Effect of organic soil amendments on carbon dynamics and productivity in saline and non-saline soils from Saskatchewan and Nigeria

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ABSTRACT

Carbon storage in salt affected and low organic matter (<3%) soils may be enhanced through the use of high carbon content soil amendments along with growing salt-adapted crops. To investigate and compare carbon dynamics in low organic matter, saline and non-saline soils, a field experiment was established in the Brown soil zone in southern Saskatchewan in the spring of 2017 to assess effects of three added amendments (leonardite, humic acid, and composted steer manure) and three crops seeded that spring (AC Saltlander green wheatgrass, Invigor canola and Tully Champion willow) on total soil organic carbon, carbon fractions and crop growth via randomized complete block design (RCBD) experiments conducted in saline and non-saline areas of a farm field. The soil samples collected in the spring of 2017 prior to establishment of treatments revealed similar organic carbon levels of 1.47% and 1.23% in the saline and non-saline sites, respectively. Soil samples taken in the fall of 2017 and spring of 2018 revealed that soils from the saline site amended with leonardite had significantly more light fraction organic carbon compared to unamended control plots. Furthermore, the total soil organic carbon mass in the 0-10 cm depth was significantly greater by 23% and 16% in the leonardite amended treatment compared to all other treatments in the non-saline and saline soils, respectively. The green wheatgrass had the largest impact on soil carbon fractions measured, increasing the concentration of water extractable organic carbon by 15mg C kg^{-1} in the plots at the saline site. After one year, the total soil organic carbon in the 0-10 cm depth in the non-saline site treatments seeded to green wheatgrass was significantly higher than that found under canola and willow. Biomass production in the 2017 growing season was less on the saline than the non-saline soil, and the organic amendments did not significantly increase growth of any of the crops.

To better understand the effect of the three amendments on short-term carbon turnover, a 29-day microbial respiration experiment was conducted using soils collected within 10 m of the two field sites. A low organic matter (0.61%) degraded tropical soil collected from an agricultural field in Ogbomosho, Nigeria was included in the incubation for comparison purposes. The saline soil had significantly higher cumulative CO_2-C production compared to the non-saline and Nigerian soil, but organic amendment treatment had no influence on CO_2-C production in the saline soil itself. In the non-saline and Ogbomosho soil, the composted steer manure produced significantly greater cumulative CO_2-C emissions compared to the control and leonardite and humic acid treatments, respectively. The results suggest saline soils from southern Saskatchewan may not be lower in soil organic carbon content than non-saline comparable, and that under ideal moisture conditions, short-term carbon dioxide release through microbial respiration may be the same or higher than in non-saline soils due to an abundance of labile soluble organic carbon. Seeding saline and non-saline areas to salt tolerant green wheatgrass and applying 10 tonnes ha^{-1} of a high carbon content amendment like leonardite appears to be a relatively effective means of increasing the soil organic carbon content of the surface soil over a short time period.

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DEDICATION

I would like to dedicate this work to my parents, Rob and Michele, who have continually supported and helped to guide me down the varied paths of life. You have both made many things possible in my life and have encouraged me to pursue all the things I hope to accomplish. I would not be where I am, nor who I am today without you.

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LIST OF ABBREVIATIONS

Humic acid	HA
Leonardite	LEO
Composted steer manure	CSM
Carbon	C
Organic carbon	OC
Water extractable organic carbon	WEOC
Light fraction organic carbon	LFOC
Soil organic carbon	SOC
Electrical conductivity of saturated paste	EC_e
Sodium adsorption ratio	SAR
Exchangeable sodium percentage	ESP
Sodium	Na
Organic matter	OM
Soil organic matter	SOM
Nitrogen	N
Phosphorus	P
Potassium	K
Humic substances	HS
Microbial biomass carbon	MB-C
Metabolic quotient	qCO_2
Dissolved organic carbon	DOC
Total organic carbon	TOC
Gigatons	Gt
Electrical conductivity	EC
Dissolved organic matter	DOM
Calcium	Ca
Soil microbial biomass	SMB
Carbon dioxide	CO_2
Cattle manure	CM
Magnesium	Mg
Poultry manure	PM
Sulfur	S
Iron	Fe
Manganese	Mn
Boron	B
Control	CNTL
Mono Ammonium Phosphate	MAP
Ogbomosho	OG
Field capacity	FC
Chloroform	$CHCL_3$
Potassium sulfate	K_2SO_4

Nitrate	NO_3-N
Sulfate	SO_4-S
Randomized complete block design	RCBD
Analysis of variance	ANOVA

1. Introduction

Soil organic matter is the foundation of soil fertility, soil quality and soil health. It improves soil structure and aggregation, stores and releases essential plant nutrients, increases cation exchange capacity, and supports microbial community diversity and activity. Much (~58%) of the soil organic matter is comprised of carbon (C), such that soil organic matter is a significant component of global C stocks. The soil organic carbon (SOC) content of a soil is derived from a balance of inputs (plant litter, soil amendments) and losses (carbon dioxide (CO_2) emissions) of carbon. Soils in temperate regions that undergo conversion from natural vegetation to agricultural use can experience a reduction of up to 60% of the initial SOC (Lal, 2004).

Carbon sequestration in soil is the transfer of atmospheric CO_2 into secure pools where it is not immediately re-emitted, thereby causing a net increase in soil organic carbon stocks (Lal, 2004). There are numerous strategies that can increase SOC stocks in agricultural soils including no-till farming, proper nutrient management, improving crop growth on marginal lands, manuring, and fertilization with organic and inorganic amendments (Powlson et al., 2012; Lal, 2004; Bruce et al., 1999). These strategies can either directly or indirectly promote growth and addition of high amounts of biomass carbon and also enhance microbial activity and diversity while reducing C losses via erosion and the breakdown of aggregates (Lal, 2004). Increased SOC stocks are related to enhanced crop yield, especially in SOC deficient soils, and are closely linked with soil health and productivity (Lal, 2004; Bruce et al., 1999). For example, an increase of 1 t of soil C in degraded soil is reported to improve wheat yield by 20-40 kg ha^{-1} and maize yield by 10-20 kg ha^{-1} (Lal, 2004).

Salt affected soils in the Canadian prairies often occupy toe slope positions where the water table is close to the soil surface and evaporation exceeds infiltration. Classified as saline, sodic, or saline-sodic based on the electrical conductivity (EC) of saturated extract (EC_e), sodium adsorption ratio, and exchangeable sodium percentage, these salt-affected soils typically have limited crop growth as a consequence of adverse soil physical, chemical, and biological conditions (Amini et al., 2016). Saline soils directly affect plant growth through increased osmotic suction holding back water while sodic soil conditions often indirectly affect plant growth through poor soil physical structure which alters water, air and nutrient supplies (Wong et al., 2010). Reduced plant growth could result in depleted SOC content in saline soils, but reduced decomposition rates could also contribute to greater sequestration potential. However, little is known about carbon storage, microbial decomposition rates and turnover in salt affected soils of the Canadian prairie. Both saline and non-saline low organic matter soils of the southern prairies may offer further potential to sequester carbon through the use of salt adapted plants and soil amendment application.

The combined use of salt adapted crops and high C content soil amendments is postulated to lead to an increase in SOC content in saline and non-saline low organic matter soils from southern Saskatchewan. Green wheatgrass, canola and willow were selected for this thesis research as cultivated crops that generally have some tolerance to salinity (Steppuhn et al., 2006; Steppuhn et al., 2005b; Hangs et al., 2011) but also grow well under non-saline conditions. Canola, a moderately salt tolerant field crop, was seeded on nearly 23 million acres by Canadian farmers in 2018 and is an important crop for Saskatchewan farmers (Statistics Canada, 2018). AC Saltlander green wheatgrass was selected in Canada for root-zone salinity tolerance, winter hardiness, vegetative vigour and being a perennial forage that can grow in severely saline soil, thereby adding organic matter from above and belowground residues and litter deposition. Tully Champion willow was shown to tolerate severely saline soils and may be a suitable option for producers to grow as commercial source of bioenergy feedstocks on degraded land not used for annual or perennial crop production (Hangs et al., 2011).

Composted manure is an effective fertilizer for supplying essential plant nutrients and adding organic matter to soil (Reddy et al., 2000). Several studies have shown the potential for manure to increase crop growth in saline soils (Tejada et al., 2006; Ahmed et al., 2010). Leonardite (LEO), a concentrated carbon source, has been shown to increase crop growth and add C to soil with the use of additional soil fertilizers (Akinremi et al., 2000; Ece et al., 2007; Nazli et al., 2016). Amendment with humic acid (HA) may be effective for treating salt affected soils by improving fertility through enhanced release of plant nutrients from soil minerals and improved soil structure and water holding capacity (Ouni et al., 2014). Exploring the use of these amendments with the three crops may reveal further options for producers in Saskatchewan to ameliorate or make better use of salt affected soils.

1.1 Justification of Research

In 2001 there were 20 million ha (30% of total land area across the Canadian Prairies) of land that displayed signs of salinity or were identified at risk of salinization in the Canadian Prairies (Steppuhn, 2013). In 2006, 9% of the agricultural land on the Canadian prairies was classified as having moderate, high or very high risk of salinization (Wiebe et al., 2011). This is only a small portion of the total area affected by salinity worldwide (Rengasamy, 2010). Given that these otherwise unproductive areas continue to expand while the need for arable land grows and new emphasis is being placed on C sequestration, exploring options for improving C storage and crop growth in these soils is warranted. A large body of research suggests promotion of crop growth and SOC increases from the application of organic amendments in saline soils (Akinremi et al., 2000; Pertuit et al., 2001; Tejada et al., 2006; Ece et al., 2007; Verlinden et al., 2009; Tahir et al., 2011; Yolcu et al., 2011; Sun et al., 2016). However, there has been very little recent research on organic amendments to salt affected soils as they exist in Western Canada.

1.2 Objective

The main objective of this study was to assess the effect of three organic amendments (humic acid, leonardite, composted steer manure (CSM) on soil carbon amounts and forms, and growth of green wheatgrass, canola and willow that was seeded and grown for one year in saline and non-saline areas of a farm field located in the Brown soil zone of south-central Saskatchewan. Comparisons of the treatment effects on total soil organic carbon, water extractable organic carbon (WEOC), light fraction organic carbon (LFOC) and microbial biomass carbon and respiration in the saline and non-saline soils from south-central Saskatchewan as well as a low organic matter soil from Nigeria are made in the study.

1.3 Hypotheses

Given the research information reviewed and knowledge gaps identified in the literature, the following hypotheses were developed for testing:

i. Organic amendments applied to saline and non-saline soils will increase aboveground yield of the crops compared to non-amended soils.

ii. Organic amendments will increase soil organic carbon storage in the surface soil in relation to their rate of addition and carbon content. Greatest increases in soil organic carbon will arise from high rates of addition of high carbon content amendments.

iii. Salt tolerant perennial grass will result in greatest increases in soil organic carbon.

iv. Soil organic carbon amounts and responses to amendment will be lower in saline soils than non-saline soils.

1.4 Organization of Thesis

This thesis is formatted as a collection of six chapters covering field and controlled environment experiments. The first chapter introduces the thesis topic and provides the general study objectives and hypotheses. The second chapter provides an overview of the relevant literature and identifies research gaps to be addressed in this thesis. Chapter three covers the RCBD small plot field research trials conducted in south-central Saskatchewan at the saline and non-saline field sites. In chapter 4, an incubation experiment is described that uses soils collected near the southern Saskatchewan field research plots along with a highly weathered tropical soil collected from Ogbomosho, Nigeria for comparison. Chapter five is a synthesis of the findings, a brief discussion of overall conclusions, and identifies future areas for research. References are listed in chapter six and appendix A contains supplemental tables, graphs and analysis of variance (ANOVA) tables as well as soil tests completed outside the university.

2. Literature Review

2.1 Nature of soil salinity and influence on plants and soil

Global estimates of salt affected soils range from 400 to 960 million hectares, depending on the classification system used, of which 76 million hectares are estimated to be a result of human activity (Rengasamy, 2010; Wicke et al., 2011). Salt-affected soils are classified as saline, sodic, or saline-sodic based on the electrical conductivity of saturated extract, sodium adsorption ratio, and exchangeable sodium percentage (Amini et al., 2016). Saline soils directly affect plant growth through problems associated with soil chemical properties and osmotic potential; sodic soils have a more indirect affect on plant growth by affecting soil physical properties which alter water and nutrient supplies (Wong et al., 2010). The presence of salt in soil water inhibits plant growth in two ways: first, a reduction in the ability of the plant to take up water (osmotic effect), and second, injury to plant leaves due to excessive uptake of salts, typically sodium (Na^+) (ion-excess effect) (Munns et al., 2006; Rengasamy, 2010). These effects result in poor plant growth rate, reduced yield and, in severe cases, total crop failure (Qadir et al., 2000). Because of this, low inputs of organic matter (OM) are returned to the soil and poor vegetation cover leads to increased losses of OM from erosion and leaching (Wong et al. 2009; Wong et al., 2010). Therefore, salt-affected soils typically exhibit very low soil organic matter (SOM) and SOC content (Oo et al., 2015; Wong et al., 2010). However, there have been few studies of soil organic matter amounts and turnover in salt-affected soils of the Canadian prairies.

Salinity is reported to generally inhibit mineralization of organic materials, including organically bound nutrients like nitrogen (N) and phosphorus (P) that are associated with carbon mineralization (Walpola and Arunakumara, 2010). Therefore, in addition to the osmotic and ion-excess effect, low plant productivity in saline soils could also be attributed to a lack of OM and available nutrients, especially N, P, and potassium (K) in these soils (Lakhdar et al., 2009). In a review of amelioration strategies for saline soils, Amini et al. (2016) concluded that application of organic amendments to salt affected soils can potentially improve plant growth and addresses salinity issues inherent to these soils.

Sodicity increases the dispersion of aggregates which may lead to increased SOC mineralization and SOM decomposition (Wong et al., 2010; Amini et al., 2016). Sodicity can also cause deflocculation of clay particles because the exchangeable Na^+ in these soils are bound to the negative charges of clay (Diacono and Montemurro, 2015). Dispersion of clay may expose clay-protected organic matter to decomposition. Nelson et al. (1998) found that the decomposition of OM itself may reduce clay dispersion through the alteration of electrolyte concentration and composition. Piccolo and Mbagwu (1990) suggest that adding SOM containing high molecular weight constituents would improve aggregate stability in sodic soils. Humic acid, which is less oxidized, higher molecular weight humic matter, plays an essential role in aggregate stabilization (Tejada et al., 2006). Khaled and Fawy (2011) suggest humic acids can also improve nutrient availability in soils. Diacono and Montemurro (2015) showed both soil and foliar application of humic substances (HS) increased macro- and micronutrient uptake in corn. Wong et al. (2010) suggests more investigations are needed on how rehabilitation processes with humic materials affect C cycling and could assist in increasing C stocks in SOC deficient soils.

2.1.1 Soil salinity on the prairies

In 2006, 9% of the agricultural land on the Canadian Prairies was classified as having moderate, high or very high risk of salinization (Wiebe et al., 2011). Fig. 2.1 shows a map of the salinity risk index for the Canadian prairies based on physical factors and vegetation cover. In

2000, Huffman et al. (2000) put the area affected by significant salinity (EC_e >8 dS m^{-1}) at 1.4 million ha or 2.5% of farmland in the Canadian Prairies.

Soil salinization in the prairies is a result of the minerology of the parent material, underlying geological formations, and the hydrogeological processes that naturally occur in the landscape (Henry et al., 1987; Florinsky et al., 2009). Sodium, magnesium, and calcium sulphates (Na_2SO_4, $MgSO_4$, and $CaSO_4$, respectively) are the main salts contributing to salinity in the prairies, although in some areas, chloride salts are also present (Henry et al., 1987). As ground water moves through the soil, it accumulates salts and capillary action wicks the water to the soil surface where it evaporates, leaving the salts behind (Henry et al., 1987). For salinization to occur, two factors must be present: (1) a high water table and (2) evaporation exceeding infiltration (Henry et al., 1987). The three main underground conditions causing salinity in Saskatchewan are artesian discharge, sloughs with limited drainage often with an underlying impermeable layer, and side hill seeps (Henry et al., 1987).

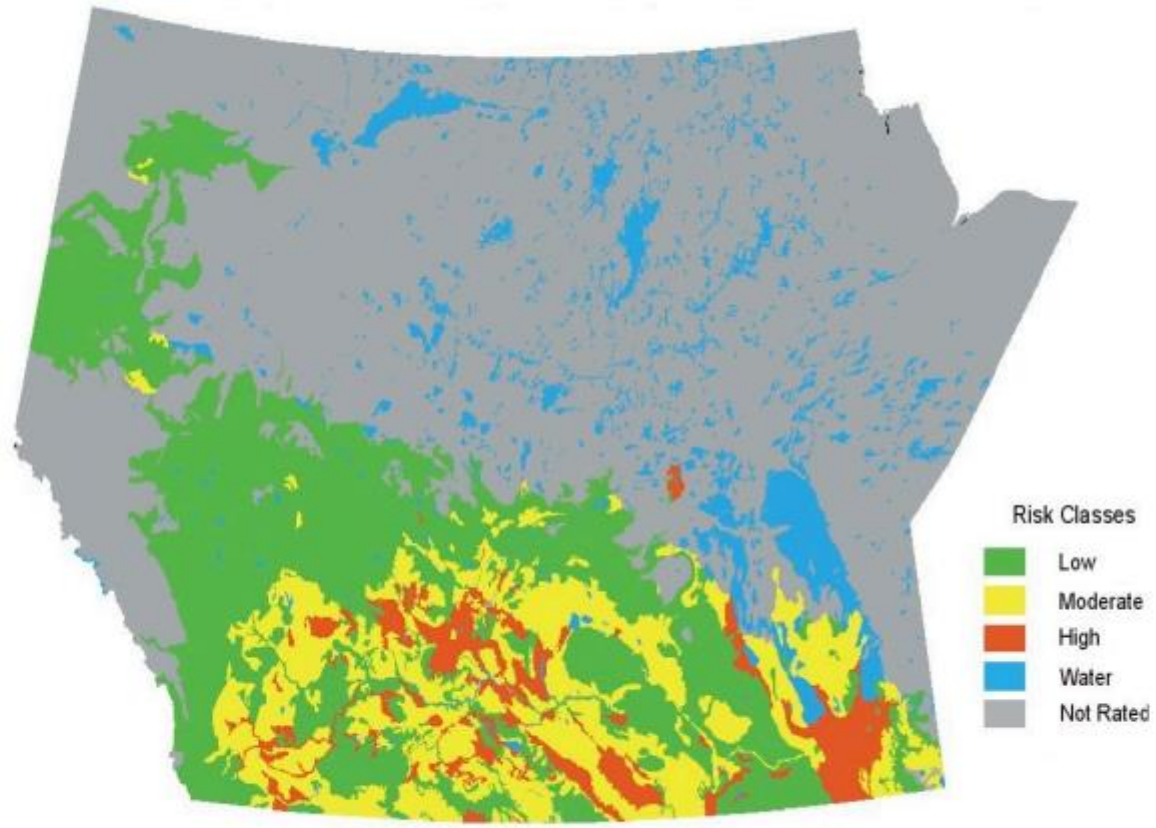

Fig. 2.1: The 1996 salinity risk index for the Canadian prairies. The risk index was based on five biological and physical factors including presence and extent of salinity, topography, drainage, aridity, and surface cover/vegetation. Each factor was assigned a value based on their influence on salinity (Wiebe et al., 2007; Steppuhn, 2013).

2.1.2 Plant growth in salt-affected soils

2.1.2.1 AC Saltlander

AC Saltlander green wheatgrass is a hybrid of Eurasian bluebunch wheatgrass and quackgrass developed collaboratively between USDA Forage and Range Research Laboratory and the Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada (AAFC) in the mid to late 1990s (Steppuhn et al., 2006). It was the first cultivar of green wheatgrass selected in Canada for root-zone salinity tolerance and further selected for winter hardiness, vegetative vigour, pest resistance, and plant morphology (Steppuhn et al., 2006). AC Saltlander averages a mid-season height of 764 mm, a salinity tolerance index of 12.51 (i.e. a

50% reduction in crop yield compared to a non-saline yield) (Steppuhn et al., 2005a) and has early spring growth while remaining palatable to livestock longer than most other wheatgrass species (Steppuhn et al., 2006). A study measuring relative yield decrease with increasing salinity by Steppuhn et al. (2006) showed AC Saltlander achieved 70% and 30% of it's optimal yield at salinity level of 4 and 8 dS m^{-1}.

2.1.2.2 Canola

In 2018, 22.7 million acres of canola was seeded by Canadian farmers (Statistics Canada, 2018). Unlike other field crops commonly grown in the Canadian prairies, canola is moderately salt tolerant with a salinity tolerance index of 8.00 compared to 3.27 for wheat (Steppuhn et al., 2005b). Its salinity level threshold is 6.0 dS m^{-1}, however, salinity levels above 4 dS m^{-1} can cause reduced rates of germination (Ashraf and McNeilly, 2004). Salinity also causes adverse effects on plant height, size, yield, and seed quality (Ashraf and McNeilly, 2004). Canola germination under saline conditions is characterized by impeded water absorption, excessive use of the nutrient pool, and disorders in protein synthesis (Bybordi and Tabatabaei, 2009).

2.1.2.3 Tully Champion willow

Willow (Salix spp.) is a moderately salt tolerant plant that can be grown in soils with an EC_e of ≤5.0 dS m^{-1} (Quinn et al., 2015). Tully Champion (S. viminalis x S. miyabeana) willow was selected for its above average salinity tolerance based on research of 37 willow varieties by Hangs et al. (2011). It showed no reduction in growth when grown under severely saline (EC_e 8.0 dS m^{-1}) soil and minimal stress with increasing salinity based on root mass fractions (Hangs et al., 2011). In a trial at two contrasting non-saline sites in New York state, Serapiglia et al. (2013) recorded yield data for Tully Champion of 10.04 Mg ha^{-1} $year^{-1}$ and 9.53 Mg ha^{-1} $year^{-1}$; Amichev et al. (2015) recorded average first-rotation biomass harvest at 17.4 Mg ha^{-1}, 70%

greater than the average biomass yield for the other 29 cultivars in their study. Stem diameter was measured at 6.8, 9.8, and 15.8 mm, height was measured at 193, 244, and 404 cm, and stem count was 9, 8.3, and 8.1 over a three-year rotation in a heavy clay Sutherland Orthic Vertisol located in Saskatoon, SK (Amichev et al., 2015).

2.1.3 Microbial activity in saline soils

Saline soils, including severely saline soils which support very little plant growth, should not be seen as inactive soils devoid of microbial activity that remain unchanged and stagnant. In general, soil microbial biomass is usually positively corelated with SOC content and negatively corelated with soluble salts in naturally occurring saline soils (Wong et al., 2010). Salt affected soils are inhabited by microbial communities that are specially adapted to saline conditions that have adapted to tolerate greater osmotic stress and exhibit modified cell morphology (Zahran, 1997). Under saline conditions, microbial community structure can shift from fungi dominated to prokaryotic dominated with less active and competitive bacterial communities (Wong et al., 2010).

In arid saline soils, Yuan et al. (2007) measured microbial biomass C (MB-C), basal respiration and metabolic quotient (qCO_2) under different levels of salinity and recorded a negative exponential relationship with all three measurements as EC increased. Soils with an EC of 4.13, 5.22, and 6.44 dS m^{-1} had MB-C of 94.6, 85.1 and 47.3 mg kg^{-1}, respectively, and basal respiration of 10.0, 7.0 and 6.8 µg CO_2-C g^{-1} soil day^{-1}, respectively (Yuan et al., 2007). Metabolic quotient was 4.38, 3.40, and 6.13 and 9.30 for soils with an EC of 4.13, 5.22, 6.44, and 23.05 dS m^{-1}, respectively, which indicates smaller and more stressed microbial communities as salinity increases (Yuan et al., 2007). Setia et al. (2011) measured soil respiration from soils collected from two salt affected areas and also recorded a negative correlation between EC and respiration; however, their results showed a positive correlation between respiration and availability of dissolved organic carbon in the salt affected soils.

Asghar et al. (2012) evaluated how microbial communities from moderate-severely saline soils respond to salinity compared to microbial communities from non-saline or slightly saline soils and found no significant differences in cumulative respiration. Changes in microbial community composition were similar among soils inoculated with microbes from severely saline soil and non-saline soil as EC increased (Ashghar et al., 2012). Their results suggest salt tolerant microbes in salt-affected soils continue to decompose substrates as salinity increases, microbes originating from severely saline soils can increase in activity after salinity is reduced, and microbial communities from saline soils decompose particulate OC at a lower rate than microbes from non-saline soils at slightly to moderate salinity levels (Asghar et al., 2012). Similarly, results from Wong et al. (2009) suggest dormant salt tolerant microbes adapted to saline conditions multiply rapidly and microbial respiration increases after the addition of substrate.

2.2 Carbon cycling and fractions

There is not a consensus on the impact of salinity on SOC stocks, microbial respiration, biological activity, and DOC dynamics. Table 2.1 provides a brief summary of C cycling experiments conducted on saline soils. Further details can be found in the text below.

