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Crop yield and SOC responses to biochar application were dependent on soil texture and crop type in southern Quebec, Canada

Rachel G. M. Backer[1], Timothy D. Schwinghamer[1], Joann K. Whalen[2], Philippe Seguin[1], and **Donald L. Smith[1]***

[1] Department of Plant Science, McGill University, Macdonald Campus, 21, 111 Lakeshore Road, Sainte-Anne-de-Bellevue, Quebec, H9X 3V9, Canada

[2] Department of Natural Resource Science, McGill University, Macdonald Campus, 21,111 Lakeshore Road, Sainte-Anne-de-Bellevue, Quebec, H9X 3V9, Canada

Abstract

Changes to soil nutrient availability and increases for crop yield and soil organic C (SOC) concentration on biochar-amended soil under temperate climate conditions have only been reported in a few publications. The objective of this work was to determine if biochar application rates up to 20 Mg ha^{-1} affect nutrient availability in soil, SOC stocks and yield of corn (*Zea mays* L.), soybean (*Glycine max* L.), and switchgrass (*Panicum virgatum* L.) on two coarse-textured soils (loamy sand, sandy clay loam) in S Quebec, Canada. Data were collected from field experiments for a 3-y period following application of pine wood biochar at rates of 0, 10, and 20 Mg ha^{-1}. For corn plots, at harvest 3 y after biochar application, 20 Mg biochar ha^{-1} resulted in 41.2% lower soil NH_4^+ on the loamy sand; the same effect was not present on the sandy clay loam soil. On the loamy sand, 20 Mg biochar ha^{-1} increased corn yields by 14.2% compared to the control 3 y after application; the same effect was not present on the sandy clay loam soil. Biochar did not alter yield or nutrient availability in soil on soybean or switchgrass plots on either soil type. After 3 y, SOC concentration was 83 and 258% greater after 10 and 20 Mg ha^{-1} biochar applications, respectively, than the control in sandy clay loam soil under switchgrass production. The same effect was not present on the sandy clay loam soil. A 67% higher SOC concentration was noted with biochar application at 20 Mg ha^{-1} to sandy clay loam soil under corn.

Key words: corn / maize / soybean / switchgrass / field trial / temperate

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1 Introduction

Charcoal has been used in traditional agriculture for thousands of years as indicated at sites in the Amazonian Terra Preta, which contain black C dated at 7,000 y old (*Neves* et al., 2003). In those times, charcoal was produced by burning waste (including bones, clay fragments, food waste) at temperatures ranging from 300 to 1,000°C with limited oxygen (*Sohi* et al., 2009). To this day, these sites contain 70 times as much black C as surrounding sites, three times as much soil organic matter and higher nutrient and nutrient retention levels than surrounding soils (*Glaser* et al., 2001). To bring the benefits of traditional charcoal soil amendments to modern agriculture, biochar soil amendments have been proposed. Biochar is produced by pyrolysis in modern reaction units as a by-product of thermochemical biofuel production from biomass materials such as purpose-grown crops and/or waste food or wood. These amendments have the potential to simultaneously increase soil C stocks and crop yields by improving soil fertility (*Jeffery* et al., 2015). The benefits are dependent upon biochar properties (pH, plant available nutrient concentration, cation exchange capacity, porosity, *etc.*), which vary based on the feedstock and pyrolysis conditions.

There are a number of reasons that biochar-amended soils may provide a better growing environment for crops. Soil incubation studies enumerated the benefits of biochars on soil fertility, which may result from (1) improvement of soil chemical properties that benefit plants, such as buffering soil pH, increasing the cation exchange capacity and plant-available nutrient concentrations in soil solution (*Gaskin* et al., 2010; *Laird* et al., 2010), (2) increased soil aggregation (*Hua* et al., 2014), which creates a porous environment for root growth, air and water exchange, and (3) altered biological activity, perhaps by providing metabolizable organic C substrates and habitat favoring growth of soil microorganisms, including the symbiotic N_2 fixing bacteria and free-living N mineralizers such as the *Bradyrhizobiaceae* and *Hyphomicrobiaceae*, both of which contribute to crop N nutrition (*Anderson* et al., 2011).

Detailed results exist about how charcoal-associated changes to soil properties result in changes to crop yields. Meta-analysis data compiled from 16 field and pot studies conducted before March 2010 indicated that increases from 7 to 30% in yield were observed on acidic, medium- and coarse-textured soils when biochar amendments increased soil pH

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* Correspondence: Dr. D. L. Smith; e-mail: donald.smith@mcgill.ca

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by at least 2.0 units and were applied with inorganic fertilizer (*Jeffery* et al., 2011). In the same study, corn (*Zea mays* L.), soybean (*Glycine max* L.), and ryegrass (*Lolium perenne* L.) showed average yield increases of 5%, 7%, and –25%, respectively, in response to biochar amendments. In the tropics, researchers observed that acidic, coarse textured soils, amended with charcoal produced 8% more corn grain and 12% more soybean (*Jeffery* et al., 2011) grain. Besides crop, *Major* et al. (2010) reported increases of 16% in N uptake and 6% to harvest index of corn in wood biochar-amended soils in Colombia. *Martinsen* et al. (2014) noted that under Zambia field conditions, biochar soil amendments increased corn yield by 232 ± 60% as a result of increased available water and decreased available Al.

