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ARTICLE

Soil Mehlich-3-extractable elements as affected by the addition of biochars to a clay soil co-amended with or without a compost[1]

Vicky Lévesque, Bernard Gagnon, and Noura Ziadi

Abstract: Biochar has the potential to sequester carbon and mitigate greenhouse gas emissions, and it may also contribute nutrients for plant growth in temperate climates. Nutrient availability in biochar-amended soil was assessed in a 338 d incubation study. The clay soil prepared with 4% *w*/*w* (dry basis) compost or without compost, then amended with wood-based biochar made at different pyrolysis temperatures [maple bark (*Acer saccharum*) at 400 (M400), 550 (M550), and 700 °C (M700)] on a dry-rate basis of 5% (*w*/*w*). After moistening the soil mixture to 44% volumetric soil water content (equivalent to 70% water-filled pore space), soil mixtures were incubated in the dark at 22 °C. Soil was sampled at days 9, 16, 23, 44, 86, 23 170, and 338 of the incubation. Biochar amendment increased the Mehlich-3 phosphorus, potassium (K), magnesium, and copper concentrations, and reduced the Mehlich-3 aluminum and iron concentrations at each sampling date, and M400 had the most significant effect on Mehlich-3-extractable nutrient concentrations. Compost addition also increased the amounts of extractable nutrients. These results suggested that M400 and carbon-rich compost promoted microbial growth and mineralization in amended soil. In addition, soil mixed with compost and amended with biochar had more Mehlich-3-extractable K than when compost or biochar was applied alone, probably due to greater growth and activity of soil K-solubilizing microorganisms. Overall, our study indicated that co-application of wood-based biochar and compost could improve soil fertility in temperate regions by increasing the availability of most plant macronutrients and micronutrients.

Key words: phosphorus extractability, potassium extractability, soil incubation, synergetic effect, wood biochar.

Résumé : Le biocharbon pourrait séquestrer le carbone et atténuer les émissions de gaz à effet de serre; il pourrait aussi procurer des oligoéléments aux plantes dans les régions à climat tempéré. Les auteurs ont évalué la concentration d'oligoéléments dans un sol amendé avec du biocharbon lors d'une étude d'incubation de 338 jours. Un sol argileux mélangé ou pas à du compost (4 % en poids sec) a été bonifié avec 5 % (poids sec) de biocharbon de bois obtenu par pyrolyse d'écorce d'érable à sucre (*Acer saccharum*) à différentes températures, soit 400 °C (M400), 550 °C (M550) ou 700 °C (M700). Après humidification jusqu'à une fraction volumique d'eau de 44 % (correspondant au remplissage de 70 % des pores), le sol a été incubé dans l'obscurité à 22 °C. Les auteurs ont prélevé des échantillons après 9, 16, 23, 44, 86, 23, 170 et 338 jours d'incubation. Le biocharbon avait accru la concentration de phosphore, de potassium (K), de magnésium et de cuivre déterminée par la technique Mehlich-3 et diminué celle d'aluminum et de fer à chaque date d'échantillonnage. Le traitement M400 est celui qui influe le plus sur la concentration des oligoéléments extractibles par la méthode Mehlich-3. Le compost concentre lui aussi les oligoéléments extractibles. Ces résultats laissent croire que le régime M400 et l'addition d'un compost riche en carbone favorisent la prolifération des unicellulaires et la minéralisation dans le sol amendé. De plus, le sol mélangé à du compost puis bonifié avec du biocharbon renferme plus de K extractible par la technique Mehlich-3 que celui amendé uniquement avec du compost ou du biocharbon, sans doute en raison de la multiplication et de l'activité plus importantes des microorganismes qui solubilisent le K

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du sol. Dans l'ensemble, l'étude révèle qu'en appliquant du biocharbon de bois et du compost, on améliorerait la fertilité du sol dans les régions à climat tempéré par une hausse quantitative de la majorité des macro-éléments et des oligoéléments dont les plantes ont besoin pour croître. [Traduit par la Rédaction]

Mots-clés : extractabilité du phosphore, extractabilité du potassium, incubation du sol, synergie, biocharbon de bois.

Introduction

Biochar, a carbon (C)-rich material obtained by thermal combustion of biomass at temperatures ≤700 °C under low-oxygen environments (Lehmann and Joseph 2015), has been the subject of numerous studies worldwide over the last few decades. Biochar is viewed as being able to increase soil C storage (Lehmann et al. 2006; Zimmerman 2010), reduce greenhouse gas emissions (Cayuela et al. 2014; Hangs et al. 2016; Ashiq et al. 2020), and improve soil health and microbial activities (Gul et al. 2015; Tan et al. 2017). Soil fertility is often reported to increase in response to biochar application in weathered or acidic degraded soils, predominantly in the tropics (Jeffery et al. 2011; Spokas et al. 2012; Biederman and Harpole 2013). However, the potential for nutrient release other than nitrogen (N) is uncertain and misunderstood in soils of inherent high fertility as in temperate climates (Atkinson et al. 2010; Jones et al. 2012).

