THE EFFECTS OF SHORT-TERM GRASSLAND SET-ASIDES ON SOIL PROPERTIES IN THE FRASER RIVER DELTA OF BRITISH COLUMBIA

by

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Abstract

The Grassland Set-Aside Stewardship Program provides cost-share payments to agriculture producers in the Fraser River delta (FRD) region of British Columbia for placing active cropland under a grass and legume vegetation mix for a one to four-year period. While long-term grassland set-asides (GLSA) have been found to improve soil structure, reduce compaction, and increase soil organic matter; short-term set-asides (<five years) are less common and less studied. The objective of my research was to evaluate the effects of short-term set-asides on select soil properties during the first two years of enrolment in the FRD. A total of eight fields entering the GLSA program were assessed prior to seeding for soil physical and chemical properties commonly associated with crop productivity in the region. The selected soil properties of fields entering the GLSA program were found to be highly variable, and two fields contained properties commonly associated with poor crop productivity. Following GLSA seeding, these unproductive fields were noted to have poor GLSA vegetative growth during the first two seasons of enrollment and a similar bulk density, aeration porosity and aggregate stability relative to fields managed for annual crop rotations (ACR). In contrast, productive GLSA fields entering the program were found to have a higher aggregate stability, higher aeration porosity, and lower bulk density than paired ACR fields after a single season of establishment. A further analysis for total soil organic nitrogen, total soil organic carbon, and active soil organic matter pools, did not identify differences between ACR fields and paired productive GLSA fields after two seasons of establishment. These findings indicate that productive fields entering the GLSA program have improved soil structure and less compaction than ACR fields after two years of enrollment, while unproductive fields entering the program may require additional accompanying management practices or an extended enrollment period for differences to occur.
Lay Summary

The Delta Farmland and Wildlife Trust provides financial incentives to farmers in the Fraser River delta (FRD) for resting agricultural land under grass and clover vegetation for up to 4 years as part of their grassland set-asides (GLSA) program. The objective of my study was to evaluate the influence of GLSA management on soils. Soil responses to GLSA management were found to vary between degraded and productive sites enrolled in the program. After two years of GLSA establishment the degraded sites were noted to have similar soil properties to fields continuously cultivated for annual crops, while the productive GLSA fields had more stable soil structure and reduced soil compaction in the second season of establishment. The findings from my study provide useful information to agriculture producers on how to best use the GLSA program to maintain soil productivity in the FRD.
Preface

This thesis represents unpublished work which I conducted with assistance from undergraduate students and advisors. I was the lead investigator in the studies included in Chapter 2, 3 and 4 and was responsible for all major areas of research question formation, data collection, data analysis and thesis composition. Early sample collection and field selection for this project was led by Dru Yates and Christine Terpsma. Laboratory and fields assistance was provided for collecting and processing samples by Alfred Ke and Monica Nederend who were hired as undergraduate research assistants under my supervision. Undergraduate research projects under the supervision of myself and Dr. Maja Krzic also contributed to the research in this thesis. Specifically, a study by Thea Rodgers provided the permanganate oxidizable carbon data in Chapter 4, while a study by Chantel Chizen provided the dilute acid-extractable polysaccharide data in the same chapter. The Sustainable Agricultural Landscape (SAL) lab Coordinator, Katie Neufeld, provided guidance and support on several laboratory procedures included in this study.

Dr. Maja Krzic was the supervisory author on this project and was closely involved in all studies include in this thesis. This project was done in collaboration with Dr. Sean Smukler who was also closely involved in project development and contributed to thesis edits, while Dr. Art Bomke provided project guidance and thesis edits.
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<tr>
<td>ACR</td>
<td>Annual crop rotations</td>
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<tr>
<td>CRP</td>
<td>Conservation Reserve Program</td>
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<tr>
<td>DF&amp;WT</td>
<td>Delta Farmland and Wildlife Trust</td>
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<tr>
<td>DAEP</td>
<td>Dilute acid-extractable polysaccharides</td>
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<td>FRD</td>
<td>Fraser River delta</td>
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<td>GLSA</td>
<td>Grassland set-aside</td>
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<td>MAP</td>
<td>Mean annual precipitation</td>
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<tr>
<td>FT-MIR</td>
<td>Fourier transform mid-infrared spectroscopy</td>
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<td>MWD</td>
<td>Mean weight diameter</td>
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<tr>
<td>NIR</td>
<td>Near infrared spectroscopy</td>
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<td>PCA</td>
<td>Principal component analysis</td>
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<td>PCP</td>
<td>Permanent Cover Program</td>
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<td>POXC</td>
<td>Permanganate oxidizable carbon</td>
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<td>TOC</td>
<td>Total soil organic carbon</td>
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<td>SOM</td>
<td>Soil organic matter</td>
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<td>SOC</td>
<td>Soil organic carbon</td>
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<td>WSA</td>
<td>Water stable aggregates</td>
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Chapter 1: General Introduction

1.1 Soils of the Fraser River Delta

The Fraser River delta (FRD) of British Columbia is a productive agricultural region. However, an abundance of rainfall during the fall and winter months makes the medium textured soils of the FRD highly susceptible to structural degradation and compaction. Agricultural fields managed for annual crop rotations (ACR) are especially prone to these issues as frequent tillage and harvesting practices disturb soil aggregates, deplete soil organic matter (SOM), and compact soils (Paul and de Vries, 1979; Coote et al., 1981; Hermawan, 1995; Krzic et al., 2000; Principe, 2001; Lui et al., 2005; Yates et al., 2017). Other soil productivity issues in the region include soil acidification (Principe, 2001) and the accumulation of salts in soils that are in close proximity to the ocean (Principe, 2001; Barron et al., 2014 and Yates et al., 2017).

A complex history of social and economic factors since the late 1960s has promoted more intensive cropping systems in the FRD (Fraser, 2004), and reports have indicated increasing soil quality concerns in the region. For example, a study by Bomke and Temple (1990) used 30 years of soil data to show a decline in SOM content in five rented ACR fields, while a survey by Klohn Leonoff Ltd. (1992) noted one out of three ACR fields to have soil quality issues related to poor soil structure and low organic matter. Several more recent studies have also reported ACR fields to have issues related to poor soil structure, compaction, low organic matter, and high acidity and/or salinity (Hermawan and Bomke, 1996; Krzic et al., 1999; Principe, 2001; Lui et al., 2005; Yates et al., 2017).
Soil conservation practices are often implemented in the FRD to improve soil structure by increasing soil organic matter and protecting soil aggregates (Bomke and Temple, 1990). These practices commonly include crop rotation (Fraser, 2004), cover cropping (Hughes-Games and Bertrand, 1991), and manure applications (Bomke et al., 2008). Infrastructure alterations such as the installation of sub-surface drainage systems and laser leveling may also be done to prevent surface ponding and salt accumulations. While all these conservation practices are considered effective for improving long-term soil quality, the short-term economic costs are often a barrier for farmers operating on low profit margins and/or on unsecure short-term leases (Bomke and Temple, 1990; Fraser, 2004). In response to these challenges, the Delta Farmland and Wildlife Trust (DF&WT) has established several cost-share programs which aim to help farmers undertake conservation practices on farmland. One of these programs offers farmers the opportunity to place fields into set-aside for a period of one to four years.

