Effect of biochar on soil quality and potato productivity in New Brunswick, Canada

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Abstract

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Soil degradation is a global issue that threatens the productivity and resilience of agroecosystems. Environmentally-sensitive technologies must be developed to improve soil quality for sustainable crop production. The use of biochar, a carbon-rich alternative end product for forestry residues, has been proposed to counteract soil degradation, improve soil quality and help the agricultural sector to mitigate climate change. The objective of this study was to determine the effects of biochar type and biochar application rate on potato crop response and on physico-chemical indicators of soil quality in a potato cropping system. It was hypothesized that biochar application would positively affect soil structure, soil moisture regimes and soil fertility. Further, it was hypothesized that these changes in soil quality would lead to higher potato yields. A fully phased rotational field experiment was established in October 2015. Five treatments were arranged in a Latinized block design with five replicates. The treatments were an untreated control and a factorial combination of two biochar products (Airex and Maple Leaf), amended at two application rates (10 and 20 t ha^{-1}). Soil and plant tissue samples were analyzed during the growing season, and potato yields were measured. Eight months after they were applied, both biochar products improved soil aggregate stability and lowered soil bulk density, but biochar did not significantly affect the soil moisture regimes. Biochar raised soil pH, while increasing soil organic matter, soil potassium, and soil phosphorus contents. No difference was found between potato yields in the control plots and the biochar-amended plots. Results from this experiment suggest that wood-based biochars that are not manufactured to address specific soil quality issues will affect soil quality in a manner similar to other organic amendments (increase the pH, lower bulk density, increase aggregate stability, and improve the concentration of some soil nutrients). They also suggest that biochar will not necessarily increase yield in a well-managed potato cropping system.

Résumé

M.Sc. Jonathan Delisle Natural Resource Sciences

La dégradation des sols est un problème mondial qui menace la productivité et la résilience des agroécosystèmes. Des technologies respectueuses de l'environnement doivent être développées pour améliorer la qualité des sols et pour promouvoir une agriculture durable. L'utilisation du biochar, un produit riche en carbone et produit à partir de résidus forestiers, a été proposée pour atteindre les objectifs d'amélioration des sols et d'atténuation des changements climatiques. L'objectif de cette étude était de déterminer les effets de l'utilisation de deux types de biochars et de deux taux d'application sur la productivité de la pomme de terre et sur les indicateurs physico-chimiques de la qualité du sol. L'hypothèse principale était que l'application du biochar affecterait positivement la structure du sol, les propriétés hydriques du sol et la fertilité des sols. De plus, une deuxième hypothèse prédisait que ces changements de la qualité du sol entraineraient des rendements supérieurs pour la production de pommes de terre. Une expérience en champ a été établie en octobre 2015. Cinq traitements ont été organisés dans un modèle de blocs latins avec cinq répétitions. Les traitements étaient un contrôle non traité, et des combinaisons factorielles de deux types de biochar (Airex et Maple Leaf) et deux taux d'application (10 et 20 t ha^{-1}). Des échantillons de sol et de tissus végétaux ont été prélevés et analysés au cours de l'été 2016, et les rendements de pommes de terre ont été mesurés au moment de la récolte. Les deux biochars ont amélioré la stabilité des agrégats du sol et réduit la densité apparente du sol. Le biochar n'a par contre pas affecté de manière significative les propriétés hydriques du sol. Le biochar a augmenté le pH du sol, tout en augmentant la teneur en matière organique, et les concentrations de potassium et de phosphore du sol. Aucune différence significative n'a été observée en ce qui a trait aux rendements des pommes de terre. Les résultats de cette expérience suggèrent que les biochar non spécialisé produit à base de bois affectent la qualité du sol d'une manière similaire à d'autres amendements organiques (augmentation du pH, réduction de la densité

apparente, augmentation de la stabilité des agrégats et augmentation de la concentration de certains nutriments dans le sol). Ils suggèrent également que le biochar n'augmentera pas nécessairement le rendement dans un système de culture de pommes de terre bien géré.

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I would like to thank AAFC and the Government of Canada for funding this project. I would like to thank AAFC's José Owen, Dr. Bernie Zebarth, and Dr. Claudia Goyer who co-authored the funding proposal for this experiment. Over the past four years, Josée and AAFC have provided me opportunities to grow as a soil scientist and as a person, and for this I will always be grateful. I owe my love of soil science and biochar to Professors Asim Biswas, Joann K. Whalen, and Tim Moore. Their help and inspiration have been instrumental during different part of this project. I would like to particularly thank Dr. Whalen for her knowledge, patience and dedication. I could always count on her quick feedbacks and insightful comments to keep this thesis moving forward. I am thankful for the financial help I received from McGill University, from the Walter M Stewart Fellowship in Agriculture, and from *Les Fonds de recherche du Québec - Nature et technologies* (FRQNT). The scholarships and grants I have received have allowed me to dedicate myself to learning, and to generating knowledge. I would like to thank the researchers, technicians and students who have been on this scientific journey with me. I feel privileged to have had the opportunity to share ideas and laughs with you.

This thesis is dedicated to my family in Québec and BC because it takes a village.

Merci!

Contribution of Authors

This thesis is written in a classical thesis format according to the guidelines of the Graduate and Postdoctoral Studies Office. It is composed of a general introduction explaining the context of this research project, and presenting the project's hypotheses and objectives, a literature review summarizing current knowledge in the thesis research field, the methodology, results and discussion associated with the field experiment, and a general conclusion to highlight key findings and future research needs.

The research project was conducted at Agriculture and Agri-Food Canada's Fredericton Research and Development Center in Fredericton New Brunswick. The experiment was designed by the candidate, Scientist Josée Owen, Dr. Asim Biswas, Dr. Bernie Zebarth, and Dr. Claudia Goyer. The experiment was established by the candidate, and technician Sheldon Hann. The candidate collected and processed the soil and plant samples, and performed the analysis associated with soil physical properties. Soil chemical analyses were performed by PEI Analytical Laboratories on samples collected by the candidate. Petiole nitrate analyses were performed by the candidate, and nutrient conversion technician Karen Terry. Plant tissue analyses were performed by chemist Gaston Mercier with the assistance of the candidate. Potato harvest and yield measurements were performed by the candidate with the help of field assistants. The candidate conducted data analysis and interpretation under the guidance of Dr. Joann K. Whalen, statistical project manager Sherry Fillmore, and Dr. Jose Correa.

Table of Content

List of Tables

List of Figures

List of Abbreviations and Symbols

CHEMICAL ELEMENTS			
C	carbon	Mg	magnesium
C_{org}	organic carbon	Mn	manganese
Ca	calcium	N	nitrogen
Cu	copper	O	oxygen
Fe	iron	P	phosphorus
H	hydrogen	S	sulfur
K	potassium	Zn	zinc

CHEMICAL COMPOUNDS			
Al_2O_2	dialuminium dioxide	H_2SO_4	sulfuric acid
CH_4	methane	K_2O	potassium oxide
CO	carbon monoxide	N_2	nitrogen gas
CO_2	carbon dioxide	N_2O	nitrous oxide
CaO	calcium oxide	NO_3^-	nitrate
Fe_3O_3	iron oxide	NH_4^+	ammonium
H_2	hydrogen gas	P_2O_5	phosphorus pentoxide
H_2O	water	Si_2O	silicon oxide

UNITS OF MEASUREMENT			
sec	second	mm	millimeter
min	minute	cm	centimeter
h	hour	m	meter
d	day	L	litre
mg	milligram	ha	hectare
g	gram	°C	degree Celcius
kg	kilogram	kPa	kilopascal
t	tonne	dS	deciSiemens
µm	micrometer		

FROM EQUATIONS 1 TO 7

W_{wet}	wet weight
W_{dry}	dry weight
ρ_b	bulk density
V	volume
θ_v	volumetric water content
h_i	water level inside if the ring holder
h_o	water level outside if the ring holder
L	length
A	cross-section surface of the sample
t	*time*
W_s	weight of water-stable soil aggregate
W_l	weight of the loose soil
θ_{FC}	volumetric water content at field capacity
θ_{pwp}	volumetric water content at permanent wilting point

ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
AEC	anion exchange capacity
ANOVA	analysis of variance
AWC	available water content
BMP	best management practices
CEC	cation exchange capacity
CV	coefficient of variation
EC	electrical conductivity
GHG	greenhouse gases
HTT	highest treatment temperature
K_{sat}	saturated hydraulic conductivity
NUE	nutrient use efficiency
OM	organic matter
pH	potenz hydrogen
SG	specific gravity
SL	sandy loam
SMB	soil microbial biomass
SOM	soil organic matter
WAS	wet aggregate stability
WHC	water holding capacity

General Introduction

Soil quality is a term used to acknowledge that soils provide many services essential to both ecosystems and society. Considering that soils support primary production to meet the nutritional demands of humans and animals while also acting as an environmental buffer, the term soil quality can be defined as: "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). Soil quality is dynamic and management dependent, and can be affected by natural and anthropogenic disturbances such as climate change and commercial food production. The tillage, harvesting practices, and high inputs of fertilizer and agrichemicals used in intensive agriculture can contribute to, and exacerbate issues of soil degradation such as: erosion, loss of soil carbon (C), salinization, nutrient depletion, acidification, and pollution.

Potato (*Solanum* tuberosum) is the leading non-grain commodity in the global food system, and the most economically important vegetable crop in Canada (AAFC 2015; FAOSTAT, 2013). Potato cultivation requires multiple tillage events during the growing season, creating a highly disturbed environment, and a major concern in potato cultivation is sustaining the soil quality of the production systems (Khakbazan et al., 2009). Although modifying tillage practices has proven effective in reducing tillage erosion, potato production will always involve soil disturbance (Tiessen et al., 2007). Besides the fact that potato land is repeatedly tilled, potatoes have a low (0.25) aboveground residues to primary harvest ratio (Lal, 2004). As a potato crop returns a low amount of carbon to the soil, soil organic matter (SOM) is gradually depleted, resulting in a degraded soil structure, smaller microbial biomass and an increased potential for soil erosion (Carter and Sanderson, 2001; Gagnon et al., 2001; Haynes and Tregurtha, 1999). Potatoes in continuous production cause a significant reduction in the percentage of water stable aggregates and the soil's porosity (Saini and Grant, 1980). The major soil degradation problems experienced in eastern Canada (erosion, compaction, loss of organic matter and acidification) have a direct impact on potato growth and yield because degraded soils constrain water and nutrient acquisition, and impair root respiration and development (DeHaan et al., 1999; Miller, 1985). The negative impacts of soil degradation have often been masked by technological advances such as better varieties, weed control and better fertility practices, but the loss of soil quality experienced in some areas of New Brunswick (Canada's fourth potato producing province) threatens the profitability of the potato production systems (Miller, 1985). The development of environmentally sensitive technologies to improve soil quality and to improve the resilience of soil functions represents one of the most important challenges to sustainable potato production in the Maritimes.

Biochar is the name given to charcoal products intended for use in agronomic and environmental applications. Along with bio-oil and syngas, biochar is one of the three products obtained through the process of pyrolysis, the thermal decomposition of biomass at elevated temperature in the absence of oxygen (Demirbas and Arin, 2002). Biomass pyrolysis is an attractive alternative for the production of energy and for the disposal of costly and difficult to manage waste products such as forestry and agricultural by-products, manufacturing residues, and dairy waste. In addition to waste management, and energy production, the two other objectives of biochar production are mitigation of climate change through long-term carbon sequestration, and soil quality improvement. The use of wood-based biochars as a soil amendment to improve soil quality and crop productivity is of particular interest in the province of New Brunswick where the 848 thousand tons of woody forest biomass generated annually could be converted to upwards of 200 thousand tons of biochar for biochar-assisted agriculture (Bradley, 2010).

Development in the precision and production capacity of pyrolysis technologies, and standardization of biochar characterization techniques are creating new opportunities for biochar research and for the large-scale use of biochar in food production systems. The use of biochar as a soil additive has been proposed to support soil productivity, and to address soil degradation issues such as those encountered in New Brunswick agricultural soils. By virtue of its complex physical microstructure and reactive surfaces, biochar can significantly affect soil physico-chemical properties. Specifically, the addition of a carbon-rich and highly porous material to degraded potato soils could increase SOM, improve soil aggregate stability and soil moisture regimes, reduce nutrient leaching, and stimulate soil microbes (Cheng et al., 2008; Esmaeelnejad et al., 2016; Gul et al., 2015; Whitman et al., 2015).

Currently however, results of much of the biochar research with respect to soil quality and crop productivity are conflicting and reliable field data in Canada is scarce. Few field studies have been conducted in a temperate climate, and even fewer studies have used biochar produced from large-scale processes. Insufficient data exists to draw conclusions on if and how biochar application can enhance crop production. The regulatory environment currently restricts the use of biochar in Canada, and a greater understanding of biochar's interactions in the soil is needed to provide policy makers and agricultural food producers with the benefits and challenges associated with biochar use. Research is needed to understand how the interaction of different biochar products, soil types, climatic conditions, and cultivars can minimize environmental degradation and improve crop productivity.

The objective of this research was to determine the effects of biochar type and application rate on potato crop response and on physico-chemical indicators of soil quality. Specifically, this research was conducted to answer three questions:

(1) Can commercially available biochar improve soil quality and potato productivity in an optimally-managed potato cropping system on a loamy soil under rainfed production?
(2) Will greater improvements in soil quality attributes be achieved with higher biochar application rates?
(3) Will soil quality attributes respond differentially to the type of biochar applied?

The following hypotheses were developed to address these questions:

Hypothesis 1: Biochar will positively affect soil properties associated with soil structure, soil moisture, and soil fertility, and will increase tuber yield.

Hypothesis 2: Increasing the biochar application rate will augment the positive effect of biochar on soil properties and tuber yield.

Hypothesis 3: Wood-based biochar made from diverse feedstock and manufacturing processes will be equally effective at benefiting soil properties and potato yield.

1: Literature Review

Biochars: Their production, characteristics, and potential to affect soil quality and crop productivity.

In December 2015, the Canadian Food & Inspection Agency (CFIA) approved the use of biochar in soil following extensive consultation over a period of two years with researchers, industry and other biochar proponents. Among the reasons for the lengthy consultation period was that the characteristics of biochar vary greatly depending on the feedstock biomass, pyrolysis conditions, and post-production treatments used in their fabrication. Understanding how the production parameters affect biochar properties is essential in anticipating how biochar applied as a soil amendment will affect soil quality and crop productivity.

This literature review aims to:

(1) describe the origin and development of biochar porosity, surface reactivity, and elemental composition, and relate these characteristics to the various goals associated with biochar application,
(2) describe the physical, chemical and biological mechanisms of biochar-induced changes in soil quality and crop productivity, and
(3) review the suitability of biochars to improve soil quality and crop productivity in Canadian Maritime potato cropping systems.

1.1 Production Parameter Effects on Biochar Characteristics

1.1.1 WHAT IS BIOCHAR?

Biochar is the name given to charcoal products intended for use in agronomic and environmental applications. Along with bio-oil and syngas, biochar is one of the three products obtained through the process of pyrolysis, the thermal decomposition of biomass at elevated temperature in the absence of oxygen (Demirbas and Arin, 2002). The thermochemical process of biomass pyrolysis produces energy while offering an option for disposing of many waste products, including forestry and agricultural by-products, manufacturing residues, and dairy waste. When applied to agricultural soils, C-rich biochars contribute to long-term C sequestration for climate change mitigation, and to soil quality improvement.

1.1.2 FEEDSTOCK BIOMASS

The availability of biomass varies regionally, and nationally across economic landscapes and climatic zones (Figure 1-1 & 1-2). Most organic material can be converted to biochar through pyrolysis but not all biomass is suitable for soil application. Mitigation of climate change and soil quality improvement are best achieved through the valorization of waste biomass material, such as crop residues, yard, food and forestry by-products, and animal manures rather than using higher-value biomass that is destined for other purposes (e.g., fiber for pulp mills, food for human and animal consumption). The transformation of waste biomass to valuable materials and energy through pyrolysis also promotes the recycling of nutrients contained in waste biomass, and reduces the speed with which C cycles from the biomass to the atmosphere (Dia et al., 2016; Roy and Dias, 2017). In Canada, most of the residual biomass is found in provinces with significant forestry activities: British-Columbia, Ontario, Quebec, Alberta and New Brunswick (Bradley, 2010).

1.1.3 BIOMASS PYROLYSIS

The major components of biomass are cellulose, lignin and hemicellulose with smaller quantities of organic extractives (terpenes, fatty acids, aromatic compounds and volatile oil) and inorganic minerals (Demirbas, 2009). During pyrolysis, a series of simultaneous and successive reactions occur to thermochemically transform the biomass, namely dewatering (0-150°C), cracking (200-400°C) and aromatization (400-700°C) (Xiao et al., 2014; Xu et al., 2013; Yang et al., 2007). The process of dewatering initiates thermal decomposition of organic materials, which lose chemically bound moisture (Downie et al., 2009). Hemicellulose begins to degrade between 200°C and 280°C, cellulose between 240°C and 350°C and lignin between 280°C and 500°C (Sjöström, 1993). The long chains of C, hydrogen (H) and oxygen (O) compounds that form biomass components break down into smaller molecules in the form of gases (CO, CO_2, H_2, CH_4 and N_2), condensable vapors, and solid char (LeBlanc et al., 2016). Above 400°C, high pyrolysis temperatures cause the condensation of C structures in complex aromatic rings, which are more resistant to weathering and microbial degradation than fresh biomass (Ascough et al., 2011).

Within the pyrolysis temperature range (350°C to 1000°C) cellulose, hemicellulose and extractive components provide the volatile pyrolysis products (liquids and gases), lignin decomposes to liquid, gas and solid char products, and minerals are oxidized (e.g., as K_2O, CaO) and remain as ash associated with the char (composed of CHO compounds) (Antal and Grønli, 2003). The pyrolysis of high lignin biomass (i.e., woody residues) at low temperature and a low heating rate tends to achieve higher biochar yield and form more recalcitrant biochars, compared to biochars made from lignin-poor, mineral-rich feedstocks (e.g., crop residues, manures and food waste), as described in Table 1-1 (Dumirbas, 2004; McBeath et al., 2014; Sun et al., 2017; Tripathi et al., 2016). Biochars from mineral-rich biomass tend to have a high exchangeable nutrient content and a high cation exchange capacity (CEC) making them particularly relevant for soil amelioration and to enhance crop productivity (Kookana et al., 2011). While the proportion of organic extractives, cellulose and hemicellulose might be of interest for those focusing on bioenergy production from pyrolysis, the lignin and mineral content of feedstock are particularly important in the production of biochar for application to soil. This point can be demonstrated by explaining how biomass sources and their transformation by pyrolysis affect the three crucial characteristics of biochar: their porous structure, their surface reactivity, and their elemental composition.

1.1.4 BIOCHAR POROSITY

Physically, biochar is a highly porous material. Biochar pores provide spaces for water retention, and surfaces for biological colonization and chemical sorption. The classification of pores in biochar materials differs from the one used in soil science, since biochar pores are divided in the following three classes: micropores (<0.002 μm), mesopores (0.002 μm to 0.05 μm), and macropores (>0.05 μm). Pores in the micro to mesopore range make the greatest contribution to the total surface area of biochar materials, while macropores provide most of the pore volume. Based on their role in chemical sorption processes, micro and mesopores will be referred to as sorption pores whereas macropores will be referred to as storage pores. Feedstock biomass and pyrolysis processes affect each pore class differently, as described in the next sections.

1.1.4.1 Storage pores

Macropores, the large storage pores in biochar, were originally the transport pores in living plants. The interconnected cells that form discrete groups of transport channels (0.1-150 μm), including vessel elements and tracheids, are morphological structures that enable movement of nutrients and water through the xylem tissue between plant organs, such as roots and leaves (Wildman and Derbyshire, 1991). The cell walls of vessel elements and tracheids in secondary xylem tissue are lignified with reinforcing lignin compounds. Both vessel elements and tracheids contain pits in their sidewalls, while vessel elements have perforation plates at the end opening. The species specific arrangement of vessels and tracheids, their size, density and number provide each biomass feedstock with a unique elementary macroporosity (Figure 1-3). For example, softwood has a uniform pore structure due to the high abundance of a single cell type (tracheids), whereas hardwoods have more complex vascular structures with large water conducting pores surrounded by narrower pores from fiber cells (Brandt et al., 2013).

During pyrolysis, the lignin contained in the vessel elements and tracheids condenses into robust two-dimensional nanosheets of conjugated aromatic C (Figure 1-4) (Deng et al., 2016). The C skeleton of condensed lignin largely retains the structure of the vascular tissues in the original plant biomass (Fuertes et al., 2010; Wildman and Derbyshire, 1991; Yao et al., 2011). Lignin's ability to resist complete thermochemical degradation under standard pyrolysis conditions (350°C to 1000°C) explains why the macroporosity of biochar materials depend primarily on the choice of feedstock biomass.

