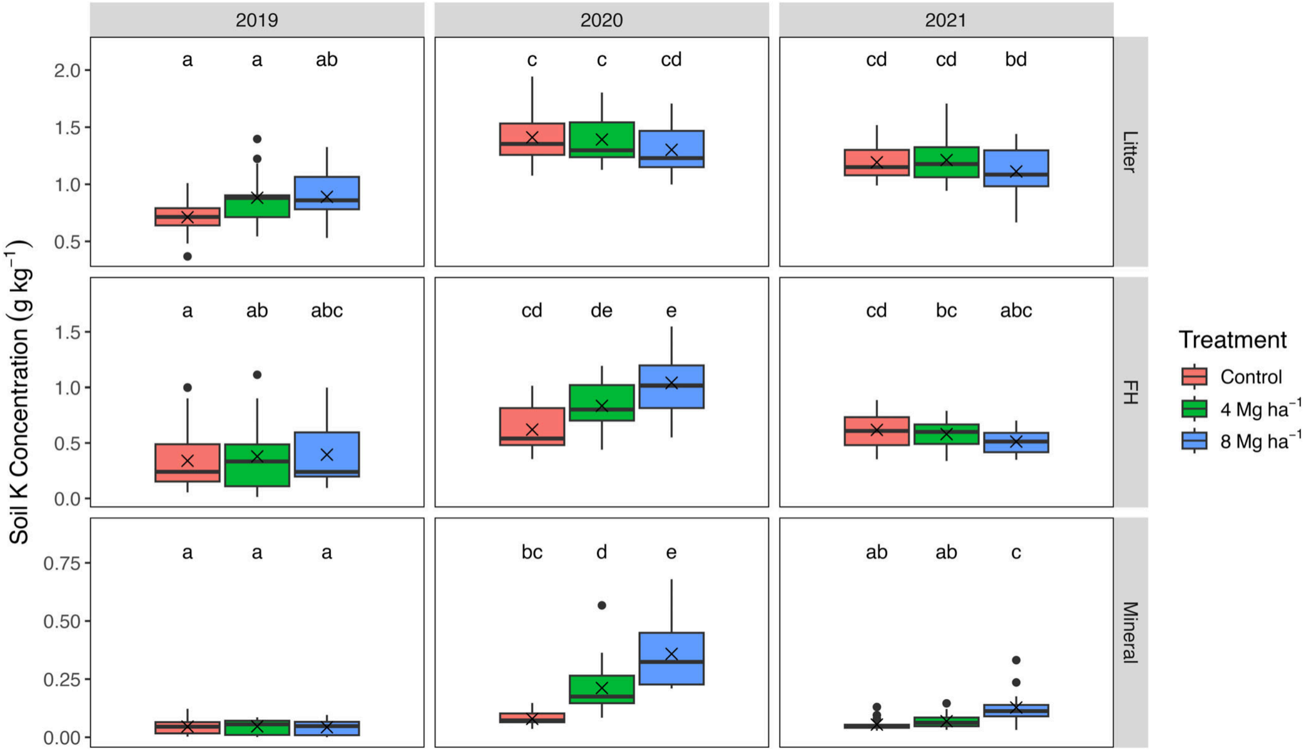

Figure 4. Soil K concentrations 1 year before (2019), and 1 (2020) and 2 (2021) years after 4 and 8 Mg/ha non-industrial wood ash (NIWA) application in the litter, FH, and upper mineral (0–10 cm) soil horizons averaged across the three experimental sites in Muskoka, Ontario. Black X's indicate mean K concentrations, and letters indicate statistically significant differences ($p < 0.05$) among all treatment–year combinations within each horizon. Statistical differences were determined using linear mixed-effects models with treatment and year as fixed effects and site as a random intercept. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment.

