Forest-derived Liming By-products:

Potential Benefits to Remediate Soil Acidity and Increase Soil Fertility

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Core Ideas

● Forest-derived liming by-products are widely available and under-used in agriculture.

● At equivalent CCE rate basis, forest materials were as effective as calcitic lime in increasing soil pH.

● Lime mud quickly reacted when incorporated into the soil.

● De-inking paper sludge progressively increased soil pH upon decomposition.

● Among materials, wood ash and maple biochars were interesting sources of P, K, Ca, and Mg.

Abstract

Soil acidification is an important cause of declining crop yields in many countries, including North America. Meanwhile, alkaline by-products from forest resources are widely available but under-used in agriculture despite their expected benefits on soil pH and fertility. The aim of this study was to determine the effects, throughout a 40-wk laboratory incubation, of six different forest-derived liming materials on soil pH and Mehlich-3 extractable major nutrients in two acidic soils. Lime mud, two wood ashes (papermill biosolids and wood bark), two biochars (maple and pine), and a de-inking paper sludge (DPS) were applied at calcium carbonate equivalence based-rates, according to the amount of lime required to achieve a target pH of 6.5 on each soil. In addition, a calcitic lime (CL) was used as a reference. All forest-derived materials except pine biochar were equally effective as CL in increasing pH of

the two acidic soils after 40 wk of incubation. Lime mud quickly raised pH after soil incorporation and then pH progressively declined. By contrast, DPS upon decomposition gradually increased soil pH over time. In terms of liming value based on dry mass of each material, lime mud was needed at the lowest amount (0.8 CL unit) to increase pH to the target value. Wood ash particularly from wood combustion was a significant direct source of P, K, and Mg, while maple biochar supplied large amounts of available K and Mg. This study demonstrated that forest-derived alkaline by-products can efficiently remediate soil acidity and improve the soil fertility.

Abbreviations: CCE, calcium carbonate equivalence; CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; LR, lime requirement; M700, maple bark biochar produced at 700°C; P700, pine chip biochar produced at 700°C; WA, wood ash.

1 | INTRODUCTION

Soil acidification is a major concern responsible for degradation of agricultural land in many countries, including North America. It affects about 30% of total ice-free surface land area in the world (Sumner & Noble, 2003) and 50% of arable soils (von Uexküll & Mutert, 1995). Soils of moderate to high acidity (pH < 5.5) are particularly problematic due to the solubility and toxicity of Al^{+3}, which may impair crop growth (Sumner & Noble, 2003). In agriculture, field application of ammonium-based fertilizers and urea, legume growth, and organic matter decomposition are primary contributors to soil acidification (Goulding, 2016; Obour, Mikha, Holman, & Stahlman, 2017).

Forest resources provide several by-products that can benefit land application in acidic soils. North America (USA and Canada) and the European Union produce annually 112×10^6 Mg of pulp (Monte, Fuente, Blanco, & Negro, 2009; Pervaiz & Sain, 2015; Smith, Rice, & Ince, 2003). As part of the pulping process, solid wastes such as wood ash (WA), lime mud (LM), and biosolids from treatment of wastewater are generated. In addition, large production of WA and also biochar comes from timber mill and logging operations and plans of bioenergy production using forest biomass of little economic value (Matovic, 2011; Hannam et al., 2018). Annual production of ash from forest industry is estimated at $3–5 \times 10^6$ Mg in USA (Vance, 1996) and $> 750 \times 10^3$ Mg in Canada, including 420×10^3 Mg in pulp and paper mills (Elliott & Mahmood, 2015; Hannam et al., 2018; Sharifi, Cheema, McVicar, LeBlanc, & Fillmore, 2013). About 1×10^6 Mg dry LM are produced annually in USA (Bird & Talberth, 2008).

A number of studies have investigated the potential of forest-derived alkaline by-products to lime acidic soils. Clearly, these materials increase soil pH, but the effect is dependent on the calcium carbonate equivalence (CCE) and the composition of the product. The LM issued from the kraft paper process has a high CCE (91-109%; Morris, Nutter, Miller, & Overcash, 2000) with a fast reaction once applied to soil (Muse & Mitchell, 1995; Simson, Kelling, & Liegel, 1981). Conversely, WA varies considerably from source to source but that originating from pure wood combustion is the most interesting in terms of CCE and major nutrients content (Demeyer, Voundi Nkana, & Verloo, 2001).

Biochar is the C-rich solid material obtained by thermal conversion (pyrolysis) of biomass under an oxygen-limited environment (Lehmann & Joseph, 2015). Biochar with its

alkaline nature and high pH buffering capacity, particularly when produced at high temperatures ~ 700°C (Zornoza, Moreno-Barriga, Acosta, Muñoz, & Faz, 2016), may remediate acidity of soil pH < 5.5 (Dai et al., 2017).