The effects of biochar under temperate field conditions have been reported in several studies, however, the results are inconsistent and depend on soil type, crop grown, and biochar material applied. *Gaskin* et al. (2010) noted a decline and then no effect corn yield in first and second years following pine wood biochar and inorganic N fertilizer application to loamy sand in Georgia (USA), due to a decrease in soil pH and increase in Mehlich-I Ca in surface (0–15 cm depth) soil. A corn field trial conducted on a loamy sand in NE Germany found that a biochar-compost mixture applied at 20 Mg ha^{-1} increased SOC by a factor of 2.5 and plant-available Ca, K, P, and Na by a factor of 2.2, 2.5, 1.2, and 2.8, respectively, over the unamended control; corn grain yield on the plots was not reported (*Liu* et al., 2012). In a Chinese rice (*Oryza sativa* L.) paddy study, biochar effects were more consistent: rice yield increased by approx. 10 and 20% over control plots in the first and second cropping cycles, respectively, after biochar application at 10 to 40 Mg ha^{-1} (*Zhang* et al., 2012). The increased yield corresponded to increased soil pH, SOC, and total N and to decreased soil bulk density and N_2O emissions (*Zhang* et al., 2012). *Glaser* et al. (2015) used novel strategies for biochar application in Lower Saxony, Germany. Here, biochar was added at 1 Mg ha^{-1} with mineral fertilizer; this increased corn yield by 20% compared to plots receiving only mineral fertilizer; the biochar-fertilizer combination increased K, Mg and Zn uptake and reduced Na, Cu, Ni and Cd uptake by corn plants. In the same study, biochar was applied at 10 Mg ha^{-1} with compost resulting in a 26% increase in corn grain yield compared to plots receiving only compost. However, biochar does not always benefit crop yields: biochar produced from corn did not alter (*Triticum aestivum* L.) yield in a pot experiment using loamy sand soil from Germany (*Reibe* et al., 2015). The same paper also showed that low nutrient biochar cannot be used to replace N fertilizer application in temperate field soil. In general, published biochar effects on crop yields grown on temperate-zone field soils are neutral or positive and present when biochar is applied in combination with inorganic or organic fertilizers, suggesting that nutrient retention in soil may be an important mechanism for these effects. Biochar effects under Canadian field conditions have yet to be reported in the scientific literature.

In Quebec, Canada, biochar effects on N supply to plants could result in biochar-associated crop yield improvements as a result of increased chemical N retention in soil or by altered N cycling in soil as a result of biochar effects on soil microorganisms. The humid growing conditions in E Canada pose a challenge to sustaining the N supply for non-N_2 fixing crops because NO_3^- is susceptible to leaching, particularly in sandy soils that are acceptable for corn and preferred for switchgrass production. This could be reduced in biochar-amended soils due to greater N retention and subsequent desorption from biochar of plant-available NH_4^+ and NO_3^- ions. We hypothesize that under field conditions in Quebec, Canada, biochar will favor the retention of NH_4^+ and NO_3^- in soil and/or N_2 fixation to meet crop N requirements and produce higher crop yield in biochar-amended soils. It is expected that the effects on chemical N retention will primarily benefit corn grown on sandy soil, which is prone to N leaching; this is in part because corn has a high mineral N requirement. It is expected that the effects on biological N fixation will benefit soybean and that this effect will be independent of soil type.

In addition to nutrient retention, the SOC pool is important for maintaining long-term soil fertility. The SOC pool is comprised of physically and chemically stabilized by-products of organic residue decomposition, which may also include the organic C in biochar that was stabilized by pyrolysis (*Nelson* and *Sommers*, 1996). Additionally, biochar can have positive or negative effects on the size of the SOC pool by promoting or reducing C mineralization by soil microorganisms (*Liang* et al., 2010; *Zimmerman* et al., 2011). Biochar soil amendments can contribute to the SOC pool in three ways: (1) by increasing the fraction of slowly degradable C, as indicated by a high stable C content (*Mašek* et al., 2013) which can persist in soils for hundred to thousands of years (*Neves* et al., 2003), (2) by increasing crop growth to generate more above- and belowground biomass, including non-harvested residues that remain in the field and contribute to the SOC stocks, or (3) by formation of biochar-associated soil aggregates to stabilize both biochar C and indigenous SOC (*Hua* et al., 2014). However the residence time of biochar in soil will depend on whether environmental conditions promote or hinder C degradation, and how biochar interacts with biological properties of soil that contribute to SOC accumulation (*e.g.*, root growth and soil microbial community structure). Biochar has also been shown to alter plant root growth. Under controlled environment conditions, *Arabidopsis thaliana* plant height doubled and root length increased by 12% when poplar (*Populus*) wood chip biochar was applied at 20 Mg ha^{-1} in the presence of N fertilizer (*Viger* et al., 2015) due to increases to soil pH, total N, and available P and K concentrations. In a column study, Danish researchers demonstrated that 1% (w/w, equivalent to 10 Mg ha^{-1}) straw biochar amendment to subsoil improved barley (*Hordeum vulgare* L.) root penetration by 22% and grain production by 22% by increasing subsoil water content and wilting point. We hypothesize that biochar-amended soils will retain more SOC stocks as a result of altered root growth or increased residues returned to soil as a result of increased biomass production on these plots. We expect this effect to be highest for switchgrass followed by corn and then soybean plots. Switchgrass is a perennial crop, which contributes 20 to 35 g C kg^{-1} in the top 10 cm of soil, depending on soil texture (*Bonin* and *Lal*, 2014). Corn, compared to soybean, may also demonstrate increased SOC concentration in response to biochar application as a result of

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increased aboveground residues that contribute to SOC stocks (*Kong* et al., 2005).

The objective of this study was to provide field data on nutrient availability in soil following biochar application, SOC concentration and crop yield properties in two soils (loamy sand, LS; sandy clay loam, SCL), located in SW Quebec, Canada, amended with pine wood biochar. Three crops were studied: switchgrass, corn and soybean, which were selected based on their economic importance in the study area and their contrasting physiologies. This research adds to a growing body of research that details agronomic effects of biochar soil amendments under humid temperate field conditions.