Prior to ash application there were few differences in base cation concentrations in each soil layer. After NIWA application, the rate of base cation movement through the soil profile follows the order K > Mg > Ca, whereby K is the most mobile and Ca is the least. Potassium is highly soluble in wood ash (Steenari et al. 1999) and has a lower affinity for soil exchange sites relative to the divalent cations Ca and Mg, thus resulting in its faster leaching through the soil horizons (Ozolinčius et al. 2005, 2007). Soil Ca responded similarly to pH, with large, rapid increases the first year in the litter followed by increases in the FH, and higher concentrations in the mineral layer the second year. Our results are consistent with previous research, where increased Ca concentrations persist in the soil up to 16 years after applications of 1–8 Mg/ha wood ash (Saarsalmi et al. 2001; Augusto et al. 2008). A high binding affinity in the organic horizons helps to retain Ca in the rooting zone which is important particularly on Canadian Shield soils where concentrations have been depleted by acidic deposition (Driscoll et al. 2001). Evidently, wood ash addition can help replace the substantial losses of Ca from the exchangeable soil pool in the twentieth century (Likens et al. 1996; Watmough & Dillon 2003). Additionally, Ca should particularly benefit sugar maple trees via increased photosynthesis and transpiration, protection against and repair of damage, improved stress tolerance and crown health, and increased sap volume and sweetness (Kim et al. 2022).

Magnesium and K behaved slightly differently from Ca and pH, moving more rapidly through the soil. Magnesium concentrations were elevated in all three layers the first year but began dissipating the second year. Leaching of Mg from the organic horizons led to increasing concentrations in the mineral horizon 2 years after application. Though Mg has the same charge density as Ca, has a smaller ionic radius, and typically exhibits slow leaching rates from wood ash (Steenari et al. 1999), soil exchange sites have a higher affinity for Ca. Thus, as base saturation approaches capacity in the organic horizons Ca preferentially displaces Mg and K from exchange sites (Long et al. 2022).

The behavior of K in the soil was consistent with past research (Saarsalmi et al. 2004; Ozolinčius et al. 2007; Augusto et al. 2008). Soil K concentrations increased in the first year after application primarily in the higher treatment dose in the FH and mineral horizons. By year 2, K concentrations fell in the FH layer and were mostly back to baseline in the mineral soil. Some natural year-to-year variability in K concentrations in the litter input was also present. Wood ash K is highly soluble (Azan et al. 2019) and has a lower charge density relative to Mg and Ca resulting in greater mobility and displacement for preferred