1.2 Set-asides

Set-asides are a conservation practice in which a farmer places a previously cropped field into fallow for a minimum of one year. Set-aside programs have been used around the world and are often implemented for wildlife habitat provision, market surplus reductions, and soil restoration (Skold, 1989; Dunn, et al., 1993; Gebhart et al., 1994; Sotherton, 1998). The length of set-aside enrolment is often variable, but the majority of programs encourage the establishment of long-term (>five years) set-asides (Skold, 1989; Gebhart et al., 1994; Vaisey et al., 1996; Sotherton, 1998; Post and Kwon, 2000). The primary feature of a set-aside field is the establishment of undisturbed perennial vegetative cover and a grassland set-aside (GLSA) is defined in this study as a field which is predominantly seeded with grasses.
1.2.1 Set-aside Programs

Several examples of large scale set-aside programs may be found around the world. The Conservation Reserve Program (CRP) in the United States established in 1985 is the most extensive set-aside program which is active today— with a current enrolment cap of 10 million hectares (Stubbs, 2014). Under the contracts provided by the government, agriculture producers are paid to plant either grass species or trees on environmentally sensitive agricultural land for a minimum of 10 years (Goodwin and Smith 2003; Sperow, 2003).

The Permanent Cover Program (PCP) is a large scale Canadian set-aside program that was available to farmers in Manitoba, Alberta, Saskatchewan, and British Columbia from 1988 to 1992. Similar to the CRP, the PCP was established primarily to address issues of soil degradation (Vaisey et al., 1996), and farmers received payments for replacing cultivated marginal lands with perennial vegetation for 10-20 years (Vaisey et al., 1996). Over the duration of the program, a total of 522,000 hectares of land were enrolled. Following the success of the national PCP, in 1991, the province of Ontario developed a similar service via the Land Management Assistance Program. Under this program, contracts ranging from five to 15 years were provided to farmers for converting environmentally sensitive cropland to grassland and forest (Vaisey et al., 1996).

Set-aside programs have been shown to improve soil quality (Hermawan and Bomke, 1996; Riley et al., 2008; Yates et al., 2017), reduce soil erosion (Fullen and Booth, 2006), increase species diversity (Kovács-Hostyánszki et al., 2011), sequester carbon (Post and Kwon, 2000), and improve wildlife habitat (Riffell et al., 2008); however, the overall benefits to agriculture systems and communities has been criticized. For instance, unproductive sites are commonly
placed into long-term set-aside (Yates, 2014) and critics have claimed these programs to indirectly promote more intensive management of non-degraded land which is kept in production (Helms, 1985; Vaisey et al., 1996). Furthermore, the long-term enrolment of land into set-aside has been noted to limit the availability of farmland, thereby, restricting the expansion of smaller farming operations (Helms, 1985).

1.2.2 The Grassland Set-aside Stewardship Program

The Grassland Set-Aside (GLSA) Steward Program is offered in the FRD by the Delta Farmland and Wildlife Trust (DF&WT) and is currently the only active set-aside program in Canada. The program was initiated in 1994 and provides annual cost-share payments to farmers in the FRD for leaving fields under a grass and legume restoration mix for a period of one to four years (DF&WT, 2014). The relatively short enrolment period is unique, and has resulted in a low-cost, inclusive program that allows many farmers to participate for a short period of time. Since the inception of the program, local farmers have shown a strong interest for incorporating “short-term” GLSAs into their farm management plan and enrollment is often near a maximum capacity of ~225 hectares (DF&WT, 2014).

The unique short-term set-aside model offered by the DF&WT requires a shorter commitment from farmers than other long-term programs, and this flexibility has led to diverse reasons for enrolling fields (Yates et al., 2017). As with long-term set-aside programs, highly degraded sites with limited economic value may be a common choice for enrollment; however, non-degraded sites are also enrolled in the program as a method to maintain soil productivity. Fields are also sometimes placed into GLSA during the 3-year transition period required for organic
certification in Canada. The different reasons for enrolling fields into the GLSA program most likely means that fields with a wide range of soil properties (from heavily degraded to highly fertile) are entering this program; however, this has never been evaluated.

1.3 The Effects of Short-term Grassland Set-aside on Soil Properties

1.3.1 Soil Organic Matter

While the rates of organic matter accrement may be highly variable under GLSA management, studies have generally found this practice to increase soil organic matter (SOM) over time. Annual increases of total soil organic carbon in set-asides have been reported to be as low as 3.1 g C m$^{-2}$ y$^{-1}$ (Burke et al., 1995) and as high as 110.0 g C m$^{-2}$ y$^{-1}$ (Gebhart et al., 1994), while a meta-analysis study by Post and Kwon (2000) reported an average annual total soil organic carbon increase of 33 g C m$^{-2}$ y$^{-1}$. A comprehensive study by Karlen et al. (1999) found a significant difference in total soil organic carbon in a 2.5 year GLSA enrolled in the CRP relative to a nearby paired field under conventional tillage; however, the majority of studies have reported significant increases to occur over a longer period of time (Gebhart et al., 1994; Post and Kwon 2000). This was confirmed in a local study by Yates et al. (2017) that found similar total soil organic carbon levels between 2-6 year GLSA fields and paired fields managed for ACR.

Several studies have noted the isolated measurement of active carbon pools to provide increased sensitivity to short-term SOM changes under set-aside management (Burke et al., 1995; Robles and Burke; 1998; Karlen et al., 1999). Active carbon represents 3-4% of total organic carbon and
consists of organic matter which is quickly decomposed in soils (Cambardella and Elliott, 1996). This pool is closely correlated to aggregate stability and biological activity, and is therefore, considered an important indicator of overall soil quality (Weil et al., 2003).

In recent years, several methodologies have been developed to isolate active carbon pools in soils (Cambardella and Elliott, 1996; Lowe, 1994; Six et al., 2000; Weil et al., 2003). Permanganate oxidizable carbon (POXC) and dilute acid-extractable polysaccharides (DAEP) are examples of operationally defined active carbon pools. In addition to having a strong relationship to soil microbial biomass (Cullman et al., 2012) and soil aggregation (Weil et al., 2003), recent studies have found POXC to be sensitive to short-term effects of management practice (DuPont et al., 2010; Lewis et al., 2011; Lopez-Garrido et al., 2011; Margenot et al., 2015). Similarly, DAEP is an effective indicator of short-term changes of SOM (Lui et al., 2005) and has been found to have a strong relationship to aggregate stability (Tisdall and Oades, 1982; Lui et al., 2005). No study has evaluated either of these active SOM pools under GLSA management in the FRD.

