REPORT

NON-INDUSTRIAL WOOD ASH CHEMISTRY AND ITS BIOGEOCHEMICAL EFFECTS ON SUGAR MAPLE IN THREE CENTRAL ONTARIO SUGAR-BUSHES

2 YEARS AFTER TREATMENT

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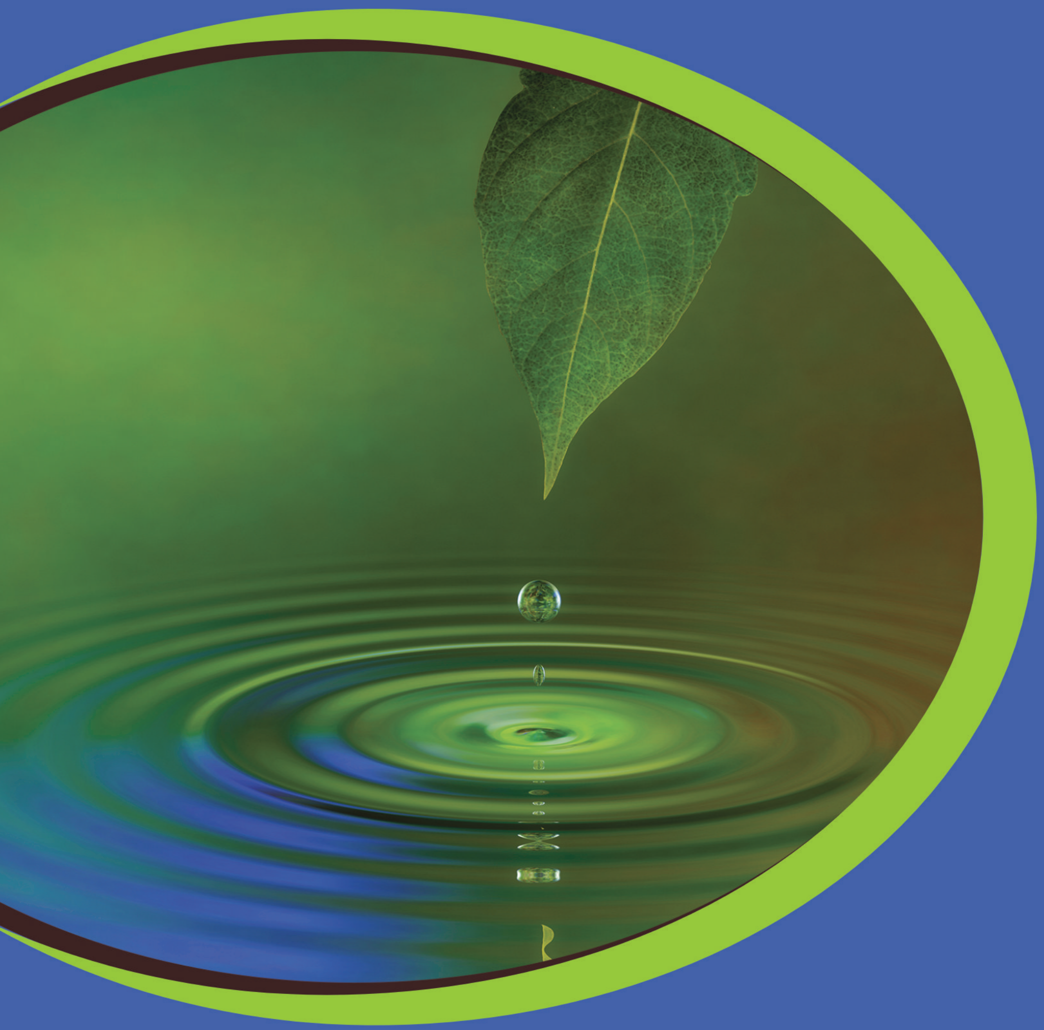

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Friends of the Muskoka Watershed

Non-industrial wood ash chemistry and its biogeochemical effects on sugar maple (Acer saccharum, Marsh.) in three central Ontario sugar-bushes 2 years after treatment

A report submitted to the Friends of the Muskoka Watershed

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Introduction

Acidic deposition has enhanced the leaching of base cations (Ca, K, Mg, Na), from forest soils in Europe and North America (Johnson et al., 1985). Exchangeable base cations are leached when H^+ ions in soil solution increase and displace cations from soil into soil solution (Talhelm et al., 2012). In poorly buffered soils, H^+ loading can enhance dissolution of reactive forms of soil Al, exacerbating base cation leaching, as it competes for adsorption at soil exchange sites (Lawrence et al., 1995). The magnitude of leaching loss is dependent upon the concentrations of base cations in the soil but typically, $Ca^{2+}>Mg^{2+}>K^+>Na^+$ (Haynes & Swift, 1986). Nutrient losses from soil can also be amplified by timber harvesting, given that tree biomass contains large pools of base cations (Olsson et al., 1996; Thiffault et al., 2011).

Declines in tree health linked to losses of soil nutrients have been observed throughout North America (Drohan et al., 2002; Duchesne et al., 2002). In eastern North America low levels of foliar K, Mg, and Ca have all been linked to sugar maple (*Acer saccharum*) decline (Bernier & Brazeau, 1988b, 1988c; Kolb & McMormick, 1993). Low soil exchangeable Ca was linked to hardwood forest canopy decline across southern Ontario (McDonough et al., 2021). Several studies have reported significant improvement in tree health following liming and Ca additions (Huggett et al., 2007; Juice et al., 2006; Long et al., 2011). For example, at the Hubbard Brook Experimental Forest in New Hampshire, USA, significant increases in foliar Ca concentrations, healthier crown conditions and significant increases in sugar maple seedling density were reported after an addition of 0.85 Mg Ca/ha in the form of wollastonite ($CaSio_3$) (Juice et al., 2006).

The application of wood ash is a potential remediation measure to replace base cations lost from soil (Pitman, 2006, Ludwig et al., 2002, Saarsalmi et al., 2006). Wood ash is the inorganic and organic residue generated by the combustion of wood and wood by products (Siddique, 2012), through commercial and domestic use (Azan, 2017; Hannam et al., 2018). Wood ash has a high but variable alkalinity, which can be accredited to its large concentrations of base cations, especially Ca, usually in the form of oxides, hydroxides, and carbonates (Campbell, 1990; James et al., 2014).