The quality of biochar for soil nutrient availability is conditioned primarily by the feedstock type, which is then modified by the pyrolysis parameters (Enders et al. 2012; Domingues et al. 2017; Zhang et al. 2017). For instance, biochars produced from wood residues are more acidic and with less ash and nutrients but have high concentrations of stable C. These biochars are consequently more resistant to degradation once mixed with soil compared with those derived from animal manure (Singh et al. 2010; Enders et al. 2012; Domingues et al. 2017). In addition, high pyrolysis temperature increases total and fixed C, ash, and pH, but decreases N content and hydrogen (H)/C ratio. It is possible that the structure of biochars produced at high temperature is more likely to resist biological and thermochemical degradation (Ronsse et al. 2013; Ahmed et al. 2016; Domingues et al. 2017; Pariyar et al. 2020). In contrast to C and N, the concentration of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), copper (Cu), and zinc (Zn) increases with pyrolysis temperature, but this depends on the pyrolysis process and the mineral element itself (Pariyar et al. 2020).

The production methods, the pyrolysis conditions, and the biomass type, however, produce biochars with variable properties which have different effects on soil parameters (Kookana et al. 2011). Moreover, wood biochar plant availability of nutrients other than N has been the object of various results. For example, using hardwood biochar (primarily a mixture of oak and hickory), Laird et al. (2010) reported increases in Mehlich-3 P, K, and Ca, whereas Zhang et al. (2017) reported that hardwood biochar derived from oak contributed more to crop nutrition than softwood biochar derived from pine. Moreover, the availability of soil nutrients can be affected with increasing pyrolysis temperature due to phosphate and carbonate precipitation with the Ca, Mg, and Fe complex in soil (Xu et al. 2016; Zornoza et al. 2016; Adhikari et al. 2019). Therefore, the information on physicochemical properties of biochars is crucial not only in governing their biogeochemical interactions in the soil environment but also in determining their agronomic and environmental impact (Kookana et al. 2011).

In contrast, biochar nutrient availability may be positively affected by organic material addition because of the porous nature of biochar and its ability to adsorb and hold soluble organic matter and inorganic nutrients (Mukherjee et al. 2011). Co-applying biochar and compost was reported to further increase total organic C and plant-available K, whereas the effect was not additive for P and Ca (Liu et al. 2012). This co-application might thus serve as a slow-release nutrient amendment and stabilized organic matter (Agegnehu et al. 2017).

To our knowledge, information is missing about the effects of biochars on the nutrient availability for plant growth other than N in fertilized soils of temperate climate. The objective of our study was to evaluate the effects of three biochars having different physicochemical properties co-amended with or without a compost on the extractability of macro- and micro-nutrients of a fertilized clay soil under a controlled environment. According to the physicochemical properties of biochar, our hypotheses were that (*i*) the extractability of macro- and micro-nutrients in fertilized clay soil depends on the chemical properties of biochar and that (*ii*) compost addition increases the extractability of macro- and micro-nutrients due to its rich nutrient input.

Materials and Methods

This incubation study was part of a larger experiment conducted to assess the effect of biochar on soil greenhouse gas emissions, C and N dynamic, and microbiological properties (Lévesque et al. 2020). The production methods and physicochemical characteristics of biochars and compost (Table 1) were previously reported by Lévesque et al. (2018).

Soil characterization

A Kamouraska clay soil (Orthic Humic Gleysol) was collected from the surface (0–15 cm) layer after spring wheat harvest from a field located at the Harlaka

Table 1. Main physicochemical characteristics of biochars and a compost used in the incubation study.

	Biochar[b]			
Parameter[a]	M400	M550	M700	Compost[c]
pH (H_2O)	10.1	11.3	11.1	6.8
CEC ($cmol_c \cdot kg^{-1}$)	53.5	62.6	60.5	ND
Ash ($g \cdot kg^{-1}$)	158	236	201	ND
Volatile matter ($g \cdot kg^{-1}$)	366	294	337	ND
Fixed C ($g \cdot kg^{-1}$)	476	470	462	ND
Total C ($g \cdot kg^{-1}$)	592	546	540	356
H/C molar ratio	0.50	0.45	0.54	ND
O/C molar ratio	0.19	0.18	0.20	ND
Total P ($g \cdot kg^{-1}$)	1.0	1.4	1.1	4.4
Total K ($g \cdot kg^{-1}$)	7.9	11.1	9.0	8.3
Total Ca ($g \cdot kg^{-1}$)	62	84	67	ND
Total Mg ($g \cdot kg^{-1}$)	2.3	3.3	2.8	ND
Total Fe ($g \cdot kg^{-1}$)	1.1	3.0	2.1	ND
Total Al ($g \cdot kg^{-1}$)	0.9	2.5	2.1	ND
Total Cu ($mg \cdot kg^{-1}$)	10	13	10	ND
Total Zn ($mg \cdot kg^{-1}$)	344	86	86	ND

Note: CEC, cation-exchange capacity; ND, not determined; C, carbon; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Fe, iron; Al, aluminum; Cu, copper; Zn, zinc.

[a]Most physicochemical characteristics of biochars presented in Lévesque et al. (2018).

[b]M400, M550, and M700: maple bark biochar pyrolyzed at 400, 550, and 700 °C, respectively.

[c]Compost of peat and shrimps.