The extensive time and high-cost involved with evaluating various SOM pools is often a barrier for including them in soil quality evaluations. In recent years, the use of diffuse reflectance Fourier transform spectroscopy has proved to be a rapid and inexpensive alternative to traditional methods for determining carbon pools (Calderón et al., 2017). A large body of research has found Fourier transform spectroscopy calibrations with the mid-infrared (FT-MIR) region (400-4,000 cm⁻¹) to be effective in parameterizing total soil organic carbon pools in the FRD (Theil et al., 2015) and other regions of the world (Bellon-Maurel and McBractney, 2011; Peltre et al., 2014; Veum et al., 2014; Calderón et al., 2017). Studies have also shown the potential for FT-
MIR to accurately predict active carbon pools (Veum et al., 2014; Calderón et al. 2017). For instance, Veum et al. (2014) and Calderón et al. (2017) reported the FT-MIR method to be effective for predicting POXC, while Calderón et al. (2013) also observed polysaccharides to have a strong relationship to various MIR frequency regions. Establishing local FT-MIR calibrations for these important soil quality indicators could provide researchers and producers in the FRD with a quick and low-cost option for assessing SOM.

1.3.2 Soil Structure and Compaction

Significant improvements in soil structure and compaction relief in set-asides have been generally found to occur at a faster rate than SOM build-up (Hermawan, 1995; O’Brien and Jastrow, 2013; Yates, 2014). Aggregate stability is a good indicator of soil structure changes under set-aside management (Hermawan and Bomke, 1996; Karlen et al., 1999; Principe, 2001; Riley et al., 2008; O’Brien and Jastrow, 2013; Yates et al., 2017), while responses of soil bulk density are less clear (Karlen et al., 1999; Hermawan, 1995; Yates, 2014). Studies carried out in the FRD by Hermawan (1995) and Yates (2014) found aeration porosity (i.e., the relative pore volume occupied by so-called aeration pores that have diameter >50 µm) to be more responsive to soil management practices than soil bulk density.

Short-term changes in soil physical properties under GLSA management were noted by Karlen et al. (1999) in a study which included multiple GLSA fields established for 2.5 to 6.5 years. These set-asides were all enrolled in the CRP program (located in the Northern Plains, Columbia Plateau and the Corn Belt region), and were compared to nearby fields under varying crop management practices, including no-till, reduced-till, and conventional tillage. The percentage of
water stable soil aggregates (WSA) from the 2-6 mm size fraction were reported to be significantly higher in a 2.5-year set-asides (24.6%) relative to a field under conventional tillage (19.2%). However, no difference in aggregate stability was noted between a group of 5 to 6.5-year GLSA and cropland in the same study. The authors concluded extensive variation between sites to be largely attributed to both differences in environmental conditions between geographic locations and the varying tillage practices used in the cropland.

The use of short-term GLSA in rotation with cash crops over an extended period of time has been reported to be an effective method to maintain good soil structure. A study by Riley et al. (2008) monitored several 4-year crop rotations with the inclusion of short-term set-asides at either 0, 1, 2 or 3-year intervals. The four-year rotations were conducted over a 15-year period on a silty loam soil under a humid continental climate (Mean annual precipitation (MAP) of 600 mm) in Norway. Set-asides were planted with a grass and clover mix and the crops included a mixture of wheat, oats, barley and potato. Using the simulated rainfall method, it was found that continuously cropped rotations contained 25% less stable aggregates in the 2-6 mm size class than 4-year crop rotations that included either a 1, 2 or 3 year GLSA. Furthermore, 4-year crop rotations with the inclusion of either a 2 and 3-year GLSA were found to be above an 85% porosity threshold determined for optimal crop productivity. The authors conclude the establishment of 2-year GLSA in rotation with cash crops to be sufficient to maintain good soil structure.

Within the FRD, a repeated measures study by Hermawan and Bomke (1996) found a 2 and 3-year GLSA site to have more stable aggregates than a paired field under continuous cultivation. The study was conducted on a single site and sub-surface drainage was installed in a portion of
each treatment prior to GLSA seeding. Soil water content was reported to have a negative relationship to aggregate stability and seasonal changes in this soil property corresponded with seasonal precipitation patterns. The GLSA treatment on the sub-surface drainage section was found to have a significantly higher mean weight diameter (MWD) of water stable aggregates in the second and third seasons of establishment.

Other studies carried out in the FRD reported varying effects of short-term GLSA on soil structure. A study by Armstrong (2013) corroborated findings by Hermawan and Bomke (1996), and reported a higher MWD of water stable aggregates after a single season of GLSA establishment relative to an adjacent field recently managed for potatoes. Intensive tillage practices commonly done for the management of potatoes in the FRD were believed to have amplified the differences observed in this study. In contrast to these findings, a study by Principe (2001) did not report a difference in aggregate stability on samples collected after a single season of GLSA establishment.

Varying results were also noted in a recent study by Yates et al. (2017) in the FRD, which evaluated selected soil properties in sites containing either a 2, 3, 4 and 6 year GLSA and paired ACR fields recently managed for potatoes. While the study concluded GLSA management to benefited soils in the FRD by reducing mechanical resistance and bulk density, the improvements were noted to be largely dependent on accompanied management practices such as sub-surface drainage installation, sub-soiling, previous manure applications and laser-leveling. Although a baseline assessment was not done in this study, varying soil properties prior to GLSA establishment were also speculated to have influenced findings. This was also speculated by Principe (2001) in an FRD study, which noted areas with poor GLSA establishment and growth
to be associated with a higher exchangeable sodium concentration and electrical conductivity. The characterization of baseline properties prior to GLSA establishment has been recommended as a necessary component to track soil change in GLSA fields over time.

1.4 Summary of General Introduction

The Fraser River delta (FRD) of British Columbia is a fertile agricultural region faced with several soil productivity concerns. Intensive rainfall in the winter months causes the agricultural soils to be highly susceptible to structural degradation and compaction, and fields that are managed for annual crop rotations (ACR) are especially prone to these issues. Another common issue for soil productivity in the region is the accumulation of salts in soils which are in close proximity to the ocean. In response to increasing soil productivity concerns, the Delta Farmland and Wildlife Trust (DF&WT) has established several cost-share programs to encourage farmers in the FRD to undertake land conservation practice.