1.1.4.2 Sorption pores

The small sorption pores in biochar were not originally present in the living plant. They formed on the surfaces of the larger storage pores when high pyrolysis temperatures triggered the decomposition of two structural compounds of the plant cell wall, cellulose and hemicellulose.

In contrast to lignin and other aromatic compounds, cellulose and hemicellulose are rich in O, meaning that they possess a large quantity of O-containing functional groups (i.e., hydroxyl groups) and are more susceptible to thermal decomposition within the pyrolysis temperature range. During thermal decomposition, the hydroxyl groups of cellulose and hemicellulose compounds undergo dehydration and condensation leading to the formation of volatile substances such as CO, CO_2, and H_2O. As the pyrolysis temperature increases, the pressure produced by these volatiles increases and leads to the development of fractures and the opening of micro and mesopores on the cellular surfaces of storage pores (Birds et al., 2008; Deng et al., 2016). Due to the impact of cellulose and hemicellulose on microporosity and surface area development, the sorption capacity of biochars is strongly related to the cellulose and hemicellulose content of feedstock biomass (Carrier et al., 2013).

1.1.4.3 Biochar porosity and pyrolysis conditions

The fine physical structure of biochars is affected by the choice of feedstock biomass, as described above, as well as factors controlling the release of small molecules during the thermal decomposition of biomass. Thermal decomposition is controlled by pyrolysis temperature, which provides the activation energy to start thermochemical reactions, and the length of the pyrolysis process, which determines the extent of the decomposition reaction (Downie et al., 2009). The pore structure of biochar undergoes significant changes during pyrolysis, and the porosity is expected to increase substantially at the highest treatment temperatures (HTT). Total pore volume and specific surface area remain low at temperatures less than 350°C and increase sharply between 350 and 500°C (Trigo et al., 2016; Zhao et al., 2014). The surface area and micropore volume generally keep increasing with the HTT and pyrolysis time until the rate of destruction due to pore enlargement exceeds the rate of pore formation (Zhang et al., 2004). Heating rates also impact the pore structure of biochars because they influence the formation and release of volatiles. At lower heating rates, the slow release of pyrolysis gases through the feedstock pores maintains the inherent pore structure of the feedstock biomass. In contrast, rapid heating rates can lead to plastic deformation, melting, fusion and sintering, which diminishes the porosity of biochars (Cetin et al., 2004; Chia et al., 2015).

1.1.5 SURFACE REACTIVITY

As discussed above, biochars with larger proportions of structural pores have greater surface area for biological colonization and chemical sorption. However, the chemical properties of the surfaces will determine the binding strength of biochar for microorganisms, water, solutes and other compounds. The chemical reactivity of biochar surfaces is due to the presence of atoms, ions, or groups of atoms with electron-sharing properties. These reaction sites or functional groups influence sorption processes through such mechanisms as: electrostatic attraction, of π- π interactions, H-bonding, and ion exchange (Amonette and Joseph, 2009; Tan et al., 2015). As with its physical structure, the chemical reactivity of biochar surfaces depends on the choice of feedstock biomass and on the thermal degradation process used to produce the biochar, but it also depends on the post-production treatment and storage of the fresh biochar.

1.1.5.1 Feedstock and thermal degradation processes affecting biochar surface reactivity

Most biomass is dominated by O- and H- containing functional groups. In lignocellulosic materials, these functional groups are primary and secondary hydroxyls (-OH), carbonyls (C=O), carboxyls (R-COOH), carbon-carbon (C-C), ether (C-O-C), and acetal linkages ($R_2C(OR')_2$) (David, 1996). The O-containing groups are the most important groups in C-rich materials because they are responsible for many physico-chemical and surface properties, such as surface acidity, CEC, and adsorption of polar and non-polar gases and vapours (Ruiz-Martinez et al., 2007). During biomass pyrolysis, heat induces the weakening and cleavage of chemical bonds leading to the removal of O- and H-containing functional groups and the dehydrogenation of single bounded $R\text{-}CH_n$ (Harvey et al., 2012; Nanda et al., 2014). With increasing pyrolysis temperature, the cleavage of OH···O-type H-bonds, oxidation of free primary hydroxyls to carboxyls (carboxylation; HTT ≤ 500 °C), and their subsequent dehydrogenation/dehydroxylation (HTT > 500 °C) are responsible for the development of surface reactivity in biochar (Harvey et al., 2012). In contrast, the dehydrogenation of methylene groups, which yields increasingly condensed structures (R-CH2-R → R=CH-R → R=C=R), controls biochar's recalcitrance to microbial degradation (Harvey et al., 2012). Reactivity also varies among feedstock biomass sources. The mineral components of biomass (e.g., Si_2O, Al_2O_2, Fe_2O_3, P_2O_5) serve as additional adsorption sites, and contribute to the high adsorption capacity of biochars made from nutrient-rich biomass (Cao et al., 2009; Tan et al., 2015; Xu et al., 2013a,b).

High pyrolysis temperature reduces the total number of functional groups present on the surfaces of fresh biochar, lowers the number of electron-donating phenolic moieties and increases the number of electron accepting quinone moieties (Klüpfel et al., 2014; Trazzi et al., 2016). Due to the removal of O- and H- bearing functional groups during pyrolysis, the surfaces of fresh biochar are often hydrophobic and have low surface charge (Glaser et al., 2000).

1.1.5.2 Biochar storage affecting surface reactivity

The number of surface functional groups increases rapidly when biochar is exposed to an oxygenated environment (Hammes and Schmidt, 2009; Tan et al., 2015). Biochar reacts readily with atmospheric O to generate negatively charged O-containing carboxyl, hydroxyl and phenolic surface functional groups (Atkinson et al., 2010; Uchimiya et al., 2011). These oxidized functional groups enable the adsorption of organic C, which in turn adds to the functionality of biochar (Hammes and Schmidt, 2009). With time, the increase in functional groups leads to a replacement of positive surface charges by reactive, negatively charged carboxyl, hydroxyl and phenolic surfaces (Cheng et al., 2006, 2008). Aged, oxygenated biochar is a complex material with heterogeneous surfaces that can exhibit hydrophilic, hydrophobic, acidic and basic properties.

1.1.6 ELEMENTAL COMPOSITION

Biochar is primarily C (56.4-86.4%), but it can also contain O, H and mineral compounds (Yao et al., 2012). During the pyrolysis process, some of the minerals contained in the feedstock biomass are preferentially volatilized in the form of gases and particulates, and other become co-stabilized with C (Angst and Sohi, 2013). For example, up to 50% of nitrogen (N), potassium (K) and sulphur (S) are commonly lost when pyrolysis temperatures exceed 500°C (Bagreev et al., 2001). Considering that 17 elements are essential plant macro- and micro-nutrients, it is informative to know how these substances will be affected by pyrolysis. During pyrolysis, the elements lost from the feedstock biomass often follow the order N >> K > Mg > Ca > P (Schlesinger and Bernhardt, 2013). Due to the preferential volatilization of N, most biochars have very low N concentrations and thus cannot be regarded as N-fertilizers (Allaire et al., 2015). In contrast, pyrolysis increases the concentration of total P and micronutrients (Ca, Fe, Mg, S, Cu and Zn) in biochars (Hossain et al., 2011). Biochars from mineral-rich biomass tend to have a higher nutrient content than those from mineral-poor biomass (Table 1-2), making them particularly relevant for soil application to improve soil quality and enhance crop productivity.

1.2 Biochar-induced changes in soil quality and crop productivity

1.2.1 PHYSICAL INDICATORS OF SOIL QUALITY AFFECTED BY BIOCHAR APPLICATION

Biochar is proposed as a soil additive that will mitigate climate change through long-term sequestration of C while simultaneously improving soil quality and crop production (Jeffery et al., 2011; Kookana et al., 2011; Verheijen et al., 2010). Soil quality is assessed through the quantification of management-dependent soil properties or soil quality indicators. This section will review the mechanisms by which biochar amendments can affect some of these indicators, namely: bulk density, aggregate stability, water holding capacity, pH, CEC, SOM content, and nutrient content.

1.2.1.1 Bulk density

Bulk density reflects the fraction of dry soil and pore space within the three-dimensional soil matrix. It affects gas diffusion, water and solute movement, as well as plant root growth and soil tilth. Biochar-amended soils generally have a significantly lower bulk density than those that are not mixed with biochar in controlled laboratory experiments (Abel et al., 2013; Herath et al., 2013; Jien and Wang 2013; Laird et al., 2010; Novak et al., 2012; Ulyett et al., 2014) and field experiments (Abel et al., 2013; Hardie et al., 2014; Major et al., 2010; Mukherjee et al., 2014a; Rogovska et al., 2014; Zhang et al., 2010). Most studies agree that the dilution of soil mineral fraction following biochar addition is the mechanism responsible for bulk density reduction (Busscher et al., 2010; Herath et al., 2013; Ulyett et al., 2014). Physical dilution occurs when low-density materials displace some of the solid soil mass and increases the pore space in a given volume of soil. As the bulk density of biochar materials ranges from 0.08 Mg m^{-3} to 1.7 Mg m^{-3} (Gundale and DeLuca, 2006; Oberlin, 2002), generally below the threshold separating high and low bulk density of clay soils (1.24 Mg m^{-3}), loamy soils (1.33 Mg m^{-3}) and sandy soils (1.65 Mg m^{-3}), the use of biochar amendments can be an effective way to alleviate compaction in soils with high bulk density (Pachepsky and Park, 2015).

In addition to the physical dilution effect, biochar could further reduce bulk density by promoting the formation of soil macroaggregates. In controlled laboratory experiments, Herath et al. (2013), and Jien and Wang (2013) observed reductions of soil bulk density that were greater than what could be explained by physical dilution alone. In a field experiment, Obia et al. (2016) reported that the dilution effect was responsible for reducing bulk density of sandy soils whereas increased macroporosity contributed more to reduce bulk density in loamy soils. In conclusion, evidence suggests that biochar could be a good soil amendment to reduce bulk density, thereby improving soil tilth and alleviating the negative effects of soil compaction on soil functions and crop growth.

1.2.1.2 Soil aggregate and aggregate stability

Soil aggregates bind loose particles together and retain organic C and other nutrients that would otherwise be susceptible to erosion (Sachdeva, 2013). The formation of soil aggregate occurs when organo-minerals make contact with organic and inorganic binding agents (Lynch and Bragg, 1985; Oades, 1993; Tisdall and Oades, 1982). While soil organic matter content and clay content are the primary determinants of aggregation in biochar-amended soil (Khademalrasoul et al., 2014), biochar properties such as surface area and the O:C ratio on reactive surfaces could enhance the preliminary stage of aggregate formation and stabilization by providing additional binding sites for clays and organic compounds (Joseph et al., 2010). Biochar amendments promote the formation of macroaggregates (Jien and Wang, 2013; Sun and Lu, 2014), and increase the stability of both macroaggregates (Herath et al., 2013; Khademalrasoul et al., 2014; Lu et al., 2014; Obia et al., 2016) and microaggregates (Hua et al., 2014; Sachdeva., 2013). Positive effects of biochar on aggregate formation and stability have been observed in longer (>100 days) laboratory and greenhouse experiments, but seldom in shorter laboratory trials and field experiments (Borchard et al., 2014; Busscher et al., 2011; Hardie et al., 2014; Mukherjee et al., 2014a; Peng et al., 2011). Researchers have proposed three mechanisms through which biochars can positively affect soil aggregate formation and stability: (1) increased soil hydrophobicity, (2) development of organo-mineral complexes, and (3) stimulation of plant and microbial activity.

Increased soil hydrophobicity is related to the hydrophobic nature of fresh biochar, which could enhance the water-stable aggregates in the short-term. This effect is not expected to persist because surface oxidation causes biochar to become more hydrophilic, which would make it more susceptible to physical, chemical, and biological weathering (Glaser et al., 2000; Hammes and Schmidt, 2009; Zimmerman, 2010). The second mechanism proposes that biochars could increase the binding of soil particles. Oxidized biochar has negatively charged functional groups (e.g., carboxylic and phenolic groups) and high net negative surface charge, relative to fresh biochar (Atkinson et al. 2010; Uchimiya et al. 2011). As oxidation develops surface functionality, biochar particles could bind with soil microaggregates to form larger macroaggregates (Jien and Wang, 2013). The interactions of biochar with SOM and soil minerals could further promote the development of organo-mineral complexes and soil aggregates that contain biochar, thereby protecting the biochar from degradation and increasing its residence time in the soil (Gul et al., 2015). A third possible mechanism is that biochars could affect soil aggregates by stimulating the growth of plants (Bruun et al., 2014; Naeem et al., 2016; Schulz et al., 2013) and soil microbes (Jaafar et al., 2015; Jones et al., 2012; Lehmann et al., 2011). Soil aggregates in the 20-2000 μm range are bound together by microbial and plant derived binding agents (root, root hair, fungal hyphae, and polysaccharides) (Scott et al., 1998). Biochar addition to soil could increase biological activity, and have an indirect and positive effect on soil aggregation. Field studies monitoring the formation and stability of soil aggregates in biochar-amended soils are required to investigate the supporting evidence for these mechanisms.

1.2.1.3 Soil moisture regimes

Agricultural soils must have the right balance between water storage and water movement to support crop production and ecosystem functions. Non-irrigated soils that can retain moisture have the capacity to support plant growth during dry periods, and are less susceptible to losses of nutrients by leaching during wet episodes. Increasing the soil water holding capacity (WHC) may become increasingly important to optimize water use as the growing conditions become more stressful (i.e., more heat stress and water stress) in the context of global climate warming. Improvements to soil moisture regimes are soil-specific, such that it might be desirable to increase the meso and microporosity of coarse textured soil, or to increase the number of macropores in fine textured soils.

Biochar properties that directly impact soil water dynamics are particle shape, size, internal porosity, and biochar surface chemistry (ratio of hydrophilic to hydrophobic domains) (Masiello et al., 2015). Biochar amendments have been reported to decrease water movement in saturated sandy soils (Barnes et al., 2014: Brockoff et al., 2010; Ibrahim et al., 2013; Uzoma et al., 2011) and increase water movement in saturated medium to fine textured soils (Asai et al., 2009; Herath et al., 2013; Jien and Wang, 2013). Biochar amendments have also been reported to increase the water holding capacity and plant available water in coarse-textured soils (Abel et al., 2013; Basso et al., 2012; Brigg et al., 2012; Busscher et al., 2011; Githinji et al., 2014; Liu et al., 2012). When differences in soil water regimes are observed after biochar application they are generally attributed to: (1) water retention in biochar pores, and (2) changes in the volume, size and connectivity of the pore space within the soil (Barnes et al., 2014; Hardie et al., 2014; Karhu et al., 2011; Sun and Lu, 2014; Tammeorg et al., 2014;).

The general effects of biochar on soil moisture regimes are not consistent, as many studies do not report differences between biochar amended soils and control soils (Hardie et al., 2014; Sekar et al., 2014; Verheijen et al., 2010). One possible explanation is that a biochar effect would be more easily observed if the physical characteristics of the biochars differ from those of the amended soil. Time could also be an important consideration, as biochar oxidation, weathering and biochar-mediated aggregate formation could all affect soil moisture regimes long after biochar application to agricultural soils.

1.2.2 CHEMICAL INDICATORS OF SOIL QUALITY AFFECTED BY BIOCHAR APPLICATION

The general causes of fertility depletion are due to: (1) loss of nutrients and OM resulting from a negative balance between outputs (resulting from harvesting, burning, leaching) and inputs (e.g., manure, fertilizers, returned crop residues), and (2) a decline in CEC due to loss of base saturation, or reduction of pH through soil acidification, that lowers the concentration of exchangeable and bioavailable nutrients (Osman, 2014). Although the effects of biochar amendments are known to vary between soil type and agricultural production system, biochars have been observed to increase soil pH, soil CEC, and SOM content, and improve nutrient retention and fertilizer use efficiency (Atkinson et al., 2010; Cao et al., 2009; Sohi et al., 2010; Spokas et al., 2009).

1.2.2.1 Soil pH and CEC

A pH increase is often observed in biochar-amended soils because of the presence of negatively charged carboxyl, hydroxyl and phenolic groups (Brewer and Brown, 2012; Chintala et al., 2014) that bind H^+ ions, thereby reducing the H^+ ion concentration in the soil solution and increasing the soil pH value (Gul et al., 2015). As biochar increases the pH-dependent charge of the soil, it contributes to an increase in CEC (Chan et al., 2007; Ducey et al., 2013; Liang et al., 2008; Masto et al., 2013; Mukherjee and Lal, 2013; Nelissen et al., 2012; Taketani et al., 2013). This is attributed to retention of base cations via enhanced binding to the negatively charged functional sites of biochar, as well as to SOM and organo-mineral complexes which have more negative charges when exchangeable H^+ ions are present in soil solution (Gul et al. 2015). Oxygen containing alcohol, carbonyl, and carboxylate functional groups are all believed to contribute to the CEC of biochar because they are negatively charged and serve as Lewis bases for the sorption of cations (Lawrinenko and Laird, 2015). Biochars containing oxonium and pyridinic functional groups also have significant levels of anion exchange capacity (AEC), which could play an important role in reducing the leaching of anionic nutrients such as nitrate (NO_3^-) (Lawrinenko and Laird, 2015).

1.2.2.2 Organic matter

Organic matter is a key component for the maintenance of a high quality soil, since many soil properties (e.g. microbial activity, CEC and soil aggregation) are directly affected by the SOM content (Dick and Gregorich, 2004). Organic inputs, such as biochars, can affect SOM content as a result of their quantity and biodegradability, and there is generally a direct relationship between the amount of organic inputs and SOM content (Paustian et al., 1997). Biochar applications can increase the SOM content (Agbna et al., 2017; Kimetu et al., 2008; Zhang et al., 2016) especially when biochar is co-amended with other organic amendments (Luo et al., 2017; Plaza et al., 2016). The changes in the SOM content of biochar-amended soils are not simply a function of the amount of biochar added since fresh biochar can accelerate or slow down the rate of native SOM mineralization (Whitman et al., 2015). Biochar amendments have been observed to increase (Keith et al., 2011; Singh and Cowie, 2014; Zimmerman et al., 2011), decrease (Dempster et al., 2011; Jones et al., 2012; Keith et al., 2011; Kuzyyakov et al., 2009), or have no significant effect (Cross and Sohi, 2011; Mukome et al., 2013; Prayogo et al., 2013) on SOM mineralization. Increase in native SOM mineralization rates were attributed to increased microbial activity and enzyme production stimulated by: (1) direct effects related to the presence of metabolizable substrates in biochar, namely labile C compounds that are readily hydrolyzed by extracellular enzymes and assimilated by soil microorganisms, and (2) indirect effects such as changes in soil pH, alleviation of nutrient constraints or improved microbial habitat that favor biochemical or microbial processes (Luo et al., 2013; Singh and Cowie, 2014; Whitman et al., 2015). Decrease in native SOM mineralization rates were attributed to: (1) direct effects such as substrate switching when energy rich organic compounds from biochar compounds were used preferentially by soil microorganisms, and (2) indirect effects, such as the sorption of labile soil organic C on biochar surfaces (Singh and Cowie, 2014; Whitman et al., 2015; Zimmerman et al., 2011).

Biochar characteristics such as the proportion of labile to aromatic C, surface functionality, pH, nutrient content, and porosity should be considered for their effect on SOM dynamics. It is difficult to predict how biochar induced changes in SOM will affect the SOM content in the long-term, but Ameloot et al. (2013) suggest that rapid mineralization of labile biochar compounds by microorganisms, followed by a slower decomposition of the more stable aromatic C components in biochar, could increase the SOM content. Since conventionally managed agroecosystems are a net source of GHG due to CO_2 and N_2O emissions, biochar represents an opportunity to offset GHG emission by increasing carbon storage in agricultural soils. With its aromatic structure, biochar represents a stable and recalcitrant carbon pool, which provides a promising potential carbon storage strategy as a soil amendment. Mathews, (2008) suggests that the use of biochar soil amendments could lead to the removal of up to 4 gigatonnes of atmospheric C per year, and Roberts et al., (2010) estimated the net GHG emissions of crop residues and yard waste biochars to be in the order of -850 kg CO_2 equivalent (CO_2e) emissions reductions per tonne of dry biomass.

1.2.2.3 Soil N and P concentrations

Nitrogen is the most limiting plant nutrient in most cold or temperate terrestrial ecosystems, including agroecosystems (Vitouset and Howarth, 1991), but it can become a highly problematic pollutant once it leaves terrestrial ecosystem and enters aquatic systems or the atmosphere (Groffman, 2012). Large quantities of N are lost from agroecosystems in runoff waters in the form of NO_3^- and in emissions of N-containing gases such NO_x, N_2O and N_2, the most deleterious of these being N_2O due to its global warming potential (Schlesinger and Bernhardt, 2013). Although the total N content of biochars can reach 58.5 g kg^{-1} (Table 1-2), the amount of plant-available N present as NO_3^- is <0.01 percent (Ippolito et al., 2015). The low concentration of plant-available NO_3^- and ammonium (NH_4^+) in biochar are expected, given that bioavailable N is susceptible to loss in gaseous N forms during pyrolysis (Amonette and Joseph, 2009). Despite its minimal direct N contribution, biochars have a significant effect on soil and atmospheric N.