Table 2.1: Summary Table of C cycling dynamics in salt affected soils. Additional details and experiment descriptions provided below.

Author(s)	**Location**	**Main Findings**
Yuan et al. 2007	Gansu, China	Negative exponential relationship between EC and MB-C, respiration, qCO_2
Asghar et al. 2012	Kadina, South Australia	No significant difference in respiration between microbial communities from severely SA to NS soil when subjected to increasing salinity
Bischoff et al. 2018	Siberia, Russia	SOC stocks increased with increasing salinity in SA soils
Pankhurst et al. 2001	SE Australia	Salinity associated with decreased SOC, N, MB-C, microbial activity compared to NS soil
Mavi et al. 2012	Monarto, South Australia	DOC increased with increasing salinity; cumulative respiration decreased by 8% and 40% when EC adjusted to 1.3 and 4.0 dS m^{-1}, respectively
Setia et al. 2013	Monarto, South Australia	High levels of Ca^{2+} causes sorption of DOC, decreased loss from leaching in SA soil
Chowdhury et al. 2011	Monarto, South Australia	SA soils less prone to lose C, show smaller flush in respiration compared to NS soils upon rewetting after dry periods
Garcia and Hernandez 1996	SE Spain	Increase in EC with the use of SA irrigation water had a negative effect on biological and biochemical fertility

2.2.1 Total soil organic carbon

Soil organic carbon (SOC) accounts for 1550 Gigatons (Gt) of the 2500 Gt global soil carbon pool which is more than three times the size of the atmospheric pool and over four times the size of the biotic pool (Lal, 2004). The conversion from native vegetation to agricultural use has led to a depletion in soil organic carbon pools by 60% in temperate regions of the world (Lal, 2004). Soil degradation due to salinization exacerbates losses of soil C and is indicated to result in severely reduced SOC pools (Wong et al., 2010; Lal, 2004). Soil C content is governed by the net result of carbon inputs and carbon loss (Wong et al., 2010; Bruce et al., 1999). Therefore, effects of salinity on plant growth adversely impacts SOC stocks in saline soils leading to lower inputs of plant residues and generally lower pools of SOC (Wong et al., 2010).

While lower inputs of OM in salt affected soils may decrease SOC over time, changes in C cycling impact C turnover and persistence in saline soils. Carbon cycling in saline soils is affected by EC since increasing EC results in flocculation of clay particles that can physically protect SOM from degradation (Wong et al., 2010). However, if sodium is the dominant cation, sodium induced dispersion of clay could expose SOM and enhance decomposition.

There is a large potential for increasing SOC stocks in salt affected soils through revegetation of these landscapes (Wong et al., 2010). Pankhurst et al. (2001) showed increased salinity is associated with decreased SOC, total nitrogen, microbial biomass and microbial activity when comparing soil characteristics between saline and non-saline soils. However, Bischoff et al. (2018) measured increased SOC stocks with increasing salinity in saline soils of the southwestern Siberian Kulunda steppe. Bruce et al. (1999) estimated potential C sequestration in salt affected soils could be 1000 kg ha^{-1} per year. Given that there are approximately 22.2 million ha of salt affected soils in Canada and the United States (1999 estimate), the potential C sequestration rate through restoration of these soils could be 2.2 Teragrams (Tg) per year (Bruce et al., 1999).

2.2.2 Light fraction organic carbon

Physically uncomplexed organic matter refers to OM in soil that is not held onto exchange sites and is a mixture of plant, animal, and microorganisms at varying stages of decomposition (Gregorich and Beare, 2008). Light fraction organic carbon (LFOC) is a common form of physically uncomplexed organic matter that can be isolated from the soil by density using a heavy liquid with a known specific gravity, usually 1.6 to 2.0 (Gregorich and Beare, 2008). It is generally characterized by plant residues and microbial debris in various stages of decomposition, high C:N ratios, easy decomposability, high lignin content, and low net N mineralization potential (Six et al., 2002). Light fraction organic carbon is an important nutrient source and substrate for the soil microbial community (Six et al., 2002).

Light fraction organic carbon is a useful measurement to understand larger changes in SOC because it is a sensitive indicator of management and cropping practices on SOM (Janzen et al., 1992; Six et al., 2002). Biederbeck et al. (1994) analyzed LFOC in a Brown Chernozem from southern Saskatchewan and measured 3.15, 1.55, and 1.17 mg C kg^{-1} soil under continuously cropped spring wheat, bare fallow-wheat-wheat, and bare fallow-wheat, respectively. Similarly, Bremer et al. (1994) measured an increase in LFOC with reduced fallow periods in a dark brown chernozem in Lethbridge, AB. In salt affected soils of Siberia, LFOC made up less than 10% of the total SOC in three different soil types (Bischoff et al., 2018).

2.2.3 Water extractable organic carbon

Dissolved organic carbon (DOC), defined as the OM in solution that can pass through a 0.45 µm filter, makes up only a small fraction of total SOC in soils, approximately 0.04-0.2%, but is often considered to be the most active fraction of SOC because of its highly mobile nature and availability to be readily decomposed (Chantigny et al., 2008). While DOC refers to any OM dissolved in solution, water extractable organic carbon (WEOC) refers to soluble SOM extracted with low ionic strength aqueous solutions (in this case 5 mM $CaCl_2$), however, WEOC is considered an acceptable surrogate for DOC in soil solution collected in situ (Chantigny et al., 2008). The extraction procedure for WEOC minimizes soil disturbance and physical disruption of structure so as to not release OM from exchange sites that would otherwise not be considered in the DOC fraction (Zsolnay, 2003).

Dissolved organic matter (DOM) originates from plant litter, root exudates, microbial biomass and decomposing organic substances in soil and largely contributes to soil formation, mineral weathering, and pollutant transport (Kalbitz et al., 2000). Biotic and abiotic controls both contribute to the formation of DOC and its persistence in soil is dominantly controlled by adsorption to mineral surfaces, however, microbial decomposition also affects the amount of DOC in soil solution with several studies suggesting 10-40% of DOM is easily decomposable by microbes (Nelson et al., 1994; Yano et al., 1998; Kalbitz et al., 2000). Rewetting of soil after dry periods increases DOC which is caused by decreased microbial consumption of DOC, accumulation of microbial products, cell lysis and death, and release of DOC after soil disturbance from previously protected sites (Lundquist et al., 1999; Zsolnay et al., 1999). Compared to SOC, WEOC is more active and sensitive, so it is useful as an indicator of short-term change to SOM.

Salinity can increase the concentration of DOC due to increased solubility of SOM under saline conditions which then increases available substrate for microbial decomposition (Wong et al., 2010). High clay content and electrolyte concentration reduce accessibility of OM to microbes (Mavi et al., 2012); since clay dispersion and EC are negatively correlated, increasing salinity leads to flocculation and a decrease in microbial access to dissolved organic carbon (Mavi et al., 2012). However, the types of salts present in saline soils affect sorption of DOC; Na^+ forms weak bonds with negatively charged particles whereas Ca^{2+} form more stable bonds. Setia et al. (2013) showed increasing levels of Ca^{2+} resulted in sorption and retention of DOC and lower loses of DOC via leaching in saline soils. Mavi et al. (2012) recorded an increase of

20% and 38% in DOC when a non-saline soil was adjusted to an EC of 2.5 and 4.0 dS m^{-1}, respectively.

2.2.5 Microbial biomass

Soil microbial biomass (SMB) makes up 1-5% of TOC in arable soils and is a useful indicator of SOM turnover and nutrient cycling changes caused by management and cropping practices and other forms of soil disturbance (Voroney et al., 2008). Compared to SOC and other SOC fractions, SMB is extremely sensitive to disturbance and as such, is useful as an early indicator of ecosystem stress before meaningful changes can be measured in other C fractions; therefore, SMB measured over short experimental periods can indicate future trends in TOC that cannot yet be measured (Powlson et al., 1987; Voroney et al., 2008).

Soil microbial biomass consists of bacteria and fungi which make up the living portion of SOM and are responsible for decomposition of plant and animal residues which releases CO_2 and nutrients back into the soil in plant available form. Soil microbial biomass is significantly related to clay content, SOC and total N content in soils (Schnürer et al., 1985). Soil microbial biomass is typically concentrated in the surface layer of soil and as such cultivation reduces SMB and microbial activity, especially in macroaggregates (Gupta and Germida, 1988).

2.3 Soil amendments in improving problem soils

2.3.1 Composted steer manure

Organic manures, such as cattle manure (CM), are effective soil fertilizers for supplying plant nutrients and adding organic matter to agricultural soils (Reddy et al., 2000). Agronomic benefits of solid CM application for improving crop yield in canola and other crops commonly grown on the Canadian Prairies are well documented (Mooleki et al., 2004). Increased crop growth from organic manure application results in increased plant residues, decaying roots and litter being returned to the soil and therefore an increase in SOM. Increases in SOM from organic manure applications results in improved water holding capacity, infiltration, water stable aggregation, increased microbial activity and decreased bulk density and surface crusting (Haynes and Naidu, 1998). However, large amounts of added organic manures can result in increases in K^+ and Na^+ in soils (Haynes and Naidu, 1998). Unlike chemical fertilizers which may not be accessible to farmers in developing countries because of price or availability, organic manures are relatively easy to obtain.

Livestock manure contains considerable amounts of salts and the application of CM to saline agriculture land may exacerbate problems associated with salinity. Hao and Chang (2003) studied the effect of CM application (0, 30, 60, and 90 Mg ha $^{-1}$ yr^{-1}) on soil salinity over a 25 year period on a brown Chernozemic clay loam soil near Lethbridge AB. After 25 years, the amount of soluble salt added to the soil was 20.4, 40.5 and 60.2 Mg ha^{-1} for the 30, 60, and 90 Mg ha $^{-1}$ treatments of manure application, respectively (Hao and Chang, 2003). Soluble Na^+, K^+, Mg^{2+} and chlorine (Cl^-) concentration significantly increased with all rates of manure application. Hao et al. (2004) reported seed oil content significantly decreased and total N content significantly increased in canola grown in soils amended with 30, 60, and 90 Mg ha $^{-1}$ per year of cattle manure. Qian and Schoenau (2002) found the addition of solid manure, including several different cattle manures, did not generally affect canola yield and N uptake when applied at a rate of 100 mg of total N kg^{-1} of dry soil. Tejada et al. (2006) showed the addition of poultry manure (PM) in a saline-sodic soil (EC 9.1 dS/m^{-1} and ESP 15.7) resulted in the appearance of spontaneous vegetation in treated plots one year after treatment began. They also observed increased water-soluble carbohydrates, increased biochemical properties and enzyme activity (urease, protease, b-glucosidase, phosphatase, arylsulfatase and dehydrogenase) in PM amended soils (Tejada et al., 2006). Ahmed et al. (2010) showed farmyard manure was an efficient amendment for increasing winter wheat growth in sandy soil irrigated with saline water (0.11 and 2.0 dS m^{-1}).

2.3.2 Leonardite

Leonardite (LEO), a brown coal -like substance, is an oxidized form of lignite often overlying more compacted coal and contains 30-80% humic acid (Akinremi et al., 2000). Humic substances improve overall soil health by acting as reservoirs for N, P and S and affect soil physical properties by improving soil structure, aeration, drainage and increase buffering and exchange capacities (Qian et al., 2015). Therefore, LEO is an attractive potential soil amendment and offers benefits for increasing plant growth, seed germination, and fruit quality (Qian et al., 2015).

A pot study conducted in a greenhouse to test the use of LEO as a soil amendment to supply nutrients to crops commonly grown on the Canadian Prairies (canola, wheat, green beans) was set up by Akinremi et al. (2000). They applied freshly mined LEO at 0.5, 1, 5 and 10 g to 3 kg of soil. The results showed an increase in dry matter yield and a significant increase in N, P, K and S uptake in canola amended with LEO grown in a low OM, low fertility, sandy loam soil (Akinremi et al., 2000). Leonardite applied at 10 g per 3 kg soil and in conjunction with N, P, K and other nutrients, resulted in a 27% increase in dry matter yield and the highest rates of nutrient uptake (Akinremi et al., 2000.). Nazli et al. (2016) reported a significantly increased yield of silage maize when LEO was applied at a rate of 500 kg ha^{-1} with recommended rates of inorganic fertilizer. Ece et al. (2007) studied the effects of LEO application (10 and 20 t ha^{-1}) and N and P fertilizer on climbing bean growth and soil properties. They found significant ($p<0.01$) differences in OM and P content from soils amended with LEO compared to control but no significant differences between the rate of LEO applied (Ece et al., 2007). They also reported significantly increased marketable yield of beans with the recommended fertilizer plus 10 t ha^{-1} of LEO compared to control (Ece et al., 2007). No difference in EC was reported with the application of LEO (Ece et al., 2007). Pertuit et al. (2001) reported an increase in plant height, leaf area, root and shoot weight in tomatoes with the application of 1/3 (v/v) LEO to growing medium in combination with recommended fertilizer rates. Yolcu et al. (2011) found LEO applied at 250, 500 and 750 kg ha^{-1} increased ryegrass hay yield, K, S, Ca, Mg, Fe, Mn and B hay content compared to the control. The authors found increasing levels of tissue nutrients with increasing levels of LEO application (Yolcu et al., 2011).

2.3.3 Humic acid

Soil humic substances (HS), such as humic acid and fulvic acid, constitute 65-70% of SOM (Ouni et al., 2014). Humic substances are reported to improve overall soil health (Qian et al., 2015) and can hold seven times their volume in water and create a soil structure that facilities water infiltration and holds water in the root zone as well as acting to buffer soil pH and enhance uptake of N, P, and K (Pettit, 2013).

Humic substances may be an effective amendment for treating salt affected soils by improving fertility by enhancing release of plant nutrients from soil minerals, increasing the availability of trace minerals, and improving soil structure and water holding capacity (Ouni et al., 2014). A review by Ouni et al. (2014) suggests high supplies of calcium, magnesium, and potassium minerals in HS decrease soil Na, EC and pH and allow for Na leaching during precipitation events by minimizing adsorption of Na on exchange sites, provided sufficient drainage is present. In salt affected soils, Ca^{2+} from HS can replace exchangeable Na^{+} on the root adsorption sites (Ouni et al., 2014). Additionally, HS is believed to improve fertilizer efficiency and reduce N leaching and volatilization by holding N in a molecular form and reducing its solubility in water (Pettit, 2013).

Humic acids (HA) are brown to black polymeric constituents of soil and are the fraction of HS that is soluble in water at pH >2 (Ouni et al., 2014). Humic acids bind clay minerals to form stable organic clay complexes and function as ion-exchange and chelating systems which results in the dissolution of primary and secondary soil minerals which become available for plant uptake via roots (Pettit, 2013). Humic acid and fulvic acids may also enhance root development and increase root growth, especially in young plants (Pettit, 2013). Sun et al. (2016) reported increased root length and Verlinden et al. (2009) stimulated root growth and increased fine lateral and secondary roots with the application of HS in maize. Positive effects of HS are more likely to appear in low quality soils (Verlinden et al. 2009). Hartz and Bottoms (2010) reported recommended field application rates for some commercial products that were <5 kg/ha^{-1} that were ineffective in improving nutrient availability for crops. Albiach et al. (2000) reported that commercially recommended application rates of HA at 100 L ha^{-1} per year were too low to be effective in significantly improving microbial biomass content and enzymatic activities. Tahir et al. (2011) applied humic acid at 30, 60 and 90 mg kg^{-1} soil (60, 120 and 180 kg ha^{-1}) and found 60 mg kg^{-1} of humic acid application significantly increased wheat growth while 90 mg kg^{-1} failed to enhance growth or nutrient uptake compared to the lower rates.

There are opposing ideas regarding the molecular structure of humic substances in soil and poorly defined speciation of humic acid and other HS materials has resulted in inconsistent and improper use of the terms associated with these materials (i.e. HA, HS). Advances in recent technology have allowed for direct observation of intact microaggregates in order to investigate the nature of humic substances as they exist in soil. Previous methods relied on alkali extraction of OM and observations were made on the extractant (Schmidt et al., 2011). The humic substances observed in these extracts have not been observed in situ (Lehmann and Kleber, 2015; Schmidt et al., 2011); instead, humic substances extracted by alkali are components of OM that exist separately in the soil (Lehmann and Kleber, 2015). The composition of OM in soils is now thought to be that of a complex mixture of identifiable biopolymers rather than chemically complex humic material (Lehmann et al., 2008).

2.4 Carbon mineralization and CO_2 emissions

Over the past 200 years, global land use change in terrestrial ecosystems is responsible for nearly half the increase in CO_2 emissions, of which 50 Pg can be attributed to cultivated land as C in SOM is mineralized (Paustian et al., 2002). Carbon mineralization is the conversion of organic C to inorganic C which is released as CO_2. A soil is a C sink if the photosynthetically-fixed CO_2 entering the soil as plant residues is greater than the CO_2 emissions from C mineralization through decomposition, and a C source if the opposite is true (Paustian et al., 2002). Initial cultivation of native ecosystems typically causes a loss of SOC and an increase in CO_2 emissions but over time the system will generally shift towards equilibrium and changes in C (i.e. C sequestration or losses) are then affected by management practices such as reduced tillage and crop cover.

2.5 Tropical soils and C cycling

In sub-Saharan Nigeria, highly weathered soils are comparatively poor in fertility and lack essential plant nutrients and SOM content (Ojo et al., 2016). Severely degraded soils in sub-Saharan Africa cover an area of 3.5 million km^2 which makes up 20-25% of the total land area (Vågen et al., 2005). High soil temperatures, low clay content, energetic fauna activity, and low shoot and root growth contribute to low SOC content and rapid C turnover (Bationo et al., 2007). Farming practices in Africa, namely complete residue removal for fodder and fuel, exacerbate fertility issues by reducing SOC derived from roots and plant litter resulting in depleted SOC stocks (Lal, 2004).

Since clay and silt content play a major role in OC stabilization and persistence time in soil, coarse textured sub-Saharan soils suffer from a lack of suitable minerology to retain large amounts of SOC. Lobe et al. (2001) measured SOM content in particle sizes in a coarse textured Savanah soil under cultivation and recorded an average loss of 65% since cultivation in the order of clay > silt > coarse sand > find sand. Bationo et al. (2007) measured annual loss of SOC from sub-Saharan sandy and sandy loam soils under continuous cultivation at 4.7 and 2%, respectively. As such, a highly weathered sandy tropical soil offers a good contrast to the relatively unweathered and clay rich temperate soils of Saskatchewan when evaluating the effects of organic amendment on carbon respiration and storage.

This literature review has identified similar, but sometimes contrasting findings on the effects of soil salinity and sodicity on carbon storage and cycling. Furthermore, the reported effects and benefits of adding organic amendments like manure and humic materials, especially to salt-affected soils, are inconsistent. Little if any work on C cycling in salt-affected soils of the Canadian prairies was found, and the effects of amendments in general on plant growth and C dynamics in these soils is lacking. The following sections of this thesis describe work undertaken to address this gap.

3. Soil carbon and plant productivity as affected by crop and organic amendment application in saline and non-saline portions of a farm field in southern Saskatchewan.

3.1 Preface

A review of relevant literature has shown that the nature of salt affected soils and salinity effects on plants growth have been extensively studied. However, recent research addressing soil salinity and relevant approaches to remediation in the Canadian prairies is lacking. The objective of the work described in Chapter 3 was to assess the effect of three organic amendments on crop (green wheatgrass, canola, willow) growth, nutrient uptake, C sequestration and dynamics in saline and non-saline portions of a farm field in south-central Saskatchewan.

3.2 Abstract

Enhancing soil carbon storage and productivity of salt affected, low organic matter (<3% O.M.) soils in southern Saskatchewan may be possible through the combined use of salt-adapted crops and amendments containing high amounts of carbon. A field experiment was established in the spring of 2017 to evaluate the effect of three amendments (leonardite: LEO; humic acid: HA and composted steer manure: CSM) and three crops (AC Saltlander green wheatgrass, canola and willow) on soil carbon forms and crop growth in saline and non-saline portions of a farm field located in south central Saskatchewan in the Brown soil climatic zone. After one year of growth, the saline soil treatments that were seeded to AC Saltlander had water extractable organic carbon concentrations (WEOC) that were ~15mg C kg^{-1} higher. Total soil organic carbon (SOC) mass under AC Saltlander at the non-saline location in the field was significantly higher than under willow and higher than under canola. Amendment with leonardite at 10 tonnes ha^{-1} had the greatest impact on increasing soil organic C fractions. In the fall of 2017 and spring of 2018, saline location soils that were amended with LEO had significantly more light fraction organic carbon (LFOC) compared to the unamended control plots and those amended with humic acid (HA) at 200. kg ha^{-1}. After one year, the SOC mass in the 0-10 cm depth was significantly greater by 23% and 16% in LEO amended plots compared to all other treatments in both non-saline and saline soils, respectively. Our results suggest seeding saline areas to salt tolerant forages such as AC Saltlander and applying humified amendments with high C content such as LEO in high amounts (~10 tonnes ha^{-1}) to both saline and non-saline soils can increase total SOC mass in the surface as well as easily decomposable C fractions that contribute to microbial activity. From the results of this study it appears this may be accomplished over a relatively short period. However, none of the crops responded positively in above-ground yield to amendment

addition in the first year. Evaluation of effects over several years would be desirable to determine the permanence of soil carbon storage changes as well as impacts on productivity in these and other salt affected soils in the Canadian prairies.

3.3 Introduction

The risk of salinization affects nearly 10% of cultivated land in the Canadian prairies (Wiebe et al., 2011). Soil salinity has adverse effects on soil physical, chemical, and biological properties and processes with a generally negative impact on plant growth due to osmotic effects and ion toxicity. In salt affected soils, SOC levels are adversely affected by reduced plant growth, and therefore less C inputs. Reductions in microbial biomass activity reflect lower C turnover in salt affected soils as well (Setia et al., 2011b). Soil salinity on the Canadian prairies typically occurs in localized areas of farm fields such as water discharge areas in the toe slopes of catenas and where high-water table contributes to movement of water to the soil surface. Upon evaporation of the water, soluble sulfate salts are left behind (Henry et al., 1987). The unproductive salt affected areas or patches in the field may offer potential to further sequester C through improved crop growth and carbon additions. In particular, there is potential for utilization of salt tolerant forages that can add considerable amounts of soil carbon and improve soil physical attributes via their perennial growth and extensive root mass. Some field crops can tolerate moderate to moderately-high salinity, but it has been long recognized that the most suitable crop for saline areas are forages (Holm, 1982). More recently, the higher salt tolerance of hybrid canola varieties (Steppuhn 2013) and salt tolerance of certain willow clones (Hangs et al., 2011) has also been identified but have not been extensively evaluated on the Canadian prairies.

Further benefits to soil carbon storage and productivity may be achieved through combination of organic amendment addition along with seeding of crops that are more salt tolerant. Some previous studies (Ahmed et al., 2010; Tejada et al., 2006) have indicated that organic amendments made to soils challenged by high salt levels and low organic matter can improve total soil organic carbon (SOC) amounts as well as enhancing labile fractions of organic carbon such as water extractable (WEOC) and light fraction (LFOC) organic carbon that promote microbial activity and carbon turnover in soils. However, there has been little or no research on this strategy in salt-affected soils of the Canadian prairies. Recent research on addressing salt affected soils through organic amendment and crop selection has been conducted in Australia (e.g. Setia et al., 2013b; Mavi et al., 2012; Pankhurst et al., 2001), the Mediterranean (e.g. Garcia et al., 1994; Garcia and Hernandez 1996), and other regions significantly impacted by salinity and sodicity, but has less relevance to the Canadian prairies where only specific zones of a landscape are typically affected by salinity, and the salts are mainly sulfate salts rather than chloride salts.

The objectives of this research chapter were to assess the effect of three organic amendments (leonardite: LEO; humic acid: HA and composted steer manure: CSM) and three crops (AC Saltlander green wheatgrass, hybrid argentine canola, and a salt tolerant willow clone) on soil carbon amounts and forms, and crop growth and nutrition. A research location that had both salt affected soils and low organic matter content (<3% OM) was selected for the research. The study was conducted from spring of 2017 to spring of 2018 using replicated RCBD trials conducted in saline and non-saline portions of a typical farm field landscape located in the Brown soil climatic zone in south-central Saskatchewan. Crops were seeded in 2017 and above ground yields determined. Initial amounts of total SOC, LFOC, and WEOC in the soil profile were assessed in the spring of 2017 and again following growth of the crops. Changes in LFOC and WEOC are useful early indicators that can be used to predict future changes in more stable SOC pools; understanding the crop response to the selected amendments is valuable for assessing potential agronomic viability of the amendments because increased crop growth can lead to additional carbon inputs to the SOC pool. After an initial soil characterization of both field sites, crop and soil samples were taken again in the fall of 2017 and spring 2018.