Wood ash has been used as a soil amendment for decades in several European countries, but its use in North America is limited in comparison (Pitman, 2006; Corcharan 2023). In Ontario, wood ash is considered a hazardous waste material and most of it is diverted to landfill (Hannam et al., 2016). There is increasing interest in studying the biogeochemical response of wood ash application in Canadian context. Wood ash has been reported to increase base saturation (Jacobson et al., 2004), increase extractable Ca and Mg concentrations in soil (Saarsalmi et al., 2001), and contribute to the decomposition of recalcitrant organic matter, thus increasing available nitrogen (N) pools (Mortensen et al., 2019). However, elevated levels of potentially phytotoxic metals within the upper soil horizons have also been reported (Ozolincius & Varnagiryte, 2005), while in other research exchangeable Al concentrations in soil have been observed to decrease after ash application (Saarsalmi et al., 2001).

Existing literature suggests that the application of wood ash in low doses (~3 Mg ha^{-1}) has minimal to no adverse affect on plant community composition (Arvidsson et al., 2003; Jacobson & Gustafsson, 2001) and positive effects on tree growth have been observed (Solla-Gullon et al., 2008). Improvements in tree growth were attributed to increases in soil Ca and Mg (Solla-Gullon et al., 2008) and decreases in Ca deficiencies in sugar maple seedlings and mature trees (Arseneau et al., 2021). However, there are other studies which have recorded significant changes in understory vegetation composition with a complete transformation of the species, and significant decreases in bryophytes species number and cover after ash application (Moilanen et al., 2002; Okland et al., 2022).

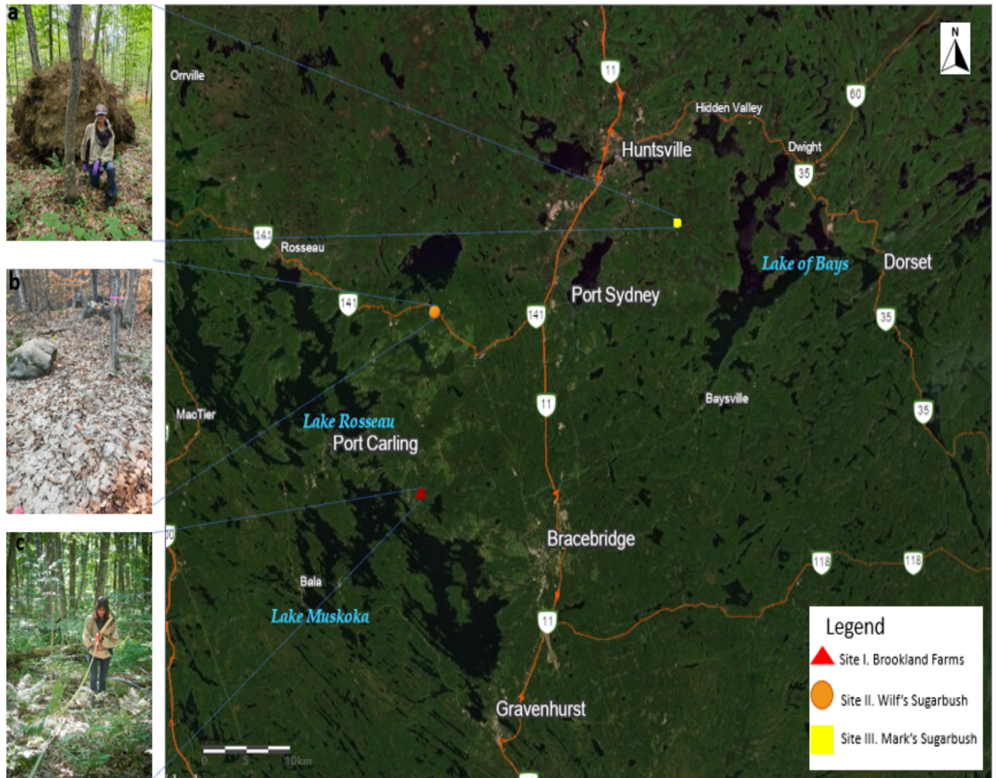
South central Ontario has received high levels of acidic deposition, leading to widespread soil and lake acidification (Dillon et al., 2007; Gorham & Gordon, 1960). Although large reductions in acidic deposition have been recorded, the recovery in soils from excessive nutrient depletion will likely take centuries, even though S and N deposition rates have declined, while forest harvesting levels remain consistent (Ott & Watmough, 2022). Therefore, the application of wood ash, a substance rich in base cations could replace lost nutrients and improve the health of sugar maple (Deighton & Watmough, 2020), a highly valued but Ca demanding tree species (Momen et al., 2015). Ontario produces approximately 18,000 tonnes of nonindustrial wood ash (NIWA) annually (Azan, 2017) that is rich in macro-nutrients and may be useful in countering the effects of acidification and nutrient losses in central Ontario, forests, and lakes (Azan et al., 2019; Deighton & Watmough, 2020). The objective of this study was to evaluate the short-term (2 yr.) response of non-industrial wood ash application applied to three sugar bushes in Muskoka, Ontario. Changes after 1 year have been published in B. Syeda's MSc thesis and are not repeated at length here (Syeda 2023).

It was hypothesized, that wood ash application would increase nutrient availability to plants. Wood ash treatments were expected to significantly increase pH and nutrient concentrations (Ca, Mg, K) and metal concentrations in the organic soil horizons. Nutrient (Ca, Mg, K) concentrations in foliage of both mature and sugar maple saplings were predicted to increase in ash treated plots, with no increases in trace metal concentrations.

Methods

Study Area

The study took place at three sugar bushes in the Muskoka River Watershed in south-central Ontario, Canada (Figure 1). 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), underlain with silicate bedrock (Reid & Watmough, 2015). The soils are acidic with slow mineral weathering rates and receive low levels (< 3 kg/ha/yr.) of atmospheric Ca deposition (Watmough & Dillon, 2003). Sixty-six percent of the region is comprised of forests, dominated by mixed hardwood, and some coniferous species (O'Connor et al., 2009; Reid & Watmough, 2015). Wetlands cover approximately 12% of the region, and 15% is covered by lakes (Reid & Watmough, 2015), of which 60% are in headwater reaches (O'Connor et al., 2009). The mean annual temperature reported for the period of 1981 – 2010 was 5.8°C, with an annual precipitation of 985 mm (Environment and Climate Change Canada, 2018).



