NOVEL ORGANIC AMENDMENTS TO IMPROVE SOIL FERTILITY AND PLANT NUTRITION

A Thesis Submitted to the College of

Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

in the Department of Soil Science

University of Saskatchewan

Saskatoon, Canada

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ABSTRACT

There is worldwide demand for organic materials that would be suitable for addition to soils to improve fertility and thereby enhance the production of annual crops and forages. The expansion of biofuel production worldwide has resulted in co-products from fermentation such as distillers' grain that, when fed to cattle, enable the nutrients used in ethanol production to be recycled by land application of the manures. Other organic co-products from bioenergy production include chars that are left behind from combustion. Leguminous crop residues have a high nitrogen content compared to many other residues and could act as useful "green manures" when added to soil. Such materials have potential as soil amendments but have not been extensively evaluated. The overall objective of the work described in this thesis was to determine the fertility benefits that may be realized by adding these amendments to soil. In this thesis work, three types of novel organic amendments (dried distillers' grains and solubles (DDGS)-fed cattle manure, alfalfa pellets, and biochar) were evaluated for their effect on plant growth and nutrition and soil fertility in specific, promising applications. Three studies were implemented: 1) a study on the effect of adding different types of DDGS-fed cattle manure on canola growth and nutrition in the growth chamber, 2) a field reclamation study with alfalfa pellets and biochar added to disturbed soils near a potash mine, and 3) a growth-chamber study on use of biochar to improve canola growth and the use efficiency of added fertilizer nutrients on two contrasting Saskatchewan soils.

In the manure study, the effect of wheat and corn DDGS-fed cattle manure (fresh and composted) on canola biomass yield, canola N, P, K, and S concentration, soil available N, P, K, S, Cu, Zn, and the recovery of added manure N was determined. Four rates of manure (60, 120, 180, and 240 t ha^{-1}) were applied to two contrasting Saskatchewan soils (Brown and Black

Chernozems) in controlled environment conditions, and canola was grown over a five week period.

The reclamation study examined the effect of the addition of oat hull-based biochar and alfalfa pellets on biomass of tall wheatgrass and the concentration of N, P, K, and S as well as on soil concentrations of available N, P, K, S, and cation exchange capacity. Two plot areas adjacent to the PCS Cory Potash Mine (near Saskatoon) were utilized, including one on a degraded level area and one on a tailings pond containment berm. The amendments were applied in the fall of 2009 and the site was seeded with tall wheatgrass (*Thinopyrum elongatum*) in the spring of 2010. Plants were harvested from one m^2 areas in each plot in the fall of 2010 and the soil in each plot was sampled in the spring and fall of 2010.

The evaluation of biochar to improve plant growth and recovery of fertilizer nutrient was conducted in the growth chamber using biochar derived from willow feedstock. The willow biochar was added at 5, 10, and 20 t ha^{-1} rates alone, and also a treatment with biochar at 10 t ha^{-1} with urea and superphosphate fertilizer. The plant N, P, K, and S concentration, soil N, P, K, and S, and N recovery by canola were analyzed following a five-week growth period of canola on Brown and Black Chernozem soils.

In the DDGS-fed manure study, the wheat-based DDGS-fed composted cattle manure added the most nutrient per unit weight of added manure of the different manure sources evaluated. Distillers grain fed cattle manure is higher in nutrient content than regular grain ration manure. The composting process further increases the concentration of nutrient ions in the manure and toxicity effects were observed at high rates of application (180 and 240 t ha^{-1}). In the reclamation field trial, there was increased biomass of tall wheatgrass on soil amended with alfalfa pellets that is attributed to increased soil N availability, as also shown in increased soil

nitrate contents. The biochar treatment on the berm resulted in increased soil organic carbon (SOC) contents. Biochar added to two Saskatchewan agricultural soils under controlled environment conditions revealed no significant effect of biochar, without or with fertilizer, on the canola yield, nutrient concentration, or fertilizer N recovery by canola grown on the two soils.

All three types of organic amendments studied have different characteristics and potential for enhancing soil fertility, plant growth, and nutrition. Manure feed-source (such as wheat or corn DDGS) and processing (composting) all must be considered when determining rates of application for maximizing plant growth and nutrition in the first year following application. Including DDGS in the ration followed by composting will increase the nutrient concentration in the manure per unit weight, necessitating lower application rates of manure product. Alfalfa pellets provide a slow release fertilizer that can be beneficial in increasing plant growth in reclamation of disturbed soils. Biochar appears to have relatively little impact on plant growth and nutrient recovery in the year of application. Further field-scale research on the application of these amendments is required to determine the long-term effects on plant growth and nutrition.

ACKNOWLEDGEMENTS

I would like to acknowledge a number of people for their support and assistance in this project. I would like to thank my co-supervisors, Dr. Jeff Schoenau and Dr. Richard Farrell, for their guidance and advice along the research process. I am very appreciative of the mentorship and committed time and effort that I have received along this process from Dr. Schoenau. My advisory committee, including Dr. Derek Peak and Dr. Diane Knight, has also provided guidance and different viewpoints for my project. I would like to thank Cory Fatteicher who has assisted in my learning of many soil and plant analysis procedures in the laboratory as well as provided a helping hand and words of encouragement when required. I would like to extend a heartfelt thank-you to Jesse, my mother and father, and all of my family and friends for providing support, understanding, and encouragement throughout the whole process.

I would like to thank the Agriculture Development Fund, the Beef Cattle Research Fund, and the Saskatchewan Potash Producers Association environmental group for financial assistance. Thank-you also to Dr. Xiying Hao with the Agriculture and Agri-Food Canada Research Centre in Lethbridge, Alberta for her support in supplying the manure.

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LIST OF SYMBOLS AND ABBREVIATIONS

AB	Alberta
Al	aluminum
ANOVA	analysis of variance
C	carbon
Ca	calcium
$CaCl_2$	calcium chloride
CEC	cation exchange capacity
CH_4	methane
CO_2	carbon dioxide
Cu	copper
DDGS	dried distillers' grains and solubles
DTPA	Diethylenetriaminepentaacetic acid
EC	electrical conductivity
(g)	gas
GLM	general linear model
H_2O_2	hydrogen peroxide
K	potassium
KCl	potassium chloride
LSD	Fischer's least significant difference
Mg	magnesium
N	nitrogen

Na	sodium
NH_3	ammonia
NH_4	ammonium form of nitrogen; NH_4^+; NH_4-N
NO_3	nitrate; NO_3^-; NO_3-N
N_2O	nitrous oxide
NUE	nitrogen use efficiency
P	phosphorus
PO_4	phosphate form of phosphorus; PO_4-P
rpm	revolutions per minute
S	sulphur
SK	Saskatchewan
SOC	soil organic carbon
SO_2	sulfite
SO_4	sulphate form of sulphur; SO_4-S
SOM	soil organic matter
Zn	zinc

1.0 INTRODUCTION

There are global concerns surrounding the decreasing levels of organic matter in soils as a result of anthropogenic activities. Soil organic matter (SOM) levels can decrease significantly over time due to reduced C inputs and accelerated losses associated with cultivation and erosion. The addition of organic amendments like manure can increase the organic matter content in soils (Reeves, 1997; Ladha et al., 2011), and contribute significantly to the long-term nutrient supplying power of the soil (Schoenau and Davis, 2006). The need for increased SOM and nutrients that will enhance plant nutrition and growth strengthens the demand for new sources of organic amendments that can be added to soil.

Perhaps the best known and most widely used organic amendment in agriculture is manure, which has long been applied in conventional agricultural systems to increase soil fertility and crop yields. Conventionally fed cattle manure, a well-documented soil amendment, provides a long-term source of nutrients to the soil and can influence soil properties such as increasing soil C and N concentrations, soil pH, cation exchange capacity, and soil available P and K concentrations (Schoenau et al., 2010; Eghball et al., 2004). Distillers' grains is a by-product of the ethanol production process that is recently being incorporated into cattle rations in western Canada (Feed Opportunities from Biofuel Industries, 2010). Manure from cattle fed distillers' grains was determined to have higher nutrient content than cattle fed conventional grain rations (Hao et al. 2009). Hao et al. (2009) concluded that more research is required to study the behavior of dried distillers' grains and solubles (DDGS)-fed cattle manure and its effects on soil quality and plant nutrition. For example, it is likely that the nutrient content and performance of the manure as a fertilizer will depend on distillers' grain source and will also be influenced by manure processing practices such as composting. Therefore, there is a need to

investigate the effect of different distillers' grain feedstocks and the composting of the manure on its behavior as an organic fertilizer in prairie soils.

Alfalfa pellets represent a green manure that is a simply processed (pelletized) form of plant residue. This is in contrast to animal manures derived from plant material that has gone through a digestive tract. Alfalfa pellets can also provide a slow-release form of N and P fertilizer, which is beneficial for improving the soil quality in degraded soils (Agehara and Warncke, 2005). Alfalfa can have similar C:N (13:1 to 17:1) ratios compared to manure but may produce different concentrations of available nutrients as it breaks down in the soil. Compared to urea fertilizer, alfalfa pellets had approximately 30 to 50 % lower N availability in a five week incubation study (Qian et al., 2011). However, alfalfa pellets are attractive compared to animal manures, owing to their ease of handling, transport and application.

Biochars are novel organic amendments that are a co-product of bioenergy production created when organic materials are combusted under low or no oxygen in a process termed pyrolysis. Chars are reported to improve the efficiency and plant recovery of fertilizers in highly weathered soils due to increased adsorptive surface area provided by the char (Calvelo Peirera et al., 2011). Biochar amendments have a high concentration of recalcitrant C and low concentration of N (C:N up to 700:1) with relatively small concentrations of other nutrients such as P (Verheijen et al., 2009). The efficacy of biochars as soil amendments has not yet been extensively studied in soils from temperate regions, with little or no information available from the northern Great Plains. They may play a role in improving the soil carbon content and in enhancing nutrient availability and recovery in agricultural soils and disturbed lands requiring reclamation.

It is postulated that adding DDGS-fed cattle manure, alfalfa pellets, and biochar to Saskatchewan soils will increase soil fertility and plant growth. The overall objective of the research described in this thesis is to determine the effect of adding fresh and composted DDGS-fed cattle manure, alfalfa pellets, and biochar on plant nutrient uptake and yield and soil available nutrients and chemical properties using relevant soils and site conditions in the evaluations. Specifically, the effects of DDGS-fed cattle manure and biochar are evaluated on agricultural soils, with canola grown as a high nutrient demanding crop under controlled environment conditions, using low fertility Brown and Black Chernozem soils collected from typical farm fields. The effects of alfalfa pellet and biochar application were evaluated on a disturbed soil adjacent to a potash mine, with the intent of evaluating their suitability in reclaiming the disturbed soil and promoting growth of vegetation. Finally, the ability of biochar to improve canola growth, nutrition, and recovery of fertilizer nitrogen is investigated on two contrasting Saskatchewan agricultural soils in the growth chamber. A flow chart of the layout of the project is presented in Figure 1.1. The thesis is organized as follows:

1) Literature Review (Chapter 2)
2) Behavior of Different DDGS-fed Fresh and Composted Cattle Manures (Chapter 3)
3) Application of Alfalfa Pellets and Biochar To Reclaim Productivity of a Disturbed Soil (Chapter 4)
4) Amendment of Two Agricultural Soils With Biochar To Improve Plant Nutrition and Fertilizer Use Efficiency (Chapter 5)
5) General Discussion and Conclusions (Chapter 6)

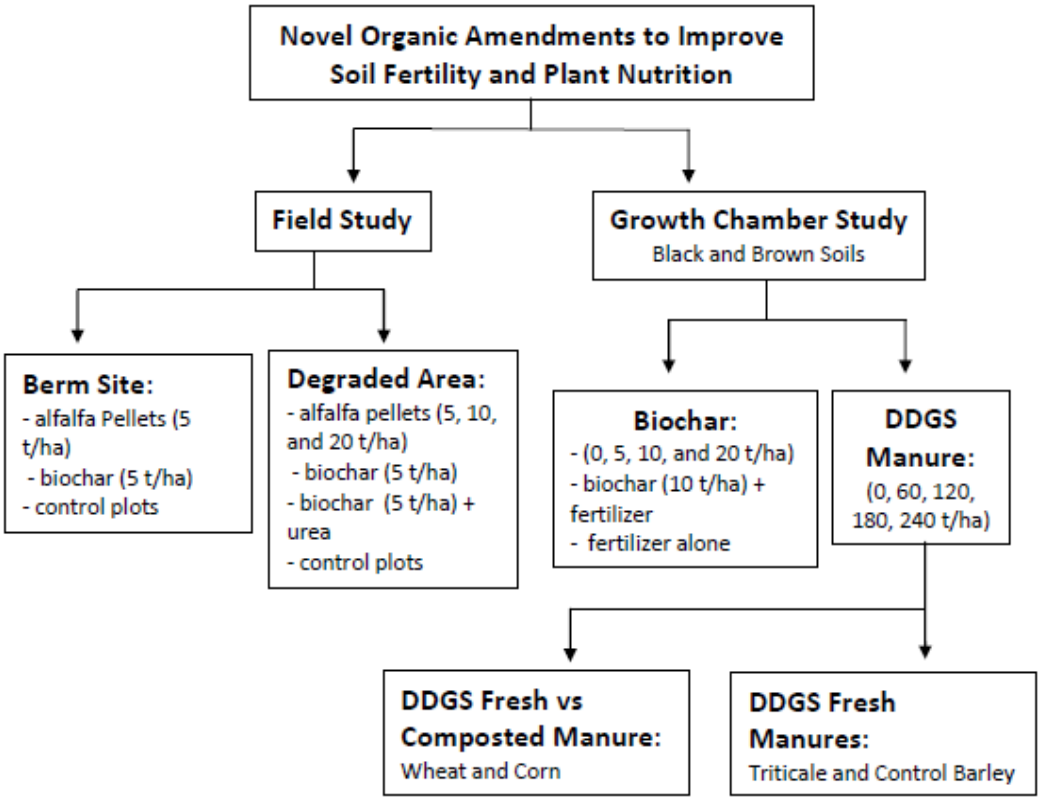

Figure 1.1 Project flow chart outlining studies on alfalfa pellets, biochar, and DDGS-fed cattle manure.

2.0 LITERATURE REVIEW

2.1 Soils and organic amendments

Organic amendments have long been used as an effective way to increase the soil organic matter (SOM) content and to provide and help retain nutrients for enhanced plant growth. The value of organic amendments as fertilizers is dependent on their composition and rates of decomposition. For example, much of the N in organic amendments is in organic form and requires mineralization by microbes to be rendered plant available. Most synthetic fertilizers are readily available for plant uptake in the first year of application but do not provide a continuous release of nutrients over time like organic amendments do. Bulluck et al. (2002) conducted a study in Virginia and Maryland where organic amendments, including composted cotton-gin trash, composted yard waste, and cattle manure, increased the soil organic carbon (SOC) content and cation exchange capacity (CEC) of the soil compared to the treatments that used synthetic fertilizer.

Organic amendments enhance the storage and cycling of C and N in soil ecosystems in soil microbial processes such as mineralization. Mineralization rates in soil are affected by factors such as C:N ratio of the organic matter, the C:N of the consuming microbial biomass, and the texture and porosity of the soil (Hassink et al., 1993). Different types of organic amendments have differing N mineralization potential, which affects the plant uptake of nutrients over time (Levi-Minzi et al., 1990). Organic amendments such as cattle manure provide high levels of total organic N to soil and act as a long term N fertilizer (Gong et al., 2011). The quality or degradability of the organic amendment will also affect the release rate of plant available N (Booth et al., 2005). Some types of organic amendments such as rye straw can actually decrease the organic C in the soil, likely because of the straw contributing to porosity and aeration (Levi-

Minzi et al., 1990). Farmyard manure and municipal refuse compost were found to increase or at least maintain the organic matter in the soil (Levi-Minzi et al., 1990). The mineralization of organic C and N over time provides a slow release of nutrients for plant growth past the first year of application.

Soil organic carbon (SOC) can be an indicator of soil quality and can have varying decomposition rates because of the C existing in different SOM fractions. Density fractions of SOM are categorized into heavy, medium, or light. The heavy fraction SOM has the lowest decomposition rate and contains plant material that is no longer distinguishable while the light fraction has the highest decomposition rate and consists of recognizable plant material (Hassink et al., 1997). Farmyard manure increased the C in the heavy fraction to a greater extent than chaff or alfalfa in a study in northern Netherlands after 25 years of manure application. The medium SOM fraction had the greatest proportion of SOM after 15 years of manure application. The light and medium fractions were determined to be early indicators of SOM quality in the soil as affected by soil management (Hassink et al., 1997).

Many studies conducted on organic matter dynamics in soil have encompassed effects over one or two years (short term) or three to several years (long term). A short term (11-month) study in Denmark, Sweden claimed that long term incubation studies do not improve the understanding of N dynamics following application of household compost and sewage sludge because the crop roots compete for immobilized N (Debosz et al., 2002). Paul (1984) concluded that the long-term (e.g. seven years) decomposition of organic matter is a function of the substrate composition and that there is a stabilizing effect to soil over time. Other authors stress that long term studies are required to determine the turn-over of various fractions of organic

matter and to reveal the effect of organic amendments on long-term soil quality (Larney et al., 2005; Gong et al., 2011).

Organic fertilizers can be important to restoring the level of organic matter in soils that have been degraded. In addition to agricultural activities, other anthropogenic disturbances such as oil and gas exploration and mining activities can also decrease the soil productivity and organic matter content. Organic matter additions are an integral part of restoring these degraded soils. In many cases, these soils have been stripped of topsoil which is then replaced following the disturbance. A study in southern Alberta examined the restorative effects of soil amendments including compost, manure, wheat straw, and alfalfa hay on three oil and gas sites. Alfalfa hay increased the soil plant available N content to the greatest extent because of the enhanced mineralization of N from the alfalfa hay compared to the other soil amendments (Larney et al., 2005). There are various types of organic amendments that have potential for agricultural and reclamation purposes to enhance plant growth and improve soil quality.

2.2 Novel organic amendments

Novel organic amendments are arising due to the expansion of industries such as biofuel and bioenergy production that create organic co- or by-products containing carbon and plant nutrients. There as an increasing need for an end-use for dried distillers' grains and solubles (DDGS), a by-product of the ethanol distillation process. The pyrolysis process produces biochar, a high C by-product, which may have potential as a soil amendment. The transformation of alfalfa pellets as a processed form of plant residue used solely as a livestock feed source to an organic amendment creates another novel organic amendment opportunity.

There have been numerous studies on manure, which is a "conventional" organic amendment used for centuries, with numerous studies on its effects as an amendment, both short-

and long-term. There is opportunity for novel organic amendments to have potential beneficial effects on soil fertility and plant nutrition.

2.2.1 Dried distillers' grains and solubles-fed cattle manure and compost

Ethanol production plants are present in each of the Prairie Provinces in Canada and produce high volumes of DDGS. Approximately 290 kg of DDGS is produced from one tonne of wheat grain and an 80 million L ethanol plant can produce 70,000 tonne of DDGS (Government of Alberta, 2010). The increased need for a value-added use of DDGS has initiated recent research on distillers' grains as feed source for beef cattle (Walter et al., 2010). The ethanol production process removes the starch from the grains, resulting in a by-product higher in protein compared to unprocessed grain, such as barley. The DDGS can be added to beef cattle diets as a portion of the protein required (Spiehs et al., 2002). A study conducted by Walter et al. (2010) found that cattle on a ration of 20 to 40 % corn DDGS (as replacement of a portion of the barley fed in ration) had increased dry matter intake and reduced amount of days that the beef cattle were required to be on feed before slaughter.

An additional finding as a result of the animal nutrition studies was that the DDGS-fed cattle produced manure of different nutrient composition than conventional grain ration-fed cattle (Hao et al., 2009). The increase in protein from the addition of DDGS in cattle feed results in a cattle manure that is higher in N (Hao et al., 2009). The P content in the DDGS is also higher compared to unprocessed barley grain, which results in higher N and P content in the DDGS-fed cattle manure (Table 2.1) (Hao et al., 2009). The differences in manure composition related to feed source can affect soil nutrient availability and plant production as well as nutrient loss through run-off and erosion.

Table 2.1 Nutrient content of manure from wheat dried distillers' grains and solubles (DDGS)-fed cattle at four different DDGS diet rations. The rations consisted of 5% mineral supplements, 10% barley silage, and 85% grain. The DDGS was substituted for part of the grain in the ration (adapted from Hao et al., 2009).

Diet (%DDGS)	N	P	Ca	Mg	K	SO_4
	---------- g kg^{-1} ----------					
0	3.7	0.34	1.36	0.87	12.7	4.4
20	6.9	0.57	0.95	0.39	13.3	6.0
40	7.1	0.57	0.73	0.21	12.4	7.4
60	12.8	0.88	0.69	0.07	16.0	10.1
60 + Ca †	11.2	0.76	0.80	0.07	16.0	9.6

†1% of Ca was added to the ration to increase feed Ca:P from 1.1:1 to 1.6:1.

Adding DDGS as a portion of cattle rations can have effects on greenhouse gas emissions. Addition of DDGS as a portion of cattle feed rations decreased the methane (CH_4) emissions from cattle in a study by McGinn et al. (2009). In the same study, they found that increased N content in the DDGS fed cattle manure resulted in manure that may increase the volatilization process causing increased N losses from DDGS amended soil. Hao et al. (2011) studied the greenhouse gas emissions from the composting of wheat DDGS fed cattle manure and found that the CH_4 and CO_2 emissions were similar to barley-fed cattle manure but the N_2O emissions were higher in the DDGS fed cattle manure. Greenhouse gas emissions may be important when considering the handling and storage of the DDGS-fed cattle manure.

Composting is an aerobic process in which microbes break down organic matter, thereby changing the physical and chemical parameters of the material (Larney et al., 2006). To compost cattle manure, the manure is commonly placed into long piles called windrows where it is aerated to encourage microbial activity that is vital to the composting process. Factors that affect microbial growth and activity such as temperature and water content can, in turn, change the composition and rate at which the compost is formed (Larney et al., 2006). Composted material is much lower in moisture than the initial manure, and composting concentrates the nutrients in

the manure (Richard et al., 2002). Larney and coauthors (2008) recorded a mean water loss of 77.5% from the composting of wood chip bedding manure.

The composting process can change the C and N dynamics and C:N ratio of the manure due to the significant C loss as the microbes consume the C in the fresh manure and release CO_2. While most of the N is conserved, there is a transformation of NH_4-N form to NO_3-N form in the nitrification process during composting (Larney et al., 2006). Some of the N can be also be lost in the composting process through conversion of NH_4 to $NH_3(g)$ which is lost to the atmosphere (volatilization). The microbial, physical, and chemical processes that occur during composting can increase the stability of the manure compared to fresh manure. The C and N are in more stable forms in compost because intense microbial activity has already occurred in the composting process (Eghball, 2002).

Crop uptake of N and P applied as fresh versus composted manure has been investigated in a few studies. In a three-year study on a southern Alberta soil, the dry matter yield of barley was not significantly different between composted and fresh manure types (Miller et al., 2004). In the same study, fresh manure amendment resulted in higher N availability than the composted manure, especially in the straw bedding treatment. Manure that has been through the composting process has different C and N contents, and thus mineralization rates are likely to differ from fresh manure (Eghball, 2002).

A lower C:N ratio of soil or manure increases the N available for plant uptake, which is associated with increased plant growth and plant biomass production (Qian and Schoenau, 2002). Different types of manure will also have different concentrations of inorganic N (Miller et al., 2010). Cattle manure collected from pens with wood chip bedding had a C:N ratio of 26:1 compared to straw bedding manure with a C:N ratio of 15:1 (Larney et al., 2008). Straw bedding

manure with the narrower C:N ratio had greater concentrations of NO_3 but lower levels of NH_4 than the wood chip bedding with wider C:N ratios in fresh and composted cattle manures. Overall the straw bedding manures with narrower C:N produced a greater release of N over time (Miller et al., 2010).

Matching the crop N uptake with manure N application rate is important to ensure that the nutrients are not lost and that the plant's nutrient needs will be met for greatest production potential. Mooleki et al. (2004) found that with increased application rate of feedlot cattle manure, there was also increased concentrations of available N in the soil following harvest of the plants. In the same study, only seven to ten % of the N applied as cattle manure was recovered in the first year of application on a Saskatchewan soil. Miller et al. (2004) found that on a Dark Brown Chernozem near Lethbridge, Alberta there was no difference in N recovery from fresh versus composted manure over a three year period, with values ranging from two to 11 %. Manure N recovery was significantly lower than fertilizer N recovery in the same study (mean fertilizer N recovery of 19 %). Eghball and Power (1999) found that manure N recovery for corn was 17 % for fresh manure and 12 % for composted manure over a four year period, and was significantly lower than the N recovery for inorganic N fertilizer (45 %). Determining the characteristics of the manure such as available and total N as well as N recovery can help in the understanding of N availability for plant uptake in the year of application and subsequent years.

Manure is a significant source of other nutrients, especially P. The majority of P in manure is of high availability to plants in the form of PO_4-P, with the availability in composted manure reported to be higher than fresh manure (Eghball and Power, 1999). The composting process concentrates non-volatile inorganic nutrients such as P and K in the manure because some organic carbon and moisture is lost during decomposition and composting (Larney et al.,

2008). Inorganic P in beef cattle fresh manure and composted manure can be applied at rates that are too high to be retained in the soil, and the soluble P is lost through leaching and run-off (Eghball, 2003).

High rates of manure application can increase the levels of salinity in agricultural soils by adding salts. Wood chip bedded cattle manure was observed to have lower salinity effects on surface soil compared to straw bedded cattle manure (Larney et al., 2008). Hurisso et al., (2011) found that fresh dairy manure at a rate of 44.8 Mg ha^{-1} increased the soil salinity to 0.68 dS m^{-1}. Saskatchewan regulations for manure applications state that manure application should not increase the soil electrical conductivity (EC) by more than one dS m^{-1} and manure should not be applied to soil over four dS m^{-1} where salts are already elevated (The Prairie Provinces Committee on Livestock Development and Manure Management, 2001). Increased salinity due to addition of compost products can be an issue in agricultural operations and can decrease plant growth at high rates of application (Roca-Perez et al., 2009). Manure applied at the correct rate for reduced losses of nutrients and risk of salinity following application is important for maximizing the beneficial effects of manure on soil quality and plant nutrition.

2.2.2 Alfalfa pellets

Alfalfa pellets have traditionally been used as a feed source for livestock and poultry but can also be used as a sustainable organic amendment that is beneficial for crop growth. Miyasaka et al. (2001) found that alfalfa pellets, added to soil as an organic fertilizer, were effective in improving plant growth and soil conditions predominantly due to increased soil moisture content on a silty clay loam off the coast of Hawaii. When using organic fertilizers such as alfalfa pellets, N release characteristics of the organic amendment are also important for determining the effectiveness of the fertilizer (Agehara and Warncke, 2005).

Alfalfa pellets can be effective in improving soil-water relations and plant N nutrition. Alfalfa pellets can expand to four times their original size when swelled with water and are reported to increase the soil water holding capacity (Stoklas, 1999). Barley plants had increased germination rate and plant health in a treatment with 90 % sand and 10 % alfalfa pellets (Stoklas, 1999).

In greenhouse trials conducted by the Crop Diversification Centre in Brooks, Alberta in 2005, there were favorable results for alfalfa pellets as a soil amendment for remediation (Savidov and Bansal, 2005). These authors found that with the alfalfa pellet amended treatment there was increased growth of barley (plant height, stem diameter, and leaf width) grown in brine-contaminated soil from an actual brine spill site. Plants in the trials with the alfalfa pellet amendment were also noted to have increased uptake and content of Na and Cl in the plant tissue. The results of the study indicate that pelletized alfalfa has potential as an amendment for reclamation.

Dehydrated alfalfa products can have beneficial effects on plant growth but timing of application is also important. Alfalfa powder addition to a Saskatchewan soil from the Brown soil zone improved canola biomass yield (Qian et al., 2011). However, application of alfalfa pellets to soil directly before planting may have negative effects on seed germination due the allelopathic chemicals in the pellets. Alfalfa excretes phytotoxic chemicals such as saponins and salicylic acid as it decomposes. These allelopathic properties of alfalfa pellets were reported to decrease weed germination in rice but disappeared 10 to 25 days after application (Xuan et al., 2005).

The N in alfalfa products is released in the soil over time in plant available forms. Alfalfa mulch added at the highest rate (3.9 and 5.2 t ha^{-1} that was equivalent to 162 and 184 kg

N ha^{-1} respectively) to a range of Manitoba soils over two years had N uptake in oats similar to the 20 and 60 kg N ha^{-1} ammonium nitrate fertilizer treatments (Wiens et al., 2006). In the same study, the alfalfa mulch treatments resulted in N recovery values of 11 to 68 % over two years.

2.2.3 Biochar

Biochar is a relatively stable, inert form of black C material that is created using technology called pyrolysis (Chan et al., 2007). In pyrolysis the biochar is produced by heating (roasting) organic material, such as crop residue and wood by-products, at high temperatures in the absence of oxygen. The recalcitrant C in biochar creates the potential to increase the amount of C stored in soils when biochar is amended to soil. Lehmann (2007) has pointed out that biochar can be a significant tool for C sequestration in soils.