De-inking paper sludge (DPS) from recycling newsprints is a long-lasting neutralizing organic material previously used to revegetate abandoned sandpit and mine soil (Fierro, Angers, & Beauchamp, 1999). Its beneficial effect is likely due to the $CaCO_3$ present in the paper process (Camberato, Gagnon, Angers, Chantigny, & Pan, 2006). Khiari et al. (2013) found, in an incubation study, that DPS with a CCE of 37.5–45 progressively increased soil pH, needing 20 wk to completely react with the soil.

Besides partly substituting for agricultural lime to correct soil acidity, forest-derived alkaline by-products can also improve soil fertility, either directly by adding essential nutrients or indirectly through increasing soil pH (Gao & DeLuca, 2016; Xu, Wei, Sun, Shao, & Chang, 2013). For instances, WA contains appreciable amounts of P and K that can replace inorganic fertilizers (Arshad, Soon, Azooz, Lupwayi, & Chang, 2012; Cabral, Ribeiro, Hilário, Machado, & Vasconcelos, 2008; Demeyer et al., 2001; Sharifi et al., 2013). Biochars are also an excellent source of readily-available K, but P is less plant-available and more tightly bound and insoluble with charring process (Adhikari et al., 2019; Zornoza et al., 2016).

Research comparing the different forest-derived liming materials including DPS is scarce. When applied at equivalent CCE rate, Arshad et al. (2012) found a similar response for WA and calcitic lime (CL), whereas Muse and Mitchell (1995) obtained a higher soil pH with WA and LM than with dolomitic limestone, both in lab incubation and under field

conditions. For a unique study, Noyce et al. (2017) observed that softwood WA consistently had a more pronounced pH effect than maple (*Acer saccharum* Marsh) biochar when applied to acidic forest soils. Despite all potential benefits, less than 50% (in some cases < 10%) of forest-derived alkaline by-products are land applied, with the largest amounts usually being landfilled (Bird & Talberth, 2008; Hannam et al., 2018).

The aim of this study was to evaluate the effects of different liming by-products from forest resources on soil pH and Mehlich-3 extractable major nutrients of two acidic soils of contrasting properties under controlled laboratory conditions. We hypothesized that when applied at an equivalent CCE rate, all materials have comparable effect on soil pH and a different one on soil nutrient availability.

2 | MATERIAL AND METHODS

2.1 | Liming material description

Six different forest-derived liming by-products were evaluated. The LM was obtained from Smurfit-Stone, La Tuque, QC, Canada. One WA (WA1) consisted of combustion of remaining wood and bark in a sawmill from *Picea*, *Abies*, and *Populus* spp. (Abitibi-Bowater, La Tuque, QC), whereas the other (WA2) consisted of burned papermill biosolids with some bark (Kruger, Trois-Rivières, QC). Two biochars were investigated. One was produced from maple bark at 700°C in a Max Caddy 113-L modified furnace (M700; Award Caoutchouc & Plastique Ltée, Plessisville, QC). The other was produced from pine chips (*Pinus strobus* L.) at 700°C in a BEC Beta Base Unit (P700; Biochar Engineering, Golden, CO). Biosolids from

de-inking recycled papers (DPS) were obtained from Papiers Scott, Crabtree, QC. A natural CL was retained for comparison (Graymont Portneuf, Saint-Marc-des-Carrières, QC). All materials were used in previous studies (Gagnon & Ziadi, 2012; Gagnon, Ziadi, Chantigny, Bélanger, & Massé, 2012; Lévesque, Rochette, Ziadi, Dorais, & Antoun, 2018) and kept frozen at -18°C or dried (biochars).

2.2 | Liming material characterization

A composite sample of each material was analyzed in triplicate. The pH of the LM, both WA, DPS, and CL was measured using a glass electrode after 30 min of agitation and 30 min of standing of 5.0 g fresh material in 20 mL of distilled water. The pH of both biochars was obtained using 1.0 g of material in 20 mL of distilled water with 1.5 h of agitation followed by filtration through a 410 filter paper (Lévesque et al., 2018). The CCE (%) was determined by back-titrating excess acid after reacting 1 g of material in boiling HCl (AOAC, 2005), relative to pure $CaCO_3$. Moisture content was determined after drying the materials at 55°C to constant weight.

Major total nutrients (P, K, and Mg) were determined by wet acid digestion (Isaac & Johnson, 1976), whereas Ca in the material was extracted by dry ashing in a furnace (4 h, 500°C) with recovery of ash in 2 mol L^{-1} HCl (Pelletier et al., 2007). The concentrations of P were measured using an automated continuous-flow injection analyzer (Lachat Instruments, model QuickChem 8000 FIA+, Loveland, CO) with the vanadomolybdate reaction (method 15-301-3) whereas those of K, Ca, and Mg were determined using an inductively coupled plasma optical emission spectrometer (ICP-OES, Perkin Elmer Optima 4300DV, Shelton, CT).