This map was created by Batool Syeda using AcrGIS Online Software. Earthstar Geographics Esri Canada

Figure 1 Regional map of the study area and the three study sites, located in Muskoka, Ontario, Canada. Also featuring site photographs taken at a.) Mark's Muskoka Maple Sugarbush, b.) Wilfrid Creasor's Sugarbush, and c.) Brooklands Farm Site I. Brooklands Farm [45'08 N, 79'46W]

Brooklands farm is a 400-acre farm located near Bracebridge, Ontario at an elevation of 304 m above sea level. The property consists of various wetlands, patches of farmlands and forests. The study site was located within a 60-acre sugarbush stand on the northeast corner of the property. The area consists of uneven terrain with several steep slopes and rocky outcrops. The mean thickness of the LFH layer was 3.05 cm. The soils were classified as Orthic Sombric Brunisols (Canadian System of Soil Classification, 1998). The average soil pH (top 0 to 15 cm) was 3.83. The site was dominated by sugar maple however also contained a mix of other hardwood forest species, and the basal area was measured at 26 m^2 ha^{-1} in 2019 (Table 1). The site is being actively used to produce maple syrup. Based on a 2016 study deficit levels of Ca and Mg were reported in the sugar maple leaf tissue on this site (Riley, 2017). Understory plant composition consists of naturally occurring hardwood forest species such as, sugar maple, wood fern *(Dryopteris),* Solomon's seal (*Polygnatum spp.),* trillium *(Trillium spp.)*.

Site II. Wilfrid Creasor (Wilf's) Sugarbush [45'21 N, 79'44W]

Wilfrid's sugarbush is west of Huntsville, Ontario at an elevation of 291 m above sea level. The area is an 83-acre forest primarily dominated by sugar maple, along with other hardwood species (Table 1). The property also contained small ponds and wetlands. The study site was located on the northern end of the property, consisting of uneven terrain with gentle undulating slopes. The mean thickness of the LFH layer was 3.92 cm. The soils were coarse sandy loam, classified as Sombric Brunisols (Soil Classification Working Group, 1998). The mean soil pH (0 – 15 cm) was 3.96, and the basal area was measured at 31 m^2 ha^{-1} in 2019 (Table 1). The study area was used to produce maple syrup commercially however in more recent years the operation has been scaled down for private consumption. Understory plant composition consisted primarily of sugar maple saplings, wood fern, hobble bush *(Viburnum lantanoides),* wild raspberry (*Rubus occidentalis)*.

Site III. Mark's Muskoka Maple (Mark's) Sugarbush [45'28 N, 79'14W]

Mark's sugarbush is south-east of Huntsville, Ontario at an elevation of 291 m above sea level. The area is a 49-acre forest dominated by sugar maple intermingled with other hardwood forest species. The study site was located on the northwestern end of the property and consists of relatively flat terrain. The soils were coarse sandy loam, classified as Sombric Brunisols (Soil

Classification Working Group, 1998). The mean soil pH (0 – 15 cm) was 3.88, and the basal area was measured at 26 m² ha^{-1} in 2019 (Table 3.1). The study area was used to produce maple syrup since 1980. Understory plant composition comprised of common hardwood forest species including sugar maple saplings, Ground pine *(Lycopodium obscurum),* wild raspberry.

Table 1. Baseline site characteristics for the three sugar bushes in Muskoka, Ontario. Tree species relevant to each site marked by B (Brookland Farms) /W (Wilf's sugarbush) /M (Mark's sugarbush)

Year 2019	Brookland Farms	Wilf's Sugarbush	Mark's Sugarbush
Land cover (Hectares)	24	33	20
Elevation (m)	304	291	291
Mineral Soil pH (0 - 15 cm)	3.83	3.96	3.88
Basal Area All Species (m² ha^{-1})	26.08	30.67	26.21
Basal Area Sugar Maple (m² ha^{-1})	22.22	29.69	25.74
Stem Density (trees/ha)	635	577	677
Other Tree Species	Basswood (*Tilia americana*) B Balsam Fir *(Abies balsamea*) W/M Beech (*Fagus grandifolia*) B/W/M Black Cherry (*Prunus serotina*) B Red Maple (*Acer rubrum*) B/W/M Sugar Maple (*Acer saccharum*) B/W/M White Ash (*Fraxinus americana*) B/W White Pine *(Pinus strobus*) B/W/M Yellow Birch (*Betula alleghaniensis*) B/W		

Land cover data was obtained from the individual land owners, soil pH data was obtained from the soil samples collected in 2019, basal area and stem density data was calculated using the DBH data collected in 2019

Plot setup and study design

Three replicated experiments were conducted by establishing eighteen 10 x 10-metre plots at each site in August of 2019. Plots were randomly located within each sugar bush, but each plot had to contain a minimum of two mature (> 10 cm diameter at breast height (DBH)) sugar maple trees, and some sugar maple saplings. Sites were chosen with relatively flat topography to minimize runoff after ash application, a requirement of our ash addition permit. Wooden stakes were used to mark the corners of each plot, and the stakes were labelled with the corresponding plot number. Special care was taken to leave a buffer area (>10m) between neighboring plots, to minimize the risk of cross contamination.

Field sampling and ash application

Ash samples were collected from residents in the Muskoka region at monthly ash drives run by the Friends of the Muskoka Watershed. The ash was stored in large metal bins prior to field application. Before ash application in the field, the individual ash samples were amalgamated into a homogenous composite using a large cement mixer and distributed into multiple containers for ease of transport.

Baseline (i.e. pre-treatment) soil samples consisting of the litter layer (L), the fibric and humic (FH) layer and the mineral layer to a depth of 15 cm were collected at each plot, in late summer of 2019, prior to wood ash application. The samples were taken from all four corners, and the middle of each plot for a representative soil sample. Ten grab samples in total (Five from the Litter horizon and five from the FH horizon) were collected from each plot. Five mineral soil (0 – 15cm) samples were collected from each plot using a Dutch auger (Figure 2). Each sample was placed in a zip-lock bag and each bag was labeled with its corresponding site, plot number and soil layer ID code. Soil sampling was repeated in 2020, ten months after ash application and again in the summer of 2021.

Wood ash was applied in late fall of 2019, after leaf fall. Three treatment dosages were employed, consisting of 8 Mg ha^{-1} (80 kg for a 10 x 10m plot), 4 Mg ha^{-1} (40 kg at a 10 x 10m plot), and a control (no ash). At each site, six plots per treatment were established for a total of 18 plots at each site - (Brooklands Farm was an exception, where there were six controls, six plots with 4 Mg ha^{-1} and five plots with 8 Mg ha^{-1}). Plots were assigned ash treatments at random. To maximize dosage application accuracy, ash was poured from the larger metal bins into smaller 8 - L plastic buckets and each bucket was individually weighed in the field to ensure that every plot received the correct dosage (Figure 3). The application to plots took place by hand using small jugs, taking care to spread the ash as evenly as possible within each plot. Ash applied at each site was similar in its chemical composition, with only a few exceptions in differences between pH, Pb, Cu and Fe concentrations (Table 2). To confirm consistency in chemical composition, at each site sub samples of ash were collected at varying intervals throughout the application process (Table 2).