Research Farm of Agriculture and Agri-Food Canada at Lévis near Québec City, QC, Canada (46°47′N, 71°08′W). The fresh soil was sieved at 6 mm, air-dried, and then sieved at ≤2 mm. The main soil properties were 32 g $C_{tot} \cdot kg^{-1}$, 47 mg Mehlich-3 $P \cdot kg^{-1}$, 106 mg Mehlich-3 $K \cdot kg^{-1}$, 410 g $clay \cdot kg^{-1}$, and 295 g $sand \cdot kg^{-1}$ dry soil, and a pH water of 5.5.

Biochar and compost characterization

Three biochars derived from sugar maple barks (*Acer saccharum*) were produced by Award Caoutchouc & Plastique Ltée (Plessisville, QC, Canada) at 400 °C (M400) in a BEK biochar experimenter's kit with continuous-flow production (All Power Labs; ~10 $°C \cdot min^{-1}$ heating rate, ~1 h residence time), and at 550 (M550) and 700 °C (M700) in a Max Caddy 113 L furnace (St-Augustin-des-Desmaures, QC, Canada) modified for the batch production of biochar (Lévesque et al. 2018). A commercial compost (C/N of 20) of peat and shrimp (Fafard, Saint-Bonaventure, QC, Canada) was used in half of the treatments as a source of C to stimulate soil microbial activity owing to the long incubation period without plants (Lévesque et al. 2020) and as a source of nutrients.

Incubation study

The 338 d incubation study was carried out in a controlled environment chamber located at Québec Research and Development Centre (Québec, QC, Canada) of Agriculture and Agri-Food Canada. The experiment consisted of a randomized complete block design with eight treatments (control, M400, M550, and M700; with or without compost) and four replicates for each sampling date (days 9, 16, 23, 44, 86, 170, and 338) allowing destructive sampling. The treatments were prepared with air-dried soil, biochars, and compost at varying rates (*w*/*w*): (*i*) 100% soil (control); (*ii*) 95% soil + 5% biochar; (*iii*) 96% soil + 4% compost (control with compost); (*iv*) 91% soil + 4% compost + 5% biochar, whose biochar and compost corresponded to a field application equivalent to 60 and 45 $Mg \cdot ha^{-1}$ in the 10 cm surface layer, respectively. Thus, a total of 224 microcosms were used. Because biochars derived from maple barks had a high calcium carbonate equivalence, lime was only added to the control with and without compost [2.5 g $Ca(OH)_2$ $kg \cdot sol^{-1}$] to adjust pH to 6.6 (Lévesque et al. 2020).

The microcosm consisted of a polyvinyl chloride cylinder with a volume of 104.1 cm^3 (4.7 cm diameter, 6.0 cm height) placed in a 500 mL Mason™ glass jar. Dry soil mixtures were thoroughly mixed and then packed to a bulk density of 1.00 $g \cdot cm^{-3}$. The soil mixtures in each cylinder were previously wetted by capillary rise with distilled water and finally adjusted to 70% water-filled pore space (Lévesque et al. 2020), equivalent to 44%

volumetric soil water content. A mineral particle density of 2.65 $g \cdot cm^{-3}$ was used to calculate the water-filled pore space (Linn and Doran 1984). The jars were covered with an aluminum lid holed in the middle (0.5 cm diameter) to allow gas exchange and minimize water loss. The jars were then placed in a dark chamber at a constant temperature of 22 °C with 80% relative humidity for 338 d after a pre-incubation period of 14 d to allow stabilization of microbial activity due to rewetting. Soil moisture content was adjusted every week by weighing, and distilled water was added as needed.

On days 0, 84, 168, and 252, 3 mL of a mineral fertilizer solution (1204 mg $N \cdot L^{-1}$, 351 mg $P \cdot L^{-1}$, and 885 mg $K \cdot L^{-1}$) was evenly injected in each experimental unit using a multi-syringe with 10 injection points (10 injections of 0.3 mL each) to simulate periodic mineral fertilizer applications in a field (Lévesque et al. 2020).

Soil sampling and analysis

At each sampling date, a set of jars was removed from the experiment, and the soil was thoroughly mixed before analyses. Soil pH (H_2O) was determined by adding 20 mL of deionized water to 10 g of fresh soil (Hendershot et al. 2008). A subsample of soil was air-dried, and then 2.5 g was extracted with 25 mL of a Mehlich-3 solution (Mehlich 1984). The concentrations of P, K, Ca, Mg, Al, Fe, Cu, and Zn were determined (Tran et al. 1990) using an inductively coupled plasma optical emission spectrometer (ICP-OES, Perkin Elmer Optima 4300DV, Shelton, CT, USA).

Statistical analysis

Statistical analyses were performed using the MIXED procedure of SAS version 9.3, 2012 (SAS Institute Inc., Cary, NC, USA). A three-way analysis of variance was used to test the effects of time, biochar type, and compost addition and their interactions on soil pH and soil Mehlich-3 P, K, Ca, Mg, Al, Fe, Cu, and Zn concentrations. The normality of data was examined using the Shapiro–Wilk's test, and a log-transformation was required to improve the normality of distribution of K and Cu. Significant differences between means were established using Tukey's test at $p \leq 0.05$. Pearson's product-moment correlation was performed to assess the linear relationship between two normally distributed interval variables.