In addition to adding a recalcitrant form of SOC to soil, biochar has the potential to reduce pollution from inefficient use of fertilizers through increased nutrient retention. The increased fertilizer use efficiency associated with biochar is attributed to its role in preventing the leaching of N and increasing the availability of N to the plant, thus enhancing N cycling (Stelner et al., 2008). The low biodegradability of biochar, high porosity, and high surface area create a soil amendment that is stated to contribute to long term soil quality (Stelner et al., 2008).

Biochar has been found to increase the immobilization of N in soil; therefore, timing of biochar addition is important to ensure that N is not immobilized during times of increased plant N requirements (Bruun et al., 2011). In a study testing biochar amendment on soil treated with biosolids, biochar decreased the rate of N leached from the soil solution, possibly through immobilization as well as sorption (Knowles et al., 2011).

Research conducted by Rondon et al. (2006) on beans found that there was improved biological N fixation and therefore increased biomass production with soils amended with

biochar. The increased biological N fixation was likely due to the increased availability of other nutrients due to the biochar addition (Rondon et al., 2006). Growth chamber trials conducted on a nutrient depleted Alfisol showed that there were no significant increases in plant yield with the application of biochar alone but the biochar plus N fertilizer treatments resulted in a significant increase in plant yield (Chan et al., 2007). At rates over 50 t ha^{-1} of biochar, the soil also had decreased tensile strength and increased moisture holding ability. Chan et al. (2007) state that biochar has potential to improve N fertilizer use efficiency as well as increase SOC, soil cation exchange capacity (CEC), and soil pH.

The material that the biochar is produced from, as well as the temperature and duration of the pyrolysis process, can affect the properties of biochar. For example, biochar with a high pH can buffer acidic soils to create a more favorable soil for nutrient retention (Clough and Condron, 2010).

Biochar may affect uptake of nutrients other than N. In soils where biochar and no N fertilizer was applied, the uptake of K, Ca and P by radish was increased at the 50 and 100 t ha^{-1} rates of biochar addition (Chan et al., 2007). In this same experiment, the addition of N fertilizer increased the N uptake in radish, which was balanced by an increase in K uptake. Biochar created from pyrolysis of greenwaste can have increased levels of P and K which can provide nutrients to the plant (Chan et al., 2007). Conversely, Kimetu et al. (2008) found that biochar addition had no effect on plant uptake of P, K, Ca, or Mg compared to control treatments with no biochar. The type of biochar and soil may affect the nutrient retention of the biochar amended soil.

Biochar can increase the soil cation exchange capacity in highly weathered soils. In Anthrosols with and without biochar, Liang et al. (2006) found that biochar increased the CEC of

soils when the organic matter from plant material was separated from more recalcitrant organic C. These authors also calculated the surface charge to be higher in the soils containing biochar, as a result of both increased negative charge density and surface area.

Studies of biochar amendment effect on plant growth and crop productivity have reported variable effects. In a severely degraded soil in Kenya, biochar amendment increased SOC by 45% and the biochar plus N fertilizer increased uptake of N in plants over N fertilizer alone (Kimetu et al., 2008). Compared to other organic amendments such as green manure, animal manure, and saw dust, biochar was found to reverse declines in crop productivity, although long-term studies are required to determine the effectiveness of the biochar amendment in sustaining productivity (Kimetu et al., 2008). In the work in Kenya (Kimetu et al., 2008), the biochar had a greater positive effect on the soil that was not as severely degraded. This claim suggests that even the prairie soils in Saskatchewan, which may be considered to be of relatively higher quality and SOC than degraded tropical soils, would have potential benefits from biochar addition.

Most research with biochar amendment to date has been focused on nutrient poor soil in tropical regions. There is a need for research on biochar as a soil amendment as it pertains to soils in temperate regions of the world where soils are relatively more nutrient rich. Woolf (2008) states that it is important to study all types of agricultural soils to determine the potential of biochar as an amendment on a global scale.

3.0 BEHAVIOR OF DIFFERENT DDGS-FED FRESH AND COMPOSTED CATTLE MANURES

3.1 Introduction

Cattle manure has been long used as a soil amendment because it is a significant source of nutrients for plant growth. There is a high variation among different manure sources and each manure type will have its own unique characteristics and behave differently in soils. Nutrient composition of manure depends on factors such as animal species, animal age, feed composition, and storage (Eghball et al., 2002). The N contained in manure is mainly in organic N form and needs to be mineralized by microbes to the plant available forms NH_4^+ and NO_3^- to become available for plant uptake. Mineralization of manure nutrients is dependent on factors that affect microbial populations including moisture, temperature, C:N ratio, and particle size of manure (Eghball et al., 2002). Understanding the characteristics of manure that affect the mineralization of N such as C:N as well as available N, P, K, and S is important when attempting to match nutrient availability in the applied manure to plant requirements. Nutrient availability in manure is also variable between manure types.

Manure from cattle fed different grain feedstock and rations may contain different concentrations of nutrients. Feed rations in many cattle operations have recently included a portion of DDGS, a by-product of the ethanol production process. Walter et al. (2010) reported that cattle performance (weight gain per amount of feed consumed) was improved in treatments where up to 40% of corn DDGS was included in the feed ration compared to traditional barley-fed cattle. In a study with grazing beef steers in Nebraska, cattle supplemented with corn DDGS feed displayed an increase in body weight gain per hectare compared to fertilized and non-fertilized grass treatments (Greenquist et al., 2009). Moreover, cattle fed rations consisting of 40

and 60 % wheat DDGS had up to 125 % increase in crude protein in their diet compared to a traditional barley ration (Hao et al., 2009). The high potential for DDGS fed beef cattle warrants more research on the manure from the DDGS-fed cattle.

Manure composition is affected by diet and the proportion of DDGS in feed. A diet of 40% and 60% wheat DDGS in cattle feedlot rations in southern Alberta resulted in a three-fold increase in manure NH_4^+ content which was directly correlated to crude protein levels in the cattle diet (Hao et al., 2009). Crude protein that is not absorbed during the digestion of DDGS is excreted and hydrolyzed, resulting in high NH_4^+ content in the manure (Hao et al., 2009). Corn DDGS fed at 2.3 kg per day to beef cattle improved pasture forage [smooth brome (*Bromus inermis*)] growth as a result of the cattle manure returned to the soil surface, which created increased N availability compared to the non-fertilized, non-supplemented treatment (also grazed) (Greenquist et al., 2009).

Adding DDGS to cattle feed rations may influence manure chemical properties such as pH and electrical conductivity (EC). Manure pH was positively correlated with increasing proportion of DDGS in feed, which reflected increasing manure NH_4^+ content (Hao et al., 2009). Elevated EC values were evident in the cattle manure as DDGS in the feed ration increased, which is likely because of the increased concentration of NH_4^+, SO_4^{2-}, and K^+ in the manure (Hao et al., 2009).

Different feedstocks of DDGS include wheat, corn, triticale, and sorghum including mixes of sorghum and barley or corn (US Grains Council, 2009). Wheat DDGS is more commonly produced in ethanol plants in Canada due to the higher availability of wheat grain compared to corn grain in the Prairie Provinces with more than 0.26 million tonnes of wheat DDGS produced annually (Feed Opportunities from Biofuel Industries, 2010). A study on wheat

versus corn DDGS feedstock in cattle rations determined that cattle dry matter intake of wheat DDGS was increased compared to corn DDGS had decreased dry matter intake (Walter et al., 2010). Increased dry matter intake is favourable for beef cattle operations to improve cattle weight gain. Wheat DDGS in a ration fed to dairy cattle resulted in a greater P excretion compared to corn DDGS- fed treatment (Undi et al., 2011).

Manure storage and handling also has a large influence on the resulting nutrient concentration and availability in manure. Composting manure is a common practice for manure storage that decreases the volume of manure to be hauled and concentrates manure nutrients. Additionally, composting decreases weed seed and pathogen levels because the heat generated by microbial activity during composting decreases the viability of the seeds (Erickson et al., 2009). The composting process can change manure nutrient levels and C and N dynamics compared to the initial fresh manure. Net N immobilization occurred in swine-straw manure over a six-week composting process, although approximately 2-3 % of the N was mineralized as well during this time (Cambardella et al., 2003). These authors suggest that NO_3-N is lost during the composting process through denitrification. A study on composting beef cattle manure revealed a loss of up to 40 % of total N in the composted manure compared to fresh manure of the same source (Eghball et al., 1997).

The composting process can decrease the mineralizable C and N in the manure and thus increase the stability of the manure. The stability of composted manures is strongly dependent on the age or duration of composting (Cambardella et al., 2003). Nitrogen mineralization can be lower for composted manure than fresh manure, but can still contribute to significant increases in the available N pool for crop growth (Eghball et al., 2002; Whalen et al., 2008). Mineralization

that occurs during composting can result in reduced water and C content and thus the concentration of nutrients and ions in composted manure is increased (Larney et al., 2006).

Recovery of N varies between different manure sources and can be related to N mineralization and N availability. The C:N ratio as well as the composition of the carbon and nitrogen in the manure can affect mineralization. Qian and Schoenau (2002) suggest that C:N ratio of manure is negatively correlated with net N mineralization. These authors reported that manure C:N ratios above 15:1 resulted in decreased available N supply rates. The amount of N mineralized from manure is also affected by the composition of the C and N in the manure (Eghball et al., 2002). The release of N from manure can continue in subsequent years following the first year of application and there can be a build-up of residual N in the soil as a result of successive manure applications (Mallory et al., 2010).

Soil organic carbon is often used as an indicator of soil quality and manure can be a source of SOC. Soil amended with composted manure had to significantly higher SOC levels compared to plots where compost was not added in a sandy loam soil near Ste. Anne de Bellevue, Québec (Whalen et al., 2008).

Manure is a significant source of P and most of the P in composted manure was is in inorganic form (Eghball, 2003). The N:P ratio of manure is important for determining if there may be loss of P to the environment because often the N and P requirements of plants are different from concentration of those nutrients in manure. Decreasing the amount of P in the animal diet can result in decreased levels of P in the resulting manure (McCallister et al., 2010). A decrease in P input of 33 to 45% in feedlot cattle diets decreased the P in manure by 40-50 % (Satter et al., 2002). Hao et al. (2009) determined that total P levels in cattle fed a ration

including 40 and 60 % DDGS had significantly increased manure total P levels compared to barley-fed cattle manure.

The objective of this study was to compare the effects of adding fresh and composted manure from cattle fed wheat-based DDGS and corn-based DDGS on biomass and nutrient uptake by canola and residual soil nutrients. The concentrations of soil and plant nutrients were used to assess the fertilizing effects of four different manures: wheat-based DDGS-fed fresh cattle manure, wheat-based DDGS-fed composted cattle manure, corn-based DDGS-fed fresh cattle manure, and corn-based DDGS-fed composted cattle manure. The four types of manures were grown on two contrasting Saskatchewan soils at five different rates: 0, 60, 120, 180, and 240 t ha^{-1}. The research work described was conducted in controlled environment conditions in the phytotron facilities at the University of Saskatchewan.

The hypothesis of this study was that composting will increase manure nutrient content, resulting in lower rates required to meet plant nutrient demand and that the DDGS feedstock (wheat versus corn) will influence manure fertilizer value.

3.2 Materials and Methods

Canola (*Brassica napus* Invigor 5030) was grown in controlled environmental conditions over 35 days with four different DDGS-fed cattle manure amendments: wheat based DDGS-fed fresh cattle manure (wheat fresh), wheat-based DDGS-fed composted cattle manure (wheat compost), corn-based DDGS-fed fresh cattle manure (corn fresh), and corn-based DDGS-fed composted cattle manure (corn compost).

3.2.1 Pot study protocol

Two soils from different soil-climatic zones in Saskatchewan were selected for the study. The first soil was collected from the top 0-15 cm of control (unmanured, unfertilized) plots in a

long-term manure field trial that was planted to wheat in 2009 (Mooleki et al., 2004). The soil, collected in September 2009, is a Black Chernozem belonging to the Cudworth Association in the Black soil zone (LSD NW 21-37-23 W2M) (Black soil). The second soil type was collected from the 0-15 cm depth from a wheat stubble field near Central Butte, Saskatchewan. The second soil, also collected in September 2009, is of the Haverhill Association located in the Brown soil zone (LSD NW 30-20-3 W3M) (Brown soil). Properties of the two soils are shown in Table 3.1.

The soils were air-dried and mixed to ensure they were homogeneous, then passed through a 2-mm sieve. The NO_3^- and NH_4^+ were determined by extracting with 2 *M* KCl at a 1:10 soil:solution (weight:volume) ratio and analyzing colorimetrically (Keeney, 1982). Available P and K were extracted using the modified Kelowna reagent as described by Qian et al. (1994) and quantified using the colorimetric method. Organic C was determined using LECO Carbon Analyzer combustion. The pH and EC (electrical conductivity) was determined using a 1:2 soil:deionized water solution.

The soils were low in available N and P, and the Brown soil was especially low in organic carbon (Table 3.1). The pH is neutral to slightly basic and the EC (salinity) is low (non-saline) in both soils.

Table 3.1 Soil properties of initial soils used in the growth chamber studies collected in the fall of 2009.

Soil	NO_3	NH_4	PO_4	K	SO_4	OC†	pH	EC‡
	---------- mg kg^{-1} ----------					%		mS cm^{-1}
Black soil	13.7	10.3	9.9	710.1	6.9	3.4	7.9	0.17
Brown soil	11.3	8.3	17.4	436.4	2.0	1.7	7.7	0.22

† OC denotes organic carbon
‡ EC denotes electrical conductivity.

The field capacity for each soil was determined by sieving soil through a 2-mm sieve and weighing out 50 g of soil into four vials. Water was added to each of the four vials of soil to represent 20, 25, 30, and 35% water by weight. The vials were equilibrated for 24 h. The value of field capacity was estimated as the average of the percentage of water by weight added that resulted in movement of the wetting front to the bottom of the vial but did not produce free-standing water. The estimated field capacity values of the two soils were 28 % for the Black soil and 25 % for the Brown soil.

Pots of 15 cm diameter and trays were washed, labeled, and a filter paper placed on the bottom of each pot to prevent soil leakage. The amendments were weighed out for each pot (Table 3.2) and the amendment and 900 g of soil were mixed in a bucket followed by placement into the correct labeled pot. Pots were weighed and watered with distilled water to 80% field capacity and left on the lab bench for 48 hours to equilibrate. After the equilibration was complete, the pots were seeded with 10 canola seeds (*Brassica napus* Invigor 5030) and 100 g of soil was placed on top ensuring no large lumps were on the surface. The pots were watered again to 80 % field capacity and the total weight of each pot was recorded.

The pots were placed in a growth chamber with 16 hour days at 24^{o}C and 8 hour nights at 21^{o}C. The humidity was not controlled in the growth chamber. The pots were moistened on the soil surface twice daily for the first 7 days and watered daily to 80 % field capacity over 35 days. The pots were re-randomized weekly to account for any uneven light or air distribution. Sticky traps were placed in the chamber to control fly infestation. Notes were taken daily and visual observations were made of the plants. Photos were also taken periodically to track the growth of the plants.

Table 3.2 Rate of manure addition on a weight basis and corresponding N, P, and K manure rates for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments.

		DDGS Manure			
Manure Rate		**Wheat Fresh**	**Wheat Compost**	**Corn Fresh**	**Corn Compost**
g kg^{-1}	t ha^{-1}	N Rate (mg kg^{-1})			
0	0	0	0	0	0
30	60	216	474	219	312
60	120	432	948	438	624
90	180	648	1422	657	936
120	240	864	1896	876	1248
		P Rate (mg kg^{-1})			
0	0	0	0	0	0
30	60	120	288	41	130
60	120	241	576	82	260
90	180	361	864	123	390
120	240	481	1152	164	520
		K Rate (mg kg^{-1})			
0	0	0	0	0	0
30	60	183	564	144	366
60	120	366	1128	287	732
90	180	549	1692	431	1098
120	240	732	2256	575	1464

The canola plants were harvested from the pots on day 35 in the growth chamber. The plants were beginning to bolt at the time of harvest. The plants were harvested by cutting the stems about 0.5 cm from soil level at the base and placing in labeled paper bags. The bags of plant material were oven-dried at 40^{o}C, weighed, then ground using a coffee grinder to approximately 0.5 mm size and placed into plastic vials until further lab analysis. The soil from the pots was laid out to air dry at 30^{o}C, then passed through a 2-mm sieve (roots removed) and placed in plastic vials for further lab analysis.

3.2.2 Manure amendments

Manures were obtained from the University of Lethbridge Research station in Lethbridge, Alberta. Manures were received frozen and kept in the freezer before use, at which time they were thawed overnight and mixed before applying to the various treatments.

The beef cattle diet that resulted in the manures for this study was based on a diet of barley silage, barley grain, mineral supplement and the two DDGS grain sources (Table 3.3). The DDGS grain was included as a portion of the feed from 40 to 60 % based on recommended standard practice.

Table 3.3 Cattle diet for the dried distillers' grains and solubles (DDGS)-fed cattle manure trials.

DDGS Manure Treatment	Feed	% of Diet
Wheat (Fresh/Compost)	Wheat DDGS	60
	Barley Grain	25
	Barley Silage	10
	Mineral Supplement	5
Corn (Fresh/Compost)	Corn DDGS	40
	Barley Grain	46
	Barley Silage	9
	Mineral Supplement	5

The fresh manures were collected within one to five weeks of completion of a four to five month feeding trial. A portion of the fresh manures collected were frozen while the rest was composted for 100 days, followed by 100 days of curing. Bedding materials used in the trials consisted of straw bedding for corn DDGS and wood chip bedding in the wheat DDGS trials.

The four manure types were analyzed for nutrient content prior to adding to the soil. Available N, P, K, and S in the manures were analyzed using the sulfuric acid digest method and determined on the Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000) (See Section 3.2.4).

The apparent N recovery by the canola plants was calculated with the following formula from Mooleki et al. (2004):

$$N\ Recovery\ (\%) = \frac{Crop\ N\ uptake\ (manure\ treated) - Crop\ N\ uptake\ (control)}{N\ Applied\ as\ manure} x\ 100 \qquad [3.1]$$

3.2.3 Soil lab analysis

Soils (initial soils and treated soils) were analyzed for nutrient content and chemical properties. The NO_3-N and NH_4-N were determined using 2*M* KCl extracts (Keeney and Nelson, 1982). Approximately 5.0 (±0.1) g of soil was extracted with 50 mL of 2*M* KCl solution. The soil:KCl suspension was shaken on a rotary shaker at 142 rpm for 1 h then filtered through VWR 454 filter paper into plastic vials. The vials were capped and placed in the fridge/freezer to await colorimetric analysis on the Technicon AutoAnalyzer II (Tarrytown, NY).

Available P and K were determined using the Modified Kelowna method (Qian et al., 1994). An extracting solution was prepared by measuring 28 mL of acetic acid, 38.5 mL of ammonium acetate, and 1.11 g of ammonium fluoride into a 2 L bottle. Soil was measured into plastic bottles at a measurement of 3 g along with 30 mL of Kelowna extracting solution. Bottles were shaken horizontally on a shaker at 160 rpm for 5 min then poured through VWR No. 454 filter paper into vials. The P in the extracts was determined colorimetrically using the Technicon Authoanalyzer II. The Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000) was used to determine the concentration of K in the extract.

Available SO_4-S was extracted using 20.0 (±0.1) g of soil, which was weighed into a 100 mL extraction bottle containing 40 mL of 0.01 *M* $CaCl_2$ solution. The extraction bottles with solution were placed on the rotary shaker to be shaken at 142 rpm for 30 min. The solution in

each bottle was filtered through VWR No. 454 filter paper into plastic vials then analyzed colorimetrically using the Technicon Autoanalyzer II.

For extraction of bioavailable Cu and Zn, a diethylenetriaminepentaacetic acid (DTPA) solution was prepared using 0.005 *M* DTPA, 0.01 *M* calcium chloride, and 0.1 *M* triethanolamine (pH 7.3) (Lindsay and Norvell, 1978). Ten g of the DTPA solution was added to 1 g of soil and shaken for 2 h. The suspension was then filtered through VWR No. 454 filter paper and the filtrate analyzed for Cu and Zn concentration using a Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000).

Prior to analysis of organic carbon in the soils, the sieved soil samples were sub-sampled and ball ground to pass through a 0.5 mm mesh sieve to provide a more uniform sample. The C 632 Carbon Determinator (Leco Corporation, St. Joseph, Missouri USA) was used for dry combustion of organic carbon at a temperature of 842^{o}C for determination of percentage of total organic carbon (Wang and Anderson, 1998). At least four blanks with just a ceramic boat (no material) were run as well as standard material samples. Once there were consistent readings for the standard material samples, a curve was set up, and samples of 0.15 g were weighed into the ceramic boats. The sample material in each boat was placed into the oven for approximately 120 seconds when the organic C content in the sample was recorded.

Soil pH and EC were determined using a 1:2 (w/v) soil:water extraction. Approximately 20 g of soil was added to an extraction bottle with 40 mL of distilled water and shaken on a rotary shaker at 142 rpm for 20 min then left to settle for 1 h. The supernatant solutions were filtered through Whatman 1 filter paper into plastic vials that were then capped (Rhoades, 1982). Soil pH measurements were obtained by inserting a pH probe into the extractant and the reading recorded from a Beckman pH meter. A Beckman EC meter was used for the EC measurements

(Richards, 1969) by inserting the probe into the extraction solution and recording the reading. The probe was rinsed thoroughly with distilled water between each measurement for both pH and EC.

3.2.4 Plant and manure analyses

Total plant and manure N, P, and K was determined using the sulphuric acid-peroxide digest method (Thomas et al., 1997). Finely ground plant or manure material (0.2500 to 0.3000 g) was weighed into each 100 mL digestion tube. Two checks that included 0.0300 g of glycine and two blank tubes were included with each set of digests. In the fume hood, 5 mL of 18*M* sulphuric acid was added to each tube and mixed with a vortex mixer. The heating block in the fume hood was heated to 360^{o}C before samples were placed in the block. The tubes, once on the heating block, were heated for 30 minutes then removed and cooled for about 20 min at which time 0.5 mL of 30 % (v/v) hydrogen peroxide was added to each tube and mixed with a vortex mixer. The rack of tubes was then returned to the heating block and the process was repeated six times. When the solution was colorless, hydrogen peroxide was added to each tube and the glass tubes were returned to the heating block to be heated 60 min to remove all hydrogen peroxide. Once the rack of glass tubes was removed and allowed to cool overnight, deionized water was added to each tube just below the volume line while mixing on a vortex mixer. The tubes were again allowed to cool from the chemical reaction after added the water. When the tubes were again at room temperature the tubes were carefully filled with deionized water to the volume line which is at exactly 75 mL. The tubes were capped with a rubber stopper and inverted five to six times to mix well. The solution was sub-sampled into a vial and the rest of the solution was disposed of as hazardous waste. The extracts were placed in the fridge/freezer until colorimetric analysis on the Technicon Autoanalyzer II.

Total plant S was determined using a Leco TruSpec Sulphur Analyzer. Ball ground plant material was weighed into a ceramic boat and placed in the LECO Sulphur analyzer. The S in the samples is converted to SO_2 by combustion over a 3 min period and SO_2 concentration from the sample combustion is compared to standard material samples in order to determine S concentration in the plant material.

3.2.5 Statistical analysis

The experimental design was a completely randomized design. The R Statistical Program (Crawley, 2007) was used to analyze the data using general linear models and one-way ANOVA. Linear regressions were also performed in the R program for SOC and EC. A probability level of $p \leq 0.05$ was used to assess if treatments produced a significant effect on the parameter measured. Significant differences between treatments were determined using mean separation with Fischer least significant difference (LSD) at $p \leq 0.05$.

3.3 Results and Discussion

3.3.1 Manure characteristics

The manure treatments were added on a fresh weight basis in this study to simulate how manure would be applied in the field. As the N content of the manures used varied, the rate of N added as manure varied for the different sources (Table 3.2). The manure with the highest N and P content was the wheat compost (Figure 3.1). The wheat compost has the highest N content of all the manure sources and both of the composted manures had increased P content compared to the fresh manure of the same feedstock. The wheat compost amendment is more concentrated in total N compared to the other manure treatments (Figure 3.1) and adds more N to the soil for a given manure rate. Manure composition is influenced by animal diet, age, and breed as well as collection, storage, and exposure to climatic variables (Eghball, 2002).

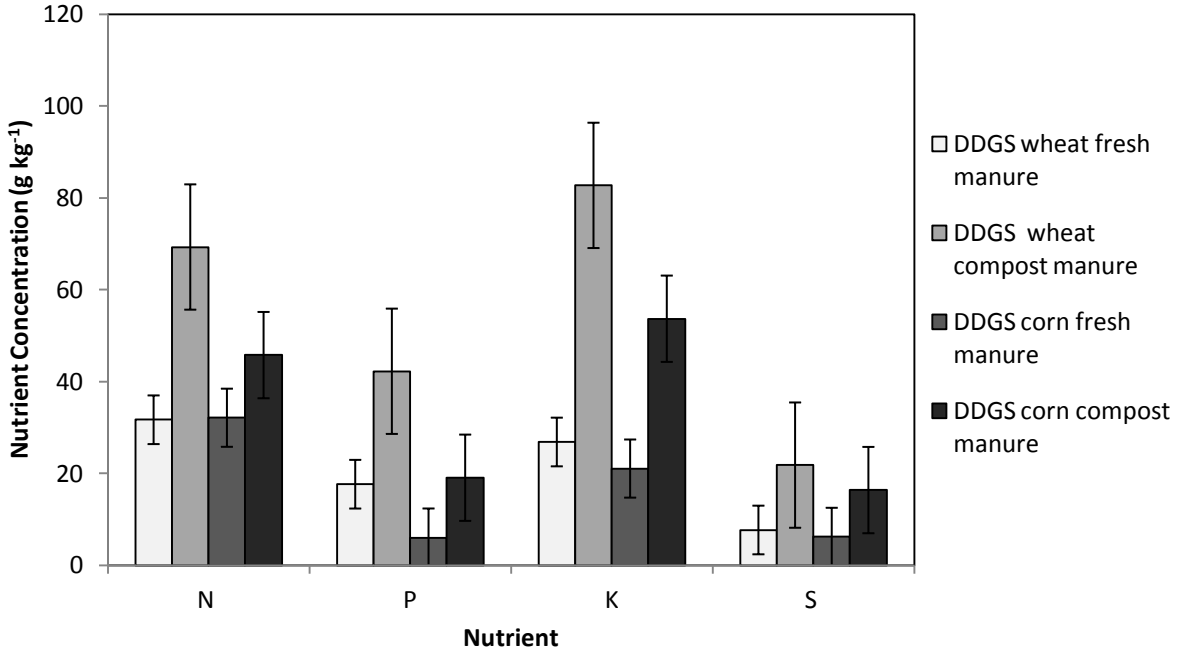

Figure 3.1 N, P, K, and S concentration of four distillers' grains and solubles (DDGS) manure sources used in the growth chamber studies. Bars represent standard error of the mean.

The composted manures had higher N and P contents compared to the fresh cattle manures (Figure 3.1). Overall, the wheat compost manure had the highest nutrient contents, making this manure a more concentrated nutrient source. The composting process concentrates nutrients because of the evaporation of water and loss of carbon as CO_2, decreasing the volume of material (Larney et al., 2006). Significant mass loss can occur during the composting process. Eghball et al. (1997) reported a mass loss of 20 % over a 100-day composting period in windrows. Four manures tested by Eghball (2002) had increased NO_3-N and EC in the composted manure versus the fresh manure from the same source.

The N:P ratio of manure is smaller than that of soil and required by plants; therefore the addition of manure based on plant N requirements may exceed the P holding capacity in the soil,

making the P susceptible to run-off loss (Eghball, 2002). The manures used in our study had an N:P ratio of 2:1 except for the corn fresh manure which had an N:P of 5:1 (Table 3.4). An N:P ratio of about 4.5 is required for winter wheat (Eghball, 2002), indicating that the N:P ratios of the corn fresh manure is closer to that of plant uptake.

The C:N ratio of the manure sources ranged from about 10:1 to 20:1 (Table 3.4). The C:N ratio was greatest for the wheat fresh manure at 20:1 which may indicate decreased availability of N following application (Qian and Schoenau, 2002). The corn compost manure had the lowest C:N (~10:1), which would predict net mineralization to occur. The composted treatments both had lower C:N compared to the fresh manures of the same feed source. Eghball et al. (1997) also suggests that the readily decomposable forms of C and N are transformed into more stable forms in the composting process, causing lower mineralization to occur in the more stable composted manure when added to soil. The higher C:N in the wheat-fed manure may also be due to the different bedding type. Wood chip bedding used in the wheat-fed treatments has a higher C:N ratio compared to straw bedding that was used in the corn-fed treatments (Larney et al., 2008). The wheat fresh manure had the highest moisture content as well, which diluted the nutrients in that manure source (Table 3.4; Table 3.2).

Table 3.4 The C:N ratio, N:P ratio, and moisture content of four distillers' dried grains with solubles (DDGS)-fed manure sources.