The Grassland Set-Aside Stewardship Program, is one of the programs offered by the DF&WT, and provides payments to farmers for seeding active agricultural cropland with a perennial grass and legume restoration mix for a period of one to four years. This unique short-term set-aside model requires a shorter commitment than other long-term programs (>five years enrollment), and this flexibility has led farmers to enroll fields in the FRD program for a number of different reasons. For instance, farmers have reported placing fields into short-term GLSA as a method to restore highly degraded fields, transition fields into organic production, or maintain soil productivity. The different reasons for enrolling fields into GLSA most likely means that fields
with a wide range of soil properties (from heavily degraded to highly fertile) are entering this program; however, this has never been evaluated.

The cessation of tillage and the establishment of perennial vegetation in GLSA are believed to restore soils by increasing soil organic matter, improving soil structure, and relieving soil compaction. Variable results have been reported in the few studies that have evaluated the effects of short-term set-asides on soil properties. In the FRD, some studies have found improvements in aggregate stability after one to three years of establishment, while others have not. Contrasting bulk density and aeration porosity responses have also been observed and no increases in total soil organic carbon have been documented under short-term set-asides in the FRD.

While some studies have found these variable findings to be associated with different management practices which commonly accompany GLSA enrollment (e.g., sub-surface drainage, laser leveling, sub-soiling), researchers have also speculated varying soil properties prior to GLSA establishment to influence vegetation growth and soil responses. The characterization of baseline properties prior to GLSA establishment has been recommended as a necessary component to track GLSA induced soils changes over time.
1.5 Study Objectives

This study examines the effects of GLSA on selected soil properties in the FRD during the first and second year of establishment and is guided by the following objectives and associated hypotheses.

Study objective 1: Compare baseline soil properties of fields entering the GLSA program and determine if these properties affect the growth of GLSA vegetation.

Hypothesis 1: Fields entering the GLSA program will have a wide-variety of soil baseline properties and lower vegetation growth will be observed in GLSA fields with poor baseline soil properties.

Study objective 2: Compare aggregate stability, bulk density, and aeration porosity in productive and unproductive GLSA fields after 2 seasons of enrollment, relative to fields managed for ACR.

Hypothesis 2: Unproductive GLSA fields will have a lower aeration porosity, higher bulked density, and lower aggregate stability relative to productive GLSA fields and ACR fields after 2 seasons of GLSA establishment.

Study objectives 1 and 2 are addressed in Chapter 2 of this thesis.

Study objective 3: Conduct the first FRD-based replicated field experiment with repeated measures over time to evaluate the short-term effects of GLSA management on select soil properties in productive GLSA fields relative to adjacent ACR fields.

Hypothesis 3: Short-term improvements due to GLSA on productive fields will be observed on aggregate stability, aeration porosity and bulk density relative to adjacent fields managed for ACR, while no difference in total soil organic carbon or total soil organic nitrogen will be observed.

Study objective 3 is addressed in Chapter 3 of this thesis.
**Study objective 4:** Compare total soil organic carbon, POXC, and DAEP between ACR fields and paired GLSA fields after 2 seasons of enrollment, and assess the relationship of these soil organic matter pools to each other and the stability of soil aggregates.

*Hypothesis 4:* A greater POXC and DAEP concentration will be found in GLSA fields relative to paired fields managed for ACR, and no difference in total soil organic carbon will be observed. POXC and DAEP will have a stronger relationship to both each other and aggregate stability, while the relationship of these properties to total soil organic carbon will be weaker.

**Study objective 5:** Evaluate the use of Fourier transform mid-infrared spectroscopy (FT-MIR) for predicting DAEP, POXC, and water stable aggregates.

*Hypothesis 5:* The FT-MIR method will be effective for predicting DAEP and POXC and less effective for predicting water stable aggregates.

*Study objectives 4 and 5 are addressed in Chapter 4 of this thesis.*
Chapter 2: A comparison of select soil properties between short-term grassland set-asides and annual crop rotations on productive and unproductive sites

2.1 Introduction

The Fraser River delta (FRD) of British Columbia is a fertile agricultural region faced with several soil productivity issues. The combination of intensive rainfall from October to April (Environment Canada, 2017) makes the medium texture soils susceptible to structural degradation and compaction. Fields which are managed for annual crop rotations (ACR) are particularly prone to these issues as frequent tillage and harvesting practices disturb soil aggregates, deplete organic matter, and compacts soils. (Paul and de Vries, 1979; Coote et al., 1981; Hermawan, 1995; Krzic et al., 2000; Principe, 2001; Lui et al., 2005; Yates et al., 2017). Other soil productivity issues in the region include high salinity in fields that are in proximity to the ocean (Principe, 2001; Barron et al., 2014 and Yates et al., 2017) and soil acidification (Principe, 2001).

In response to increasing soil productivity concerns, the Delta Farmland and Wildlife Trust (DF&WT) has established several cost-share programs to encourage farmers in the FRD to undertake land conservation practices. The Grassland Set-Aside Stewardship Program provides payments to farmers for taking active agricultural land out of production and seeding it with a perennial grass and legume restoration mix for a period of one to four years. The unique short-term set-aside model offered by the DF&WT requires a shorter commitment from farmers than

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1 NOTE: A version of this chapter will be submitted for publication in the Canadian Journal of Soil Science - J.M. Lussier, M. Krzic, S.M. Smukler, A.A. Bomke, and D. Bondar. A comparison of selected soil properties between short-term set-asides and annual crop rotations on productive and unproductive sites.
other long-term programs (>five years enrollment) and this flexibility has led to diverse reasons for enrolling fields. As with long-term set-aside programs, highly degraded fields with limited economic value are a common choice for enrollment in the DF&WT program; however, non-degraded sites are also enrolled as a method to maintain soil productivity or transition fields to organic production (Yates et al., 2017).

Improvements in soil structure and compaction relief have been commonly reported under long-term GLSA management (Karlen et al., 1999; O’Brien and Jastrow, 2013; Rosenzweig et al., 2016); however, variable findings have been noted when evaluating the effects of short-term GLSA on soil properties. A FRD study by Hermawan and Bomke (1996) found a higher mean weight diameter (MWD) of water stable aggregates in a GLSA field after two and three seasons of enrolment relative to a paired field under cash crop rotation. In contrast, a study by Principe (2001) did not find an increase in the percentage of water stable aggregates in a GLSA field after one season of establishment relative to pre-establishment values.

A recent study by Yate et al. (2017), which compared selected soil physical properties between GLSA and paired fields recently managed for potatoes, reported varying response on aggregate stability, bulk density and aeration porosity in a 2, 3, 4 and 6 year GLSA. The mixed responses reported in this study were believed to be partially attributed to a wide-range of accompanying management practices such as laser levelling, sub-surface drainage, manure applications and sub-soiling in the GLSA fields. Although a baseline assessment was not done in this study, varying soil properties prior to GLSA establishment were speculated to have also influenced soil responses to GLSA. This was also suggested by Principe (2001) who noted areas with poor
GLSA growth to be associated with a higher exchangeable sodium concentration and electrical conductivity.