Results and Discussion

Biochar properties

Contrary to what we expected (Ahmed et al. 2016; Domingues et al. 2017; Zhang et al. 2017; Bavariani et al. 2019; Pariyar et al. 2020), the pH, cation-exchange capacity (CEC), ash, P, and cation content did not increase, and the O/C and H/C ratios did not decrease with increasing pyrolysis temperature. In fact, compared with M400 and M700, M550 showed the highest pH, CEC, ash, P, and cation content, except Zn (Table 1). The O/C and H/C ratios were slightly lower in M550 than with both M700 and M400. The observed nonlinearity for nutrient concentrations with pyrolysis temperature in our study might be due to the different conditions used during the biochar production. Indeed, M400 was produced in a continuous-flow system, whereas M550 and M700 were made by batch production and in an artisanal way, explaining the non-linearity for nutrient concentrations with pyrolysis temperature. In addition, the high Zn concentration in M400 is probably due to an industrial contamination during its production (Table 1), introducing thereby an artifact in analysis, so the results need to be interpreted with caution. These results are in agreement with Ashworth et al. (2014), who reported that the biochar conversion method influenced the physicochemical properties of biochar. Indeed, these authors concluded that, at the same pyrolysis temperature (400 °C), biochar produced from the batch system showed lower macro (P and K) and micro (Ca, Mg, Cu, and Zn) nutrients and higher lignin content than that produced from the continuous flow system.

Biochar effect on soil pH

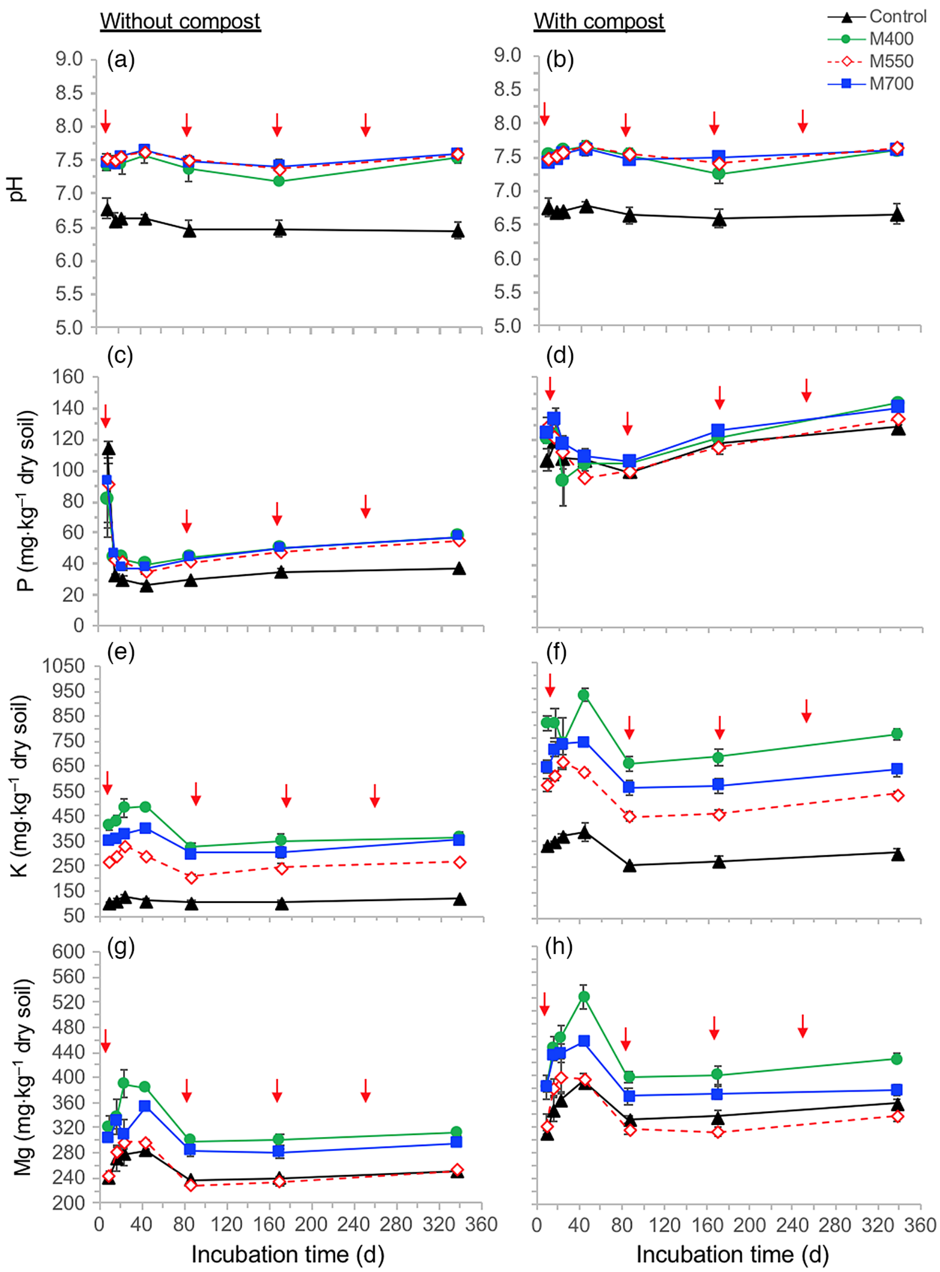
Even if the soil pH in all treatments was 6.6 prior to the pre-incubation, all biochars increased soil pH by 1.0 unit as observed at the beginning of the incubation, following by a steady state (Fig. 1*a*). Several studies reported that high pH and ash content in biochars can have a high liming effect, contributing to increase soil pH and availability of plant nutrients (Mukome et al. 2013; Zhang et al. 2017). In general, increased soil pH through biochar application tends to decrease the concentration of H^+ cations, resulting in increased positive charges that can be exchanged per mass of soil (Gul et al. 2015).