The particle-size distribution was determined in triplicate on 50-g dry samples using a Ro-Tap® Sieve Shaker, model RX-29 (WS Tyler, Mentor, OH) with seven progressive sieves (2.00 mm, 1.00 mm, 0.500 mm, 0.250 mm, 0.150 mm, 0.106 mm, and 0.053 mm; Altland & Locke, 2012). The content retained by each sieve and the pan was weighed and reported as a percentage of total sample weight.

2.3 | Soil description

Two acidic soils were collected from the Ap horizon of fields located in eastern Canada: a Kamouraska clay (fine, mixed, frigid typic Humaquept) near Québec, QC (46°47′N, 71°08′W) and a Charlottetown fine sandy loam (coarse-loamy, mixed, frigid typic Haplorthod) in Charlottetown, PEI (46°41′N, 63°23′W). The soils were sieved field moist to 6 mm, air-dried and sieved again to 2 mm.

The Kamouraska clay had a high organic matter content but was low in available P, which contrasted with the Charlottetown sandy loam (Table 1). It had also a higher cation exchange capacity, which meant that more lime had to be applied to correct the soil acidity. Based on the SMP buffer pH of each soil (Shoemaker, McLean, & Pratt, 1961), 9.0 Mg ha^{-1} and 5.5 Mg ha^{-1} of lime (100% neutralizing capability value, dry basis) were required on the Kamouraska and Charlottetown soils, respectively, to increase the soil pH to the target value of 6.5 (Centre d'expertise en analyse environnementale du Québec, 2003).

2.4 | Incubation study

A randomized complete block design was laid out in triplicate with ten treatments within each soil. Before application, each material except DPS was sieved to 2 mm. Materials were

subdivided into three groups according to their CCE values (Table 2): i) with a CCE around 90% (CL and LM), ii) with a CCE of 40-50% (WA1 and DPS), and iii) with a CCE < 25% (WA2, M700, and P700). Their application rate on each soil was shown in Table 2. For agronomic and economic reasons (quantity and financial costs of production and application), we decided to not exceed these application rates (Dai et al., 2017). Additional treatments consisted of CL applied at rates of 50%, 100% and 200% lime requirement (LR), and an unamended control soil.

Fresh materials, corrected for their moisture, were individually mixed with 100 g of air-dried soil at the prescribed rates, considering a mean soil bulk density of 1.2 g cm^{-3} and an incorporation depth of 20 cm (CRAAQ, 2010), and incubated in 500-mL Mason™ glass jars. The soil-liming material mixture was moistened to 60% water-filled pore space with distilled water, corresponding to a gravimetric soil moisture content of 0.341 g g^{-1} for the Kamouraska soil and 0.240 g g^{-1} for the Charlottetown soil. The amount of water to be added to each soil was determined using the apparent bulk density in a naturally settled condition and the porosity that allows optimum microbial process (Franzluebbers, 1999). The jars were loosely closed and incubated in the dark in a controlled environment chamber at 25°C for 40 wk, which should permit a more complete reaction of the liming materials with the soil. These incubation conditions, notably temperature, allow a greater magnitude in the mineralization (Sierra, Fontaine, & Desfontaines, 2001). Moisture content was adjusted twice a week by weighing and adding distilled water as needed. At the same time, the soil was well aerated before reclosing to maintain constant aerobic and mineralization conditions.

2.5 | Soil sampling and analysis

After 1, 2, 4, 6, 8, 10, 12, 16, 20, 24, 28, 32, 36, and 40 wk of incubation, the jars were opened and thoroughly mixed before sampling. A subsample of moist soil mixture was collected (6.7 g for Kamouraska and 6.3 g for Charlottetown) and air-dried. Thus, 5.0 g were weighed into 50-mL centrifuge tubes, shaken for 30 min with 10 mL of distilled water on a reciprocal shaker, and left to stand for 30 min (Hendershot, Lalande, & Duquette, 2008). The pH was measured using a glass electrode. Soil pH at the end of incubation was also determined in a 1:2 soil to 0.01 mol L^{-1} $CaCl_2$ solution to detect if accumulation of salts derived from the soil or dissolution of liming materials would affect the soil pH of each treatment differently (Bloom, Skyllberg, & Sumner, 2005).

Soil samples were also collected at the end of incubation, air-dried and sieved to pass a 2-mm screen. Phosphorus, K, Ca, Mg, and Al contents were extracted using the Mehlich-3 solution (Mehlich, 1984). The P was determined by colorimetry (DU720, Beckman Coulter, Mississauga, ON) using the ascorbic acid-molybdate reaction (Murphy & Riley, 1962), whereas the other elements were determined by the ICP-OES.

2.6 | Statistical analysis

All data were normally distributed and no transformation was needed. Because the experiment design separated soils for incubation, treatment effects were analyzed by soil using the MIXED procedure of SAS (SAS Institute, 2010). Treatments (liming by-products) were considered as fixed effect, incubation time as repeated effect (pH only), and replicates and replicates × treatments as random effects. Main treatment effects and their interactions

were tested using differences of least squares means. Statistical significance was defined as $P \leq .05$. Because of the very low variability between replicates for pH, a difference of least squares means of 0.2 unit was used instead of 0.02-0.11 as a basis to separate treatments as previously used by Jones and Mallarino (2018).