DDGS Manure Type	C:N	N:P	Moisture
			%
Wheat fresh	20	2	64.2
Wheat compost	16	2	21.5
Corn fresh	15	5	53.9
Corn compost	11	2	21.4

3.3.2 Canola plant biomass yield

In both the Brown and Black soils, the wheat fresh manure tended to produce the highest canola biomass (Figure 3.2 and Figure 3.3). At lower rates of manure addition, composted manures tended to result in higher yield than fresh manures. These results contrast with Miller et al. (2004) where there was no significant difference in barley dry matter yield between composted or fresh manure treatments. The results of Miller et al. (2004) were based on three years of field applied manure amendments on a Dark Brown Chernozemic soil in Lethbridge, Alberta. Their results may have differed from the results in this study because of environmental conditions and differences in manure composition. Work by Eghball and Power (1999) revealed higher corn plant biomass in composted treatments compared to fresh manure over a three-year field study on a silty clay loam soil in Nebraska. It is important to note that restricted rooting volume in a pot can create differences in response compared to what may be observed in the field with the same amendment. Nutrients may be concentrated in the pot, which is evident in the composted manure treatments that appear to produce a toxic effect when added at the higher rates as indicated by decreased the plant biomass.

The corn fresh manure has significantly lower biomass compared to the other treatments at the 90 g kg^{-1} and 120 g kg^{-1} rates on the Brown soil. This manure source has lower N content compared to the composted manures but similar to the wheat fresh manure (Figure 3.1). The decreased biomass in the corn fresh manure treatment is not understood because of the similarities with the other manures.

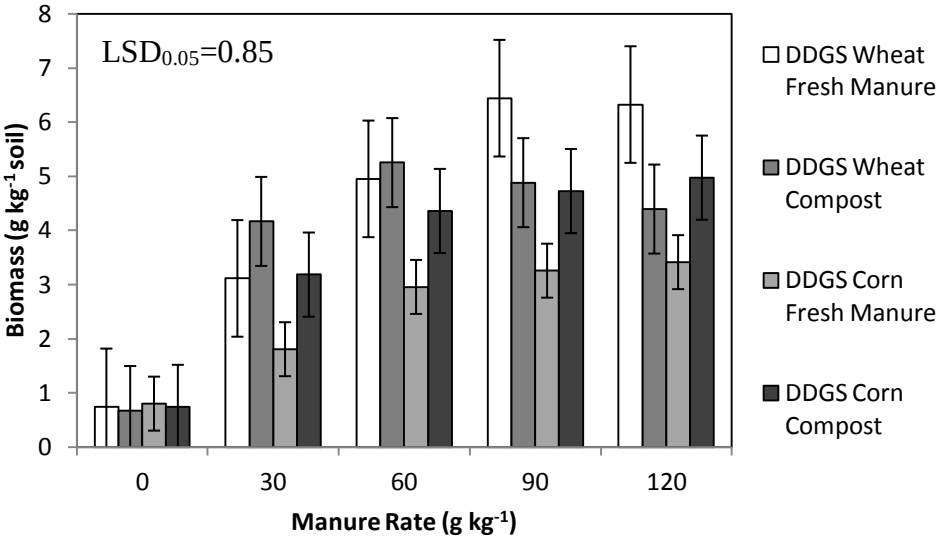

Figure 3.2 Mean dry biomass for canola grown on a Brown soil amended with manure from cattle fed wheat-based dried distillers' grains and solubles (DDGS) (fresh and composted) and corn-based DDGS (fresh and composted) manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates. Bars represent standard error of the mean.

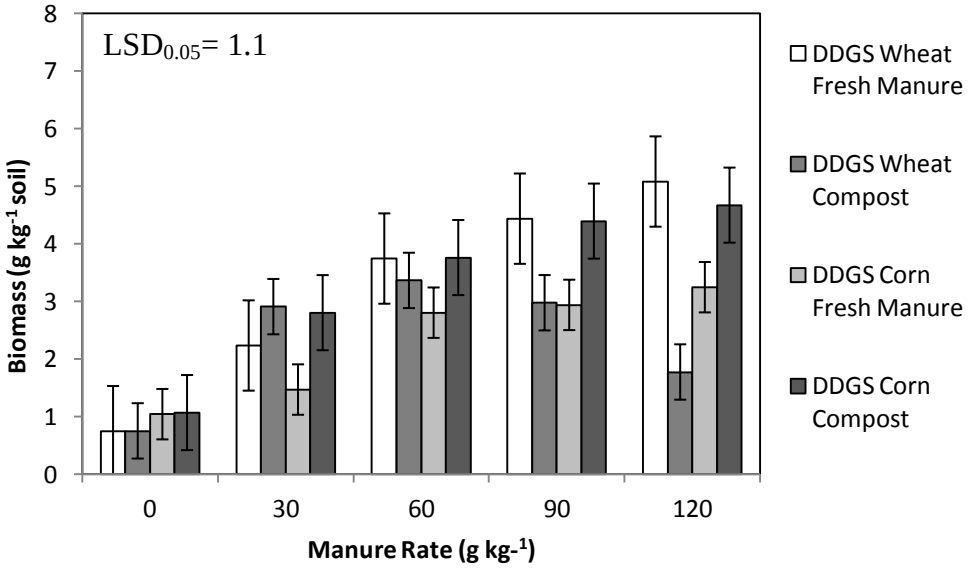

Figure 3.3 Mean dry biomass for canola grown on a Black soil amended with manure from cattle fed wheat-based dried distillers' grains and solubles (DDGS) (fresh and composted) and corn-based DDGS (fresh and composted) manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates. Bars represent standard error of the mean.

The composted and fresh manure evaluation on the Black soil showed that the DDGS wheat fresh manure resulted in the highest biomass, which occurred at the 120 g kg^{-1} rate (Figure 3.3). Canola grown on the Black soil yielded lower as a result of a negative response to higher rates of the wheat composted manure compared to the canola grown on the Brown soil. The canola biomass in the treatment amended with wheat compost manure at the highest rate (120 g kg^{-1}) on the Black soil was not significantly higher than the control treatment.

All manure amendments on the Brown soil resulted in little to no increase, and even a decrease in biomass at the 90, and 120 g kg^{-1} rates compared to the two lower rates (Figure 3.2). This trend was similar in the Black soil treatments, although there was still increased biomass in the highest rate compared to the 60 g kg^{-1} rate in the wheat fresh manure treatment, indicating that this manure was still supplying nutrients to canola. Canola biomass was higher when corn compost manure was applied compared to the corn fresh manure treatment at all rates. The wheat fresh treatment resulted in higher plant biomass than the wheat composted treatment at the 60, 90, and 120 g kg^{-1} rates.

At the lowest rate of addition (30 g kg^{-1}) the composted treatments for both the wheat and corn-fed manures had higher canola biomass compared to the corresponding fresh manure type. Decreased biomass yields at the highest rates can be due to the toxic effects of manure as a result of excessive ion loading. This toxic affect, often termed ‘salt effect’, is especially evident in the wheat compost manure on the Black soil. The high concentration of cations such as K in the wheat compost treatment illustrates the reason for the toxicity and can be due to decreased osmotic potential (Figure 3.1). These results indicate that high rates of composted manure may be especially deleterious due to their concentrated nature.

The wheat fresh manure increased canola biomass with increasing rate on the Black soil indicating the wheat fresh did not produce the same toxic effects as the wheat compost at the highest rate. Helgason et al. (2007) also found increased plant growth with manure addition which followed a similar trend to plant N uptake.

3.3.3 Manure nitrogen recovery

The two composted manures increased plant N concentration with increasing rate of addition to the Brown and Black soils (Table 3.5; Table 3.6). The composted amendments also resulted in a greater increase in plant N concentration at the high rates of application than fresh manures. Canola grown on soil amended with wheat compost manure at the 120 g kg^{-1} rate had the highest N concentration in both soils. Increase in canola N concentration relates back to the N added in the manures (Table 3.2).

The composting process decreases the N:P and C:N ratio of manures (Eghball et al., 1997). The N concentrated in the composted manures gives rise to a greater rate of N added per unit of manure. Nitrogen is lost in the composting process through NH_3 loss during turning of windrows, which can provide lower concentrations of NH_4^+ for nitrification to NO_3^- (Tiquia et al., 2002). However, greater losses of C than N and losses of water result in compost with higher N concentrations than fresh manure (Miller et al., 2004).

Composting may also stabilize some of the N. Miller et al. (2004) reported increased plant N uptake in a fresh manure treatment compared to a composted manure treatment on a Dark Brown Chernozem in the treatments with 39 and 77 t ha^{-1} rates of added manure.

Table 3.5 Mean dry canola total N, P, K and S concentration for dried distillers' grains and solubles (DDGS) wheat fresh and composted, and DDGS corn fresh and composted treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

DDGS Manure	Rate	N	P	K	S
	g kg^{-1}	---------- % ----------			
Wheat Fresh	0	1.1	0.35	2.1	0.83
	30	0.8	0.26	1.8	0.58
	60	1.0	0.26	2.5	0.70
	90	1.2	0.28	3.0	0.57
	120	1.9	0.34	4.0	0.85
Wheat Compost	0	1.2	0.33	2.2	1.20
	30	1.0	0.28	2.4	0.67
	60	1.8	0.35	3.9	0.72
	90	3.0	0.42	5.1	0.78
	120	3.6	0.43	6.4	0.61
Corn Fresh	0	1.0	0.32	2.0	0.98
	30	1.0	0.33	2.3	0.82
	60	1.1	0.30	2.3	0.66
	90	1.1	0.30	2.7	0.65
	120	1.2	0.31	3.0	0.85
Corn Compost	0	1.3	0.36	2.3	0.96
	30	0.9	0.26	2.2	0.61
	60	1.4	0.28	3.4	0.80
	90	2.2	0.34	4.5	0.70
	120	2.8	0.37	5.4	0.67
$LSD_{(0.05)}$		0.40	0.06	0.88	0.45

Crop N recovery increased with increasing manure rate in the wheat fresh manure and the corn compost manure treatments on the Brown soil (Table 3.7). There is a decrease in N recovery in the wheat compost manure at the highest rate of manure addition. The decrease may be due to a toxic effect from the high concentration of ions from this manure source, as well as the supply of available N beyond what the canola plants could assimilate. The corn composted treatment also decreased in N recovery as rate increased and had lower N recovery values compared to all other treatments. This manure had increased total N concentration compared to

the fresh manures (Figure 3.1) and a narrow C:N value, therefore it is uncertain why this manure had lower N recovery.

Table 3.6 Mean dry canola total N, P, K and S content for dried distillers' grains and solubles (DDGS) wheat fresh and composted, and DDGS corn fresh and composted treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

DDGS Manure	Rate	N	P	K	S
	g kg^{-1}	---------- % ----------			
Wheat Fresh	0	1.2	0.18	3.3	1.4
	30	1.1	0.30	3.3	1.3
	60	1.1	0.31	3.4	1.1
	90	1.5	0.36	4.1	1.2
	120	1.8	0.39	4.2	1.3
Wheat Compost	0	1.3	0.18	3.0	1.3
	30	1.4	0.35	3.8	0.9
	60	2.6	0.42	5.0	1.0
	90	3.5	0.45	6.2	0.9
	120	4.1	0.51	5.1	0.8
Corn Fresh	0	1.2	0.20	2.4	1.2
	30	1.1	0.30	2.7	0.9
	60	1.2	0.33	3.2	0.9
	90	1.3	0.33	3.3	0.9
	120	1.4	0.35	3.4	1.1
Corn Compost	0	1.0	0.19	2.1	0.8
	30	1.2	0.29	3.2	0.7
	60	1.5	0.31	3.7	0.7
	90	2.2	0.36	4.3	0.8
	120	2.8	0.39	5.4	0.8
$LSD_{(0.05)}$		0.55	0.06	1.23	0.6

Similar to the Brown soil results, canola grown on the corn compost and the wheat fresh manure recovered manure N to a greater extent than other treatments in the Black soil (Table 3.7). The wheat compost at the highest rate showed a decrease in N recovery in the Black soil, likely due to toxicity effects and N supplied in surplus of plant needs.

Table 3.7 Mean N recovery (nitrogen uptake efficiency) for dried distillers' grains and solubles (DDGS) wheat fresh and composted, and DDGS corn fresh and composted treatments at 30, 60, 90, and 120 g kg^{-1} rates on the Brown and Black soils.

DDGS Manure	Rate	N Recovery	
		Brown Soil	Black Soil
	g kg^{-1}	----------%----------	
Wheat Fresh	30	8	7
	60	10	7
	90	11	9
	120	13	10
Wheat Compost	30	7	6
	60	9	8
	90	10	7
	120	8	3
Corn Fresh	30	5	1
	60	5	5
	90	4	4
	120	4	4
Corn Compost	30	6	8
	60	8	7
	90	10	9
	120	11	10

Overall low N recovery values of cattle manure N by the canola (<10 %) agree with results of Mooleki et al. (2004) in field trials in Saskatchewan. They also report crop recovery of fresh cattle manure N in year of application in Saskatchewan to be less than 10 % of the applied cattle manure N. Much of the N in cattle manure is in organic form and is mineralized slowly to plant-available inorganic forms NH_4^+ and NO_3^- (Eghball, 2002). Nitrogen recovery values in a silty clay loam soil in Nebraska over four growing seasons of corn resulted in fresh manure treatments having a plant N recovery value of 20 % which was higher than the reported N recovery of 13.7% for composted manure (Eghball and Power, 1999).

Soil NO_3-N in the 120 g kg^{-1} wheat compost manure treatment (mean NO_3 = 10.7 mg N kg^{-1}) was significantly higher than all other treatments in the Brown soil and greatly elevated

(>100 mg N kg^{-1}) in the Black soil at 90 and 120 g kg^{-1} rates compared to the two lower rates (Table 3.8). The increased available NO_3-N is indicative of excess N not utilized by the plant and may have caused plant toxicity at the highest manure rates. The excess NO_3-N in the soil after plant growth may be because of the decreased biomass and thus decreased N uptake at the two highest rates of manure addition in the Black soil.

Soil NH_4-N contents at the end of the growth period were relatively low for all treatments on the Black and Brown soils (Table 3.8; Table 3.9). Mean NH_4-N ranged from 4 mg kg^{-1} in the control treatment to 8.8 mg kg^{-1} in the wheat composted treatment at the 60 g kg^{-1} rate on the Brown soil with the highest concentration of 10.3 mg kg^{-1} in the wheat fresh (120 mg kg^{-1}) treatment. Mean soil residual NH_4-N is relatively low in all treatments because most of the N in the manure is added in the organic form that only slowly mineralizes to inorganic plant available forms. Also, NH_4-N would be rapidly nitrified to NO_3-N (Qian and Schoenau, 1994).

3.3.4 Canola P, K, and S

The canola P and K concentrations were increased by manure amendment to the greatest extent in the wheat compost manure treatments on the both the Brown and Black soils (Table 3.5 and Table 3.6). The canola P concentrations did not differ between treatments in the fresh manures types on both soils (Table 3.5 and Table 3.6). The canola P concentration in the wheat compost manure treatment at 120 g kg^{-1} rate was significantly higher than all other treatments and rates on the Black soil (Table 3.6). Although all treatments resulted in a significant increase in plant P concentration at the lowest rate (30 g kg^{-1}) compared to controls, the increase in plant P concentration above 30 g kg^{-1} rate was not large except with the wheat compost manure on the Black soil.

Table 3.8 Mean soil available NO_3-N and NH_4-N concentration following harvest of canola following 35-day growth period for wheat-basded distillers' grains and solubles (DDGS) fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown and Black soils.

DDGS Manure Treatment	Rate	Soil Type			
		Brown Soil		Black Soil	
		NO_3-N	NH_4-N	NO_3-N	NH_4-N
	g kg^{-1}	---------- mg kg^{-1} ----------			
Wheat Fresh	0	2.1	5.3	3.1	7.2
	30	2.5	5.2	4.4	8.2
	60	1.7	4.9	2.0	9.3
	90	2.5	5.7	1.9	8.7
	120	2.0	6.7	2.5	10.3
Wheat Compost	0	1.9	6.5	5.6	7.7
	30	1.7	7.3	3.0	6.3
	60	1.2	8.8	8.1	7.6
	90	2.6	7.5	38.8	8.2
	120	10.7	8.4	103.4	9.2
Corn Fresh	0	1.9	5.0	4.8	6.8
	30	3.5	6.0	4.0	6.8
	60	2.8	6.9	4.3	7.1
	90	4.6	6.4	4.7	6.7
	120	4.2	6.1	4.3	6.7
Corn Compost	0	2.1	4.0	4.2	5.7
	30	3.2	5.2	3.0	7.2
	60	3.0	6.3	3.2	7.8
	90	4.0	7.6	3.8	9.5
	120	3.0	7.1	4.8	8.9
$LSD_{(0.05)}$		3.5	2.6	11.2	2.5

The increase in canola P concentration in the composted manures compared to fresh manures may reflect lower availability of P in the fresh manure sources and/or a lower rate of P added per unit weight of manure addition. Similar canola P uptake was observed between fresh and composted manure treatments on a Dark Brown Chernozem in Alberta, which disagrees with our results (Miller et al., 2004). The different results may be due to different manure types in our study and the DDGS feedstocks. There also may have been dilution effect with the increased

plant biomass causing decreased plant P concentration when comparing the 0 and 30 g kg^{-1} treatments. The composting process concentrates the P in the manure causing a higher level of plant available P in the soil per unit of manure added (Eghball et al., 1997).

Similar to P, plant K concentration increased with increasing rate in the composted manure treatments to a greater extent than the fresh manure treatments on both the Black and Brown soils (Table 3.5 and Table 3.6). Plant K concentration was highest in the composted manure treatments at the 90 and 120 g kg^{-1} rate on the Black soil (Table 3.6). Composted treatments at the higher rates resulted in increased plant K content compared to their corresponding fresh manure treatments of the same feed type (Table 3.5). The composting process concentrates K elevating the K content in the resulting composted manures (Figure 3.1). Increased K in the composted manures is likely the reason for K accumulation in the plant tissue and is reflective of the soil K levels in both of the composted treatments.

Sulphur content of canola tissue was more variable than K or P on both the Black and Brown soils. There was a tendency for S concentration to remain the same or decrease with manure addition, although not significantly so. This may reflect the relatively high available S content of the soil and low amount of S added in the manure.

3.3.5 Soil cations and anions

In line with the high K content of the manures (Figure 3.1), extractable K in the soil increased with increasing rate, and was highest in the composted manure sources on both the Brown and Black soils (Table 3.9 and Table 3.10). In both soils the extractable K is higher in the wheat composted manure treatment compared to the other manure types. The corn compost treatment resulted in a significant increase in soil K concentration at the two highest rates

compared to the 30 g kg^{-1} rate (Table 3.9 and Table 3.10). Mooleki et al. (2004) also found elevated levels of soil exchangeable K following manure application in central Saskatchewan.

The elevated levels of soil K were consistent with plant tissue K content. The composting process likely concentrated the K in the composted manure treatments. Eghball et al. (1997) reported losses of K in the windrow composting process due to leaching from rainfall events. In this pot study, the K that was not taken up by the plant was accumulated in the soil.

Soil PO_4-P and SO_4-S followed similar trends for the Black soil and the Brown soil, with the wheat compost manure having the greatest impact on increasing soil residual P and S at a given rate compared to the other manure treatments (Table 3.9; Table 3.10). Soil available P and S increase as manure rate increases. The wheat fresh manure and corn compost manure have a very similar effect on the soil P levels at each rate. The wheat compost treatment adds more P and S, which are reflected in the soil nutrient levels following plant growth. The increase in soil P in the composted manure treatments is because during the composting process, manure P is concentrated and may be mineralized, with up to 75 % of P being in inorganic labile form (Eghball, 2003). The soil extractable P concentrations in the composted manure treatments were all near or above the 100 mg extractable P per kg soil concentration threshold where no response to P fertilizer addition would be expected.

Soil extractable Cu levels were slightly increased with manure amendment while effects on extractable Zn were variable in the Brown soil (Table 3.8). Lipoth and Schoenau (2004) noted that addition of cattle manure to four Saskatchewan soils resulted in only small increases in extractable metal micronutrients.

Table 3.9 Mean soil K, PO_4-P, SO_4-S and extractable Cu and Zn concentration for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

DDGS Manure Treatment	Rate	K	PO_4-P	SO_4-S	Cu	Zn
	g kg^{-1}	----------	----------	mg kg^{-1}	----------	----------
Wheat Fresh	0	412	11.0	33.0	0.90	8.5
	30	551	42.0	45.0	0.93	5.8
	60	647	68.0	51.0	0.95	5.9
	90	752	101.0	63.0	1.00	6.2
	120	913	134.0	72.0	1.05	8.0
Wheat Compost	0	431	12.0	48.0	0.87	10.2
	30	787	98.0	65.0	0.87	7.7
	60	1132	147.0	92.0	0.88	7.0
	90	1432	241.0	115.0	1.00	8.0
	120	1840	380.0	146.0	1.07	10.0
Corn Fresh	0	422	10.0	35.0	0.88	4.3
	30	536	21.0	42.0	0.95	5.2
	60	640	39.0	49.0	1.06	6.4
	90	746	44.0	67.0	1.05	6.5
	120	862	46.0	78.0	1.04	6.4
Corn Compost	0	395	10.0	37.0	0.90	5.2
	30	607	44.0	45.0	0.90	5.5
	60	762	80.0	52.0	0.92	5.8
	90	1015	121.0	69.0	0.93	6.5
	120	1161	138.0	81.0	0.94	7.5
$LSD_{(0.05)}$		112	40.0	22.0	0.10	0.4

Addition of manure tended to increase soil extractable Zn and Cu slightly in the Black soil (Table 3.10). Composted manure forms resulted in greater soil Zn at the same rate of manure addition. Similar results were observed in a study by Lipoth and Schoenau (2007) where addition of manure to a Black sandy loam soil in field trials increased the extractable Cu. Analytical error in either the extraction process or the atomic absorption analyses may account for the very low

soil extractable Cu in the 30, 60 and 90 g kg^{-1} wheat compost treated soils compared to all others (Table 3.10).

Table 3.10 Mean soil K, PO_4-P and SO_4-S, Cu, and Zn concentration for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

DDGS Manure Treatment	**Rate**	**K**	**PO_4-P**	**SO_4-S**	**Cu**	**Zn**
	g kg^{-1}	---------- mg kg^{-1} ----------				
Wheat Fresh	0	644	6.5	44.0	0.88	9.0
	30	780	38.0	58.0	0.99	8.7
	60	925	72.0	68.0	1.00	9.5
	90	989	100.0	66.0	1.10	9.2
	120	1142	115.0	75.0	1.20	11.5
Wheat Compost	0	658	7.0	46.0	0.91	8.5
	30	1009	97.0	67.0	0.07	5.0
	60	1383	143.0	91.0	0.03	5.0
	90	1738	263.0	124.0	0.03	3.8
	120	2204	453.0	183.0	1.20	16.8
Corn Fresh	0	661	4.3	48.0	0.85	8.8
	30	769	17.0	65.0	0.96	10.2
	60	891	41.0	64.0	1.10	10.9
	90	984	55.0	66.0	1.10	11.1
	120	1061	60.0	71.0	1.10	10.5
Corn Compost	0	662	4.0	46.0	0.89	9.3
	30	837	39.0	47.0	0.90	11.5
	60	994	86.0	55.0	0.97	12.5
	90	1280	140.0	82.0	1.00	18.3
	120	1456	168.0	92.0	1.00	19.5
$LSD_{(0.05)}$		239	52.0	21.0	0.11	3.9

3.3.6 Soil pH, salinity, and organic carbon

Both corn composted and fresh manure treated soil in general had higher pH values than the wheat-based manure sources (Table 3.11). The DDGS corn-based feed source may result in

slightly more basic manure than DDGS wheat-fed manure. Eghball (2002) also noted that manure greatly increased the pH of acidic soils and was linked to calcium being applied in the cattle diets. In the Black soil, the wheat composted manure treatment at the 120 g kg^{-1} rate was significantly lower in pH compared to all other treatments (Table 3.11). The trend in pH was different in the Black soil compared to the Brown soil in that the wheat compost manure was the only manure type that caused a decrease in pH in the Black soil. The pH was not greatly affected by other manure treatments.

Soil electrical conductivity (EC), a measure of salt content, was related to rate of manure application. The EC increased with increasing rate in all treatments and especially for the wheat cattle composted manure treatment in both the Black and Brown soils (Figure 3.4; Figure 3.5). The wheat composted manure at 90 and 120 g kg^{-1} rates had significantly elevated EC levels compared to all other treatments on the Black soil (Figure 3.5). These treatments may show signs of plant toxicity because of the high salts added in the manure. Hao et al. (2009) also reported that soil EC increased with increasing portion of DDGS in feed and with increasing rate of manure addition.

Electrical conductivity levels above 1-2 mS cm^{-1} (1:2 soil:water suspension) may be harmful to the growth of some crops in Saskatchewan (Saskatchewan Agriculture Knowledge Centre, 2008). Guidelines for Alberta, Manitoba, and Saskatchewan state that manure should not be applied to soil if it has an electrical conductivity greater than or equal to 4 mS cm^{-1} because there is a risk of adding too many salts such as NH_4, K, Ca, Mg, and Na (The Prairie Province's Committee on Livestock Development and Manure Management, 2001). The high EC in the wheat compost manure treatments is consistent with the decrease in plant biomass at the highest rates because of the salinity affecting plant growth.

Table 3.11 Mean soil pH for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown and Black soils.

DDGS Manure Treatment	Rate g kg^{-1} soil	pH	
		Brown Soil	Black Soil
Wheat Fresh	0	7.5	7.8
	30	7.5	7.8
	60	7.6	7.8
	90	7.5	7.8
	120	7.5	7.7
Wheat Compost	0	7.5	7.7
	30	7.5	7.8
	60	7.6	7.6
	90	7.5	7.6
	120	7.5	7.3
Corn Fresh	0	7.5	7.8
	30	7.6	7.9
	60	7.7	7.8
	90	7.7	7.8
	120	7.7	7.8
Corn Compost	0	7.5	7.7
	30	7.7	7.6
	60	7.7	7.7
	90	7.7	7.7
	120	7.6	7.7
$LSD_{(0.05)}$		0.2	0.2

Soil organic C concentration increased as rate increased for wheat compost manure treatment, with the 120 g kg^{-1} rate having significantly higher organic C than all other treatments on both the Brown and Black soils (Figure 3.4; Figure 3.5). The wheat compost manure at 90 g kg^{-1} rate and the wheat fresh manure at 120 g kg^{-1} rate are the only other two treatments that have significantly increased SOC content compared to the control on the Black soil (Figure 3.5). The other manure types do not have a significant rate effect on SOC. Whalen et al. (2008) observed a similar trend with SOC content from cattle composted manure application in a field study in

Quebec. In this study, SOC increased at a rate of 1.35 Mg C ha^{-1} yr^{-1} as a result of manure addition and significant C inputs from adding composted manure to soil. The stabilized nature of the C in the composted manure may contribute to greater sequestration of C in the soil.