3.4 Materials and Methods

3.4.1 Site description

The saline and non-saline sites used for the field trials described in this thesis are located in a farm field (legal location: SW quarter of section 31-Township 20- Range 3 – West of 3rd Meridian) with the soil in the field generally described as a Brown Chernozem (Haverhill association) on upper and mid slopes (non-saline) intermixed with Solodized Solonetz soils often affected by bathtub ring salinity in toe slope positions (Rosemae association) and with Humic Luvic Gleysols in depressions (Saskatchewan Soil Survey). The field is located ~ 14 km south east of Central Butte, Saskatchewan (Fig 3.1). The general saline and non-saline portions of the field selected for the study (Fig. 3.2) were first identified on the basis of visual crop and weed growth differences, presence of salts on the soil surface, and subsequently confirmed using conductivity meter readings. The specific site locations and plot study area boundaries within the saline and non-saline portions were laid out based on assessment of uniformity across the proposed trial area using an EM38-MK2 Ground Conductivity Meter (Geonics Limited. Mississayga, ON). The study plot areas were selected based on areas having the most uniform conductivity meter readings.

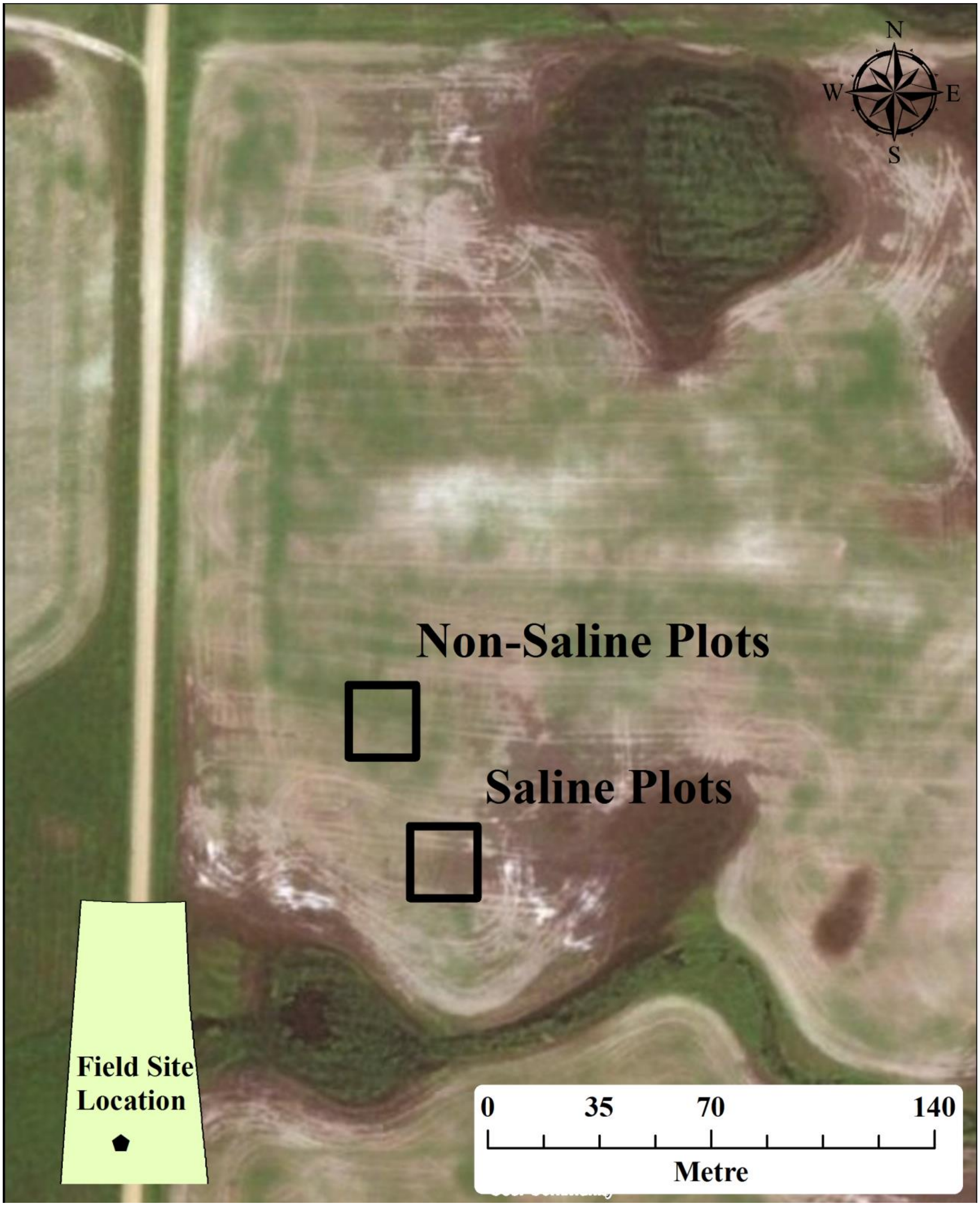

Fig. 3.1: Satellite imagery map showing the location of the saline and non-saline plots at the field site established in the spring of 2017. Image was taken July 3rd 2014.

The chosen non-saline site was located approximately 50 m north of the saline site and was at a slightly higher elevation (Fig. 3.2, 3.3 and 3.4) in the same cultivated field. The cropping history of the field for the last 25 years was a cereal-legume-oilseed rotation in reduced or zero-tillage management with fertilizer and crop protection products applied at the recommended rates each year. In 2016, the field was cropped to green field pea and in the trial season of 2017, the plots were established on the pea stubble. The soils at the site developed on thin glacial till parent material overlying Cretaceous marine clay-shale bedrock with high concentrations of Na, Ca, and Mg sulphate salts (Table 3.2). Using electrical conductivity (EC) measurements, the saline site is classified as severely saline and the non-saline site is classified as non-saline according to Henry et al. (1987). A detailed salinity analysis for both the saline and non-saline sites is shown in table 4. The surface (0-15cm) layer at the saline site had higher extractable available nutrient levels (N, P, K, S) compared to the non-saline site (Table 3.1). This is explained by lower plant growth, uptake and removal of indigenous and applied nutrient on the salt-affected portions of the field over the years.

Fig. 3.2: Photo of the saline and non-saline plots at the field site taken June 11, 2018.

Table 3.1: Summary of the soil properties measured in soil cores collected from the non-saline and saline field trial sites in spring 2017 before planting. Values are means from analysis of ten individual soil cores taken to a 60 cm depth and divided into three depth increments. Samples were collected in May 2017 before any treatments or field operations were conducted.

Depth	Soil Property									
	NO_3-N[†]	MK-P [‡]	MK- K[‡]	SO_4-S[§]	Na[¶]	Ca[¶]	Mg[¶]	pH[#]	EC[††]	OC
(cm)	----- mg kg soil^{-1} -----								(dS m^{-1})	(%)
					Non-saline site					
0-15	8.9	9.6	296	16.1	9.8	3582	616	7.94	0.315	1.23
15-30	6.1	7.7	229	12.2	17.0	4065	897	8.02	0.275	0.93
30-60	4.8	6.3	147	15.2	32.3	4219	1001	8.19	0.297	-
					Saline site					
0-15	16.4	12.0	529	718	577	6625	1790	7.89	6.32	1.47
15-30	6.6	6.1	434	717	750	7234	1997	7.93	6.29	1.05
30-60	3.5	6.7	437	721	77	7457	2063	7.95	6.75	-

[†] NO_3-N = $CaCl_2$ extractable nitrate, NO_3-N (Houba et al., 2000)
[‡] MK P and K = Modified Kelowna extractable P and K (Qian et al., 1994)
[§] SO_4-S = $CaCl_2$ extractable sulphate, SO_4-S (Houba et al., 2000)
[¶] Na, Ca and Mg = 1M ammonium acetate extraction (Hendershot et al., 2008)
[#] pH measured in a 1:2 soil:water suspension (Hendershot et al., 2008)
[††] EC measured in a 1:2 soil:water suspension (Miller and Curtin, 2008)

Table 3.2: Detailed salinity characterization of soils at the two Central Butte field sites using samples taken in the spring of 2017. Ten soil cores were taken at each site, divided into three depth increments and composited into one sample per depth. The detailed salinity analysis was conducted using a saturated paste by ALS Environmental Laboratories Saskatoon, SK.

Depth	Soil Property						
	Ca[†]	K[†]	Mg[†]	Na[†]	SAR[‡]	pH[§]	EC$_e$[¶]
(cm)	----- mg/L -----						(dS m^{-1})
				Non-saline site			
0-15	122	35.6	46.0	16.6	0.33	7.30	0.89
15-30	92.4	12.9	44.2	20.4	0.44	7.43	0.75
30-60	69.1	10.1	47.7	31.9	0.72	7.62	0.73
				Saline site			
0-15	575	124	932	919	5.51	7.87	8.55
15-30	574	108	1090	1210	6.85	8.04	9.73
30-60	580	120	1210	1320	7.14	8.14	10.3

[†] Ca, Mg, Na and K in a saturated soil extract were determined by inductively coupled plasma atomic emission spectroscopy.

[‡] SAR = Sodium adsorption ratio calculated as $\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{1}{2}(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})}}$ where Na, Ca, and Mg concentrations are expressed in milliequivalets/litre.

[§] pH of a saturated soil paste was measured using a pH meter.

[¶] EC$_e$ = Electrical conductivity of saturated paste. After equilibration, the extract is obtained by vacuum filtration, with conductivity of the extract measured by an electrical conductivity meter.

3.4.2 Experimental design and field operations

The experiment was set up as a 3 x 4 factorial experiment laid out in a randomized complete block design with 4 replications of the treatments at each of the two sites. Individual plot sizes were 1 m x 3 m with 2 m pathway spacing between each block and each alleyway between the crops. The two treatment factors were (1) crop type (green wheatgrass, canola and willow) and (2) soil amendment (humic acid, leonardite, composted steer manure and unamended control). The crop varieties selected for this study were AC Saltlander green wheatgrass (Elymus hoffmannii) that was seeded in rows spaced 25 cm apart at a rate of 10 kg ha^{-1}, Liberty Link Invigor LL 252 argentine hybrid canola (*Brassica napus*) seeded at a rate of 10 kg ha^{-1} in rows spaced 25 cm apart, and Tully Champion willow (Salix viminalis x S. miyabeana) planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot. On May 11, 2017, the AC Saltlander and canola were seeded using a manual double disc seeder in three 3 m length rows per plot with 25 cm row spacing at a depth of approximately 2 cm. The four amendment treatment rates were as follows: leonardite applied at 10 t ha^{-1}, humic acid applied at 200 kg ha^{-1}, bagged composted steer manure applied at 10 t ha^{-1}, and an unamended control. The rates for the solid amendments (CSM and LEO) were selected based on recommended application rate of solid manure for the region (~10 tonnes ha^{-1}) while the liquid HA amendment rate was selected based on normal fertilizer product application rate (~200 kg ha^{-1}). The leonardite and humic acid was sourced from Wapaw Resources Inc. (Zenon Park, SK) while the bagged composted steer manure was sourced from Federated COOP (Saskatoon, SK). The leonardite and steer manure were broadcast and incorporated, and the humic acid was seed-row placed. Selected characteristics of the organic amendments are given in Table 3.3. All plots received a blanket application of 50 kg N ha^{-1} as urea and 20 kg P_2O_5 ha^{-1} as MAP fertilizer which was broadcast and incorporated before seeding; application rates of commercial fertilizer were based on normal fertilizer recommendations for the area.

Table 3.3: Selected properties of organic amendments used in this experiment.

Amendment[†]	Properties[‡]										
	MC[§] (%)	pH	EC (dS m^{-1})	Total C	Total N	P	K	S	Na	Ca	Mg
							----- (g kg^{-1}) -----				
CSM	60.1	-	-	88.5	6.4	1.60	3.06	1.72	0.67	36.45	2.59
LEO	2.94	-	-	305	4.1	<1.0	<1.0	7.05	<1.0	7.80	<1.0
HA	-	10.01	14	-	0.78	<0.010	17.4	0.86	0.03	0.67	0.02

[†] CSM denotes composted steer manure, LEO denotes leonardite, HA denotes humic acid.
[‡] Subsamples of each amendment were sent to ALS Laboratories, Saskatoon for analysis.
[§] MC, moisture content.

3.4.3 Weed Control

Weed control during the 2017 growing season was managed using a combination of manual, mechanical, and chemical treatments. On June 7, 2017 the AC Saltlander plots were sprayed with Attain™ plus Achieve™ herbicides, specifically: fluoxypyr at 0.095 litres/ acre + 2,4D at 0.260 litres/acre + tralkoxydim at 0.15 litres/acre; on July 29, 2017 the plots were sprayed with MCPA to help further control kochia weed infestation. On June 1, June 12 and July 2, 2017, the canola plots were sprayed with 1.3 liters per acre of Liberty™ herbicide (glufosinate). As there is no selective herbicide for weed control in willow, on June 21, 27, July 13, Aug 1, 10, 24, and Sept 15, 2017 plots were weeded by hand and a garden hoe was used to weed around the edges of the plots; alleyways of all plot areas were tilled using a Kubota tractor with a rototiller throughout the season.

3.4.4 Climate data

The climate data for the 2017 growing season (May to September) in the Central Butte area, based on meteorological data collected from a weather station located at the field site is provided in Table 3.4. Growing season temperatures were higher compared to 1981-2010 historical data and precipitation, especially in May and June, was well below the 1981 – 2010 average during each month of the 2017 growing season. The hot and dry conditions experienced in the area during the 2017 season helps to explain the overall poor establishment and survival of the willow, a plant which prefers ample moisture, on the plot areas.

Table 3.4: Comparison of mean monthly temperature (ºC) and precipitation (mm) during 2017 growing season to 30 year (1981 – 2010) historical data collected at Elbow, SK weather station (Environment Canada).

	Mean Monthly Temperature (ºC)		Monthly Precipitation (mm)	
Month	2017	HM[†]	2017	HM[†]
May[‡]	14.1	10.4	7.1	50.4
June	16.9	15.2	31.3	78.9
July	21.8	18.3	34.7	53.4
August	18.6	17.6	44.5	45.2
September	13.3	12.0	13.7	33.9
October[§]	6.3	5.1	60.6	13.0

[†] HM = Historical means (1981 to 2010).

[‡] May weather data collection began on May 11th.

[§] October weather data collection ended Oct 9th

3.4.5 Spring 2017 soil sampling and analysis

Once each site was measured and flags placed to mark the plots, soil samples were taken in the last week of April along a 10-point diagonal transect from the north-west to the south-east corner of each site to a depth of 60 cm using an AMS dutch auger with a 7.5 cm core diameter. Before seeding and amendment application, each plot (48 saline/48 non-saline) was sampled for bulk density, OC, and EC using a 10 cm metal bulk density coring device. A plastic scraper was used to clean the bottom and sides of the core and a screw driver was used to assist in removal of each core from the sampling device into a labelled plastic bag. On May 18, 2017, one week after the amendments were applied, the surface layer (0-10cm) of each plot was sampled using a dutch auger for WEOC and LFOC analysis. The samples were immediately transported back to the laboratory in Saskatoon, chilled to 4ºC, and the WEOC analysis was completed the following day on the field moist soils.

Soil samples from the transect were air-dried, mixed and ground to pass through a 2 mm sieve and analyzed for OC, pH, EC, extractable nutrients (N, P, K, S, Ca, Na). Inorganic N (NH_4^+-N and NO_3^--N) and inorganic P were measured using 2.0 *M* KCl and modified Kelowna extractions, respectively, with the extracts analyzed colorimetrically (Qian et al., 1994). Extractable S was measured using 0.01 *M* $CaCl_2$ and analyzed using microwave plasma-atomic emission spectrometry (Houba et al., 2000). Extractable K, Ca, and Na were measured using 1.0*M* NH_4OAc and analyzed using atomic emission (K) and absorption (Ca and Na) spectroscopy. Soil organic C was measured using the LECO C632 Carbon Analyzer after sulfurous acid pre-treatment to remove inorganic C (Skjemstad and Baldock, 2007). Water extractable organic carbon was measured on field moist soils one day after sampling to avoid cell lysis and the release of soluble components into the extraction solution as described by Carter (1993) and adapted from Zsolnay (1996) and Kalbitz et al. (2003). Soil pH and EC (1:2 soil suspension, soil:water on a weight basis) was measured using pH and EC meters (Hendershot et al., 2008; Miller and Curtin, 2008).

3.4.6 Fall 2017 harvest and soil sampling and analysis

At the non-saline site, the canola and AC Saltlander crops were harvested using a hand sickle by taking two 1 m row lengths from the middle row of each plot. All aboveground biomass was harvested from each willow plot at both the non-saline and saline sites. Willow survival was poor and sporadic across the plot area, especially in the saline site due to the hot, dry spring. At the saline site, the entire area of each canola and AC Saltlander plot was harvested because patchy and sporadic growth within the plot due to salinity made conventional sampling using row lengths a less reliable method for comparison between treatments. Crops were cut approximately 3 cm from the ground and placed in cloth bags on site. All crops were harvested on Aug 10 and bags were transported back to the U of S where they were hung in a drying room at approximately 28° C. Once dried, the samples were ready for processing.

After threshing and cleaning the crop samples, the canola was analyzed for straw and grain yield, and N, P, Na, and Ca content in the straw and grain. The AC Saltlander green wheatgrass was analyzed for total biomass and N, P, Na, and Ca content in the above-ground biomass harvested. Total biomass was measured for the willow but due to very low survival (<15%), no further analysis was completed.

Total N, P, S, Ca and Na content of plant material was assessed using a hot sulfuric acid-peroxide digest performed on the grain and straw as outlined by Thomas et al. (1976). The extract was analyzed using atomic absorption/ flame emission spectroscopy for Ca and Na, microwave plasma emission spectroscopy for S and a Technicon™ automated colorimeter (AA-3) for N and P.

After harvest in the fall of 2017, in each plot, two soil core samples, one taken between the seed row and one taken within the seed row, were taken to a 60 cm depth and further divided into 0-15, 15-30, and 30-60 cm increments. The seed row and between seed row samples were combined into one bag to provide a composite sample for each depth increment and kept frozen until they were air dried, mixed, and ground to pass a 2 mm sieve. The processed samples were analyzed for total OC, pH, EC, and extractable nutrients (N, P, K, S, Ca, Na) as described previously. Two 0-10 cm soil cores, one inside the seed row and one outside, were also taken separately for the WEOC and LFOC analysis which was completed the following day on the field moist soil.

3.4.7 Spring 2018 soil and plant sampling

At the non-saline site and saline site, the AC Saltlander was harvested using a hand sickle by taking one quarter m^2 crop samples from each plot (Fig. 3.3 and 3.4). Samples of the AC Saltlander green wheatgrass taken in the spring of 2018 were taken from a different location in the plot than the fall 2017 samples. Crops were cut approximately 3 cm from the ground and placed in cloth bags on site. All crops were harvested on May 23, 2018 and bags were transported back to the U of S where they were hung in a drying room at approximately 28°C. Once dried, the samples were ready for processing. AC Saltlander was weighed for total biomass so that yield could be calculated and compared between treatments one year after seeding and amendment application.

At each plot, two soil core samples, one taken between the seed row and one taken within the seed row, were taken to a depth of 10 cm using metal bulk density rings for WEOC and LFOC analysis which was completed the following day on the field moist soil. The seed row and between seed row samples were combined into one bag to provide a composite sample. Separate composite samples were kept frozen until they were air dried, mixed, and ground to pass a 2 mm sieve. The processed samples were analyzed for bulk density and total SOC. Analysis was conducted using the same analytical methods used for the spring and fall 2017 samples as described above.

Fig. 3.3: AC Saltlander non-saline plots on June 3, 2018, approximately one year after seeding and amendment application. The blue flags mark the corners of each plot.

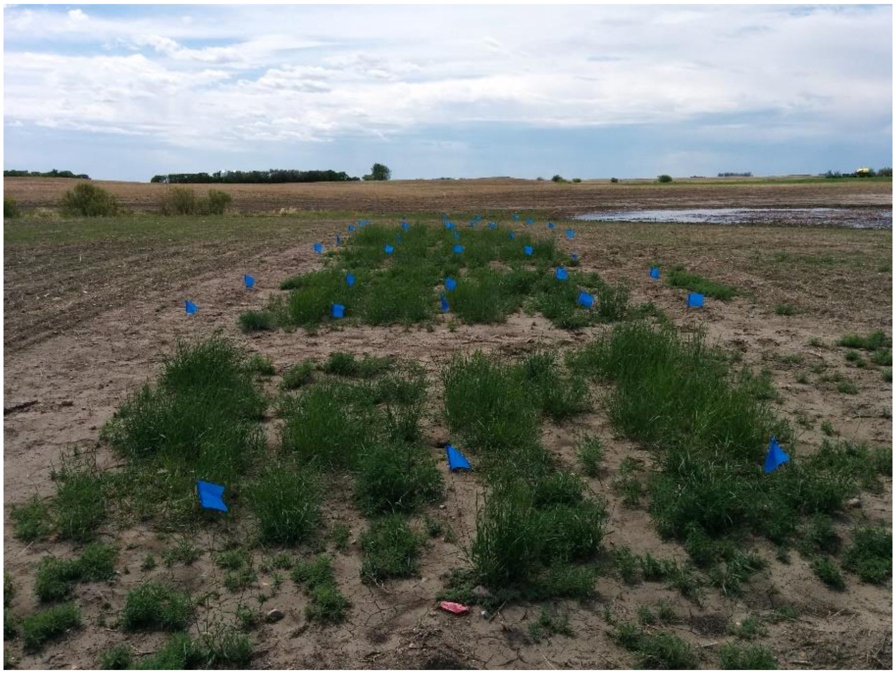

Fig. 3.4: AC Saltlander saline plots on June 3, 2018, approximately one year after seeding and amendment application.

3.4.8 Calculation of Mass of Soil Organic Carbon

The mass of soil organic carbon for each depth increment was calculated using the following equations (Nelson, 2002; Nelson et al., 2008):

$Mass_{SOC} = Conc_{SOC} \times \rho_b \times T \times 10{,}000\ m^2\ ha^{-1} \times 0.001\ Mg\ kg^{-1}$ **[Eq. 3.1]**

Where: $Mass_{SOC}$ = mass of OC per unit area ($Mg\ ha^{-1}$)

$Conc_{SOC}$ = OC concentration ($kg\ Mg^{-1}$)

ρ_b = air dry bulk density ($Mg\ m^{-3}$)

T = depth segment or thickness of soil increment layer (m)

3.4.9 Calculation of mass of light fraction organic carbon

The following two equations were used to calculate the mass of light fraction organic carbon in the 0-10cm depth at the saline and non-saline field sites (King et al., 2015).

3.4.9.1 Concentration of LFOC

$Conc_{LFOC} = [(dry_{LFOM} \times \%C_{LFOM}) / Wt_{soil}] \times 1000$ **[Eq. 3.2]**

Where $Conc_{LFOC}$ = concentration of the C in the light fraction ($kg\ Mg^{-1}$)

dry_{LFOM} = dry weight of light fraction organic matter (g)

$\%C_{LFOM}$ = percent of carbon in the light fraction organic matter (%)

Wt_{soil} = dry weight of soil from which the light fraction was separated from (g)

(Nelson, 2002)

3.4.9.2 Mass of Light Fraction Organic Carbon

$Mass_{LFOC} = Conc_{LFOC} \times \rho_b \times T \times 10\ 000\ m^2\ ha^{-1} \times 0.001\ Mg\ kg^{-1}$ **[Eq. 3.3]**

Where: $Mass_{LFOC}$ = mass of light fraction organic carbon per unit area ($Mg\ ha^{-1}$)

$Conc_{LFOC}$ = concentration of C in the light fraction ($kg\ Mg^{-1}$)

ρ_b = air dry bulk density ($Mg\ m^3$)

T = depth segment or thickness of the soil increment layer (m)

0.01 $Mg\ kg^{-1}$ = conversion factor

This calculation makes an adjustment for equivalent mass (Nelson, 2002).

3.4.10 Statistical analysis

All statistical analysis was completed using SAS version 9.4 (SAS Institute, Toronto, ON). Before analysis, all data was checked for outliers based on studentized residuals. Any observation >2 was considered an outlier and removed before analysis. For the field trial, data were analyzed as a RCBD design using the PROC GLIMMIX procedure with a significance level of 0.05. Since the GLIMMIX procedure accounts for normality and variances in the data set, no data transformation is necessary prior to analysis. An ANOVA was conducted, with the amendment treatment and crop as the fixed effects and replicate as a random effect. Least square means (LSMEANS) was used to compute each effect as well as the interaction between effects; LINES was used to compare means between effects; PDIFF was used to generate *p*-values for differences in the means comparisons; SLICE was used to specify effects within interactions for which to test for differences.