3 | RESULTS AND DISCUSSION

3.1 | Liming material characteristics

The liming materials varied widely in their properties (Table 2). The CL and LM had the highest CCE (~ 93%) and total Ca content (> 260 g kg^{-1}). At the opposite, WA from papermill biosolids (WA2) and both biochars showed a low neutralizing capability (12-22%). The CCE of materials were typical of those found in literature (Demeyer et al., 2001; Khiari et al., 2013; Muse & Mitchell, 1995; Sharifi et al., 2013). Among the materials, ashes from wood combustion (WA1) had the highest content in total P, K, and Mg.

3.2 | Soil pH

Liming materials were added at CCE-based rates predicted to raise pH to a target value of 6.5 (Table 2). Consequently, all materials except P700 increased pH of the two acidic soils, in many cases to a level comparable to CL applied at 100% LR (Tables 3-4). To increase each unit of pH, based on the 40-wk incubation time, 10.8 and 5.8 Mg CL ha^{-1} were required in the Kamouraska clay and Charlottetown sandy loam, respectively (Figures 1a and b). In terms of liming value based on dry mass, each Mg of CL was equivalent to 0.8, 2.1, 2.2, 4.4, and 8.7 Mg of LM, WA1, DPS, M700, and WA2, respectively, on both soils. These effective CCE

corresponded well to the CCE measured with the AOAC method, except for LM which induced a higher pH response than expected. Simson et al. (1981) reported a neutralizing effectiveness for LM between 1.5 and 2 times than that of dolomitic limestone. A previous study reported that effective CCE can provide a good estimate of neutralizing ability when particle size was accurate; however, crumbly organic materials like paper mill sludge or DPS failed to estimate the effective CCE (Yang, Mitchell, & Howe, 2018).

For the first 4 to 6 wk of incubation, LM increased soil pH to the level achieved with CL 200% LR on both soils (Figures 2-3). Thereafter, the pH of LM-amended soils progressively decreased to approach that of CL 100% LR. This high reactivity of LM was observed in other studies (He, Lange, & Dougherty, 2009; Muse & Mitchell, 1995; Simson et al., 1981) and was due primarily to the fineness of the material and also to the presence of some oxides and hydroxides (Kinnarinen, Golmaei, Jernström, & Häkkinen, 2016; Simpson, King, Carlile, & Blickensderfer, 1983; Simson et al., 1981). Using natural agricultural limestone, Jones and Mallarino (2018) found that a finer particle size reacts more quickly in contact with the soil and reaches a higher maximum pH value. This seems also the case with the forest-derived by-products here and elsewhere (Cabral et al., 2008; Muse & Mitchell, 1995) where 86% of particles in LM were < 0.106 mm compared with 43% for CL (Table 2).

In this study, WA1 contributed more to increasing soil pH than WA2 (Figures 2-3). Higher neutralizing capability of WA derived from wood relative of WA from papermill biosolids has been reported by Demeyer et al. (2001). This can be explained by the CCE value and the content in Ca and Mg carbonates (Table 2), which act on the liming effect (Pitman, 2006). Nonetheless, when applied at a rate predicted to provide an equal effective

CCE, WA were equivalent to CL in remediating the soil acidity (Arshad et al., 2012). The reactivity of WA in the present study appeared slower than in other studies (Cabral et al., 2008; Muse & Mitchell, 1995), maybe because of coarser particles here (38% < 0.106 mm [Table 2]) vs. 53-90%).

The pH in DPS-amended soils was similar than that in soils with CL 50% LR at the beginning of incubation (Figures 2-3). Upon material decomposition, the soil pH increased gradually with time and reached that of CL 100% LR in the last weeks of incubation. In a laboratory incubation, Khiari et al. (2013) observed that DPS were almost equivalent to pure $CaCO_3$ (81-100%) in increasing soil pH, but they need 20 wk to fully express their liming potential. One detrimental aspect, however, of using DPS in crops is the temporary soil N immobilization that it causes due to their C/N ratio (Camberato et al., 2006; Joseph, Khiari, Gallichand, & Bouslama, 2017). A previous study with this DPS (C/N ratio = 47) showed that this material caused a soil N immobilization soon after its application that lasted 3 wk in the Kamouraska clay but at least 6 wk in the sandy loam soils (Gagnon and Ziadi, 2020).

The maple biochar (M700) increased the soil pH but pine biochar (P700) failed (Figures 2-3). The ability of biochar to effectively remediate soil acidity has been determined by the ash content associated with the presence of $CaCO_3$, $KHCO_3$, and calcite (Domingues et al., 2017). Biochars of hardwood such as maple and oak (*Quercus*) generally have a higher ash content than those of coniferous trees (Mukome, Zhang, Silva, Six, & Parikh, 2013), and this was the case in this study (M700 = 20.1% ash whereas P700 = 4.8% ash; Lévesque et al., 2018). Domingues et al. (2017) concluded that biochars derived from pine bark made at 750°C have a great stability against degradation and a high C residence time when

incorporated into the soil, which in counterbalance reduce their role in correcting soil acidity and supplying major nutrients.