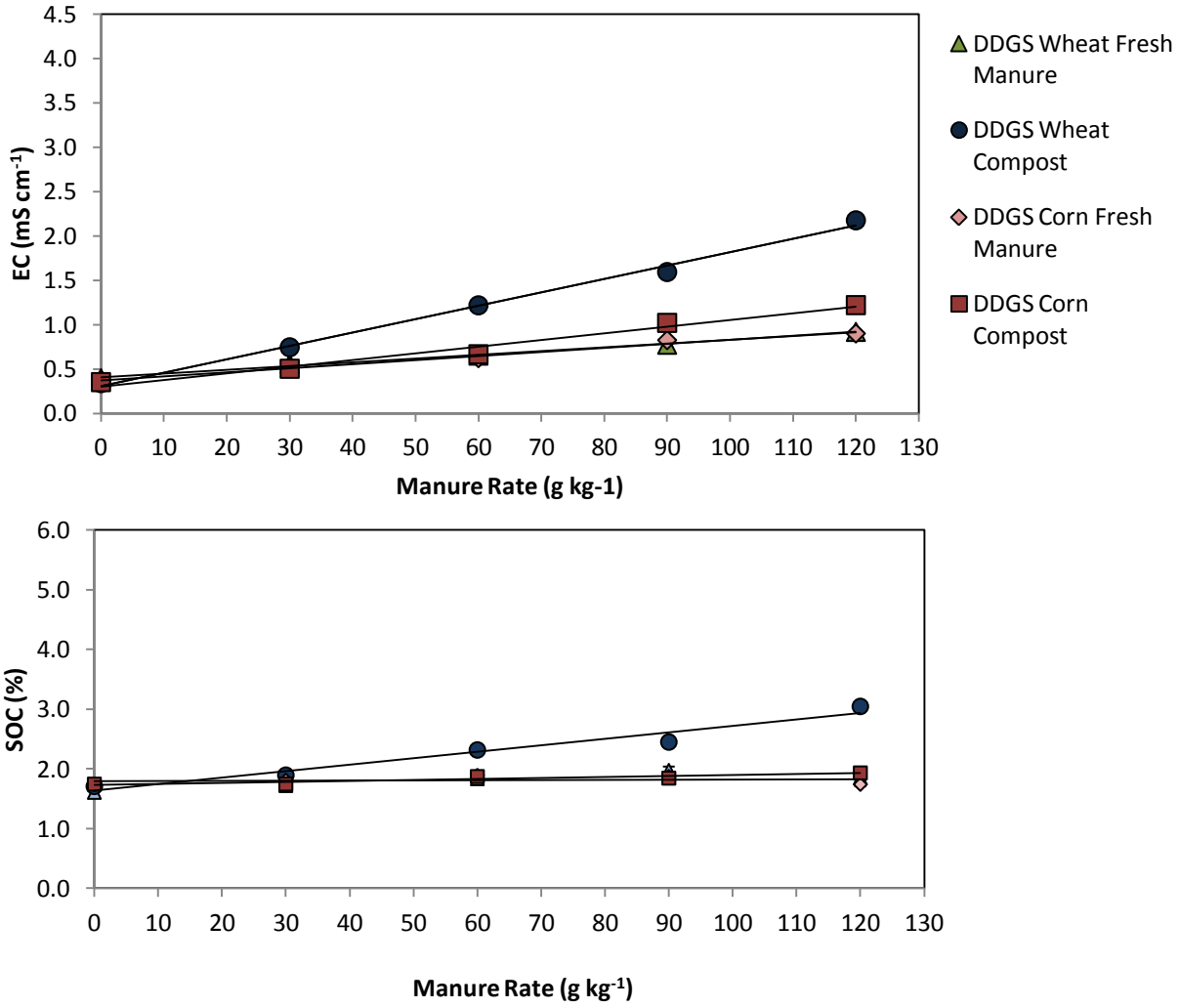

Figure 3.4 Mean soil electrical conductivity (EC) and soil organic carbon (SOC) for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

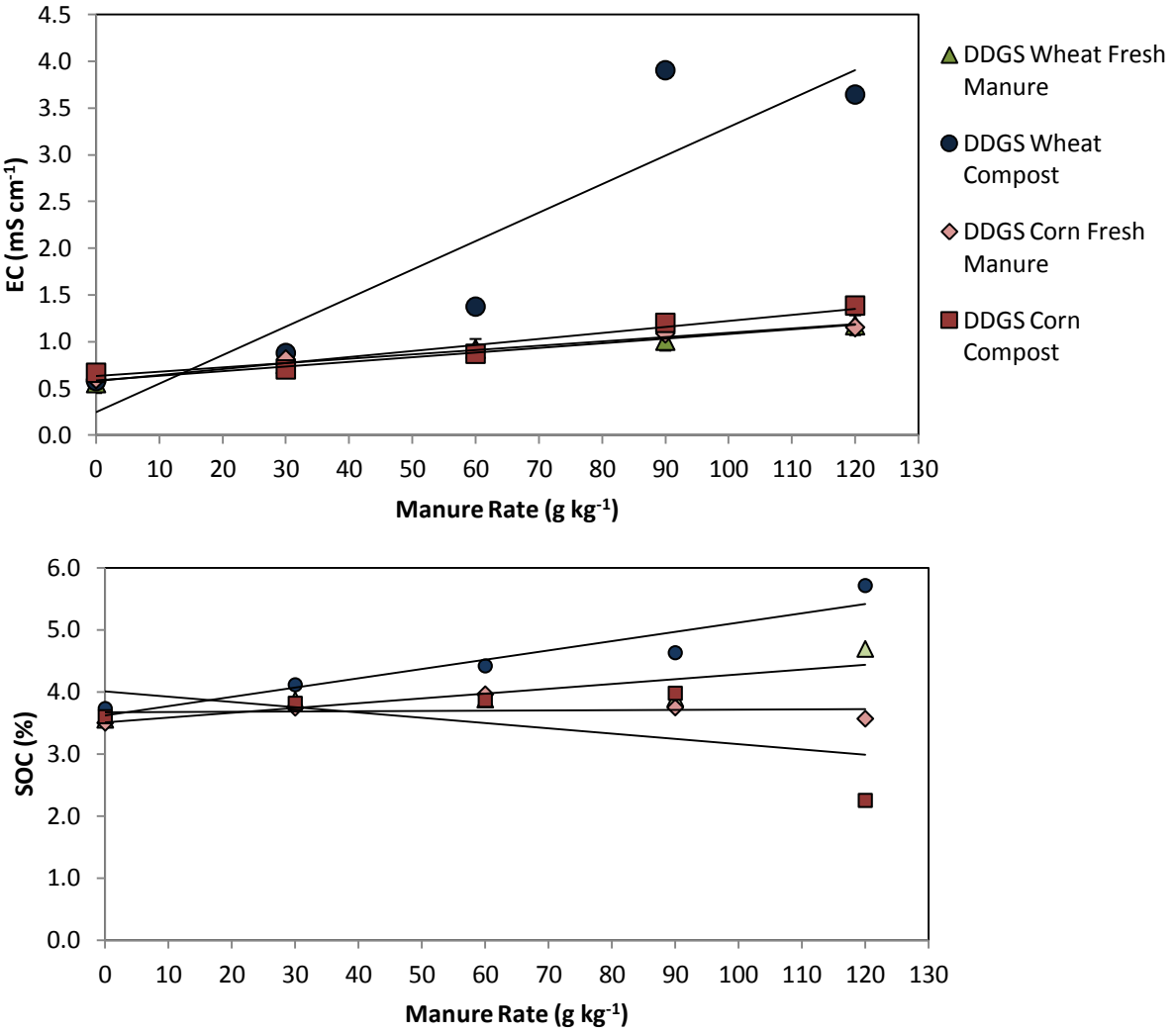

Figure 3.5 Mean soil electrical conductivity (EC) and soil organic carbon (SOC) content for dried distillers' grains and solubles (DDGS) wheat fresh and composted and DDGS corn fresh and composted manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

3.4 Conclusion

The wheat-based DDGS fresh manure produced the highest biomass yield and resulted in the highest N recovery compared to all other manures in this study. The DDGS-fed composted cattle manure contained elevated concentrations of N and P which were concentrated through the composting process. Application of the wheat DDGS-fed composted manure resulted in greater

accumulation of nutrients in plant material and soil than the other sources, and was associated with toxicity to canola at rates above 60 g kg^{-1} (90 and 120 t ha^{-1}). The increased concentration of salts in the wheat DDGS -fed composted manure treatments was likely a cause of the decrease in plant biomass with increased rate of manure addition. The plant biomass yield also reflects the N recovery values which decreased at the highest rates of addition for the wheat DDGS -fed composted manure treatments. The toxic effects at high rates appeared to be more pronounced in the Black soil compared to the Brown soil. The N in wheat DDGS manures in general was recovered by canola to a greater extent compared to the corn DDGS manures.

Composted treatments resulted in higher soil residual P levels compared to the fresh manure treatments, in line with higher manure P content. The increased P in the composted manures has the potential for P loading in soil and would require reduced rates to avoid excessive build-up of PO_4-P in the soil. Phosphorus-based applications of manure would better match crop demand than N-based manure applications.

The wheat DDGS compost manure application resulted in a trend of increased soil EC, SOC, P, and S with increasing rates. Loss of dry matter content and moisture in composting concentrates the anions and cations (salts) in the remaining solids. A toxic effect is possible if the wheat DDGS -fed composted cattle manure is applied at high rates over short intervals. Even a single application at a high rate of 120 g kg^{-1} may be detrimental.

The Black soil and Brown soil responded in a similar manner to the addition of the different manures under controlled environment conditions. Out of the four DDGS-fed manures studied, the wheat-based DDGS fresh manure at 180 t ha^{-1} on the Brown soil and the wheat-based DDGS fresh manure at 240 t ha^{-1} on the Black soil is the manure and rates that resulted in

the highest biomass yield, favourable N recovery, and low toxic effects. Evaluation of DDGS-fed cattle manures under field conditions where environmental conditions differ is suggested.

Meeting crop nutrient demands is important with the application of manure and it is important to consider that cattle feed source and manure processing such as composting creates manure with increased levels of nutrients such as N and P. The composting process creates a more stable and uniform manure product that is more concentrated in nutrients and cations compared to fresh manure, therefore, rates should be adjusted downward accordingly for DDGS-based composted manures. The optimum rate of manure is very much influenced by feed grain source and manure processing.

4.0 APPLICATION OF ALFALFA PELLETS AND BIOCHAR TO RECLAIM PRODUCTIVITY OF A DISTURBED SOIL

4.1 Introduction

Traditionally, farm yard manure has been used as an organic amendment in agricultural operations to increase the soil N and P fertility and nutrient cations in the soil (Wahid et al., 1998). In addition, organic amendments have been used in the reclamation of contaminated or disturbed soils for many years (Wahid et al., 1998; Grigg et al., 2006; Park et al., 2010). Organic composts and municipal wastes can improve soil fertility, increase plant growth, and enhance bioremediation (Park et al., 2010). Moreover, municipal solid waste compost has been shown to increase soil productivity in salt-affected soils (Lakhdar et al., 2011).

Saskatchewan is the world's largest producer of potassium fertilizers, all of which are a product of the mining and refining of potash deposits. As with any large construction, however, the establishment of potash mines and refineries is associated with significant ecosystem disturbance. Moreover, there is the potential for soil salinization through seepage from tailings ponds and pipeline breaks causing brine spills, as well as from aeolian deposits of refinery dust. In addition to minimizing risks, the reclamation of any disturbed or salt-affected soils is often required, and one of the least invasive and most cost-effective methods of accomplishing this is phytoremediation. Phytoremediation is the name given to a set of technologies that involve the use of plants to remediate contaminated or disturbed sites. Of particular interest is the technique known as phytostabilization, which uses plants and plant roots to prevent contaminant migration via wind and water erosion, leaching, and soil dispersion (USEPA, 2000). Phytoaccumulation, on the other hand, involves the uptake of soil constituents into the plant tissue, which, when

followed by plant removal, results in extraction of the contaminant from the site. An example is the use of native, hyperaccumulating halophytes to decrease Na^+ concentrations in salt-affected soils (Keiffer and Ungar, 2002). Regardless of the mechanism involved, phytoremediation often requires the application of soil amendments to achieve enhanced plant germination and growth (Neuman and Ford, 2006).

Organic amendments can assist in the successful reclamation of degraded or salt-affected soils by improving soil quality. Park et al. (2010) suggest that organic amendments play an important role in improving rhizosphere conditions for plant growth by enhancing the plant-available nutrient supply and reducing contaminant bioavailability. However, the release of nutrients from organic sources depends on the chemical composition of the organic amendment (Agehara and Warncke, 2005). Thus, Puschell et al. (2011) concluded that the amount of amendment required was plant-specific and that even low rates can have beneficial effects on the reclamation of mine spoil banks.

Keiffer and Ungar (2002) reported that increased germination of autumn-sown halophytic plant species on salt-affected sites was associated with increased soil moisture. Alfalfa pellets, which absorb water and can swell to nearly three times their original size, can increase the water holding capacity of the soil (Qian et al., 2008). Moreover, alfalfa powder applied as a soil amendment has been shown to increase the plant uptake of nutrients such as P, K, and S (Qian et al., 2011). Thus, alfalfa pellets appear to have potential as a low-cost, natural way to add organic matter, increase the supply of both plant-available nutrients and water, and promote plant growth for reclamation purposes.

Biochar has been used as a soil amendment to improve the agronomic qualities of degraded soils for centuries (See Chapter 2: Literature Review); thus, there is potential to use

biochar as an amendment for the purpose of reclaiming contaminated or degraded soils. Fellet et al. (2011) used biochar to increase the cation exchange capacity and water holding capacity of mine spoil soils in Italy and to promote phytostabilization by assisting in the development of a "green cover". Stelner et al. (2008) concluded that treatments with charcoal (a form of biochar) increased plant N uptake, as well as N retention in a highly weathered soil in Brazil. Clough and Condron (2010) and Gathorne-Hardy et al. (2009) also reported that biochar increased the efficiency of N fertilizers in degraded tropical soils and in some temperate soils. However, few studies have assessed the performance of biochar in the reclamation of degraded soils in temperate regions.

The objective of this study was to evaluate the effect of adding alfalfa pellets or biochar on soil conditions and plant growth at the perimeter of the PotashCorp-Cory Division mine and refinery. Experimental plots were established at two locations: (1) a degraded soil adjacent to a brine containment pond and (2) on the berm surrounding the brine containment pond. Effects of the amendments on soil chemical properties (EC, pH), soil and plant nutrients (C, N, P, K, Cu, and Zn), and grass yield were determined following the first year of application.

The hypothesis of this study was that the addition of the alfalfa pellet and biochar amendments will improve the soil quality and increase plant growth on degraded soils.

4.2 Materials and Methods

4.2.1 Site selection

The research plots were located at the Potash Corporation of Saskatchewan (PCS) Cory Division mine and refinery, located approximately 6.5 km west of the city of Saskatoon, along Highway 7. A site visit was carried out on September 29, 2009 to select a suitable location for the field studies, with two areas selected as being appropriate for reclamation trials due to their

low percentage of plant cover. The first site (termed the "Degraded" area) was located approximately 30 m south of a containment pond, in an area disturbed by excavation activity during construction of the berm surrounding the pond (Figure 4.1A). The second site (termed the "Berm" area) was located on the south sloping face of the berm itself (Figure 4.1B).

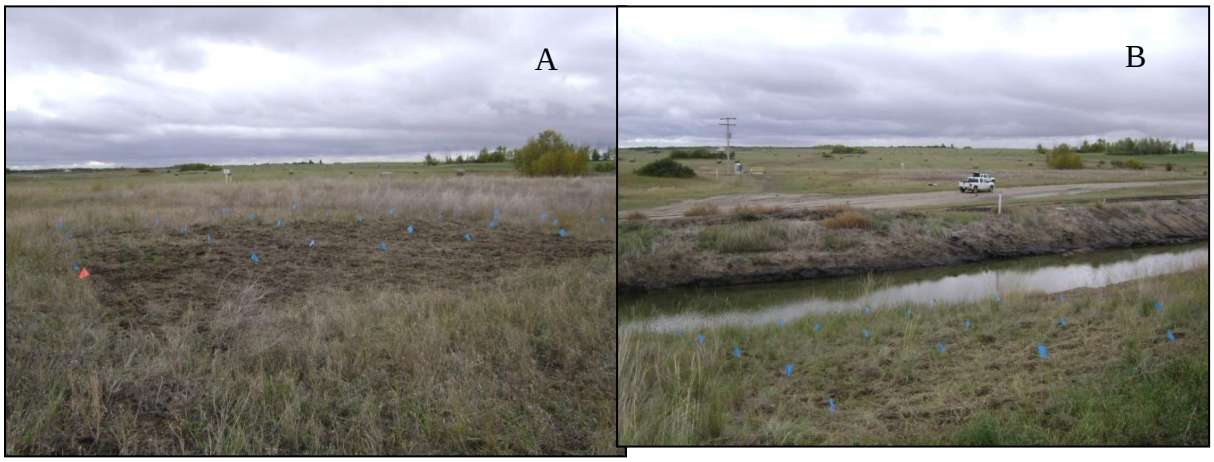

Figure 4.1 Southwest facing photographs of the experimental plots in the (A) Degraded area and (B) the Berm area in the fall of 2009.

Soil samples (0–30 and 30–60 cm) were collected from the Degraded area at the time of the initial site selection. The electrical conductivity (EC in a 1:2 soil:water paste) of the samples was found to be relatively low, averaging 0.11 (±0.01) mS cm^{-1} at 0–30 cm and 0.12 (±0.03) mS cm^{-1} at 30–60 cm (Appendix B – Table B.2). The low ECs in the Degraded area led to the decision to have a companion trial on the Berm, which was thought to be more impacted by salt. Indeed, ECs were about 6- to 13-times greater in the Berm plots [averaging 0.63 (±0.30) mS cm^{-1} at 0–30 cm and 1.54 (±0.69) mS cm^{-1} at 30-60 cm] than in the Degraded area. The clay Berm consisted of material that was hauled in to create a containment area for saline clay tailings from the refinery; consequently, the Berm plots were on a steep (*ca*. 10%) slope.

4.2.2 Plot design

Plots (2 m x 2 m) in the Degraded area were set-up in a Randomized Complete Block Design (RCBD) with six treatments replicated four times (Figure 4.2A). The six treatments were: the control (unamended); alfalfa pellets at 5, 10 and 20 t ha^{-1}; and biochar at 5 t ha^{-1} with or without added urea (46-0-0) fertilizer (50 kg N ha^{-1}=109 kg urea ha^{-1}) (see Table 4.1). Each block ran east to west.

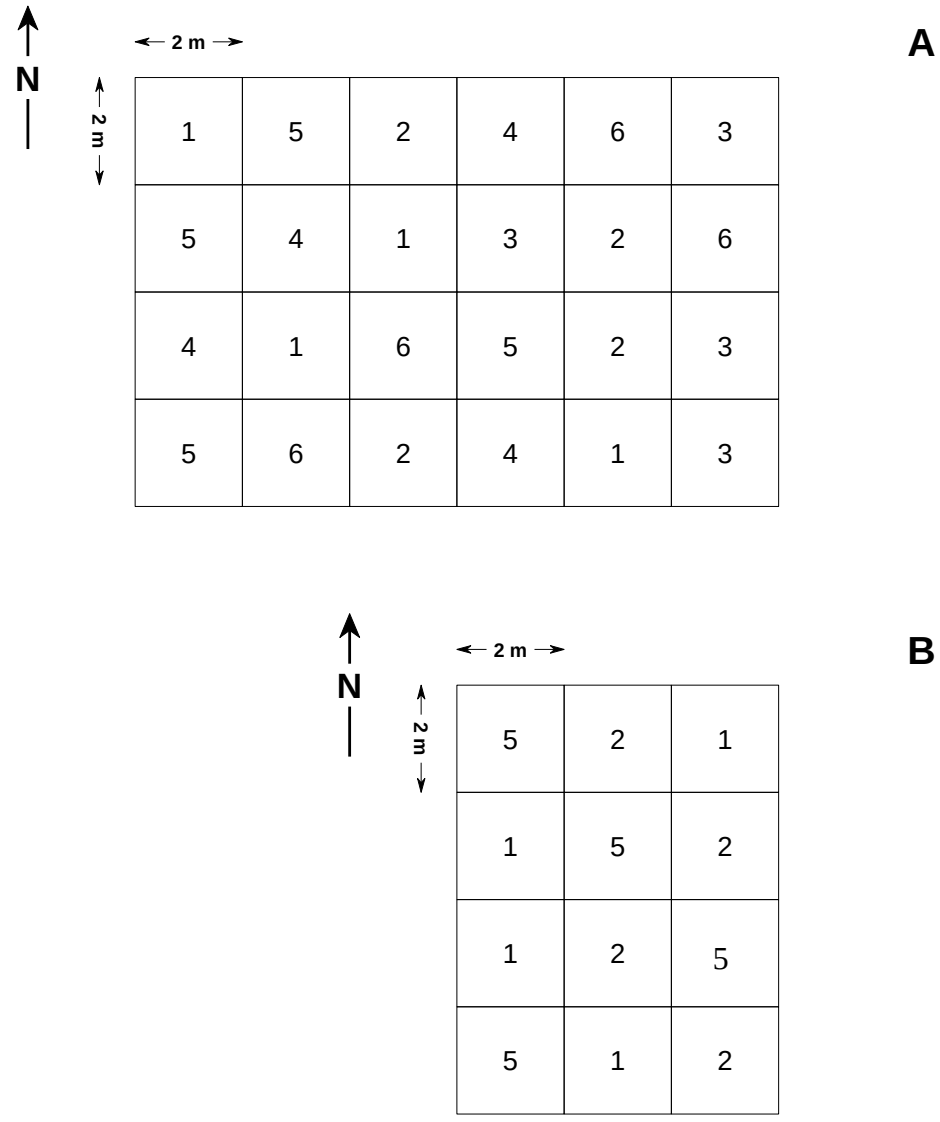

Figure 4.2 Diagram of the experimental plots in (A) the Degraded area adjacent to berm and (B) the Berm area itself. The field plots were located at the PCS–Cory Division site.

Plots (2 m x 2 m) in the Berm area were set-up in a Randomized Complete Block Design (RCBD) with three treatments replicated four times (Figure 4.2B). The three treatments were the control (unamended; Trt. 1); alfalfa pellets at 5 t ha^{-1} (Trt. 2) and biochar at 5 t ha^{-1} (Trt. 5). Each block ran east to west across the slope of the berm.

Table 4.1 Soil amendments and application rates used at the PCS–Cory Division site[†].

Trt No.	Amendment Type	Application Rate		
		t ha^{-1}	kg ha^{-1}	kg per 4 m^2 plot
1	Control	0	0	0
2	Alfalfa pellets	5	5000	2
3	Alfalfa pellets	10	10000	4
4	Alfalfa pellets	20	20000	8
5	Biochar	5	5000	2
6	Biochar + Urea[‡]	5	5000	2

[†] All six treatments were applied at the Degraded site, but only Treatments 1, 2 and 5 were applied at the Berm site.

[‡] 109 kg urea ha^{-1}or 44 g urea per 4 m^{-2} plot.

The Biochar used in this study was produced from oat hull feedstock by Titan Resources (Craik, SK). The alfalfa pellets were manufactured and supplied by Western Alfalfa Milling Co., Ltd. (Norquay, SK). The total C, N and S contents of the biochar and alfalfa pellets were determined using a Leco analyzer. Total P content of the biochar and alfalfa pellets was determined by ALS Laboratories (Saskatoon, SK). Results of the analyses are summarized in Table 4.2. Treatment No. 6 consisted of biochar supplemented with urea (46-0-0) fertilizer, which was applied (broadcast) at a rate of 50 kg N ha^{-1} or 44 g of urea per 4 m^2 plot.

The experimental plots were established on October 5, 2009. The soils were prepared by first roto-tilling the surface to a depth of approximately 10 cm to break-up the soil and prepare a

level seed bed. After roto-tilling, the amendments (pre-weighed) were applied by spreading evenly over the plot area by hand and then gently raking the amendment into the topsoil layer.

Table 4.2 Chemical properties of the oat hull biochar and alfalfa pellets applied at the PCS–Cory Division site.

Amendment	C	N	S	P	C:N	C:S
			%			
Biochar	71.4	1.54	0.12	2.5	46	1020
Alfalfa Pellets	73.8	4.1	0.57	0.2	18	130

4.2.3 Field operations

The plots were sampled on May 7, 2010, with three soil cores (0–60 cm, at 15-cm depth intervals) collected from each plot using a Dutch auger. For each sampling depth, the cores were combined into a single composite sample and returned to the Department of Soil Science in Saskatoon for processing and analysis. Each plot was then seeded with tall wheatgrass (*Thinopyrum elongatum*) at a rate of 5 g m^{-2}. The pre-weighed seed was spread evenly over each plot by hand and raked into the surface layer of soil. Digital photography was used to record the status of the plant communities on June 7 and July 14, 2010 (see Appendix B, Figure B.3; Figure B.4; Figure B.5).

The plots were harvested for above-ground biomass on August 6, 2010. The dominant plant species in each plot was recorded prior to harvest; a representative sample of the above-ground biomass was collected from a 1-m^2 area in the southwest corner of each plot by cutting the plants *ca*. 5 cm above the soil surface. The plant samples were placed in cloth bags and returned to the Department of Soil Science.

Soil samples also were taken from each plot at harvest, with three soil cores (0–60 cm, at 15-cm depth intervals) collected from each plot using a Dutch auger. For each sampling depth,

three cores were combined into a single composite sample and returned to the Department of Soil Science for processing and analysis.

Soil samples were air-dried at 30^{o}C, then pulverized to pass through a 2-mm sieve. The processed, dried samples were then put into vials for further lab analysis. The plant samples were air-dried in a forced-air oven at 30^{o}C in the cloth bags, weighed for yield, then sub-sampled and ground. The ground plant material was placed in vials for further lab analysis.

4.2.4 Soil analysis

Soil pH and electrical conductivity (EC) were determined using 1:2 (w/v) soil:water extracts; i.e., 20 g of soil was weighed into extraction bottles to which 40 mL of distilled water was added. The bottles were shaken on a rotary shaker at 142 rpm for 20 minutes and then left to settle for one hour. The supernatant solutions were filtered (Whatman No. 1 filter paper) into plastic vials which were then capped (Rhoades, 1982). Soil pH measurements were obtained by inserting a pH probe into the extractant and the reading recorded from a Beckman pH meter. A Beckman EC meter was used for the EC measurements (Richards, 1969) by inserting the probe into the extraction solution and recording the reading. The probe was rinsed thoroughly with distilled water between each measurement for both pH and EC.

The concentrations of NO_3 and NH_4 were determined using 2*M* KCl extracts (Keeney and Nelson, 1982). Approximately 5.0 (±0.1) g of soil was extracted with 50 mL of 2*M* KCl solution by shaking the soil:KCl suspension on a rotary shaker at 142 rpm for one hour, filtering the suspension (VWR No. 454 filter paper) into plastic vials, and storing the vials in a refrigerator/freezer until the available N could be colorimetrically determined using the Technicon Autoanalyzer II (Tarrytown, NY).

Available P and K were extracted using the Modified Kelowna method (Qian et al., 1994). The extracting solution was prepared by combining 28 mL of 0.25*M* acetic acid, 38.5 mL of 0.25*M* sodium acetate, and 1.11 g of 0.015*M* ammonium flouride in a 2-L bottle. Approximately 3.00 (±0.1) g of soil was weighed into a small plastic bottle along with 30 mL of the Kelowna solution. The resulting suspensions were shaken on a reciprocating shaker at 160 rpm for 5 minutes, filtered (VWR No. 454 filter paper) into plastic vials, and stored in a refrigerator/freezer until the extracts could be analyzed. The P in the extracts was determined colorimetrically using the Technicon Autoanalyzer II. The Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000) was used for analysis of K in the extract.

Available SO_4–S was extracted using 20.0 (±0.1) g of soil, which was weighed into a 100-mL extraction bottle containing 40 mL of 0.01*M* $CaCl_2$ solution. The bottles were placed on the rotary shaker and shaken at 142 rpm for 30 minutes; the solution in each bottle was then filtered (VWR No. 454 filter paper) into a plastic vial and placed in a refrigerator/freezer to await analysis colorimetrically on the Technicon Autoanalyzer II.

Degraded soil can be deficient in micronutrient metals such as Cu and Zn; therefore, soil samples from 2010 were analyzed for Cu and Zn. Plant available Cu and Zn were extracted using a diethylenetriaminepentaacetic acid (DTPA) solution (Lindsay and Norvell, 1978). The DTPA solution was prepared using 0.005 *M* DTPA, 0.01 M $CaCl_2$, and 0.1 *M* triethanolamine (pH 7.3). Ten grams of the DTPA solution was added to about one gram of soil and shaken at 142 rpm for two h. The suspension was then filtered (VWR No. 454 filter paper) and the filtrate analyzed for Cu and Zn concentration using a Varian SpectraAA 220 flame atomic absorption spectrometer (Varian Australia, 2000).

Cation exchange capacity (CEC) was determined using an ammonium acetate extraction with 40 mL of 1*M* ammonium acetate and 10 g of soil combined and shaken at 142 rpm for approximately 5 min (Hendershot et al., 1993). The concentrations of exchangeable Na^{+}, Ca^{2+}, Mg^{2+}, and K^{+} in the extracts were determined using a SpectraAA 220 Atomic Absorption Spectrometer (Varian Australia Pty Ltd., Mulgrave, Victoria, Australia), and calculating the CEC ($cmol_c\ kg^{-1}$) based on the sum of the NH_4OAc-extractable cations (Equation 4.1).

$$CEC\left(cmolc/kg\right)=\left(\frac{ppmCa}{200}\right)+\left(\frac{ppmMg}{120}\right)+\left(\frac{ppmK}{390}\right)+\left(\frac{ppmNa}{230}\right) \qquad [4.1]$$

Prior to analysis of soil organic C, and to obtain a more uniform sample size, sub-samples of the sieved soils were ball milled to pass a 100 mesh sieve. Percentage total organic carbon (TOC) was then determined via combustion at 842°C (Wang and Anderson, 1998) using the Leco 632 Carbon Determinator (Leco Corporation, St. Joseph, Missouri USA).

4.2.5 Plant analysis

Total plant N, P, and K were determined using the sulphuric acid-peroxide digest method (Thomas et al., 1997). Finely ground plant material (0.2500 to 0.3000 g) was weighed into a 100 mL glass digestion tube and, under a fume hood, 5 mL of concentrated (18*M*) sulphuric acid was added to each tube. The soil:H_2SO_4 suspensions were then mixed on a vortex mixer and placed in a heating block that was pre-heated to 360^{o}C. Once on the heating block, the suspensions were digested for 30 minutes then removed and cooled for about 20 minutes, at which time 0.5 mL of 30% (v/v) H_2O_2 (hydrogen peroxide) was added to each tube which was then mixed on a vortex mixer. The digestion tubes were then returned to the heating block and the process repeated until the solution became colorless (about six times). Once the solution was colorless, 0.05 mL H_2O_2 was added to each tube and the tubes returned to the heating block for an additional 60 minutes

to remove all the H_2O_2. The tubes were then removed from the heating block and allowed to cool overnight; the next day, deionized water was added to each tube to just below the volume line while vortexing. The tubes were again allowed to cool to room temperature at which time they were brought to a final volume of 75 mL with deionized water. The tubes were then capped with a rubber stopper, inverted five to six times to mix well, and then sub-sampled into a vial. The extrant was analysed for N, P, and K concentration using the Technicon Autoanalyzer II.