3.5 Results

3.5.1 Soil water extractable organic carbon

Water extractable organic carbon content of the soils measured one week after amendment application in the spring of 2017 showed no significant differences among amendment treatments (Table 3.5). However, WEOC content in the top 10 cm of the soil was significantly higher at the saline site compared to the non-saline site for all treatments (Table 3.5). At the end of the 2017 growing season, the WEOC content in the 0-10 cm depth at the non-saline site was significantly lower in plots amended with HA and CSM compared to control plots (Table 3.6); however, there was no significant effect of amendment application at the saline site (Table 3.6). The effect of crop was significant at both the saline and non-saline sites. At the non-saline site, plots seeded with AC Saltlander green wheatgrass had significantly higher WEOC compared to the canola and willow plots (Table 3.7). At the saline site, plots seeded with AC Saltlander and canola had significantly higher WEOC content compared to the willow plots (Table 3.7). Figures 3.5 and 3.6 depict the changes in WEOC from the beginning to the end of the growing season as affected by treatment. At the non-saline and saline sites in the fall after harvest, the surface soils under AC Saltlander green wheatgrass had WEOC that was 13 and 15 mg C kg^{-1} higher than in the spring one week after seeding (Fig. 3.6). At the saline site, WEOC after canola in the fall was 13.5 mg C kg^{-1} higher while at the non-saline site, there was a decrease in WEOC from spring to fall in the canola soil (Fig. 3.6). For all amendment treatments as well as the unamended control, the WEOC measured in fall after crop growth was higher than initially in the spring (Fig. 3.6). At the non-saline site, for all three amendments the increase in WEOC from spring to fall was significantly less than the control; conversely, there was no significant effect of amendment application on WEOC at the saline site (Fig. 3.6).

Table 3.5: Effect of organic amendment on water extractable organic carbon (mg C kg^{-1}) measured in the spring of 2017 in the 0-10 cm soil depth one week after amendment addition.

Site	Amendment[†]			
	CNTL	LEO	HA	CSM
Non-saline	$5.13^{a, B}$	$7.15^{a, B}$	$7.18^{a, B}$	$7.03^{a, B}$
Saline	$18.70^{a, A}$	$22.18^{a, A}$	$21.23^{a, A}$	$20.64^{a, A}$

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}). Means within a row followed by a different small letter are significantly different (n = 16, $P<0.05$). Means within a column follow by a different capital letter are significantly different (n = 16, $P<0.05$).

Table 3.6: Effect of organic amendment on water extractable organic carbon (mg C kg^{-1}) measured in the fall of 2017 in the 0-10 cm soil depth.

Site	Amendment[†]			
	CNTL	LEO	HA	CSM
Non-saline	$14.12^{a, B}$	$10.62^{ab, B}$	$9.87^{b, B}$	$8.76^{b, B}$
Saline	$31.68^{a, A}$	$33.53^{a, A}$	$29.95^{a, A}$	$32.30^{a, A}$

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}). Means within a row followed by a different small letter are significantly different (n = 16, $P<0.05$). Means within a column follow by a different capital letter are significantly different (n = 16, $P<0.05$).

Table 3.7: Effect of crop on water extractable organic carbon (mg C kg⁻¹) measured in the fall of 2017 in the 0-10 cm soil depth.

Site	Crop†		
	AC Saltlander	Hybrid Argentine Canola	Tully Champion Willow
Non-saline	22.71$^{a, B}$	5.24$^{b, B}$	4.58$^{b, B}$
Saline	34.43$^{a, A}$	35.23$^{a, A}$	25.94$^{b, A}$

[†] A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha⁻¹; Liberty Link 252 hybrid argentine canola seeded at a rate of 10 kg ha⁻¹ in rows spaced 25 cm apart; and Tully Champion willow planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot. Means within a row followed by a different small letter are significantly different (n = 48, P<0.05). Means within a column follow by a different capital letter are significantly different (n = 48, P<0.05).

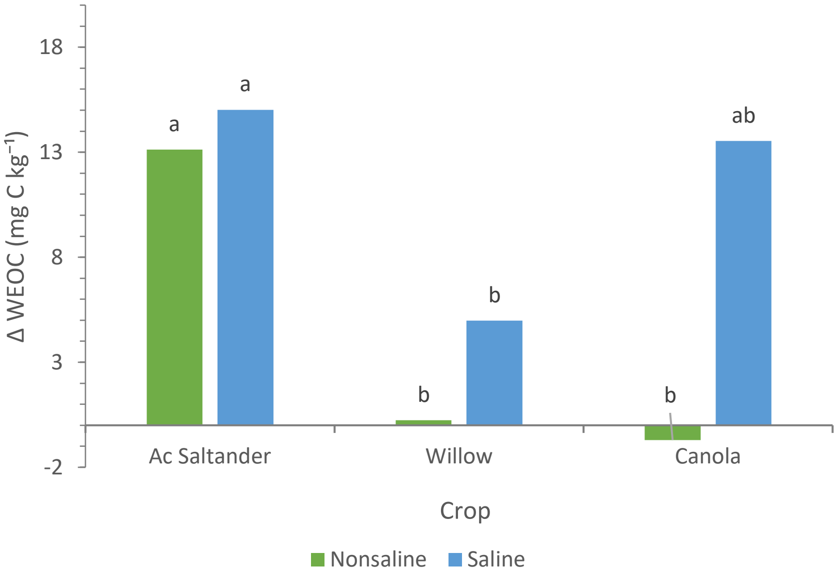

Fig. 3.5 Change in WEOC (mg C kg⁻¹) from the spring one week after seeding and amendment application to the fall of 2017 after harvest in the 0-10cm depth under the different crop treatments. Means within a site (non-saline, saline) followed by a different letter are significantly different (n = 48, P<0.05). A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha⁻¹; Liberty Link 252 hybrid argentine canola seeded at a rate of 10 kg ha⁻¹ in rows spaced 25 cm apart; and Tully Champion willow planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot.

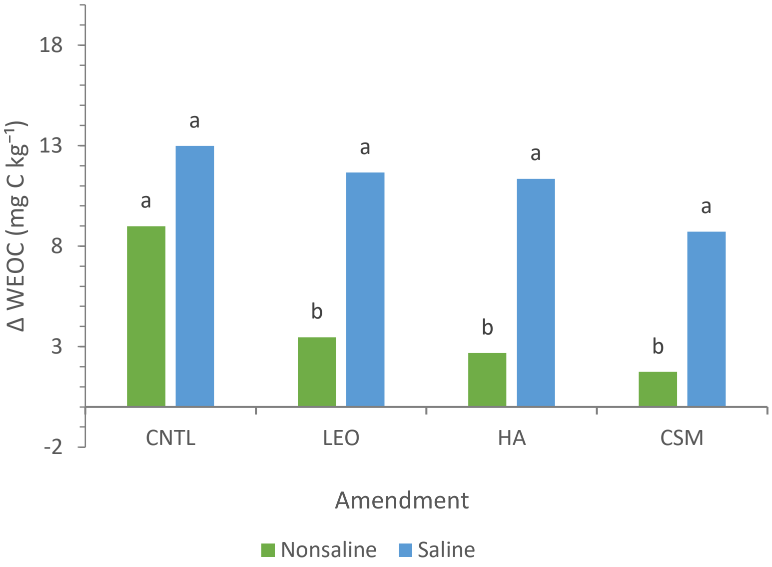

Fig. 3.6: Change in WEOC (mg C kg^{-1}) from the spring one week after seeding and amendment application to the fall of 2017 after harvest in the 0-10 cm depth under the different amendment treatments. Means within a site (non-saline, saline) followed by a different letter are significantly different (n = 16, P<0.05). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

3.5.2 Light fraction organic carbon

At the saline site after the first season of crop growth in the fall of 2017, the AC Saltlander green wheatgrass plots amended with leonardite had significantly more LFOC in the 0-10cm layer of soil compared to unamended plots or the CSM and HA treatments (Fig. 3.7). This effect was also evident when soil samples were collected from the same 0-10cm depth in the spring of 2018 and the LFOC was measured (Fig. 3.8). Plots amended with LEO contained an average of 3.91 Mg ha^{-1} of LFOC which was significantly greater than the CNTL plots which had an average of 1.97 Mg ha^{-1} of LFOC at the saline site (Fig. 3.8). The LFOC mass in the LEO and CSM amended plots were not significantly different from each other in the spring of 2018 but the HA treatments only contained an average of 1.64 Mg ha^{-1} of LFOC, which was significantly lower than LEO amended plots (Fig. 3.8). An amendment treatment effect was not apparent in the non-saline soil in either the fall of 2017 or the following spring of 2018.

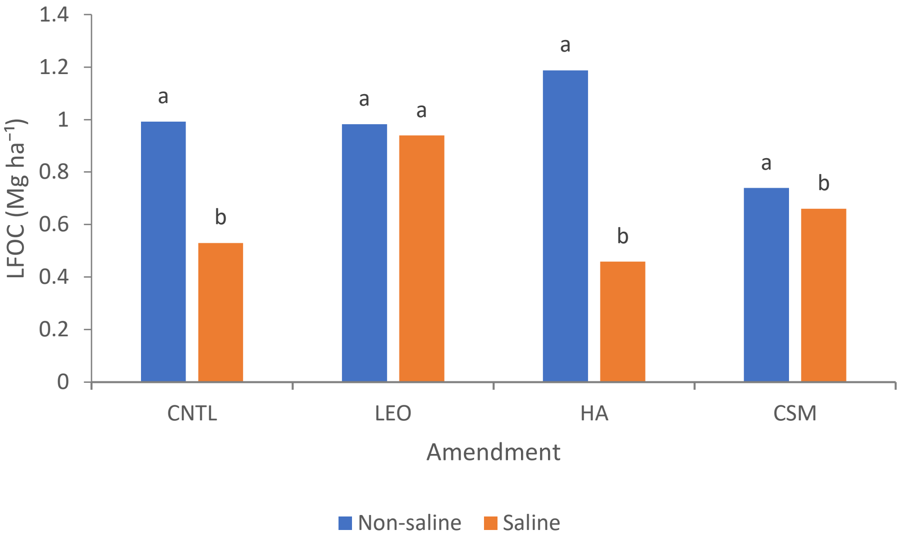

Fig. 3.7: Effect of amendment on LFOC mass in the 0-10 cm depth of the AC Saltlander green wheatgrass plots measured in the fall of 2017. Means within a site (non-saline, saline) followed by a different letter are significantly different (n = 16, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

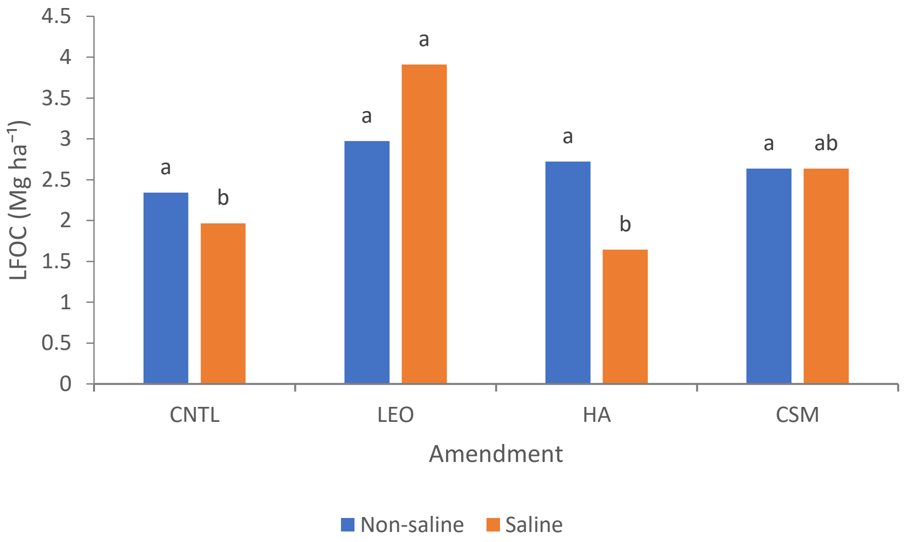

Fig. 3.8: Effect of amendment on LFOC mass in the 0-10 cm depth of the AC Saltlander green wheatgrass plots measured in the spring of 2018. Means within a site (non-saline, saline) followed by a different letter are significantly different ($n = 16$, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

3.5.3 Total soil organic carbon

The amounts of total soil organic carbon in the soil profile were similar among the two sites (Table 3.8). This contradicts expectations that the total soil organic carbon content would be lower in the saline site than the non-saline site. The mass of total soil organic carbon in the 0-15, 15-30, and 30-60 cm depths at the saline and non-saline sites measured in the fall of 2017 after amendment that was made in the spring followed by one season of crop growth showed none of the amendments had a significant effect on the total amount of SOC compared to the control (Table 3.8). However, the effect of the crop grown was significant. At the non-saline site, AC Saltlander green wheatgrass had significantly higher OC at all depths compared to the willow plots (Fig. 3.9 and Table 3.9) and at the 15-30 cm depth compared to the canola (Table 3.9). At the saline site, total SOC was significantly greater under canola compared to willow at the 30-60 cm depth (Table 3.9) but there was no significant difference among the three crops in the 0-15 cm depth (Fig. 3.10). In the spring of 2018 at the non-saline site, all three amendments resulted in significantly higher total SOC compared to the control in the 0-10 cm depth (Fig. 3.11), with the leonardite amended surface soils having significantly higher total SOC mass compared to the HA, CSM, and CNTL treatments (Fig. 3.11). Similarly, at the saline site, LEO amendment resulted higher total SOC mass in the surface which was significantly greater than the CNTL and HA (Fig. 3.12); the CSM plots also contained significantly higher amounts of total SOC compared to the HA but were not significantly different compared to the CNTL (Fig. 3.12). After one year, LEO amended AC Saltlander plots significantly increased total SOC in the 0-10 cm depth by 6.71 and 7.59 Mg C ha^{-1} in the non-saline and saline plots, respectively (Fig. 3.13). Unamended AC Saltlander plots (i.e. CNTL) lost 2.86 Mg C ha^{-1} from the spring of 2017 to the spring of 2018 and in the saline plots, both LEO and CSM increased total SOC significantly more than CNTL and HA after one year (Fig. 3.13).

Table 3.8: Effect of amendment on total soil organic carbon mass (Mg ha⁻¹) measured in the fall of 2017 to a depth of 60 cm in three depth increments.

Depth (cm)	Amendment[†]			
	CNTL	LEO	HA	CSM
	Mg C ha^{-1}			
	Non-saline site			
0-15	26.00^{a}	26.51^{a}	26.92^{a}	26.46^{a}
15-30	14.32^{a}	14.00^{a}	15.47^{a}	15.92^{a}
30-60	28.15^{a}	27.82^{a}	26.07^{a}	28.09^{a}
	Saline site			
0-15	29.53^{a}	31.14^{a}	28.22^{a}	29.61^{a}
15-30	20.85^{a}	20.10^{a}	19.08^{a}	19.39^{a}
30-60	31.56^{a}	32.55^{a}	31.45^{a}	29.30^{a}

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha⁻¹); HA: humic acid (seed placed at 200 kg ha⁻¹); and CSM: composted steer manure (broadcast and incorporated at 10 t ha⁻¹). Means within a row followed by a different letter are significantly different (n = 48, P<0.05).

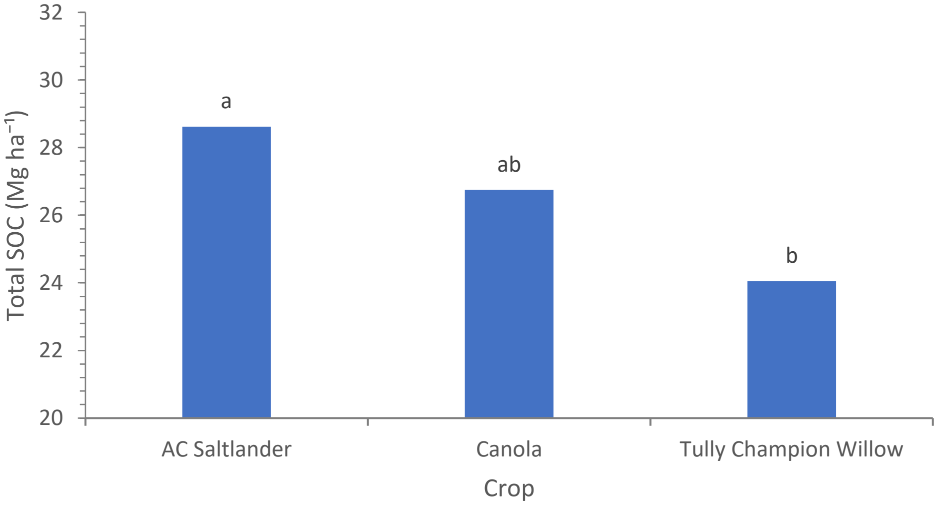

Fig. 3.9: Effect of crop on total soil organic carbon (Mg ha⁻¹) measured in fall of 2017 at the end of the growing season in the 0-15 cm depth at the non-saline site. Means followed by a different letter are significantly different (n = 48, P<0.05). A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha⁻¹; Liberty Link 252 hybrid argentine canola seeded at a rate of 10 kg ha⁻¹ in rows spaced 25 cm apart; and Tully Champion willow planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot.

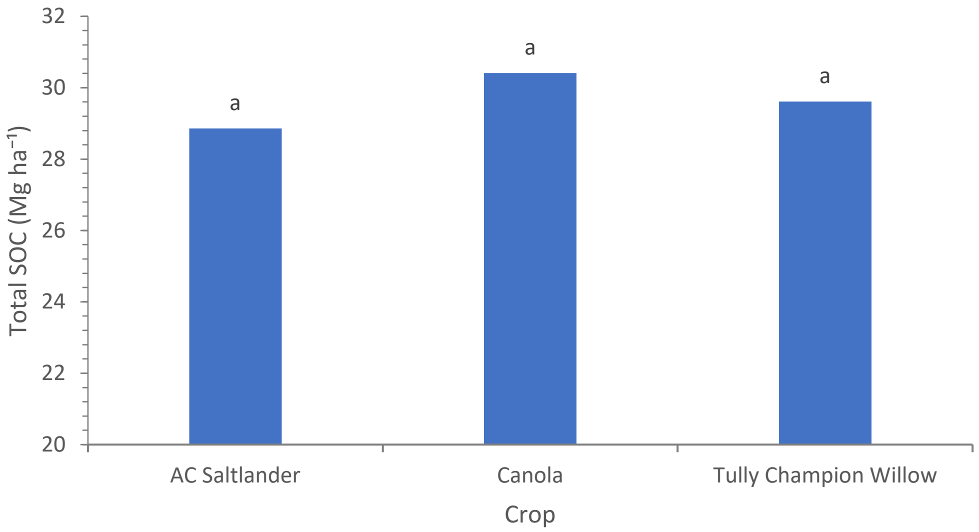

Fig. 3.10: Effect of crop on OC (Mg ha^{-1}) measured in the fall of 2017 at the end of the growing season in the 0-15 cm depth at the saline site. Means within site followed by a different small letter are significantly different ($n = 48$, $P<0.05$). A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha^{-1}; Liberty Link 252 hybrid argentine canola seeded at a rate of 10 kg ha^{-1} in rows spaced 25 cm apart; and Tully Champion willow planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot.

Table 3.9: Effect of crop on total soil organic carbon (Mg ha^{-1}) measured in the fall of 2017 to a depth of 60 cm in three depth increments. Means within a row followed by a different small letter are significantly different (n = 48, P<0.05).

Depth (cm)	Crop[†]		
	AC Saltlander	Canola	Tully Champion Willow
		Mg C ha^{-1}	
	-------------------------------- Non-saline site --------------------------------		
0-15	28.62^{a}	26.75^{ab}	24.05^{b}
15-30	16.55^{a}	14.65^{b}	13.58^{b}
30-60	30.15^{a}	27.42^{ab}	25.03^{b}
	---------------------------------- Saline site ----------------------------------		
0-15	28.86^{a}	30.41^{a}	29.61^{a}
15-30	20.43^{a}	20.14^{a}	18.99^{a}
30-60	30.44^{ab}	33.89^{a}	29.32^{b}

[†] A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha^{-1}; (InVigor L252) Liberty Link 252 canola seeded at a rate of 10 kg ha^{-1} in rows spaced 25 cm apart; and Tully Champion willow planted at 3 plants per row with 60 cm spacing between plants and 25.4 cm row spacing for a total of 9 plants per plot.

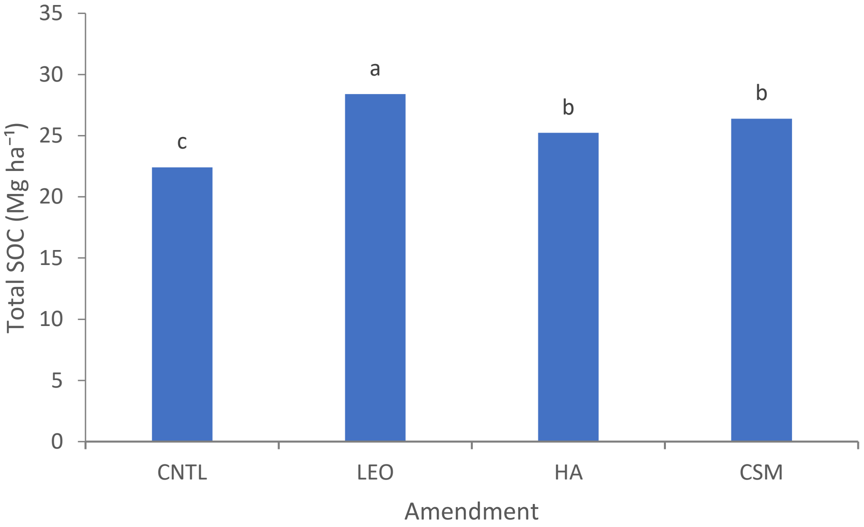

Fig. 3.11: Effect of amendment on total soil organic carbon (Mg ha^{-1}) measured in the spring of 2018 one year after amendment application in AC Saltlander plots in the 0-10 cm depth at the non-saline site. Means within site followed by a letter are significantly different (n = 16, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

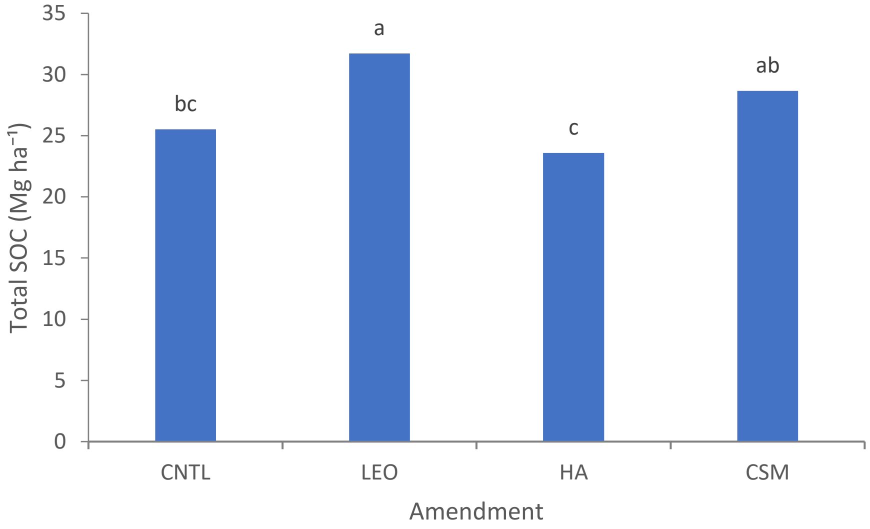

Fig. 3.12: Effect of amendment on total soil organic carbon (Mg ha^{-1}) measured one year after amendment application in the spring of 2018 under AC Saltlander plots in the 0-10cm depth at the saline site. Means within site followed by a small letter are significantly different (n = 16, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

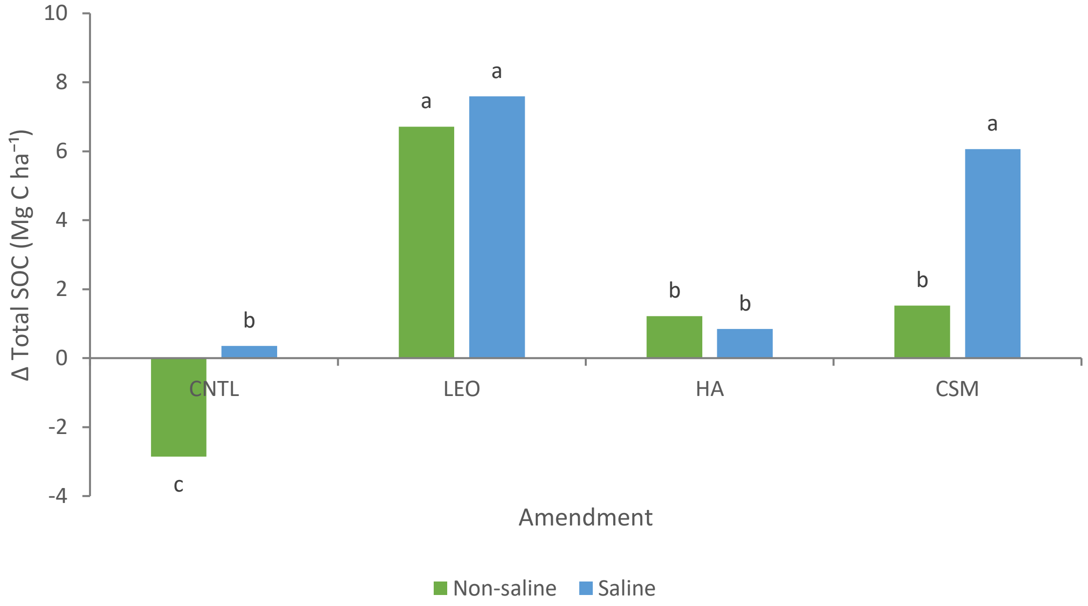

Fig. 3.13: Change in total SOC (Mg C ha^{-1}) over one year, from the spring of 2017 to the spring of 2018 in the AC Saltlander plots. Means within site followed by a letter are significantly different (n = 16, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

3.5.4 Crop yield

The yields of AC Saltlander green wheatgrass and canola measured in the fall of 2017 were 4 to 5 fold greater on the non-saline site compared to the saline site (Figs. 3.14 and 3.15) reflecting the effect of the severely saline nature of the soil on reducing plant growth, especially under the dry conditions of the 2017 season. None of the amendments had a significant effect on the yield of the AC Saltlander or canola at the non-saline or saline sites (Figs 3.14 and 3.15). However, at the non-saline site, canola amended with CSM tended to have lower yields compared to CNTL, LEO, and HA, although no significant differences were observed (Fig. 3.15). The composted cattle manure amendment visibly resulted in more variable germination, emergence and growth of the canola across the plot area, possibly due to uneven distribution of the manure lumps, leaving a seedbed that was uneven. Compared to the non-saline site, crop yields at the saline site were about 5 times lower for AC Saltlander (Fig. 3.14) and 4-5 times lower for canola (Fig. 3.15). Significant precipitation received at the site in the fall of 2017 encouraged late fall and early spring growth of the AC Saltlander wheat grass forage on the saline site. Yield measurements taken one year after seeding in the spring of 2018 revealed less difference in yield between the saline and non-saline sites (Fig 3.16). As in the fall 2017 yield assessment, the spring 2018 AC Saltlander biomass yield was not significantly influenced by amendment. As well, in spring 2018 the CSM treatment had the highest mean yield. This may reflect the further breakdown and decomposition of the cattle manure compost in the fall and spring and release of nutrients by mineralization induced by the later fall rains.