2 Material and methods

2.1 Biochar characterization

Pyrovac (Jonquiere, QC, Canada) biochar was produced from pine wood chips in a pyrolysis unit heated to 500°C for 12 min. It was characterized using methods recommended by the International Biochar Initiative (*IBI*, 2013) at the Soil Control Laboratory (Watsonville, CA, USA; Table 1). The surface area of the biochar was measured using N adsorption-desorption isotherms at 77 K as measured by an automated gas adsorption analyzer ASAP2000 (Micrometrics, Norcross, GA, USA) with ± 5% accuracy (*Azargohar* and *Dalai*, 2006). Particle size analysis was conducted by progressive dry sieving according to ASTM D2862-10 Method for activated C. This indicated a distribution ranging from < 0.150 to 2.0 mm.

2.2 Field experiments

2.2.1 Site and experimental design

Plots of corn, soybean, and switchgrass were established in May 2010 at the Emile A. Lods Agronomy Research Centre, Sainte-Anne-de-Bellevue, QC, Canada (45°28' N 73°45' W). Experiments were carried out on two differently textured soils, a loamy sand (LS) and a sandy clay loam (SCL). The LS (Saint Amable loamy sand) contained 815 g kg^{-1} sand, 89 g kg^{-1} silt, and 96 g kg^{-1} clay. The previous summer crops were grain corn in 2007, 2008 and 2009, Japanese millet (*Echinochloa esculenta*) in 2006, and soybean in 2005. The SCL soil (Chicot sandy clay loam) contained 476 g kg^{-1} sand, 231 g kg^{-1} silt, and 293 g kg^{-1} clay. The previous summer crops were sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) in 2008 and 2009, bean (*Phaseolus vulgaris*) in 2007, fallow in 2006, and green manure oat (*Avena sativa*) in 2005. Initial soil data, measured in spring 2010, are shown in Table 1.

Table 1: Biochar and soil properties at the beginning of the field study characteristics prior to start of experimentation.

	LS[a] soil	SCL[b] soil	Biochar[c]
Nutrient content / mg kg^{-1}			
NO_3^--N[d]	78	22	2.3
NH_4^+-N[d]	23	51	23
P (available)[e]	135	81	42.9
K[e]	121	141	NA
Mg[e]	52	124	NA[f]
Ca[e]	671	868	NA
Elemental analysis			
Organic C / g kg^{-1}	18.0	8.7	732
N / mg kg^{-1}	2,080	1,510	50
C/N	8.6	5.7	NA
Ash content / %	NA	NA	9.9
Characteristics			
pH	5.5	5.1	8.3
% $CaCO_3$ equivalence	NA	NA	5.19
Electrical conductivity / dS m^{-1})	NA	NA	0.29
Total pore volume / cc g^{-1}	NA	NA	0.015
Surface area / m^2 g^{-1}	NA	NA	22

[a] LS denotes loamy sand.
[b] SCL denotes sandy clay loam.
[c] Load is less than 100 g ha^{-1} per nutrient at an application rate of 20 Mg ha^{-1} biochar; all heavy metals (As, Cd, Cr, Co, Cu, Pb, Mo, Hg, Ni, Se, Zn) were below maximum levels dictated by IBI standards.
[d] 2 M KCl extractable NH_4^+ and NO_3^- (*Sims* et al., 1995).
[e] Mehlich-III nutrients (P, K, Ca, Mg, Al) were analyzed by extracting with Mehlich-III solution (*Tran* and *Simard*, 1993).
[f] NA indicates not analyzed.

Each crop was established as a separate experiment on each soil type. Within each experiment, biochar was applied at 3 rates (0, 10, and 20 Mg dry biochar ha^{-1}), assigned in a randomized complete block design with four blocks. All plots were 4 m long. Corn plots were 3 m wide and contained 4 rows at a 75 cm row spacing. Switchgrass and soybean plots were 1.4 m wide and contained 7 rows at a 20 cm row spacing. All experimental sites were prepared by disk harrowing to a depth of 15 cm in May 2010. Subsequently, biochar was manually applied to treatment plots in a one-time application in 2010. One third of the total N fertilizer (applied as NH_4NO_3, Plant Products, Brampton, ON, Canada) was applied to plots (60 kg N ha^{-1} for corn and 33 kg N ha^{-1} for switchgrass); biochar and fertilizer were incorporated to a depth of 10 cm by secondary tillage. The remaining two thirds of the N fertilizer was broadcasted approx. 6 weeks after seeding on corn and switchgrass plots at 120 and 66 kg N ha^{-1}, respectively. In 2011 and 2012, N fertilizer was applied at the same rates and timing as in 2010. Biochar and N fertilizer were incorporated into soil immediately (> 1 h) after application.

The mean monthly precipitation levels during the interval May 1st to October 31st in 2010, 2011 and 2012 was 110, 122, and 84 mm, respectively. The mean monthly temperatures during the interval May 1st to October 31st in 2010, 2011 and 2012 were 17.0, 17.5, and 17.9°C, respectively. Weather data was recorded by a weather station at the Pierre Elliott Trudeau International Airport, located 19 km from the field site (Envi-

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ronmental Canada, National Climate Data and Information Archive).