Various experiments have reported reductions of N-leaching from soils where biochar was added (Ding et al., 2010; Kameyama et al., 2012; Laird et al., 2010; Lehmann et al., 2003). These reductions are attributed to: (1) the increased sorption of NH_4^+ to biochar surfaces, and (2) the stimulation of microbial N-immobilization in response to the presence of labile C in the biochar (Angst et al., 2014; Clough and Condron 2010; Clough et al., 2013). Although very few biochars display NO_3^- adsorption ability, the negatively charged surfaces of biochar can have a significant effect on NH_4^+ sorption (Yao et al., 2012), leading to a lower concentration of extractable NH_4^+ in agricultural soils amended with hardwood biochar (DeLuca et al., 2015; Zhang et al., 2015). Aside from providing additional surfaces for NH_4^+ sorption, biochar can further reduce N leaching by promoting the activity of N-immobilizing microorganisms through the provision of labile C (Van Zwieten et al., 2015). Biological immobilization of mineral N is biochar dependent however, and may be only applicable to fresh biochar produced through fast pyrolysis at low temperature (Bruun et al., 2012).

Biochar-induced changes in soil water regimes, soil pH, and changes in bacterial community composition provide additional mechanisms to control N_2O emissions. Changes in soil aeration / soil moisture content associated with biochar addition can reduce N_2O emissions by decreasing the prevalence of anaerobic pockets where bacterial mediated denitrification processes are more likely to occur (Rondon et al., 2005; Yanai et al., 2007). There is also evidence that when the pH of a soil is increased, denitrification liberates less N_2O and the ratio of N_2O / N_2 is lower (Yanai et al., 2007). The more alkaline soil pH achieved through biochar addition can encourage the activity of the N_2O -reductase enzymes of denitrifying organisms, which converts N_2O into N_2 gas (Yanai et al., 2007). These same denitrifying organisms (e.g. Bradyrhizobium) have the capacity to completely reduce NO_3^- to N_2, thus minimizing the N_2O flux from biochar-amended soils (Anderson et al., 2011).

Phosphorus, like K, is an example of a non-volatile mineral that is concentrated during pyrolysis. The pyrolysis process used to produce biochar preferentially volatilizes organic C over P, such that biochar may contain up to 4 times higher P concentration than in the original feedstock (Angst and Sohi, 2013). Thermal mineralization also changes P availability from plant tissue by cleaving organic P bonds and converting organic P into inorganic forms (Angst and Sohi, 2013; DeLuca et al., 2015). As a result of these changes, biochars contain an important pool of soluble P. Since 5 to 20% of the P contained in biochar is soluble and readily released into the soil solution, the contribution of biochar to the soil nutrient supply can be significant (Buecker et al., 2016; DeLuca et al., 2015). Studies such as Angst and Sohi, (2013) have also shown that the release of P from biochar tends to be gradual, sustained and can extend over several field seasons.

Biochar provides an input of plant-available P, but it also influences P behavior in soil, directly and indirectly, by altering the soil pH, changing the microbial community structure and affecting enzyme efficiencies (DeLuca et al., 2015). The bioavailability of P in soil is significantly reduced through precipitation reactions with aluminum (Al^{3+}) and iron (Fe^{3+}) when pH is below 6.5 and with calcium (Ca^{2+}) when pH is greater than 6.5 (DeLuca et al., 2015; Stevenson and Cole, 1999). Biochar can influence precipitation of P into insoluble pools by altering the pH and thus the strength of P binding reactions with Al^{3+}, Fe^{3+} and Ca^{2+} (Lehmann et al., 2003; Topoliantz et al., 2005). Most biochars applied as soil amendments tend to have a liming effect and increase the pH of acidic soils, so are seen as a way to reduce P precipitation and improve the bioavailability of P to crops.

Biochar amendment to agroecosystems may change the rates of P cycling by promoting the growth of bacteria involved with P mobilization. Laboratory studies have shown that biochar addition induces an increase in phosphatase activity (Bailey et al., 2010; Jindo et al., 2012; Yoo and Kang, 2010), which is responsible for the release of P from SOM and organic residues. Molecular analyses of soils amended with biochar also revealed more genes of bacterial genera that produce P solubilizing compounds (Anderson et al., 2011; Hamdali et al., 2008). These observations indicate that biochar amendment could be integrated in a new set of best management practices to control P cycling in agroecosystems and increase the the amount of P available for plant uptake.

1.2.3 CROP PRODUCTIVITY OF BIOCHAR-AMENDED SOILS

The interest in using biochar as a soil amendment to improve the productivity of modern food production systems was sparked by the archeological discovery of the *Terra preta* soils in the Amazonian forest of Brazil. These soils were formed over two thousand years ago as a consequence of human activity (Glaser et al., 2000). *Terra preta* soils differ from the weathered Oxisol that characterize tropical rain forests in that they possess high levels of stable OM, CEC, and a high resistance to degradation (Glaser et al., 2002). They can achieve yield 63 times greater, and sustain plant species richness 11 times greater than the corresponding adjacent Oxisols (Major et al., 2005). The exact mechanisms operating in *Terra preta* soils are not fully understood, but scientists believe that the biochar inputs are responsible for the fertile nature of these soils and could be replicated in other soil types and growing environments.

Many reports exist on crop production in biochar-amended soils, and were summarized by Liu et al. (2013), who concluded that crop responses to biochar-amended soils are variable. The greatest yield gains were observed in acidic, and poorly-structure tropical soils, and in pot experiments (Liu et al., 2013). Results from Table 1-3 indicate that biochar amendments are not generally as effective at increasing field crop productivity in temperate climate. However, biochar amendments to temperate agroecosystems have generated positive yield increases when: (1) the soil had low inherent fertility at initiation of the experiment (Zhang et al., 2016), (2) the annual rainfall was low (Genesio et al., 2015), and (3) the biochar had had a chance to interact with the soil environment for more than one cropping season (Griffin et al., 2017; Jones et al., 2012; Rogovska et al., 2014). These findings suggest that biochar could enhance crop yields if it contributes to overcome specific constraints (i.e., fertility, water limitation) that are limiting productivity. It also suggests that biochar could provide resilience to a cropping system experiencing abnormal stress conditions (e.g., drought). Finally, researchers should remember that biochar is a dynamic substance that is modified from its original form after it is introduced into the soil environment, and that multi-year field research is essential to capture the impact of these changes in the long term.

1.2.4 SUITABILITY OF BIOCHAR MATERIALS TO IMPROVE SOIL QUALITY AND CROP PRODUCTIVITY IN CANADIAN MARITIME POTATO CROPPING SYSTEMS

Canada's Maritime provinces are characterized by naturally compacted subsoils, in addition to compaction from farming activities on moist soils. In this region, almost one-third of the arable land used for annual crops has poor soil structure (Acton and Gregorich, 1995). Soil structural degradation is a serious problem in land under potato production in northeastern New Brunswick. Compaction, the most common type of soil degradation in this region, is the result of machinery traffic on soils that have been pulverized by tillage and harvesting operations. The practice of continuous row-cropping without adequate crop rotation has also degraded soils by depleting SOM and causing structural instability, fertility problems, and accelerated water erosion. Additionally, the sustained export of farm products without compensating organic amendments causes a decline in levels of SOM, the degradation of soil structure, a decline in soil CEC, a decline in the capacity of soils to hold nutrients and water, and ultimately a decline in soil productivity (Wilhelm et al., 1986). In Atlantic Canada, the on-farm costs of soil degradation already total over 48 million dollars annually, and in high risk areas, it is estimated that many farmers either have had their net returns from farming reduced by 50% or more, or have been forced to expand their operation by cultivating marginal land (Girt, 2013).

Biochar has potential to improve the soil quality and plant productivity in degraded potato soils because it could overcome the current limitations of those soils by: improving soil structure, soil aggregate stability, and soil moisture regimes, increasing SOM, reducing nutrient leaching, and stimulating soil microbes. To date, only six published experiments have studied the use of biochar in potato production. In pot experiments, biochar was observed to increase plant biomass and plant P uptake under low P fertilization (Liu et al., 2017). Biochar adsorption of Na^+ ions was responsible for mitigating salinity stress in potato (Akhtar et al., 2015). Soil pH and EC were observed to increase with increasing rates of biochar application (Upadhyay et al., 2014). In field experiments, soil bulk density decreased, and soil porosity increased with increasing rates of biochar application, and biochar application significantly increased soil-extractable K, Mg, and B, but the addition of biochar did not affect soil moisture regimes, or the yields of potato tubers (Jay et al., 2015; Koga et al., 2017; Yang et al., 2015). Field experiments monitoring both soil quality indicators, and crop response are necessary to determine whether biochar amendments are well suited for commercial potato cropping systems, and whether the benefits of biochar application can offset the costs associated with its use.

1.2.5 FUTURE DIRECTIONS

The availability of feedstock biomass, and the development of pyrolysis technologies, create opportunities for the use of biochars in Canada. Benefits such as improvements in soil quality, long-term C-storage, and increases in crop productivity have all been observed in biochar-amended soil, but it is also well understood that these benefits are dependent on the interactions between biochar, soil, climate, and time. With this in mind, and because of the longevity of biochar in the soil environment, it is essential to develop a local understanding of the challenges and opportunities associated with the use of biochar. Field studies are needed to determine if the biochar products currently available in Canada can: (1) be used in Canadian food production systems without negatively impacting yields, and (2) be used to remediate the soil degradation issues encountered in these same food production systems. This study aims to do just that by amending commercially produced biochars made from locally sourced biomass to a traditionally managed potato cropping system.

The objective of this research was to determine the effects of biochar type and application rate on potato crop response and on physico-chemical indicators of soil quality. Specifically, this research was conducted to answer three questions:

(1) Can commercially available biochar improve soil quality and potato productivity in an optimally-managed potato cropping system on a loamy soil under rainfed production?
(2) Will greater improvements in soil quality attributes be achieved with higher biochar application rates?
(3) Will soil quality attributes respond differentially to the type of biochar applied?

The following hypotheses were developed to address these questions:

Hypothesis 1: Biochar will positively affect soil properties associated with soil structure, soil moisture, and soil fertility, and will increase tuber yield.

Hypothesis 2: Increasing the biochar application rate will augment the positive effect of biochar on soil properties and tuber yield.

Hypothesis 3: Wood-based biochar made from diverse feedstock and manufacturing processes will be equally effective at benefiting soil properties and potato yield.

Table 1-1. General properties of biochars from lignin-rich and lignin-poor substrate

Feedstock	Reaction conditions			Biochar yield (g kg^{-1})	Total C (g kg^{-1})	H:C[a]	Mineral constituents (g kg^{-1})			Reference
	HTT (°C)	Heating rate (°C min^{-1})	Residence time (min)				N	P	K	
Miscanthus grass	350	6	240	408	669	0.67	7	N.D.	N.D.	Brewer et al., 2014
Miscanthus grass	550	6	240	283	818	0.31	5	N.D.	N.D.	
Miscanthus grass	700	6	240	240	842	0.12	6	N.D.	N.D.	
Mesquite wood	350	6	240	505	700	0.65	7	N.D.	N.D.	
Mesquite wood	550	6	240	342	798	0.36	13	N.D.	N.D.	
Mesquite wood	700	6	240	299	843	0.15	7	N.D.	N.D.	
Bull manure	350	<10	80-90	N.D.	663	0.72	13	2.644	24.389	Enders et al., 2012
Bull manure	500	<10	80-90	N.D.	741	0.41	11	3.115	33.477	
Corn stover	350	<10	80-90	N.D.	652	0.69	12	1.889	21.486	
Corn stover	500	<10	80-90	N.D.	703	0.32	11	1.852	24.817	
Dairy manure	350	<10	80-90	N.D.	632	0.77	18	1.81	10.074	
Dairy manure	500	<10	80-90	N.D.	725	0.42	14	1.754	9.63	
Poultry manure	350	<10	80-90	N.D.	187	0.89	20	21.256	31.751	
Poultry manure	500	<10	80-90	N.D.	168	0.35	11	30.555	48.616	
Hazelnut shells	350	<10	80-90	N.D.	731	0.60	5	0.279	4.142	
Hazelnut shells	500	<10	80-90	N.D.	806	0.44	5	0.275	4.297	
Oak wood	350	<10	80-90	N.D.	748	0.54	2	0.011	1.147	
Oak wood	500	<10	80-90	N.D.	853	0.41	2	0.050	1.171	
Pine wood	350	<10	80-90	N.D.	707	0.74	1	0.049	0.387	
Pine wood	500	<10	80-90	N.D.	818	0.42	1	0.001	0.682	
Pine wood	450	N/A	0.5	266	718	0.66	2.3	0.162	1.684	Kim et al., 2011
Pine wood	600	N/A	0.5	152	846	0.4	2.3	0.281	2.889	
Pine wood	800	N/A	0.5	95	897	0.17	2.6	0.439	4.237	

Switchgrass	450	N/A	0.5	313	665	0.62	12.8	1.963	11.309	
Switchgrass	600	N/A	0.5	169	715	0.42	11.3	2.400	16.452	
Switchgrass	800	N/A	0.5	114	716	0.19	8.6	4.046	16.734	
Waste paper	500	N/A	120	N/A	554	N/A	2.6	0.05	N.D.	Rehrah et al., 2016
Waste paper	500	N/A	240	N/A	568	N/A	N/A	0.04	N.D.	
Waste paper	500	N/A	360	N/A	574	N/A	3.5	0.04	N.D.	
Landscape waste	500	N/A	120	N/A	458	0.66	17.6	0.85	N.D.	
Landscape waste	500	N/A	240	N/A	457	0.50	18.4	0.95	N.D.	
Landscape waste	500	N/A	360	N/A	436	0.57	16.1	0.95	N.D.	
Wood waste	500	N/A	120	N/A	711	0.18	N/A	0.05	N.D.	
Wood waste	500	N/A	240	N/A	858	0.44	1.1	0.03	N.D.	
Wood waste	500	N/A	360	N/A	789	0.45	0.7	0.05	N.D.	
Cow manure	500	18	240	572	437	N.D.	N.D.	0.646	1.021	Zhao et al., 2013
Pig manure	350	18	240	575	391	N.D.	N.D.	2.940	2.380	
Pig manure	500	18	240	385	427	N.D.	N.D.	4.386	3.560	
Pig manure	650	18	240	358	453	N.D.	N.D.	4.720	3.830	
Shrimp hull	500	18	240	334	521	N.D.	N.D.	2.585	2.585	
Waste paper	500	18	240	366	560	N.D.	N.D.	0.124	0.079	
Sawdust	500	18	240	283	758	N.D.	N.D.	0.061	1.189	
Grass	500	18	240	278	621	N.D.	N.D.	0.590	5.151	
Wheat straw	350	18	240	525	598	N.D.	N.D.	0.042	2.940	
Wheat straw	500	18	240	298	625	N.D.	N.D.	0.074	5.182	
Wheat straw	650	18	240	265	689	N.D.	N.D.	0.082	5.750	
Peanut shell	500	18	240	320	737	N.D.	N.D.	0.166	1.733	

[a] Molar ratio
N/A not available
N.D. not determined

Table 1-2. Nutrient content of biochars from mineral-rich substrate

Feedstock	Reaction conditions		Total C	H:C[a]	Mineral constituents (g kg^{-1})							Reference
	HTT (°C)	Residence time (min)	(g kg^{-1})		N	P	K	Ca	Mg	Fe	S	
Dairy manure	0	N/A	465	1.42	22.9	5.6	6.7	16.0	6.9	2.29	2.5	Cantrell et al., 2012
Dairy manure	350	120	558	0.92	26.0	10.0	14.3	26.7	12.2	3.64	1.1	
Dairy manure	700	120	567	0.20	15.1	16.9	23.1	44.8	20.6	6.48	1.5	
Feedlot manure	0	N/A	450	1.46	23.7	7.1	20.2	14.0	4.6	1.55	4.4	
Feedlot manure	350	120	533	0.91	36.4	11.4	32.0	22.7	7.7	2.26	4.5	
Feedlot manure	700	120	524	0.21	17.0	17.6	49.1	35.0	12.2	3.45	4.0	
Poultry litter	0	N/A	421	1.49	36.7	13.9	30.5	18.0	6.4	0.68	5.8	
Poultry litter	350	120	510	0.89	44.5	20.8	48.5	26.6	9.5	1.32	6.1	
Poultry litter	700	120	459	0.52	20.7	31.2	74.0	40.2	14.5	1.89	6.3	
Swine solids	0	N/A	474	1.52	41.1	24.7	10.9	23.9	15.0	3.15	9.4	
Swine solids	350	120	515	1.14	35.4	38.9	17.8	39.1	24.4	4.84	8.0	
Swine solids	700	120	440	0.20	26.1	59.0	25.7	61.5	36.9	7.48	8.5	
Turkey litter	0	N/A	404	1.50	34.3	16.1	25.0	24.1	5.3	1.47	4.8	
Turkey litter	350	120	492	0.88	40.7	26.2	40.1	40.4	8.5	2.78	5.5	
Turkey litter	700	120	447	0.24	19.4	36.6	55.9	56.1	12.4	3.65	4.1	
Poultry litter	400	40	431	N.D.	51.8	5.8	24.9	33.4	6.8	N.D.	4.9	Singh et al., 2010
Poultry litter	550[b]	40	413	N.D.	37.9	6.0	23.0	39.8	7.5	N.D.	5.1	
Cow manure	400	40	175	N.D.	13.5	4.4	26.4	17.5	10.7	N.D.	4.5	
Cow manure	550[b]	40	156	N.D.	11.4	4.9	23.1	18.8	11.8	N.D.	3.7	
Poultry litter	400	N/A	521	N.D.	58.5	20.0	38.8	28.3	17.3	2.91	N.D.	Subedi et al., 2016
Poultry litter	600	N/A	528	N.D.	40.1	28.7	58.8	35.9	24.0	4.31	N.D.	
Swine manure	400	N/A	549	N.D.	22.3	22.1	16.2	20.3	15.7	5.39	N.D.	
Swine manure	600	N/A	579	N.D.	17.9	28.2	35.3	28.9	21.3	6.67	N.D.	