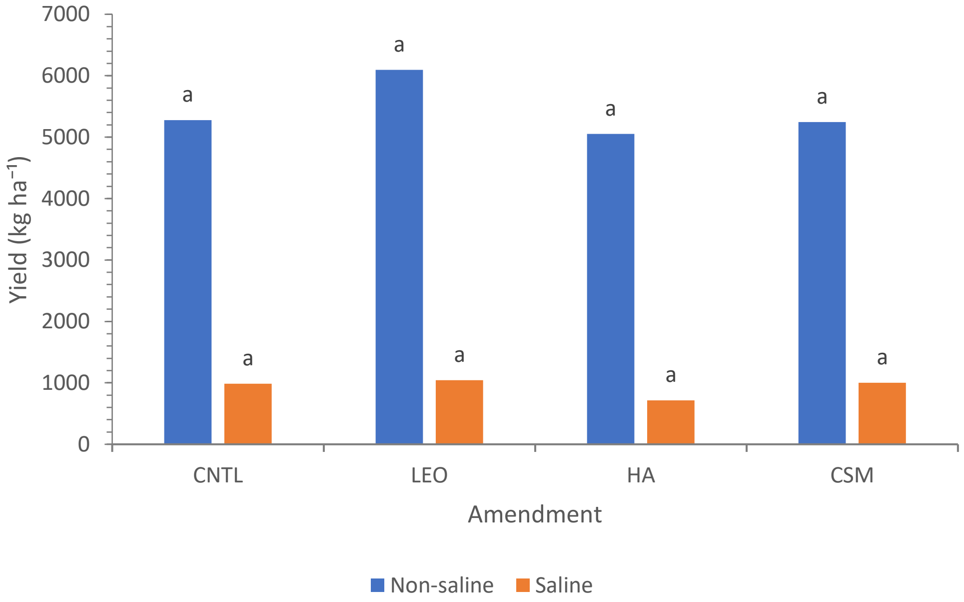

Fig. 3.14: Effect of organic amendment on total above ground biomass yield of AC Saltlander green wheatgrass in the fall of 2017 after one growing season in the non-saline and saline sites. Means for amendment treatments within each site (non-saline, saline) followed by a different letter are significantly different (n = 16, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

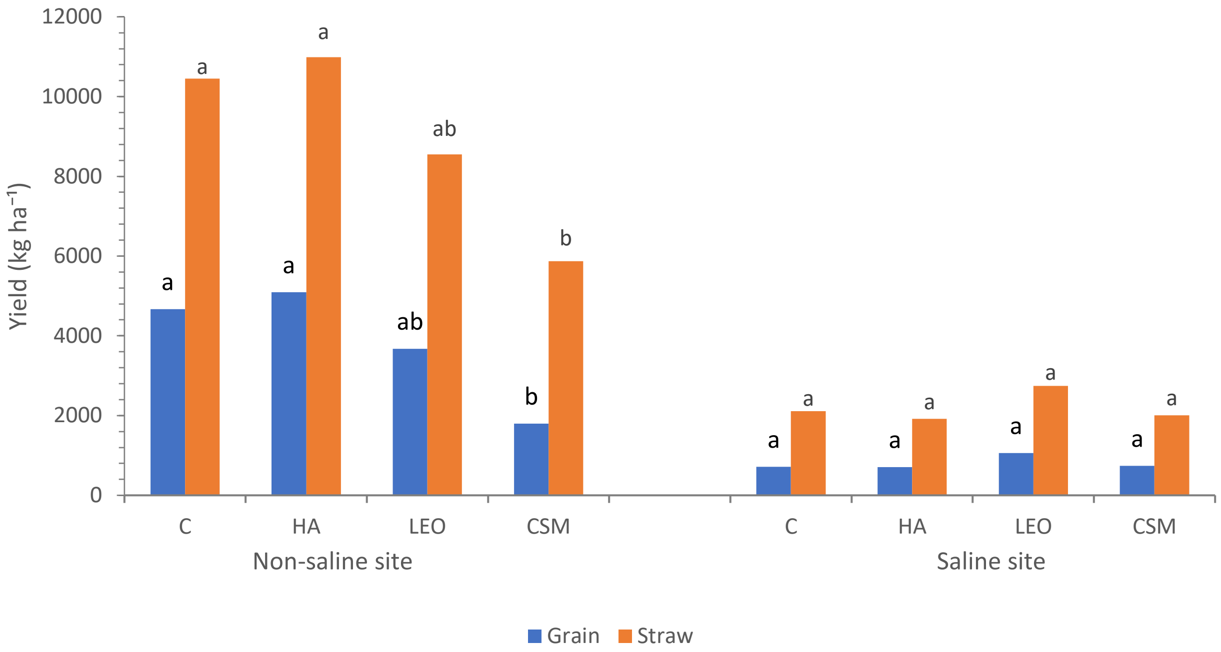

Fig. 3.15: Effect of organic amendment on grain and straw yield of canola in the fall of 2017 after one growing season in the saline and non-saline sites. Means within each site followed by a different letter are significantly different ($n = 16$, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

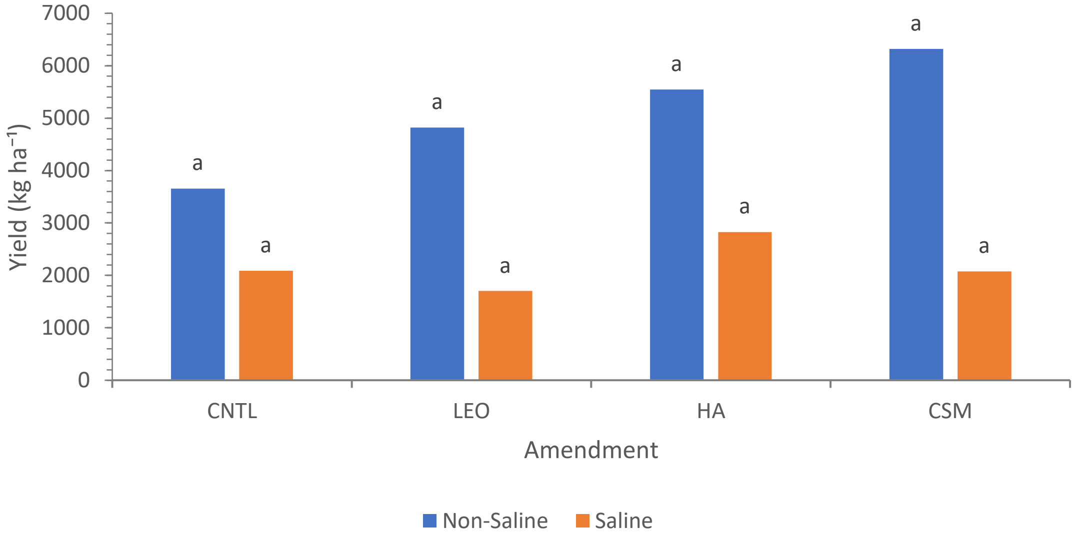

Fig. 3.16: Effect of organic amendment on total above-ground biomass yield of AC Saltlander green wheatgrass in spring of 2018 one year after seeding and amendment application. Means within a site (non-saline, saline) followed by a different letter are significantly different ($n = 16$, $P<0.05$). A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

3.5.5 Nutrient uptake in AC Saltlander green wheatgrass and canola

AC Saltlander green wheatgrass and canola straw N, P, Na, and Ca nutrient uptake at the non-saline and saline sites are shown in Table 3.10. There were no significant differences in N, P, Na, or Ca nutrient uptake among the amendment treatments applied to AC Saltlander green wheatgrass at either the non-saline or saline site (Table 3.10). Na uptake in canola straw was significantly higher in the CNTL and HA treatments compared to CSM at the non-saline and Ca uptake was significantly higher in HA amended plots compared to both the LEO and CSM plots at the non-saline site (Table 3.10). Lower nutrient uptake by canola in the CSM amendment treatment is explained by low and variable canola yield in this treatment. There were no significant differences between treatments at the non-saline or saline sites for N, P, Na, or Ca nutrient uptake in canola grain.

Table 3.10: Nutrient uptake (kg ha^{-1}) in AC Saltlander green wheatgrass above-ground biomass and canola straw at the saline and non-saline sites in fall 2017. Means in a row within a site followed by the same letter are not significantly different (n = 16, P<0.05).

	Site									
	Non-saline					Saline				
	Treatment[†]					Treatment[†]				
Nutrient uptake (kg ha)	CNTL	LEO	HA	CSM	*P* value	CNTL	LEO	HA	CSM	*P* value
-------------------------- AC Saltlander --------------------------										
N[‡]	78^{a}	85^{a}	85^{a}	78^{a}	0.9042	16^{a}	18^{a}	13^{a}	17^{a}	0.7557
P[‡]	6^{a}	7^{a}	6^{a}	6^{a}	0.6243	2^{a}	2^{a}	1^{a}	2^{a}	0.5734
Na[§]	1^{a}	1^{a}	1^{a}	1^{a}	1.000	0.3^{a}	0.3^{a}	0.2^{a}	0.3^{a}	1.000
Ca[§]	19^{a}	19^{a}	20^{a}	18^{a}	0.9958	3^{a}	4^{a}	2^{a}	4^{a}	0.8460
-------------------------- Canola --------------------------										
N[‡]	55^{a}	41^{a}	57^{a}	38^{a}	0.3397	13^{a}	15^{a}	12^{a}	12^{a}	0.9325
P[‡]	4^{a}	3^{a}	3^{a}	3^{a}	0.6941	1^{a}	1^{a}	1^{a}	1^{a}	1.000
Na[§]	73^{a}	52^{ab}	63^{a}	37^{b}	0.0231	12^{a}	19^{a}	12^{a}	17^{a}	0.3355
Ca[§]	45^{ab}	33^{bc}	53^{a}	27^{c}	0.0126	6^{a}	7^{a}	5^{a}	5^{a}	0.8138

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

3.5.6 Post-harvest soil nutrient content

The effect of LEO, HA, CSM, and CNTL treatments on soil NO_3-N, SO_4-S, P, K, Na, Ca, Mg, pH, and EC in the 0-15, 15-30 and 30-60 cm depth under AC Saltlander, canola, and willow measured after harvest in the fall of 2017 are presented in the appendix (Tables 7.1, 7.2 and 7.3). Overall, there was no significant effect of amendment on post harvest soil nutrient concentrations under AC Saltlander at the saline or non-saline site. For soils under canola, there was only significantly higher Na in CSM amended plots compared to HA and CNTL at the non-saline site, possibly reflecting addition of Na in the manure. At the saline site, there was significantly higher SO_4-S in LEO amended plots compared to HA and CSM, and significantly higher Ca in LEO and HA amended plots compared to CSM and CNTL plots. For willow, there was significantly higher NO_3-N in plots amended with LEO, HA, and CSM compared to CNTL at the non-saline site. This may reflect enhanced mineralization with the organic amendments coupled with low plant uptake of N in the willow plots due to establishment failure.

3.6 Discussion

3.6.1 Carbon content and dynamics in saline soils

It was hypothesized that amounts of total SOC and labile WEOC and LFOC fractions would be higher in non-saline compared to the saline soils. However, the results of this thesis work conducted on adjacent non-saline and saline soil in the same field revealed similar amounts of soil organic carbon and its fractions. This is in contrast to other studies such as Pankhurst et al. (2001), Garcia et al. (1994), and Setia et al. (2013b) who measured or reported lower SOC stocks in saline compared to non-saline soils. This may be explained by the continued growth of well adapted, salt-tolerant plants in the saline areas of the field since conversion of the field from native short grass prairie to annual cropping in the 1920's. Salt-tolerant weeds including foxtail barley (*Hordeum jubatum*) and eventually other introduced species like kochia (*Bassia scoparia*) that grew on salt-affected areas of the field since cultivation would continue to add significant amounts of carbon. Unlike agricultural crops where the majority of aboveground biomass is harvested and removed from the field, these salt tolerant weeds can return comparatively large amounts of OM to the soil since they are left to decompose in the field. The dense cover provided by these weeds also protects the soil surface from wind and rain erosion leading to decreased losses of surface SOC. Though foxtail barley and kochia may stabilize and add OM to the soil, it can cause problems when used as feed for cattle, especially when fed in excessive amounts (Henry et al., 1987).

Despite the saline field site having an EC > 8.0 dS m^{-1}, and therefore being classified as severely saline, salt adapted plants like kochia can take hold and grow in these areas. However, the research conducted in this thesis shows other more useful plants, such as AC Saltlander green wheatgrass are also adapted for these extreme soil environments and cannot only compete with kochia but provide a source of palatable forage grass for livestock. After just one year of growth, the stands of AC Saltlander in the research plots were well established and weed growth was greatly reduced.

Water extractable organic carbon is a highly dynamic fraction of soil organic carbon of short-term residence that fuels microbial activity (Chantigny et al., 2008). Due to its dynamic nature, WEOC is often measured several times throughout a season. In the current study, it was measured only at the beginning and end of the growing season. However, the results suggest that the AC Saltlander tended to increase WEOC amount from beginning to end of season. At the saline site, seeding to AC Saltlander increased WEOC by ~ 15 mg C kg^{-1} over one growing season.

An interesting finding of this research work is the overall higher levels of WEOC found in the soils of the saline site compared to the non-saline field site. Mavi et al. (2012) found that salinity adversely affects microbial activity and also increases dissolved organic carbon, provided the soil has a low SAR which was true for the severely saline (>8.0 dS m^{-1}) but not highly sodic (SAR 5.51-7.14 < 13) soil in this study. It would be worthwhile to further examine this proposed relationship between salinity, sodicity and WEOC. Setia et al. (2013b) suggested adsorption that reduces decomposition along with decreased leaching losses of WEOC could also contribute to more WEOC in saline soils.

Unlike WEOC and total SOC, the LFOC tended to be similar or slightly higher in the non-saline compared to the saline plots. Recent plant residue inputs would be present in both systems to contribute to LFOC. Measurements taken in the fall of 2017 showed LFOC was higher in all non-saline plots compared to the saline site which was also the trend when LFOC was measured in the spring 2018 with the exception of the LEO amended plots where LFOC was higher at the saline site compared to the non-saline site. The LFOC amounts measured at both sites were similar to those reported in a study by Biederbeck et al. (1994) who also measured LFOC in a Brown Chernozem from southern Saskatchewan.

The non-saline site soils showed no significant treatment effect of added organic amendment, but at the saline site, leonardite significantly increased LFOC mass in the surface soil compared to the CNTL, HA, and CSM amended plots in the fall of 2017. When LFOC was measured again in soils collected in the spring of 2018, the LEO amended plots continued to have significantly higher amounts of LFOC compared to CNTL and HA in the saline soil. The greater treatment effect in the saline soil may be a result of decreased microbial activity leading to less mineralization of the added C in the leonardite.

3.6.2 Carbon storage in saline and non-saline soils

At the end of the 2017 growing season, the selected amendments made in the spring had little impact on total SOC in the three depths at both the saline and non-saline sites. However, measurements taken in the following spring in May 2018, one year after seeding and amendment application, showed significant treatments effects at both sites with leonardite amended plots having the greatest increase in total SOC in the surface soil followed by CSM. This finding supports the hypothesis that LEO and CSM will have greater impacts on C dynamics and sequestration compared to HA and CNTL due to the greater amounts of organic carbon directly added in the amendment. This effect was not detected in the fall 2017 sampling which may be due to dry conditions in the spring and summer of 2017 and variable distribution and decomposition of the amendments within the plots (Wuest 2014). A reduced sampling depth of 10cm in spring of 2018 versus 15 cm in fall of 2017 may also have enabled the treatment effect to be more easily detected due to less dilution and variability introduced from soil and organic carbon added from the B horizon. The higher SOC in LEO amended plots is likely explained by lower decomposition rate of LEO due to its more humified nature and C:N ratio of 74:1 compared to that of the CSM which was 14:1. Our results are in agreement with a similar study by del Mar Montiel-Rozas et al. (2016) that showed leonardite was a more suitable treatment for long-term C storage compared to biosolid compost.

Growing the AC Saltlander for one year had a significant effect on increasing total SOC compared to the canola and willow at the non-saline site, however, this effect of crop species was not evident at the saline site, likely due to the overall inhibitory effect of salinity on plant growth. Without severe salinity hampering growth, the extensive root network and below ground productivity of perennial grasses such as AC Saltlander can manifest itself and significantly add to the SOC pool, which was observed in our study. This likely explains the differences in total SOC amounts observed between the AC Saltlander, canola, and willow, especially at the lower depths sampled. A similar study by Liebig et al. (2005) showed significantly higher SOC in switchgrass stands compared to cultivated land in the northern Great Plains of the United States, which agrees with our results.

3.6.3 Crop yield, nutrient uptake and residual soil nutrients

Not surprisingly, biomass yield and nutrient uptake was significantly higher for crops grown at the non-saline site compared to the saline site. However, the hypotheses that organic amendments will increase yield and nutrient uptake and that the response of yield and nutrient uptake response will be greater in non-saline compared to saline soils was not confirmed in this study as no significant differences in crop yield or nutrient uptake were observed from amendment application in either the saline or non-saline site (Table 3.10). Yields of AC Saltlander measured in the fall of 2017 in the non-saline soil were similar between CNTL and the amendments. However, in the spring of 2018 there was a trend of higher yield of green wheatgrass in the organic amendment treatments compared to the CNTL. This may be a consequence of continued decomposition with narrowing of the carbon to nitrogen ratio and eventual onset of nutrient release. The same trend was not observed in the saline site. This may suggest the amendments have potential to eventually improve yield of AC Saltlander, but this response may be delayed until the second or subsequent years of growth especially in saline soils where decomposition rates of amendments may be limited. The decrease in yield of AC Saltlander in the saline compared to non-saline site (Fig. 3.14) were similar to the relative yield decrease of AC Saltlander measured by Steppuhn et al. (2006) under similar salinity levels.

Canola showed no significant response to amendment application for either straw or grain yield or nutrient uptake at the non-saline or saline site, with a negative trend evident for the CSM, possibly due to problems in canola germination and emergence arsing from uneven distribution of the manure and canola seeds in the soil. This is in contrast to a study by Akinremi et al. (2000) who showed an increase in yield and significant increase in N, P, K, and S uptake in canola in a controlled environment pot study with LEO amendment. However, in their study, Akinremi et al. (2000) used low fertility soil and saw the greatest response of canola to LEO when no other nutrients were added which was attributed to S provided by the LEO. In our field experiment, fertilizer application at recommended rates was made, and soil sulfate levels were high, especially in the saline soil. This may have masked any benefit of LEO to supply S to canola plants leading to differences in yield or nutrient uptake. This may also the be the case for the CSM treatment as inorganic fertilizers applied to the plots were sufficient for supplying nutrients required by the crops grown in the initial growing season. Residual soil available N and P were relatively low at the end of the 2017 season so more benefit from slow release of nutrient from the amendments may be anticipated in subsequent years.

4. Incubation Experiment

4.1 Preface

To further explore C dynamics in non-saline and saline soils, an incubation experiment was set up under controlled environmental conditions to measure soil microbial respiration (SMR) and the response of microbial communities to the three amendments (LEO, HA, CSM) used in the field study outlined in Chapter 3 of this thesis. A low fertility tropical soil collected near Ogbomosho, Nigeria, was also included in this study to evaluate how microbial respiration responds when high amounts of C are added to soils with low OM content and to compare to the non-saline and saline soils of Saskatchewan. The controlled environment study described in this chapter offers the ability to examine and compare organic carbon short-term turnover under ideal moisture and temperature conditions as affected by LEO, HA, and CSM amendment.

4.2 Abstract

To assess short-term carbon turnover via mineralization as affected by soil conditions and organic amendment treatment, a one-month incubation experiment was setup to measure the effect of leonardite (LEO), humic acid (HA), and composted steer manure (CSM) amendment compared to an unamended control (CNTL) on soil microbial respiration in low organic matter, non-saline and saline surface soils collected from a farm field in south-central Saskatchewan as well as from the Ogbomosho region of Nigeria. In the non-saline soil from Saskatchewan, the CSM produced significantly greater cumulative CO_2-C emissions compared to the CNTL; in the Ogbomosho soil, CSM produced significantly greater cumulative CO_2-C emissions compared to LEO and HA amended soils. In the saline soil, however, no significant amendment effect was observed, which may be explained by the higher availability of easily decomposable substrate (water extractable organic matter) measured in this soil compared to the other two soils which dominated over the carbon provided by the amendments. The saline soil had significantly higher CO_2-C production than the non-saline soil for the CNTL, LEO and HA amendments and for all treatments compared to the Ogbomosho soil. The results of this experiment indicate that microbial carbon turnover in saline soils under ideal moisture and temperature conditions of incubation is high, with C mineralization rates are that are comparable to non-saline soils from the same environment.

4.3 Introduction

Measurement of soil microbial respiration can be used to investigate soil organic matter decomposition and make relative assessments of microbial activity as affected by an imposed treatment. Emission of CO_2 from the soil is a consequence of SOC mineralization by the soil microbial community and has been assessed through incubation of cores of soil and measurement of the CO_2 produced (Alotaibi and Schoenau, 2013). Several previous experiments assessing microbial respiration in saline soils have shown a negative relationship between EC and SMR (Garcia and Hernandez 1996; Pankhurst et al., 2001; Yuan et al., 2007; Mavi et al., 2012), which has been attributed to negative effects of increased osmotic potential on increasing water stress to the microbial population. However, other studies have suggested that a well-adapted salt tolerant microbial community exists that may respond quickly to C additions, especially when subjected to heavy rain events leading to the leaching of salts from the soil surface (Wong et al., 2009; Asghar et al., 2012).

The field experiment conducted in 2017 in south-central SK on non-saline and saline portions of a farm field, described in detail in Chapter 3, revealed some significant effects of amendment applications on contents of total soil organic carbon, as well as labile organic fractions. Differences in the amounts of carbon in the fractions were also observed between the non-saline and saline site soils that suggest that responses to amendment and crop differ under different salinity scenarios. To further explore the hypothesis that soil salinity and organic amendment are important factors controlling carbon amounts and turnover, a 29-day incubation experiment was conducted under controlled conditions to provide further insight into the mechanisms that affect C cycling in these Saskatchewan soils. For comparative purposes, a non-saline low organic matter soil from the Ogbomosho region of Nigeria was included in the incubation study. The experimental design is similar to that used in experiments reported on by

Alotaibi and Schoenau (2013) and Hangs et al. (2013). The objectives of the research described in this chapter were to evaluate and compare the short-term soil microbial respiration as affected by three amendments (LEO, HA and CSM) made to contrasting soils.

4.4 Materials and Methods

4.4.1 Soils

The saline and non-saline soils used for this study were collected from the surface layers (0-15 cm) of a cultivated (cereal-legume-oilseed rotation) Brown Chernozem (Haverhill-Rosemae soil association) near Central Butte, Saskatchewan in the non-amended portions of the saline and non-saline field study sites described in section 3.1.1. The non-saline soil was collected from an upper slope area approximately 50 m north of where the saline soil was collected, which was a slightly lower depressional area. To provide another contrasting low organic matter non-saline soil from a completely different environment for comparison, a soil that had been collected from the Ogbomosho region of Nigeria was included in the incubation study as well. The Ogbomosho (OG) soil was collected from the 0-20 cm depth from an agricultural site in the Savanah eco-region near Ogbomosho, Nigeria, then packaged and shipped back to Canada. Although a sandy soil from Saskatchewan could have been used in place of the Ogbomosho soil, the highly weathered tropical soil with a different biological profile, management practices, and organic matter inputs provided the greatest contrast to the Saskatchewan soils when comparing the effects of amendments. The soils were each mechanically mixed using a large mixer to provide homogenized samples that were then stored at approximately 20°C until use. The soils were potted on Sept 11, 2017 to reduce the impact of storage on biological properties (Zelles et al., 1991). Selected chemical properties of the soils are given in Table 4.1.