Total plant S was determined using a Leco TruSpec Sulphur Analyzer. Ball ground plant material was weighed (approx. 0.010 ±0.001 g) into a ceramic boat and placed in the LECO Sulphur analyzer. The sulphur in the samples is converted to SO_2 during a three minute combustion, and the SO_2 concentration output was recorded.

4.2.6 Statistical analysis

The R Statistical Program was used to analyze the data using General Linear Model (GLM) and a one-way analysis of variance (ANOVA). Significant differences between treatments were determined using mean separation with Fischer least significant different (LSD) at $p \leq 0.05$.

4.3 Results and Discussion

4.3.1 Degraded area soil properties

Surface applications of the soil amendments often produced significant changes in the chemical properties in the upper 0–15 cm of the soil profile, but rarely had any significant effect on the properties of the sub-surface (15–30 and 30–60 cm depth) soils. Consequently, only the data for the surface soils (0–15 cm depth) will be considered in the following discussion[1].

[1] Note: data for all three sampling depths (0–15, 15–30 and 30–60 cm depths) are shown in Appendix B.

Surface (0–15 cm) soils in the Degraded area were classified as being slightly alkaline (with pHs ranging from 7.3–7.7) and non-saline (EC < 2 mS cm^{-1}) (Table 4.3; Table 4.4). These values are similar to those reported elsewhere for the PCS–Cory Division mine/refinery site (Farrell et al., 2010) and indicate that there have been minimal salt effects from the nearby tailings pond. Surface ECs in the biochar-amended plots were slightly, but not significantly, greater than those in the control plots in the fall of 2010, which presumably reflects an effect of the biochar itself. The EC values in the Degraded area are 0.2-0.3 mS cm^{-1}, which is less than 4 mS cm^{-1} when some restriction on growth of non-salt tolerant plants may occur (Saskatchewan Ministry of Agriculture, 2008).

Table 4.3 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Degraded area for all six treatments. (AP5 = alfalfa pellets at 5 t ha^{-1}; AP10 = alfalfa pellets at 10 t ha^{-1}; AP20-alfalfa pellets at 20 t ha^{-1}; B5 = biochar at 5 t ha; B5u =biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	pH	EC	CEC	OC
			mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control	6.2	0.2	10.0	0.9
2	AP5	7.5	0.2	11.3	1.2
3	AP10	7.7	0.2	11.6	1.3
4	AP20	7.7	0.2	11.5	1.1
5	B5	7.4	0.3	11.8	1.1
6	B5u	7.5	0.2	11.6	1.3
$LSD_{0.05}$		ns	ns	ns	ns

The addition of alfalfa pellets or biochar to the plots resulted in only small increases in the organic carbon content of the surface soils (Table 4.3). Moreover, SOC content did not vary from spring 2010 to fall 2010 (Tables 4.3 and 4.4). Not surprisingly, given that the biochar and alfalfa pellets were surface applied, amendment effects were not observed in the subsurface (i.e., at 15–30 or 30–60 cm depth). Nevertheless, reclaiming soil by establishing grasslands is known

to increase soil organic carbon over time (Nelson et al., 2008), which is beneficial to the long-term soil health.

Table 4.4 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Degraded area for all six treatments. (AP5 = alfalfa pellets at 5 t ha^{-1}; AP10 = alfalfa pellets at 10 t ha^{-1}; AP20-alfalfa pellets at 20 t ha^{-1}; B5 = biochar at 5 t ha; B5u = biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the fall of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	pH	EC	CEC	OC
			mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control	6.0	0.1	9.3	0.8
2	AP5	7.6	0.1	10.3	1.3
3	AP10	7.5	0.1	10.4	1.4
4	AP20	7.4	0.1	10.2	1.4
5	B5	7.5	0.2	10.2	1.0
6	B5u	7.5	0.2	10.5	1.4
$LSD_{0.05}$		ns	ns	ns	ns

Cation exchange capacity (CEC) was significantly higher in the upper 0–15 cm of the soil profile compared to the 30–60 cm depth (see Appendix B, Table B.8; Table B.9). Whereas, the amendment additions resulted in small increases in CEC (Tables 4.3 and 4.4), treatment differences were not significant. Spring CEC values in the surface horizon ranged from 10.0 $cmol_c$ kg^{-1} in the control to 11.8 $cmol_c$ kg^{-1} in the biochar (5 t ha^{-1}) treatment. Cation exchange capacity in the fall samples decreased slightly, relative to the spring samples, ranging from 9.3 $cmol_c$ kg^{-1} in the control to 10.5 $cmol_c$ kg^{-1} in the biochar + urea treatment. The small decrease in CEC observed in the fall samples presumably reflects the effects of plant uptake. Likewise, the small increase in CEC in the topsoil layer of this sandy degraded area most likely reflects the small increase in soil organic matter content (Liang et al., 2006).

The addition of both alfalfa pellets and biochar to the soil initially resulted in small increases in the mean NO_3-N concentration in the top 0-15 cm of the soil profile (Table 4.5). Due to large inherent spatial variability, however, treatment differences were not significant. Alfalfa

pellets had no significant effect on the concentration of NH_4-N in the upper 0-15 cm, although other studies have shown that microbial decomposition and mineralization of the alfalfa pellets releases NH_4^+ ions into the environment (Godde and Conrad, 2000; Qian et al., 2011). This suggests that there was incomplete decomposition of the alfalfa pellets.

Table 4.5 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Degraded area for all six treatments. (AP5 = alfalfa pellets at 5 t ha^{-1}; AP10 = alfalfa pellets at 10 t ha^{-1}; AP20-alfalfa pellets at 20 t ha^{-1}; B5 = biochar at 5 t ha^{-1}; B5u = biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		mg kg^{-1}				
1	Control	3.1	6.6	4.5	4.0	297.9
2	AP5	8.2	6.0	4.7	4.7	388.8
3	AP10	6.5	5.3	6.8	4.3	410.9
4	AP20	8.2	7.3	6.0	5.5	417.1
5	B5	9.8	12.1	5.3	9.6	473.4
6	B5u	10.9	6.5	9.1	6.0	438.2
$LSD_{0.05}$		ns	ns	ns	ns	ns

Table 4.6 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Degraded area for all six treatments. (AP5 = alfalfa pellets at 5 t ha^{-1}; AP10 = alfalfa pellets at 10 t ha^{-1}; AP20 = alfalfa pellets at 20 t ha^{-1}; B5 = biochar at 5 t ha^{-1}; B5u = biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the fall of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		mg kg^{-1}				
1	Control	1.0	1.7	4.8	1.5	206.6
2	AP5	2.3	2.6	6.0	1.7	287.3
3	AP10	1.4	2.6	9.5	1..3	321.0
4	AP20	2.6	2.9	6.3	2.8	228.0
5	B5	2.5	2.4	4.2	2.6	221.2
6	B5u	1.9	2.7	7.8	1.7	242.7
$LSD_{0.05}$		ns	ns	3.4	ns	ns

By the fall of 2010, any inorganic N added as a result of the soil amendments was not apparent; i.e., the inorganic N pool in the soil had been depleted during the growing season by plant uptake (Table 4.6). Again, as in the spring, there was no significant difference between treatments.

In general, extractable soil P levels were quite low in the Degraded area, ranging from 4.5–9.1 mg PO_4-P kg^{-1} in the spring and from 4.2–9.5 mg PO_4-P kg^{-1} in the fall (Tables 4.5 and 4.6). Whereas there were no significant treatment differences in the spring samples, significant treatment effects were observed in the fall samples ($p = 0.001$). Soil available P levels in the biochar plus urea treatment were higher than those in either the control or biochar-amended plots. Likewise, the alfalfa (10 t ha^{-1}) treatment exhibited significantly higher soil available P concentrations than the control. There was also evidence from the fall *vs.* spring data that the alfalfa pellets may have acted as a source of available/extractable P, whereas the biochar may have acted as a sink for this P. That is, fall available P levels in the soils amended with alfalfa pellets tended to be comparable to, or greater than those found in the spring; conversely, fall available P levels in the soils amended with biochar tended to be lower than those measured in the spring (see Tables 4.5 and 4.6).

As the alfalfa pellets decompose in the soil, plant available P can be released through mineralization, explaining the increase in soil available P in the topsoil layer. Alfalfa pellets improved the uptake of nutrients in a growth chamber experiment with canola (Qian et al., 2008; 2011). In the biochar + urea treatment, the increase in soil P also may reflect enhanced release of the native soil-P as a result of an increase in the soil pH associated with urea hydrolysis and dissolution of the soil organic matter (Hartikainan et al., 1996).

The soil amendments had no significant effect on available sulphur (i.e., SO_4–S) in either the spring or fall (Table 4.5 and 4.6). Much like the available N, however, there was significant depletion of the available SO_4–S pool during the growing season. Similar trends were observed for ammonium acetate extractable K (Table 4.5 and 4.6), Ca, Na, and Mg (Appendix B, Table B.8; Table B.9). Likewise, the concentrations of extractable Cu and Zn in the soils exhibited no significant treatment effect (Appendix B - Table B.10).

4.3.2 Berm area soil properties

Soils in the Berm area were naturally more alkaline and slightly more saline than soils in the Degraded area, and were less affected by the biochar and alfalfa pellet amendments (Tables 4.7 and 4.8). Likewise, the CEC in the Berm soils was about 2.5-times greater than that in the Degraded area. These differences presumably reflect the fact that the Berm is a "constructed soil" likely derived from carbonate- or gypsum-rich C-horizon material with a high clay content.

Table 4.7 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha-1; B5=biochar at 5 t ha-1). Soil samples were taken in the spring of 2010 at the 0-15 cm depth.

Trt. No.	Trt. ID	pH	EC	CEC	OC
			$mS\ cm^{-1}$	$cmol_c\ kg^{-1}$	%
1	Control	8.3	0.4	26.2	0.8
2	AP5	8.1	0.5	25.9	0.7
5	B5	8.2	0.5	27.7	0.9
$LSD_{0.05}$		ns	ns	ns	0.2

The initial soil organic carbon content of the Berm soils (Table 4.7) was comparable to that of the Degraded soils (Table 4.3), which again is thought to be an artifact of the Berm construction. The biochar treatment resulted in a small, but significant (p = 0.01) increase in SOC compared to the control and alfalfa pellet treatment (Table 4.7). This is consistent with the

high carbon content (~70 % C) and relative recalcitrance of the biochar. Steinbeiss et al. (2009) also reported increases in SOC in a silty clay soil amended with biochar. Novak et al. (2009) also observed a significant increase in SOC in a highly weathered sandy acidic soil amended with 2% biochar.

Table 4.8 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the fall of 2010 at the 0-15 cm depth.

Trt. No.	Trt. ID	pH	EC	CEC	OC
			mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control	8.1	0.4	24.2	0.5
2	AP5	8.1	0.3	26.1	0.6
5	B5	8.2	0.3	25.9	0.7
$LSD_{0.05}$		ns	ns	ns	ns

No significant difference in organic carbon was observed between treatments in the fall samples, though the response pattern was similar to that observed in the spring, with the biochar treatment having slightly higher organic carbon (Table 4.8). Biochar provides a recalcitrant form of organic carbon when added to the soil. However, the biochar may not have been added at a high enough rate to produce a detectable increase in total organic C content of the soil over the longer term. An increase in SOC was observed in a growth chamber study on an Australian Alfisol after radishes were grown for six weeks (Chan et al., 2007). The biochar may only have a significant effect on soil SOC in extremely degraded soils such as highly weathered tropical soils.

Concentrations of inorganic N were considerably lower in the unamended Berm soils (Table 4.9) than in the soils from the Degraded area (Table 4.5). Conversely, concentrations of SO_4–S were much higher in the Berm soils than the Degraded soils. Again, these differences

presumably reflect the composition of the soil materials used to construct the Berm, and are consistent with the types of gypsum-containing materials present at the PCS–Cory Division site (Farrell et al. 2011). Available P concentrations in the Berm and Degraded area soils were not significantly different; the same was true of the NH_4OAc-extractable soil K (Table 4.9) and the DTPA-extractable Cu and Zn (Appendix B, Table B.10).

Table 4.9 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Berm for all three treatments. (AP5 = alfalfa pellets at 5t ha^{-1}; B5 = biochar at 5 t ha^{-1}). Soil samples were taken in the spring of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		---------- mg kg^{-1} ----------				
1	Control	0.5	2.8	4.8	36.4	227.9
2	AP5	0.8	2.6	4.6	13.5	383.7
5	B5	0.3	2.5	4.2	13.9	410.0
$LSD_{0.05}$		ns	ns	ns	ns	ns

Treatment effects were generally not significant for available N on the berm, though there was a small increase in available N associated with the Alfalfa pellet treatment (Table 4.9). Biochar, on the other hand, had no significant effect on available N. These results are similar to those reported by Gathorne-Hardy et al. (2009), who suggested that biochar would have a greater effect on soils with low water holding capacity due to its capacity to retain both water and nutrients.

Table 4.10 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Berm for all three treatments. (AP5 = alfalfa pellets at 5 t ha^{-1}; B5 = biochar at 5 t ha^{-1}). Soil samples were taken in the fall of 2010 at the 0–15 cm depth.

Trt. No.	Trt. ID	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		---------- mg kg^{-1} ----------				
1	Control	1.0	1.7	4.8	1.5	206.6
2	AP5	2.3	2.6	6.0	1.7	287.3
5	B5	2.5	2.4	4.2	2.6	221.2
$LSD_{0.05}$		ns	ns	ns	ns	ns

Changes to the soil nutrient pools in the Berm area (Tables 4.9 and 4.10) followed the same trends during the growing season as those observed in the Degraded area (see Tables 4.5 and 4.6). That is, whereas there was a general decrease in available S and K during the growing season, there was no such decrease in available P. In addition, there was a small increase in the soil concentration of NO_3-N in the fall samples with the largest increases occurring in the plots amended with biochar and alfalfa pellets (see Tables 4.9 and 4.10).

4.3.3 Fall 2010 plant harvest

There was greater diversity in the plant community in the Degraded area than on the Berm; though, in both areas, tall wheatgrass (*Thinopyrum elongatum* L.) and alfalfa (*Medicago sativa* L.) were the dominant plant species (Appendix B - Table B.18). In the Berm area only, foxtail barley (*Hordeum jubatum* L.) was present in three of four plots amended with alfalfa pellets and in one of the four plots amended with biochar, but was not present in the control (unamended) plots (Appendix B - Table B.19). In the Degraded area, the yield data were confounded by the variation in plant community composition and, as a result, there were no significant treatment differences ($p > 0.05$) (Figure 4.3). The alfalfa treatment at 20 t ha^{-1} produced the highest mean yield on the Degraded area, although not significantly (Appendix B - Figure B.1).

On the Berm, the harvested plant biomass was significantly ($p < 0.05$) greater in the alfalfa treatment compared to the control; the biochar treatment, on the other hand, did not differ significantly from the either the control or the alfalfa pellet treatment (Figure 4.3). Zvomuya et al. (2008) found that the soil incorporation of alfalfa hay significantly increased the grain yield of spring wheat in a field experiment in southern Alberta. Alfalfa pellets increase the soil water holding capacity, which is important for plant growth in a semi-arid region. Wahid et al. (1998)

observed that increased water holding capacity with organic matter additions of farmyard manure and clover mulch was partly responsible for the increased plant growth and yield of wheat. Little benefits were likely recognized as a result of the increased water holding capacity with alfalfa pellet addition because of the high precipitation in 2010.

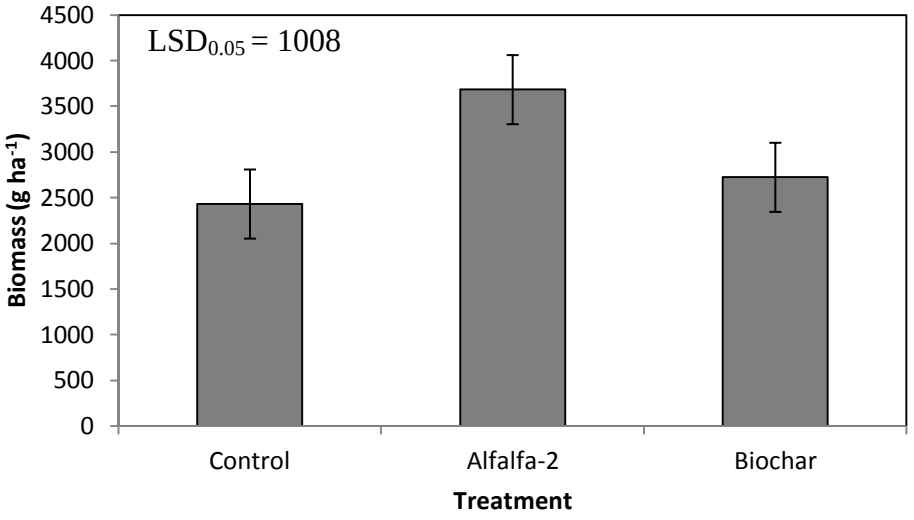

Figure 4.3 Plant biomass of vegetation (predominantly grass) collected from the Berm area plots in the fall of 2010.

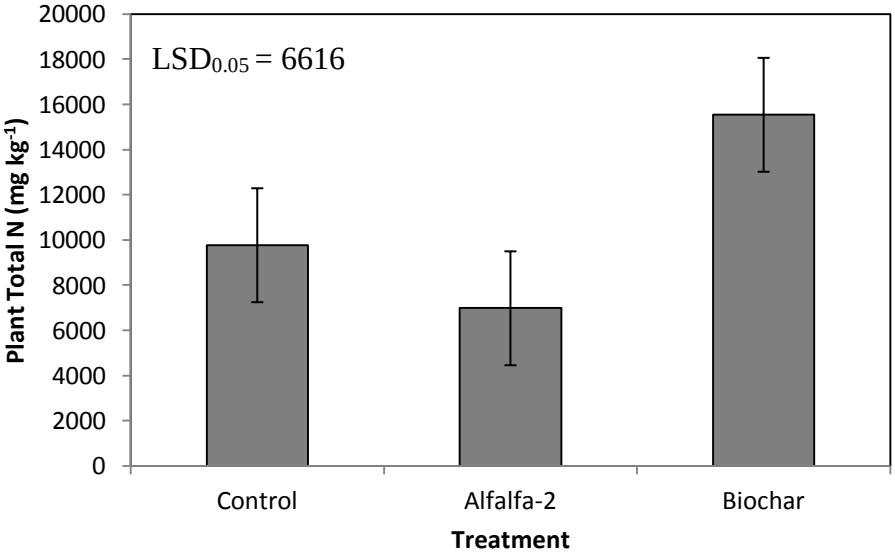

Figure 4.4 Plant total N concentration (mg N $kg^{-1}$of dry plant matter) from plots on the Berm area in the fall of 2010. Error bars represent standard error of the mean.

Alfalfa pellets release N continuously in the slow mineralization phase (Agahara and Warncke, 2005), but overall, plant N concentration (kg N ha^{-1}) on the Berm was not significantly different between treatments (Figure 4.4). Despite a higher yield of the alfalfa pellet treatment, lower plant N concentration resulted in similar plant N concentration among treatments. In the alfalfa treatment, higher biomass production because of improved soil water conditions could have resulted in the lower concentration of plant N compared to the plots with lower biomass. In other studies biochar addition resulted in increased NH_3 retention in soils receiving urea fertilizers (Clough and Condron, 2010).

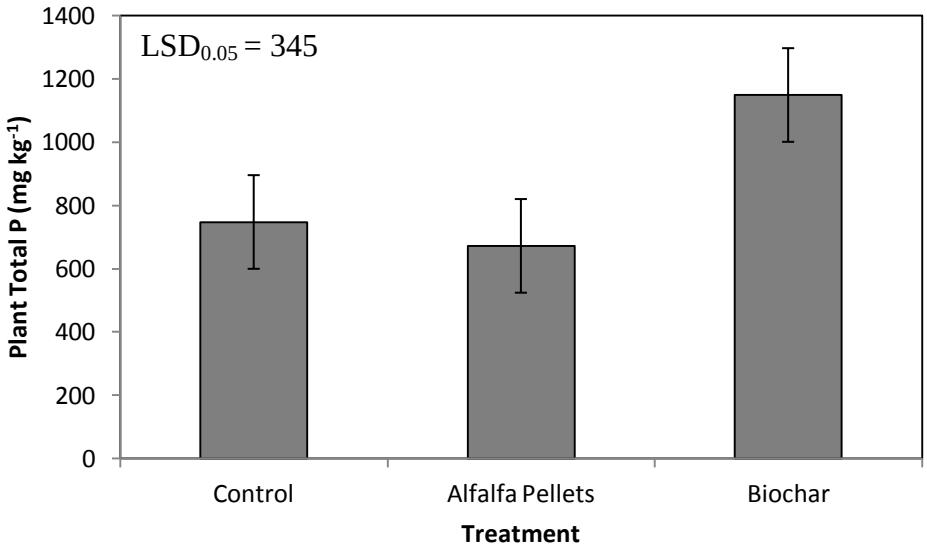

Figure 4.5 Plant total P concentration (mg kg^{-1}dry plant material) from plots on the Berm area in the fall of 2010. Bars represent standard error of the mean.

Phosphorus concentration in plants grown on biochar amended soils in the Berm area was significantly higher than that in either the control or alfalfa treatments (Figure 4.5). Biochar has been reported to provide a slow release of P to the soil, and to increase as soil pH decreases (Warren et al., 2009). In the present study, however, soil pH was generally unaffected (or increased slightly) in response to the biochar additions. Thus, it is likely that the enhanced plant

uptake of N and P observed in biochar amended soil reflects some small contribution of the oat hull biochar itself; i.e., provides a small, direct contribution to the N and P nutrition of the plants (see Table 4.2).

Plant concentration of K, S, Na, Cu, and Zn from soils in the Degraded or Berm areas showed no significant treatment effect. There was also no significant difference among treatments in plant content of N or P on the Degraded area site (Appendix B, Table B.5).

4.4 Conclusion

The addition of alfalfa pellets, biochar, or biochar + urea did not significantly affect plant growth or nutrient uptake on the Degraded area during the first season following application of the amendments. Biochar + urea increased the soil extractable phosphate levels at the start of the growing season (i.e., in the spring following application) and at harvest in the fall. These effects were attributed to pH effects associated with the amendment additions. The application of alfalfa pellets (at 10 t ha^{-1} rate) also resulted in increased levels of available soil P in the fall of 2010. However, the increase in soil P in the alfalfa and biochar + urea treatments was not reflected in plant uptake of P. Phosphorus is relatively immobile in the soil, and is unlikely to migrate very far during a single growing season; thus, given that the amendments were surface-applied, it may not have migrated into the root zone to be available for plant uptake. The Degraded area also experienced a wide variety of different plant species growing on it that contributed to high variability in measured plant parameters.

Biochar applications initially increased the SOC content in the Berm area, though no significant effect was observed in the fall. The plant-N concentration was increased in the biochar treatment compared to the alfalfa treatment; a similar observation was made regarding plant-P. Alfalfa pellets increased soil NO_3-N levels in the fall on the Berm. Improved soil N

availability and water relations may have been contributing factors to the alfalfa treatment resulting in significantly higher yield of grass on the berm site than control and biochar treatments.

The Berm and the Degraded area were both relatively low in SOC and nutrients. Neither of the sites contained high amounts of salts that would inhibit plant growth but the increased salts at lower levels in the soil profile indicate that there may be some movement of salts from the tailings pond into the Berm.

Addition of alfalfa pellets was beneficial in increasing the plant growth and likely can have positive benefits as a soil amendment for revegetation of Berm areas. Biochar can increase the soil carbon and may have positive implications as a soil amendment, especially when combined with fertilizer. Although this study encompassed only a single year, it is predicted that both types of organic amendments will provide benefits to soil quality and plant growth in future years. Examining the effects of both alfalfa pellets and biochar on saline field sites in future studies is recommended to determine potential of each amendment to enhance soil quality and plant growth on highly salt affected areas.

5.0 AMENDMENT OF TWO AGRICULTURAL SOILS WITH BIOCHAR TO IMPROVE PLANT NUTRITION AND FERTILIZER USE EFFICIENCY

5.1 Introduction

Biochar is created by heating organic matter to very high temperatures (200 to 750^{o}C) in the absence of oxygen or under low oxygen conditions (Novak et al., 2009b). This process, called pyrolysis, is used for the production of biogas, with biochar as a by-product consisting of what remains of the organic material. Biochar is mostly C that is highly resistant to microbial breakdown and chemical degradation (Paris et al., 2005). Recently biochar has been the focus of many research projects to assess its use as a soil amendment in modern agriculture.

Few studies have been conducted on biochar as a soil amendment in temperate climates. Most research to date has been focused on highly weathered, nutrient poor tropical soils where it has been shown that the most consistent effect of biochar is to significantly enhance the SOC levels (Novak et al., 2009a). One study conducted in a temperate region in Italy showed an increased yield of durum wheat over a two-year period with addition of wood-derived biochar at rates of 30 and 60 t ha^{-1} (Vaccari et al., 2011). Char has been found to be an important natural component in the Black Chernozem soils in Saskatchewan (Ponomarenko and Anderson, 2001). Char in Saskatchewan soils is derived from past prairie and forest fires and is a natural phenomenon. Amendment with chars could increase the soil fertility and quality in prairie soils, enhancing production especially in soils low in organic carbon. The positive effect of the biochar in temperate regions suggests potential for use in soils of the northern Great Plains of North America.

Soil C increases as a result of biochar addition thus increasing the C:N ratio of the soil (Steiner et al., 2008). However, biochar is a recalcitrant form of organic C in the soil compared to other organic matter sources, therefore the increased C:N ratio does not have a great effect on N mineralization and immobilization by microbes compared to plant residues and fresh organic amendments. The C:N ratio in organic amendments, such as manure, can help predict the N availability with more N available at a C:N less than 15:1. Some biochars may have a portion of decomposable C which may lead to immobilization and a decrease in available N for plant uptake, as was noted in a study where a large amount of biochar (100 t ha^{-1}) was added (Steiner et al., 2009). The different C and N forms in biochar create a need for different methods of estimating nutrient availability in the soil following biochar application. Response of plant growth and N uptake to biochar amendment is a reasonable approach.

The responses of the soil microbial population are affected by biochar type. Steinbeiss et al. (2009) discovered that different types of biochar promoted the growth of different microbial populations that were adapted to break the material down (Steinbeiss et al., 2009). These authors suggested that some biochars have a stimulatory effect on microbial activity, which in turn increases the rate of degradation of other SOM. Biochar also has been observed to enhance beneficial plant-soil associations such as with soil mycorrhizae (Warnock et al., 2007).

Methods for improving the N use efficiency or the N recovery from fertilizers are being sought after in agricultural operations (Jackson et al., 2008). The large surface area of biochars can promote increased retention of nutrients, including available N and cations (Steinbeiss et al., 2009). For example, in England the addition of biochar improved the efficiency of fertilizer N uptake in barley with increasing rate of fertilizer addition (Gathorne-Hardy et al., 2009). Chan et

al. (2007) also observed enhanced N recovery by radish when biochar was added along with commercial fertilizer.

Studies focusing on soil N improvement using biochar as a soil amendment have shown variable effects. Novak et al. (2009a) observed that there was no effect on soil N with any rate of biochar addition to a U.S. coastal plain soil in South Carolina, likely because the N in the biochar was not in a bioavailable form and the soil N status was initially low. Biochar properties may affect the N cycling processes in the soil, by increasing aeration and providing a stable form of C. This was suggested to result in decreased nitrous oxide emissions (Lehmann et al., 2006). Steiner et al. (2009) reported increased soil N retention and increased radish N uptake on a highly weathered soil in Brazil with biochar (100 t ha^{-1}) added along with N fertilizer (Chan et al., 2007). Moderate rates of biochar addition to tropical, acidic soils in Columbia improved the N fixation by common beans (*Phaseolus vulgaris* L.) by increasing the availability of B and Mo (at a biochar rate of 60 g kg^{-1}), although high biochar rates (90 g kg^{-1}) decreased the N fixation rate (Rondon et al., 2006).

Biochar can increase the cation exchange capacity (CEC) in the soil compared to non-amended tropical soils (Liang et al., 2006). These authors suggest that biochar increased the surface area and provided exchange sites for ion sorption, and thus increased the CEC and cation fertility. Biochar increased pH in acidic soils due to the increased retention of Ca and Mg, and was reported to enhance the availability of other nutrients in soils as a result (Yuan et al., 2011; Rondon et al., 2006; Vaccari et al., 2011).

Soil P is released from addition of bone char, although this may be related to soil acidity as the dissolution of P from calcium phosphates contained in the bone char would be more pronounced in acidic soils (Warren et al., 2009; Atkinson et al., 2010). It is likely that the release

of P and cations from biochar would be of less significance in soils of neutral to alkaline pH and relatively high organic matter and clay content, typical of agricultural soils in western Canada.