2.2.2 Soil analysis

In 2010, prior to biochar application, 10 soil samples were taken per block to a depth of 10 cm, combined to form a composite sample. After harvest in 2012, four soil samples were taken per plot to a depth of 10 cm, combined to form one composite sample. All soil samples were dried at 60°C for 48 h, ground, and sieved to pass through a 2-mm mesh. Plant available N ($NH_4^+ + NO_3^-$) concentrations were determined in 2 M KCl extracts (1:10 soil: extractant ratio) by colorimetry with the modified indophenol-blue method of *Sims* et al. (1995) on a BioTek μQuant microplate reader (BioTek Instruments Inc., Winooski, VT, USA). The nutrients P, K, Mg, and Ca were determined by extracting 2.5 g soil with 25 mL Mehlich-III solution (*Tran* and *Simard*, 1993). Phosphorus concentrations were measured colorimetrically on a Lachat Quick Chem auto-analyzer (Lachat Instruments, Milwaukee, WI, USA), and K, Mg, and Ca were measured using atomic absorption spectrometry (AAS). Approximately 7 g of soil were analyzed for pH at a 1: 2 soil: water ratio. Total C and total N contents were measured by combustion at 900°C using a Carlo-Erba CN analyzer (Milano, Italy). As the soils did not contain carbonates (confirmed after treatment with 1 M HCl), it was assumed that total C was equivalent to organic C given the low inorganic C content of the soils in this region.

2.2.3 Crop establishment

Switchgrass [*Panicum virgatum* (L.) Cave-in-Rock] was seeded at 10 kg ha^{-1} on 20 May 2010. Corn [*Zea mays* (L.) Dekalb Hybrid DK 40-22] was planted on 24 May 2010, 27 May 2011, and 31 May 2012 at 72 000 seeds ha^{-1}. Soybean [*Glycine max* (L.) OAC Champion], inoculated according to the manufacturer's instructions with *Bradyrhizobium japonicum* (HiStick® N/T, Becker Underwood, SK, Canada), was planted on 3 June 2010, 2 June 2011 and 5 June 2012 at 400 000 seeds ha^{-1}. Herbicide was not applied to the plots, instead plots were maintained in a weed-free condition by hand weeding.

2.2.4 Plant material harvest, data collection, and analyses

Prior to harvest, five height measurements were taken randomly in each plot. Switchgrass plots were harvested on 22 October 2010, 15 October 2011, and 20 October 2012. Tillers were manually cut at a 10 cm stubble height in three 1 m row-lengths randomly selected on each plot after the first killing frost. Corn plots were harvested on 29 October 2010, 25 October 2011, and 27 October 2012. Ten whole plants were sampled per plot. Soybean plots were harvested on 27 October 2010, 24 October 2011, and 22 October 2012. Ten whole plants were sampled per plot to determine number of seeds per plant. Soybean grain yield per plot was harvested using a small Wintersteiger combine. All harvested plant material was dried to a constant weight at 60°C (4 d) and weighed. The number of seeds per plant was determined for corn and soybean; the number of tillers (per m^2) was determined for switchgrass. Grain yield (Mg ha^{-1}) was determined for corn and soybean; biomass yield (Mg ha^{-1}) was determined for switchgrass. Grain and residues were ground (Udy Cyclone Lab Sample Mill, Udy Corporation, Fort Collins, CO, USA and Thomas Model 4 Wiley Mill, Thomas Scientific, Swedesboro, NJ, USA, respectively) to pass through a 1-mm mesh sieve, and 2–3 mg of powder was used for quantification of tissue N content (%) using an elemental analyzer (ThermoQuest C/N Analyzer, NC 2500, Thermo Quest, Milan, Italy). Analyses were carried out in triplicate. For corn and soybean, grain N (kg ha^{-1}) was determined by multiplying grain yield (kg ha^{-1}) by grain N content (%); for switchgrass, total N uptake was determined by multiplying biomass yield (kg ha^{-1}) by biomass N content (%).

2.2.5 Statistical analyses

Data were analyzed using PROC MIXED (Version 9.3) of the SAS System for Windows (SAS Institute, Inc., Cary, NC, USA). Data were pooled to include both investigated soils and all years after performing a Fisher F-test to verify the assumption of equal variances among sample populations. For plant data, fixed effects included in the model were: soil type (LS, SCL), year (2010, 2011, 2012) and biochar rate (0, 10, 20 Mg ha^{-1}), and all their interactions; block was included as a random factor. For soil data, fixed effects were the same except year was excluded since samples were only collected in 2012. Normal distribution of residuals and homogeneity of variance was tested for all models. In the case when residuals were not normally distributed, data were log transformed. Significant differences among treatment groups were determined from estimates using Bonferroni-adjusted *p*-values: differences were considered significant when the probability of occurring by chance alone was < 0.05. Biologically interesting numerical differences with probabilities of occurring by chance alone was between 0.05 and 0.1 are also presented; when this occurs, the *P* values are given.

3 Results

After 3 y, pH and nutrient availability to 10 cm depth were not different between all plots for switchgrass (data not shown). For corn plots at the LS soil, there was a biologically interesting biochar × soil interaction effect ($p = 0.0727$) on soil NH_4^+. On LS soil receiving 20 Mg biochar ha^{-1}, NH_4^+ concentration decreased by 4.10 ± 0.15 mg kg^{-1} ($p < 0.05$; Table 2). For corn soil on the SCL soil, no effects of biochar were observed for any of the soil fertility variables. There were no biochar effects on soil fertility in soybean plots on either soil type.