Table 4.1: Summary of the properties of the soil collected from the non-saline and saline field sites near Central Butte SK, Canada and Ogbomosho, Nigeria. Values are means from analysis of ten individual soil cores.

Depth					Soil Property						
	N[†]	P[‡]	K[‡]	S[§]	Na[¶]	Ca[¶]	Mg[¶]	pH[#]	EC[††]	OC	MB-C[‡‡]
(cm)				----- mg kg soil^{-1} -----					(dS m^{-1})	(%)	(μg g^{-1} soil)
					Non-saline soil						
0-15	8.9	9.6	296.	16.	9	3582	616	7.9	0.31	1.23	563
					Saline soil						
0-15	16.4	12.0	529	718	577.	6625	1790	7.9	6.32	1.47	495
					Ogbomosho soil						
0-20	9.6	-	95	2.5	5.4	460	84	6.5	0.11	0.61	80

[†] N = $CaCl_2$ extractable nitrate, NO_3-N (Houba et al., 2000)

[‡] P and K = Modified Kelowna extractable phosphate, PO_4-P and K (Qian et al., 1994)

[§] S = $CaCl_2$ extractable sulphate, SO_4-S (Houba et al., 2000)

[¶] Na, Ca and Mg = 1N ammonium acetate extraction (Hendershot et al., 2008)

[#] pH measured in a 1:2 soil:water suspension (Hendershot et al., 2008)

[††] EC measured in a 1:2 soil:water suspension (Miller and Curtin, 2008)

[‡‡] Microbial biomass carbon measured by chloroform-fumigation extraction method (Voroney et al., 2008).

4.4.2 Experimental Design

The incubation study was set up as a completely randomized design with four treatments replicated 4 times in a saline and non-saline soil from Central Butte Saskatchewan and the soil collected from Ogbomosho, Nigeria. A total of 48 pots and PVC chambers were used for this study (4 treatments x 3 soils x 4 replicates). The treatments evaluated in this study were the same amendments used in the field study (LEO, HA, CSM) and properties of the amendments are listed in Table 3.3 of Chapter 3. Moisture content in the pots was kept at 75% field capacity (FC) for the duration of the experiment by weighing pots and adding distilled water every 1-2 days.

4.4.3 Treatment Application

Homogenized soils (1 kg) were weighed into 1.67 L pots of a 14 cm height x 15 cm diameter (tapered) with a surface area of 176.72 cm^2. The 1 kg of soil sat below the top of the pot and the actual surface area of the potted soil was calculated to be 170.87 cm^2. The soil was brought up to 100% FC to initiate a CO_2 flush from the microbes and was subsequently kept at 75% FC for 2 weeks to allow the soil to equilibrate before amendments were applied. To simulate a broadcast and incorporate method of application of organic amendment that would be typical of a field operation, 100 g of soil was removed from the top of each pot and mixed with either LEO, CSM and HA at a rate of 10 t ha^{-1} for the leonardite and steer manure and 200 kg ha^{-1} for humic acid, which was the same as used in the field experiment described in section 3.1. Since only 0.25 g of HA was required for each pot, it was mixed with 5 ml of deionized water to enable a more even application of the amendment. For the control pots, 100 g of soil was removed, mixed, and placed back on the surface of the soil.

4.4.4 CO_2 Emissions Sampling

After the treatment application, all pots were equilibrated for 24 h and then each pot was placed inside a sealable chamber created from two PVC pipes (15 cm diameter, 15 cm long) with caps on each end. The two sections were attached using a rubber coupling and hose clamps which could be tightened around each section to create an air tight seal. A rubber septum inserted into the top cap was used to extract gas samples. The incubation study was conducted similar to Nelson et al. (2007) and Hangs et al. (2013). To avoid stratification of gas inside the chamber, an internal fan (0.037 m^3 min^{-1}, Sunon Inc., Brea, CA, USA) was used to continuously mix the air while the chambers were sealed during the sampling (Hangs et al., 2016). The chambers were moved to a growth chamber automatically set for 16 h at 25 °C (day) and 8 h at 18 °C (night) and incubated for a period of 29 days. The top of each chamber was left open when gas sampling was not taking place (Fig. 4.1).

Gas samples were collected on days 1, 2, 3, 4, 5, 8, 13, 17, 21, and 29 beginning at noon. For each sampling date, chambers were sealed, and gas samples taken after 1, 3, and 5 hrs using a 20-cm^3 syringe needle via the rubber septum from the chamber headspace (5379 cm^3). Gas concentrations were measured using a LI-COR LI-7000 (LI-COR Biosciences, Lincoln, NE) immediately after sampling. Fluxes of CO_2 were calculated as the change in gas concentration over each sampling period (Hangs et al., 2016) and as described in Agnew et al. (2010) using the following equation:

$F = \rho \times V/A \times \Delta C/\Delta t$ **[Eq. 4.1]**

where F = surface gas flux (mg m^{-2} s^{-1})

ρ = density of gas (kg m^{-3})

V = volume of chamber (m^3)

A = area of chamber (m^2)

$\Delta C/\Delta t$ = rate of change of gas concentration (ppm s^{-1})

Fig. 4.1: Incubation chamber setup in the phytotron between sampling times. During each day of sampling lids are sealed onto the top of each chamber containing soil and the gas samples are taken 1, 3, and 5 hrs after sealing.

4.4.5 Microbial Biomass Carbon

Soil microbial biomass carbon was determined in amended soil using the chloroform-fumigation extraction method described by Voroney et al. (2008). Briefly, six 25 g portions of sieved unamended soil (<2 mm) that had been preincubated at 75% water holding capacity for 14 days was used to estimate the microbial biomass carbon in the soils present at the start of the incubation. Three portions (25 g each) were fumigated with ethanol-free $CHCL_3$ for 24 h under vacuum and then extracted with 0.5 M K_2SO_4 (1:2 soil: extractant ratio). The other three sample portions were extracted immediately. Total C from the fumigated and non-fumigated soil extracts were analyzed using a liquid CN analyzer (TOC-V $_{CPH}$ -TN Shimadzu). The non-fumigated values were subtracted from the fumigated values and MBC was calculated using a K_{EC} factor of 0.38 since C analysis was done using K_2SO_4 extraction solution (Joergensen, 1996). Microbial quotient was calculated by dividing microbial respiration measurements by initial microbial biomass C amounts.

4.4.6 Statistical analysis

The treatments consisted of three amendments (LEO, HA, M) plus control where no amendments were added; each of the three soils received the same treatments. The measured parameter was CO_2 emissions that were repeatedly measured from the sampling unit (chamber) over the duration of the experiment. This allowed for statistical analysis using repeated measures analysis with the PROC MIXED procedure in SAS version 9.4 (SAS Institute, Toronto, ON). Data was checked for outliers using studentized residuals and values >2 were excluded from analysis; normal distribution was checked using Shapiro-Wilk values at $P < 0.05$. Covariance structures were compared on the basis of Akaike information criterion (AIC) and Bayesian information criterion (BIC) to find the most suitable model and it was determined the Ante-

Dependence (ANTE(1)) covariance structure provided the best fit. The effects of treatments, day of sampling, and their interaction with CO_2 production were tested. In addition, cumulative CO_2 emissions were also calculated for the incubation period and compared using an ANOVA with the PROC GLIMMIX procedure. PROC GLIMMIX was also used for ANOVA when comparing treatment effects for microbial metabolic quotient (qCO_2) and CO_2 emissions per unit C added. Because of the inherent variability in CO_2 emissions, the alpha level was set at 0.10 and means declared significantly different at $p<0.10$ to minimize the chance of making a type II error.

4.5 Results

4.5.1 Effect of amendment on total CO_2 emissions

The effect of individual amendments on CO_2-C emissions differed among the three soils. In the non-saline soil, CSM produced significantly more total CO_2-C compared to the CNTL (Fig. 4.2). The HA and LEO had similar cumulative emissions despite much more organic C added in the LEO treatment compared to the HA. In the saline soil (Fig. 4.3), none of the amendments produced significantly different total CO_2-C emissions compared to the CNTL or any other amendment. However, there was a trend of higher total CO_2-C emissions in the LEO and HA amended soils compared to the CNTL (Fig. 4.3). It is noteworthy that the CSM amendment treatment had the highest cumulative CO_2 production in the non-saline soil but resulted in the lowest cumulative production of the amendment treatments in the saline soil. The Ogbomosho soil responded differently than the other two Saskatchewan soils. In the Ogbomosho soil, the CSM and CNTL amendments produced similar total amounts of CO_2-C that were both significantly higher compared to the LEO and HA amendments (Fig. 4.4).

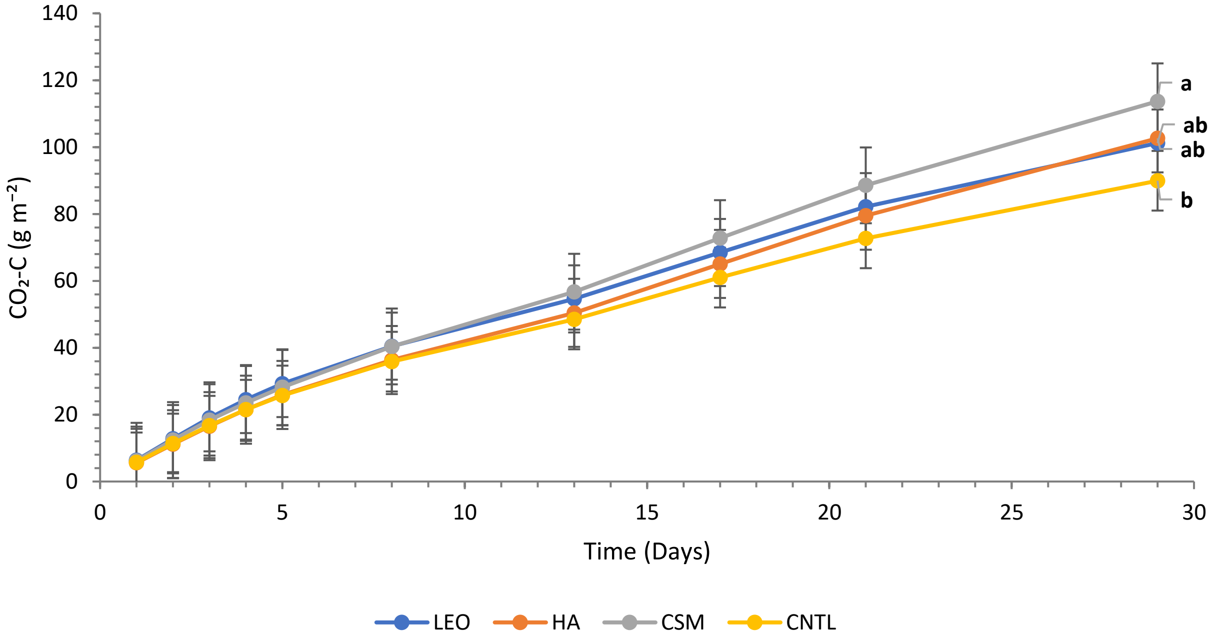

Fig. 4.2: Effect of amendment on total CO_2-C emissions in the non-saline Saskatchewan soil over the 29-day incubation period. A description of the amendment treatments are as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).Values are means from four replicates of each treatment. Letters denote significant differences ($n = 16$, $P<0.10$) in cumulative CO_2-C emissions between treatments.

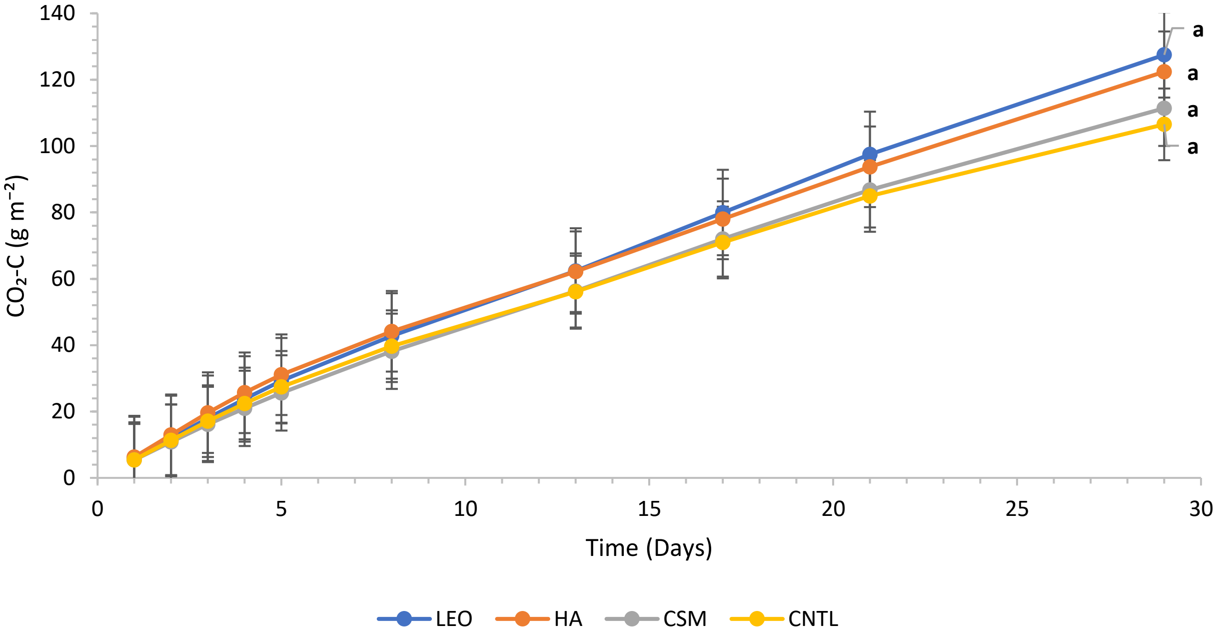

Fig. 4.3: Effect of amendment on total CO_2-C emissions in the saline Saskatchewan soil over the 29-day incubation period. A description of the amendment treatment are as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).Values are means from four replicates of each treatment. Letters denote significant differences ($n = 16$, $P<0.10$) in cumulative CO_2-C emissions between treatments.

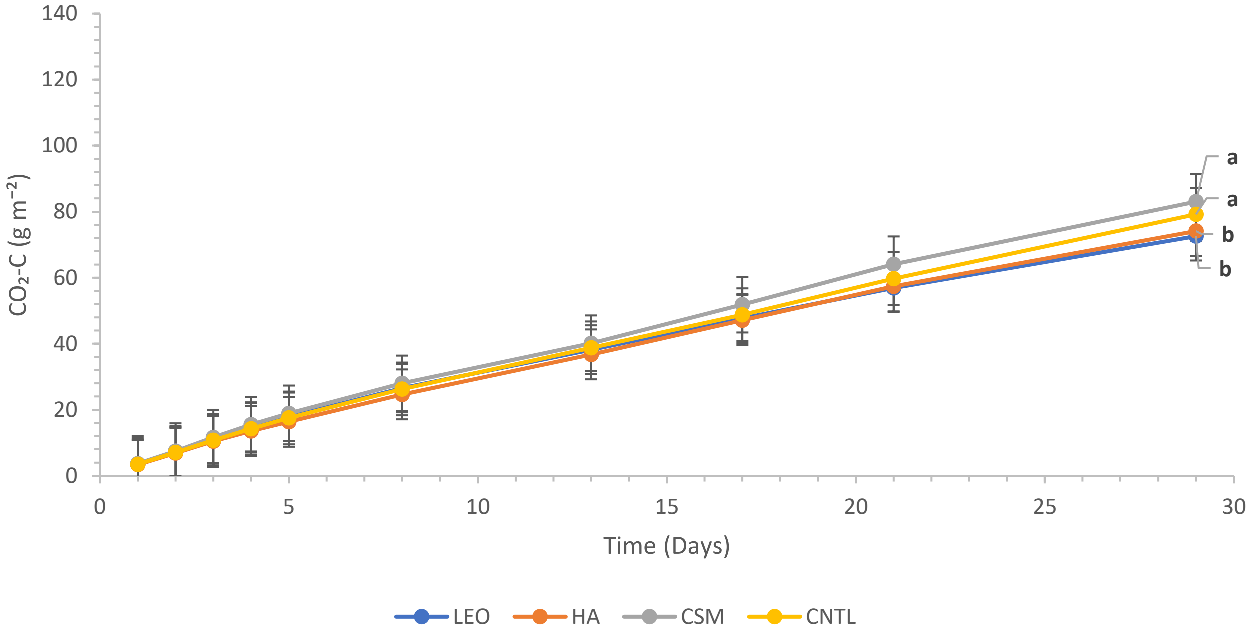

Fig. 4.4: Effect of amendment on total CO_2-C emissions in the Ogbomosho Nigerian soil over the 29-day incubation period. A description of the amendment treatments are as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).Values are means from four replicates of each treatment. Letters denote significant differences (n = 16, P<0.10) in cumulative CO_2-C emissions between treatments.

4.5.2 Total CO_2-C emissions among soils

Interestingly, the SK saline soil had significantly higher cumulative CO_2-C production compared to both the SK non-saline and Nigerian Ogbomosho soil when LEO, HA, or no amendment (CNTL) was applied (Fig. 4.5). Both the saline and non-saline soils had significantly higher cumulative CO_2-C production compared to the Ogbomosho soil after CSM was applied (Fig. 4.5). Cumulative CO_2-C production in the Ogbomosho soil was significantly lower compared to the SK soils when any of the three amendments were applied (Fig. 4.5).

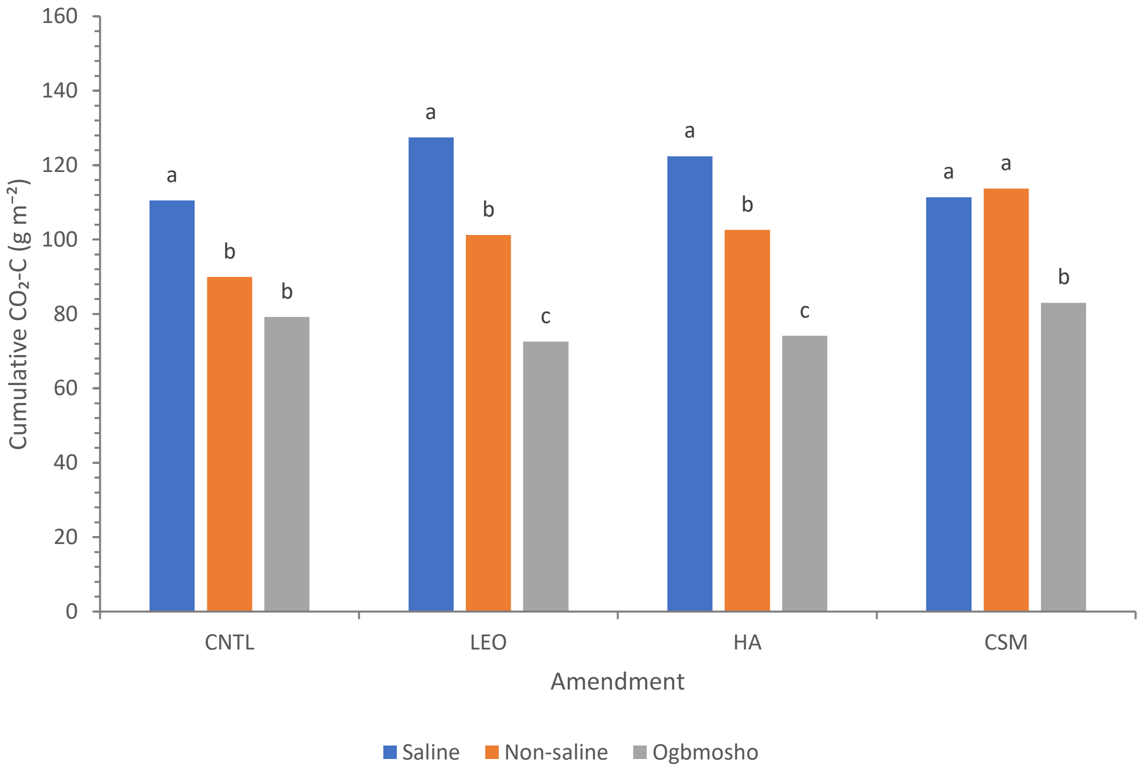

Fig. 4.5: Comparison of total cumulative CO_2-C emissions after 29-day incubation among the three soils. A description of the amendment treatments are as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}). Means within each amendment followed by a different small letter are significantly different (n = 16, $P<0.10$).

4.5.3 CO_2-C emissions per unit of C added

Cumulative CO_2-C produced per unit of C added was significantly higher for the CSM amended soil compared the LEO in all three soils (Fig. 4.6). The C:N ratios between the two amendments differ greatly, where CSM and LEO had C:N ratios of 14:1 and 74:1, respectively.

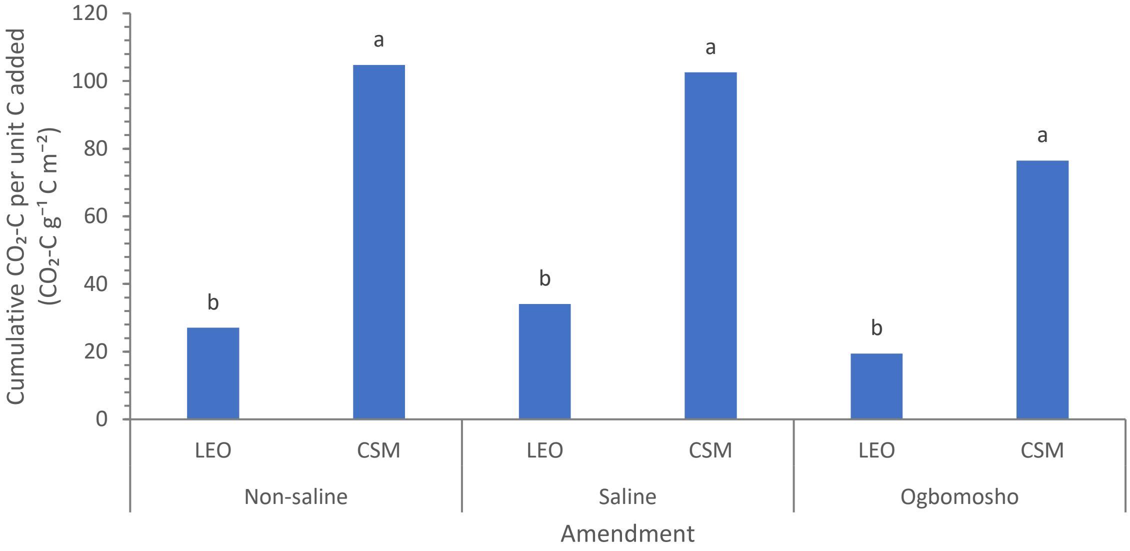

Fig. 4.6*:* Total cumulative CO_2-C emissions per unit C added to soil in the LEO and CSM amendments after 29-day incubation for the three soils (Non-saline and saline Saskatchewan soils and Ogbomosho Nigerian soil) used in the study. The HA treatment was not included as the amount of total C added was <0.01g. A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}). Means within each soil followed by a different letter are significantly different (n = 16, $P<0.10$).

4.5.4 Microbial metabolic quotient

The microbial metabolic quotient (qCO_2) was similar between the saline and non-saline Saskatchewan soils but was several times higher than the Ogbomosho soil, suggesting a greater degree of C turnover and influence of disturbance in the Ogbomosho soil (Fig. 4.7, 4.8 and 4.9). In all three soils, the qCO_2 followed a similar trend of an initial increase followed by a steady decrease after day 3, which indicates ecosystem development starting from day 4. Soil amendments significantly affected qCO_2; in the non-saline SK soil, qCO_2 in the LEO amended soil was significantly higher than the CNTL during days 2, 3, 4, 5 while the CSM amended soil was significantly higher than the CNTL on days 3, 5, 8, 13, 17, 21 (Fig. 4.7). In the saline SK soil, amendments had less effect on qCO_2; HA was significant higher compared to CNTL on day

2, 3, 29 (Fig. 4.8). In the Ogbomosho soil, CSM appeared to have the greatest effect on qCO_2 which was significantly higher on days 2, 3, 17, 21 (Fig. 4.9).