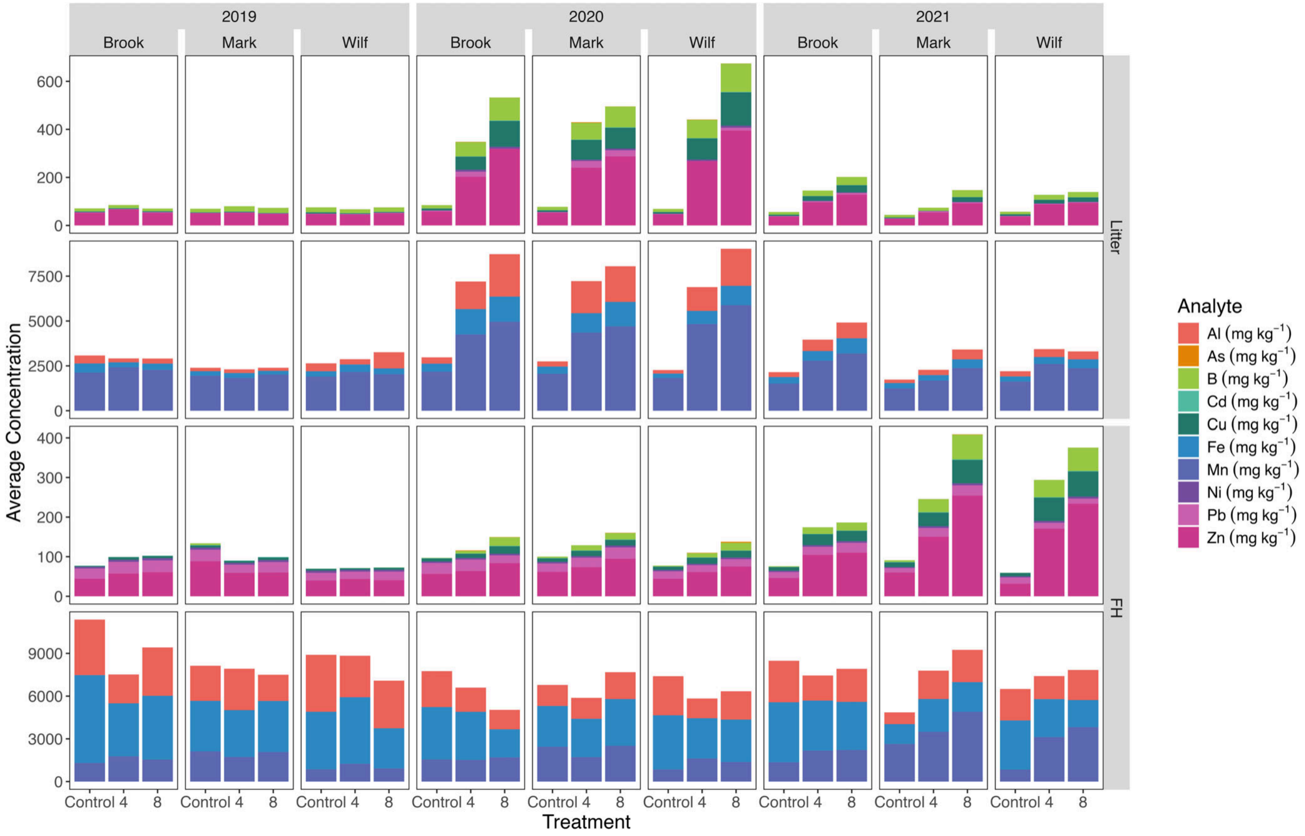

Figure 5. Average metal concentrations in the litter and FH soil sampled at three sugarbushes prior to (2019), 1 (2020), and 2 (2021) years following treatment with 4 and 8 Mg/ha non-industrial wood ash (NIWA). Given their larger concentrations, Al, Fe, and Mn are illustrated in a separate row for both layers. Mineral soil and significant differences can be found in Table S1, and results of the linear models can be found in Table S2.

cations in the organic horizons (Long et al. 2022). Given the amount of K added in the 4 and 8 Mg/ha NIWA treatments (approximately 433 kg K ha^{-1} and approximately 867 kg K ha^{-1} on average, respectively) and the lack of differences between the treated and control plots in each layer in the second year, it is likely that a large portion of the ash-derived K was leached at a faster rate through the soil profile relative to the other base cations. However, it is also likely that some of the ash-derived K was absorbed by plant roots and is further evidenced by significantly higher foliar K concentrations in the treatment plots compared to the controls. Overall, treatment, site, and year effects were significant in our analysis, suggesting that the response of soil to NIWA amendment is both spatially and temporally dependent, but that NIWA can provide considerable nutritional value especially to base-poor, acidic sites.

Prior to ash application there were few differences in metal concentrations within and between sites. Following application, metal concentration changes also exhibited a “wave” behavior, increasing in year 1 but falling in year 2 in the litter, while increasing in the FH in the second year. Higher metal concentrations in the organic horizons are expected following wood ash application based on the ash composition, natural weathering and persistence in the top layer of soil, particularly when not mechanically incorporated (Pitman 2006). The mineral layer was mostly unresponsive to metals, as others have observed (Saarsalmi et al. 2004; Ozolinčius et al. 2007; Arseneau et al. 2021), both because the natural soil metal pool is large, and metals are retained in the organic horizons and precipitate out of the soil solution at the elevated pH (Neina 2019; Cairns et al. 2021). In some cases, both Al and Fe decreased primarily in the mineral horizon. Similar decreases in soil exchangeable Al and Fe have been observed following wood ash application while fine root concentrations remained unchanged, suggesting that uptake of Al and Fe may depend more on plant dynamics than on soil chemistry and thus there is little risk of toxicity to plants (Brunner et al. 2004). On the other hand, levels of B, Cd, Pb, and Zn increased in the litter and FH. While B and Zn are essential micronutrients (Kohli et al. 2023), Cd and Pb are toxic, especially to sugar maple (Watmough 2010). However, wood ash has been reported to specifically immobilize Cd, Cu, Pb, and Zn in soils (Cairns et al. 2021), and thus it is unlikely that increased concentrations pose a risk of toxicity to plants following application.