Table 2 pH, LOI, CNS, nutrient and metal concentrations of amalgamated nonindustrial wood ash applied to each study site (n=10 each) and Ontario Regulation 267/03 of the Nutrient Management Act limits for unrestricted (CM1) and restricted (CM2) use of wood ash for land application as a non-agricultural non-aqueous source material are also shown.

Study Sites	Amalgamated Non-industrial Wood Ash				NASM** Limits	
	Mean	*Median*	*SD*	*Cv (%)*	*CM Level 1*	*CM Level 2*
Brookland Farms						
pH	13.5					
LOI	3.5	3.5	0.8	22.9		
C (%)	11.6	10.0	4	34.0		
N (%)	0.2	0.1	0.2	100		
S (%)	BDL	BDL	NA	NA		
Ca (g.kg⁻¹)	305	305	15	5.0		
Mg (g.kg⁻¹)	24.2	23.8	2.5	10.7		
K(g.kg⁻¹)	109	108	13	12.0		
P (g.kg⁻¹)	8.8	8.5	1	13.4		
Cd (mg.kg⁻¹)	2.7	2.8	0.4	14.4	3	34
As (mg·kg⁻¹)	3.9	0.2	6	153	13	170
Ni (mg·kg⁻¹)	10.5	9.6	3	30.4	62	420
Pb (mg·kg⁻¹)	24.3	21.3	17	71.8	150	1100
Cu (mg·kg⁻¹)	140	133	41.9	29.8	100	1700
Zn (mg·kg⁻¹)	523	495	109	20.9	500	4200
Mn (mg·kg⁻¹)	6306	6373	683	10.8		
Fe (mg·kg⁻¹)	2793	2607	1150	41.0		
Wilf's Sugarbush						
pH	13.3					
LOI	5.8	5.0	1.0	17.7		
C (%)	8.8	8.5	0.8	9.0		
N (%)	0.1	0.1	NA	NA		
S (%)	BDL	BDL	NA	NA		
Ca (g.kg⁻¹)	273	289	48.4	17.7		
Mg (g.kg⁻¹)	22.1	22.7	3.5	16.0		
K(g.kg⁻¹)	112	118	21.7	19.3		
P (g.kg⁻¹)	7.9	8.1	1.2	15.1		

Cd (mg.kg^{-1})	2.5	2.5	0.6	24.7	3	34
As (mg·kg^{-1})	3.1	BDL	7.4	237.5	13	170
Ni (mg·kg^{-1})	8.8	8.9	2.0	22.5	62	420
Pb (mg·kg^{-1})	12.7	13.5	3.8	30.3	150	1100
Cu (mg·kg^{-1})	154	129	92.1	59.8	100	1700
Zn (mg·kg^{-1})	516	504	151	29.3	500	4200
Mn (mg·kg^{-1})	6837	7029	1023	15.0		
Fe (mg·kg^{-1})	1322	1199	528	39.9		
Mark's Sugarbush						
pH	11.5					
LOI	5.6	5.5	1.0	17.8		
C (%)	9.1	8.8	0.9	9.8		
N (%)	0.1	0.1	NA	NA		
S (%)	BDL	BDL	NA	NA		
Ca (g.kg^{-1})	294	308	46.4	15.7		
Mg (g.kg^{-1})	22.5	23.0	3.8	16.9		
K(g.kg^{-1})	104	107	20.3	19.5		
P (g.kg^{-1})	7.8	8.1	1.2	15.0		
Cd (mg.kg^{-1})	2.6	2.7	0.4	15.2	3	34
As (mg·kg^{-1})	3.7	0.9	5.7	153	13	170
Ni (mg·kg^{-1})	7.9	8.4	1.5	19.1	62	420
Pb (mg·kg^{-1})	48.5	20.9	64.2	132	150	1100
Cu (mg·kg^{-1})	106	102	15.2	14.3	100	1700
Zn (mg·kg^{-1})	439	457	61.5	14.0	500	4200
Mn (mg·kg^{-1})	6329	6443	1215	19.2		
Fe (mg·kg^{-1})	1872	1691	634	33.9		

*Nutrient and Management Act 2002**, BDL Below Detection Limit*

Figure 2 Site photograph of mineral horizon soil obtained using a Dutch auger, at Brookland farms.

In July 2020 and 2021 foliage samples were collected from mature sugar maple trees (minimum of two trees, 3 when possible) and sugar maple saplings (trees under 10 cm DBH) from each plot. Samples from mature trees were collected from mid canopy using extendable pole pruners. The trees selected for sampling were dominant in the plot canopy, receiving direct sunlight. Sapling samples were collected by hand from each plot. All samples were placed in zip-lock bags; sapling and mature foliage tree samples were kept separate. Each bag was labeled with the corresponding site and plot number, along with an identification code to separate sapling foliage from tree foliage. Post ash application samples of soil were also collected in late summer of 2020 and 2021, in the same manner as the baseline samples (Figure 3).

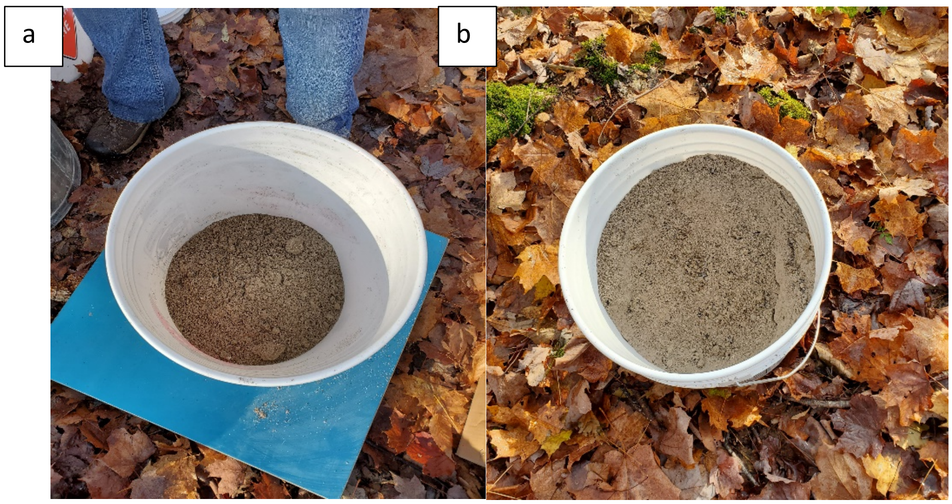


Figure 3 Site photographs of nonindustrial wood ash samples (a) being weighed in field before application to treatment plots, using a weigh scale and (b) 4-gallon plastic buckets. Wood ash collected from residents of Muskoka, Ontario in 2019.