Changes in the soil-soluble salt concentration following dissolution of liming materials may affect pH differently depending on material source. In fact, soluble salts (e.g., Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) may displace H^{+} and Al^{3+} ions from soil surfaces into the solution lowering soil pH (Bloom et al., 2005). To counteract the effect of varying concentrations of salts, an ionic medium such as 0.01 mol L^{-1} $CaCl^{2}$ can be used. Both soil methods provided the same treatment effects but with values proportionally higher by 0.3 units for pH water (Figure 4). Therefore, treatments such as lime source, particle size, or incubation time did not increase salt concentration to a degree that it changed the relationships (Jones & Mallarino, 2018).

3.3 | Soil fertility

Liming material addition significantly increased the soil Mehlich-3 P in the Kamouraska clay but had a more limited effect in the Charlottetown sandy loam (Tables 3 and 4) which was richer in available P (Table 1). Soil P availability, a complex process, is affected directly by the material P addition but also indirectly through alteration of soil pH and P mineralization and by reduction in P fixation (Gao & DeLuca, 2016; Xu et al., 2013). In this study, both WA contributed the most at increasing Mehlich-3 P over the control with 7-12 mg kg^{-1} in Kamouraska clay and 5-10 mg kg^{-1} in Charlottetown sandy loam. This corresponds to a total P recovery in extractable soluble forms of 23% for WA1 and 12% for WA2. Several studies reported increases in soil P availability following WA addition (Arshad et al., 2012; Cabral et al., 2008; Noyce et al., 2017; Sharifi et al., 2013). For its part, M700 also contributed to

increase Mehlich-3 P but to a lesser extent mainly due to a reduced availability of P following pyrolysis process (Adhikari et al., 2019; Xu, Zhang, Shao, & Sun. 2016; Zornoza et al., 2016).

Maple biochar (M700) and WA1 caused the largest increases in Mehlich-3 K and Mg on both soils with respectively 82 and 48 mg kg^{-1} more Mehlich-3 K and 23 and 29 mg kg^{-1} more Mehlich-3 Mg (Tables 3 and 4). Such increases mainly originated from the materials with a recovery as extractable soluble forms averaging 74% for total K and 58% for total Mg for M700 and 32-35% for total K and Mg in the case of WA1. Several studies reported a high availability of total K in WA and biochars which even reached 80-90% (Cabral et al., 2008; Sharifi et al., 2013; Zornoza et al., 2016). Tree species (hardwood vs. softwood) and type of plant tissue burnt influence the composition of WA (Pitman, 2006).

All materials except P700 increased soil Mehlich-3 Ca on both soils (Tables 3 and 4). In terms of recovery, 97% of total Ca in LM was found in extractable soluble forms whereas that of CL represented on average 82%. For the other materials, between 47% to 75% of total Ca added were solubilized. Lalande et al. (2009) reported that LM produced one of the largest increases in available Ca when it was applied to two contrasting textural soils. As expected, there was a negative relationship between soil concentrations in available Ca and available Al as extracted by the Mehlich-3 solution (Figure 5), and this relationship was sharper in the Charlottetown sandy loam than in Kamouraska clay.

4 | CONCLUSION

The purpose of this study was to determine the effects of six different widely available forest-derived alkaline by-products on soil pH and Mehlich-3 extractable major nutrients of two acidic soils throughout a 40-wk laboratory incubation. All materials were applied at CCE-based rates predicted to raise pH to a target of 6.5 on each soil. Based on this assumption, all forest materials except P700 were equally effective as CL in increasing pH of the two acidic soils. Among materials, LM quickly raised pH once incorporated into the soil followed by a progressive pH decline. By contrast, DPS upon decomposition induced a gradual increase in pH over time. In terms of liming value based on dry mass, each unit of CL was equivalent to 0.8, 2.1, 2.2, 4.4, and 8.7 units of LM, WA1, DPS, M700, and WA2, respectively. On the other hand, WA and particularly that issued from wood combustion were significant direct sources of P, K, and Mg. Moreover, M700 supplied large amounts of available K and Mg. Finally, the P700 can be viewed more as a means to increase C storage and reduce greenhouse gas emissions.