Sugar Maple Foliar Response and Diagnosis and Recommendation Integrated System Indices

Base cation concentrations increased in both treated saplings and mature foliage, and while the degree and significance depended on the nutrient, foliage type, and time following application, overall concentrations generally fell within critical foliar

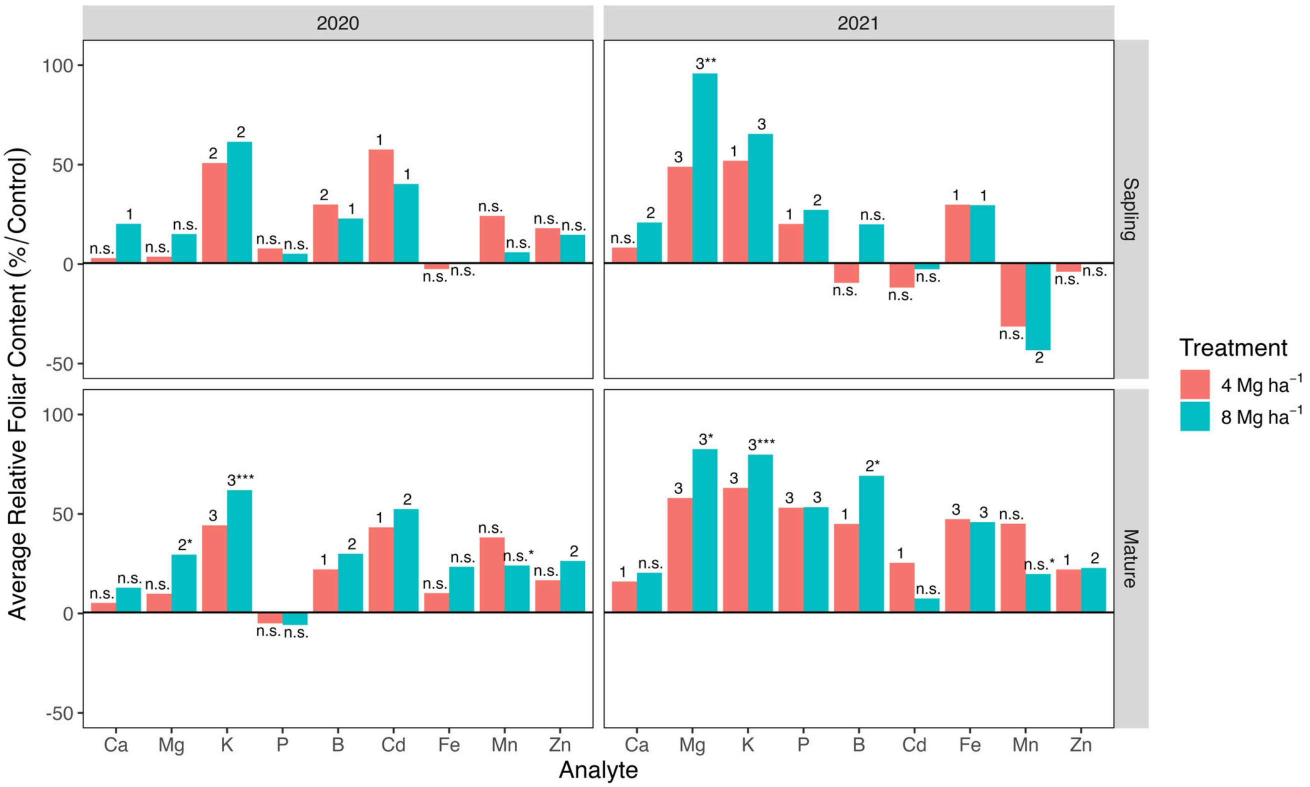

Figure 6. Percent change in the average treated foliar concentrations across all sites relative to the controls for sapling and mature sugar maple foliage in the 4 and 8 Mg/ha non-industrial wood ash (NIWA) treatment plots. Numbers above the bars indicate that relative changes observed in *n* number of sites were significant (compared to the control plots). Where not significant (n.s.), changes relative to the controls were not significant at any of the three sites. Asterisks indicate that the percent change in the 8 Mg/ha treatment was also significantly different compared to the 4 Mg/ha treatment, and the number of asterisks indicates how many sites where this significance occurred. Concentrations of all nutrients and metals and significant differences are included in Table S3, and results of the linear models are included in Table S4. Statistical differences were determined using linear models with treatment, year, and site as fixed effects. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment.

Table 2. Sapling and mature foliar Diagnosis and Recommendation Integrated System (DRIS) indices one (2020) and two (2021) years following treatment with 4 and 8 Mg/ha non-industrial wood ash (NIWA) averaged across three sugarbush sites in Muskoka, Ontario. Significant differences among all treatment–year combinations within each foliar tissue (sapling and mature) are indicated with letters ($p < 0.05$), and deficiencies/excess