Laboratory Analyses

Soil analyses

Soil samples collected at each plot (4 corners, 1 middle) were combined into a single sample by horizon and oven dried for 24 hours at 110°C. Once dried the L and FH layer samples were grounded individually, into a powder using a Wiley mill machine, meanwhile the mineral layer was disaggregated by hand using a mortar and pestle and sieved to 2mm. All samples were analyzed for exchangeable cations (EC), pH, loss-on-ignition (LOI), total carbon, and nitrogen content (CN), and acid extractable metal concentration (Zn, Pb, Ni, Mn, Fe, Cu, Cd, B, Al).

Soil pH was measured using an OAKTON pH 510 series multimeter. A 0.01M $CaCl_2$ slurry was used at a ratio of 1:5. The slurries were shaken for 45 mins and rested for an additional 45 mins before a pH reading was taken. To determine the organic matter content of the soil, the loss on ignition method was used (Ball, 1964). A five-gram sample of mineral soil (two grams for organic) was placed into a crucible and oven dried at 105°C for 24 hours. Samples were reweighed and ashed in Fisher Scientific Isotemp Muffle Furnace at 450°C for 8 hours. Samples were placed in a desiccator and reweighed, and the difference in soil mass was determined to calculate percent organic matter.

To determine soil CN content, soil samples were packed into foil pellets and combined with tungsten, which helps with the oxidation of the elements during analysis (1:2 leaf litter: tungsten ratio), prior to analysis using an Elementar MAX Cube. Acid extractable metal concentrations were derived using inductively coupled plasma - optical emission spectrometry (ICP-OES) after hot digestion using concentrated trace metal grade nitric acid (67 – 70%). Approximately 0.2 grams of soil and ash samples were weighed into digiTUBEs (SCP Science, Quebec, CA), and 2.5 mL of 100% nitric acid added using a precision repeater. Samples were digested on a hot plate for 8 hours at a 100°C, then further digested at room temperature for an additional 8 hours until the entire sample dissolved. After the cold digestions, samples tubes containing the digests were individually rinsed with B-pure water approximately three times and transferred into 25 mL volumetric flasks via P8 Fast Flow Filter Paper. The solution was diluted to 25 mL with B-pure water and transferred into a 50 mL Falcon tube and refrigerated until analyses. Soil standards (EnviroMat SS-1) and blanks were used at the beginning and end of every 48-sample set to test for precision. All tubes were labelled with the appropriate site, plot, and soil layer ID codes.

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 weighed into 50 mL centrifuge tubes, and 25 mL of NH4Cl were added to each tube. Samples were placed on a shaker table overnight (16 hours), removed in the morning, and left to sit for an additional hour. Samples were filtered through Fisher P8 filter paper (fast flow, removes particles >20 µm) in a Buchner funnel using vacuum filtration. An additional 25 mL of NH_4Cl was added to the centrifuge tube to ensure removal of all soil from the tube walls and was passed through the filter. The filtrate was transferred from the flask into a new 50 mL centrifuge tube. Exchangeable cation samples were diluted by dispensing 1.0 mL of each solution into a 15 mL centrifuge tube, followed by the addition of 0.2 mL of trace metal grade nitric acid, and 8.8 mL of B-pure water. Analyses were performed using a Perkin Elmer Optima 7000 DV ICP-OES.

Foliage analyses

Annual foliage collections from multiple mature trees and saplings per plot were amalgamated into one larger sample (one for mature tree and one for saplings). Each bulk sample was oven dried for 24 hrs at 100°C. Each sample was then ground using a coffee grinder into a fine powder for analyses. Foliage samples from mature trees and saplings were analyzed for carbon, nitrogen, content (CN), and metals and macro-nutrients (Zn, Pb, Ni, Mn, Fe, Cu, Cd, B, Al, Ca, Mg, K, P) as described above.

Results

Two years after ash additions to the soil, there were large, likely beneficial and dose-dependent changes in pH at Brooklands Farms and Mark Lupton's sugar bushes, with somewhat reduced changes in Wilf Creasor's bush (Table 3). At all control plots, the mineral layer remained very acidic, pH 4.1 to 4.3, but the litter and FH layers were somewhat less acidic, pH 4.6 to 5.1. However, effects of ash additions were clear in both the litter and FH layers. It appears that neutralizing ash elements have migrated down to the FH layer which shows the largest increase in pH, Specifically at 4 tonnes per ha, pH was 0.4 to 0.6 pH units higher in the litter layer, but 1.4 to 2.2 pH units higher in the FH layer.