For switchgrass plots on the LS soil, there was no biochar effect on SOC concentration to a depth of 10 cm. For switchgrass plots on the SCL soil, biochar application at both rates resulted in higher SOC concentrations, by 10.8 ± 3.8 and 31.0 ± 3.8 g C kg^{-1} soil, compared to the control, at 10 and 20 Mg biochar ha^{-1}, respectively ($p < 0.05$ and < 0.0001, respectively; Fig. 1). For corn plots on the LS soil, there was no biochar effect on SOC concentration. Biochar application at 20 Mg ha^{-1} caused an increase in SOC concentration by

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Table 2: Soil characteristics of corn plots 3 y after biochar application. Means are presented with standard errors in parentheses.[a]

Soil type	Biochar / Mg ha^{-1}	NO_3^--N / mg kg^{-1} soil	NH_4^+-N	P	K	Mg	Ca	pH units
LS[b]	0	36.9 (5.28)	15.7 (1.16)	139.8 (10.29)	83.6 (11.16)	52.2 (3.16)	736 (44.6)	5.6 (0.08)
	10	24.2 (5.28)	13.7 (1.16)	131.2 (10.29)	73.4 (11.16)	46.1 (3.16)	674 (44.6)	6.1 (0.08)
	20	32.2 (5.28)	11.7 (1.16)	120.7 (10.29)	122.6 (11.16)	58.7 (3.16)	802 (44.6)	6.1 (0.08)
SCL[b]	0	37.6 (5.28)	6.9 (1.16)	78.7 (10.29)	114.6 (11.16)	77.4 (3.16)	686 (44.6)	4.7 (0.08)
	10	45.3 (5.28)	5.7 (1.16)	77.2 (10.29)	96.9 (11.16)	78.5 (3.16)	707 (44.6)	4.8 (0.08)
	20	42.0 (5.28)	5.4 (1.16)	81.1 (10.29)	108.4 (11.16)	79.3 (3.16)	744 (44.6)	4.9 (0.08)
ANOVA								
BC		NS	0.072	NS	NS	NS	NS	NS
Soil		*	**	**	NS	***	NS	***
BC x Soil		NS	NS	NS	NS	NS	NS	NS

[a] *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$; p-value is given when biologically interesting numerical differences occur with p-values between 0.05 and 0.1; NS, not significant.

[b] LS denotes loamy sand; SCL denotes sandy clay loam.

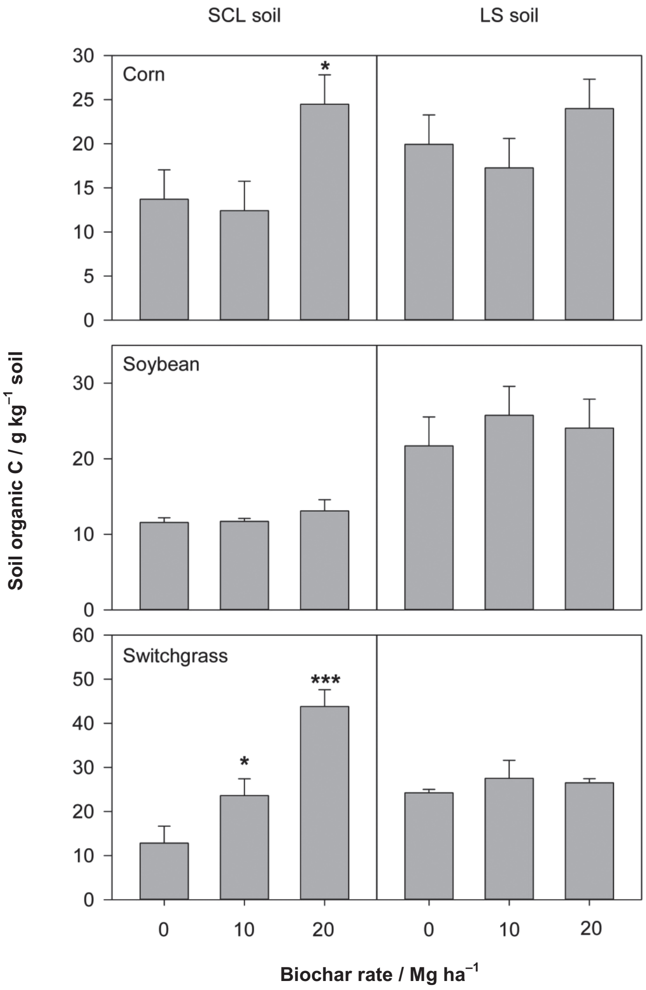

Figure 1: Mean SOC concentration (g C kg^{-1}) to a 10-cm depth and standard error 3 y after biochar application. Significant biochar effects are indicated by * $P < 0.05$ and *** $P < 0.001$.

10.8 ± 3.4 g C kg^{-1} soil to a depth of 10 cm on corn plots on the SCL soil ($p < 0.05$). After 3 y, no difference in SOC concentrations was detected due to biochar application on either soil type under soybean production.

Biochar addition did not affect switchgrass aboveground properties on either study soil (Table 3). On the LS soil, biochar application at 20 Mg ha^{-1} resulted in significantly higher mean corn grain yield over the control by 1.35 ± 0.36 Mg ha^{-1}, number of grains per plant by 57 ± 16 units, and a biologically interesting increase in total grain N by 22.1 ± 7.7 kg grain N ha^{-1} (p-values < 0.05, < 0.05, and $= 0.0811$, respectively). Biochar application at 20 Mg ha^{-1} increased grain yield over the control in 2010 and 2011, but not in 2012 (p-values < 0.05, < 0.05, and > 0.10, respectively; Fig. 2). Plant height did not differ significantly between biochar application rates (Table 3). For corn plants on the SCL soil, biochar application did not result in increased corn grain yield. There was a biologically interesting biochar × soil interaction effect ($p = 0.0935$) for the number of seeds per soybean plant (Table 3): seeds per plant increased by 8.8 ± 4.9 units on the LS soil with biochar application at 20 Mg ha^{-1}, but this did not alter soybean yield on the LS soil ($p > 0.10$). With this exception, there were no biochar effects on soybean aboveground properties on either soil type.