Swine manure	0	N/A	422	1.86	40.0	30.2	8.0	49.7	11.2	N.D.	N.D.	Tsai et al., 2012
Swine manure	400	60	418	0.29	32.0	61.0	31.0	55.0	30.0	N.D.	N.D.	
Swine manure	600	60	411	0.23	25.0	69.0	29.0	60.0	34.0	N.D.	N.D.	
Swine manure	800	60	421	0.31	16.0	77.0	27.0	53.0	34.0	N.D.	N.D.	
Pig manure	0	N/A	365	1.63	26.0	N.D.	N.D.	N.D.	N.D.	N.D.	7.0	Zornoma et al., 2016
Pig manure	300	60	446	1.07	36.0	35.5	18.2	75.8	14.6	12.00	7.8	
Pig manure	500	240	405	0.59	27.0	46.5	24.1	97.7	20.4	11.20	9.5	
Pig manure	700	300	415	0.23	21.0	51.1	27.3	100.0	21.8	10.90	10.3	
Cotton crop residues	0	N/A	385	1.79	24.0	N.D.	N.D.	N.D.	N.D.	N.D.	3.9	
Cotton crop residues	300	60	502	1.07	28.0	5.9	45.1	53.5	13.4	0.41	12.8	
Cotton crop residues	500	240	479	0.52	23.0	7.1	65.3	77.7	18.9	0.43	20.6	
Cotton crop residues	700	300	471	0.30	19.0	7.1	73.0	79.7	19.7	0.54	22.7	
Municipal solid waste	0	N/A	341	1.78	17.0	N.D.	N.D.	N.D.	N.D.	N.D.	5.5	
Municipal solid waste	300	60	323	1.18	15.0	5.5	10.3	111.5	9.4	3.85	6.9	
Municipal solid waste	500	240	288	0.49	13.0	7.9	17.9	143.9	11.8	4.00	9.3	
Municipal solid waste	700	300	280	0.42	10.0	9.0	17.1	161.1	14.0	4.28	12.0	

[a] Molar ratio

[b] Steam activated

N/A not applicable

N.D. not determined

Table 1-3. Biochar effect on crop productivity, results from field experiment in temperate ecosystems

Crop	Soil type	Soil pH	Fertilization (% BMP)[a]	Field season	Feedstock	HTT (°C)	Biochar content ($g\ kg^{-1}$) N	P	K	Rate ($t\ ha^{-1}$)	Effect on crop yield	Reference
Wheat	Clay loam	8.0	100	1	Hardwood	500	12	0.5	4.3	10	NS	Baronti et al., 2010
Maize	Silty loam	7.1	100	1	Hardwood	500	12	0.5	4.3	10	NS	
Cauliflower	Loam	5.8	100	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	Boersma et al., 2017
Cauliflower	Loam	5.8	50	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	
Pea	Loam	5.8	100	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	
Pea	Loam	5.8	50	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	
Broccoli	Loam	5.8	100	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	
Broccoli	Loam	5.8	50	1	Eucalyptus wood	550	11	2.4	6.5	10	NS	
Grapes	Sandy clay loam	5.4	100	4	Orchard pruning	500	9.1	23.3	13.9	16.5	Increase	Genesio et al., 2015
Grapes		5.4	100	4		500	9.1	23.3	13.9	33	Increase	
Tomato/Corn rotation	Silty clay loam	6.7	100	4	Walnut shell	900	4.7	6.4	93.2	10	Increase in corn yield in 2nd year	Griffin et al., 2017
Spring Barley	Sandy clay loam	N/A	100	1	Sweet chestnut	400	3.2	1.2	1.4	20	NS	Jay et al., 2015

Spring Barley	Sandy clay loam	N/A	100	1	Sweet chestnut	400	3.2	1.2	1.4	50	NS	
Strawberry	Sandy clay loam	N/A	100	2	Sweet chestnut	400	3.2	1.2	1.4	20	NS	
Strawberry	Sandy clay loam	N/A	100	2	Sweet chestnut	400	3.2	1.2	1.4	50	NS	
Potato	Sandy clay loam	N/A	100	1	Sweet chestnut	400	3.2	1.2	1.4	20	NS	
Potato	Sandy clay loam	N/A	100	1	Sweet chestnut	400	3.2	1.2	1.4	50	NS	
Maize/Hay/ Hay Rotation	Sandy clay loam	N/A	100[c]	3	Mixed Ash, beech, oak	450	6.8	.01[b]	N/A	25	Increase in hay biomass in 3rd year	Jones et al., 2012
		N/A	100[c]	3		450	6.8	.01[b]	N/A	50		
Potato/wheat beet/soybean Rotation	Clay loam	5.8	100	4	Wood residue	800	8.2	N/A	N/A	10	NS	Koga et al., 2017
	Clay loam	5.8	100	4	Wood residue	800	8.2	N/A	N/A	20	NS	
	Clay loam	5.8	100	4	Wood residue	800	8.2	N/A	N/A	40	NS	
Corn	Loam	5.9	100	4	Hardwood	600	5	0.3	6.5	20	NS	Laird et al., 2017
Corn	Silt loam	4.5	100	4	Hardwood	600	5	0.3	6.5	20	NS	
Corn	Silt loam	7.5	100	4	Hardwood	600	5	0.3	6.5	20	NS	
Corn	Silt loam	6.7	100	3	Hardwood	600	5	0.3	6.5	20	Increase	
Corn	Silt loam	5.7	100	4	Hardwood	600	5	0.3	6.5	20	NS	
Wheat/Maize	Silty loam	8.0	100	4	Rice husk/ cotton shell	400	10	.47[b]	6.5	30	Increase	Liang et al., 2014
Wheat/Maize		8.0	100	4		400	10	.47[b]	6.5	60	Increase	
Maize	Loam	7.0	100	2	Mixed hardwood	575	6.4	N/A	N/A	19	Increase in grain yield in 2nd year	Rogovska et al., 2014
Maize		7.0	100	2		575	6.4	N/A	N/A	38		

Fave bean/ Wheat/ Turnip rape Rotation	Sandy clay loam	6.6	100	3	Debarked spruce and pine	600	6.2	N/A	32.2	5	NS	Tammeorg et al., 2014a
		6.6	30	3		600	6.2	N/A	32.3	10	NS	
		6.6	100	3		600	6.2	N/A	32.3	10	NS	
Wheat	Loamy sand	4.7	100	2	Debarked spruce	600	3.5	N/A	4.52	10	NS	Tammeorg et al., 2014b
Wheat		4.7	100	2		600	3.5	N/A	4.52	20	NS	
Wheat		4.7	100	2		600	3.5	N/A	4.52	30	NS	
Maize	Inceptisol	8.4	100	2	Wheat straw	450	5.9	N/A	26	20	Increase	Zhang et al., 2016
Maize		8.4	100	2	Wheat straw	450	5.9	N/A	26	40	Increase	

N/A not available

[a] as reported by the authors

[b] available P

[c] no fertilizer was applied in year 3

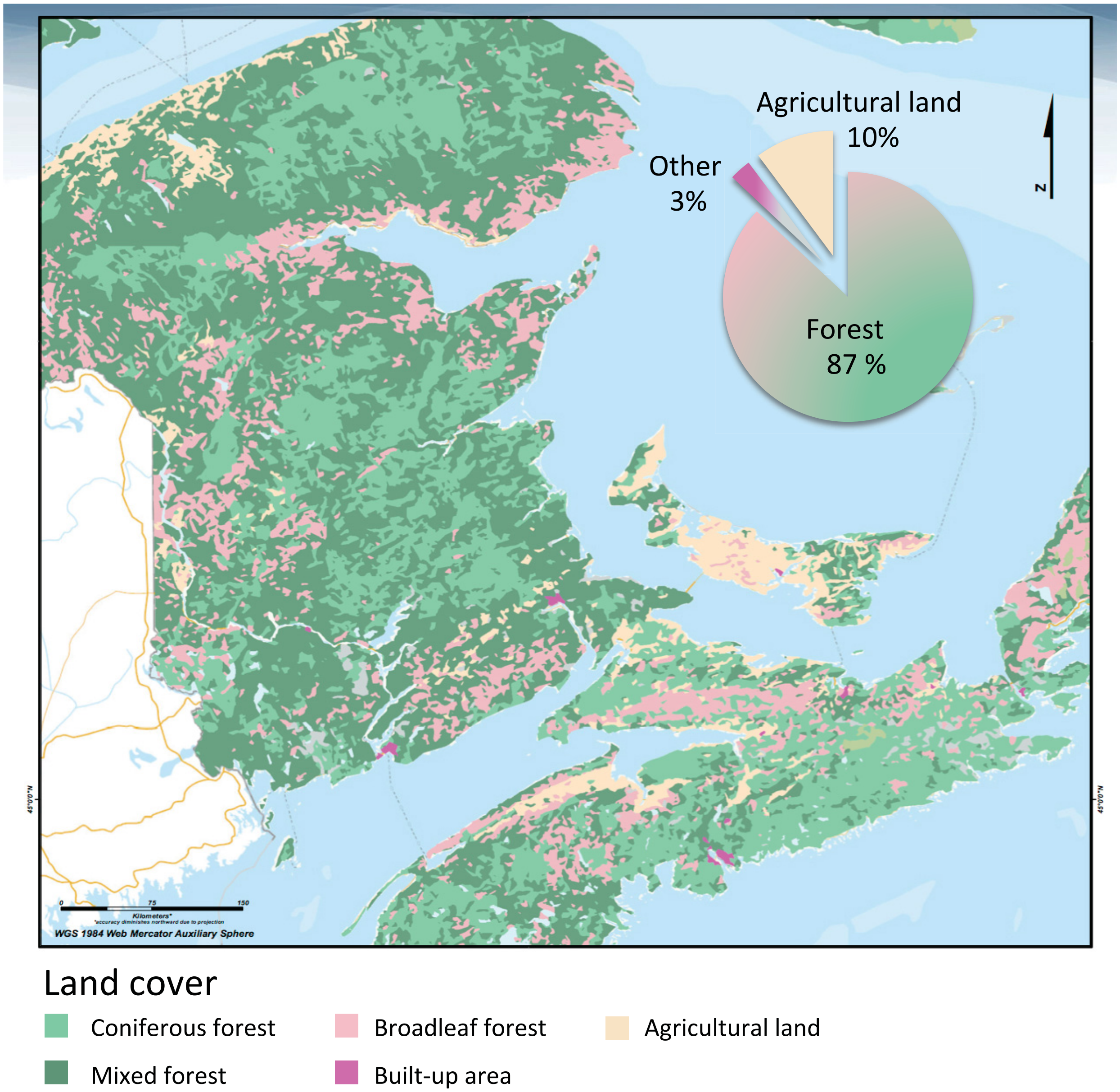


Figure 1-1. Biomass diversity in Eastern Canada (Modified from AAFC, 2017 and Ahern et al., 2011).

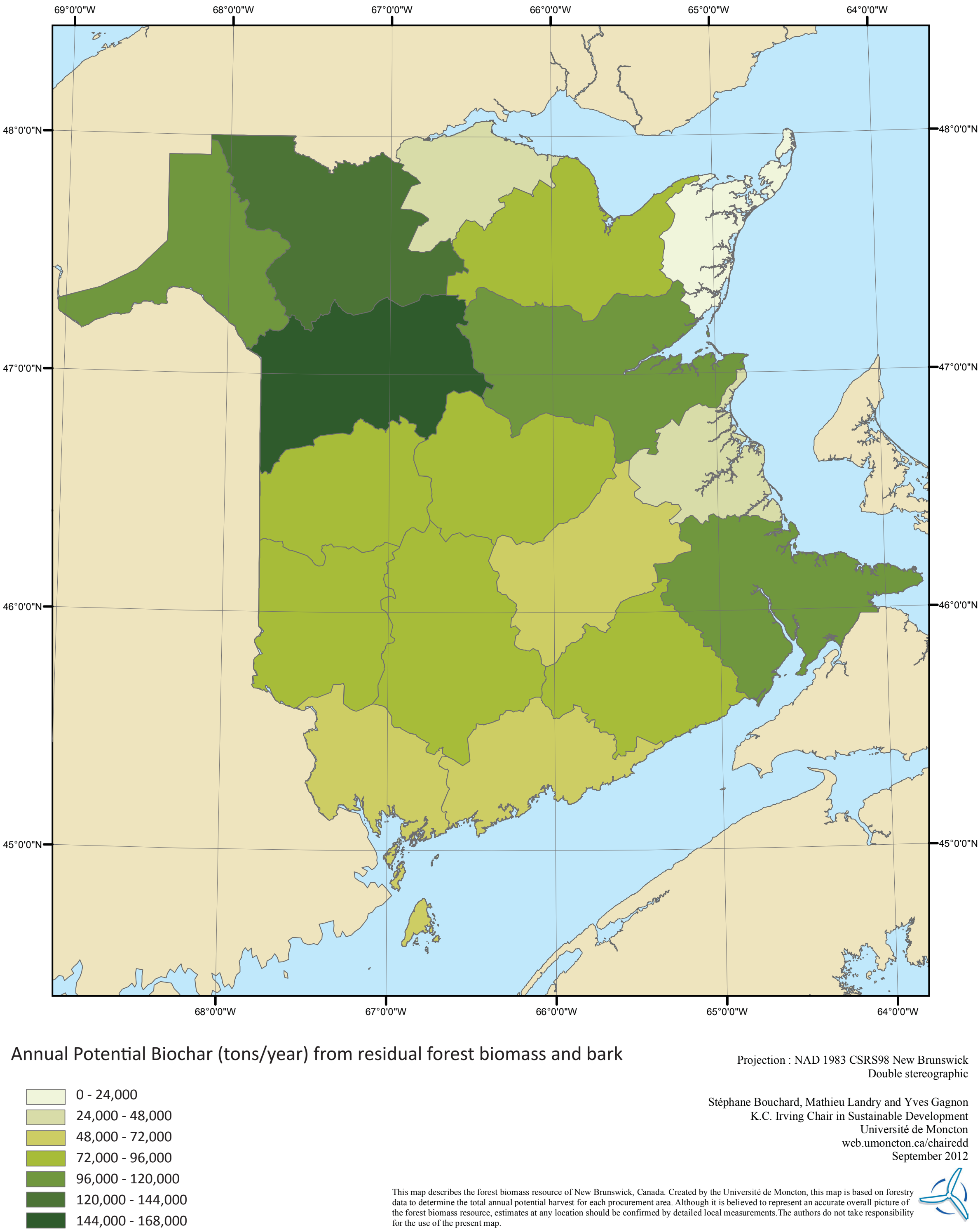
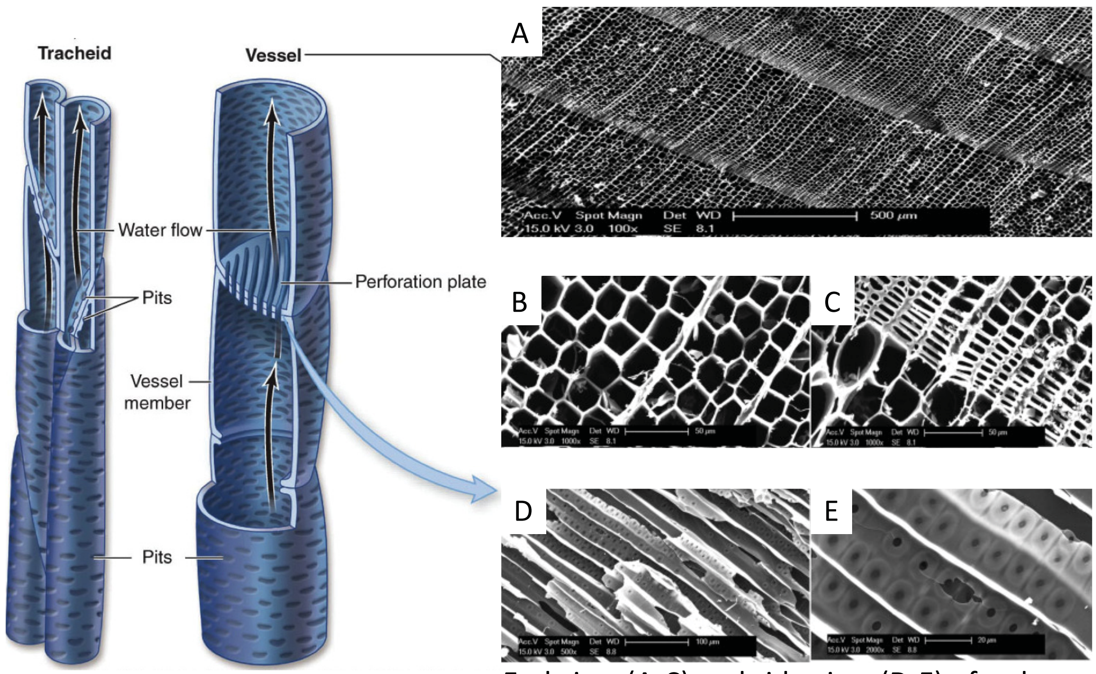


Figure 1-2. Potential biochar production from residual forest biomass in the province of New Brunswick (Modified from Bouchard et al., 2012).



End view (A-C) and side view (D-E) of red cedar biochar.

Figure 1-3. Vessels and tracheids in plant biomass as precursor of biochar macroporosity (Modified from Freeman, 2010 and Jiang et al., 2013).

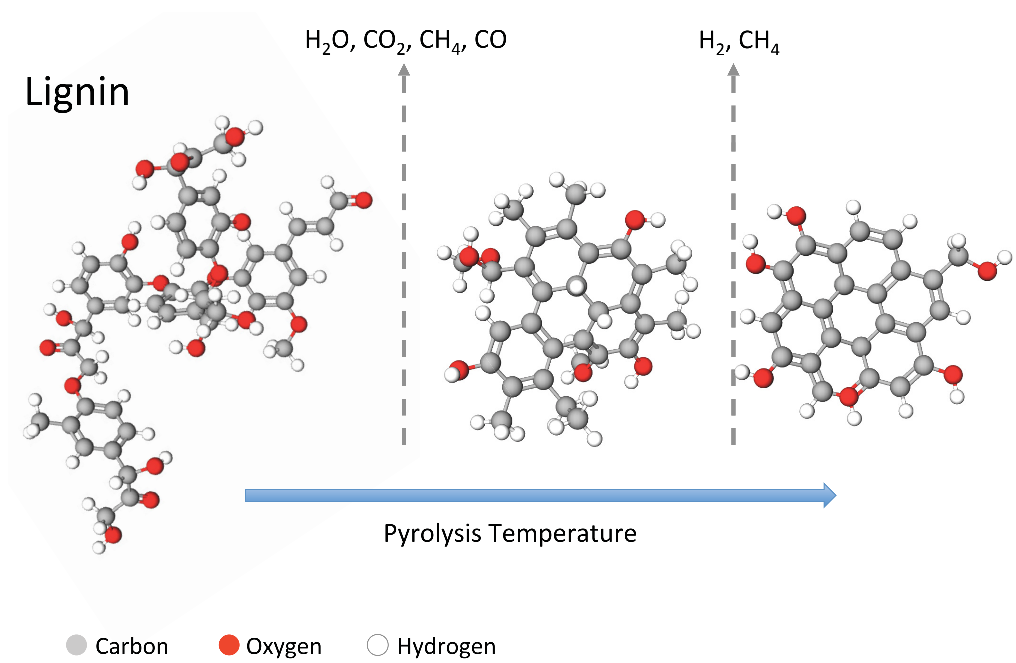


Figure 1-4. Aromatization of lignin during biomass pyrolysis (Modified from Deng et al., 2016).

2. Methods and Materials

2.1 Biochar

Two biochar products were used in this study (Table 2-1). Maple Leaf biochar is produced from unprocessed hardwood (82% maple, 18% beech logs) harvested in the Portneuf area of Québec, Canada from forests certified by the Forest Stewardship Council. The feedstock is subjected to batch-system pyrolysis in tightly closed Missouri-type ovens. Carbonization is achieved by heating the feedstock to a maximum temperature of 328°C for 37 h, followed by cooling in the kiln for an additional 70 h. Maple Leaf biochar was produced in one batch, delivered in August 2015 and stored indoors in bulk bags before it was applied to field plots in October 2015 and October 2016.

Airex biochar is produced from softwood (75% spruce and 25% fir) sawdust. The feedstock comes from the Résolu sawmill located in the municipality of La Dorée, in the Saguenay-Lac-St-Jean area of Québec, Canada. The feedstock is pyrolyzed at 454°C in a cyclonic bed reactor at atmospheric pressure using the CarbonFX technology, which involves preheating the feedstock for 3-4 min in a conditioning chamber before it is combusted for 2-3 sec in the reactor. After pyrolysis, the biochar is water cooled and stored in steel drums prior to shipping. The continuous process manufactures biochar at a rate of 250 kg h^{-1}. The biochar was produced in two batches, and delivered in August 2015 and October 2016. All heavy metals were below the maximum levels (IBI, 2015).

2.2 Site and Experimental Design

2.2.1 SITE DESCRIPTION

The experimental site was located at the AAFC Fredericton Research and Development Center in Fredericton New Brunswick (45°52' N, 66°31' W, elevation 21 m). The regional climate is a modified continental type; winters are cold and snowy, springs late and short, and summers cool and cloudy (Rees and Fahmy, 1984). The monthly mean air temperature ranges from -9.4°C in January to 19.4°C in July, with a mean annual precipitation of 1095 mm, based on climate norms from 1981-2010 (Environment Canada, 2017). Soils at the experimental site are a fine sandy loam belonging to the Fredericton series (bedded ancient alluvium, relatively free of coarse fragments), and are classified as an Orthic Humo-Ferric Podzol (Rees and Fahmy, 1984; Soil Classification Working Group, 1998). The cropping history was red clover in 2009 and 2010, Japanese millet in 2011, potatoes in 2012, and barley in 2014 and 2015. Soil texture in the 0-15 cm depth was a fine sandy loam (pipette method) with 640 g kg^{-1} sand, 260 g kg^{-1} silt and 100 g kg^{-1} clay. Soil characteristics, measured in August 2015, are shown in Table 2-1.

2.2.2 EXPERIMENTAL DESIGN

The experiment began in October 2015 with the establishment of a fully phased rotational experiment, with potato-barley as the rotational sequence. Five treatments were arranged in a Latinized block design with five replicates, in two phases. The first phase began in October 2015, and the second phase began in October 2016 and is not included in this thesis. The treatments were an untreated control, and factorial combinations of biochar product (Maple Leaf Biochar and Airex Biochar) and application rate (10 and 20 t ha^{-1}), for a total of 25 experimental plots in each phase (Appendix A). The biochar treatments were applied once in each phase, in the fall after the barley was harvested, before the potato-growing season began in the following spring. Plots were four rows (3.6 m) by 8 m in length, with the two outer rows acting as guard rows. Each row of the Latinized block design was separated by a 4-m buffer, each block was separated by a 2-m buffer, and a 1-m buffer separated the two experimental phases within each block.