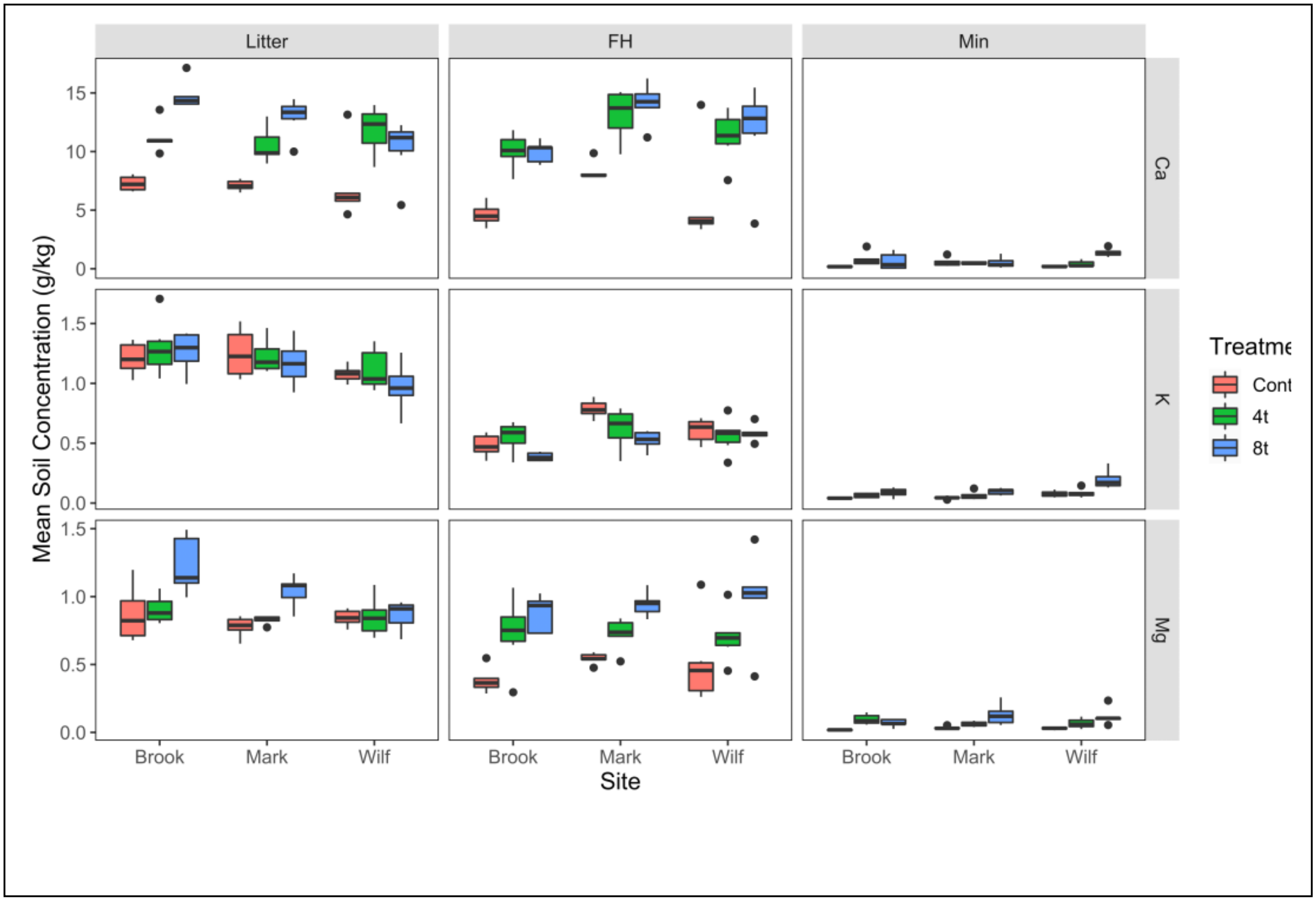
After 2 years benefits are also appearing in the mineral layers of the soil, i.e. at 4 tonne/ha dose, the pH of the mineral layer is 0.3 to 1.5 pH units higher in the mineral layer than in the control plots. The pH changes in the 8 tonne/ha treatments are quite similar to those in the 4 tonne treatments (Table 3). One year after additions, most of the acid-neutralizing effects were confined to the litter layer, but after two years it is clear that the ash is continuing to dissolve, and its acid-neutralizing benefits are manifesting deeper in the soils.

Table 3: average pH of litter, fibrous humic (FH) and mineral layers of soil 2 years after ash additions at the three sugar bushes

		Treatment		
Sugar Bush	Soil layer	control	4 tonne/ha	8 tonne/ha
Brooklands Farm	Litter	5.1	5.7	6.1
	FH	4.9	6.6	6.8
	Mineral	4.3	4.6	4.5
Mark Lupton	Litter	4.8	5.2	5.4
	FH	5.1	6.5	7.2
	Mineral	4.3	5.5	5.0
Wilf Creasor	Litter	4.7	5.4	5.3
	FH	4.6	6.8	5.2
	Mineral	4.1	5.6	4.6

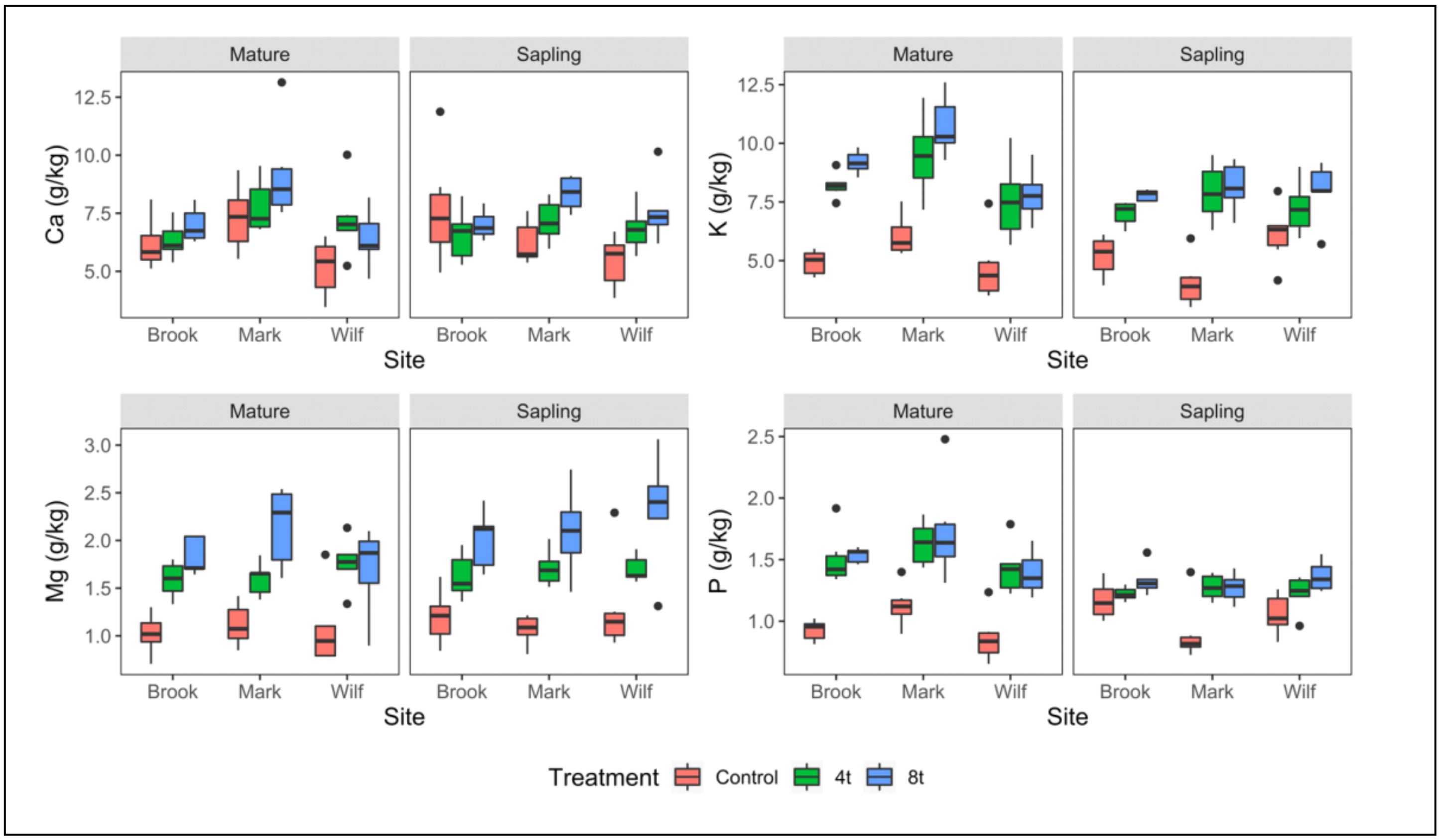
Changes in the soil chemistry were not restricted to pH after ash additions. Levels of Ca roughly doubled in the Litter layer, but by year 2 were also much higher in the FH layer in all three sugar bushes. There was even some evidence that Ca had moved into the mineral layer in the plots at Wilf Creasor's bush, although mineral Ca levels were still much lower than in the litter and FH layers, as expected (Figure 4). Levels of Mg were also appreciably higher in the litter layers at Brooklands Farm and Mark's sugar bush. But in the FH layer, Mg levels were higer in the treated than control plots in all three sugar bushes. The K story differed, again as expected. It is much more soluble in the ash than Ca and Mg. Hence, it moves through the forest ecosystem more rapidly than Ca and Mg. Hence, K levels appeared to not differ among the three treatments in any sugar bush in the litter and FH levels. However, having moved down in the soil after two years, there was a suggestion of a dose response in K levels in the mineral layer of the soil. In all three sugar bushes, K levels in the mineral soil increased with ash dose, although the levels were much lower than in the litter and FH layers (Figure 4).