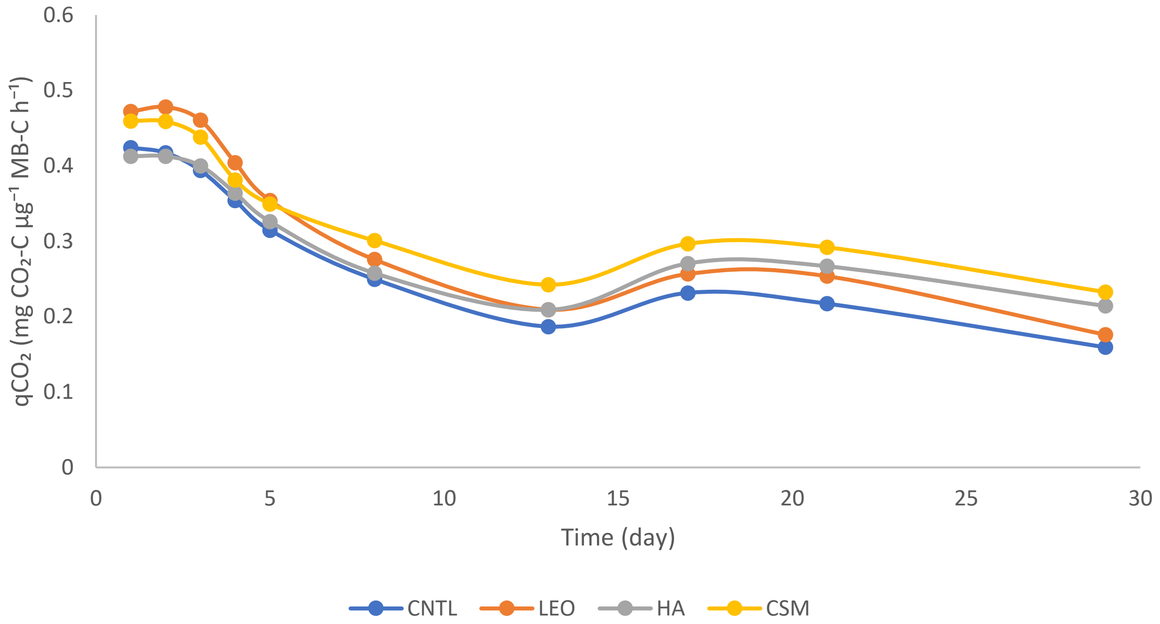

Fig. 4.7: Microbial metabolic quotient qCO_2 calculated for each sampling day in the non-saline Saskatchewan soil during the incubation study. Initial MB-C measurements taken at the beginning of the incubation study were used in the calculation of qCO_2 for each day. A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).

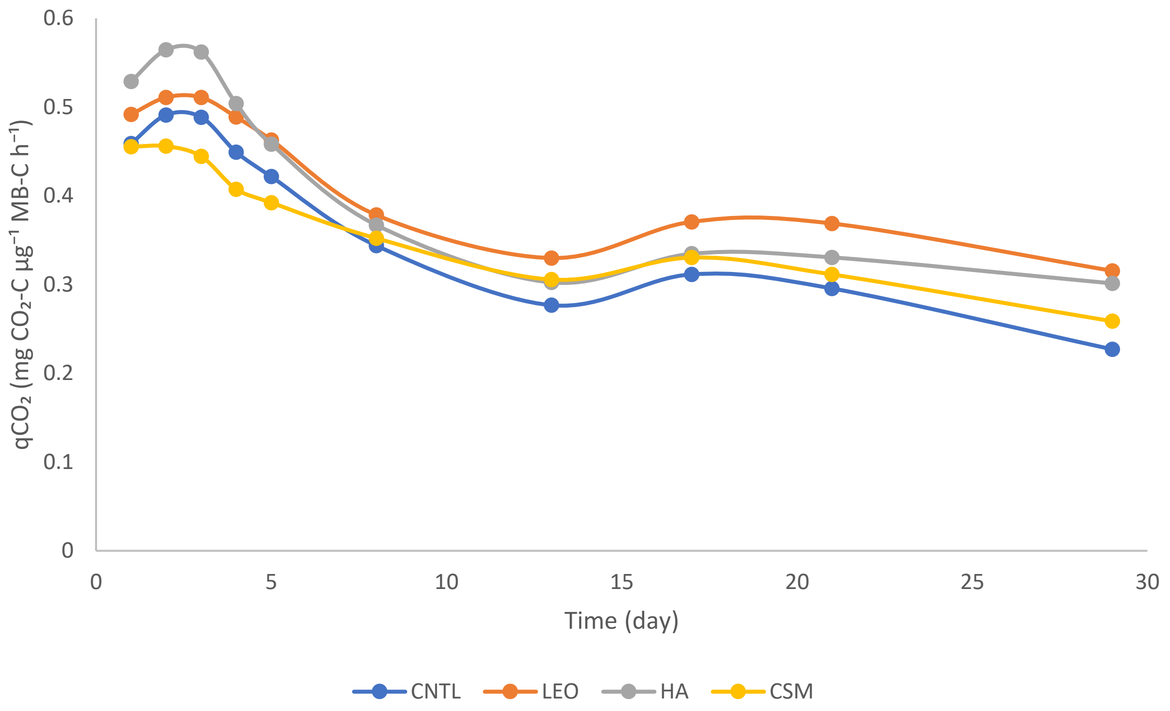

Fig. 4.8: Microbial metabolic quotient (qCO_2) calculated for each sampling day in the saline Saskatchewan soil during the incubation study. Initial MB-C measurements taken at the beginning of the incubation study were used in the calculation of qCO_2 for each day. A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).

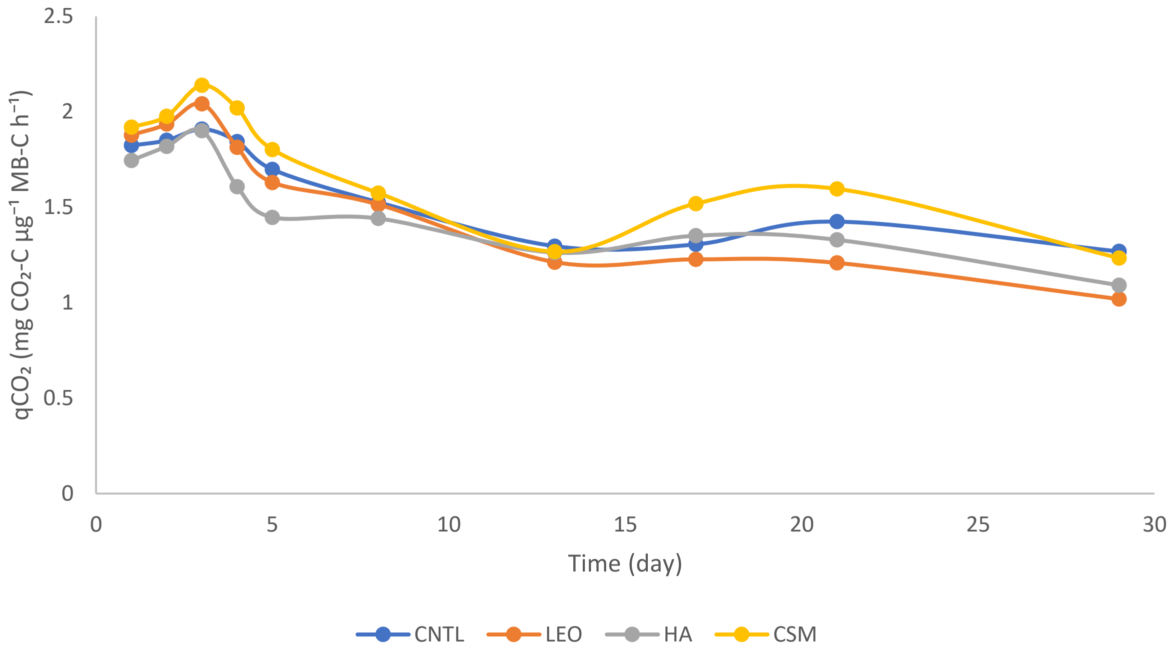

Fig. 4.9: Microbial metabolic quotient qCO_2 calculated for each sampling day in the Ogbomosho Nigerian soil during the incubation study. Initial MB-C measurements taken at the beginning of the incubation study were used in the calculation of qCO_2 for each day. A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (simulated broadcast and incorporated at a rate of 10 t ha^{-1}); HA: humic acid (simulated broadcast and incorporated at a rate of 200 kg ha^{-1}); and CSM: composted steer manure (simulated broadcast and incorporated at a rate of 10 t ha^{-1}).

4.6 Discussion

4.6.1 Effect of amendments on CO_2 production

The effect of amendments on measured CO_2 production over 29 days differed among the soils. The hypothesis that LEO and CSM will have larger effects on microbial respiration than humic acid because of the larger amount of substrate carbon added was not apparent in this experiment. Cumulative CO_2-C production was significantly greater in CSM than CNTL treatment in the non-saline soil, but LEO was significantly lower than CNTL and CSM in the Nigerian soil. Different influences of amendments in the soils suggests an interaction between amendment and the decomposing population. A positive effect of CSM is expected due to lower C:N ratio and less humified nature of OM compared to LEO and many studies (e.g. Ndayegamiye and Cote, 1989) have shown increased carbon dioxide production in cattle manure amended soils. However, the negative effect of LEO in the Nigerian soil, with reduced respiration compared to the unfertilized control, suggests possible adverse effect of components in the leonardite amendment on microbial populations in this tropical soil.

There were no significant differences between any of the treatments or control in the saline soil. This could be explained by the large amount of easily decomposable substrate (WEOC) already present in the saline soil being preferentially decomposed over the added C sources in the amendments, which may have masked treatment effects. There was a trend of higher CO_2-C production in the LEO treatment compared to CNTL, but this was not significant. Wong et al. (2009) was able to show significant increases in microbial respiration after an organic material (*Kangaroo grass*) was added to a saline soil and suggested a salt tolerant but dormant microbial community can quickly multiply when available substrate is added. However, their soils contained considerably less total SOC (<0.31% and <1.14 in the two soils) compared to the saline and non-saline soil used in this study.

In the Ogbomosho soil, the LEO and HA amendments resulted in a significant decrease in SMR compared to unamended soils. It is possible that LEO and HA amendments had a negative toxic effect and/or did not provide significant amounts of mineralizable OC. The 29-day incubation period we selected for this experiment may also have been too short to detect eventual enhanced CO_2 emissions that may arise from the mineralization of added C in the LEO and HA amendments. This is supported by Kuzyakov et al. (2009) who showed a rate of decomposition for black carbon was about 0.5% per year and therefore would have a mean residence time of up to 2000 years in soil. They also showed that with the addition of an easily decomposable substrate (glucose), black C decomposition rapidly increased, especially during the first week after glucose addition, indicating black C decomposition relies on cometabolism. This may also be true for our experiment and explain why the addition of LEO, a material containing a high concentration (30.5%) of C and a long residence time in soil, did not lead to a significant increase in CO_2 production. It would be valuable in the future to include readily available substrates along with leonardite or other stable C soil amendments to better understand the ability of microbial communities to decompose recalcitrant forms of C when another source of energy is present. It appears that LEO added alone would be the most effective amendment in adding to stored soil C in the Nigerian and similar soils due to the direct addition of carbon and suppression of microbial respiration.

4.6.2 Soil microbial biomass and respiration differences among soils.

It was hypothesized that microbial biomass and microbial respiration would be higher in the non-saline compared to the saline soil. The results show this was the case for the MB-C but not for the microbial respiration amounts. While the MB-C was similar, though slightly higher in the non-saline compared to saline soil, the total cumulative CO_2-C emissions was significantly higher in the saline soil compared to the non-saline soil in the CNTL, LEO, and HA treatments. This suggests increased C mineralization and higher turnover rate in the saline soil compared to the non-saline soil in the field under similar conditions as that imposed in the incubation in this study. The increased respiration could be explained by the higher total SOC and WEOM in the saline soil compared to the non-saline soil (Tables 3.6, 3.7 and 3.8, previous chapter). Whether this would persist beyond the first month is unknown. In dry conditions, such as those experienced in the summer of 2017, microbial activity decreases and substrates which are easily decomposed, such as WEOC, can accumulate in the soil, especially in a saline soil where reduced soil water content greatly increases the osmotic effect. When soils are subjected to more optimum moisture and temperature conditions as in the incubation, a greater initial microbial respiration rate induced by substrate decomposition can be achieved (Anderson and Domsch, 1978). The average daily temperature of 23°C and 75% water holding capacity conditions in this incubation experiment suggests that saline soils containing easily decomposable substrates have the potential to rapidly mineralize and turn over C when sufficient moisture and temperature conditions are met. This result in is agreement with Chowdhury et al. (2011) who also showed a marked increase in microbial respiration when dry saline soils with significantly decreased water potential were subjected to rewetting. However, in their study, Chowdhury et al. (2011) observed a smaller flush in respiration after rewetting of saline soils compared to non-saline soils, although it should be noted that, unlike our experiment, the SOC in their non-saline soil was 16.4 g kg^{-1} compared to just 2.6-10.1 g kg^{-1} in the saline soils they used, and no other C fractions were reported. These findings collectively suggest that response of microbial activity is more closely related to available carbon substrate than total amount of organic carbon or the salinity of the soil. In a similar incubation study, Asghar et al. (2012) measured respiration in non-saline and saline soils adjusted to 80% water holding capacity and showed a rapid increase in microbial activity in highly saline soils (i.e. $EC_{1:5}$ 6.0 and 8.0 dS m^{-1}) when salinity is reduced by leaching salts from the soil surface as would occur during heavy rainfall events. This may further explain the increased respiration in the saline compared to non-saline soil in our experiment as the continual adjustment to 75% water holding capacity required daily watering.

The microbial respiration response is an important consideration for impacts of amelioration of salt affected soils containing significant amounts of easily decomposable C fractions because losses of C and increased CO_2 production may occur when the soil is subjected to increased moisture conditions such as those brought on by draining and leaching, which is a common strategy for addressing salinity issues in soils. The results of our experiment show saline soils can produce more CO_2 emissions compared to non-saline soils when more available substrate is available for decomposition and ideal conditions are met. However, increased CO_2 emissions would not be expected at the same rate in the field as those shown in this incubation study since changes to water content would be more gradual and sporadic.

Lower microbial respiration rates in the Ogbomosho soil compared to the saline and non-saline soils collected from southern Saskatchewan was expected. The average MB-C and total SOC in the Saskatchewan soil was 529 µg g^{-1} and 1.35% compared to just 80 µg g^{-1} and 0.61% in the Ogbomosho soil, respectively. Less available C for decomposition and a microbial community population six times lower in the Ogbomosho soils largely explains the differences in CO_2 production between the soils.

4.6.3 CO_2-C emissions per unit C and microbial metabolic quotient

Increased microbial respiration after the addition of manure amendments in varying soil types is well documented in the literature (Alvarez et al., 1999; Lalande et al., 2003; Miyittah and Inubushi, 2003; Barbarick et al., 2004; Bünemann et al., 2006;). Cumulative CO_2-C emissions per unit C of CSM were significantly higher in all three soils compared to LEO (Fig. 4.6), which is consistent with the difference in C:N ratios of the two amendments and overall recalcitrance. Soil microbes require a balance of nutrients for growth and when organic amendments are added to the soil with C:N ratios exceeding 25:1, microbes must use N in the soil solution in order to decompose the added material (Brady and Weil, 2007). The CSM, with a C:N ratio of 14:1 would provide enough N for continual mineralization of the C in the amendment whereas the C:N ratio of 74:1 in the LEO means microbes would need to scavenge for N in the soil. Since no inorganic source of N was added to any of the soils, and the residual NO_3-N was low, very little additional N would have been available for microbial use during C mineralization after amendment application.

The microbial metabolic quotient measured in the three soils during the incubation experiment was typical and, as expected, with all three soils increased after the initial disturbance from amendment application before decreasing. Increases in qCO_2 are caused by stresses to the microbial community resulting in less efficient conservation of C (Anderson and Domsch 1993). While the three amendments showed a consistent trend of more elevated qCO_2 compared to the control in both soils collected from southern Saskatchewan, differences were minimal and the CNTL treatment followed the same trend as amended soils. This suggest the disturbance caused by mixing the surface layer, which was done in all treatments including the CNTL, impacted the microbial community similarly, even without the addition of a new C source to the soil.

5. Synthesis and Conclusions

5.1 Overview

Both the field study on effects of amendment and crop on soil C and productivity in saline and non-saline soils, and the incubation experiment that examined microbial respiration, provided valuable information on soil C forms, storage and turnover as affected by soil conditions and management. The field study described in Chapter 3 revealed that a salt-affected soil from southern Saskatchewan classified as severely saline, was not depleted in SOC or more easily decomposable C fractions such as LFOC and WEOC compared to an adjacent non-saline soil in the same field. Still, carbon-rich soil amendments applied to these saline soils and growing a salt tolerant green wheatgrass were capable of increasing the mass of total SOC in the surface within one year of application. For example, LEO amended saline soil treatments had significantly higher total SOC compared to HA and CNTL treatments grown under AC Saltlander one year after amendment: the apparent total SOC increased in the 0-10 cm depth by 7.6 Mg C ha^{-1} from the spring of 2017 to the spring of 2018. This apparent increase in stored C greatly exceeds that reported for other SK seeded down to forage (e.g. Nelson et al., 2008) or for which liquid manure was applied (King et al., 2015) However, a combination of growing a perennial forage plus addition of a high carbon content recalcitrant amendment like LEO may explain the relatively large increase in stored soil carbon.

The incubation study described in chapter 4 showed that organic C added in the LEO amendment did not result in significant increases in CO_2 from microbial respiration compared to unamended soils. In fact, there was significantly less microbial respiration in saline and non-saline soils from SK and Nigeria per unit C added in LEO compared to CSM that attests to the recalcitrance of the organic C in LEO and its more difficult to decompose nature. For example, the cumulative CO_2-C emissions per unit C added from CSM was 105, 103, and 76 g CO_2-C m^{-2} compared to 27, 34, and 19 g CO_2-C m^{-2} for the LEO in the non-saline SK, saline SK, and Ogbomosho soils, respectively. It therefore appears that the permanence of C storage is greater when LEO is added as an amendment compared to manure, not unlike biochar C which is also very resistant to decomposition (Alotaibi and Schoenau, 2013).

The non-saline SK soil also responded to amendment application and the use of AC Saltlander to increase SOC and C fractions. For example, WEOC under AC Saltlander at the non-saline site increased by 13 mg C kg^{-1} between the spring and fall of 2017 which was significantly greater than for willow and canola. Unfortunately, establishment of the salt-tolerant willow on both non-saline and saline sites in 2017 was hampered by dry early growing season conditions so it is difficult to directly compare the green wheat grass to the willow. Total SOC was also significantly higher with LEO amendment under AC Saltlander compared to the other amendment or CNTL treatments one year after application.

When used in combination, AC Saltlander green wheat grass and leonardite appear to provide the greatest potential to increase amounts of labile C fractions and total SOC in the surface layer of both saline and non-saline soils in southern Saskatchewan. The composted steer manure product used in combination with AC Saltlander can also increase total SOC in non-saline soils from SK, however, the effects of the CSM were less pronounced in saline soils perhaps because of additional salts added in the manure itself, and no significant differences were observed compared to unamended soils also seeded to AC Saltlander green wheatgrass. None of the amendments significantly affected the growth of the green wheatgrass, canola or willow in either the saline or non-saline soil, suggesting that their effect on properties affecting establishment and above-ground biomass production was minimal in the first year. However, as a result of effects of decomposition over time, such as narrowing of C:N ratios and humification, monitoring of effects of the amendments on plant growth in future years would be valuable.

5.2 Synthesis and Recommendations

An important consideration revealed in study is that rather than considering severely saline areas of fields as non-productive areas to be ignored, growers could benefit from seeding these areas to a beneficial and competitive salt tolerant grass such as AC Saltlander green wheatgrass. The AC Saltlander established well as a competitive species providing both a viable grazing or haying area for livestock fodder and maintaining or increasing SOC levels by adding OM through deposition of above and belowground biomass and protecting the soil from erosion. Used in combination with LEO and CSM, AC Saltlander increased total SOC by 7.6 and 6.1 Mg C ha^{-1} in the saline and 6.7 and 1.5 Mg C ha^{-1} in the non-saline soils after one year, respectively. Over the long term, grasses like AC Saltlander, via reduction of upward migration of salts through lowering of the water table, may render these areas suitable for annual crop production.

As amendments for increasing SOC, both the field study and incubation experiment suggest LEO may offer the greatest potential to add significant amounts of C that are not rapidly mineralized and lost from the soil as CO_2 compared to the other amendments included in these studies. One year after amendment application, LEO amended plots contained significantly more total SOC (Mg ha^{-1}) compared to the CSM, HA and CNTL in the non-saline site and the HA and CNTL at the saline site. Results from the incubation study showed the addition of LEO to saline and non-saline SK soils did not result in significantly higher CO_2-C emissions compared to the other amendments or CNTL. When applied to the Ogbomosho Nigerian soil, application of LEO resulted in significantly decreased CO_2-C emissions compared to the CSM and CNTL which suggests a slow turnover of the C added in this amendment, or even an inhibitory effect on decomposition when added to low fertility and low OM highly weathered tropical soils. Together, these results predict that organic C from LEO will not be rapidly mineralized when added to soils and can add significant amounts of total SOC over a relatively short period.

At the field site in southern Saskatchewan where this research was conducted, the salt affected soils in the field contained unexpectedly large amounts of total SOC and other more easily decomposable fractions of OC like light fraction and water extractable compared to the non-saline soil. To be more conclusive on amounts and forms of stored soil carbon in salt affected soils of the prairies, especially in comparison to soils not affected by salinity, a large systematic survey would be very useful. However, based on the results of this study, saline soils may not actually offer a greater potential to sequester additional C than other areas, in part because salt adapted invasive weeds since cultivation have added OM and helped to maintain cover on the soil surface so OM can accumulate in these areas without being lost to wind and water erosion. Further, as evidenced by significantly higher CO_2-C emissions in the saline compared to non-saline soil in the incubation study, any improvement in conditions for decomposition such as leaching and improved drainage could result in rapid organic C mineralization and CO_2 flux.

5.3 Future Research

The response in microbial respiration in saline soils when exposed to more ideal moisture and temperature conditions of an incubation was an interesting finding in this research project which deserves further exploration. Results from similar studies (Wong et al., 2009; Asghar et al., 2012) have suggested a highly salt-adapted microbial community may be especially suited to rapidly decompose C substrates when ideal moisture conditions are met. Further research on microbial community composition, for example by phospholipid-derived fatty acids analysis, before and after a highly saline soil is subjected to repeated periods of wetting may allow for a better understanding of rapid changes in community composition as affected by moisture conditions and elicit information on C turnover in saline soils when amelioration strategies are implemented.

The significant increase in total SOC after leonardite application in the field study and the low C mineralization rate as indicated by decreased microbial respiration suggests leonardite behaves differently than the more common organic C containing amendments added to agricultural fields like manure, compost and crop residues. However, the extraction process involved in removing this material and costs in transportation may be limitations in widespread use of this material as an amendment, and longer term studies are needed to determine if an economic positive crop response to the amendment could be realized over a number of years to help cover the costs and justify use.

Because this research only included soils classified as Brown Chernozem (Haverhill association) intermixed with Solodized Solonetz and Humic Luvic Gleysols in depressions, the inference space is limited. To better assess amendment and cropping effects on C storage, cycling and productivity of salt affected soils in the Canadian Prairies, a soil survey and wider range of soil types would be needed.

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Appendix A

Nutrient Uptake in Straw of AC Saltlander and Canola

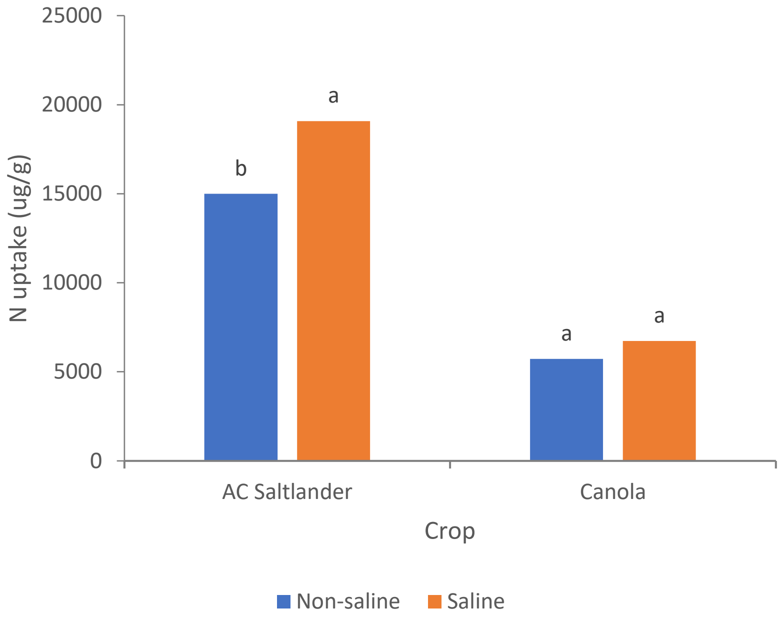

Fig. A.1: Comparison of N concentration in straw of AC Saltlander and canola at the saline and non-saline sites. Plants were harvested in the fall of 2017. Means within the same crop followed by a different letter are significantly different ($P<0.05$). A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha^{-1}; and (InVigor L252) Liberty Link 252 canola seeded at a rate of 10 kg ha^{-1} in rows spaced 25 cm apart.