Soil P extractability

A variety of chemical and biochemical processes are involved in the soil P cycle such as adsorption/desorption, precipitation/dissolution, and mineralization/immobilization. Biochar amendment interferes with these processes and, thereby, interferes with soil P availability (Li et al. 2019). Biochar can act as a direct P source or indirectly alter soil P solubility through pH changes (Xu et al. 2013; Gao and DeLuca 2016). The maximum solubility of P in soil is generally achieved at pH around 6.0–7.0. At low soil pH, P tends to bind with Al or Fe compounds, whereas at high soil pH, P tends to precipitate with Ca, making P less available for the plant nutrition.

According to our results, Mehlich-3 P concentration in soil was affected by biochar (Table 2). At the beginning of incubation (day 9), Mehlich-3 P concentration was lower in all biochar treatments than in the control (Fig. 1*c*). A sharp decrease of P content was observed in all treatments at day 16, followed by a slight and constant increase until the end of incubation. The sharp decrease in all treatments, including the control, early in

Fig. 1. Effect of biochars and compost on pH and Mehlich-3-extractable phosphorus (P), potassium (K), and magnesium (Mg) in a clayey soil fertilized at days 0, 84, 168, and 252 during an incubation period of 338 d. Bars show standard errors (±SE) of means ($n = 4$). Control, treatment without biochar; biochar treatments received 5% (*w*/*w*) of maple bark pyrolyzed at 400 (M400), 550 (M550), or 700 °C (M700); compost treatments received 4% (*w*/*w*) of peat and shrimp compost. Arrows represent the days when mineral fertilization was applied. [Colour online.]



incubation was probably caused by a chemical adsorption of P on surfaces of clay-mineral (Ghoshal 1975) or by a temporary P immobilization by soil microorganisms (Richardson and Simpson 2011), and biochar could also have fixed P on its surface (Li et al. 2019), limiting its extraction. This low P availability was short-lived, especially in soils amended with biochars (Fig. 1*c*). From day 23 until the end of incubation, Mehlich-3 P concentration was higher in biochar treatments than in the control. Laird et al. (2010) observed a significant increase in Mehlich-3 P with increasing rates of hardwood biochar (5, 10, and 20 g biochar·kg^{-1}) without fertilization. The Mehlich-3 P concentration also increased in two contrasted soils amended with switchgrass biochar (10% *w*/*w*) during a growth chamber experiment (Kelly et al. 2015). Another study showed that the P availability was enhancing due to the reduction of phosphate adsorbed on ferrihydrite in soil by adding rice straw-derived biochar (Cui et al. 2011). Authors of this study reported that the surface of the Fe-(hydr) oxides bear

Table 2. Analysis of variance for the effect of addition of biochars and compost to a clayey soil on pH and soil Mehlich-3-extractable elements.

Effect ($Pr > F$)	pH	P	K	Ca	Mg	Al	Fe	Cu	Zn
Compost	***	***	***	***	***	***	0.28	***	***
Biochar	***	***	***	***	***	***	***	***	***
Biochar × compost	**	0.64	***	0.79	0.80	0.47	0.72	0.59	0.21
Time	***	***	***	***	***	***	***	***	***
Time × compost	0.37	***	0.12	0.71	0.09	0.80	0.86	0.21	0.08
Time × biochar	***	0.91	0.12	0.09	*	*	0.19	0.21	0.72
Time × biochar × compost	0.73	0.34	**	0.99	0.69	0.95	0.80	0.99	0.75

Note: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$. Numbers indicate non-significant value of F at the 0.05 level. C, carbon; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Fe, iron; Al, aluminium; Cu, copper; Zn, zinc.

more negative charges as the pH increases, causing a greater electrostatic repulsion toward the more negatively charged P forms (HPO_4^{2-} and PO_4^{3-}) that predominate at the higher pH. Therefore, their results showed that surface charge or function groups on the surface of ferrihydrite can be altered by combining with biochar. However, this alteration can occur as long as the activity of Ca and Mg is low enough to prevent the Ca/Mg–P precipitation (Li et al. 2019).