The characterization of baseline properties prior to GLSA establishment has been recommended as a necessary component to track GLSA effects on soil properties over time (Principe, 2001; Yates et al, 2017). The objectives of this study were to: (1) compare baseline soil properties of fields entering the GLSA program and determine if these properties affect the establishment of GLSA vegetation; and (2) compare aggregate stability, bulk density, and aeration porosity responses in productive and unproductive GLSA fields after 2 seasons of enrollment relative to fields managed for ACR.

2.2 Materials and Methods

2.2.1 Study Sites

This study was carried out from April 2015 to September 2016 in the FRD on eight sites located within the Municipality of Delta and Richmond, BC (49°05’N, 123°03’W; elevation 2 m above sea level). This region is characterized by a mean annual temperature of 11.1°C and a mean annual precipitation of 1,189 mm, with approximate 80% occurring between October and April (Environment Canada, 2017). All soils included in this study were developed from surficial fluvial deltaic deposits and were classified as Humic Luvic Gleysol, Orthic Gleysol, and Rego Humic Gleysol (Luttmerding, 1981).
Nine sites were randomly selected for this study (Fig. 2.1); however, in the spring of 2016 one of the sites (Site 6) was taken out of agriculture production for industrial use and was removed from the study. The remaining eight sites all included both a GLSA (seeded in spring 2015) field and an adjacent field managed under ACR for either potatoes, beans, peas, barley, wheat, or corn (Table A.1). The ACR fields were selected based on similar management history and soil type to the their paired GLSA fields (Fig. 2.2). The fields included in this study ranged from approximately 6 to 25 acres in size.

The GLSA fields were all part of the Grassland Set-aside Stewardship Program offered by the DF&WT. Fields were taken out of production in September of 2014 and then seeded in 2015 between April 15th and May 10th with a standard restoration seed mix composed of 25% (by seed weight) orchard grass (*Dactylis glomerata*), 28% tall fescue (*Festuca arundinacea*), 30% short fescue (*Festuca rubra* var. *commutata* and *F. rubra* var. *rubra*), 15% timothy grass (*Phleum pratense*), and 2% red clover (*Trifolium pratense*).

The study was conducted on operational farms and management practices varied by field. For instance, the ACR fields at Sites 5 and 8 were under organic management and a standard rate of composted chicken manure of ~12.35 t/ha per year was applied in these fields. The same manure rate was also applied on the ACR field at Site 2 and synthetic fertilizers were applied in all non-organic ACR fields at typical regional rates for the selected crops. A variety of tillage practices were implemented at each site and included practices such as diskig, rotovating, plowing, and pulvi-mulching.
2.2.2 Sampling and Analysis

All soil and vegetation samples in this study were collected from four sub-plots located in both the GLSA and paired ACR fields. Sub-plots with a 6m radius were randomly generated in each field in the spring of 2015. All sub-plots were located at least 10 m away from each other and 10 m away from field edges to avoid areas where edge effects may have interfered with the experimental treatment.

Samples for baseline soil properties were collected from sub-plots in GLSA fields only in April 2015 (prior to GLSA seeding) and were analyzed for exchangeable sodium concentration, total soil organic carbon, bulk density, and the MWD of water stable aggregates. Following 2-years of GLSA establishment, samples for bulk density, aeration porosity and MWD were collected in both GLSA and paired ACR fields in September 2016 (after ACR fields were harvested). Vegetation biomass samples were collected after the first season of GLSA establishment on September 2015 and again in the second season on September 2016. Specific sample collection and analysis methods for each soil property varied and are described in more detail below.

2.2.2.1 Exchangeable Sodium

Soil samples for exchangeable sodium were collected from three locations at each sub-plot in GLSA fields on April 2015 (before GLSA seeding) from depths of 0-15cm and 15-30cm. Samples were then air dried, ground, passed through a 2-mm sieve and sent to the British Columbia Ministry of Environment Technical Service Laboratory in Victoria, BC for determination of exchangeable sodium (Carter and Gregorich, 2008). Exchangeable sodium was
extracted using 0.1 \( M \) barium chloride and analyzed with an Inductively Coupled Plasma Spectrometer. Due to the high mobility of sodium ions, exchangeable sodium is reported for the whole sampled layer (i.e., 0-30 cm).

### 2.2.2.2 Total Soil Organic Carbon

Total soil organic carbon was determined on a single sample collected from each sub-plot in GLSA fields only on April 2015 (before GLSA seeding) at a depth of 0-15 cm. Total carbon was determined by the diffuse Fourier transform mid-infrared spectroscopy (FT-MIR) method (Reeves et al., 2001) run on a Tensor 37 HTS-XT spectrometer (Bruker Optics, Ettlingen, Germany). Three replicates of 0.025 g each of ball mill ground soil samples were scanned 60 times for FT-MIR spectral reflectance between 400 and 4,000 cm\(^{-1}\) at a resolution of 2 cm\(^{-1}\). Prediction for total soil organic carbon values were done using a pre-existing regional database (n= 1038) provided by the Sustainable Agricultural Landscape (SAL) laboratory at the University of British Columbia. The validation test for the FT-MIR calibration of total soil organic carbon found a coefficient of determination of 0.92 with a RMSE of 0.34. The coefficients of determined and RMSE were derived using a partial least squares (PLS) regression with the QUANT package in OPUS 7.5 (Bruker Optik GmbH, 2012). The optimal regression model, pre-processing methods, and spectral wavenumber ranges were chosen using a leave one out cross-validation procedure.
2.2.2.3 Aggregate Stability

Aggregate stability samples were collected at the 0-7.5cm depth from sub-plots in GLSA fields on April 2015 (prior to GLSA seeding) and again on September 2016 from sub-plots in both GLSA and ACR fields. Organic matter debris from the surface was removed before samples were taken and composites of 5-7 samples were collected at each sub-plot. Samples were stored at 4°C until being passed through a 6-mm sieve and collected on a 2-mm sieve.