4 Discussion

4.1 Biochar effects on nutrient availability in soil and crop yield

For switchgrass producing plots, biochar not did alter soil pH or nutrient availability to a depth of 10 cm, relative to the control on either the LS or SCL soil. As a result, there were no changes to aboveground yield. Our results contrast with *Allaire* et al. (2015) who reported an 11% increase to switch-

Table 3: Harvest data for switchgrass, soybean and corn. Summary shows the means for pooled data from 2010, 2011, and 2012 growing seasons with SEs in parentheses.[a]

Soil	Biochar	Switchgrass				Soybean				Corn			
		Height	Stand count	Yield[b]	N uptake	Height	Seeds	Yield[c]	Grain N	Height	Seeds	Yield[d]	Grain N
	/ Mg ha^{-1}	/ cm	/ stems m^{-2}	/ Mg ha^{-1}	/ kg ha^{-1}	/ cm	/ plant^{-1}	/ Mg ha^{-1}	/ kg ha^{-1}	/ cm	/ plant^{-1}	/ Mg ha^{-1}	/ kg ha^{-1}
SCL[e]	0	157 (3.6)	588 (33.8)	4.0 (1.1)	42.9 (5.6)	67 (2.9)	52 (3.6)	3.1 (0.16)	205 (11.9)	202 (4.8)	483 (20.8)	8.1 (0.49)	107 (8.8)
	10	158 (2.9)	580 (33.8)	4.8 (1.1)	48.6 (5.6)	66 (2.9)	48 (3.6)	3.0 (0.16)	198 (11.9)	200 (4.8)	493 (20.8)	8.4 (0.49)	112 (9.9)
	20	152 (3.3)	603 (33.8)	4.4 (1.1)	40.5 (5.6)	64 (2.9)	46 (3.6)	2.9 (0.16)	197 (11.9)	199 (4.8)	480 (20.8)	8.4 (0.49)	110 (8.8)
LS[e]	0	157 (4.4)	749 (30.9)	8.6 (1.1)	113.8 (15.4)	93 (3.0)	59 (3.8)	3.2 (0.17)	227 (12.4)	235 (5.0)	507 (20.8)	9.1 (0.49)	121 (8.1)
	10	159 (4.8)	676 (30.9)	9.2 (1.1)	113.4 (15.4)	93 (3.0)	58 (3.8)	3.2 (0.17)	220 (12.4)	229 (4.8)	502 (20.8)	9.1 (0.49)	123 (8.1)
	20	155 (5.0)	726 (30.9)	8.3 (1.1)	106.7 (15.4)	95 (3.0)	67 (3.8)	3.1 (0.17)	217 (12.4)	246 (4.8)	564 (20.8)	10.4 (0.49)	143 (8.1)
ANOVA													
BC		NS	NS	NS	NS	NS	NS	NS	NS	**	*	**	0.0811
Soil (S)		NS	***	**	***	***	*	NS	*	**	NS	0.0998	0.0936
Year (Y)		***	***	***	***	***	***	***	***	***	***	***	***
BC x S		NS	NS	NS	NS	NS	0.0935	NS	NS	***	**	*	*
BC x Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
S x Y		***	***	***	*	***	***	***	***	***	**	NS	NS
BC x S x Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; p-value is given when biologically interesting numerical differences occur with p-values between 0.05 and 0.1; NS, not significant.

[b] Average switchgrass yield in the region ranges from 5.0 to 13.0 Mg ha^{-1}.

[c] Average soy yield in the region is 3.1 Mg ha^{-1}.

[d] Average corn yield in the region in 9.1 Mg ha^{-1}.

[e] SCL denotes sandy clay loam; LS denotes loamy sand.

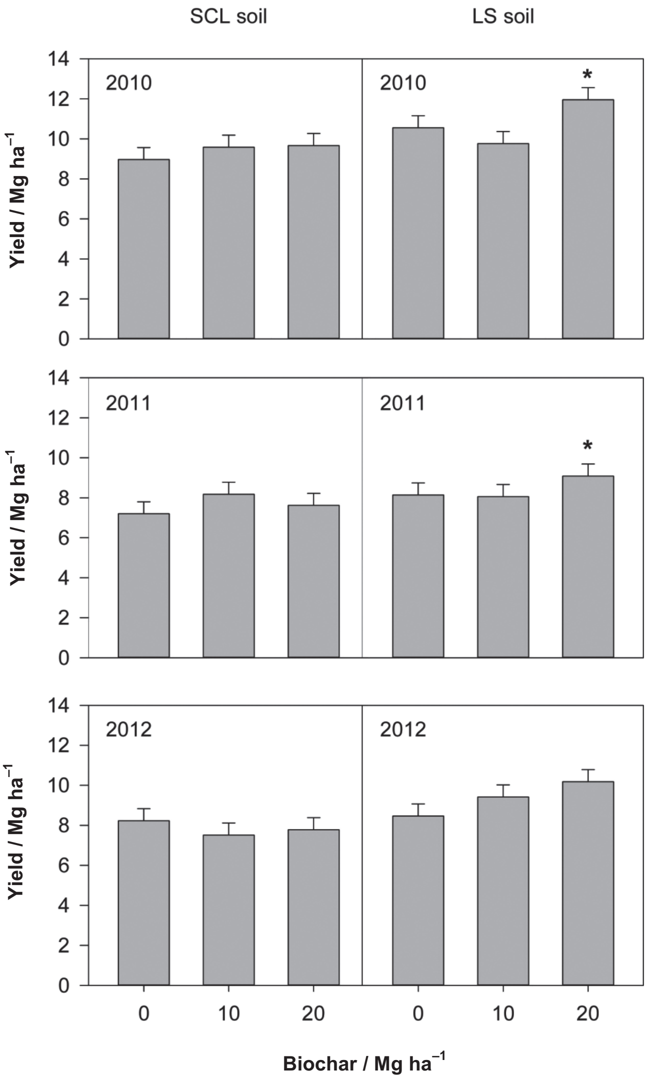

Figure 2: Mean corn yield (Mg ha^{-1}) by soil type and year. Significant biochar effects are indicated by * $P < 0.05$.