The addition of 10 mg fertilizer P·kg^{-1} soil at days 84, 168, and 252 seems to converge towards a slight but constant increase in P concentration from day 84, especially in biochar treatments (Fig. 1*c*). An increase of 54% P extractability (~20 mg·kg^{-1}) was obtained in the soil amended with biochars, whereas this increase was 42% (11 mg·kg^{-1}) in the control. The higher Mehlich-3 extractable P content in the biochar treatments than in the control at each fertilization event confirms that biochars limited P adsorption on clay-mineral surfaces or its immobilization.

Because compost contains plant-available nutrients (Table 1), there was more extractable P in the soil amended with compost and biochar than the soil receiving biochar alone. Indeed, soil enrichment with compost, containing 4.4 g total P·kg^{-1} (Table 1), increased the Mehlich-3 P concentration in all soil treatments during the incubation (Figs. 1*c*, 1*d*). In contrast to the treatments without compost (Fig. 1*c*), the low decreases observed for Mehlich-3 P at the beginning of incubation (Fig. 1*d*) and the low compost effect on soil pH (Fig. 1*b*) also indicated that compost probably limited P adsorption on clay-mineral surfaces or its immobilization (Fig. 1*d*). The higher positive response on Mehlich-3 P concentration in the soil after each periodic mineral fertilizer application in the treatments enriched with compost confirms that P was not strongly bound on surfaces of clay-mineral, allowing a better P extractability. In addition, the higher abundance of *Pseudomonas* spp. in treatments with than without compost (Supplementary Table S1[2]) suggests that these bacteria might also have favored P solubilization and mineralization (Estrada-Bonilla et al. 2021).

Soil K extractability

Traditionally, soil K is subdivided into four pools: water-soluble K, exchangeable K, non-exchangeable K, and mineral K (Öborn et al. 2005). The exchangeable and water-soluble K are often considered to be readily available to plants (Öborn et al. 2005; Li et al. 2018). In our study, the exchangeable K pool determined by Mehlich-3 extraction was affected by biochar and compost amendment and the extent varied with time (Table 2). The addition of 26 mg fertilizer K·kg^{-1} dry soil from periodic applications had a negligible effect compared with the K input from biochars (Fig. 1*e*).

A high extraction of K occurred between days 16 and 44 (Fig. 1*e*). This increase in soil extractable K was probably caused by the release of K from the dissolution of ash contained in biochar itself (Demeyer et al. 2001; Glaser et al. 2002; Laird et al. 2010). In contrast to P which remains relatively insoluble, K from ash dissolves very quickly (Demeyer et al. 2001), partly explaining its high extractability in the soil amended with biochars at the beginning of our study. The K release from the biochars could then have been quickly fixed on sites in the interlayer space of clay-mineral limiting its accessibility (Öborn et al. 2005). After day 86, the soils amended with biochars maintained a higher Mehlich-3 K concentration than the control. At the end of incubation, soil Mehlich-3 K was from 148 (M550) to 247 mg·kg^{-1} (M400) higher in biochar-amended soils than in the control, representing an increase of 123%–206% (Table 3). A similar trend was observed in a different 224 d incubation (Manirakiza et al. 2020). Authors reported that the Mehlich-3 K concentration increased with the increase of pine biochar application rate in two acidic soils amended with paper mill biosolids, and this effect was primarily due to increasing K input from the biochar itself. Noyce et al. (2017) also obtained a high ammonium

[2]Supplementary data are available with the article at https://doi.org/10.1139/cjss-2020-0087.

Table 3. Effect of biochar and compost on pH and Mehlich-3-extractable elements (mg·kg^{-1} dry soil) in a fertilized clayey soil at the end of the 338 d incubation.

Treatment	pH	P	Ca	Mg	Al	Fe	Cu	Zn	K[a]	
									Without compost	With compost
Biochar effect										
Control	6.6 ± 0.1b	83 ± 7c	3418 ± 123c	304 ± 20c	1073 ± 18a	170 ± 3a	4.7 ± 0.1c	10.7 ± 0.8c	120 ± 4c	306 ± 13d
M400	7.6 ± 0.1a	100 ± 4a	4362 ± 144b	369 ± 22a	942 ± 18b	159 ± 2b	5.5 ± 0.1a	15.6 ± 0.9a	367 ± 22a	768 ± 22a
M550	7.6 ± 0.1a	94 ± 3b	4781 ±107a	295 ± 17c	919 ± 20b	157 ± 2b	5.0 ± 0.1b	10.6 ± 0.7c	268 ± 8b	534 ± 12c
M700	7.6 ±0.1a	99 ± 6ab	4308 ± 78b	337 ± 16b	940 ± 22b	155 ± 2b	5.2 ± 0.1b	13.6 ± 0.8b	355 ± 4a	628 ± 23b
Compost effect										
Without compost	7.3 ± 0.1B	52 ± 2B	3951 ± 132B	277 ± 7B	1013 ± 16A	158 ± 2B	5.3 ± 0.1A	10.7 ± 0.5B	—	—
With compost	7.4 ± 0.1A	136 ± 2A	4465 ± 131A	375 ± 9A	927 ± 18B	163 ± 3A	4.9 ± 0.1B	14.6 ± 0.6A	—	—

Note: In each column, means ± standard errors followed by different lowercase or uppercase letters are significantly different according to Tukey's test ($p < 0.05$). Control, treatment without biochar, and biochar treatments received 5% (*w*/*w*) of maple bark pyrolyzed at 400 (M400), 550 (M550), or 700 °C (M700). Compost treatments received 4% (*w*/*w*) of peat and shrimps compost. C, carbon; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Fe, iron; Al, aluminium; Cu, copper; Zn, zinc.
[a]Significant biochar × compost interaction (Table 2), thereby statistical analysis shows the simple effect of biochar with and without compost.

acetate extractable K concentration in three acidic soils amended with a maple sawdust biochar.