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FIGURE CAPTIONS

FIGURE 1 Soil pH response to rate of CL application (dry mass basis) in the (A) Kamouraska clay and (B) Charlottetown sandy loam at the end of the 40-wk incubation study

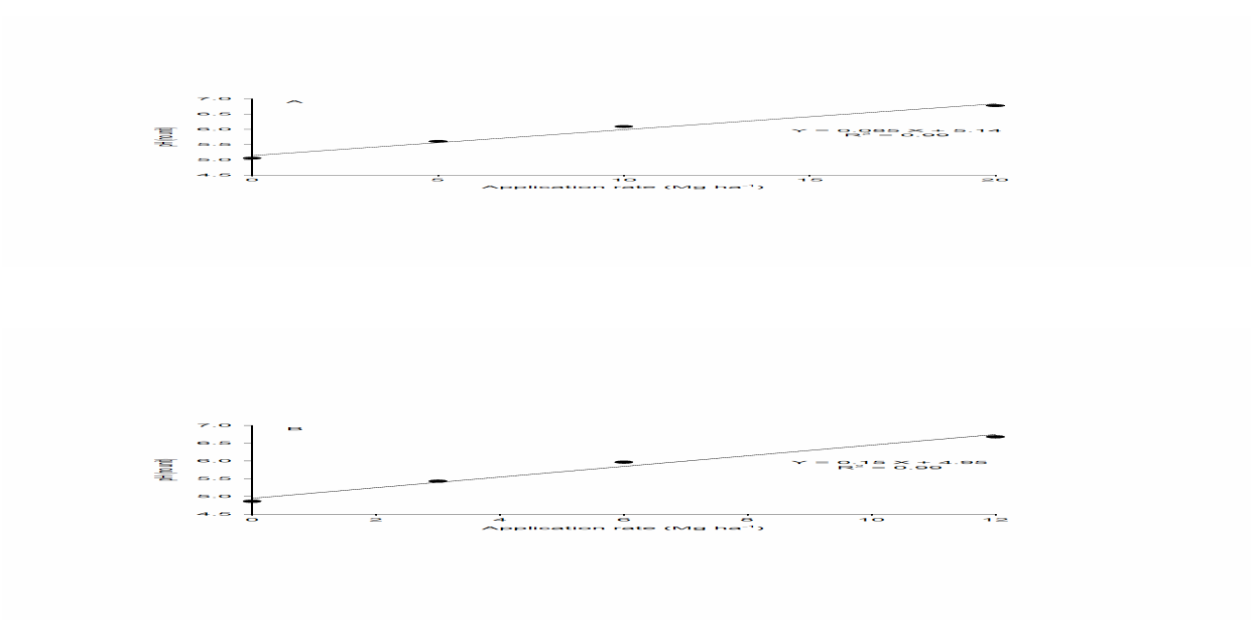

FIGURE 2 Soil pH changes over the 40-wk incubation in the Kamouraska clay amended with different liming materials. CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; M700, maple bark biochar produced at 700°C; P700, pine chip biochar produced at 700°C; WA1, wood ash from combustion of wood and bark; WA2, wood ash from paper mill biosolids; LR, application according to lime requirement. Vertical bars represent least significant difference values at $P = .05$ for each sampling date

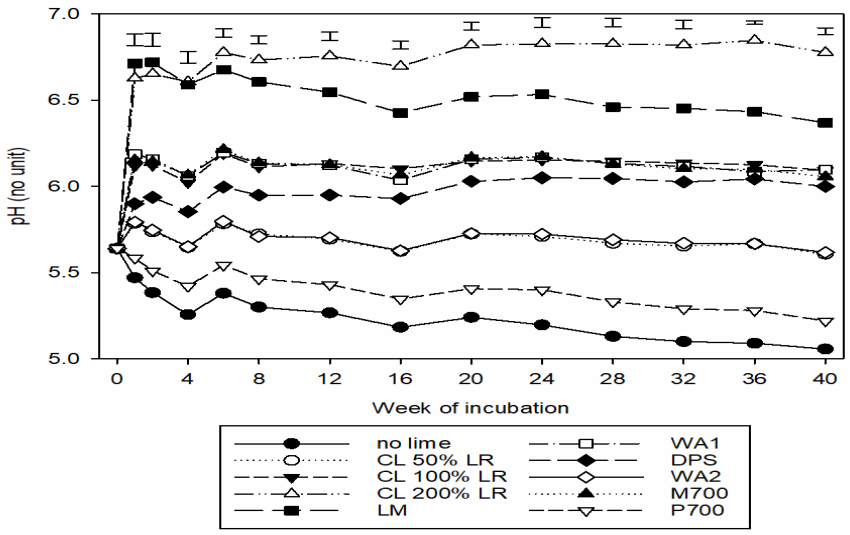

FIGURE 3 Soil pH changes over the 40-wk incubation in the Charlottetown sandy loam amended with different liming materials. CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; M700, maple bark biochar produced at 700°C; P700, pine chips biochar produced at 700°C; WA1, wood ash from combustion of wood and bark; WA2, wood ash from paper mill biosolids; LR, application according to lime requirement. Vertical bars represent least significant difference values at $P = .05$ for each sampling date