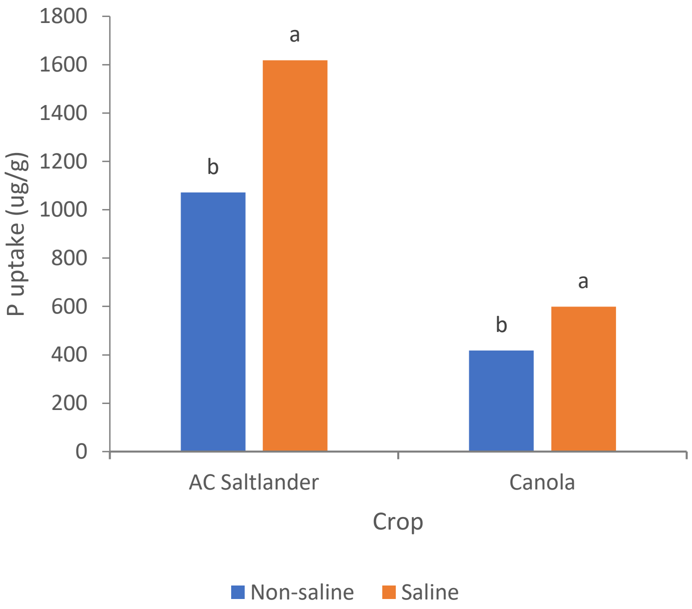

Fig. A.2: Comparison of P concentration in straw of AC Saltlander and canola at the saline and non-saline sites. Plants were harvested in the fall of 2017. Means within the same crop followed by a different letter are significantly different ($P<0.05$). A description of the crop seeding and planting is as follows: AC Saltlander green wheatgrass seeded in rows spaced 25 cm apart at a rate of 10 kg ha^{-1}; and (InVigor L252) Liberty Link 252 canola seeded at a rate of 10 kg ha^{-1} in rows spaced 25 cm apart.

Residual Nutrient content in saline and non-saline soils after harvest in fall 2017.

Table A.1: Residual nutrient content in plots under AC Saltlander at the saline and non-saline sites measured in three depths increments in the fall of 2017 after one year of crop growth. Means followed by a different letter within a site within a row are significantly different (*P*<0.05).

		Site									
		Non-saline Treatment[†]					Saline Treatment[†]				
	Depth (cm)	CNTL	LEO	HA	CSM		CNTL	LEO	HA	CSM	
			------ mg kg soil^{-1} ------			*P* value		------ mg kg soil^{-1} ------			*P* value
NO_3-N[‡]	0-15	1.26a	2.25a	3.70a	2.29a	0.8933	1.95a	2.43a	1.92a	2.06a	0.7185
	15-30	1.20a	1.26a	3.11a	1.09a	0.4831	0.74a	0.74a	0.70a	0.66a	0.9750
	30-60	0.73a	0.91a	1.01a	1.03a	0.9860	0.69a	0.57a	0.87a	0.79a	0.4311
SO_4-S[¶]	0-15	12.48a	25.31a	15.62a	16.35a	0.0518	1867.31a	1656.98b	1655.85b	1689.53b	0.0495
	15-30	4.86a	9.45a	8.70a	10.65a	0.3495	1697.45a	1662.70a	1642.27a	1533.01a	0.7307
	30-60	36.92a	108.63a	137.58a	40.78a	0.0527	1411.37a	1134.09a	1319.14a	1236.50a	0.7770
P[§]	0-15	10.13a	9.44a	10.52a	9.52a	0.9762	10.62a	9.57a	9.07a	12.66a	0.3700
	15-30	2.64a	1.79a	2.12a	2.53a	0.0773	5.58a	3.40a	4.78a	5.06a	0.2623
	30-60	2.34a	2.50a	2.39a	2.23a	0.9906	7.01a	3.21b	5.81ab	3.89b	0.0113
K[§]	0-15	317.34a	293.69a	350.82a	307.99a	0.2028	399.73a	324.75a	374.03a	370.15a	0.9559
	15-30	191.18a	182.49a	209.41a	204.56a	0.8456	305.05a	189.75a	235.98a	233.22a	0.8794
	30-60	197.91a	200.56a	205.99a	253.85a	0.2397	293.33a	232.18a	270.90a	276.30a	0.9564
Na[#]	0-15	33.48a	30.23a	27.39a	27.40a	0.8722	1035.77a	1069.97a	974.43a	1049.94a	0.8233
	15-30	35.08a	55.11a	36.79a	38.01a	0.2841	861.29a	974.19a	980.21a	915.74a	0.6626
	30-60	142.12a	574.58a	497.77a	347.17a	0.0585	624.56a	748.75a	775.87a	672.44a	0.4165
Ca[#]	0-15	2953.73a	3096.67a	3140.45a	2953.73a	0.9844	7241.61a	8102.77a	6877.36a	7480.34a	0.4991
	15-30	3228.45a	3172.93a	4010.15a	3382.26a	0.7775	6920.06a	8711.65a	8291.10a	7546.11a	0.5567
	30-60	4731.16a	4734.21a	4671.46a	4927.74a	0.7136	8112.71a	5442.76a	7162.91a	6776.53a	0.8160
Mg[#]	0-15	587.82a	601.34a	598.46a	715.69a	0.3944	2264.87a	2213.43a	2257.31a	2309.34a	0.9250
	15-30	829.28a	1082.88a	986.50a	1037.80a	0.4523	2160.28a	2222.66a	2234.28a	2213.92a	0.9779
	30-60	1065.20a	1376.06a	1398.90a	1357.79a	0.4247	1969.92a	2086.19a	2066.61a	2023.48a	0.9544
pH[††]	0-15	7.66a	7.59a	7.75a	7.70a	0.8278	7.71a	7.55a	7.56a	7.56a	0.6037
	15-30	7.69a	7.67a	7.78a	7.79a	0.8525	7.71a	7.50a	7.60a	7.60a	0.6650
	30-60	8.04a	7.93a	7.95a	7.91a	0.9015	7.66a	7.64a	7.66a	7.65a	0.9985
			------ dS m^{-1}------					------ dS m^{-1}------			
EC[‡‡]	0-15	0.24a	0.33a	0.28a	0.27a	0.2681	7.66a	7.66a	7.19a	7.36a	0.6777
	15-30	0.20a	0.27a	0.21a	0.23a	0.1781	6.92a	7.01a	6.90a	6.66a	0.9726
	30-60	0.40a	0.72a	0.58a	0.45a	0.2908	5.98a	4.89a	5.70a	5.38a	0.6124

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

[‡] N = $CaCl_2$ extractable nitrate, NO_3-N (Houba et al., 2000)

[§] P and K = Modified Kelowna extractable phosphate, PO_4-P and K (Qian et al., 1994)

[¶] S = $CaCl_2$ extractable sulphate, SO_4-S (Houba et al., 2000)

[#] Na, Ca and Mg = 1N ammonium acetate extraction (Hendershot et al., 2008)

[††] pH measured in a 1:2 soil:water suspension (Hendershot et al., 2008)

[‡‡] EC measured in a 1:2 soil:water suspension (Miller and Curtin, 2008)

Table A.2: Residual nutrient content in plots under canola at the saline and non-saline sites measured in three depths increments in the fall of 2017 after one year of crop growth. Means followed by a different letter within a site within a row are significantly different ($P<0.05$).

						Site					
				Non-saline Treatment[†]					Saline Treatment[†]		
	Depth (cm)	CNTL	LEO	HA	CSM		CNTL	LEO	HA	CSM	
			------ mg kg soil^{-1} ------			*P* value		------ mg kg soil^{-1} ------			*P* value
NO$_3$-N[‡]	0-15	10.06a	11.31a	4.47a	6.02a	0.1676	2.98a	1.95a	2.22a	2.07a	0.1321
	15-30	1.88a	1.41a	1.29a	2.19a	0.9233	1.15a	0.93a	0.91a	1.01a	0.4592
	30-60	1.36a	1.50a	1.25a	1.27a	0.9927	0.92a	0.63a	0.72a	0.73a	0.3787
SO$_4$-S[¶]	0-15	25.79a	33.46a	27.09a	22.48a	0.0834	2253.45ab	2429.63a	2185.49b	2159.14b	0.0237
	15-30	6.24a	14.08a	9.21a	10.71a	0.1913	2223.99a	2180.84a	1969.70a	2116.61a	0.3860
	30-60	42.07a	33.59a	12.94a	49.24a	0.8227	1451.07a	1781.27a	1757.55a	1451.07a	0.2504
P[§]	0-15	9.94a	10.13a	12.97a	12.29a	0.6419	14.91a	9.07a	11.42a	11.32a	0.0740
	15-30	2.83a	3.46a	2.88a	2.56a	0.1721	2.80a	3.61a	3.52a	3.48a	0.9143
	30-60	2.29a	2.96a	2.27a	2.05a	0.6798	4.13a	3.39a	4.54a	2.91a	0.5381
K[§]	0-15	291.75a	296.68a	345.60a	341.67a	0.1212	784.23a	821.80a	788.80a	747.53a	0.9554
	15-30	183.10a	193.95a	196.01a	208.50a	0.9000	714.63a	722.83a	692.18a	616.28a	0.8580
	30-60	167.38a	176.58a	185.59a	180.85a	0.9503	672.08a	590.78a	653.90a	520.60a	0.5118
Na[#]	0-15	36.93bc	25.68c	44.17ab	54.46a	0.0132	981.40a	1038.78a	893.89a	980.38a	0.6612
	15-30	34.33a	46.93a	51.29a	40.71a	0.4569	1007.65a	949.31a	846.29a	980.17a	0.5685
	30-60	355.71a	271.48a	282.64a	477.12a	0.6232	785.77a	791.37a	732.76a	795.23a	0.9376
Ca[#]	0-15	2338.66a	2275.13a	2494.17a	2657.05a	0.8980	6036.79a	6246.05a	6886.50a	6241.59a	0.7463
	15-30	3072.02a	3577.26a	3872.69a	3293.76a	0.8261	7149.79a	5955.73a	6881.01a	6954.73a	0.8152
	30-60	4765.28a	4672.72a	4653.90a	4550.91a	0.7862	6271.10b	14665a	14792a	7219.88b	0.0027
Mg[#]	0-15	693.43a	686.79a	737.17a	724.21a	0.9249	2116.32a	2194.49a	2018.97a	2077.47a	0.6513
	15-30	873.07a	1039.27a	940.48a	947.10a	0.7960	2190.00a	2081.16a	2066.09a	2011.75a	0.7969
	30-60	1076.38a	1318.90a	1204.62a	1227.91a	0.7630	1892.47a	1718.53a	1763.90a	1743.06a	0.8634
pH[††]	0-15	7.69a	7.52a	7.59a	7.78a	0.4810	7.53a	7.66a	7.68a	7.69a	0.6183
	15-30	7.65a	7.86a	7.76a	7.84a	0.5516	7.51a	7.71a	7.69a	7.75a	0.5033
	30-60	8.08a	8.03a	7.90a	8.17a	0.5234	7.69a	7.69a	7.70a	7.87a	0.6904
			------ dS m^{-1}------					------ dS m^{-1}------			
EC[‡‡]	0-15	0.30a	0.28a	0.29a	0.31a	0.9045	8.30a	8.24a	8.04a	7.86a	0.7728
	15-30	0.20a	0.23a	0.22a	0.26a	0.4303	8.05a	7.04a	7.30a	6.92a	0.4459
	30-60	0.46a	0.51a	0.75a	0.52a	0.4522	5.69a	6.57a	6.63a	5.83a	0.5747

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

[‡] N = CaCl$_2$ extractable nitrate, NO$_3$-N (Houba et al., 2000)

[§] P and K = Modified Kelowna extractable phosphate, PO$_4$-P and K (Qian et al., 1994)

[¶] S = CaCl$_2$ extractable sulphate, SO$_4$-S (Houba et al., 2000)

[#] Na, Ca and Mg = 1N ammonium acetate extraction (Hendershot et al., 2008)

[††] pH measured in a 1:2 soil:water suspension (Hendershot et al., 2008)

[‡‡] EC measured in a 1:2 soil:water suspension (Miller and Curtin, 2008)

Table A.3: Residual nutrient content in plots under willow at the saline and non-saline sites measured in three depths increments in the fall of 2017 after one year of crop growth. Means followed by a different letter within a site within a row are significantly different ($P<0.05$).

		Site									
		Non-saline Treatment[†]					Saline Treatment[†]				
	Depth (cm)	CNTL	LEO	HA	CSM		CNTL	LEO	HA	CSM	
			------ mg kg soil^{-1} ------			*P* value		------ mg kg soil^{-1} ------			*P* value
NO_3-N[‡]	0-15	18.85b	28.28a	26.70a	26.38a	0.0305	1.56a	1.42a	1.49a	1.47a	0.9943
	15-30	6.45a	8.27a	8.83a	7.70a	0.4707	0.70a	0.83a	0.67a	0.84a	0.6682
	30-60	4.15a	4.71a	5.92a	4.93a	0.2430	0.69a	0.59a	0.53a	0.74a	0.6020
SO_4-S[¶]	0-15	12.85a	13.70a	11.43a	17.27a	0.5619	1968.80a	1908.62a	1921.30a	1968.80a	0.9019
	15-30	5.95a	8.15a	8.45a	8.23a	0.8754	1830.81a	1902.56a	1782.20a	1830.81a	0.8559
	30-60	13.21a	37.63a	24.68a	47.04a	0.9050	1793.54a	1794.70a	1754.59a	1703.64a	0.9857
P[§]	0-15	8.34a	8.24a	7.74a	10.79a	0.6957	8.44a	8.46a	8.07a	7.75a	0.9858
	15-30	3.09a	2.95a	2.63a	2.26a	0.0663	4.92a	5.41a	5.10a	4.86a	0.9622
	30-60	2.89a	3.80a	3.29a	2.75a	0.4499	7.51a	9.60a	6.45a	7.80a	0.1081
K[§]	0-15	277.18a	282.73a	259.41a	309.45a	0.3337	530.83a	527.60a	565.28a	497.93a	0.9661
	15-30	164.74a	173.34a	182.15a	161.51a	0.9391	508.43a	473.75a	488.80a	448.68a	0.9763
	30-60	170.67a	178.63a	208.47a	196.37a	0.6943	500.88a	492.88a	460.05a	466.90a	0.9779
Na[#]	0-15	37.44a	37.78a	30.01a	38.95a	0.6842	781.92a	733.98a	713.92a	739.34a	0.9318
	15-30	28.62a	47.20a	49.63a	48.83a	0.3658	667.95a	971.97a	660.41a	630.04a	0.9798
	30-60	384.16a	273.91a	401.15a	408.24a	0.8314	676.15a	642.85a	629.14a	605.19a	0.9424
Ca[#]	0-15	2445.55a	2425.42a	2255.68a	2735.37a	0.8993	6990.38a	7619.26a	7771.44a	7106.82a	0.7245
	15-30	4304.87a	3043.92a	3661.89a	3348.42a	0.5460	7581.34a	7674.87a	8769.19a	6830.97a	0.5525
	30-60	4510.19a	4591.25a	4696.18a	4626.09a	0.8715	10193a	11882a	10790a	10174a	0.9307
Mg[#]	0-15	731.33a	724.22a	757.72a	766.67a	0.9561	2019.31a	2030.12a	1921.59a	2011.61a	0.8587
	15-30	982.75a	974.73a	1234.13a	926.65a	0.3458	1959.69a	2005.51a	1881.54a	1766.29a	0.5783
	30-60	1204.94a	1359.52a	1304.36a	1586.70a	0.3989	1781.01a	1792.71a	1646.16a	1835.26a	0.8735
pH[††]	0-15	7.67a	7.50a	7.60a	7.79a	0.4773	7.77a	7.79a	7.72a	7.80a	0.9412
	15-30	7.68a	7.78a	7.67a	7.86a	0.6909	7.88a	7.76a	7.77a	7.86a	0.8621
	30-60	7.99a	8.10a	8.02a	8.18a	0.6845	7.84a	7.78a	7.78a	7.86a	0.9449
			------ dS m^{-1}------					------ dS m^{-1}------			
EC[‡‡]	0-15	0.28a	0.37a	0.33a	0.34a	0.3586	7.24a	6.93a	7.06a	7.08a	0.9329
	15-30	0.28a	0.28a	0.27a	0.29a	0.9935	6.07a	6.70a	6.42a	6.41a	0.8769
	30-60	0.69a	0.47a	0.60a	0.56a	0.5124	6.52a	6.40a	6.25a	6.14a	0.9708

[†] A description of the amendment treatment is as follows: CNTL: control (no amendment applied); LEO: leonardite (broadcast and incorporated at 10 t ha^{-1}); HA: humic acid (seed placed at 200 kg ha^{-1}); and CSM: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

[‡] N = $CaCl_2$ extractable nitrate, NO_3-N (Houba et al., 2000)

[§] P and K = Modified Kelowna extractable phosphate, PO_4-P and K (Qian et al., 1994)

[¶] S = $CaCl_2$ extractable sulphate, SO_4-S (Houba et al., 2000)

[#] Na, Ca and Mg = 1N ammonium acetate extraction (Hendershot et al., 2008)

[††] pH measured in a 1:2 soil:water suspension (Hendershot et al., 2008)

[‡‡] EC measured in a 1:2 soil:water suspension (Miller and Curtin, 2008)

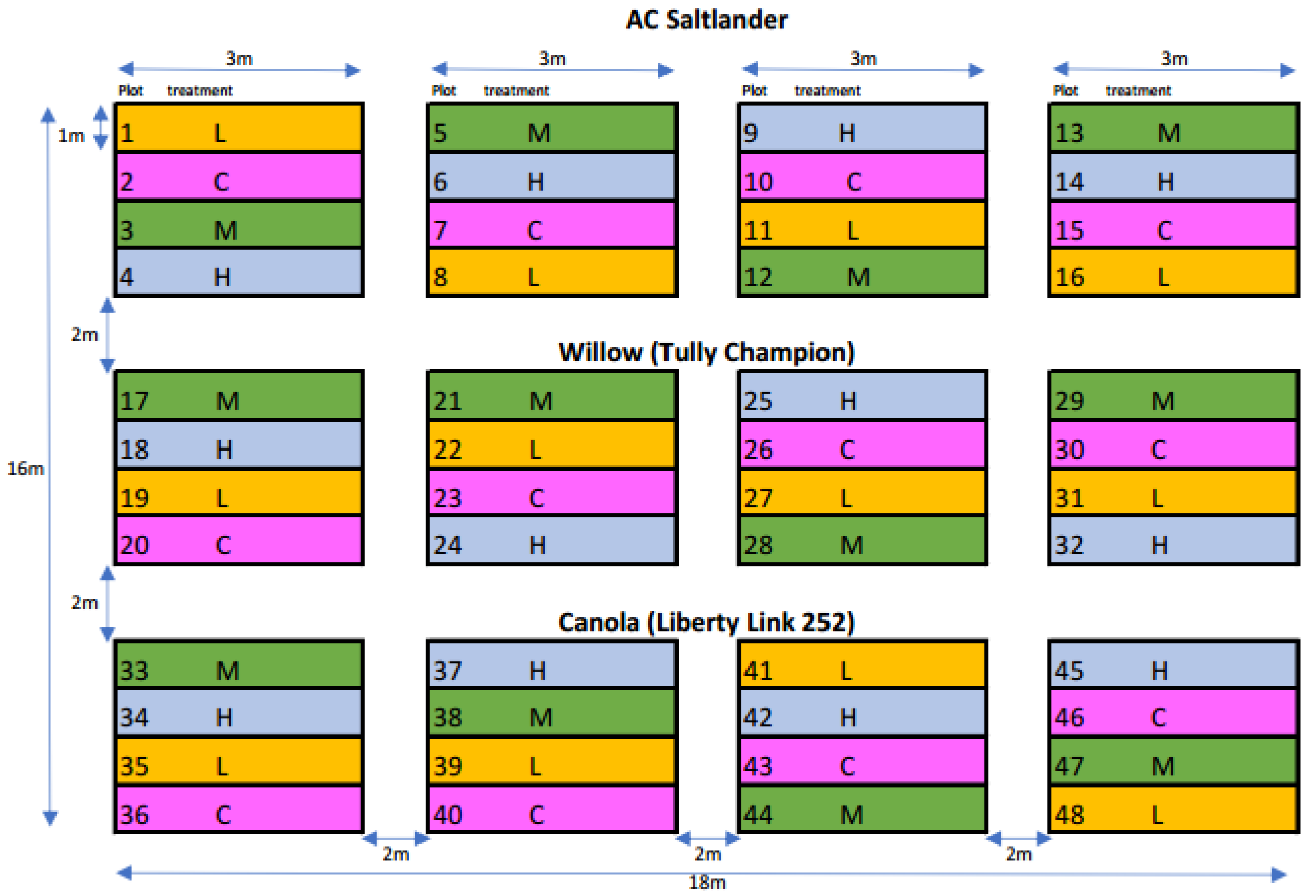

Fig. A.3: Non-saline plot map showing the RCBD design, crop and amendment application layout. A description of the amendment treatment is as follows: C: control (no amendment applied); L: leonardite (broadcast and incorporated at 10 t ha^{-1}); H: humic acid (seed placed at 200 kg ha^{-1}); and M: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).

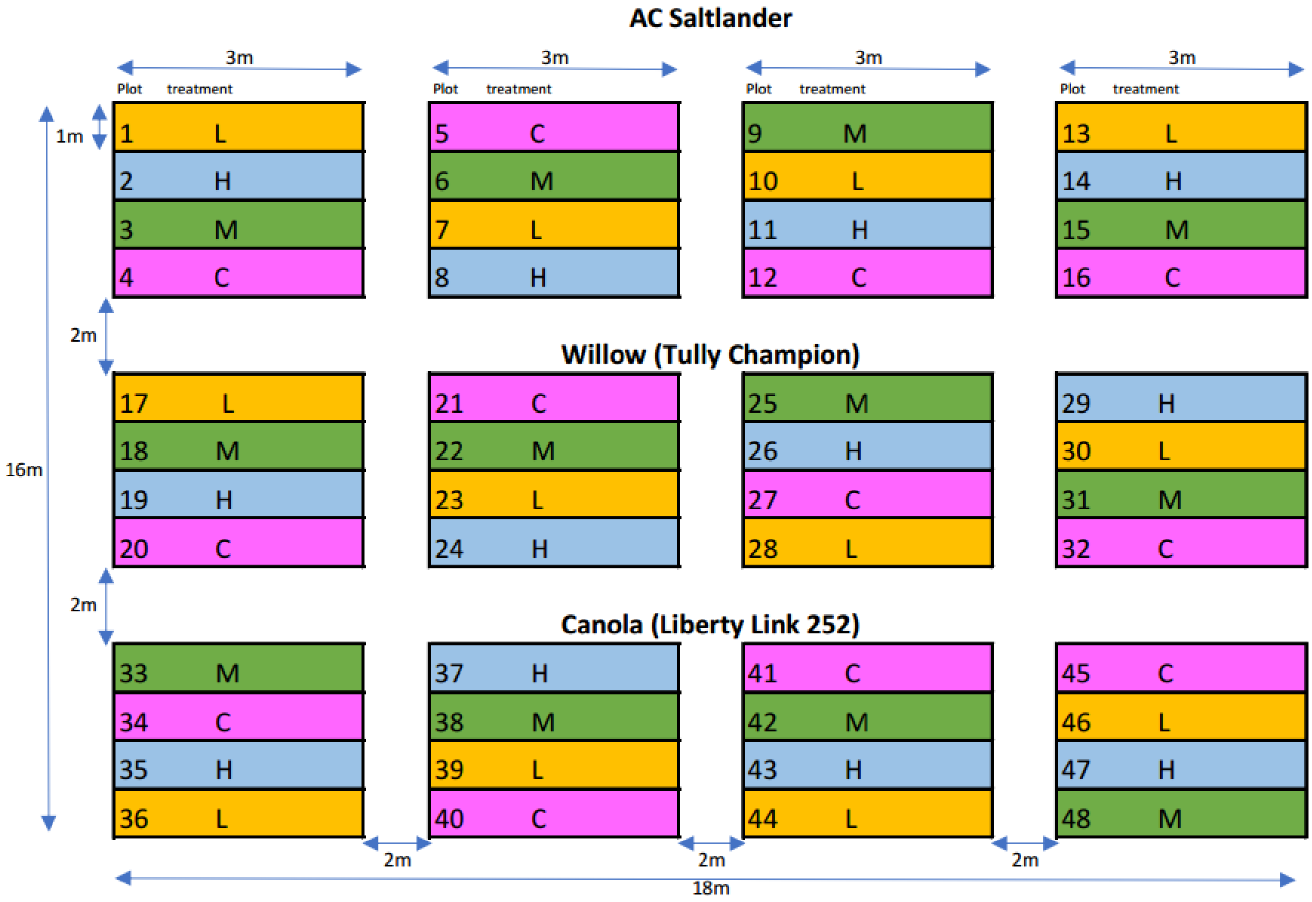

Fig. A.4: Saline plot map showing the RCBD design, crop and amendment application layout. A description of the amendment treatment is as follows: C: control (no amendment applied); L: leonardite (broadcast and incorporated at 10 t ha^{-1}); H: humic acid (seed placed at 200 kg ha^{-1}); and M: composted steer manure (broadcast and incorporated at 10 t ha^{-1}).