greater than −20/+20, respectively, are bolded. Statistical differences were determined using linear mixed-effects models with treatment and year as fixed effects and site as a random intercept. Post hoc analyses were conducted using EMMs with a Bonferroni adjustment. Significance *p* values are listed in Table S5.

		2020			*2021*		
Tissue	*Indices*	*Control*	*4 Mg/ha*	*8 Mg/ha*	*Control*	*4 Mg/ha*	*8 Mg/ha*
Sapling	Ca	-10.72^{ab}	-12.69^{ab}	-8.03^{b}	-13.72^{ab}	-18.70^{a}	-19.06^{a}
	Mg	7.45^{ab}	4.40^{a}	5.67^{a}	5.70^{a}	15.96^{b}	**25.04^{c}**
	K	-6.80^{a}	7.00^{b}	6.66^{b}	-17.94^{c}	-5.98^{a}	-6.55^{a}
	P	**24.99^{a}**	**28.42^{ab}**	**24.16^{a}**	**29.87^{abc}**	**36.55^{bc}**	**39.32^{c}**
	N	-14.93^{ac}	**-27.13^{ab}**	**-28.47^{ab}**	-3.90^{c}	**-27.83^{ab}**	**-38.76^{b}**
Mature	Ca	-3.38^{a}	-4.65^{a}	-4.64^{a}	-12.72^{b}	**-20.43^{c}**	**-21.78^{c}**
	Mg	-0.45^{a}	0.20^{a}	5.30^{ab}	1.10^{a}	10.28^{bc}	13.91^{c}
	K	-5.39^{a}	5.33^{cd}	6.83^{d}	-14.63^{b}	-4.07^{a}	-2.33^{ac}
	P	**31.89^{a}**	**23.62^{ab}**	18.19^{b}	**26.06^{ab}**	**46.18^{c}**	**44.67^{c}**
	N	**-22.67^{a}**	**-24.50^{a}**	**-25.68^{ab}**	0.19^{c}	**-31.97^{ab}**	**-34.47^{b}**

thresholds. Patterns of deficiency or excess indicated by DRIS were consistent between sapling and mature foliage in both years but varied among nutrients. DRIS indices are valuable because they provide an unbiased assessment of nutrient status and have been previously used in soil amendment research to assess nutrient responses relative to other nutrients (Moore & Ouimet 2006; Arseneau et al. 2021). While useful for assessing relative nutrient balance, it should be noted that DRIS norms were developed based on healthy trees that also exhibited nutrient imbalances (Lozano & Huynh 1989) and therefore should be interpreted in that context.