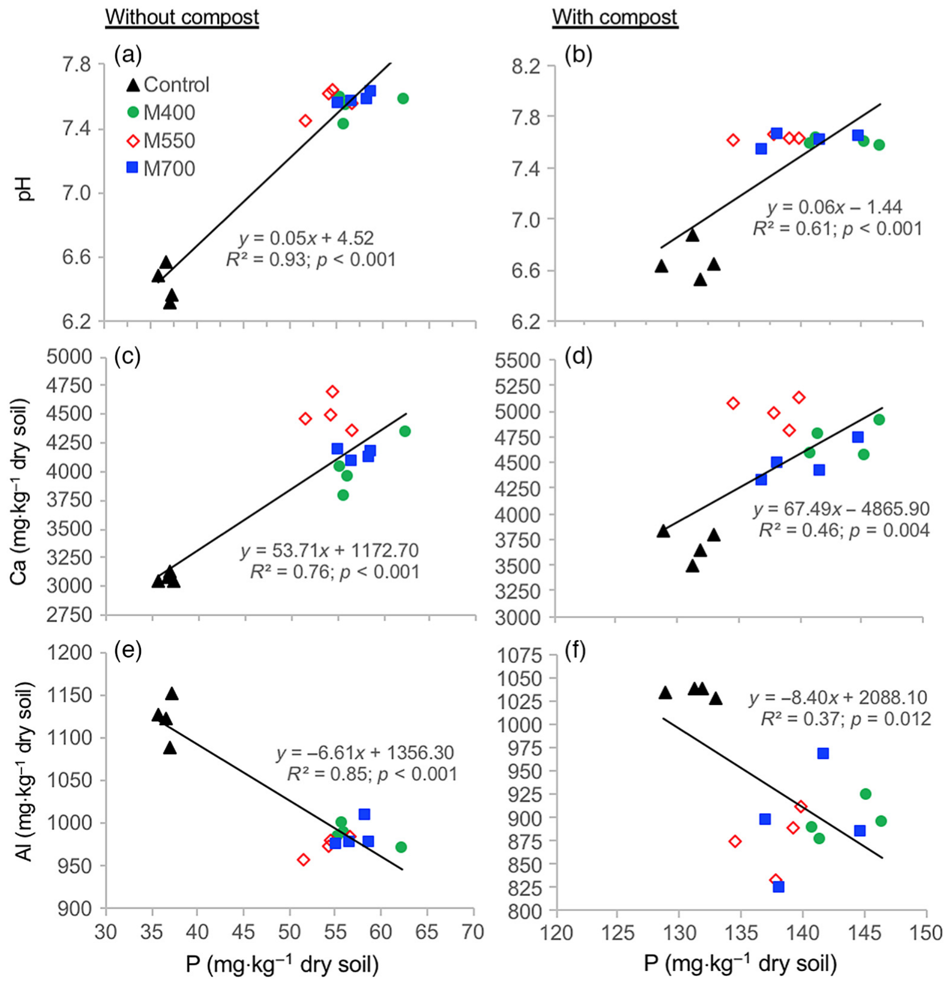
Many K-dissolving bacteria (KDR) such as *Acidothiobacillus ferrooxidans*, *Paenibacillus* spp., bacteria belonging to the genus *Bacillus* spp. (e.g., *B. mucilaginosus*, *B. edaphicus*, and *B. circulans*), *Enterobacter* spp., and *Pseudomonas* spp., are able to solubilize soil K-bearing minerals by excreting organic and inorganic acids, acidolysis, polysaccharides, complexolysis, chelation, and exchange reactions (Etesami et al. 2017; Dong et al. 2019). Recent results showed that the application of bamboo biochar made at 450 °C enhanced the growth of KDR in two different soils, which induced changes in the soil pH and water-soluble K (Wang et al. 2018). Three bacterial genera (*Bacillus* spp., *Paenibacillus* spp., and *Pseudomonas* spp.) were found in the clay soil mixtures (Supplementary Table S1[2]), and the relative abundance of *Pseudomonas* spp. was higher in M700 followed by M400, M550 than in the control enriched with compost at day 44 of incubation. In addition, a higher C availability in the soils amended with biochar than in the control was found at day 44 of incubation favoring a better microbial activity as observed in the soils amended with M400 followed by M700 (Supplementary Table S2[2]).