Biochar feedstock and pyrolysis temperature affects the properties of biochar as a soil amendment. Perier et al. (2011) suggest that pyrolysis temperature can affect the porosity and the surface area of the biochar, thus affecting its properties as a soil amendment and its influence on parameters such as CEC. Pyrolysis of different crop residues resulted in different biochar properties. For example, increased soil pH was noted with addition of legume biochars compared to canola and rice straw based biochars (Yuan et al., 2011). Biochar derived from willow (Titan Resources, Craik, Saskatchewan) was used in this study as the supply of oat-hull biochar used in the potash mine site field study described in Chapter 4 was exhausted.

The objective of this study was to evaluate the effect of a biochar derived from willow on canola growth, canola nutrient uptake, and soil nutrient concentration in two contrasting Saskatchewan soils (Black and Brown). The willow biochar was applied at three rates: 5, 10, and 20 t ha^{-1} with an additional treatment of willow biochar at 10 t ha^{-1} along with commercial fertilizer. The trials were conducted under controlled environment conditions in a phytotron at the University of Saskatchewan. Effects of the amendment on canola biomass yield and soil chemical properties (EC, pH), soil elements (C, N, P, K, Cu, Zn) post-harvest were determined.

The hypothesis of this study was that the willow-based biochar amendment will improve nitrogen recovery and enhance the growth of canola.

5.2 Materials and methods

5.2.1 Treatment properties

Soil was collected in the spring of 2010 from the top 0-15 cm of control (unmanured, unfertilized for 13 years) plots at a long-term field research site in east-central Saskatchewan

near Dixon in the Black soil zone (Black soil). The previous crop was wheat and the soil was classified as belonging to the Cudworth Association (Orthic Black Chernozem). A second soil was also collected from 0-15 cm depth from a wheat stubble field in south-central Saskatchewan near Central Butte (Brown soil). The soil was classified as Haverhill Association (Orthic Brown Chernozem). The soils were air- dried and mixed following collection to ensure homogeneity. Both soils were relatively low in available N and P (Table 5.1), and would be considered deficient in these nutrients for production of most annual crops. The two soils provide a large contrast in SOC content, as the Black SOC (%) is more than three times that of the Brown soil. The soils are neutral to alkaline in pH.

Table 5.1 Soil properties of initial soils used in the growth chamber studies collected in the spring of 2010.

Soil	NO_3	NH_4	PO_4	K	OC	pH
	---------- mg kg^{-1} ----------				%	
Black soil	9.6	6.0	10	584	6.9	7.0
Brown soil	4.3	2.8	17	411	2.0	7.5

The field capacity for each soil was determined by sieving soil through a 2 mm sieve and weighing out 50 g of soil into a vial. Water was added to each of the four vials of soil to represent adding 20 %, 25 %, 30 %, and 35 % water by weight. The vials were equilibrated for about 24 h. The value of field capacity was then estimated by taking the average of the percentage of water by weight added that resulted in wetting of the soil to the bottom of the vial but did not leave free-standing water. The field capacity of the two soils was 28 % (average of 25 and 30 %) for the Black soil and 25 % for the Brown soil.

To prepare the treatments in pots, plastic pots of 15 cm diameter (volume = 0.27 m^3) and trays were washed and labeled, and a filter paper was placed on the bottom of each pot to prevent

soil leakage. The amendments were weighed out for each pot (See Table 5.2 for rates) and the amendment and 900 g of soil were mixed in a bucket then put into the pot. The biochar was incorporated into 1 kg of soil in each pot to provide rates of 5, 10, and 20 t ha^{-1} (2.5, 5, and 10 g kg^{-1} soil) for the biochar trials and 10 t ha^{-1} for the biochar plus fertilizer treatment and with a fertilized control and a control with no amendments for each soil type (Table 5.2). Four replicates were used for each treatment.

Pots were weighed and watered with distilled water to bring the soil to 80 % field capacity and left on the lab bench for 48 h to equilibrate. Following equilibration, each pot was seeded with 10 canola seeds (*Brassica napus* Invigor 5030 seed). Then the remaining 100 g of soil was placed on top ensuring no large lumps were on the surface. The pots were watered again to 80 % field capacity and the total weight of each pot was recorded.

For the fertilizer and the biochar plus fertilizer treatments, urea (46-0-0) was added at a rate of 200 mg N kg^{-1} soil for every 1 kg pot and triple superphosphate (0-45-0) was added at a rate of 20 mg P kg^{-1} per pot. The actual amount of each fertilizer added to each 1-kg pot was 0.435 g urea and 0.0813 g triple superphosphate. The rates of biochar added to each pot and the relative N rates (Table 5.2) were calculated based on the amount of fertilizer or biochar added and the percentage of N in that amendment, with biochar containing 0.92 % N and urea consisting of 46 % total N.

The pots were placed in a growth chamber with 16-hour days at 24^{o}C and 8-hour nights at 21^{o}C to represent summer growing conditions and encourage rapid growth of canola. The humidity was not controlled in the growth chamber and the pots were moistened on the soil surface twice daily for the first seven days and watered daily to 80% field capacity over the

remainder of the 35-day period. The pots were randomized weekly to ensure even light and air distribution.

Table 5.2 Rates of biochar and the relative N rates added (biochar N + fertilizer N) for each treatment on the Black and Brown soils.

Treatment	Biochar Rate		N rate
	t ha^{-1} †	g kg^{-1} soil	mg kg^{-1} soil
Control	0	0	0
Biochar	5	2.5	240
Biochar	10	5	480
Biochar	20	10	960
Biochar + Urea Fertilizer	10	5	680
Urea Fertilizer	0	0	200

† t ha^{-1} assumes a soil depth of 0.15 m and a bulk density of 1.3 g cm^{-3}.

The canola plants were harvested on day 35 in the growth chamber. The plants were in the vegetative state at about the 4- to 6-leaf stage at the time of harvest (Appendix C – Figure C.1). The plants were then harvested by cutting at the base and placing in labeled paper bags. The bags of plant material were oven-dried at 40^{o}C, then ground and placed into vials for further lab analysis. The soil from the pots was laid out to air-dry at 30^{o}C then put through a 2 mm sieve and placed in vials for further lab analysis.

5.2.2 Biochar properties

The willow biochar used in this growth chamber study had a higher C:N ratio and was lower in total N, P and S compared to the oat hull biochar (Table 5.3) that was used in the field study described in Chapter 4. The C:N ratio in the biochar in this study are lower than values reported for biochars in other studies. For example, Chan et al. (2007) determined that biochar produced from feedstock of grass clippings, cotton trash, and plant prunings had a C:N of 200.

The external surface area of willow biochar used in the research described in this chapter and the oat hull biochar used in the previous chapter was measured using the helium void method on the NOVA BET Surface Area Analyzer. The mean surface area was determined from two replicates for the unground oat hull biochar and three replicates from the willow biochar.

Different methods of surface area measurement probe either external (BET) or total (EGME) specific surface area. For organic materials, chemical interactions with EGME may overestimate specific surface area; whereas for materials with internal pore space or interlayers BET measurements may underestimate surface area. Soil organic matter and humus have been shown to have an EGME surface area of 560-800 $m^2\ g^{-1}$ (Chlou et al., 1990).

Table 5.3 Properties of the two biochars that were used in the thesis research. (P=total P from acid digest, C, N, and S are from analysis on the Leco C, N, and S analyzer).

Biochar Type	P	C	N	S	C:N	Surface Area
	---------- % ----------					$m^2\ g^{-1}$
Oat Hull Biochar	2.95	71.4	1.54	0.12	46.4	13.4
Willow Biochar	0.15	91.3	0.92	0.05	99.2	24.7

Willow biochar had higher surface area compared to the oat hull biochar despite the larger apparent particle size (Figure 5.1). In a study by Pereira et al (2011), willow biochar that underwent pyrolysis at higher temperatures (550^{o}C) had a specific surface area of 149 $m^2\ g^{-1}$ while it was as low as 3 $m^2\ g^{-1}$ when produced at lower temperatures (400^{o}C). The low surface area of the willow biochar in our study may reflect a low temperature pyrolysis, as higher temperatures result in a more ashy material. Surface area that was higher for the willow biochar may influence the nutrient holding capacity and cation exchange capacity (CEC) of the biochar (Liang et al., 2006).

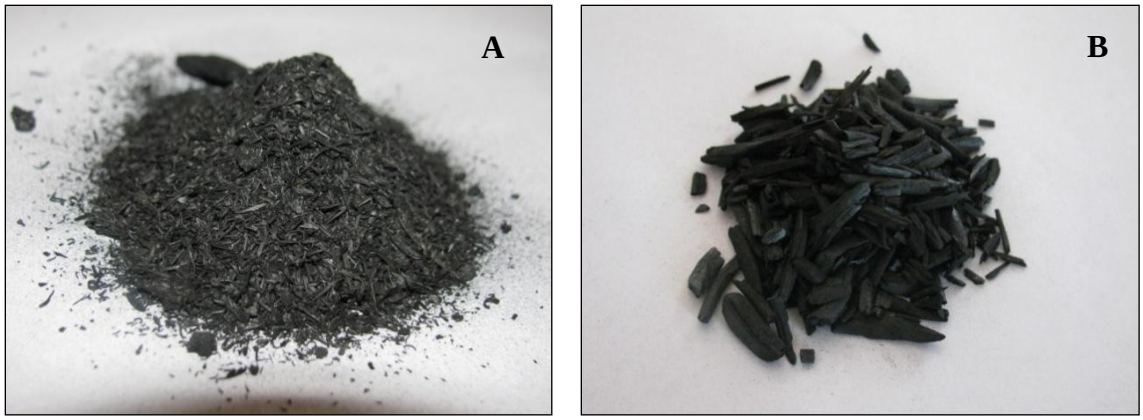

Figure 5.1 Oat hull biochar (A) and willow biochar (B).

5.2.3 Soil analysis

Soil available NO_3-N and NH_4-N were determined by a 2*M* KCl extraction (Keeney and Nelson, 1982) in a 10:1 solution:soil ratio. Available P and K was determined using the Modified Kelowna method (Qian et al., 1994) while SO_4 was extracted in a 0.01 *M* $CaCl_2$ solution at a 2:1 solution:soil ratio. Automated colorimetry was used to determine the inorganic N, P, and S, extracts using the Technicon AutoAnalyzer II. Detailed descriptions of the methodology are found in Chapter 3.

For analysis of Cu and Zn, a DTPA solution was prepared using 0.005 *M* DTPA, 0.01 *M* $CaCl_2$, and 0.1 *M* triethanolamine (pH 7.3) (Lindsay and Norvell, 1978). Ten grams of the DTPA solution was added to one gram of soil and shaken for two hours. The solution from the bottles was filtered and the supernatant was analyzed using atomic absorption spectroscopy.

The sieved soil samples were sub-sampled and ball ground to provide a more uniform sample for determination of organic carbon using the LECO Carbonator at 842^{o}C according to the procedure described by Wang and Anderson (1998).

For the pH measurements (Rhoades, 1982), a pH meter was used by inserting the probe into the supernatant from a 2:1 water:soil suspension and recording the reading. An EC meter was used for the EC measurements (Richards, 1969) by inserting the probe into the extraction solution and recording the reading.

5.2.4 Plant analysis

Total plant N, P, and K were determined using the sulphuric acid-peroxide digest method (Thomas et al., 1997). Into digestion tubes, 0.25 g of ground plant material is added and heated to 360^{o}C with sulphuric acid and peroxide six times. The solution was then sub-sampled into a vial. The digest solutions were then colormitrically analyzed on the Technicon Autoanalyzer II for element concentration as described in section 5.2.3. The Leco Sulphur Analyzer was used for analysis of total S in plant material. Ball ground plant material was weighed into a ceramic boat and placed in the oven of instrument where it was combusted to SO_2 in a stream of O_2 at 1000^{o}C. The SO_2 is measured using an infrared detector.

5.2.5 Statistical analysis

The experimental design was a completely randomized design. The R Statistical Program was used to analyze the data using the general linear model and one-way ANOVA. Significant differences (p<0.05) between treatments were determined using the Fischer least significant difference (LSD) test.

5.3 Results and discussion

The willow biochar alone treatments did not significantly increase canola biomass yield over the unfertilized control nor did combining the biochar with N and P fertilizer have any enhancement over fertilizer alone on plant biomass (Figure 5.2; Figure 5.3). As expected, fertilizer N and P significantly (p<0.05) enhanced canola dry plant biomass. The canola grown

on the biochar plus fertilizer treatment was not significantly different from the fertilizer alone treatment in biomass, plant nutrient concentration (Table 5.4; Table 5.5), or soil nutrient concentrations (Table 5.6; Table 5.7). As well, there was no significant biochar rate effect for the concentration of most nutrients in the canola plant and soil. The reason for lack of effect of the biochar on these parameters may be that the soils used in this research were not as nutrient poor and acidic as soils used in other research where biochar increased the biomass of plants grown on biochar amended soils (Novak et al., 2009a; Atkinson et al., 2010). These authors also applied higher rates of biochar (up to 100 t ha^{-1}) than used in the current study.

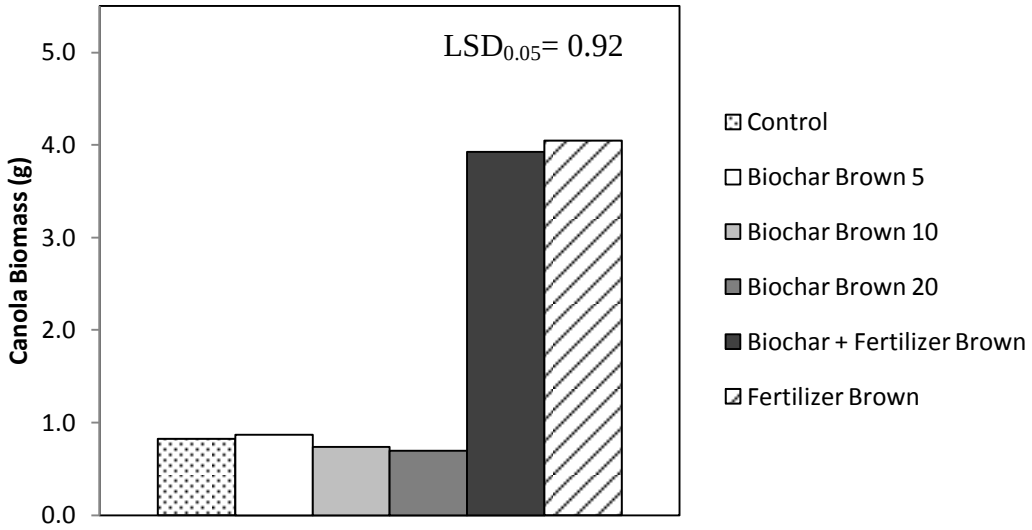

Figure 5.2 Mean canola dry matter biomass for willow biochar added at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus N and P fertilizer, fertilizer and control treatments on the Brown soil.

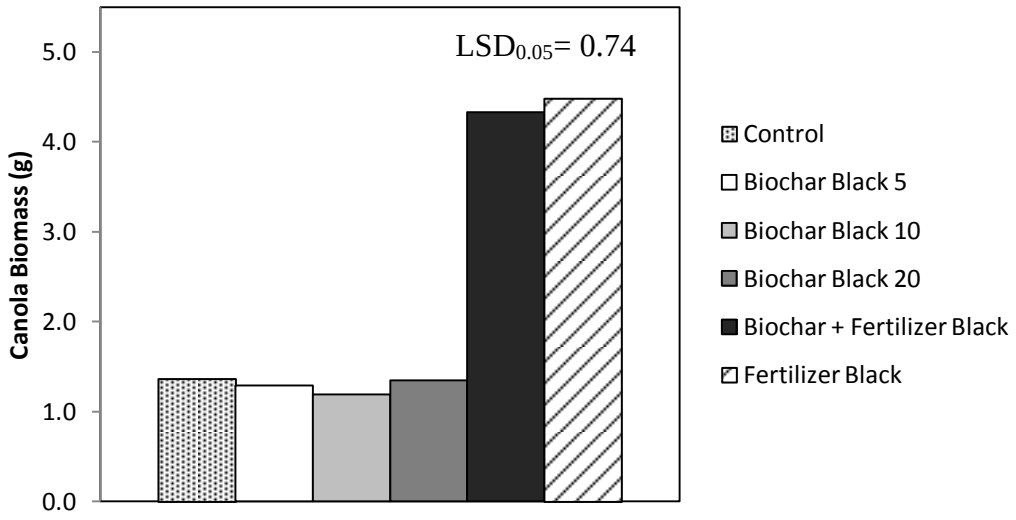

Figure 5.3 Mean canola dry matter biomass for willow biochar added at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus N and P fertilizer, fertilizer and control treatments on the Black soil.

5.3.1 Canola nutrient concentration

In both Black and Brown soils, canola N concentration was significantly higher in the biochar plus urea and the urea treatments than other treatments (Figure 5.3), which is expected from the addition of commercial N fertilizer. The biochar plus fertilizer and the fertilizer alone treatments had significantly lower canola P concentration in the Brown soil (Table 5.4). This is likely due to a growth dilution effect. Canola K concentrations increased in both of the fertilized treatments compared to all other treatments, except in the Black soil where the control and two fertilized treatments were significantly higher in plant K than the biochar treatments at the three different rates (Table 5.5). Increase in plant K with urea fertilization could be due to enhanced K availability in soil from NH_4^+ ions displacing K from interlayer sites in the clay minerals.

There was no significant effect of treatment on plant Cu and Zn concentration except for the Zn concentration on the Brown soil which was significantly higher in the biochar plus fertilizer treatment compared to the control, fertilizer, and biochar at 5 and 10 t ha^{-1} rates

(Appendix C – Table C.1; Table C.2). The urea fertilizer acidifies the rhizosphere in the urea nitrification process and this may have enhanced Zn availability in this calcareous soil (Hartikainen and HliHalla, 1996).

Table 5.4 Mean canola dry matter canola P and K concentration for willow biochar at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Brown soil.

Treatment	Biochar Rate	N	P	K
	t ha^{-1}	---------- mg kg^{-1} ----------		
Control	0	16877	3310	30755
Biochar	5	13595	3256	25954
Biochar	10	14217	2874	31008
Biochar	20	12966	2867	26953
Biochar + Fertilizer	10	25623	1706	46173
Fertilizer	0	26265	1710	44297
$LSD_{(0.05)}$		7534	625	9652

Table 5.5 Mean canola dry matter canola P and K concentration for willow biochar at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Black soil.

Treatment	Biochar Rate	N	P	K
	t ha^{-1}	---------- mg kg^{-1} ----------		
Control	0	16399	1809	39320
Biochar	5	11830	1652	28185
Biochar	10	13109	1783	27559
Biochar	20	11509	1717	27371
Biochar + Fertilizer	10	25128	1717	45951
Fertilizer	0	26142	1755	43738
$LSD_{(0.05)}$		5399	ns	10451

5.3.2 Soil results

The soil pH was significantly increased with biochar amendment in all treatments compared to the control on both the Black and Brown soils (Table 5.6; Table 5.7). Biochar also increased soil pH in acidic soils in the study by Chan et al. (2007) where the highest rates of

biochar increased the pH from 4.8 in the control to 6.0 in the 100 t ha^{-1} biochar treatment. Soil electrical conductivity was not significantly affected by the treatments on both soils (Appendix C).

Table 5.6 Mean soil pH, soil organic carbon (SOC), and available NO_3-N, NH_4-N, and PO_4-P concentration for willow biochar added at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer, and control treatments on the Brown soil.

Treatment	Biochar Rate	pH	SOC	NO_3-N	NH_4-N	PO_4-P
	t ha^{-1}		%	---------- mg kg^{-1} ----------		
Control	0	7.5	1.4	6.1	2.3	16.9
Biochar	5	7.9	1.5	3.3	3.0	19.3
Biochar	10	7.9	1.6	1.8	1.6	16.8
Biochar	20	7.9	1.6	2.4	3.1	16.0
Biochar + Fertilizer	10	7.8	1.8	3.4	4.3	19.5
Fertilizer	0	7.8	2.0	3.5	4.2	21.3
$LSD_{(0.05)}$		0.15	ns	ns	1.4	2.6

Table 5.7 Mean soil pH, soil organic carbon (SOC), and available NO_3-N, NH_4-N, and PO_4-P concentration for willow biochar added at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Black soil.

Treatment	Biochar Rate	pH	SOC	NO_3-N	NH_4-N	PO_4-P
	t ha^{-1}		%	---------- mg kg^{-1} ----------		
Control	0	6.8	3.3	4.0	4.4	11.7
Biochar	5	7.9	3.4	2.3	3.5	11.5
Biochar	10	7.8	3.5	3.4	3.7	12.8
Biochar	20	7.7	3.6	2.2	3.3	12.9
Biochar + Fertilizer	1 0	7.8	3.5	4.8	5.2	16.6
Fertilizer	0	7.8	3.4	5.6	4.5	17.2
$LSD_{(0.05)}$		0.16	0.23	3.4	0.9	1.6

The high rate of biochar (20 t ha^{-1}) and biochar (10 t ha^{-1}) plus urea fertilizer treatments had significantly higher SOC concentration compared to the control treatment on the Black soil (Table 5.7). Although not significant at $p<0.05$, there was a trend of increasing organic carbon

with increasing rate of biochar addition in the Black soil treatments. These results agree with Chan et al. (2007), who also found that there was an increase in SOC content with biochar addition to an Australian Alfisol over a period of six weeks in a growth chamber study. There was no significant effect of treatment on the SOC content in the Brown soil even though the Brown soil had a lower initial SOC than the Black soil.

In the Black soil, available soil NO_3-N in the biochar plus urea fertilizer treatment was slightly elevated compared to the biochar amended treatments at 5 and 20 t ha^{-1} rates but was not significantly different from the control (Table 5.7). Overall, soil NO_3-N levels after canola harvest were low and similar among treatments. There was no significant difference in soil NO_3-N among the treatments on the Brown soil but there was a slightly but significantly higher NH_4-N concentration in the fertilizer alone and biochar plus fertilizer treatments when compared to the control and the biochar at 10 t ha^{-1} rate (Table 5.6). The NH_4-N concentrations in the Black soil were decreased in the biochar alone treatments at 5 and 20 t ha^{-1} rates compared to the control, biochar plus fertilizer, and fertilizer treatments (Table 5.7). Novak et al. (2009a) also indicated that biochar did not improve the N status of their soil in a growth chamber study conducted on a soil from the south-eastern coast of the USA.

Soil extractable PO_4-P in the Black soil was slightly higher in the fertilizer alone and biochar plus fertilizer treatment compared to other treatments (Table 5.7). This is explained by the fertilizer amendment containing urea and superphosphate. No effect of the biochar with fertilizer was observed on soil N and P compared to the fertilizer alone. The biochar itself adds little P to the soil and the P is of low bioavailability.

The extractable Cu concentrations in the two soils were not significantly different among treatments on both soils but there was a significant effect on soil Zn concentration in the Black

soil but not the Brown soil (Appendix C – Table C.3; Table C.4). The Zn concentrations were significantly higher in the urea fertilizer treatment compared to all other treatments for the Black soil. Urea hydrolysis and nitrification may have affected the availability of metal micronutrients in the fertilized treatments (Hartikainen and YliHalla, 1996).

The calculation of recovery of added N by canola plants in the amendments (biochar, N from added urea) revealed that biochar N was not recovered by the canola (Table 5.8). This supports the concept of biochar N being of an inert nature, as the biochar added 240 mg N kg^{-1} soil in the low biochar rate. The N recovery values for the N in the added urea fertilizer treatment (44 to 47 %) are within the range of what would be expected from an inorganic fertilizer N sourced to a prairie soil. Eghball and Power (1999) found N recovery from N fertilizer to be ~45% which is similar to the results in our research.

Table 5.8 Mean N recovery by canola plants for willow biochar added at 5, 10, and 20 t ha^{-1}, willow biochar (10 t ha^{-1}) plus fertilizer, fertilizer alone, and control treatments on the Brown and Black soils.

Treatment	Biochar Rate	N Rate	N uptake	N Recovery
	t ha^{-1}	mg kg^{-1}	mg kg^{-1} soil	%
		Brown soil		
Biochar	5	240	11.7	-1
Biochar	10	480	10.5	-1
Biochar	20	960	9.1	-1
Biochar + Fertilizer	10	680	99.6	45
Fertilizer	0	200	102.6	44
		Black soil		
Biochar	5	240	15.2	-3
Biochar	10	480	15.1	-1
Biochar	20	960	15.4	-1
Biochar + Fertilizer	10	680	108.6	47
Fertilizer	0	200	116.2	47

The biochar plus fertilizer treatment N recovery values were nearly identical to the fertilizer alone, indicating that biochar did not enhance efficiency of recovery of N fertilizer in

this experiment. These results differ from Chan et al. (2007) where biochar significantly increased N recovery by radish grown on an acidic, highly weathered, Australian soil. These authors also reported that the biochar treatment had decreased concentrations of Al and increased pH, K, and available P in the soil which may have also contributed to the increased plant growth and plant N recovery. No such effects on available nutrients were observed in this study. The study by Chan et al. (2007) also used higher rates of biochar addition, with differences between biochar amended and control treatments observed at biochar rates of 50 t ha^{-1} and 100 t ha^{-1}. Biochar added along with fertilizer at increasing fertilizer rates increased the N use efficiency of barley on field plots in the United Kingdom (Gathorne-Hardy et al., 2009). Further evaluations biochar are needed on the prairies to evaluate effects on N recovery under field conditions.

5.4 Conclusion

Willow biochar added to two contrasting Saskatchewan soils at rates of 5, 10, and 20 t ha^{-1} did not result in increased yield, nutrient availability, or recovery of N by canola over a five-week growth period. The biochar did increase the SOC significantly in the Black soil which is beneficial to soil quality, although no effect on extractable available nutrients were observed in the biochar alone treatments compared to the control.

The relatively high organic matter and clay content of prairie soils along with neutral to alkaline pH contributes to high ion sorption and exchange capacity. As such, these soils inherently may not be as responsive to added black carbon sources compared to acidic, highly weathered tropical soils where “terra preta” (charcoal affected soils) had originated and reported to improve agricultural soils in the Amazon. Many of the beneficial properties of biochar are due to its ability to increase the pH of acidic soils, thus increasing the retention of cations as well as

improving P and N fertility in the soil. Biochar application may have benefits if fertilizer can be retained in the soil for longer periods until the plant can access it.

Higher rates of biochar than used in this controlled environment study have been used in other research projects. The feasibility and practicality of biochar application on a large scale would be improved if decreased rates of biochar could be applied to soil, such as 1 t ha^{-1} instead of 10 or 100 t ha^{-1}. Hauling and applying many t ha^{-1} of biochar long distances from its area of production would require large, consistent yield benefits to be realized in order to be economical.

The lowest rate of biochar that can produce a significant positive effect on N recovery and plant growth would be important to determine when considering feasibility of biochar as an amendment on agricultural soils. As well, the performance of biochar originating from different source materials and manufacturing processes needs to be evaluated. Biochar as an amendment in Saskatchewan may have greatest potential benefits on soils that are highly degraded with coarse texture and of very low organic matter content. Further long-term field studies should be conducted to determine the benefits of biochar on soils of the northern Great Plains.

6.0 GENERAL DISCUSSION AND CONCLUSIONS

The organic amendments studied each had unique effects on soil nutrient status and plant growth and nutrient uptake. The effects of the amendments were generally positive, but the manure and alfalfa pellets were more effective in enhancing soil nutrient availability, uptake and plant yield than the biochar. Each of the amendments is perceived to have different applications for the agricultural and environmental industries as an amendment to improve soil fertility and plant growth.

Application of DDGS-fed cattle manure to two Saskatchewan soils resulted in significant increases in canola yield and N and P uptake. Composting, through its effect on reducing water content and concentrating the nutrients, resulted in greater canola growth enhancement than fresh manure at lower rates of manure application (e.g. 60 t ha^{-1}), but resulted in toxicity effects at the high rates (e.g. 240 t ha^{-1}). The toxicity effect was especially evident for the composted DDGS wheat-fed manure treatments. The increased nutrients in the composted treatments will affect the optimum rates of manure application. To avoid toxicity and overloading of the soil with P, composted DDGS wheat-fed cattle manure should be applied at lower manure rates on a weight basis compared to the fresh manures. The concentrated nature of the composted manure can be construed as a benefit though, since hauling and application costs will be lower per unit of nutrient in the manure.

The effectiveness of the manure depends on the feed source as demonstrated by the higher nutrient concentration in the DDGS wheat-fed composted manure compared to the DDGS corn-fed composted manure. The type of DDGS that feedlot operations purchase may be different, and in each case it is recommended that the manure be sampled and analyzed to take

into consideration the large variation in manure nutrient properties that can arise based on different feed sources. The bedding type can also affect the nutrient concentration and the subsequent decomposition and nutrient release from that manure. In this study, the DDGS wheat-fed manures were on wood chip bedding while the DDGS corn manures were on straw bedding. It is recommended that future trials with DDGS-fed cattle manure include field studies that compare different feed sources, bedding materials, and manure processing.