Figure 4: Ca, K and Mg levels in the litter, FH, and mineral layers of the soil at three sugar bushes (Brooklands Farm, Mark Lupton, and Wilf Creasor) 2 years after ash additions.



There were quite substantial changes in nutritional status of sugar maple foliage two years after ash additions – all seemingly positive (Figure 5). These changes were also quite consistent in sapling and mature trees and in all three sugar bushes. Calcium levels increased with ash treatments in 5 of 6 cases, i.e.. in mature trees in the three sugar bushes and in sapling in Mark's and Wilf's sugar bushes. The only exception was saplings at Brookland Farm (Figure 5). The K, Mg and P results were the same for both mature trees and saplings at all three sites. Foliar K levels increased monotonically with ash does, by between 50 and 100%. Mg levels increased by roughly 50% in the 4t/ha treatments, and by 100% (roughly increasing from 1 to 2 g/kg) at the 8 t/ha dose. P levels in leaves increased by roughly 50% in mature sugar maple leaves at the 4 t/ha dose, but this dose appeared to have saturated uptake, as there was no further increase at the 8 t/ha dose in mature trees.   The P response in the saplings was similar, although not quite as dramatic as in the mature trees.

Figure 5: Ca, Mg, K and P levels in leaves of mature and sapling sugar maple in the control, 4t/ha and 8t/ha plots in the three sugar bushes (Brooklands Farm, Mark Lupton and Wilf Creasor), two years after soil amendment with ash.



Unsurprisingly, levels of several metals increased in the soil after ash additions. After all, the trees that produced the ash had accumulated metals over many decades from local soils over a time when the atmosphere was both more contaminated with many metals than it is today, and when the rain was much more acidic, potentially mobilizing these metals into acidic pore water of soils. Metals levels were not apparently elevated in the mineral layers of the soil after ash additions (Syeda and Conquer, pers. Comm)). However, several metals were elevated in the litter layers of treated plots (Table 4) in comparison with control plots. Further many metals had apparently either migrated down into the FH layer in ashed plots (Table 5), or perhaps been mixed with more surficial soil layers with higher metal levels during sample collection.

While the levels of metals clearly increased in the soil with additions of ash, they were still orders of magnitude below CM2 standards in the litter layer (Table 4) and FH layer. In addition, given the much reduced acidity of the soil after ash additions (Table 3), it is probable that the speciation of most metals has changed at the higher pH levels, and their bioavailability for plant uptake would be reduced. If this is the case, we should expect to not see higher foliar metal concentrations in treated in comparison with non-treated control plots.

Table 4: Average levels of Al, B, Cd, Cu, Fe, Mn, Ni, Pb and Zn (mg/kg) **in litter layer** of soils in three sugar bushes two years after ash additions to control, 4 tonne/ha and 8 tonne/ha treatment plot. Also listed are the CM2 standards (see Table 1), above which the material is considered a hazardous waste that much be landfilled.

	Al	B	Cd	Cu	Fe	Mn	Ni	Pb	Zn
Brooklands Farms									
Control	274	10.9	0.5	5.1	362	1513	0.8	1.6	37.1
4	632	22.5	0.9	19.2	542	2784	1.9	4.2	96.6
8	877	33.9	1	29.5	846	3192	2.9	6.5	128.3
Mark Lupton									
Control	192	10.3	0.4	3.5	299	1242	0.4	1.2	28.2
4	293	12.7	0.6	0.6	308	1678	1	5	54
8	548	28.7	0.8	19.3	485	2377	1.9	4.2	92.3
Wilf Creasor									
Control	327	13.2	0.5	9.1	376	1798	1.5	2	46.7
4	440	20.1	0.7	14.8	387	2606	1.7	2.2	87.7
8	405	18.5	0.7	15.7	413	2187	1.5	2.2	84.6
CM2 levels			34	1700			470	400	4200

Table 5: Average levels of Al, B, Cd, Cu, Fe, Mn, Ni, Pb and Zn (mg/kg) **in the FH layer** of soils in three sugar bushes two years after ash additions to control, 4 tonne/ha and 8 tonne/ha treatment plot. Also listed are the CM2 standards (see Table 1), above which the material is considered a hazardous waste that much be landfilled.