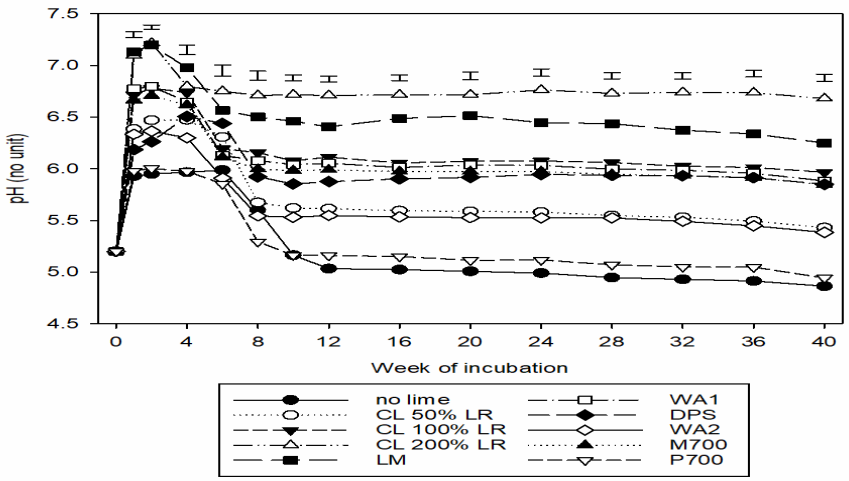

FIGURE 4 Relationship between soil pH measured in water and soil pH in 0.01 mol L^{-1} $CaCl_2$ at the end of incubation (n=60)

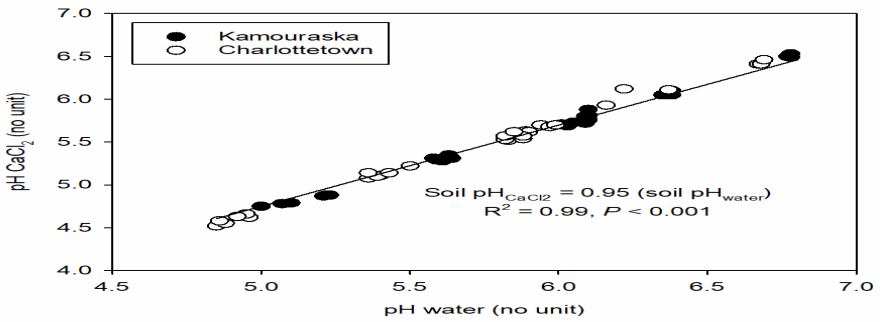

FIGURE 5 Relationship between the concentrations in soil Mehlich-3 Ca and soil Mehlich-3 Al at the end of the 40-wk incubation study in the two soils amended with the different liming materials

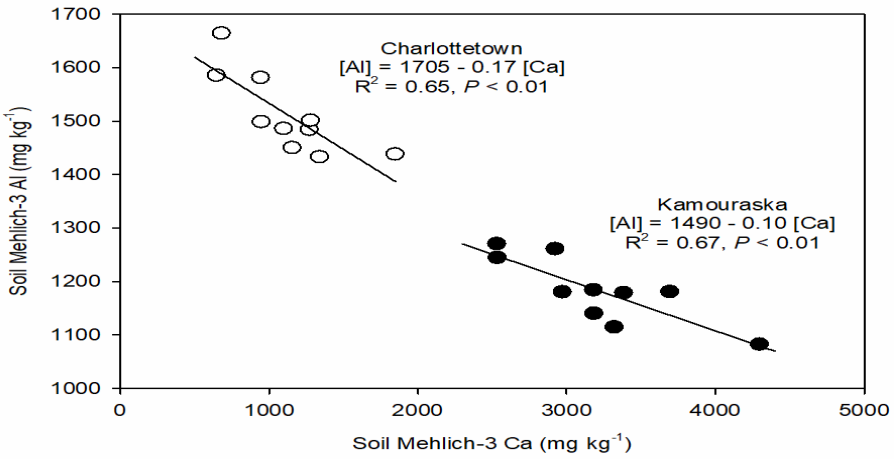

TABLE 1 Characteristics of soils used for the incubation study. †Cation exchange capacity determined by ammonium acetate (Chapman, 1965). ‡Buffer pH method (Shoemaker et al., 1961). §Lime requirement for 100% neutralizing value lime source. ¶Dry combustion (LECO TruSpec CN, Leco Inc., St. Joseph, MI). #Determined by colorimetry from Mehlich-3 extraction (Mehlich, 1984)

Attributes	Units	Kamouraska	Charlottetown
Textural class		Clay	Fine sandy loam
Sand	$g\ g^{-1}$	0.302	0.583
Clay	$g\ g^{-1}$	0.406	0.118
CEC†	$cmol\ (+)\ kg^{-1}$	42	17
Ca^{2+}	$cmol\ kg^{-1}$	10.4	4.3
Mg^{2+}	$cmol\ kg^{-1}$	0.9	0.2
K^{+}	$cmol\ kg^{-1}$	0.85	0.67
Na^{+}	$cmol\ kg^{-1}$	0.08	0.08
Base saturation	%	57	56
pH (1:2 soil to water ratio)		5.64	5.20
pH SMP‡		5.99	6.33
Lime requirement for pH = 6.5§	$Mg\ ha^{-1}$	9.0	5.5
Organic matter¶	%	5.4	3.0
Available P#	$mg\ kg^{-1}$	38	91