Aggregate stability was determined using a variation of the wet-sieving method (Nimmo and Perkins, 2002). Immediately before wet-sieving, 15 g of pre-sieved 2-6-mm sized aggregates was placed on top of nested sieves with openings of 2, 1, and 0.25 mm. Aggregates were then moistened in a humidifier for 30 minutes to minimize disruption of the aggregates by the release of trapped air and samples were wet-sieved in a motorized apparatus for 10 minutes. The apparatus had a vertical stroke of 2.5 cm, an oscillating action through an angle of 30°, and a rate of 30 strokes per minute. After the sieves were removed from the water, the material retained on each sieve was oven-dried at 105°C for 24 hours and weighed. A correction was made to account for non-aggregate particles by crushing all material and washing the finer material through the sieve. Non-aggregate particles retained were weighed and their mass was subtracted from the total size fraction mass to determine the true mass of aggregates. The mass for each size fraction was expressed as a percentage of the total non-aggregate particle-free sample mass. MWD was calculated using Van Bavel's calculation as described in Kemper and Rosenau (1986) where:

\[ MWD = \sum_{i=1}^{4} W_i D_i \]
The mean diameter of each size fraction is denoted by $x$. The proportion of the total sample weight occurring in the corresponding size fraction is denoted as $W_i$ and $D_i$ goes from 1 to $n$, where $n$ is the number of size fractions including that lost through the bottom of the smallest sieve (<0.25 mm).

### 2.2.2.4 Bulk Density and Aeration Porosity

Samples analyzed for bulk density were collected from the 0-7.5 depth from sub-plots in GLSA field on April 2015 (prior to GLSA seeding) and again on September 2016 from sub-plots in both GLSA and ACR fields. Aeration porosity was only analyzed on samples collected on September 2016 from both the GLSA and ACR fields. Soil cores with a 7.5 cm-diameter and 7.5 cm-depth were collected at one location from each sub-plot using a double-cylinder drop-hammer sampler and stored at 4°C until analysis.

Aeration porosity (i.e., soil pores having diameter $> 50 \mu m$ or macropores) was determined using a water tension table technique (Danielson and Sutherland, 1986). Soil cores were removed from the sample bags and a 4-layer cheese cloth skirt was placed on the underside of cores and held with a rubber elastic. Cores were placed in a container which was gradually filled with water until the level of water was within 1 cm of the top of the core. The cores were then left to saturate for 24 hours, weighed and placed on a degassed tension table prepared with a saturated silicon carbide sand (grit 400). After placing cores on the table, tension was set to -6 kPa of matric potential. This tension corresponds to the air entry value for soil pores greater than 50 $\mu m$ in diameter. The water-filled pore-space was calculated by determining the mass per volume of water that was retained in the soil at -6 kPa relative to the total soil volume.
Bulk density was determined from the same soil cores used for aeration porosity. The soil cores were dried at 105°C for 24 h and the oven-dry mass of soil was determined. A correction was made for coarse fragments by sieving the samples to remove particles >2 mm in diameter. Assuming a particle density of 2.65 g cm\(^{-3}\) of the volume, weight of coarse fragments was calculated and subtracted from each core sample. Bulk density was calculated on a coarse fragment-free basis as the mass of oven-dry soil per volume of soil at field moisture (Blake and Hartge, 1986).

2.2.2.5 Aboveground Vegetation Biomass in Grassland Set-Asides

Samples for aboveground vegetation biomass in GLSA fields were collected at the end of first (September 2015) and second (September 2016) season of enrollment. Samples were collected from two locations at each sub-plot using a 50 cm by 50 cm quadrant. All vegetation was cut about 2 cm from the ground and collected in paper bags. Bags were then stored in a fridge at 4°C until being oven drying. Vegetation from samples taken in September 2016 were sorted into three broad groups: clover, grasses, and weeds. The weed group encompassed all vegetation species which were not included in the GLSA restoration mix. Samples were oven dried at 60°C for one-week prior to being weighed.

2.2.3 Statistical Analysis

All statistical analysis was preformed using R software version 3.4.0 (R Core Team, 2017). Baseline properties collected from sub-plots (bulk density, exchangeable sodium, MWD of water
stable aggregates, and total soil organic carbon) were averaged for each field entering the GLSA program and the standard error of the mean was calculated (n=4).

Total dry biomass collected at each sub-plot was averaged by site and the standard error of the mean was calculated (n=4). The various vegetation groups including weeds, clover and grass were averaged by field and were represented as a proportion total biomass. A Pearson correlation analysis was done using the cor function between all baseline soil properties and total aboveground dry vegetation biomass collected on September 2016. The relationship between exchangeable sodium and total dry biomass was further analyzed using the CTree function in the partykit package (Hothorn et al., 2017). CTree is a non-parametric class of regression trees, which embeds tree-structure regression models into a well-defined theory of conditional inference procedures (Hothorn et al., 2006). Significance was set at an alpha of 0.05; the minibucket was set at 2 and the minisplit was set at 1 due to the small sample size (n=32).

A principal component analysis (PCA) of bulk density, aeration porosity and the MWD of water stable aggregates was done on sampled sub-plots in unproductive and productive GLSA fields after two seasons of enrollment, and paired ACR fields. The PCA analysis was conducted using the prcomp function on sub-plots collected from each group (unproductive GLSA, productive GLSA and ACR). A separate site analysis was also conducted to compare the same soil properties between GLSA (unproductive and productive) and paired ACR fields. For this analysis, a t-test was conducted using the lm function and the null hypothesis was rejected at an alpha of 0.10 due to extensive variability within this field experiment. The Shapiro Wilks test was used to assess normality and the Breusch-Pagan test was used to test for heteroscedasticity.
2.3 Results and Discussion

2.3.1 Soil Baseline Properties of Fields Entering the GLSA program

Common constraints to soil productivity in the FRD include high salinity, compaction, poor structure and low organic matter (Paul and de Vries, 1979; Coote et al., 1981; Hermawan and Bomke, 1996; Krzic et al., 2000; Principe, 2001; Lui et al., 2005; Yates et al., 2017); hence, these properties were assessed in fields prior to GLSA seeding in the spring of 2015. The results showed a wide range of values for the select soil properties among the eight fields entering the GLSA program in this study (Table 2.1). Specifically, exchangeable sodium was found to be between 0.07 to 2.59 cmol$_e$ kg$^{-1}$, while total soil organic carbon concentrations ranged from 1.63 to 3.07%, MWD from 0.35 to 1.66 mm, and bulk density from 1.12 to 1.32 Mg m$^{-3}$. This extensive variability was not surprising as farmers involved in this study reported different reasons for enrolling fields into the GLSA program.