2.3 Biochar Application

Biochar application took place once in October 2015 in phase 1 and in October 2016 in phase 2. Biochar applications of 10 t ha^{-1} and 20 t ha^{-1} were made on a dry weight basis (oven-dried at 105°C for 48 h). The biochar treatments were applied manually to the surface of biochar-treated plots by evenly spreading equal quantities on four quadrants that included the plot and two 4 m^2 areas at each end of the plots, to compensate for the possibility that tillage implements and machinery traffic would move biochar out of the plot area . The biochar was then mechanically incorporated to a depth of 0.15 m with two passes of a rolling basket harrow. Because of a shortage of Airex biochar, four experimental plots (1 x 20 t ha^{-1} and 1 x 10 t ha^{-1} in both blocks one and five) in phase one did not receive any biochar in the fall of 2015. As a result, the Airex-amended treatments were replicated three times, while there were five replicates in the Maple Leaf-treated plots and the control plots in phase one of the experiment.

2.4 Cultural Practices

Solanum tuberosum cv. Russet Burbank (elite 2) seed potatoes were obtained from Calvin Anderson and Sons in Glassville, New Brunswick, Canada. Seed potatoes were hand-cut (57 ± 3 g) ensuring each seed piece contained at least three eyes. Seed pieces were allowed to suberize for 14 d at a temperature of 13°C in a well-ventilated, humid environment. After disking the experimental plots to a depth of 0.15 m, potatoes were machine planted on 26 May 2016. All potato plots received the equivalent of 208 kg N ha^{-1}, 195 kg P_2O_5 ha^{-1} and 210 kg K_2O ha^{-1}, based on the recommendations obtained from PEI Analytical Laboratories following the 2015 field characterization. Fertilizer was banded on each side of the seed pieces and the seedpieces planted at the appropriate spacing (0.38 m between potatoes in one row and 0.80 m between rows) during the planting operation. Potato cultivation followed the standard industry practices, including one hilling operation during the growing season (20 June 2016), vine desiccation to terminate growth (30 August 2016) and harvesting approximately one month later (21 September 2016). Weeds, fungal diseases and insect pests were controlled using standard practices for the region (Table 2-2; Bernard et al., 1993). No irrigation was applied, which is common practice in New Brunswick.

2.5 Soil Collection and Chemical Analysis

Bulk soil sampling was performed in August 2015, before initiating the trial. Stratified sampling was used to collect six composite soil samples (0-15 cm depth) from 30 sampling points within the experimental site to characterize the field. Bulk soil sampling was then performed twice during the 2016 field season (17 May 2016 prior to field cultivation, and 29 August 2016 at vine desication). Six soil cores (0-15 cm depth) were taken from each experimental plot (using a random sampling pattern for the pre-plant sampling, and sampling from the potato hills in late August) with a Dutch auger (5 cm diameter) and mixed to give one composite sample per plot. One half of each soil sample was sent to PEI Analytical Laboratories for soil chemical analysis, and the other half was air-dried at 20°C for 48 h, sieved to pass through a 2-mm mesh, and used for physical analyses. The soil was analyzed for pH and EC in 1:2 soil: distilled water slurries (PEI Analytical method SFL_22M). Soil organic matter was determined by loss on ignition at 360°C for 4 h (PEI Analytical method SFL_23M). 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). The cation exchange capacity was determined from the Mehlich-III extractable concentrations of potassium, magnesium, calcium, sodium and hydrogen, which were extracted in the soil analysis.

2.6 Soil Collection and Physical Analysis

On 10 June 2016 (14 days after planting), eight undisturbed cylindrical soil cores (3 x 344.23 cm^3 and 5 x 100 cm^3) were taken from the top of the potato guard row in each experimental plot (Figure 2-1). Bulk density cores (344.23 cm^3) were placed in Ziplock bags for transport to the laboratory, weighed (in g, W_{wet}) oven-dried at 105°C for 48 h and weighed (in g, W_{dry}). The soil bulk density (ρ_b, Mg m^{-3}) was determined as:

$$\rho_b = \frac{W_{dry}}{V} \qquad (1)$$

Volumetric water content (θ_v,cm cm^{-3}) was determined with the bulk density cores using equation 2:

$$\theta_v = \frac{W_{wet} - W_{dry}}{W_{dry}} * \rho_b \qquad (2)$$

Soil saturated hydraulic conductivity (K_{sat} in cm h^{-1}) was measured using the constant head method on the 100 cm^3 cores with an Eijkelkamp soil water permeameter (Model 09.02.01.05, Giesbeek, The Netherlands). Briefly, a small piece of hydrophilic gauze was fastened on the bottom end of the sample. The samples were placed in a water tank to saturate for 24 h. A strainer cap was attached to the blunt side of the sample ring, which was placed in the ringholder. Samples were randomly selected and processed in batches (n=5). For each sample, the water level was measured inside (h_i in cm) and outside (h_o in cm) of the ringholder and the volume of water (V in ml) flowing through the length (L in cm) of the soil sample per unit time (t in min) was recorded. Readings were taken at 5 min intervals during a 15 min measurement period for each sample and the K_{sat} was determined as:

$$K_{sat} = \frac{V * L}{A * t * (h_o - h_i)} \qquad (3)$$

where A = the cross-section surface of the sample (cm^2).

Wet aggregate stability of the soil was determined with an Eijkelkamp wet sieving apparatus (Model 08.13, Giesbeek, The Netherlands) on air-dried soil aggregate (1-2 mm) (Angers et *al*., 2008). The aggregate stability index was calculated by dividing the weight of stable aggregates (in g, Ws) by the total aggregate weight (in g, $Ws + Wl$). Percent wet-aggregate stability (g $100g^{-1}$ WAS) was determined as:

$$WAS = \frac{100\ W_S}{W_S + W_l} \qquad (4)$$

This procedure was duplicated for each composite sample and additional repeats were performed if results of duplicate sub-samples deviated by more than 4 g 100 g^{-1} WAS.

Available water capacity (cm m^{-1}) measurements were performed on 2-mm sieved samples using a Soilmoisture Equipment Corp. 5 Bar pressure plate extractor (Model 1600F1, Goleta, USA) equipped with a ½ bar high flow ceramic plate, and a Eijkelamp 15 bar pressure plate extractor (Model 08.25.21, Giesbeek, The Netherlands) equipped with a 15 bar ceramic plate. This method was based on Reynolds and Topp (2008). Available water capacity (in cm m^{-1}, AWC) was the difference between the volumetric water content at field capacity (θ_{FC} -0.33 bar) and the volumetric water content at permanent wilting point (θ_{pwp} -15 bar):

$$AWC = 100\ (\theta_{FC} - \theta_{pwp}) \qquad (5)$$

2.7 Plant Tissue Sampling and Analysis

Petioles were sampled on 14 July, 24 July, 4 August, and 15 August 2016 for determination of petiole nitrate concentration. One petiole from the last fully expanded leaf was collected from 20 randomly selected plants per plot, composited, oven dried at 60°C, and ground (< 2 mm screen). Based on the method of Porter and Sisson (1991), a 0.2 g subsample was extracted with distilled-deionized water using a 1:20 sample:extractant ratio and 15 min shaking time. The extract was diluted 25:1 using an automated diluter, and NO_3-N concentration in the extract determined as described by Zebarth and Milburn (2003).

A whole plant sample was collected on 25 August 2016 to estimate plant dry matter and nutrient (N, Ca, Mg, K, Cu, Fe, Mn, Zn, P) accumulation. Four adjacent plants from one experimental row in each plot were harvested, the plants partitioned into tuber, vines and roots, and the dry matter content was determined for each plant part as described by Zebarth and Milburn (2003). A dried (60°C) and ground (< 2 mm screen) subsample of each plant component was used to determine total N concentration by combustion.

Another subsample of each plant component underwent wet acid digestion (concentrated H_2SO_4 and 30% H_2O_2) and the concentration of Ca, Mg, K, Cu, Fe, Mn, Zn, and P were determined by inductively coupled plasma emission spectroscopy using a Thermo Fisher Scientific iCAP 7000 ICP Spectrometer (model 8423 200 72101, Waltham, USA).

Potato yield was determined as the total mass of tubers collected from previously un-sampled experimental row by hand on 21 September 2016. Tubers were classified as small (<50 mm), grade A (>50 mm and <284 g), and oversized (>50 mm and > 284 g). Approximately 4.5 kg of grade A tubers were used to determine tuber specific gravity. Specific gravity (SG) was calculated as:

$$SG = \frac{Weight\ of\ tubers\ in\ air}{Weight\ in\ air - Weight\ in\ Water} \qquad (6)$$

Nitrogen and phosphorus use efficiency (NUE-N or NUE-P %) were calculated as:

$$NUE = \frac{Nutrient\ uptake}{Nutrient\ applied} * 100 \qquad (7)$$

where the nutrient uptake represents the total nutrient uptake by whole potato plants, and nutrient applied represents the quantity of N or P applied at planting.

2.8 Statistical Analysis

The dataset was analyzed as an augmented factorial (two biochar sources × two application rates plus an untreated control). Analysis of Variance (ANOVA) was performed using the General Linear Model of SAS (SAS Institute Inc., Cary, NC, Version 9.4). The sources of variance associated with the treatments (control versus biochar treatments) and nested within the biochar treatments (2 × 2 factorial structure) were evaluated using the approach outlined by Piepho et al. (2006). Whenever the ANOVA revealed a significant difference ($\alpha = 0.05$) among treatments means, a Tukey-Kramer test was performed to identify sample means that differed significantly from each other.

Multiple linear regression analysis was used to explore the relationship between physico-chemical indicators of soil quality and soil aggregate stability. Multiple regressions were performed using the PROC REG function of the SAS statistical software (SAS Institute Inc., Cary, NC, Version 9.4). The final model was obtained through PROC SORT using the Schwarz Bayesian Criteria (SBC). The same procedure was used to explore the relationship between physico-chemical indicators of soil quality and potato yields. Exploratory path analysis was used to determine the causal relationships between physico-chemical indicators of soil quality, and potato yields. Path coefficients, their significance level, and the fit of the structural model were calculated using the PROC CALIS function of the SAS statistical software (SAS Institute Inc., Cary, NC, Version 9.4). To avoid multicollinearity, predictor variables with variance inflation factor > 3 were removed from the statistical model. Error associated with variability in soil properties across the experimental field was partitioned into block and row effects, which were often significant ($P<0.05$) for soil physical and chemical properties.

Table 2-1. Biochar and soil properties (0-15 cm depth) at the start of the field study in August 2015.

	Soil	Maple Leaf	Airex
Nutrient content / mg kg^{-1}			
NO_3^--N[a]	19	NA[b]	NA
P[a]	113	NA	NA
P[c]	NA	291	175
K[a]	86	NA	NA
K (available)[d]	NA	1350	297
Mg[a]	184	NA	NA
Mg (available)[d]	NA	35	30
Ca[a]	890	NA	NA
Ca (available)[d]	NA	100	72
Elemental analysis			
Organic C (g kg^{-1})	16	822	690
Labile C (g kg^{-1})	NA	115	297
H g kg^{-1}	NA	26.3	36.7
O g kg^{-1}	NA	103.0	196.8
N g kg^{-1}	1.97	4.40	1.20
H/C_{org}	NA	0.38	0.63
Ash content (%)	NA	3.60	2.34
Characteristics			
pH[e]	6.3	7.4	6.0
EC / dS m^{-1} [e]	NA	0.36	0.17
Particle size class[f]	NA	Kernel	Blended powder
Density / Mg m^{-3} [g]	NA	0.26	0.19

[a] Nutrients Mehlich-III extractable (Tran and Simard, 1993)
[b] NA indicates not analyzed
[c] Modified dry ashing (Enders and Lehmann, 2012)
[d] Water extractable (AGDEX 533, 1989)
[e] 1:2 water
[f] IBI classification tool, 2015
[g] Packed density ISO 5311:1992

Table 2-2. Herbicide, fungicide and insecticide application dates and rates.

Name of product	Category	Date (2016)	Application rate (ha^{-1})
Lorox®	Herbicide	7 June	2 L
Bravo®-500	Fungicide	1 July	2 L
		22 July	2 L
		9 August	2 L
Entrust™	Insecticide	7 July	28 g
Manzate®	Fungicide	14 July	2.5 kg
		13 August	2.5 kg
		27 August	2.5 kg
Reglone®	Herbicide	30 August	2.5 L

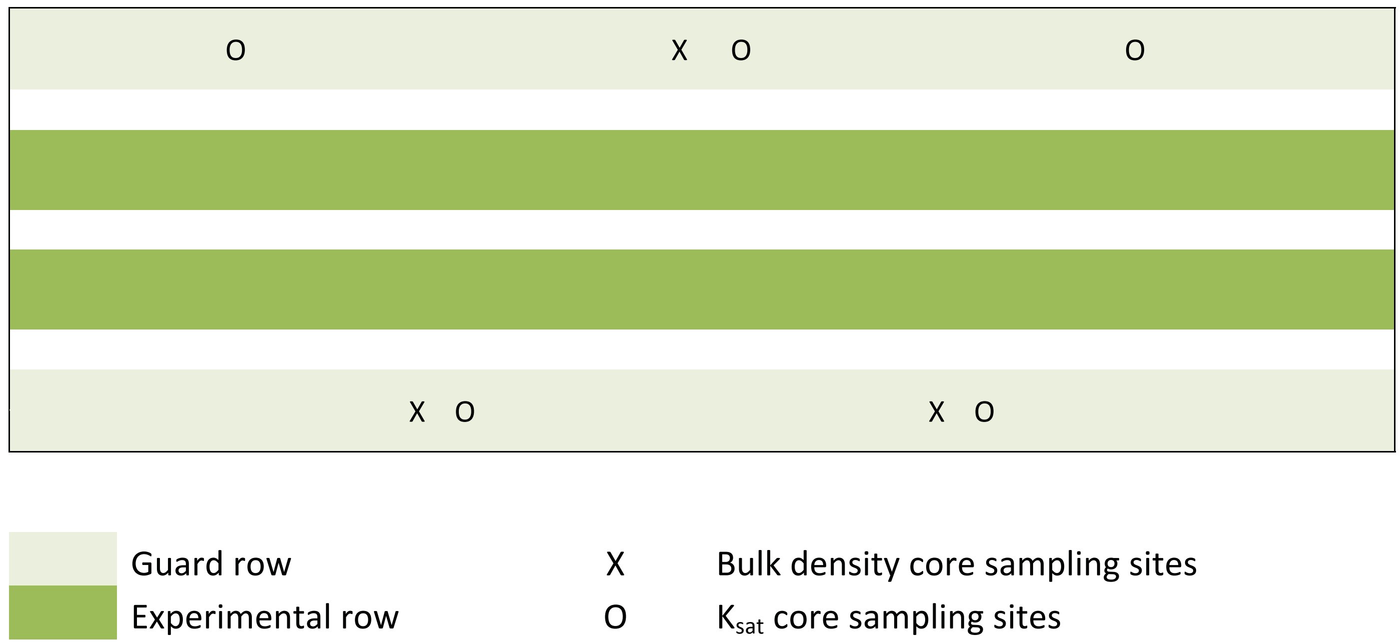


Figure 2-1. Core sampling in one experimental plot

3. Results

3.1 Physical Indicators of Soil Quality

3.1.1 SOIL BULK DENSITY

Soil bulk density measured in the potato hill mid-season was lower in biochar-amended plots than in the control plots (Table 3-1, 3-2). Soil bulk density was affected by the biochar application rate but not biochar source. Biochar application of 20 t ha^{-1} lowered the soil bulk density significantly ($P<0.05$) by 3.5%, compared to the 10 t ha^{-1} application rate. There was 5.4% lower soil bulk density with 20t ha^{-1} biochar than the control.

3.1.2 SOIL WET AGGREGATE STABILITY

In the spring, the proportion of water-stable soil aggregates was 6.0% greater in biochar-amended plots compared to the control (Table 3-3). There was, however no significant effect of biochar source or rate on WAS at this time. There was no difference in aggregate stability among treatments in the fall (Table 3-1).

3.1.3 SOIL MOISTURE PARAMETERS

Soil moisture parameters (K_{sat}, θ_v, AWC) measured in spring 2016 did not differ significantly among the control and the biochar treatments, biochar source or biochar rates (Table 3-1). Available water content measured in the fall of 2016 was affected by biochar source but not biochar rate (Table 3-1). The Airex-amended plots had 14% greater AWC than the Maple Leaf-amended plots at this time.

3.2 Chemical Indicators of Soil Quality

3.2.1 SOIL PH, ELECTRICAL CONDUCTIVITY AND CATION EXCHANGE CAPACITY

Soil pH in the spring of 2016 was greater in biochar-amended plots compared to the control ($p=0.01$; Table 3-4). There was, however, no significant effect of biochar source or application rate on soil pH in the spring. In contrast, there was no effect of treatment on soil pH measured in the fall of 2016 (Table 3-4). There was no significant effect of treatment on soil EC measured in the spring of 2016, or on CEC measured in the spring or fall of 2016.

3.2.2 SOIL ORGANIC MATTER CONTENT

In spring 2016, SOM content was greater in biochar-amended plots than in the control plots (Table 3-4, 3-5). There was a significant biochar application rate by biochar source interaction on SOM, where increasing biochar rate significantly increased SOM for the Airex-amended plots but not for Maple Leaf-amended plots. Soil organic matter content increased significantly ($P<0.05$) when Airex biochar was applied, such that the 10 and 20 t ha^{-1} treatments contained 32% and 40% more SOM than the control (Table 3-4). Plots amended with 20 t ha^{-1} of Airex biochar also contained significantly more ($P<0.05$) SOM than plots amended with 10 or 20 t ha^{-1} of Maple Leaf biochar. By fall 2016, there was no difference in SOM content among treatments (Table 3-5).

3.2.3 SOIL MACRONUTRIENTS

Soil NO_3^-, S and Mg concentrations were not affected by biochar treatments and had similar concentrations in spring and fall (Tables 3-6 and 3-7). Extractable P concentration was 11 to 13% greater in biochar-amended plots than in the control plots during the study. In spring 2016, the extractable K concentration was 17% greater in biochar-amended plots than in the control plots ($p=0.04$). Biochar application of 20 t ha^{-1} raised the extractable K concentration significantly ($P<0.05$), by 24% compared with the control. Application of Maple Leaf biochar raised the extractable K concentration significantly ($P<0.05$), by 15% compared to Airex biochar, and by 23% compared to the control (Table 3-6). In contrast, there was no significant treatment effect on extractable K concentration in the fall 2016. Soil Ca levels were 13 and 10% higher in biochar-amended plots than in the control plots in spring and fall respectively.

3.2.4 SOIL MICRONUTRIENTS

Extractable boron (B) concentration was 38% and 25% greater in biochar-amended plots than in the control plots in spring and fall, respectively (Tables 3-8, 3-9). In spring 2016, plots receiving 20 t ha^{-1} of biochar had 43% more extractable Zn concentration than the control, which was significant ($P<0.05$). Similarly, in fall 2016, biochar application of 20 t ha^{-1} raised the soil Zn content significantly ($P<0.05$), and it was 16% higher than the 10 t ha^{-1} application rate and 15% higher than the control.

3.3 Potato Productivity

3.2.5 PETIOLE NITRATE

Petiole nitrate concentration was lower in biochar-amended plots than in the control plots on 4 August 2016, whereas biochar application had no significant effect on petiole nitrate concentration on any other sampling date (Table 3-10). There was no effect of biochar source or application rate on petiole nitrate concentration on any sampling dates (Figure 3-1).

3.2.6 PLANT TISSUE ANALYSIS, NUTRIENT USE EFFICIENCY AND PLANT BIOMASS

Nutrient analysis of plant tissues collected from potato vines, tubers and roots at harvest revealed few effects of biochar treatments (Table 3-11). Maple Leaf biochar decreased the Mg concentration of vines significantly ($P<0.05$), and it was 14% lower than the control (Table 3-12). Similarly, Maple Leaf biochar reduced the root Mg concentration significantly ($P<0.05$) by 7%, relative to the control. Biochar application of 20 t ha^{-1} lowered the Fe concentration in tubers significantly ($P<0.05$), and it was 19% lower than the 10 t ha^{-1} application rate and 14% lower than the control. Root Mn concentration was lower in biochar-amended plots than in the control plots ($p=0.03$), but was not affected by the biochar application rate or the biochar type. Nitrogen use efficiency and phosphorus use efficiency were not affected by biochar sources and application rates. Vine and root dry weight were similar in biochar-treated plots and the control plots (Table 3-13).

3.2.7 TUBER YIELD

Potato tuber yield at harvest did not differ significantly among biochar treatments, or when biochar type or application rate were considered, compared to the control (Table 3-13). Multiple regression analysis of the relationship between marketable yield and other measured variables showed an effect of CEC and pH ($R^2 = 0.54$, $F (2,18) = 10.65$, $p = 0.0009$, Table 3-14). Soils with higher CEC were expected to have higher marketable yield, after controlling for the other variables in the model, while soil pH was negatively related to marketable yield ($P=0.06$).