	Al	B	Cd	Cu	Fe	Mn	Ni	Pb	Zn
Brooklands Farms									
Control	2912	1.6	0.6	9.1	4216	1352	3.2	15.2	46.1
4	1762	16.7	0.8	27.6	3512	2173	4.5	20	105
8	2320	20.2	0.9	26.1	3377	2218	4.3	24.6	110
Mark Lupton									

Control	823	4.4	1	11.8	1392	2643	2.6	11.2	60
4	1988	33	1.2	34.3	2303	3494	4.6	21.8	151
8	2269	62.2	1.7	58.8	2085	4895	5.4	25.9	254
Wilf Creasor									
Control	2077	7.6	0.5	14.6	3126	1314	3	14.5	58.9
4	1617	43.6	1.1	59	2661	3128	4.6	14.8	171
8	2227	61.4	1.5	66.2	1979	3838	5.4	13.8	240
CM2 levels			34	1700			470	400	4200

While levels of metals were somewhat elevated in the litter and FH layers of the soil in the ash treatments, there was little to no evidence of increased metal levels in foliage, two years after ash addition even at the highest ash dose of 8 t/ha (Table 6). Levels of the most toxic metals (As, Cd and Pb) were essentially identical in the control and 8 t/ha treatments two years after ash additions (Table 6). There were slight but not biological significant increases in Cu and Ni at the highest ash dose (Table 6). The largest difference was for B, but it is an essential micro-nutrient, not a toxicant.

Table 6: Average levels of metals in foliage of mature sugar maple 2 years after ash additions in the control vs. the 8 t/ha treatments in the three sugar bushes.

	Brooklands Farm		Mark Lupton's sugar bush		Wilf Creasor's sugar bush	
Metal	Control	8 t/ha	Control	8 t/ha	Control	8 t/ha
Al	19.6	20.1	16.9	20.3	12.8	20.8
As	0.3	0.3	0.2	0.3	0.2	0.3
B	36.1	41.1	24.3	48.3	20.8	32.4
Cd	0.2	0.2	0.2	0.2	0.2	0.2
Cu	11.9	13.1	10.8	12.1	10.6	11.9
Fe	41.7	57.8	41.3	61.9	31.2	54.7
Mn	1052	812	725	1032	902	1124
Ni	0.6	0.8	1	1	0.4	0.6
Pb	1.1	0.9	0.9	0.9	0.7	0.8
Zn	17	22.6	20.7	25.8	16	22

Conclusion

In conclusion, two years after ash additions to the three sugar bushes several soil and foliar changes were evident. Surface soils were less acidic than they were after one year, as neutralizing components in the ash dissolved and migrated down into the soil. Levels of Ca and Mg were much higher in the litter and FH layers of the soil than they were in year 1, while the soil K response to ash additions appears to be a rapid passing signal.   Levels of several metals have increased somewhat in the litter and FH layers of the soil; however, levels are still orders of magnitude below CM2 targets.   Two years after ash additions we do appear to be seeing real benefits in foliar nutrition. Ca levels have increased somewhat in foliage of mature trees and sugar maple saplings.   Levels of K, Mg and P have increased substantially in the foliage, with P increases appearing to saturate at the 4 t/ha dose of ash.   Levels of the micronutrient B have also increased in the foliage, but levels of all the truly problematic metals, especially As, Cd and Pb have not increased with additions of ash, even at the highest dose of 8 t/ha after two years. All evidence suggests that additions of ash at either 4 or 8 t/ha doses should be beneficial for the health of sugar maple and the chemical quality of soils in Muskoka sugar bushes. Whether there are benefits of maple syrup production, tree growth or carbon sequestration is yet to be determined.

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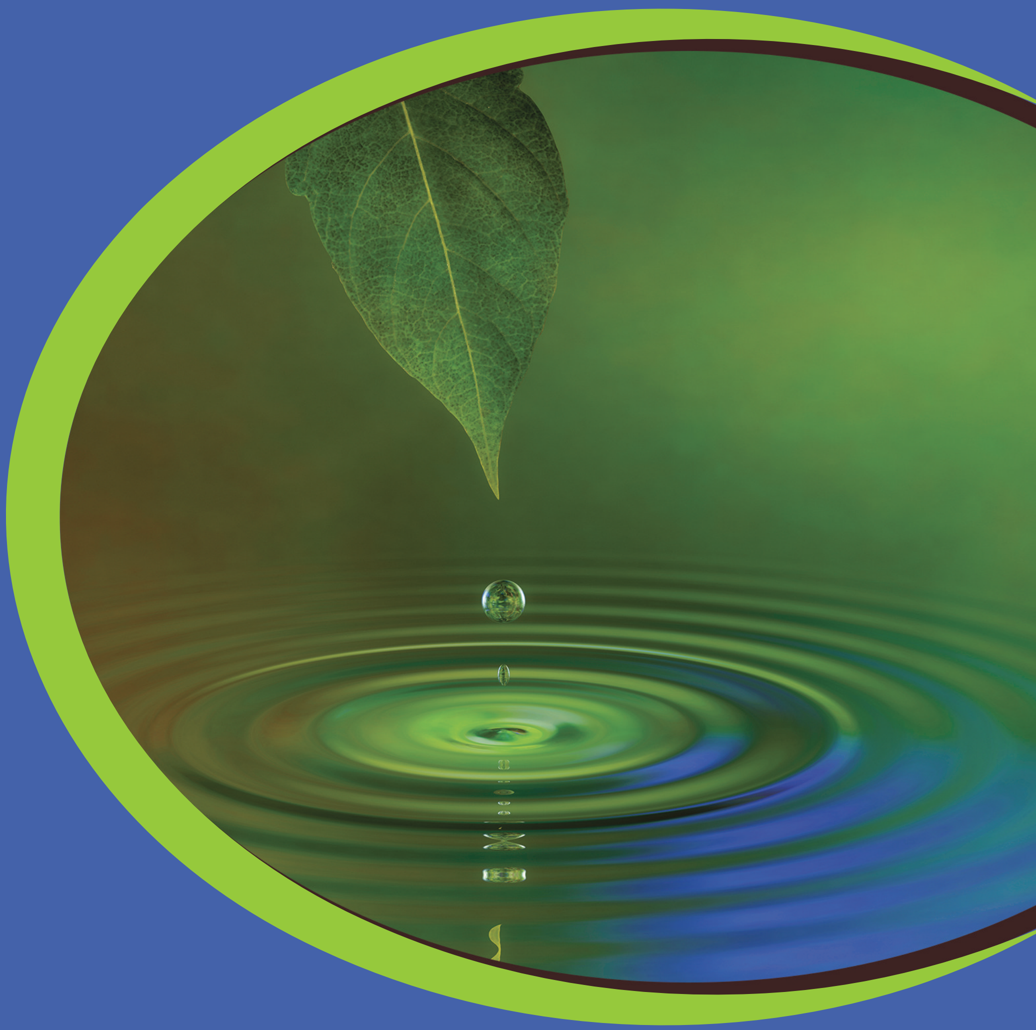

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