For instance, the GLSA fields 3 and 4 were both reported to have severe crop productivity issues and were entered into the GLSA program to restore soil properties. The baseline soil analysis on these two fields was in agreement with farmer observations regarding poor crop production (Table 2.1). Most notably, both fields contained a very high exchangeable sodium concentration and an MWD well below the 1.09 mm average observed in all other fields entering the GLSA program in this study. Furthermore, these two fields had a total soil organic carbon percentage below the 3% threshold stated by Hermawan (1995) to be necessary for stabilizing aggregates in the FRD. In addition to these poor soil properties, the GLSA field 3 had a bulk density well above the 1.19 Mg m$^{-3}$ average observed in all other fields.
In contrast, the other fields entering the GLSA program were not reported to have severe crop productivity issues and it was, therefore, not surprising to find more favorable baseline soil properties in these fields (Table 2.1). The GLSA fields 5, 8 and 9 were enrolled in the GLSA program to allow them to transition into organic production and were all characterized by having a higher total soil organic carbon percentage than other fields entering the GLSA program (Table 2.1). The GLSA fields 5 and 8 received manure applications in previous growing seasons (Fig. 2.2), which may explain the high total soil organic carbon percentage observed. GLSA field 9, on the other hand, did not receive past manure applications and the high total soil organic carbon concentration was likely related to this field being in pasture for several years prior to being managed for ACR since 2004. The GLSA fields 1, 2 and 7 were all placed into the GLSA program as part of a regular crop rotation practice and no unusual soil properties were observed in these fields (Table 2.1).

The overall poor soil properties observed in GLSA fields 3 and 4 led to the broad classification of these fields as “unproductive”, while all other GLSA fields included in this study were considered “productive”. The poor soil properties observed in the unproductive fields were likely caused by both inherent site-specific conditions and past soil management practices. For example, both the GLSA fields 3 and 4 were in close proximity to the ocean, which likely allowed some subsurface ocean water intrusion, and thus, increased sodium accumulation (Barron et al., 2012). Intensive tillage practices done for ACR in the FRD may have also contributed to these issues by depleting important organic binding constituents, disturbing aggregates, and compacting soils (Paul and de Vries, 1979; Coote et al., 1981; Hermawan, 1995; Krzic et al., 2000; Principe, 2001; Lui et al., 2005; Yates et al., 2017). Moreover, it is likely that the poor soil properties in these fields were amplified by a lack of long-term soil conservation.
management practices, such as the installation of sub-surface drainage and laser levelling (Fig. 2.2), which have been reported to reduce soil salinity and improve soils structure in the FRD (Hermawan, 1995; Hermawan and Bomke, 1996).

2.3.2 Aboveground Vegetation in Unproductive and Productive GLSA Fields

The total aboveground vegetation biomass in GLSA fields and its composition varied significantly among the sites included in this study. Following the first season of GLSA establishment (i.e. September 2015), the total average aboveground dry vegetation biomass across all eight sites was 3.09 ± 0.47 t/ha (data not shown). A large biomass increase was observed in most fields in the second season of GLSA establishment and an average total aboveground dry vegetation biomass of 8.18 ± 0.83 t/ha was recorded.

Greater variability in total aboveground dry vegetation biomass was observed among fields in the second season of GLSA establishment (Fig. 2.3). The highest total aboveground dry vegetation biomass was noted in GLSA 8 (14.06 ± 1.57 t/ha), with similar levels in GLSA 1 (13.74 ± 1.27 t/ha) and GLSA 2 (9.82 ± 1.71 t/ha). Slightly lower aboveground dry vegetation biomass was noted in GLSA 5 (6.70 ± 0.54 t/ha), GLSA 7 (7.87 ± 1.55 t/ha), and GLSA 9 (7.95 ± 1.35). The lowest aboveground dry vegetation biomass was in GLSA 4 (1.61 ± 1.03 t/ha), while GLSA 3 had a slightly higher biomass (3.71 ± 0.55 t/ha). In addition to having low vegetation growth, the unproductive fields (i.e., GLSA 3 and 4) were also characterized by having a much higher proportion of weeds (Fig. 2.4).
The results from this vegetation assessment agreed with past findings by Principe (2001), who monitored GLSA vegetation on 17 productive GLSA sites in the FRD. The study by Principe (2001), reported a similar aboveground dry vegetation biomass increase from 3.9 t/ha in the first season to 11.2 t/ha in the second season of GLSA establishment. While the total aboveground dry vegetation biomass in the first season was similar between our studies, Principe (2001) noted a higher average biomass in the second season of GLSA establishment. This study excluded anomalous (or unproductive) GLSA sites, as opposed to my study, where I included unproductive sites, which is likely why I found a lower average biomass value. Similar to my findings, Principe (2001) noted unproductive GLSA sites to be characterized by a higher proportion of weeds.

Of all baseline soil properties, exchangeable sodium had the strongest negative correlation to total aboveground dry vegetation biomass in the second season of GLSA establishment ($r = -0.61$) (Table 2.2). This was not surprising as a study by Principe (2001) also found GLSA sites with low total aboveground dry vegetation biomass to be associated with a high exchangeable sodium content. Electrical conductivity was also found in their study to be associated with varying vegetation composition in GLSA fields. For instance, timothy grass, rye grass, short-fescues and orchard grass were noted to be less successful in anomalous areas with a higher electrical conductivity, while tall fescue was more successful in these areas and was reported to be more salt tolerant than other species included in the mix.

A further analysis was done in my study to identify exchangeable sodium thresholds which could be used as a guideline for farmers and decision makers involved with the GLSA program. A regression tree analysis identified exchangeable sodium values of 0.64 and 2.08 cmolc kg$^{-1}$ to
represent thresholds associated with a significant reduction of aboveground dry vegetation biomass in the second year of GLSA enrollment (Fig 2.5). Areas with an exchangeable sodium concentration below 0.64 cmol\textsubscript{c} kg\textsuperscript{-1} were noted to have an average total aboveground dry vegetation biomass of 10.37 t/ha in the second season of enrollment, while the total aboveground dry vegetation biomass was 5.48 t/ha ($P$<0.0001) in areas with a baseline exchangeable sodium concentration between 0.64 cmol\textsubscript{c} kg\textsuperscript{-1} and 2.08 cmol\textsubscript{c} kg\textsuperscript{-1}. Areas with an exchangeable sodium concentration near or above 2.08 cmol\textsubscript{c} kg\textsuperscript{-1}, on the other hand, were found to have a significantly lower average aboveground dry vegetation biomass of only 0.90 t/ha ($P$=0.005).

It is likely that the observed reduction in aboveground dry vegetation biomass within GLSA sites with a moderate (between 0.64 and 2.08 cmol\textsubscript{c} kg\textsuperscript{-1}) and high (>2.08 cmol\textsubscript{c} kg\textsuperscript{-1}) exchangeable sodium concentration was caused by the negative influences of sodium on both plant growth (Fontenele et al., 2014) and soil physical properties (Agassi et al., 1981). However, it is also important to note that the accumulation of sodium may act as an indicator of other confounding factors linked to poor GLSA vegetation growth. For instance, areas with poor drainage in the FRD are often characterized by a higher salt concentration and have been reported to cause “drowned out patches” which do not support GLSA vegetation growth in the wet winter months (Principe, 2001). The co-existence of salinity and poor drainage in soils within the FRD makes it challenging to determine the specific cause of reduced vegetation growth in GLSA fields with a higher exchangeable sodium concentration.