Land application of alfalfa pellets is a novel use for a product which has traditionally been used for livestock feed. In comparison to many cattle manures, the low C:N ratio, high degradability and overall uniformity of the alfalfa pellets makes it attractive as an organic amendment to be applied to degraded soils. Alfalfa pellets increased soil available N and grass biomass on the berm area of a disturbed degraded potash mine tailings pond site. Increase in plant biomass in the alfalfa pellet treatment is likely a result of the increase in soil available nitrogen, but may also be related to improved soil water status. More work is suggested to elucidate the effects of alfalfa amendment on soil physical properties like soil water infiltration, water storage capacity, and aggregation. Compared to alfalfa pellets, biochar amendment was not effective in improving plant growth and nutrition on the degraded soils. However, only one type of biochar was evaluated in this study, and, like for manures, the organic source and method of manufacturing of biochar can have large impacts on its behavior as a soil amendment. The evaluation of several biochars of differing source materials and manufacturing is recommended for future work.

The willow-based biochar did not have a significant effect on improving plant growth or fertilizer recovery of urea and triple superphosphate on the loamy textured Brown and Black Chernozem soils under controlled environment conditions. Biochar did significantly increase the

pH of the soil, in agreement with the results of other studies. The increase in pH may be a main factor in the enhanced nutrient holding capacity of biochar treated soils observed in other studies on acidic, tropical soils. However, Saskatchewan soils that typically have neutral to alkaline pH combined with a high clay and humus content will have a high colloidal reactive surface such that further enhancement by char addition may produce little benefit.

High rates of biochars (e.g. 100 t ha^{-1}) that have been used in other studies may not be feasible for use in agriculture on the prairies in terms of spreading over whole fields, as transportation and application costs will be high if the site of application is far from the char production facility. Special equipment or altering the physical form of the biochar may be required for successful biochar application to prairie soils, as the char was difficult to handle and apply. More research is required to determine the feasibility and effectiveness of adding low rates of biochar on a large field scale in temperate regions. These studies should be conducted using a variety of agricultural crops with different plant nutrition requirements and be conducted in nutrient and SOC poor soils to determine the fertilizer retention and recovery in field plots. Also, biochar from different feedstocks and created at different pyrolysis temperatures may have different effects on soil properties. Long term studies that are five years or longer on a variety of biochar types would determine the lasting effects of biochar and if the biochar can inhibit or slow down soil degradation and nutrient loss over time in prairie agricultural soils. The development of equipment or creating an easier handling form of the biochar, such as pellets, would make large-scale application more feasible.

Recommendations for future research include longer term field studies on a wide range of soils with DDGS-fed manures, plant residue pellets, and biochars originating from a number of different sources. Different combinations of organic materials such as alfalfa pellets used

together with biochar may be more suitable options for organic amendments added to degraded soils. Severely degraded sites in the prairies should be the focus of future studies to assess the effects on soil quality produced by biochar amendments over long term. Salt affected sites would be an option for future studies using alfalfa pellets and biochar.

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APPENDIX A: BEHAVIOR OF DDGS TRITICALE FRESH MANURE AND BARLEY-FED FRESH MANURE

Table A.1 Soil properties of initial soils used in the dried distillers' grains and solubles (DDGS)-fed cattle manure and control barley cattle manure growth chamber studies. Soil was collected in the spring of 2010. See Chapter 3 for methods of analysis.

Soil	NO_3	NH_4	PO_4	K	OC	pH
	---------- mg kg^{-1} ----------				%	
Black soil	9.6	6.0	10	584	6.9	7.0
Brown soil	4.3	2.8	17	411	2.0	7.5

Canola Biomass and Nutrient Concentration

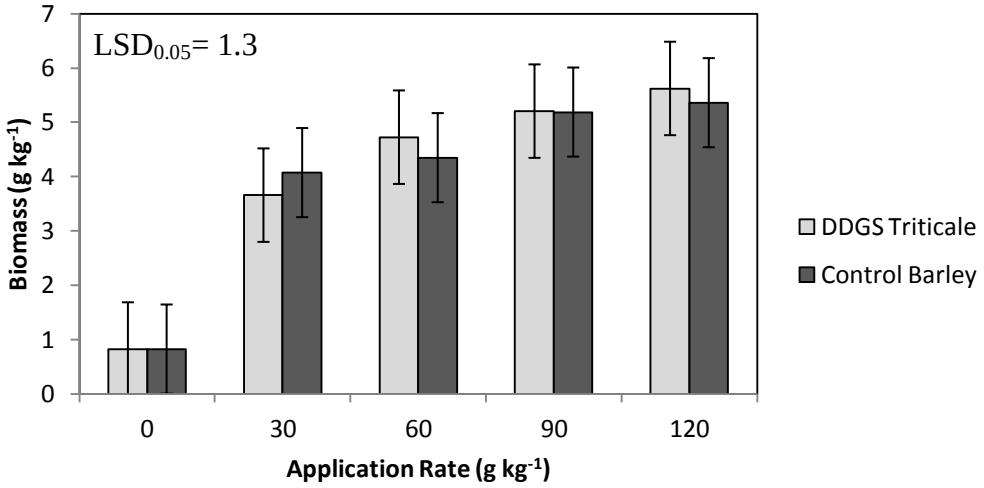

Figure A.1 Mean dry canola biomass (g kg^{-1} pot) for dried distillers' grains and solubles (DDGS) triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil. Bars represent standard error of the mean.

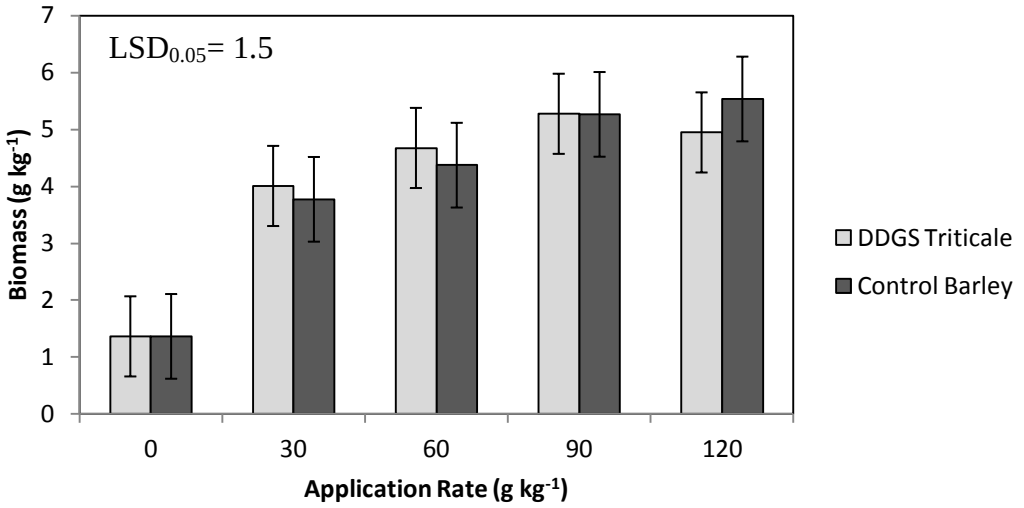

Figure A.2 Mean dry plant biomass for distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

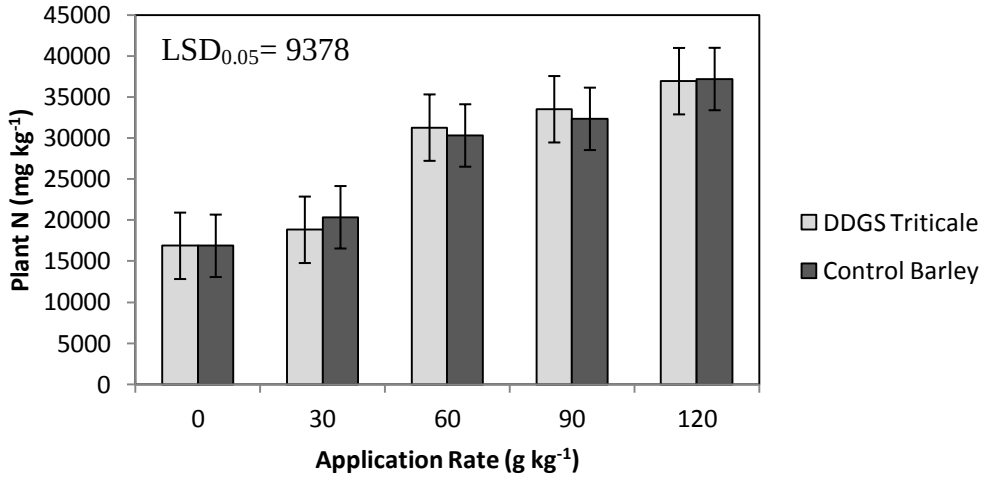

Figure A.3 Mean dry plant N concentration for DDGS triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil. Bars represent standard error of the mean.

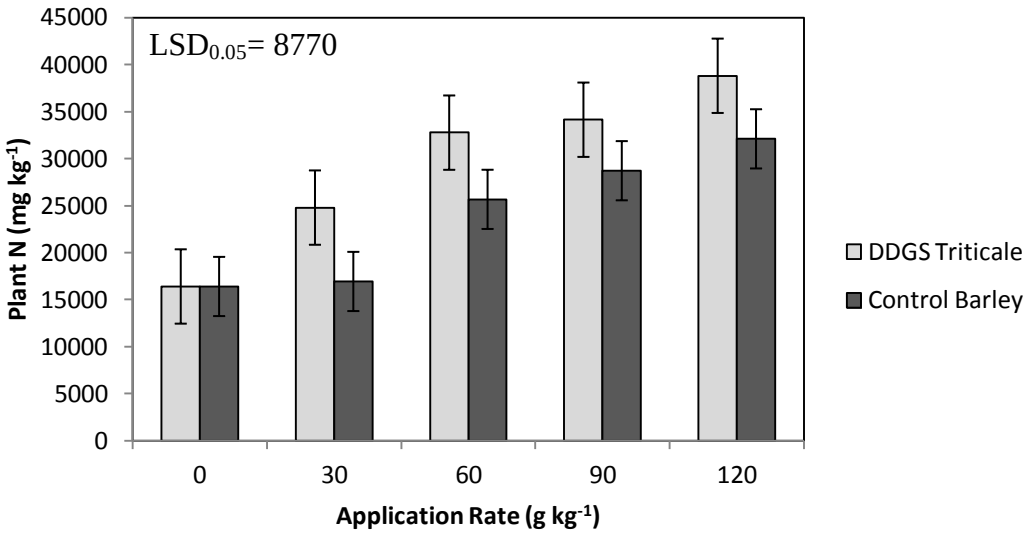

Figure A.4 Mean dry plant N concentration for distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

Table A.2 Mean N recovery for dried distillers' grains and solubles (DDGS) triticale manure and control barley manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

Manure Type	**Rate**	**N Recovery**	
		Brown Soil	**Black Soil**
	g kg^{-1}	---------- % ----------	
DDGS Triticale	30	18	25
	60	22	22
	90	18	17
	120	16	14
Control Barley	30	30	18
	60	25	19
	90	22	18
	120	20	17

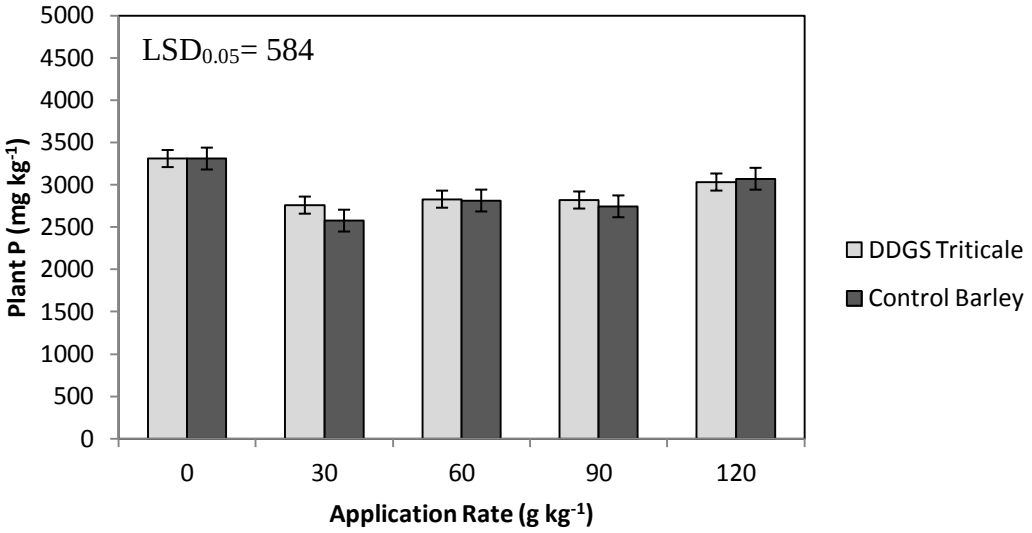

Figure A.5 Mean dry canola P concentration for distillers' grains and solubles (DDGS) triticale manure and control barley manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil. Bars represent standard error of the mean.

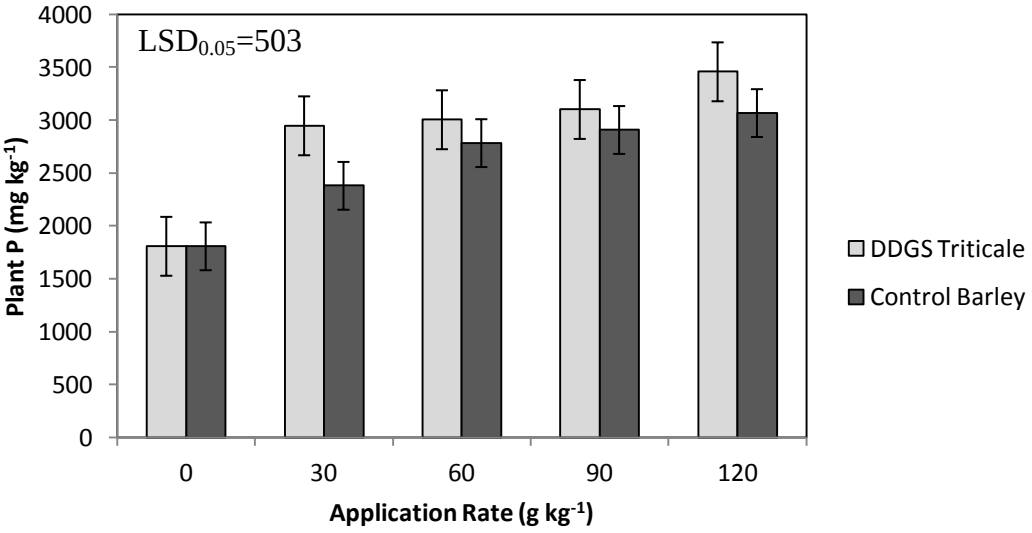

Figure A.6 Mean dry plant P concentration for DDGS triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

Table A.3 Mean dry plant K, S, Cu, and Zn concentration for dried distillers' grains and solubles (DDGS) triticale manure and control barley manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

Manure	Rate	K	S	Cu	Zn
	g kg^{-1}	---------- mg kg^{-1} ----------			
DDGS Triticale	0	30754.5	0.82	3.45	24.6
	30	45814.9	0.74	3.00	18.7
	60	59206.1	0.67	4.35	24.2
	90	63060.1	0.40	4.13	22.1
	120	62730.0	0.35	3.90	23.8
Control Barley	0	30754.5	0.82	3.45	24.6
	30	43042.5	0.70	2.90	19.2
	60	51928.2	0.70	3.30	25.3
	90	59676.4	0.66	4.80	22.6
	120	60852.2	0.64	4.20	26.1
$LSD_{(0.05)}$		10547.5	ns	ns	ns

Table A.4 Mean dry plant K, S, Cu, and Zn concentration for dried distillers' grains and solubles (DDGS) triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

Manure	Rate	K	S	Cu	Zn
	g kg^{-1}	---------- mg kg^{-1} ----------			
DDGS Triticale	0	39319.9	0.53	3.60	27.9
	30	52543.3	0.71	3.75	25.3
	60	60803.2	0.54	3.30	34.3
	90	60889.8	0.54	4.13	27.5
	120	62562.8	0.34	4.20	31.3
Control Barley	0	39319.9	0.53	3.60	9.33
	30	41357.7	0.71	2.70	6.86
	60	54410.1	0.94	2.70	4.12
	90	55631.7	0.82	3.60	5.85
	120	60203.5	0.42	4.13	7.98
$LSD_{(0.05)}$		11607.5	0.44	ns	ns

Soil nutrient concentration

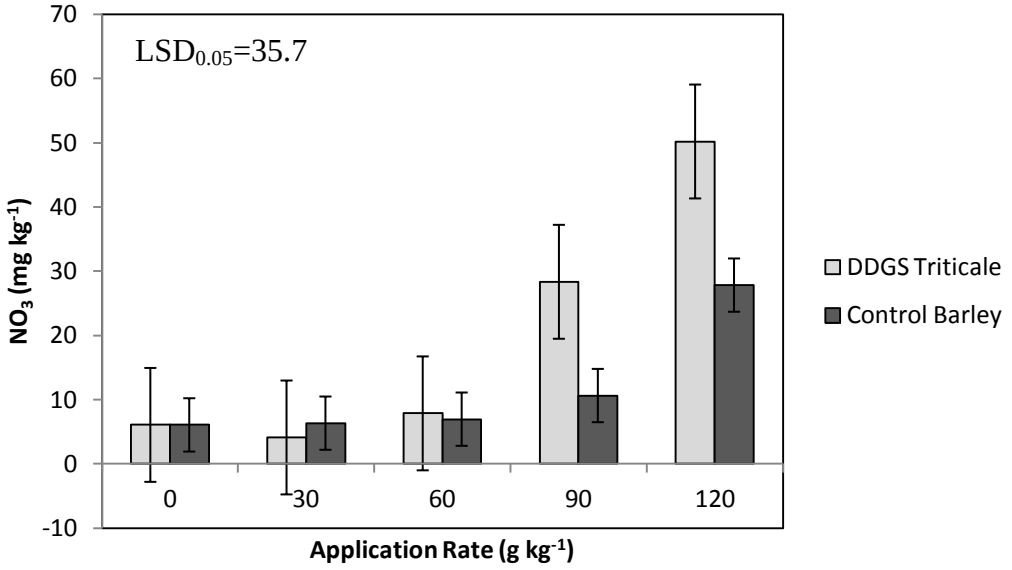

Figure A.7 Mean soil available NO_3 for distillers' grains and solubles (DDGS) triticale and control barley manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil. Bars represent standard error of the mean.

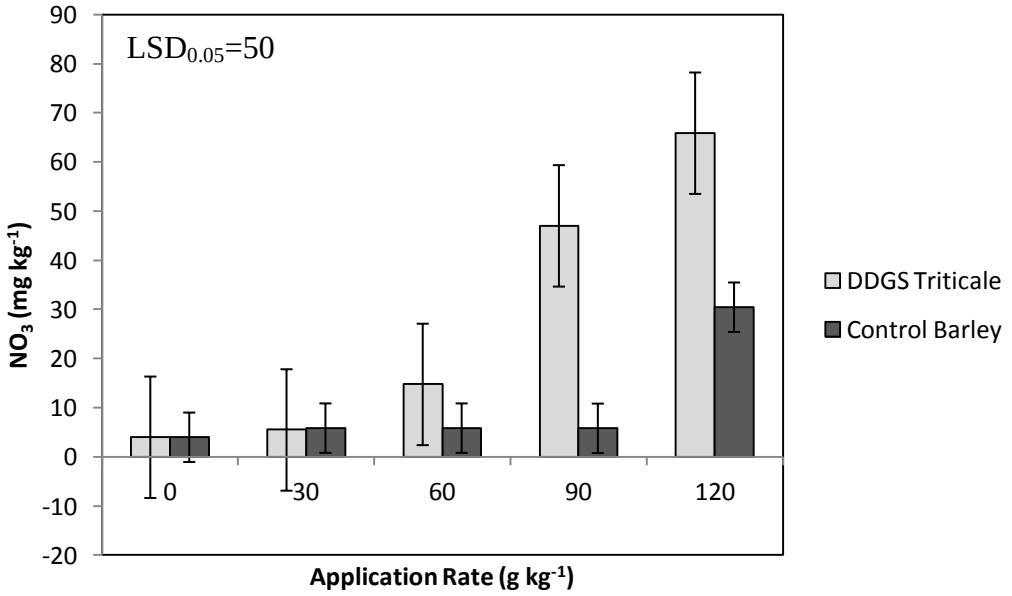

Figure A.8 Mean soil NO_3 concentration for DDGS triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

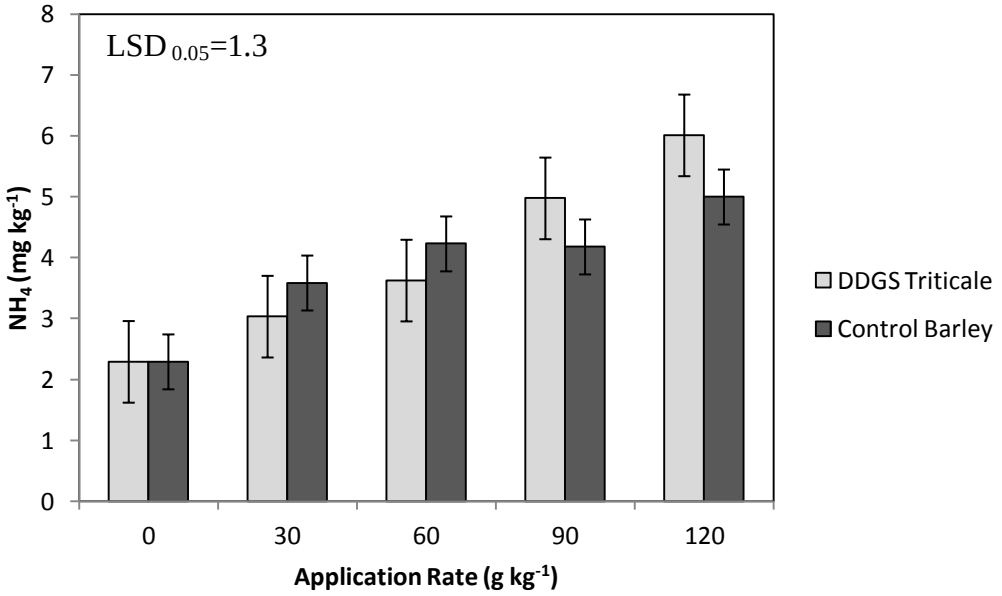

Figure A.9 Mean soil NH_4 concentration for dried distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil. Bars represent standard error of the mean.

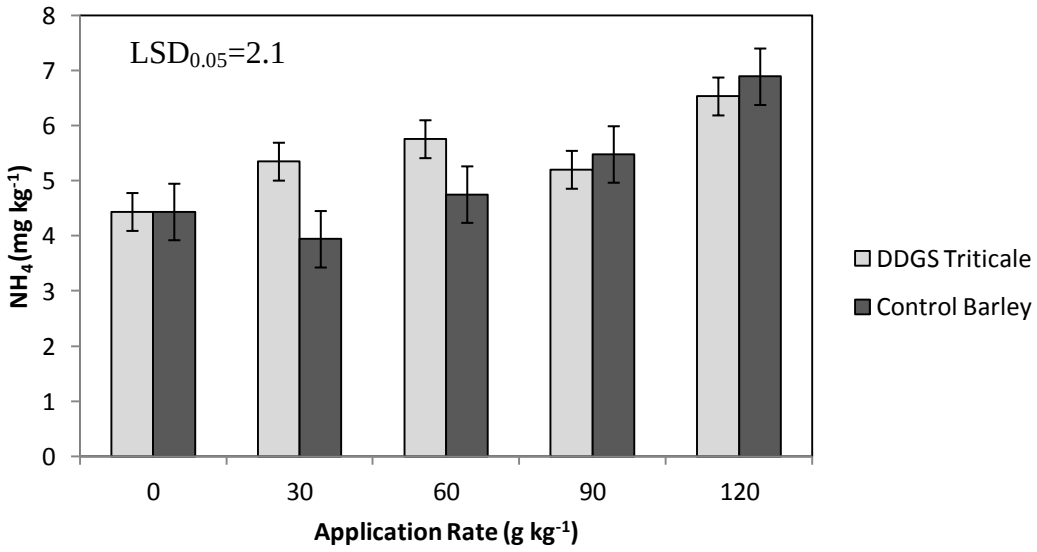

Figure A.10 Mean soil NH_4 for dried distillers' grains and solubles (DDGS) triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

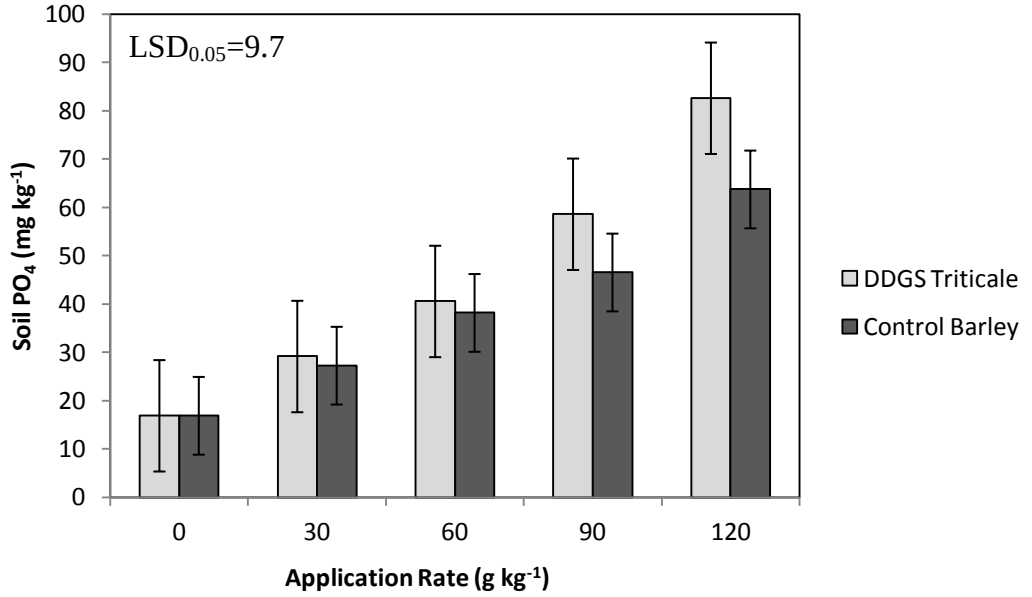

Figure A.11 Mean soil PO_4 concentration for dried distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg-1 rates on the Brown soil. Bars represent standard error of the mean.

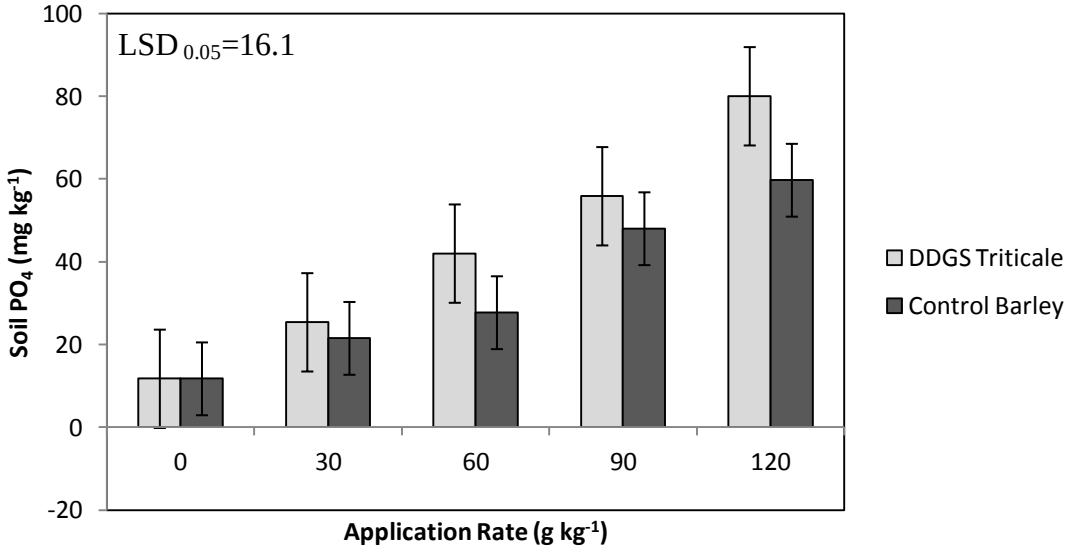

Figure A.12 Mean soil PO_4 concentration for dried distillers' grains and solubles (DDGS) triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil. Bars represent standard error of the mean.

Table A.5 Mean soil electrical conductivity (EC), pH, and soil organic carbon (SOC) concentration for dried distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

Manure	Rate	EC	pH	SOC
	g kg^{-1}	mS cm^{-1}		%
DDGS Triticale	0	0.49	7.5	1.4
	30	0.54	7.2	1.5
	60	0.63	7.0	3.0
	90	0.82	7.1	1.7
	120	1.22	7.1	1.9
Control Barley	0	0.49	7.5	1.4
	30	0.53	7.3	1.5
	60	0.58	7.4	1.6
	90	0.49	7.6	1.6
	120	0.86	7.6	1.8
$LSD_{(0.05)}$		0.30	0.4	ns

Table A.6 Mean soil electrical conductivity (EC), pH, and soil organic carbon (SOC) for DDGS triticale and control barley treatments at 0, 30, 60, 90, and 120 g kg^{-1} q rates on the Black soil.