As in the soil, K responded first with significant increases of 50–100% in both treatments in the sapling and mature foliage 1 and 2 years post-application. As indicated by DRIS analysis, K nutrition also improved both years in the treatment plots relative to the controls where concentrations were typically at or below the critical foliar limit (5.5–10.4 g/kg). On average, foliar K concentrations in the 8 Mg/ha treatment dose (7.8–12.7 g/kg) were on average approximately 10% higher than the 4 Mg/ha dose (7.0–11.6 g/kg), suggesting that though uptake is elevated, trees may hit a point of saturation where uptake is no longer proportional to dose. A similar response was observed in sugar maple foliage 1 year following NIWA application by Conquer et al. (2023). Potassium concentrations increased from the first to the second year, likely because of greater solubility at higher pH (Azan et al. 2019). At low pH, K is outcompeted for soil exchange sites primarily by H, Al, and Fe (Ferrarezi et al. 2022) and at a higher pH it is outcompeted by Ca and Mg (Han et al. 2019) resulting in greater mobility in the soil and availability for plant uptake (Barrow & Hartemink 2023). Additionally, K is primarily accessed from the topsoil—where K concentrations were highest the first year after application—in a highly efficient process that likely sustained increased foliar concentrations the following year (Römheld & Kirkby 2010). Potassium concentrations in the sapling foliage rose only in the 8 Mg/ha treatment, possibly due to a more extensive root system and a greater capacity for storage and redistribution in mature trees compared to saplings.

Higher foliar concentrations and improved DRIS indices of Mg and P were most evident in year 2. High K concentrations have an antagonistic effect on Mg uptake by plants and thus may prevent increased foliar concentrations for a period following application (Xie et al. 2021). By the second year, Mg concentrations were significantly higher at all three sites in the treated plots compared to the controls in both types of foliage, and in some cases, Mg concentrations differed between treatments. This is likely a result of both the slower leaching of Mg through the soil profiles and the slower uptake of Mg by plants compared to K (Xie et al. 2021). Wood ash application has been reported to increase P availability in acidic soils at low to moderate doses (2–8 Mg/ha; Arshad et al. 2012; Nottidge & Nottidge 2012). Although DRIS indices suggested that P was available in excess following NIWA application and excess nutrients can be problematic (Bal et al. 2015), P concentrations observed here remained within the critical foliar limits (0.8–1.8 g/kg) for healthy sugar maple.

Ca was the slowest to respond and only responded significantly in the 8 Mg/ha plots in the saplings both years, and in the 4 Mg/ha plots in the mature foliage the second year after application, but not at all sites. This response is consistent with the fact that Ca is highly retained in the organic horizons, especially with elevated soil pH (Pitman 2006). It is interesting to note that although not always significant, DRIS indices highlighted worsening Ca nutrition that tended to be greater in the higher treatment plots, sometimes to the degree of deficiency even though all reported concentrations fell within the critical foliar limits (5.0–21.9 g/kg). Improvements in low Ca concentrations in sapling and mature foliage have been observed 3 years after application (20 Mg/ha), and only after 4 years did Ca DRIS indices improve significantly at lower treatment doses (5 and 10 Mg/ha; Arseneau et al. 2021) suggesting this response will likely improve over time.

Furthermore, while N concentrations tended near the upper threshold of the critical foliar limit (16.0–23.2 g/kg), N deficiencies were significantly greater in the treatment plots compared to the controls in the sapling and mature foliage the second year after application. Wood ash contains negligible amounts of N since it is burned off during combustion (Pitman 2006) and while N DRIS indices were low in the control plots, in most cases they were not deficient. Given that significantly lower OM content in the treatment plots seemed to suggest increased microbial activity and thus mineralization, one might expect greater availability of N for plant uptake. However, greater increases in other nutrients without a corresponding addition of N may drive nutritional imbalances causing deficiencies in elements such as Ca and N. Ozolinčius et al. (2007) also reported a 1.4-fold decrease in N in the soil litter 2 years following IWA application, but this effect was not observed when IWA and N were added together. In another similar study, IWA addition led to more balanced N DRIS indices (Arseneau et al. 2021), but this occurred on sites where N was available in excess to begin with so it may be possible that this prevented the sites from moving into deficiency. Ultimately, deficiencies in important nutrients such as Ca and N will likely prevent any growth response following application and may suggest that adding N could enhance NIWA's restorative effects, as seen in other studies (Saarsalmi et al. 2004; Ozolinčius et al. 2007). Thus, while NIWA improves tree nutrition in base cations such as K and Mg in the short term, it may be beneficial to monitor for potential deficiencies over the long term.