Exploratory path analysis was conducted to determine the causal relationships between soil properties and marketable yield (Table 3-15). The direct effect of soil CEC ($r = 0.72$, $P < 0.001$) on marketable yield was greater than would be predicted from correlation analysis alone. The model also indicated a large indirect effect ($r = 0.52$, $P < 0.001$) of SOM on marketable yield and a large direct effect of SOM on CEC ($r = 0.76$, $P<0.001$), K_{sat} ($r = 0.53$, $P<0.001$), and AWC ($r = 0.52$, $P<0.01$) (Figure 3-2).

Multiple regression analysis showed that Grade A yield was related to the CEC and soil K_{sat} ($R^2 = 0.70$, $F (2,18) = 21.26$, $p < 0.0001$, Table 3-16). Soils with higher CEC and higher K_{sat} had higher Grade A yield, after controlling for the other variables in the model.

Exploratory path analysis was conducted to determine the causal relationships between soil properties and Grade A yield (Table 3-17). The direct effects of soil CEC ($r = 0.64$, $P < 0.001$) and K_{sat} ($r = 0.44$, $P < 0.001$) on Grade A yield were smaller than would be predicted from correlation analysis alone. The model also indicated a large indirect effect ($r = 0.64$, $P < 0.001$) of SOM on Grade A yield and a large direct effect of SOM on CEC ($r = 0.76$, $P<0.001$), K_{sat} ($r = 0.53$, $P<0.001$), and AWC ($r = 0.52$, $P<0.01$) (Figure 3-3).

Table 3-1. Selected physical properties of soil sampled in 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors) of *n* = 3 to 5 replicate plots.

Biochar source	Amendment rate (t ha^{-1})	*n*	Bulk density ($Mg\ m^{-3}$)	θ[a] ($cm\ cm^{-3}$)	AWC[a] Spring ($cm\ m^{-1}$)	AWC Fall ($cm\ m^{-1}$)	Ksat[a] ($cm\ hr^{-1}$)	WAS[a] Spring ($g\ 100g^{-1}$)	WAS Fall ($g\ 100g^{-1}$)
Maple Leaf	10	5	1.08 (0.04)	0.19 (0.03)	13.7 (2.0)	11.7 (1.8)	55.2 (7.3)	75.0 (3.1)	72.7 (2.0)
Maple Leaf	20	5	1.07 (0.04)	0.19 (0.03)	14.3 (1.8)	11.4 (1.8)	48.1 (6.0)	75.8 (2.4)	72.1 (0.4)
Airex	10	3	1.08 (0.01)	0.20 (0.01)	17.9 (2.5)	12.6 (1.3)	55.3 (11.7)	76.7 (2.0)	73.4 (2.6)
Airex	20	3	1.00 (0.01)	0.19 (0.01)	14.6 (2.2)	13.8 (2.7)	54.4 (0.8)	77.1 (3.8)	73.5 (3.2)
Control	0	5	1.10 (0.03)	0.19 (0.02)	14.1 (2.1)	12.6 (2.0)	48.2 (4.7)	71.5 (2.8)	70.9 (0.8)
Source of variation		d.f.							
Block		4	***	***	*	***	NS	***	*
Row		4	*	***	NS	NS	NS	NS	NS
Control versus Biochar		1	*	NS	NS	NS	NS	**	NS
Biochar rate		1	**	NS	NS	NS	NS	NS	NS
Biochar source		1	NS	NS	NS	*	NS	NS	NS
Biochar rate × source		1	**	NS	NS	NS	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant

[a]θ = Volumetric water content; AWC = Available water content; K_{sat} = Saturated hydraulic conductivity; WAS = Wet aggregate stability.

Table 3-2. Soil bulk density measured in May 2016 following biochar application in the fall of 2015, as affected by biochar application rate, and compared between control and biochar-amended soil.

Term	Level	Mean ($Mg\ m^{-3}$)[z]
Biochar rate ($t\ ha^{-1}$)	0	1.10[a]
	10	1.08[a]
	20	1.03[b]
Control vs biochar	Control	1.10[a]
	Biochar treatments	1.06[b]

[z] Treatment means followed by the same letter are not significantly different according to the Tukey-Kramer studentized range test.

Table 3-3. Soil wet aggregate stability measured in May 2016 following biochar application in the fall of 2015, and compared between control and biochar-amended soil.

Term	Level	Mean (g $100g^{-1}$)[z]
Control vs biochar	Control	71.5[a]
	Biochar treatments	76.1[b]

[z] Treatment means for a term that are followed by the same letter are not significantly different according to the Tukey-Kramer studentized range test.

Table 3-4. Selected soil chemical properties of soil sampled in 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors) of *n*=3 to 5 replicate plots.

Biochar source	Rate (t ha^{-1})	*n*	Soil pH Spring	Soil pH Fall	EC[a] (mS cm^{-1}) Spring	OM[a] (g $100g^{-1}$) Spring	OM (g $100g^{-1}$) Fall	CEC[a] (cmol $^{+}$ kg^{-1}) Spring	CEC (cmol $^{+}$ kg^{-1}) Fall
Maple Leaf	10	5	6.58 (0.09)	6.42 (0.09)	0.06 (0.01)	2.6 (0.4)	2.7 (0.4)	6.8 (1.1)	6.4 (1.1)
Maple Leaf	20	5	6.66 (0.08)	6.50 (0.07)	0.06 (0.01)	2.5 (0.4)	2.5 (0.4)	7.6 (0.7)	7.0 (1.1)
Airex	10	3	6.65 (0.20)	6.40 (0.21)	0.06 (0.00)	3.1 (0.2)	2.3 (0.2)	7.3 (0.3)	6.7 (0.9)
Airex	20	3	6.78 (0.17)	6.57 (0.27)	0.06 (0.00)	3.3 (0.2)	3.2 (0.3)	7.0 (0.0)	5.7 (0.7)
Control	0	5	6.50 (0.13)	6.36 (0.14)	0.06 (0.01)	2.3 (0.3)	2.3 (0.3)	6.8 (1.1)	6.2 (1.0)
Sources of variation		d.f.							
Block		4	***	*	***	***	*	***	***
Row		4	NS	NS	**	***	*	NS	NS
Control versus Biochar		1	*	NS	NS	***	NS	NS	NS
Biochar rate		1	NS	NS	NS	*	NS	NS	NS
Biochar source		1	NS	NS	NS	***	NS	NS	NS
Biochar rate × source		1	NS	NS	NS	**	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant
[a]EC = Electrical conductivity; OM = Organic matter; CEC = Cation exchange capacity

Table 3-5. Soil organic matter (g $100g^{-1}$) measured in May 2016 following biochar application in the fall of 2015, as affected by biochar source and application rate.

Control vs biochar	Source	Rate (t ha^{-1})	Mean[z]
Control	Control	0	2.3[a]
Biochar	Maple Leaf	10	2.6[ab]
Biochar	Maple Leaf	20	2.5[ab]
Biochar	Airex	10	3.1[b]
Biochar	Airex	20	3.3[c]

[z] Treatment means for a term that are followed by a common letter are not significantly different according to the Tukey-Kramer studentized range test.

Table 3-6. Macronutrient content of soil sampled in May 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors) of *n*=3 to 5 replicate plots.

Biochar source	Amendment rate (t ha^{-1})	*n*	Nitrate (mg kg^{-1})	Phosphate (mg kg^{-1})	Potash (mg kg^{-1})	Calcium (mg kg^{-1})	Sulfur (mg kg^{-1})	Magnesium (mg kg^{-1})	Sodium (mg kg^{-1})
Maple Leaf	10	5	8.3 (1.3)	292 (9)	110 (5)	848 (104)	12 (1)	168 (26)	15 (1)
Maple Leaf	20	5	7.5 (1.1)	294 (16)	122 (3)	889 (86)	12 (1)	172 (26)	16 (1)
Airex	10	3	8.7 (1.0)	293 (14)	95 (4)	873 (33)	13 (0)	170 (13)	14 (1)
Airex	20	3	7.4 (1.6)	295 (23)	108 (12)	881 (50)	12 (0)	166 (17)	16 (1)
Control	0	5	9.3 (1.1)	267 (9)	95 (6)	771 (100)	12 (1)	164 (24)	16 (1)
Source of variation		d.f.							
Block		4	*	NS	NS	***	**	***	NS
Row		4	*	**	NS	NS	NS	***	NS
Control versus Biochar		1	NS	**	*	*	NS	NS	NS
Biochar rate		1	NS	NS	*	NS	NS	NS	NS
Biochar source		1	NS	NS	**	NS	NS	NS	NS
Biochar rate × biochar		1	NS	NS	NS	NS	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant

Table 3-7. Macronutrient content of soil sampled in August 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors).

Biochar source	Amendment rate (t ha^{-1})	*n*	Nitrate (mg kg^{-1})	Phosphate (mg kg^{-1})	Potash (mg kg^{-1})	Calcium (mg kg^{-1})	Sulfur (mg kg^{-1})	Magnesium (mg kg^{-1})	Sodium (mg kg^{-1})
Maple Leaf	10	5	10.7 (1.9)	311 (19)	109 (7)	816 (97)	12 (0)	152 (26)	14 (1)
Maple Leaf	20	5	10.7 (2.1)	339 (20)	123 (8)	827 (102)	13 (1)	159 (26)	17 (1)
Airex	10	3	12.4 (0.7)	302 (19)	92 (2)	842 (27)	13 (1)	148 (10)	16 (1)
Airex	20	3	15.2 (1.9)	308 (34)	99 (18)	833 (55)	12 (0)	152 (18)	15 (2)
Control	0	5	12.0 (2.7)	283 (10)	103 (7)	750 (100)	13 (1)	152 (24)	19 (1)
Source of variation		d.f.							
Block		4	NS	NS	NS	***	*	***	NS
Row		4	NS	NS	NS	NS	NS	**	NS
Control versus Biochar		1	NS	*	NS	*	NS	NS	NS
Biochar rate		1	NS	NS	NS	NS	NS	NS	NS
Biochar source		1	NS	NS	NS	NS	NS	NS	NS
Biochar rate × biochar		1	NS	NS	NS	NS	NS	NS	NS

*,**,*** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively; NS, not significant

Table 3-8. Micronutrient content of soil sampled in May 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors).

Biochar source	Amendment rate (t ha^{-1})	*n*	Boron (mg kg^{-1})	Zinc (mg kg^{-1})	Manganese (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
Maple Leaf	10	5	0.4 (0.0)	0.7 (0.1)	27 (2)	4.1 (0.7)	119 (13)
Maple Leaf	20	5	0.4 (0.1)	0.8 (0.1)	28 (3)	3.9 (0.4)	119 (15)
Airex	10	3	0.3 (0.0)	0.8 (0.1)	29 (10)	4.6 (1.1)	130 (14)
Airex	20	3	0.4 (0.1)	1.0 (0.3)	37 (11)	6.0 (1.3)	126 (15)
Control	0	5	0.3 (0.1)	0.6 (0.1)	28 (6)	4.4 (1.0)	119 (16)
Source of variation		d.f.					
Block		4	*	NS	**	***	***
Row		4	NS	*	*	***	NS
Control versus Biochar		1	*	NS	NS	NS	NS
Biochar rate		1	NS	*	NS	NS	NS
Biochar source		1	NS	NS	NS	NS	NS
Biochar rate x biochar		1	NS	NS	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant

Table 3-9. Micronutrient content of soil sampled in August 2016 from a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors).

Biochar source	Amendment rate (t ha^{-1})	*n*	Boron (mg kg^{-1})	Zinc (mg kg^{-1})	Manganese (mg kg^{-1})	Copper (mg kg^{-1})	Iron (mg kg^{-1})
Maple Leaf	10	5	0.3 (0.0)	0.9 (0.0)	26 (2)	4.3 (0.8)	132 (13)
Maple Leaf	20	5	0.3 (0.0)	1.0 (0.1)	26 (2)	4.5 (0.5)	133 (13)
Airex	10	3	0.3 (0.1)	0.9 (0.1)	27 (9)	5.2 (1.4)	132 (12)
Airex	20	3	0.3 (0.0)	1.0 (0.2)	33 (9)	6.1 (1.4)	129 (12)
Control	0	5	0.3 (0.0)	0.9 (0.1)	26 (5)	4.8 (1.1)	133 (14)
Source of variation		d.f.					
Block		4	**	**	**	***	***
Row		4	NS	***	*	***	*
Control versus Biochar		1	*	*	NS	NS	NS
Biochar rate		1	NS	***	NS	NS	NS
Biochar source		1	NS	NS	NS	NS	NS
Biochar rate x biochar		1	NS	NS	NS	NS	NS

*,**,*** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively; NS, not significant

Table 3-10. Petiole nitrate concentrations measured at four growth stages in 2016 in a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors) of *n* = 3 to 5 replicate plots.

			Nitrate (g kg^{-1})			
Biochar source	Amendment rate (t ha^{-1})	*n*	49 days after planting	59 days after planting	69 days after planting	79 days after planting
Maple Leaf	10	5	23.5 (0.6)	22.1 (1.1)	17.9 (1.2)	16.6 (1.2)
Maple Leaf	20	5	22.2 (1.6)	21.0 (0.4)	18.0 (1.0)	15.7 (0.6)
Airex	10	3	25.6 (0.4)	21.3 (0.1)	19.4 (0.7)	18.4 (0.6)
Airex	20	3	23.0 (1.4)	22.0 (0.6)	17.5 (0.7)	15.8 (1.2)
Control	0	5	25.1 (0.5)	23.3 (1.0)	20.9 (0.9)	18.4 (0.4)
Source of variation		d.f.				
Block		4	*	NS	NS	NS
Row		4	NS	NS	NS	NS
Control versus Biochar		1	NS	NS	**	NS
Biochar rate		1	NS	NS	NS	NS
Biochar source		1	NS	NS	NS	NS
Biochar rate x source		1	NS	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant

Table 3-11. Biomass macronutrient concentration in the vine, root and tuber, measured in August 2016, in a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors).

Biochar source	Amendment rate (t ha^{-1})	*n*	Vine N (g kg^{-1})	Root N (g kg^{-1})	Tuber N (g kg^{-1})	Vine P (mg kg^{-1})	Root P (mg kg^{-1})	Tuber P (mg kg^{-1})	Vine K (mg kg^{-1})	Root K (mg kg^{-1})	Tuber K (mg kg^{-1})
Maple Leaf	10	5	24.5 (1.1)	18.3 (0.6)	10.8 (0.3)	1130 (81)	1188 (55)	1450 (88)	23754 (1926)	14778 (838)	13158 (115)
Maple Leaf	20	5	23.3 (2.3)	16.7 (1.6)	10.6 (1.0)	1099 (59)	1119 (67)	1442 (69)	26148 (2214)	15881 (591)	14084 (705)
Airex	10	3	24.2 (1.5)	18.0 (0.5)	11.4 (0.5)	1009 (48)	1174 (75)	1401 (25)	19058 (2736)	12927 (1019)	13635 (279)
Airex	20	3	24.1 (1.6)	17.9 (0.7)	11.6 (0.2)	984 (22)	1072 (39)	1317 (54)	19814 (1374)	14474 (552)	12346 (1326)
Control	0	5	24.9 (0.8)	18.7 (0.6)	11.3 (0.5)	1098 (67)	1137 (35)	1515 (64)	20396 (1902)	14475 (364)	13794 (314)
Source of variation		d.f.									
Block		4	**	NS	**	*	NS	***	*	NS	NS
Row		4	NS	NS	NS	NS	NS	NS	*	NS	NS
Control versus Biochar		1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Biochar rate		1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Biochar source		1	NS	NS	NS	NS	NS	NS	NS	NS	NS
Biochar rate x source		1	NS	NS	NS	NS	NS	NS	NS	NS	NS

*,**,*** Significant at P < 0.05, P < 0.01 and P < 0.001 respectively; NS, not significant

Table 3-12. Biomass micronutrient concentration in the vine, root and tuber, measured in August 2016, in a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors).

Biochar source	Amendment rate (t ha^{-1})	*n*	Vine Mg (mg kg^{-1})	Root Mg (mg kg^{-1})	Tuber Mg (mg kg^{-1})	Vine Fe (mg kg^{-1})	Root Fe (mg kg^{-1})	Tuber Fe (mg kg^{-1})	Vine Mn (mg kg^{-1})	Root Mn (mg kg^{-1})
Maple Leaf	10	5	11869 (856)	3476 (248)	709 (12)	506 (40)	988 (68)	123 (10)	112 (6)	39 (3)
Maple Leaf	20	5	11578 (1142)	3737 (312)	754 (20)	605 (96)	1086 (79)	108 (6)	119 (6)	42 (2)
Airex	10	3	12943 (757)	3645 (92)	706 (24)	710 (80)	1084 (68)	135 (13)	138 (14)	44 (3)
Airex	20	3	12368 (1289)	3508 (418)	661 (37)	539 (89)	949 (174)	93 (1)	116 (2)	36 (4)
Control	0	5	13632 (1200)	3890 (179)	756 (13)	545 (54)	1011 (140)	120 (15)	125 (20)	50 (6)
Source of variation		d.f.								
Block		4	***	***	NS	NS	NS	*	NS	NS
Row		4	NS	**	NS	NS	NS	NS	NS	NS
Control versus Biochar		1	NS	NS	NS	NS	NS	NS	NS	*
Biochar rate		1	NS	NS	NS	NS	NS	**	NS	NS
Biochar source		1	*	*	NS	NS	NS	NS	NS	NS
Biochar rate x source		1	NS	NS	NS	NS	NS	NS	NS	NS

*,**,*** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively; NS, not significant

Table 3-13. Yield and fertilizer use efficiency measured in September 2016, in a potato cropping system amended with biochar in the fall of 2015. Values are the mean (± standard errors) of *n* = 3 to 5 replicate plots.

Biochar source	Rate (t ha^{-1})	*n*	Grade A yield (t ha^{-1})	Marketable yield (t ha^{-1})	Non-marketable yield (t ha^{-1})	Vine dry weight (g plant^{-1})	Root dry weight (g plant^{-1})	NUE-N[a] (%)	NUE-P[a] (%)
Maple Leaf	10	5	10.942 (2.921)	24.655 (2.665)	0.088 (.060)	48.1 (7.2)	6.8 (0.4)	56.9 (8.2)	13.8 (1.3)
Maple Leaf	20	5	9.523 (1.594)	25.452 (1.624)	0.275 (.094)	42.5 (11.1)	6.5 (1.0)	54.2 (13.4)	13.0 (2.1)
Airex	10	3	12.203 (1.674)	27.923 (1.737)	0.052 (.052)	49.4 (6.1)	7.2 (0.6)	66.2 (7.5)	14.3 (1.4)
Airex	20	3	9.614 (1.614)	24.116 (1.335)	0.170 (.075)	38.3 (2.7)	6.4 (0.2)	58.3 (2.5)	11.8 (0.2)
Control	0	5	9.729 (2.479)	24.188 (1.070)	0.387 (.180)	39.7 (5.0)	6.0 (0.4)	51.8 (4.9)	13.1 (1.0)
Sources of variation		d.f.							
Block		4	*	NS	NS	**	NS	**	NS
Row		4	**	*	NS	*	NS	*	*
Control versus Biochar		1	NS	NS	NS	NS	NS	NS	NS
Biochar rate		1	NS	NS	NS	NS	NS	NS	NS
Biochar source		1	NS	NS	NS	NS	NS	NS	NS
Biochar rate x source		1	NS	NS	NS	NS	NS	NS	NS

*,**,*** Significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively; NS, not significant

[a]NUE-N = Nitrogen use efficiency; NUE-P = Phosphorus use efficiency.

Table 3-14. Relationship between marketable potato yield and soil variables in biochar-amended and control plots (*n*=21) determined from multiple regression analysis.

Model variables	b	SE	β	*t*	*p*	F	df	*P*	R^2
Overall model	.	.	.	.	.	10.65	2,18	.0009	**0.49**
Predictor variables									
(constant)	47.63	16.65	.	2.86	.0104				
Covariates									
CEC	1.81	0.39	0.82	4.61	.0002				
pH	-5.34	2.68	-0.36	-2.00	.0612				

b, unstandardized regression coefficient; SE, standard error; β, standardized regression coefficient; *t*, obtained t-value; *p*, probability; R^2, proportion of the variance explained.

Table 3-15. Direct and indirect effects of soil variables, and simple correlation coefficients between soil properties and marketable potato yield in biochar-amended soils. The direct effects (standardized partial regression coefficients) and correlation coefficients were not significant (NS) or significant at **P*<0.05, ***P*<0.01 or ****P*<0.001

	Marketable potato yield (t ha^{-1})		
Variable[z]	Direct effect	Indirect effect	Correlation Coefficient (r)
SOM	NA[y]	0.52***	0.67***
CEC	0.73***	NA	0.66**
Ksat	0.21	NA	0.44*
AWC	-0.29	NA	0.15

[z]SOM = Soil organic matter; CEC = Cation exchange capacity; Ksat = Saturated hydraulic conductivity; AWC = Available water capacity

[y]NA = not applicable

Table 3-16. Relationship between Grade A potato yield and soil variables in biochar-amended and control plots (*n*=21) determined from multiple regression analysis.