Manure	Rate	EC	pH	SOC
	g kg^{-1}	mS cm^{-1}		%
Triticale	0	0.55	6.8	3.3
	30	0.63	7.0	3.4
	60	0.79	7.1	3.6
	90	1.12	7.1	3.6
	120	1.37	7.1	3.8
Control Barley	0	0.55	6.8	3.3
	30	0.52	7.4	3.3
	60	0.71	7.2	3.4
	90	0.89	7.1	3.6
	120	1.03	7.1	3.7
$LSD_{(0.05)}$		0.46	0.36	0.24

Table A.7 Mean soil available K, SO_4-S, Cu, and Zn concentration for dried distillers' grains and solubles (DDGS) triticale and barley control manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Brown soil.

Manure	Rate	K	SO_4-S	Cu	Zn
	g kg^{-1}	---------- mg kg^{-1} ----------			
DDGS Triticale	0	472.6	49.8	1.1	0.97
	30	459.3	50.3	1.0	0.76
	60	529.4	59.6	1.1	1.1
	90	633.3	65.0	1.2	1.6
	120	870.1	76.9	1.2	2.3
Control Barley	0	472.6	49.8	1.1	0.97
	30	529.1	42.2	0.93	1.1
	60	625.9	37.8	0.96	1.5
	90	619.7	51.0	1.0	1.7
	120	749.7	57.9	1.1	2.6
$LSD_{(0.05)}$		122.1	14.8	0.3	1.1

Table A.8 Mean soil available K, SO_4-S, Cu, and Zn for dried distillers' grains and solubles (DDGS) triticale and control barley manure treatments at 0, 30, 60, 90, and 120 g kg^{-1} rates on the Black soil.

Manure	Rate	K	SO_4-S	Cu	Zn
	g kg^{-1}	---------- mg kg^{-1} ----------			
DDGS Triticale	0	611.2	65.6	0.98	2.0
	30	667.7	66.7	1.2	2.5
	60	734.6	83.9	1.3	2.6
	90	889.2	94.4	1.5	2.9
	120	1014.6	97.9	1.5	3.0
Control Barley	0	611.2	65.6	0.98	2.0
	30	708.1	49.6	1.3	1.7
	60	704.2	54.4	1.2	2.2
	90	788.1	72.9	1.2	3.0
	120	841.9	72.8	1.2	3.0
$LSD_{(0.05)}$		85.7	25.7	0.19	0.6

APPENDIX B: FIELD DATA

Table B.1 Properties of oat hull-based biochar used in field study. Data analysis from ALS Laboratories.

Oat Hull Biochar Property	Concentration
	%
Moisture	0.1
Total N	2.4
P	2.5
K	1.5
S	0.1
Na	0.8
Ca	4.6
Mg	0.2
Cu	0.0
Fe	0.4
Mn	0.0
Zn	0.0

Table B.2 Initial soil properties in the fall of 2009 in the control plots for the Degraded area and the Berm area taken at two depth ranges.

Plot Area	Block	Depth	pH	EC	OC
		cm		mS cm^{-1}	%
Degraded Area	1	0-30	7.68	0.099	0.491
		30-60	7.67	0.107	0.254
	2	0-30	7.31	0.128	0.767
		30-60	7.37	0.098	0.363
	3	0-30	7.3	0.108	0.693
		30-60	7.68	0.163	0.258
	4	0-30	7.63	0.119	1.146
		30-60	7.53	0.093	0.638
Berm Area	1	0-30	7.72	0.425	0.366
		30-60	7.44	1.09	0.310
	2	0-30	8.27	1.13	0.475
		30-60	7.84	2.43	0.350
	3	0-30	8.32	0.39	0.422
		30-60	8.09	0.687	0.307
	4	0-30	7.87	0.581	0.400
		30-60	7.44	1.95	0.281

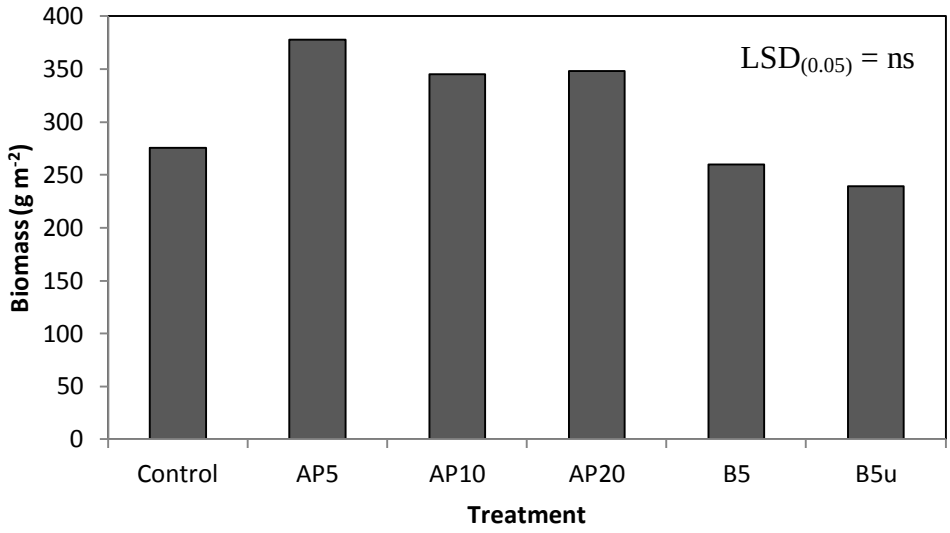

Figure B.1 Plant biomass on the Degraded are in the fall of 2010 for six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}).

Table B.3 Initial soil nutrient concentrations in the fall of 2009 in the control plots for the Degraded area and the Berm area taken at two depth ranges.

Plot Area	Block	Depth	PO_4-P	K	NO_3-N	NH_4-N
		cm	---------- mg kg^{-1} ----------			
Degraded Area	1	0-30	1.82	163.40	3.70	4.05
		30-60	1.07	113.00	3.27	3.74
	2	0-30	2.45	235.00	3.87	4.47
		30-60	1.30	117.50	3.14	4.40
	3	0-30	3.01	163.40	3.91	5.37
		30-60	2.16	73.90	3.55	4.83
	4	0-30	4.18	242.70	3.89	5.28
		30-60	3.20	128.70	3.82	4.84
Berm Area	1	0-30	0.39	402.10	3.64	5.03
		30-60	0.61	385.50	2.63	5.29
	2	0-30	1.34	767.90	2.69	4.91
		30-60	0.51	593.70	2.51	5.23
	3	0-30	0.32	346.40	3.66	5.78
		30-60	0.35	165.80	3.21	6.41
	4	0-30	0.41	326.70	3.49	6.45
		30-60	0.53	188.90	3.40	7.80

Table B.4 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Degraded area for all six treatments.

(AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	pH	EC	CEC	OC
		cm		mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control	15-30	6.3	0.11	8.9	0.61
2	AP5		7.6	0.14	9.0	0.91
3	AP10		7.7	0.14	9.7	0.81
4	AP20		7.7	0.16	9.2	0.78
5	B5		7.6	0.15	7.8	0.62
6	B5u		7.6	0.26	9.0	0.86
1	Control	30-60	6.3	0.09	7.2	0.35
2	AP5		7.7	0.12	7.5	0.52
3	AP10		7.7	0.12	7.4	0.57
4	AP20		7.7	0.13	7.5	0.48
5	B5		7.6	0.13	6.8	0.37
6	B5u		7.6	0.13	7.9	0.55

Table B.5 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the fall of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	pH	EC	CEC	OC
		cm		mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control	15-30	6.1	0.1	8.5	0.44
2	AP5		7.6	0.1	9.3	0.84
3	AP10		7.6	0.1	9.3	0.98
4	AP20		7.5	0.1	8.8	0.76
5	B5		7.5	0.1	8.6	0.59
6	B5u		7.5	0.2	9.1	0.78
1	Control	30-60	6.1	0.1	7.1	0.37
2	AP5		7.6	0.1	7.5	0.54
3	AP10		7.6	0.1	8.0	0.57
4	AP20		7.5	0.1	7.9	0.50
5	B5		7.5	0.1	7.4	0.39
6	B5u		7.7	0.1	7.5	0.51

Table B.6 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha^{-1}; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		cm	---------- mg kg^{-1} ----------				
1	Control	15-30	2.03	3.61	0.49	3.07	178.5
2	AP5		2.49	4.83	0.50	3.72	256.3
3	AP10		3.32	4.21	0.79	3.51	274.8
4	AP20		2.68	4.82	0.66	4.05	228.2
5	B5		3.14	4.82	0.15	5.25	203.0
6	B5u		4.59	4.76	1.39	4.12	253.6
1	Control	30-60	0.73	2.43	0.23	2.31	138.0
2	AP5		0.65	3.43	0.37	3.14	167.5
3	AP10		1.26	3.51	0.36	2.91	175.1
4	AP20		0.64	3.65	0.41	2.68	150.8
5	B5		0.87	3.08	0.03	3.55	133.6
6	B5u		1.05	3.27	0.81	3.05	187.1

Table B.7 Soil NO_3, NH_4, PO_4, SO_4, and K (Kelowna extractable) concentration on the Degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha^{-1}; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the fall of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		cm		- - - - - - - - - - mg kg^{-1} - - - - - - - - - -			
1	Control	15-30	0.89	1.21	2.32	1.87	147.2
2	AP5		1.57	1.63	3.34	1.44	213.5
3	AP10		1.34	0.68	3.54	0.94	283.5
4	AP20		1.36	1.74	2.64	1.56	233.6
5	B5		1.91	2.13	4.09	1.97	196.2
6	B5u		1.91	2.01	2.73	1.78	232.9
1	Control	30-60	0.47	1.13	1.73	1.19	90.1
2	AP5		0.75	1.39	2.33	1.19	139.9
3	AP10		0.68	1.38	2.70	1.02	157.7
4	AP20		1.05	1.63	2.09	1.47	135.1
5	B5		1.49	1.78	2.63	2.21	103.0
6	B5u		0.69	1.57	2.73	1.89	136.7

Table B.8 Mean cations and the calculated soil cation exchange capacity (CEC) on the degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha^{-1}; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring of 2010 at the 0-15, 15-30, and 30-60 cm depths.

Treatment	Depth	Ca	Mg	Na	K	CEC
	cm	---------- cmol kg^{-1} ----------				
Control	0-15	7.3	1.1	0.06	0.76	9.2
	15-30	5.2	1.2	0.09	0.46	6.9
	30-60	4.1	1.12	0.14	0.35	5.8
AP5	0-15	7.8	1.6	0.06	1.0	10.5
	15-30	6.7	1.6	0.09	0.66	9.0
	30-60	5.6	1.6	0.09	0.43	7.7
AP10	0-15	7.6	1.6	0.08	1.1	10.4
	15-30	6.9	1.6	0.07	0.70	9.3
	30-60	5.3	1.6	0.08	0.45	7.5
AP20	0-15	7.5	1.5	0.07	1.1	10.2
	15-30	6.7	1.5	0.09	0.59	8.9
	30-60	5.7	1.4	0.10	0.39	7.6
B5	0-15	7.3	1.5	0.09	1.2	10.1
	15-30	5.6	1.5	0.08	0.52	7.6
	30-60	5.1	1.5	0.11	0.34	7.0
B5u	0-15	7.4	1.5	0.10	1.1	10.1
	15-30	6.3	1.5	0.09	0.65	8.5
	30-60	5.8	1.4	0.11	0.48	7.8
					$LSD_{(0.05)}$	3.4

Table B.9 Mean cations and the calculated soil cation exchange capacity (CEC) on the degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha^{-1}; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the fall of 2010 at the 0-15, 15-30, and 30-60 cm depths.

Treatment	Depth	Ca	K	Na	Mg	CEC
	cm	---------- $cmol_c\ kg^{-1}$ ----------				
	0-15	7.1	0.65	0.03	1.5	9.3
	15-30	6.4	0.41	0.04	1.6	8.5
Control	30-60	5.0	0.28	0.11	1.8	7.1
	0-15	8.0	0.75	0.02	1.6	10.3
	15-30	7.0	0.53	0.03	1.7	9.3
AP5	30-60	5.5	0.32	0.07	1.6	7.5
	0-15	8.1	1.0	0.06	1.7	10.9
	15-30	7.0	0.61	0.05	1.7	9.4
AP10	30-60	5.9	0.53	0.04	1.8	8.2
	0-15	7.7	0.85	0.03	1.6	10.2
	15-30	6.6	0.47	0.03	1.7	8.8
AP20	30-60	6.0	0.28	0.03	1.6	7.9
	0-15	8.0	0.67	0.05	1.5	10.2
	15-30	6.6	0.44	0.04	1.5	8.6
B5	30-60	5.6	0.26	0.05	1.6	7.5
	0-15	8.0	0.76	0.02	1.7	10.5
	15-30	7.0	0.53	0.03	1.6	9.1
B5u	30-60	5.6	0.32	0.05	1.5	7.5
					$LSD_{0.05}$	2.5

Table B.10 Mean soil Cu and Zn concentration on the degraded area for all six treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; AP10= alfalfa pellets at 10 t ha^{-1}; AP20=alfalfa pellets at 20 t ha^{-1}; B5=biochar at 5 t ha^{-1}; B5u=biochar at 5 t ha^{-1} plus urea at 50 kg N ha^{-1}). Soil samples were taken in the spring and fall of 2010 at the 0-15, 15-30, and 30-60 cm depths.

Treatment	Depth	Spring 2010		Fall 2010	
		Cu	Zn	Cu	Zn
	cm	---------- mg kg^{-1} ----------			
	0-15	0.26	0.61	0.48	0.70
	15-30	0.24	0.25	0.35	0.47
Control	30-60	0.24	0.13	0.64	0.23
	0-15	0.34	0.90	0.33	0.84
	15-30	0.26	0.35	0.32	0.29
AP5	30-60	0.22	0.17	0.40	0.21
	0-15	0.35	0.87	0.43	0.12
	15-30	0.30	0.50	0.37	0.40
AP10	30-60	0.31	0.31	0.44	0.21
	0-15	0.32	0.81	0.38	0.72
	15-30	0.31	0.31	0.27	0.25
AP20	30-60	0.29	0.23	0.53	0.20
	0-15	0.34	0.72	0.37	0.62
	15-30	0.28	0.20	0.35	0.36
B5	30-60	0.28	0.13	0.35	0.26
	0-15	0.33	0.94	0.43	0.85
	15-30	0.26	0.38	0.30	0.26
B5u	30-60	0.30	0.21	0.40	0.18
$LSD_{0.05}$		ns	1.40	ns	1.30

Table B.11 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the spring of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	pH	EC	CEC	OC
		cm		mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control		8.2	0.3	28.3	0.61
2	AP5	15-30	8.3	0.3	3.0.5	0.57
5	B5		8.2	0.5	31.8	0.62
1	Control		7.8	0.2	29.1	0.57
2	AP5	30-60	7.7	0.4	28.1	0.57
5	B5		7.7	0.5	28.7	0.57

Table B.12 Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and organic carbon (OC) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the fall of 2010 at the 15-30 and 30-60 cm depths.

Trt. No.	Trt. ID	Depth	pH	EC	CEC	OC
		cm		mS cm^{-1}	$cmol_c$ kg^{-1}	%
1	Control		8.2	0.5	28.6	0.57
2	AP5	15-30	8.2	0.4	27.7	0.49
5	B5		8.3	0.6	30.6	0.50
1	Control		8.0	0.9	30.7	0.45
2	AP5	30-60	8.2	0.7	30.9	0.43
5	B5		7.8	1.7	32.3	0.52

Table B.13 Soil NO_3-N, NH_4-N, PO_4-P, SO_4-S, and K (Kelowna extractable) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the spring of 2010 at the 15-30 and 30-60 cm depth.

Trt. No.	Trt. ID	Depth	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		cm	---------- mg kg^{-1} ----------				
1	Control		0.81	3.65	0.01	24.9	446.6
2	AP5	15-30	1.12	3.74	0.01	19.5	486.4
5	B5		0.83	3.46	0.01	26.1	634.2
1	Control		0.86	4.47	0.01	93.4	310.6
2	AP5	30-60	1.00	3.69	0.01	100.2	390.0
5	B5		0.83	3.42	0.01	121.8	446.2

Table B.14 Soil NO_3-N, NH_4-N, PO_4-P, SO_4-S, and K (Kelowna extractable) concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the fall of 2010 at the 15-30 and 30-60 cm depth.

Trt. No.	Trt. ID	Depth	NO_3–N	NH_4–N	PO_4–P	SO_4–S	K
		cm	---------- mg kg^{-1} ----------				
1	Control	15-30	0.15	2.45	4.83	22.6	485.0
2	AP5		0.22	2.11	5.54	17.4	487.2
5	B5		0.21	2.46	4.15	26.0	532.4
1	Control	30-60	0.14	2.59	6.01	103.1	450.3
2	AP5		0.15	2.80	5.69	60.4	457.5
5	B5		0.10	3.11	5.89	176.4	575.0

Table B.15 Mean soil cation concentrations and soil cation exchange capacity (CEC) on the Berm area for alfalfa (5 t ha^{-1}), biochar (5 t ha^{-1}) and control at three depth ranges in the spring of 2010.

Treatment	Depth	Ca	Mg	Na	K	CEC
	cm	---------- $cmol_c\ kg^{-1}$ ----------				
1 - Control	0-15	20.2	1.8	0.80	1.4	24.2
	15-30	20.9	2.4	3.0	1.1	27.4
	30-60	23.0	3.6	2.4	0.80	29.8
2 - Alfalfa	0-15	20.1	2.1	1.5	1.1	24.8
	15-30	21.9	2.7	3.7	1.3	29.6
	30-60	22.6	3.5	1.2	1.0	28.3
5 - Biochar	0-15	20.3	2.0	1.4	1.7	25.3
	15-30	21.8	3.0	3.8	1.6	30.2
	30-60	23.1	3.8	0.72	1.1	28.8
					$LSD_{(0.05)}$	ns

Table B.16 Soil cation exchange capacity (CEC) as a total of mean base cations on the Berm area for alfalfa (5 t ha^{-1}), biochar (5 t ha^{-1}) and control at three depth ranges in the fall of 2010.

Treatment	Depth	Ca	K	Na	Mg	CEC
	cm	---------- $cmol_c\ kg^{-1}$ ----------				
Control	0-15	20.3	1.2	0.65	2.0	24.2
	15-30	22.9	1.1	2.2	2.4	28.6
	30-60	22.5	0.92	3.7	3.5	30.7
Alfalfa	0-15	22.3	1.1	0.60	2.1	26.1
	15-30	22.0	1.2	1.6	2.9	27.7
	30-60	23.3	0.96	3.3	3.3	30.9
Biochar	0-15	21.2	1.3	1.3	2.1	25.9
	15-30	23.6	1.4	3.1	2.6	30.6
	30-60	23.3	1.0	4.5	3.4	32.3
$LSD_{(0.05)}$						ns

Table B.17 Mean soil Cu and Zn concentration on the Berm for all three treatments. (AP5=alfalfa pellets at 5 t ha^{-1}; B5=biochar at 5 t ha^{-1}). Soil samples were taken in the spring and fall of 2010 at the 0-15, 15-30, and 30-60 cm depths.

Treatment	Depth	Spring 2010		Fall 2010	
		Cu	Zn	Cu	Zn
	cm	---------- mg kg^{-1} ----------			
Control	0-15	0.89	0.71	0.91	0.52
	15-30	1.24	0.86	1.10	0.59
	30-60	1.37	0.93	1.29	0.70
AP5	0-15	0.95	0.70	1.10	0.63
	15-30	1.24	0.835	1.16	0.46
	30-60	1.38	1.155	1.43	0.68
B5	0-15	1.05	0.78	0.94	0.52
	15-30	1.37	0.95	1.28	0.65
	30-60	1.32	1.32	1.61	0.96
$LSD_{0.05}$		0.62	ns	ns	ns

Table B.18 Plant species and plant growth observations (fall of 2010) for treatments: control, alfalfa at 5, 10, and 20 t ha^{-1}, biochar at 5 t ha^{-1}, and biochar (5 t ha^{-1}) + urea. Plots 1 to 24 were on the Degraded area while plots 25 to 36 were on the Berm area.

Plot	Treatment	Plant Species	Notes
1	Biochar	hairy golden aster, wormwood, alfalfa	low plant growth, mostly forbs
2	Biochar+Urea	tall Wheatgrass, alfalfa, hairy golden aster	
3	Alfalfa-5	tall Wheatgrass, alfalfa, wormwood	
4	Alfalfa-20	tall wheatgrass	tall, dense vegetation
5	Control	alfalfa wormwood	low growth, mostly forbs
6	Alfalfa-10	smooth brome	
7	Biochar	tall wheatgrass	denser grass
8	Alfalfa-20	alfalfa, hairy golden aster	low growth
9	Control	tall wheatgrass, hairy golden aster	
10	Alfalfa-10	alfalfa, unknown grass	low growth
11	Alfalfa-5	smooth brome, many flowered aster, tall wheatgrass	one tall clover plant
12	Biochar+Urea		
13	Alfalfa-20	smooth brome, tall wheatgrass	sparse vegetation
14	Control	tall wheatgrass, wormwood, hairy golden aster	Good growth
15	Biochar+Urea	alfalfa	low growth
16	Biochar	smooth brome, unknown grass, alfalfa	
17	Alfalfa-5	alfalfa, tall wheatgrass	sparse grass
18	Alfalfa-10	hairy golden aster, alfalfa tall wheatgrass, many flowered aster	
19	Control	alfalfa, hairy golden aster	low growth
20	Biochar	alfalfa	sparse vegetation
21	Alfalfa-5	clover, wormwood, tall wheatgrass	one tall clover plant
22	Alfalfa-20	tall wheatgrass, brome, alfalfa	dense tall wheatgrass
23	Biochar+Urea	hairy golden aster, brome	
24	Alfalfa-10	tall wheatgrass, hairy golden aster, clover	dense vegetation
25	Biochar	tall wheatgrass, alfalfa	

Table B.19 Plant species and plant growth observations (fall of 2010) on the Berm area for treatments: control, alfalfa pellets (alfalfa) at 5 t ha^{-1}, and biochar at 5 t ha^{-1}.

Plot	Treatment	Plant Species	Notes
26	Control	tall wheatgrass, alfalfa	
27	Alfalfa	tall wheatgrass, alfalfa	
28	Control	tall wheatgrass, alfalfa	
29	Alfalfa	tall wheatgrass, alfalfa, foxtail barley	
30	Biochar	tall wheatgrass, alfalfa, foxtail barley	
31	Control	tall wheatgrass, alfalfa	
32	Biochar	tall wheatgrass, alfalfa	
33	Alfalfa	tall wheatgrass, alfalfa, foxtail barley	
34	Biochar	tall wheatgrass, alfalfa	
35	Alfalfa	tall wheatgrass, alfalfa, foxtail barley	
36	Control	tall wheatgrass, alfalfa	mostly alfalfa

Figure B.2 Adding amendments in the spring of 2010 by hand spreading and raking into the tilled surface soil.

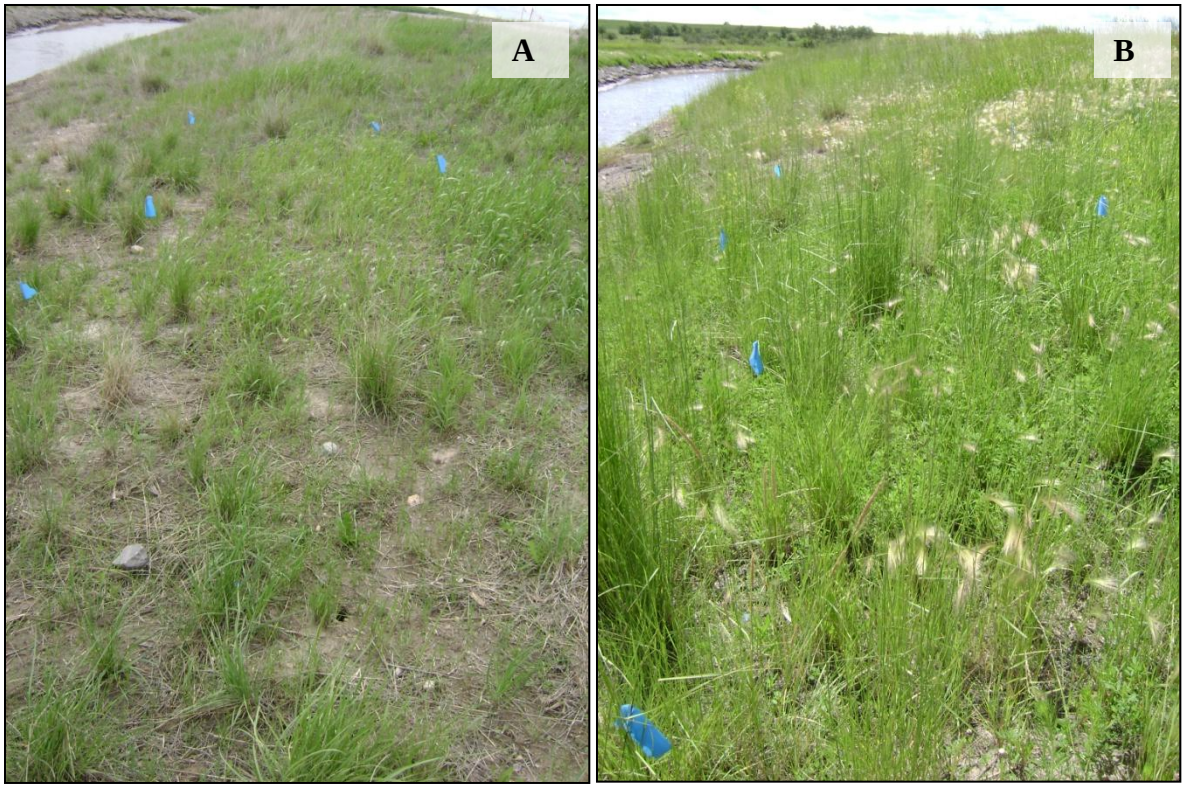

Figure B.3 Site visit on June 2010 (A) and site visit in July 2010 (B) showed Berm area that was vegetating unevenly with a variety of species. Both photos are facing west.

Figure B.4 Site visit in June 2010 showed plots on the Degraded area to show differences, although there was a diversity of plant species (facing southwest).

Figure B.5 Site visit in July 2010 also showed uneven growth and a variety of plant species, both grasses and forbs, growing on Degraded area (facing south).

Figure B.6 A diversity of plant species growing on the Berm area at harvest in August 2010 (facing southeast).

Figure B.7 A diversity of plant species growing on the Degraded area at harvest time in August 2010.

Figure B.8 Harvesting plant material in August 2010 by cutting about 2 to 5 cm above ground level from a square meter area then bagging the material for each plot.

APPENDIX C: BIOCHAR GROWTH CHAMBER STUDY

Figure C.1 Harvesting stage of canola for the willow biochar pot study.

Table C.1 Mean canola Cu and Zn concentration for willow biochar at 5, 10, and 20 t ha-1, biochar (10 t ha-1) plus fertilizer, fertilizer and control treatments on the Brown soil.

Treatment	Biochar Rate	Zn	Cu
	t ha^{-1}	---------- mg kg^{-1} --------	
Control	0	24.6	3.5
Biochar	5	24.9	3.4
Biochar	10	22.4	3.9
Biochar	20	21.8	3.9
Biochar + Fertilizer	10	11.9	4.7
Fertilizer	0	12.7	4.1
$LSD_{(0.05)}$		10.5	ns

Table C.2 Mean canola Cu and Zn concentration for willow biochar at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Black soil.

Treatment	Biochar Rate	Zn	Cu
	t ha^{-1}	---------- mg kg^{-1} --------	
Control	0	27.9	3.6
Biochar	5	25.9	2.7
Biochar	10	23.4	3.2
Biochar	20	21.6	2.7
Biochar + Fertilizer	10	21.7	3.0
Fertilizer	0	27.4	5.7
$LSD_{(0.05)}$		ns	ns

Table C.3 Mean electrical conductivity (EC) and soil extractable Cu and Zn for biochar at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Brown soil.

Treatment	Biochar Rate	EC	Zn	Cu
	t ha^{-1}	mS cm^{-1}	---------- mg kg^{-1} ------	
Control	0	0.49	0.97	1.06
Biochar	5	0.45	4.19	0.90
Biochar	10	0.47	0.69	0.91
Biochar	20	0.46	0.58	0.92
Biochar + Fertilizer	10	0.40	0.64	0.99
Fertilizer	0	0.43	0.69	0.92
$LSD_{(0.05)}$		ns	ns	ns

Table C.4 Mean electrical conductivity (EC) and soil extractable Cu and Zn for willow biochar at 5, 10, and 20 t ha^{-1}, biochar (10 t ha^{-1}) plus fertilizer, fertilizer and control treatments on the Black soil.

Treatment	Biochar Rate	EC	Zn	Cu
	t ha^{-1}	mS cm^{-1}	---------- mg kg^{-1} ------	
Control	0	0.55	1.9	0.98
Biochar	5	0.56	1.6	1.01
Biochar	10	0.51	1.7	1.00
Biochar	20	0.61	1.9	0.95
Biochar + Fertilizer	10	0.49	1.9	1.00
Fertilizer	0	0.50	2.8	0.98
$LSD_{(0.05)}$		ns	0.47	ns