Compost addition increased K extractability, mainly in the soils amended with biochars at all sampling dates, and the highest concentrations were found with M400 (Fig. 1*f*). Compared with treatments without compost, high concentrations of extractable K were also measured between days 16 and 86 in all treatments, including the control (Figs. 1*e*, 1*f*). This spike of K in all treatments was likely caused by the high K input from compost (Table 1). After day 86 and until the end of incubation, all treatments with compost maintained higher K content than those without compost (Figs. 1*e*, 1*f*). It was reported that the addition of compost, a rich C source, can stimulate microbial growth and activity such as KDR and then protect K fertilizer from being fixed in soil (Imran et al. 2020). Based on our previous results, enrichment of soil with compost enhanced microbial activity (Supplementary Table S2[2]), and the relative abundance of *Pseudomonas* spp. was significantly higher in treatments with than without compost (Supplementary Table S1[2]). The higher increases in Mehlich-3 K concentration with the co-application of biochar and compost than the sum of their effect taken separately indicate a synergetic positive effect (Liu et al. 2012). The co-application of biochar with compost could have provided a better ecological niche for the growth and activity of KDR, explaining this synergetic positive effect.

Soil calcium, magnesium, and micronutrients extractability

In our study, Ca, Mg, and micronutrients extracted by the Mehlich-3 solution were influenced by biochar amendment (Table 2). In contrast to K and Ca, Mg is comparatively mobile in soils because the ionic radius

Fig. 2. Relationships between Mehlich-3-extractable phosphorus (P) content and soil pH and content of Mehlich-3-extractable calcium (Ca) and aluminum (Al) in a clayey soil amended with biochars with or without compost at the end of incubation. Control, treatment without biochar; biochar treatments received 5% (*w*/*w*) of maple bark pyrolyzed at 400 (M400), 550 (M550), or 700 °C (M700). [Colour online.]



of Mg is smaller than that of Ca and K, which limits Mg to be bound strongly to soil charges (Gransee and Führ 2013). Based on our results, a high release of Mg in all treatments occurred between days 16 and 44 (Fig. 1g). Clay minerals are an important source of Mg reserve (Metson 1974; Gransee and Führ 2013), and like biochar, both of them could have contributed to the high extraction of Mg by Mehlich-3 at the beginning of incubation. Because a similar decrease of Mg extractability was obtained in all treatments between days 44 and 86, a balance between exchangeable and non-exchangeable forms of soil Mg might have occurred (Metson 1974). The exchangeable Mg might have been quickly transformed to non-exchangeable forms by strongly bonding on sites in the interlayer space of clay-mineral fractions.

Among biochar treatments, higher Mehlich-3-extractable Mg, Zn, and Cu were measured in the soil amended with M400 than with M700 and M550 (Table 3; Fig. 1g). The high extraction of Zn could be the result of an artifact from a possible contamination during the production of M400 biochar. In contrast to Mg and Cu, M550 contributed the most to the increase in soil Mehlich-3 Ca, with a value 10% higher than with the other biochars (Table 3). The high extraction of Ca in the soil amended with M550 converges with the amount of Ca supplied by this biochar (Table 1). This high Ca concentration in the soil amended with M550 might potentially have promoted precipitation of P with these elements (Li et al. 2019). The results, however, revealed that the concentrations of Mehlich-3-extractable P were similar between biochar treatments throughout the incubation (Fig. 1c). In addition, the Mehlich-3-extractable P content was positively correlated with soil pH ($R^2 = 0.93$) and Ca ($R^2 = 0.76$) and negatively correlated with Al ($R^2 = 0.85$) (Figs. 2*a*, 2*c*, 2*e*) indicating that the high pH in the soils amended with biochars and the high Ca content in soil amended with M550 did not limit the P extraction.

Compost addition increased the concentration of soil Ca, Mg, and Fe by 13%, 35%, and 3%, respectively, whereas it reduced the concentration of Al and Cu by 8% (Table 3). The higher concentrations of Mehlich-3 K, Mg, and Ca and lower Mehlich-3 Al with than without compost confirm that their availability was high in this compost. In addition, the results suggested that enrichment with compost helped protect basic cations from being fixed in clay soil, and this could be due to improving CEC, increasing soil organic matter content, and stimulating microbial activity and nutrient mineralization, releasing thereby more nutrients in the soil (Harrison 2008; Sharma et al. 2017; Sayara et al. 2020). Overall, our results agree with the findings of Liu et al. (2012), who further claimed that co-applying biochar and compost would provide the amounts of nutrients required by the crop than compared with application of biochar alone.

Conclusion

Our 338 d incubation showed that biochar amendment influenced nutrient availability in temperate fertilized clay soil. None of the tested biochars negatively impacted the extractability of macro- and micro-elements in this soil according to their chemical properties. The three biochars derived from maple barks made at 400, 550, and 700 °C increased the Mehlich-3-extractable P despite their high pH. Among the three biochars, M400 produced the highest increases in soil Mehlich-3-extractable essential elements for plant growth. The addition of compost enhanced the extractability of most elements in this clay soil and its co-application with biochar supplied additional nutrients, particularly K. Therefore, in temperate and boreal systems, biochars derived from maple barks combined with compost could be a significant source of nutrients for plants. Additional studies under field conditions are, however, required to determine if the increase in Mehlich-3 P and the other mineral element concentrations translates into potential gains in plant production and nutrient uptake without any negative environmental impact. Furthermore, the risk of P loss by leaching should be considered when biochar is co-applied with compost due to the increase and decrease of the extractability of P and Al, respectively.

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