Model variables	b	SE	β	*t*	*p*	F	df	*p*	R^2
Overall model	.	.	.	.	.	21.26	2,18	<.0001	**0.67**
Predictor variables									
(constant)	-8.99	3.03	.	-2.97	.0083				
Covariates									
CEC	1.47	0.36	0.56	4.08	.0007				
Ksat	0.18	0.05	0.45	3.29	.0040				

b, unstandardized regression coefficient; SE, standard error; β, standardized regression coefficient; *t*, obtained t-value; *p*, probability; adj R^2, proportion of the variance explained.

Table 3-17. Direct and indirect effects of soil variables, and simple correlation coefficients between soil properties and Grade A potato yield in biochar-amended soils. The direct effects (standardized partial regression coefficients) and correlation coefficients were not significant (NS) or significant at *$P<0.05$, **$P<0.01$ or ***$P<0.001$

	Grade A yield (t ha^{-1})		
Variable[z]	Direct effect	Indirect effect	Correlation Coefficient (r)
SOM	NA[y]	0.64***	0.76***
CEC	0.64***	NA	0.72***
Ksat	0.44***	NA	0.65**
AWC	-0.16	NA	0.28

[z]SOM = Soil organic matter; CEC = Cation exchange capacity; Ksat = Saturated hydraulic conductivity; AWC = Available water capacity

[y]NA = not applicable

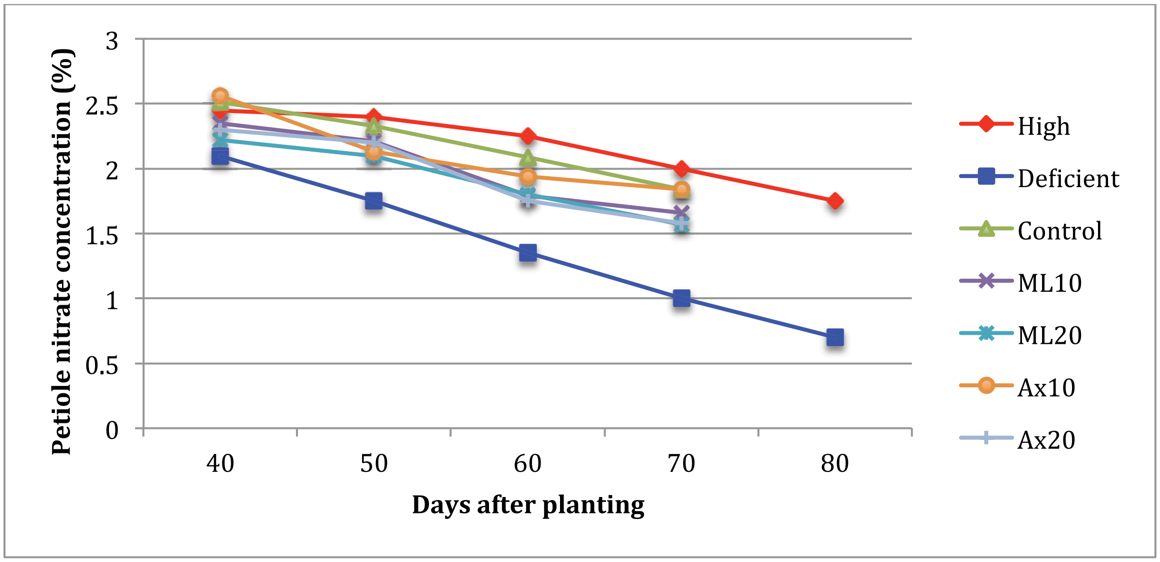


Figure 3-1. Petiole nitrate-nitrogen concentration in Russet Burbank potato grown in plots that received no biochar (Control), Maple Leaf biochar at 10 t ha^{-1} and 20 t ha^{-1} (ML10 and ML20) or Airex biochar at 10 t ha^{-1} and 20 t ha^{-1} (Ax10 and Ax20). The acceptable range of petiole nitrate-nitrogen was defined by Porter and Sission (1993).

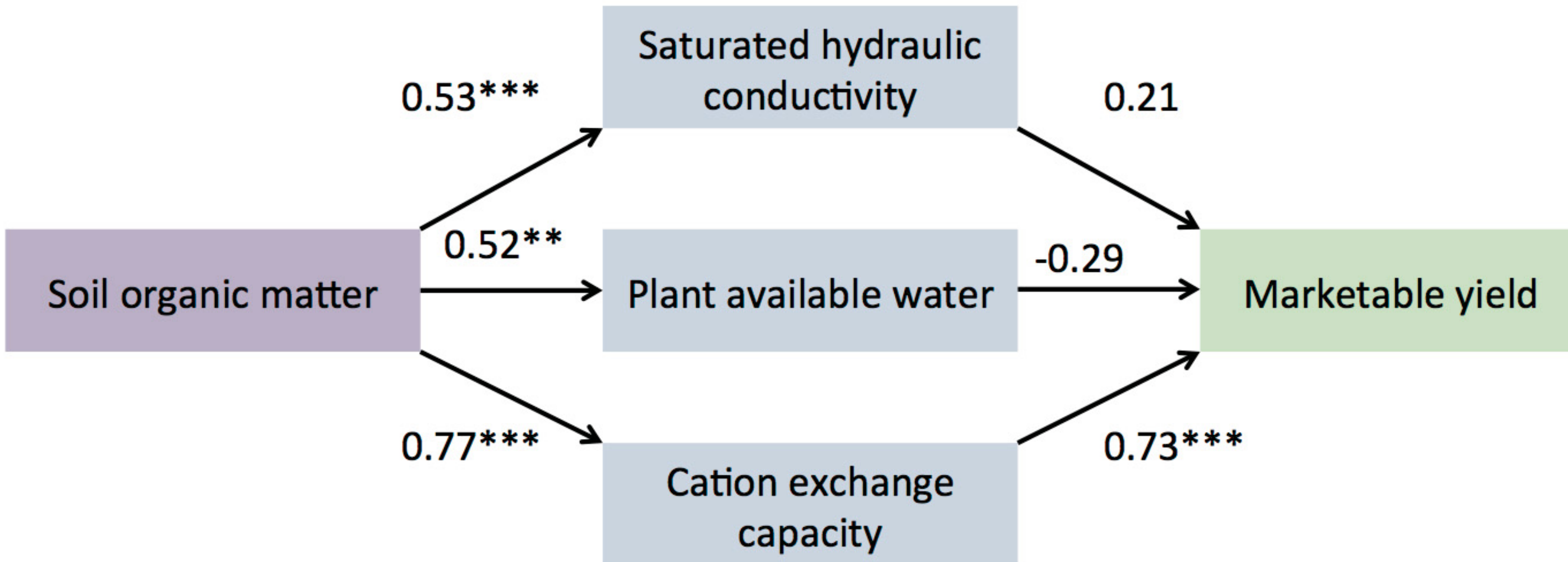


Figure 3-2. Exploratory path model describing hypothesized casual relationships between soil parameters and potato marketable yield ($t\ ha^{-1}$). For each effect path, standardized path coefficients are given (significant at * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$).

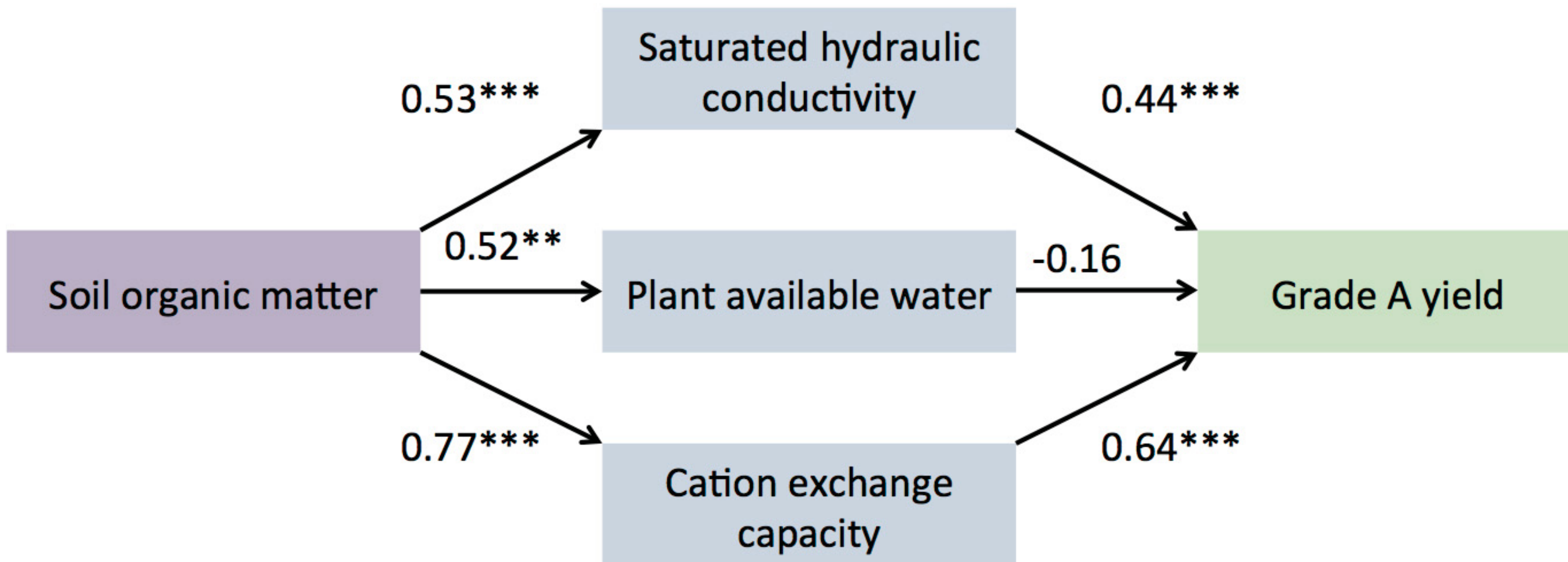


Figure 3-3. Exploratory path model describing hypothesized casual relationships between soil parameters and potato Grade A yield (t ha^{-1}). For each effect path, standardized path coefficients are given (significant at * P < 0.05, ** P < 0.01 and *** P < 0.001).

4. Discussion

4.1 Biochar effect on soil properties and crop response

The application of biochar to a loamy soil was hypothesized to positively affect soil properties associated with soil structure, soil moisture, and soil fertility, and to increase tuber yield. Biochar was expected to improve soil quality by lowering soil bulk density, and increasing soil aggregate stability, soil water storage, soil pH, and SOM content (Abel et al., 2013; Agbna et al., 2017; Busscher et al., 2011; Herath et al., 2013). These soil quality improvements in biochar-amended soil were in turn expected to generate positive crop responses (Jeffery et al., 2011).

4.1.1 SOIL PHYSICAL PROPERTIES

Eight and twelve months after being applied to a sandy loam soil, wood-based biochars had a beneficial effect on soil bulk density and soil aggregate stability. Biochar lowered soil bulk density in the potato hills by 3.6%, and increased the proportion of water-stable aggregates by 6.4% in the spring when the soil was bare, and most vulnerable to water erosion. Biochar did not affect θ_v, K_{sat} or AWC.

The lowering of bulk density in biochar-amended soils is commonly reported from both laboratory (Abel et al., 2013; Herath et al., 2013; Jien and Wang 2013; Laird et al., 2010; Novak et al., 2012; Ulyett et al., 2014) and field experiments (Abel et al., 2013; Hardie et al., 2014; Major et al., 2010; Mukherjee et al., 2014a; Rogovska et al., 2014; Zhang et al., 2010). It is generally attributed to the displacement of the solid soil fraction by low-density biochar particles (Figure 4-1) (Busscher et al., 2010; Herath et al., 2013; Ulyett et al., 2014).

Positive effects of biochar on aggregate stability are rarely observed in field experiments, but have been reported from experiment where wood-based biochars were applied to sandy loam soils (Ibrahim et al., 2013; Khademalrasoul et al., 2014). Water-stable soil aggregates form when organo-minerals make contact with organic and inorganic binding agents (Lynch and Bragg, 1985; Oades, 1993; Tisdall and Oades, 1982). Researchers have proposed three mechanisms through which biochars can positively affect soil aggregate formation and stability: (1) increased soil hydrophobicity, (2) development of biochar-organo-mineral complexes, and (3) stimulation of plant and microbial activity.

Biochar aging is an important factor in the development hydrophilic properties, and in the development of the surface functional groups responsible for binding clays and organic compounds (Joseph et al., 2010; Rechberger et al., 2017). Kloss et al. (2014) and Rechberger et al. (2017) observed that wood-based biochar can develop significant hydrophilic properties and functionality as soon as six months after being amended to sandy loam soils. The ongoing oxidation of the biochar particles in the soil environment between the first (8 months after application) and the second (12 months after application) round of soil sampling could have contributed to development of hydrophilic properties, and could have negated the initial increase in WAS. The short-term increase in WAS observed in biochar-amended plots support the role of biochar hydrophobicity in promoting soil aggregate stability.

The transient nature of biochar's effect on WAS could also be explained by biological factors masking the binding effect of biochar. For example an important difference between the two sampling dates was the presence of vegetation on the experimental plots. Plants release organic binding agents through their root system (i.e., root exudates) and stimulate microbial growth, leading to the production of microbial necromass and byproducts that bind with organo-minerals during the growing season. In addition, the fine roots of plants and hyphae of free-living fungi enmesh microaggregates and contribute to the formation of stable macroaggregates. Consequently, by the August sampling date, biologically induced aggregate formation could have masked the binding effect of biochar initially observed in the spring.

Biochar amendments were ineffective at affecting soil permeability, and soil water storage. These results differ from other studies where the amendment of wood-based biochars to sandy loam soil reduced K_{sat} and increased plant available water (Deveraux et al., 2012; Esmaeelnejad et al., 2016; Sun et al., 2015). When changes in water storage occur after biochar application to coarse textured soils, they are generally attributed to: (1) changes in the soil pore structure, and (2) water retention in biochar pores (Figure 4-2) (Barnes et al., 2014; Hardie et al., 2014). The effect of biochar on water conductivity is controlled by interparticle space, and is dependent on biochar particle size and soil texture (Liu et al., 2016). The absence of biochar effect on K_{sat} indicates that in this experiment, the application of coarse textured biochar to coarse textured soil is unlikely to have significantly changed the interpore size and tortuosity of the soil matrix. Liu et al. (2016) suggested that in coarse textured soil finely ground (0.25- 0.85 mm) woody biochars would be more effective at changing K_{sat}.

The biochar products used in this experiment had a limited capacity to retain water within their pores (Figure 4-3), which can explain why despite increasing soil porosity, biochar did not improve AWC. Capillary water may not enter biochar pores because it is physically blocked by residual bio-oils and recondensation products (McClellan et al., 2007) present in biochar pores, or due to water repellency of hydrophobic surfaces on fresh biochar (Abel et al., 2013; Briggs et al., 2012; Kinney et al., 2012).

The hydrophobic nature of fresh biochar products is a transient characteristic that impacts both the aggregate stability, and the AWC of biochar amended soils. Oxidation of biochar surfaces changes the ability of biochar to interact in the soil environment, and changes how it affects soil properties. In the case of aggregate stability, the beneficial effect of hydrophobicity on aggregate stability may dissipate over time, but the effect of biochar on the stability of soil aggregate could be sustained by the development of functional groups on biochar surfaces. Soil moisture regimes in bochar-amended soils are also susceptible to change over time. Physical and biological breakdown of large biochar particles could increase the tortuosity in sandy soil and reduce K_{sat}. Additionally, the development of hydrophilic properties is expected to improve water retention in biochar pores, and increase soil AWC.

4.1.2 SOIL CHEMICAL PROPERTIES

Sandy loam soils amended with biochar were expected to have a greater pH, SOM content and nutrient content, but a similar soil CEC and EC when compared to the control (Jones et al., 2012; Laghari et al., 2016; Zhang et al., 2016). Increases in pH are often reported in biochar-amended soils (e.g., Bierdman and Harpole, 2013; Jones et al., 2012), and are attributed to the binding of H^+ ions from the soil solution by the functional groups present on biochar surfaces (Gul et al., 2015). This is consistent with the soil pH response to biochar measured in May. By August, the soil pH was no longer affected by biochar treatments. In other studies, the gradual decline in soil pH with time after biochar application was linked to the oxidation of surface functional groups (Cheng and Lehmann, 2009; Mukherjee et al., 2014b).

The EC and CEC of biochars depend on the presence of K, Na, Ca, Mg and P in the feedstock biomass and on the ash content of the biochar (Agrafioti et al., 2013; Zhao et al., 2013). Biochars from woody feedstock tend to have low ash content, CEC values, and EC (Chan et al., 2007; Laghari et al., 2016; Major et al., 2009; Singh et al., 2010). Woody biochars were not expected to cause an appreciable change in the CEC and EC sandy loam soil, and this prediction was supported by the data collected during this experiment.

Biochar was beneficial in inducing a short-term increase in the SOM content of a sandy loam soil. Biochar amendments generally increase the SOM content, but depending on their quantity, biodegradability, and chemical composition, they can also accelerate or retard native SOM mineralization (Agbna et al., 2017; Paustian et al., 1997; Whitman et al., 2015; Zhang et al., 2016). The rapid mineralization rate of labile biochar C by microorganisms is suggested as a possible mechanism to explain the short-term increases of SOM observed in biochar-amended soils (Ameloot et al., 2013).

Although wood-based biochars are a minor source of plant-available nutrients (Ippolito et al., 2015), the addition of biochar to sandy loam soils was expected to increase the concentration of water-extractable nutrients through the direct release of macro- and micronutrients. Biochar-amended plots contained greater concentrations of extractable P, K, Ca, B and Zn in May, but the biochar effect persisted through to August for P, B and Zn only. These results are consistent with a previous study by Angst and Sohi, (2013), which found that the release of biochar P is gradual and sustained, whereas the water-available portion of K is released very quickly and unlikely to be available beyond the first year after biochar application. The transient effect of biochars on extractable K and Ca can be further attributed to the fact that fresh biochars possess very little ability to retain cations (Chan and Xu, 2009). Since the CEC of the sandy loam soil did not increase, this implies that there was no extra retention of K and Ca on soil surfaces in the longer-term.

The application of wood-based biochars produced at low pyrolysis temperature had a short-term (<12 months) positive effect on soil fertility. Biochar-amended plots had a greater soil pH, SOM content, and greater concentrations of water extractable P, K, Ca, B, and Zn. The initial effect of biochar on soil chemical properties is very much dependent on the feedstock and pyrolysis conditions used to create the biochar. The biochar products used in this experiment had a near neutral pH, and a low nutrient content, which can explain their short-term effect on soil fertility. Overall, application of wood-based biochars produced at low pyrolysis temperature is not expected to have a significant and lasting effect on fertility of a well-buffered and well-drained sandy loam soil in New Brunswick, Canada.

4.1.3 CROP RESPONSE

The addition of biochar to a potato cropping system was expected to improve soil quality, and in turn have an overall positive effect on crop productivity. The adsorption and/or immobilization of NO_3^- and NH_4^+ by biochar and microbial communities growing in biochar-amended soils were identified as possible exceptions that could limit potato productivity (DeLuca et al., 2015; Zhang et al., 2015). Although petiole nitrate concentration was lower in the biochar-amended plots than the control plots for one of the four sampling dates, the petiole nitrate concentrations were within the sufficient N range for all biochar treatments during the petiole sampling period (Figure 3-1).

In this experiment, biochar amendments did not significantly affect soil water movement and retention, and had a limited, transient effect on soil pH, SOM content, and soil extractable nutrient content. Biochar addition increase soil pH from 6.50 in the control to 6.67 in biochar amended plots, which was not large enough to affect the availability of soil nutrients, and the increase in soil-extractable P, K, Ca, B and Zn did not translate into differences in plant tissue nutrient concentrations. These findings are consistent with Jay et al., (2015), who attributed limited crop response to biochar amendment to the initially high fertility status of the soil used in their investigation. Biochar amendments were expected to increase N and P use efficiency of potato through improvement in root growth and favorable soil moisture regimes. Results from this experiment showed no effect of biochar on these two parameters, which can explain why no effect of biochar on N and P use efficiency was observed.

Biochar amendments had no significant effect on tuber yield twelve months after being applied to a potato cropping system. This finding is consistent with Jay et al. (2015), Koga et al. (2017), and Liu et al. (2017), who did not observe significant potato yield increase in short-term experiment where biochar was amended to well-managed soils. In this experiment, biochar amendments did not significantly affect CEC and K_{sat}, two parameters that data analyses suggest may be linked to potato yield (Table 3-17). Results from the exploratory path analysis suggest SOM content positively affected potato yield by increasing soil CEC, and improved the Grade A yield by increasing K_{sat} as well. These results are consistent with DeHann et al. (1999) and Porter et al. (1999), who both identified significant relationships between potato yield, SOM, CEC and K_{sat}. Monitoring the long-term effect of biochar amendments on SOM content will therefore be of particular importance in trying to predict the future productivity of biochar amended soils.