grass aboveground biomass yields when Pyrovac biochar was applied to a sandy loam soil at 10 Mg ha^{-1} in Quebec. On all plots in our experiment, soil pH and nutrient concentrations were suitable for switchgrass cultivation (Table 1) and resulted in reasonable switchgrass yield on the SCL soil (4.0 to 4.8 Mg ha^{-1}) and good switchgrass yields on the LS soil (8.3 to 9.2 Mg ha^{-1}), in a range generally comparable to those of *Zan* et al. (2001) and *Madakadze* et al. (1998) who reported switchgrass yields ranging from 5.0 to 13.0 Mg ha^{-1} in the same region without application of biochar soil amendments.

For corn producing plots, biochar application at 20 Mg ha^{-1} was associated with a 29.5% decline in [NH_4^+] to a depth of 10 cm on the LS site after three years; this corresponded with an increase in yield and N uptake on this soil. This contrasts with *Gaskin* et al. (2010) who did not observe corn grain yield increases on an LS soil when pine wood biochar was applied at similar rates in Iowa. However, in their study the biochar amendment had different effects on the soil: biochar decreased soil pH and increased Mehlich-I Ca, two effects which were not observed in our study. Our results are more similar to *Jones* et al. (2012) who observed increased foliar N and yield for the grass *Dactylis glomerata* in the second and third year, respectively, and increased soil pH following biochar application at similar rates in Wales, United Kingdom. These plant growth effects were concordant with the finding that biochar particles, recovered from the same research plots, concentrated NO_3^- and NH_4^+ (*Jones* et al., 2012). *Steiner* et al. (2008) studied biochar amendments to sorghum (*Sorghum bicolor* L.) plots in the humid tropics where fertilizer N is often lost due to leaching. Their results demonstrated that increased recovery of 15-N labelled fertilizer and improved N cycling from the first to the second crop results in increased total N recovery in soil, crop residues and grain yield ($p < 0.05$) with biochar soil amendments. In addition to demonstrating that biochar particles retained soil NO_3^-, the rhizosphere of spring barley has been shown to contain more biochar particle than bulk soil (*Prendergast-Miller* et al., 2014). This suggests that (1) biochar has the potential to concentrate soil N as NO_3^- and/or NH_4^+ and (2) crop root systems can exploit regions of soil with high biochar concentrations to improve N recovery from soil. In our study, the decline in soil [NH_4^+] could also result from consumption by soil microorganisms, but this is unlikely given that it was not accompanied by an increase in soil NO_3^-, which occurs rapidly in agricultural soils in this region (*Whalen* and *Sampedro*, 2009). Similar biochar effects on soil [NH_4^+] were not seen on the SCL site. This could be because (1) this soil texture has a significantly higher [NO_3^-] ($p < 0.05$, respectively; Table 1) than the LS soil, or (2) crop production on this soil was limited by the low soil pH (*CRAAQ*, 2010), which biochar amendment was not able to correct.

At the end of this study biochar had not changed soil nutrient availabilities or pH at a 10-cm depth on soybean plots. Since soybean yield and total N uptake were not altered by biochar application, the hypothesis that biochar would increase soybean biomass by increasing N supply from biological N fixation is rejected. This is supported by our finding that biochar did not affect nodule number of soybean plants from the same experimental plots at the mid-vegetative or flowering stages (data not shown). When *Rondon* et al. (2006) observed biochar effects on nodule number for common bean (*Phaseolus vulgaris* L.), they used a biochar material that was pyrolyzed at 350°C, in contrast with our Pyrovac biochar, which was pyrolyzed at 550°C, which could have resulted in biochar properties (ash and labile C amount and chemical composition, pore size, pH, *etc*.) that favored biological N fixation, whereas Pyrovac biochar did not.

4.2 Biochar effect on SOC concentration

On the SCL soil, SOC measurements confirmed our hypothesis that switchgrass plots would accumulate the most SOC, followed by corn and then soybean plots, in response to biochar soil amendments. At the start of this experiment in 2010, the SCL soils contained 8.7 g C kg^{-1} soil to a 10-cm depth. In 2012, switchgrass plots on this soil showed 1.5- and 3-fold increases to SOC at biochar application rates of 10 and 20 Mg ha^{-1}, respectively. This is consistent with reports in the literature from *Major* (2009) and *Liu* et al. (2012) who

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showed that biochar amendments doubled SOC when applied at 23.3 Mg biochar ha^{-1} and 20 Mg biochar ha^{-1} with 32.5 Mg compost ha^{-1}, respectively. Interestingly, for the LS soil biochar application did not change SOC concentration at a depth of 0 to 10 cm. The data collected for this experiment does not explain whether the biochar C was lost from the 0 to 10 cm soil profile by physical movement or biological degradation, however, this effect is in partial agreement with *Domene* et al. (2014) who found that 3 y after a temperate soil was amended with 12 Mg biochar ha^{-1}, SOC was significantly increased, but the when the same soil was amended with 30 Mg $biochar^{-1}$, SOC was not increased.