Overall, metal concentrations varied, and responses reflected treatment dose and time following application. In particular, metals such as Al, Fe, Zn, and sometimes Mn were typically below the lower threshold of critical concentrations in the control and treated plots both years following wood ash application. In a few cases, reported concentrations of Al and Mn were above the upper threshold of the critical limits (32–60 and 632–1630 mg/kg, respectively) in the treated plots, but this only occurred in the first year and concentrations returned within these limits the second year after NIWA application. Decreases in foliar Mn were noted despite increases in organic horizon Mn concentrations and likely resulted from the reduction in bioavailability of Mn at higher soil pH (Ferrarezi et al. 2022; Khoshru et al. 2023) and is a common response following wood ash application (Augusto et al. 2008). In some cases, significantly higher concentrations of B were observed. Boron is an essential micronutrient (Kohli et al. 2023) and though optimal concentrations vary widely depending on the type of soil and plants, 10–75 mg/kg in plant tissue is considered adequate (Arunkumar et al. 2018) and is consistent with the concentrations reported here.

Cadmium levels rose in both treatments in the sapling and mature foliage the first year after application, but not at all sites, and only at the lower ash dose in the mature foliage the second year. Increases in pH following wood ash application tend to immobilize Cd in the soil (Cairns et al. 2021) likely explaining why higher foliar concentrations were mostly not detected 2 years after ash addition in either treatment. In some cases, Zn concentrations were higher in the treatment plots compared to the controls in the mature foliage, but this was not a consistent result. While Zn is an abundant microelement in ash, its bioavailability is also inversely related to pH, resulting in its retention in the organic horizons and decreasing its likelihood of leaching (Cairns et al. 2021). Lastly, some differences were noted in Fe concentrations primarily in the mature foliage the second year after application, but on average were well within the critical foliar concentrations reported for sugar maple (59–130 mg/kg; Kolb & McCormick 1993). Ultimately, despite higher initial soil metal concentrations, foliar metal uptake did not tend to increase, and in the few cases where they did, they rarely exceeded the healthy range for sugar maple. Metals in the organic horizons are largely not bioavailable because they exhibit an inverse relationship with soil pH (Watmough 2008; Kicińska et al. 2022) and thus are not expected to pose a risk of toxicity to plants following NIWA application.

Overall, the application of NIWA increases soil and foliar nutrition while restricting metal mobility. A moderate dose of 4 Mg/ha NIWA is recommended to be a beneficial addition to forest soils with a history of acidic deposition. However, it is also important to consider that adding NIWA with an N source may be best to avoid introducing or exacerbating nutritional deficiencies in the soil and subsequently in the plants; this could also be the focus of future research. Ideally these results can be used to inform policy to lower the barriers associated with the application of NIWA given that it enhances soil nutrition, largely reduces local waste going to landfill, and fosters community involvement.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Average (± SE; $n = 6^*$) percent organic matter (OM), and total metals in the L, FH, and upper mineral (0–10 cm) soil sampled at three sugarbushes prior to (2019), one (2020), and two (2021) years following treatment with 4 and 8 Mg/ha NIWA.

Table S2. Significance p values for the L, FH, and upper mineral (0–10 cm) soil pH, organic matter (OM), and nutrient and metal concentrations as determined by a linear model ($n = 6^*$ per treatment × horizon × site).

Table S3. Average (± SE; $n = 6^{**}$) (a) sapling and (b) mature sugar maple foliar nutrient and metal concentrations one (2020) and two (2021) years following application of 4 and 8 Mg/ha NIWA.

Table S4. Significance p values for sapling and mature sugar maple foliar nutrient and metal concentrations as determined by a linear model.

Table S5. Significance p values for sapling and mature sugar maple foliar Diagnosis and Recommendation Integrated System (DRIS) indices as determined by a linear model.

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