4.2 Rate of application effect

The positive effect of biochar on soil properties and crop response was hypothesized to be more important as the biochar application rate increased. Biochar application was effective in lowering soil bulk density, increasing WAS, soil pH, SOM content, and increasing soil-extractable P, K, Ca, B and Zn. The rate of biochar application however was only significant in decreasing bulk density, increasing SOM content in the Airex-amended plots, increasing soil extractable K in the Maple Leaf-amended plots, and decreasing the concentration of Fe in potato tubers.

Biochar application of 20 t ha^{-1} was effective in lowering the soil bulk density significantly compared to the 10 t ha^{-1} application rate and compared to the control. The lowering of bulk density in biochar-amended soils can be caused by physical dilution or by an increase in soil aggregate formation (Hardie et al., 2014; Herath et al., 2013; Jien and Wang, 2013; Mukherjee et al., 2014a;). Adding biochar (density <0.30 Mg m^{-3}) reduced soil bulk density, which supports the physical dilution effect. If the change in soil bulk density was due solely to physical dilution, and assuming that the biochar was evenly distributed within the first 15-cm of soil, the application of 20t ha^{-1} of biochar would have resulted in bulk densities of 1.10 Mg m^{-3} for Maple Leaf biochar and 1.06 Mg m^{-3} for Airex biochar. Since soil bulk density values were lower (1.07 Mg m^{-3} for Maple Leaf, and 1.00 Mg m^{-3} for Airex) than these calculated values, soil bulk density could have been affected by both physical dilution and aggregate formation processes. Although aggregate formation was not measured in this experiment, biochar amendment increased the water-stable soil aggregates relative to the control. However, increasing the biochar application rate did not result in more water-stable soil aggregates. Overall, this suggests that the biochar-induced change in soil bulk density was likely due primarily to physical dilution.

Tubers harvested from plots amended with 20t ha^{-1} of biochar had a lower Fe concentration than the tubers harvested from the other treatments, but this was not related to any persistent change in soil pH or in the soil Fe content. The accumulation of Fe in potato tubers is generally the result of Fe redistribution from above-ground tissues via the phloem (Baker and Moorby, 1969) or to the direct movement of Fe across the epidermis of the developing tuber (Busse and Palte, 2006; Subramanian et al., 2011). One possible explanation could be that greater biochar application rates affected the promoter substances that enhance Fe absorption by potato tubers. Further studies are required to determine if and how high rates of biochar amendment can affect Fe accumulation in potato tuber.

Of all the soil properties affected by biochar application, only soil bulk density, SOM content, and soil extractable K were significantly affected by the rate of biochar applied. Due to inherent soil variability, it can be difficult to measure the effect of application rate on soil properties. In this study, we chose rates that may be of practical relevance to farmers. Greater rates may have resulted in more measurable changes in soil properties. Another important consideration is that the study was on a site with generally favorable soil conditions, therefore beneficial effects may not have been as noticeable. If the characteristics of the biochar do not target specific productivity limiting factors, than significant effects are unlikely to be observed even at high rates of application. Results from the first phase of this experiment indicate that the rate of biochar application can significantly affect soil properties, particularly those directly impacted by soil amendments (e.g. Bulk density, SOM content, nutrient content).

4.3 Source effect

Wood-based biochar made from diverse feedstock and manufacturing processes were hypothesized to be equally effective at benefiting soil properties and potato yield. In this experiment, the effects of a Maple-based biochar produced through slow pyrolysis at low temperature were compared to those of a Spruce-based biochar produced through fast pyrolysis at medium temperature.

Our hypothesis was supported for all measured soil and plant parameters with three exceptions. First, SOM increases were identified only in Airex-amended plots. Second, soil extractible K content was greater in Maple leaf-amended plots than in both the Airex and control plots. Third, the vine and roots of plants grown in Maple Leaf-amended plots contained less Mg than plants grown in Airex and Control plots.

Based on the conceptual model of SOM dynamics in biochar-amended soil (Figure 4-4), biochar application affects the mineralization rate of native SOM (Keith et al., 2011; Zimmerman et al., 2011). The addition of biochar to agricultural soils can induce a priming effect, leading to an increase or a decrease the mineralization rate of native SOM (Maestrini et al., 2015; Wang et al., 2016). Increases in native SOM mineralization can be attributed to increased microbial activity and enzyme production stimulated by: (1) direct effects resulting from the addition of labile C, and (2) indirect effects such as changes in soil pH, alleviation of nutrient constraints or improved microbial habitat (Whitman et al., 2015). A decrease in native SOM mineralization can be attributed to: (1) direct effects such as substrate switching when energy rich organic biochar compounds are preferentially used by microbes, and (2) indirect effects such as the sorption of labile soil organic C on biochar surfaces (Whitman et al., 2015).

The addition of readily available labile C in Airex-amended plots could have increased the SOM content by reducing native SOM mineralization through substrate switching, and by increasing the soil microbial biomass (SMB). While the addition of an organic amendment such as biochar was expected to increase the SOM content, this was not the case in Maple Leaf-amended plots. One explanation could be that the Maple Leaf biochar increased native SOM mineralization through co-metabolism. Adding recalcitrant C is not expected to stimulate SMB activity appreciably, but the Maple Leaf biochar contains a small amount of labile compounds (115 g kg^{-1}) that could trigger the production of enzymes capable of decomposing complex native SOM (Lin et al., 2012). These mechanisms are appropriate to describe SOM dynamics following the addition of Airex and Maple Leaf biochars, which are characterized as a rich source of labile C (42% of the total carbon content in the Airex biochar) and a poor source of labile C (14% of the total carbon content in the Maple Leaf biochar), respectively (Table 2-1).

By the fall sampling date, there was no difference in the SOM content of the biochar-amended and control soils, possibly because the Airex-amended plots experienced a fast mineralization of the labile biochar C, followed by a decrease in SMB as the readily available C resource became exhausted. The decrease in SOM content observed between the May and the August sampling was greater in the plots amended with 10t ha^{-1} of Airex biochar (-25%) than in the plots amended with 20t ha^{-1} of Airex biochar (-3%), which seems to support the hypothesis that the energy-rich C compounds became scarcer 10 months after biochar was applied. The observation is also consistent with the experimental data from the Maple Leaf-amended plots, which showed no significant change in SOM content between the spring and the fall sampling, presumably because most of the C input was in a recalcitrant form. Generally, labile C sources stimulate a short-term increase in soil microbial activity but do not cause a significant long-term change in SOM content, according to the meta-analysis of Maestrini et al. (2015). Additional research is needed to determine the effect of biochar application on soil microbial diversity and activity in order to understand mechanisms governing SOM dynamics in biochar amended soils.

The higher extractable K concentration observed in spring sampling in the Maple Leaf-amended plots can be attributed directly to the higher available K content of Maple Leaf biochar (Table 2-1). The nutrient input from biochar application is expected to vary according to the type of biomass and the pyrolysis process used in the production of the biochar materials (Table 1-2).

Plots amended with Maple Leaf biochar had a lower concentration of Mg in vine and root tissues when compared to the other treatments but there was no effect on the translocation of Mg to potato tubers. This result does not appear to be related to soil pH or to the soil Mg content, so it could possibly be attributed to the selective adsorption of Mg on biochar surfaces (Novak et al., 2009), which would have reduced the mass flow of Mg in the soil solution. The same mechanism could explain why the root Mn concentration was lower in biochar-amended plots than in the control plots.

Wood-based biochars were equally effective at lowering soil bulk density, and increasing soil WAS, and equally ineffective at affecting soil water regimes, and tuber yield. Where Airex biochar was effective at increasing the SOM content, Maple Leaf biochar was not. This important difference could be attributable to the nature of the C contained within these two biochar products (42% labile C in Airex, 14% in Maple Leaf, and highlight the role of pyrolysis conditions in affecting the characteristics of biochars. The difference in the length of the pyrolysis process (5 min for Airex, and 37 h for Maple Leaf) resulted in the formation of two distinctly different products. Whereas the greater labile C content of Airex could generate a rapid response from soil microorganisms, the more recalcitrant nature of the C in Maple Leaf biochar is expected to persist in the soil environment for longer periods of time.

The results presented in this thesis should not be considered as exhaustive because they were drawn from data collected in the first twelve months after biochar was applied to experimental plots at the Fredericton Research and Development Centre. Results collected from relatively small, uniform plots at a research centre that follows the recommended practices for soil conservation and crop rotations cannot be extrapolated directly to farms in the region, which show greater variability in soil conditions and management.

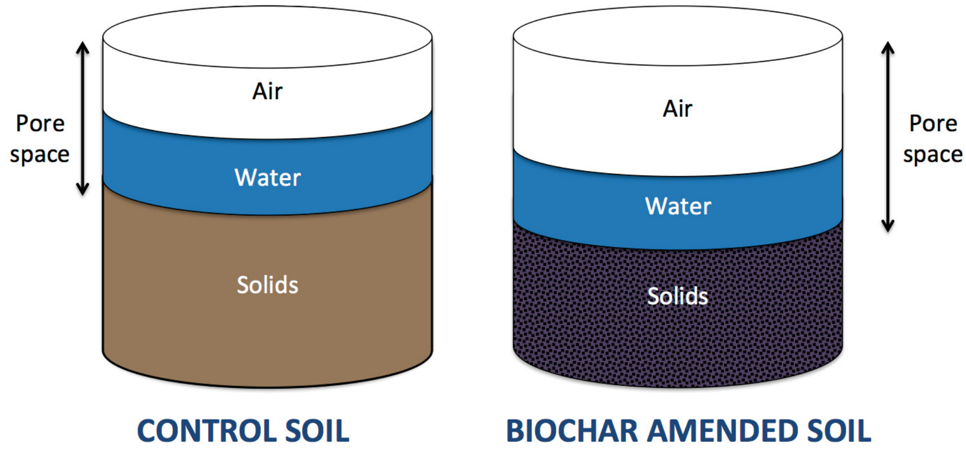


Figure 4-1. Increase in soil porosity in biochar-amended soil.

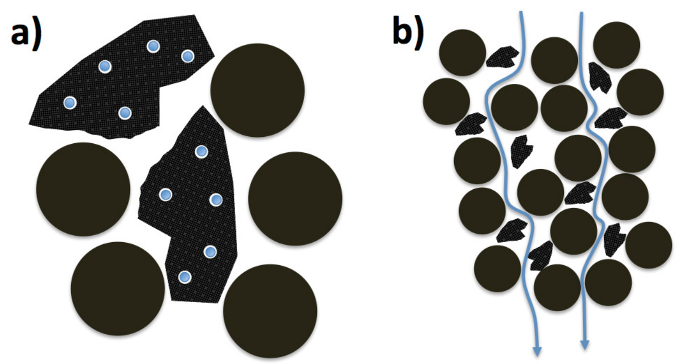


Figure 4-2. Biochar can affect hydrological properties of coarse soils by a) increasing water retention in biochar pores, and b) increasing tortuosity.

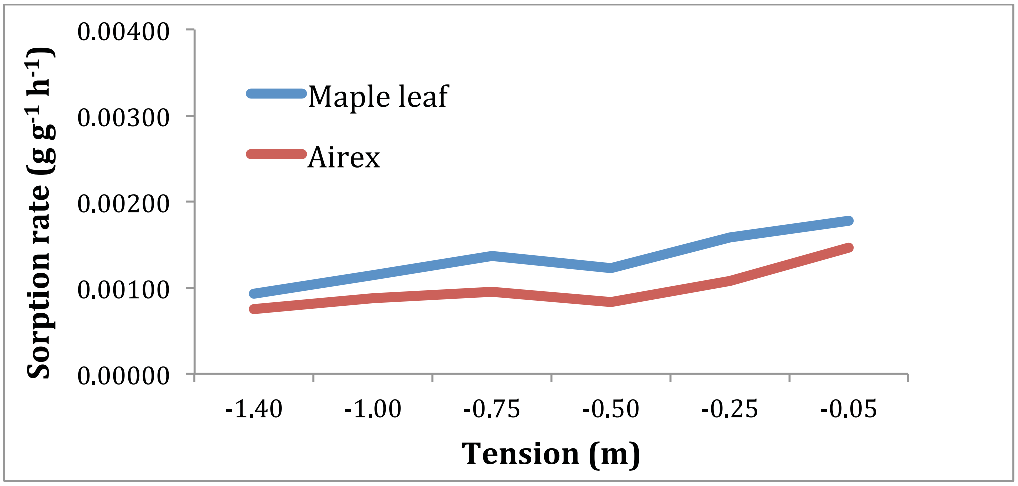


Figure 4-3. Capillary rise of Maple Leaf and Airex biochars.

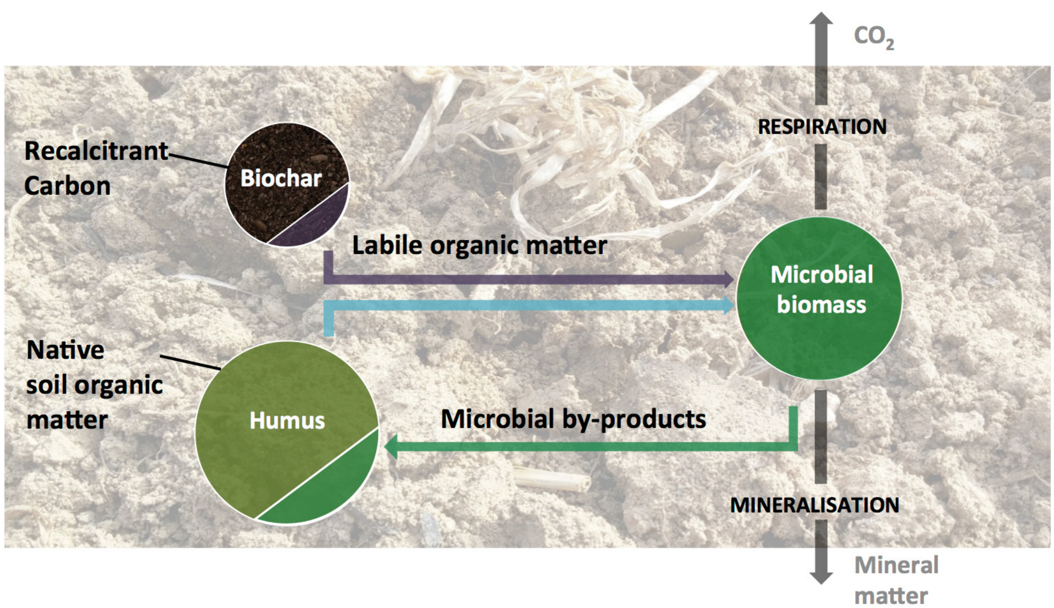


Figure 4-4. Soil organic carbon dynamics in biochar-amended soils.

5. Conclusion and recommendations for future research

In this experiment, two rates of two commercially available wood-based biochars were amended to experimental plots in order to determine the effects of biochar type and application rate on potato crop response and on physico-chemical indicators of soil quality. Specifically, the goals of this research were to answer three questions: (1) can commercially available biochar improve soil quality and crop productivity, (2) will greater improvements in soil quality be achieved with increased rates of biochar application, and (3) will soil quality attributes respond differentially to the type of biochar applied? To address these questions I hypothesized: (1) that biochar would positively affect soil properties and potato yield; (2) that increasing the biochar application rate would augment the positive effect of biochar on soil properties and potato yield; and (3) that wood-based biochars made from different feedstock and manufacturing processes would be equally effective at benefiting soil properties and potato yield.

Soil properties, and crop responses were measured in May and August 2016, eight and twelve months after the biochar treatments were applied to a rainfed potato cropping system on a sandy loam soil. Wood-based biochars were effective at lowering soil bulk density, increasing the aggregate stability, soil pH, SOM content, and soil extractable P, K, Ca, B, and Zn content. Biochar was, however, ineffective at improving the K_{sat}, AWC, and potato yield.

The beneficial effects of biochar on soil quality were for the most part transient such that twelve months after biochar application the soil extractable P, B, and Zn were the only measured soil parameters for which biochar-amended plots performed better than unamended control plots. The short-term effect of biochar on soil physico-chemical properties was likely attributable to: (1) the oxidation of biochar surfaces, which may affect biochar's capacity to bind water, nutrients, clays and organic compounds; (2) the low capacity of fresh biochar to retain cations; and (3) to the rapid mineralization of labile biochar C by soil microorganisms.

The positive effect of biochar on soil bulk density, SOM content in Airex plots, and soil extractable K in Maple Leaf plots was greater in the plots amended with 20 t ha^{-1} of biochar than in the plots amended with 10 t ha^{-1} of biochar. Two reasons were identified to explain why no other soil properties were affect by the rate of biochar application. First the inherent soil variability common in field experiments made it difficult to detect the effects of application rate. Second, application of greater quantities of a biochar that is not manufactured to target specific soil properties is unlikely to result in significant soil quality improvement.

The two wood-based biochars were equally effective at lowering bulk density and increasing soil aggregate stability, and equally ineffective at affecting soil moisture regimes and potato yield. They did, however, affect soil organic matter, and soil extractable K differently. The increase in soil organic matter observed in Airex amended plots, and the increase in soil extractable K observed in Maple Leaf plots were linked to differences in the pyrolysis parameters used to produce the two biochars. Specifically the longer pyrolysis process used in the production of Maple Leaf biochar resulted in a biochar with a greater content of K and recalcitrant C. The rapid pyrolysis process used to manufacture Airex biochar on the other hand resulted in a biochar with a greater labile C content.

Biochar-mediated changes in soil properties are dynamic and susceptible to change over time as biochar ages. In the same way that some biochar effects can occur rapidly after fresh biochar is amended to the soil and then subside, it is possible that some of the soil and plant parameters that were not affected by fresh biochar will respond differently in the future. Specifically, the effect of biochar on soil K_{sat}, and soil AWC could become significant once mechanical breakdown of large biochar particles changes the interparticle space in coarse textured soil, and once biochar oxidation increases the hydrophilic properties of biochar. These possibilities highlight the importance of long-term field studies, and continuous monitoring of soil properties and crop response in the development of recommendations on the use of biochar in agricultural soils.

Findings from this research also suggest that not all wood-based biochars applied at 10 t ha^{-1} and 20 t ha^{-1} are effective at improving plant yield and the quality of sandy loam soil in potato production systems. Careful consideration must be used in choosing what type of biochar should be applied to what type of soil. A good understanding of the effects of production parameters on biochar characteristics is necessary to maximize the benefits associated with the use of biochar. Research is still needed to identify the combination of feedstock biomass, pyrolysis conditions, and post-production treatment that will be most effective at addressing the soil degradation issues encountered in different types of soil, in different cropping systems, and under different climate.

Acknowledging that yields are variable from year to year, and that one field season of data is insufficient to draw definitive conclusion, results from this experiment suggest that:

(1) short of using customized biochar products, wood-based biochars will affect soil quality in a manner similar to other organic amendments (increase the pH, lower bulk density, increase aggregate stability, improve the concentration of some soil nutrients).
(2) biochar will not necessarily increase yield in a well-managed potato cropping system.

Recommendations for future research

It is recommended that future biochar field experiment be continued for at least two complete cropping seasons. Continuous monitoring of field experiments should aim to answer the following questions: (1) will biochar aging and mechanical breakdown of biochar particles modify soil tortuosity, and soil-water storage? (2) what are the mechanisms affecting SOM dynamics in biochar amended soils? There is additionally a need for controlled studies on SOM mineralization, perhaps with ^{14}C-labelled soil using a method similar to Reed et al. (2017) to determine how biochar contributes directly to the SOM content as a stable C product, and if biochar stimulates the formation of de novo SOM derived from plant residues and microbial byproducts. Research is needed to determine the effect of biochar application on soil microbial diversity and activity in order to understand mechanisms governing SOM dynamics in biochar amended soils. Further studies could be conducted to determine if and how biochar amendment can affect Fe accumulation in potato tuber.

For this experiment, I choose to measure the K_{sat} with intact 100 cm^3 cores using a soil water permeameter. I observed considerable variation (16 % CV) between cores within one experimental plot and suggest that K_{sat} measurement be taken: (1) by sampling more than five cores per experimental plot, or (2) in the laboratory, on re-packed soil columns. As a final recommendation, I suggest that a cover crop should always be seeded in the fall on biochar-amended soils. This should limit the displacement of biochar particles from bare soils by wind and water erosion in the non-growing season period.

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Appendix A:

Map of the biochar field experiment. Each block contains two phases. This thesis contains the results from phase 1 which is composed of plots: 506 to 515, 526 to 535, and 546 to 550**.**