TABLE 2 Selected physicochemical properties of liming materials. †CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; M700, maple bark biochar produced at 700°C; P700, pine chip biochar produced at 700°C; WA1, wood ash from combustion of wood and bark; WA2, wood ash from paper mill biosolids. ‡CCE, calcium carbonate equivalence. nd, not determined

Attributes	Units	------- Group 1 ------		-------- Group 2 -----		---------- Group 3 --------		
		CL†	LM	WA1	DPS	WA2	M700	P700
pHwater		9.3	12.0	12.7	7.2	8.2	11.1	7.4
CCE‡	$\%CaCO_3$	92	94	49	40	12	22	18
Moisture	$g\ kg^{-1}$	26	279	36	553	198	34	131
Total P	$g\ kg^{-1}$	0.6	0.7	7.3	2.0	3.7	1.1	0.4
Total K	$g\ kg^{-1}$	1.6	1.5	24.1	0.5	6.5	9.0	2.5
Total Ca	$g\ kg^{-1}$	261	281	128	149	53	67	6.4
Total Mg	$g\ kg^{-1}$	4.2	2.8	12.6	2.0	2.2	2.8	1.4
Particle-size fractions (%)								
1.0-2.0 mm		3	3	12	nd	27	20	29
0.500 mm		12	3	16	nd	18	19	24
0.250 mm		20	3	17	nd	16	20	15
0.150 mm		13	2	11	nd	13	12	9
0.106 mm		9	2	6	nd	6	5	4
0.053 mm		15	6	12	nd	8	9	9
<0.053 mm		28	80	26	nd	12	15	10

Application rate (Mg ha^{-1}, dry basis)								
Kamouraska clay		10	10	20	20	40	40	40
Charlottetown sandy loam		6	6	12	12	24	24	24

TABLE 3 Effect of liming materials on soil pH and Mehlich-3 extractable nutrients after 40-wk incubation of an amended Kamouraska clay. †CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; M700, maple bark biochar produced at 700°C; P700, pine chip biochar produced at 700°C; WA1, wood ash from combustion of wood and bark; WA2, wood ash from paper mill biosolids; LR, application according to lime requirement

Treatment	pH_{water}	P	K	Ca	Mg	Al
		---------- mg kg^{-1}----------				
Control (no lime)	5.1±0.1	38±3	111±1	2520±16	336±4	1256±31
CL† 50% LR	5.6±0.0	38±1	110±2	2970±74	337±15	1181±90
CL 100% LR	6.1±0.0	39±2	108±5	3319±141	325±13	1115±57
CL 200% LR	6.8±0.0	41±3	108±5	4295±220	317±17	1083±17
LM	6.4±0.0	39±1	109±2	3693±87	338±13	1181±39
WA1	6.1±0.0	49±1	157±7	3183±259	372±29	1141±77
DPS	6.0±0.0	40±1	111±1	3383±123	339±7	1179±13
WA2	5.6±0.0	44±1	123±2	2922±45	357±5	1261±38
M700	6.1±0.0	41±1	189±2	3180±66	369±6	1185±42
P700	5.2±0.0	39±1	134±1	2533±26	343±4	1245±1

$LSD_{.05}$	0.04	3	6	211	23	87
Treatment ($P < F$)	<.001	<.001	<.001	<.001	.001	.005

TABLE 4 Effects of liming materials on soil pH and Mehlich-3 extractable nutrients after 40-wk incubation of an amended Charlottetown sandy loam. †CL, calcitic lime; DPS, de-inking paper sludge; LM, lime mud; M700, maple bark biochar produced at 700°C; P700, pine chip biochar produced at 700°C; WA1, wood ash from combustion of wood and bark; WA2, wood ash from paper mill biosolids; LR, application according to lime requirement

Treatment	pH_{water}	P	K	Ca	Mg	Al
		---------- mg kg^{-1} ----------				
Control (no lime)	4.9±0.0	118±1	76±5	678±37	61±4	1665±61
CL† 50% LR	5.4±0.1	117±2	68±1	946±34	56±2	1499±38
CL 100% LR	6.0±0.0	116±1	65±2	1268±83	56±3	1485±70
CL 200% LR	6.7±0.0	117±2	64±1	1846±95	49±3	1439±94
LM	6.3±0.1	116±3	66±2	1337±45	55±3	1434±59
WA1	5.9±0.0	128±2	126±1	1154±22	85±3	1451±24
DPS	5.9±0.0	118±3	65±2	1276±122	57±1	1502±60
WA2	5.4±0.0	123±0	77±3	941±59	69±3	1582±71
M700	5.8±0.0	120±2	163±13	1096±55	75±6	1487±75
P700	4.9±0.0	119±1	87±5	644±65	59±6	1586±136
$LSD_{.05}$	0.07	3	8	97	6	106
Treatment ($P < F$)	<.001	<.001	<.001	<.001	<.001	.004