The increase of SOC is greater than the amount of C contributed from biochar application alone on the SCL soil. The soil carbon pool of this soil was 18 g organic C kg^{-1} (Table 1), meaning that the soil contained 40.3 Mg organic C ha^{-1} prior to biochar application (based on 2.24 x 10^6 kg soil ha^{-1}). The 20 Mg biochar ha^{-1} treatment had a 73.2% C content (Table 1), representing an input of 14.6 Mg black C ha^{-1}, which would have increased the soil carbon content by 28%, accounting for some of the gain in SOC shown in Fig. 1. To account for the SOC accumulated in plots on the SCL soil, we propose that biochar increased SOC addition as a result of (1) increased aboveground biomass left behind by harvesting machinery or (2) increased root proliferation (*Bruun* et al., 2014; *Viger* et al., 2015) in the 0 to 10 cm depth. The first option is supported by the fact that switchgrass yield increased, though not statistically significantly, with biochar application rate on the SCL but not the LS soil. The second possibility is supported by the fact that biochar is known to alter water availability in soil and soil bulk density (*Ayodele* et al., 2009), which could have increased shallow root proliferation and increased SOC concentrations by switchgrass (*Ma* et al., 2000). *Allaire* et al. (2015) found that biochar application at 10 Mg ha^{-1} increased root biomass by 51.8% in the second year after switchgrass establishment and increased root C in soil from 2.25 to 3.49 Mg ha^{-1}. In combination with increased aboveground biomass production this effect led to increased soil C accumulation on plots receiving biochar soil amendments. In our study, the increases in SOC concentration were likely greater on switchgrass plots than corn or soybean plots because switchgrass is a perennial crop that accumulates substantial root biomass since the soil was not ploughed every year (*Mishra* et al., 2010). In this case, future studies should examine switchgrass root growth under these conditions to determine if C sequestration by switchgrass roots is altered or redistributed due to a reduction of deeper root proliferation in favour of shallow root growth (*Ma* et al., 2000). We expected that switchgrass, a perennial crop which produces an extensive fibrous root system in a soil profile that is undisturbed by tillage, would accumulate more SOC in response to biochar amendments than corn or soybean plots. Corn and soybean have a lower root: shoot ratio than switchgrass and the plots were cultivated with at least two tillage operations in spring and fall, which would accelerate decomposition of SOC that was contributed by root systems. Under corn plots, SOC concentration showed bigger increases than for soybean plots on the SCL soil. This was likely due to the larger contribution of C from corn residue and root C (6.9 g C kg^{-1} soil on this soil; calculated based on the 3-y contribution of residue and root C using a root: shoot ratio of 0.18 according to *Prince* et al., 2001) compared to soybean residue and root C (3.2 g C kg^{-1} soil on this soil; calculated using a root: shoot ratio of 0.15).

5 Conclusions

The objective of this study was to evaluate if biochar can contribute to soil fertility and/or crop productivity under Quebec field conditions and could be adopted on a commercial scale in this region. Producer goals are to reduce labor, costs, and environmental impact (*e.g.*, nutrient leaching from soils as a result of fertilizer application) while maximizing yields. To meet these goals, we need a product that is well understood and gives reliable results for a given crop/soil combination that can be easily applied with on-farm equipment. Given that biochar soil amendments only increased corn but not soybean or switchgrass yield and that this effect was only present on one of two differently textured soils, this work indicates that biochar amendments will need to be tailored to the cropping system they are applied to. More extensive field trials should be conducted to provide information on how yields of crops common to Quebec respond to a wider range of biochar materials. The results of this study suggest that the biochar material used in this study (produced from pine wood chips at 500°C) may allow for reduced N fertilizer inputs when growing corn on biochar-amended LS soils. This would require farm-scale experiments to determine if this effect is consistent on high fertility soils across Quebec and how biochar amendments can be accounted for in existing soil fertility management planning practices in the area (i.e., *CRAAQ*, 2010). This paper provides only a before and after snapshot of soil nutrients and a better mechanistic understanding of biochar effects of nutrient availability in soil could be gained by measuring nutrient availability and microbial activity in soil at key corn growth stages. Alternatively, biochar materials with higher nutrient contents (*e.g.*, those produced from high nutrient feedstocks such as biosolids) could be investigated as an alternative to inorganic fertilizer amendments in regional soil fertility management planning practices as a strategy for reducing inorganic fertilizer application while meeting plant nutrient requirements, maintaining crop yields and increasing SOC. In this study, the soil pH was a limitation on the SCL soil and the biochar material used in this study did not increase soil pH or crop yields on this soil. The use of a biochar with a higher pH and/or calcium carbonate equivalence could be investigated on soils with pH limitations to allow producers to build SOC on their soils concurrently with liming, a benefit that does not exist with current liming materials. In this study, soybean did not benefit from biochar effects on N fixation as evidenced by a lack of changes to nodule number during growth, yield or grain N at harvest. A biochar with a higher labile component could be investigated to provide metabolizable C to rhizobia to improve nodulation and thus N fixation in this crop.

Soil organic C accumulation increases in response to biochar soil amendments were as expected on the SCL soil: switchgrass and corn plots had the largest responses, while soybean plots did not show SOC accumulation responses to biochar application. Future investigations should focus on deter-

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mining the forms of C (black C *vs.* organic C from root and litter decomposition) that are accumulated under switchgrass and/or corn with biochar application and how these factors are influenced in deeper soil profiles, as this is important for calculating the C budget of the system. These effects should be examined on a wider variety of soils in Quebec given the variability we observed on the contrasting soils of this study. If SOC accumulation is often favored with biochar application, C credits for producers who are increasing their SOC through this management strategy could be considered to incentivize biochar application.

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