Despite this challenge, the strong negative relationship between exchangeable sodium and aboveground dry vegetation biomass suggest that this soil property is a good indicator for predicting the growth and establishment of vegetation in GLSA fields in the first two seasons of
enrollment within the FRD. The findings from this study suggest that areas with a baseline exchangeable sodium between 0.64 and 2.08 cmol\(_c\) kg\(^{-1}\) require a GLSA seed mix which is more tolerant to elevated salinity and/or extended winter ponding. While fields with an exchangeable sodium concentration above 2.08 cmol\(_c\) kg\(^{-1}\) may require accompanying management practices, such as laser leveling or the installation of sub-surface drains, to reduce salt levels and/or improve drainage prior to GLSA seeding.

2.3.3 Soil Properties in Unproductive and Productive GLSA Fields

Several past studies carried out in the FRD have reported short term effects of GLSA on soil bulk density, aeration porosity and aggregates stability relative to fields which are continuously cultivated for annual crop rotations (ACR) (Hermawan and Bomke, 1996; Yates et al., 2017). Hence, I evaluated these soil properties in both productive and unproductive GLSA fields after two seasons of enrollment to determine short-term soil responses relative to paired ACR fields in the region.

A PCA analysis was conducted on sub-plot samples collected from both productive and unproductive fields entering the GLSA program, and paired ACR fields in the FRD (Fig. 2.6). The analysis accounted for 93.9% of the variability in the data and showed varying responses in productive and unproductive GLSA fields included in this study. Specifically, the soils from productive GLSA fields after two seasons of establishment were associated with a higher MWD, a lower bulk density, and a higher aeration porosity relative to unproductive GLSA and paired ACR fields. In contrast, the unproductive fields were found to be associated with ACR samples containing a lower MWD, high bulk density and low aeration porosity.
The select soils properties were also compared between paired GLSA and ACR fields located at the eight sites included in this study (Table. 2.3). The comparison found the MWD to be greater in the GLSA fields at Sites 1, 5, 7 and 9 relatives to neighboring ACR fields. The GLSA fields at Sites 1, 2 and 5 all had a significantly higher aeration porosity than paired ACR fields, while a significantly lower bulk density was only noted on the GLSA at Site 2. In contrast, the MWD in the GLSA fields at Sites 3 and 4 (unproductive sites) were 10% and 22% lower than paired ACR fields, respectively. The GLSA field at Site 3 had a significantly greater bulk density than its paired ACR counterpart, and no significant difference in aeration porosity was found at the unproductive site.

The results showed unproductive GLSA fields included in this study to have similar or worse properties than ACR fields after two seasons of enrollment, while most productive GLSA fields were found to have either a higher aggregate stability, lower bulk density, or higher aeration porosity. Differences in soil properties between GLSA and ACR fields were expected as the roots of GLSA vegetation can stabilize soil by enmeshing aggregates (Angers and Caron, 1998) and increasing organic constituents which stabilize aggregates (Tisdall and Oades, 1982; Angers and Caron, 1998). Furthermore, the penetration of roots can increase the overall number and size of soil pores, thereby, increasing aeration porosity and lowering bulk density (Dexter, 1991). The protection of the soil surface by perennial aboveground biomass during wet period in the FRD has also been shown to protect surface soil aggregates (Lui et al., 2005). These vegetation-induced benefits to soils were likely not as prevalent in the unproductive GLSA fields which had lower vegetation growth due to the poor baseline soil properties prior to seeding.
In addition to the positive effects of GLSA on soil physical properties, it is possible that varying management practices in the ACR fields contributed to the observed difference in soil physical properties between the treatments at each site. Since this study was carried out on operational (or active) farms, it was not possible for me to control management practices undertaken on the ACR fields over the 2-year study period; and often practices varied among fields. One of the largest sources of variability was the diversity of crops selected by farmers in the ACR treatment (Table A.1). Most notably, the ACR fields at Sites 1, 5, and 9 were all managed for potatoes in the 2016 growing season. Potato production is commonly associated with a higher number of tillage passes (Angers et al., 1999) and it is likely that management for this crop may have enhanced the observed difference in aggregate stability and aeration porosity between the treatments at these sites. Conversely, the application of manure in the ACR fields at Sites 2, 5, and 8 may have dampened the observed difference by increasing organic binding constituents which are important for stabilizing soil aggregates (Fig. 2.2).

Studies have also noted accompanying management practices in GLSA fields to enhance the impact of this management practice on soil structure and compaction (Yates et al., 2017). A study by Hermawan and Bomke (1996) found a higher MWD of water stable aggregates in a portion of a GLSA field which received the installation of sub-surface drainage prior to planting. Laser leveling has also been found to reduce surface ponding and improve soil structure. Past laser leveling in the GLSA fields at Sites 5, 7, and 9 and the installation of sub-surface drainage at Site 7 may have enhanced the observed differences in aggregates stability, bulk density, and aeration porosity. In contrast, the soils at Sites 8 and 4 were characterized by a poor to very poor drainage class (Luttmerding, 1981) and did not have a recent history of laser levelling or sub-
surface drainage installation (Fig. 2.2). It is possible that poor drainage at these sites may have contributed to the limited differences between the GLSA and ACR fields.

2.4 Conclusions

Eight fields that entered the GLSA program in the spring of 2015 had variable soil properties prior to GLSA seeding. Two out of eight study sites were classified as unproductive due to a combination of a high exchangeable sodium, low MWD, high bulk density, and low total soil organic carbon concentration. Of the baseline soil properties evaluated in this study, exchangeable sodium had the strongest negative relationship to aboveground dry vegetation biomass in GLSA fields ($r= -0.61$). Sites with an exchangeable sodium between 0.64 and 2.08 cmol$_e$ kg$^{-1}$ were associated with a lower aboveground dry vegetation biomass in GLSA fields, while sites with an exchangeable sodium above 2.08 cmol$_e$ kg$^{-1}$ were found to have very little vegetative growth. These sites likely require either a more tolerant GLSA species mix or accompanying management practices to improve drainage and/or reduce salt levels prior to GLSA seeding.

Following two seasons of enrolment, the unproductive GLSA fields in this study had a similar aggregate stability, aeration porosity and bulk density as their paired ACR counterparts, while most productive GLSA fields had either a greater aggregate stability, higher aeration porosity, or lower bulk density. The vegetation and soil assessments conducted in this study found unproductive and productive fields to have varying response to GLSA management practices and, therefore, subsequent studies in this thesis were only done on productive fields enrolled in the GLSA program.
Figure 2.1. Map of the Fraser River delta (FRD) showing eight study sites with paired (adjacent) fields. Grassland set-aside (GLSA) fields are shown in green and paired annual crop rotations (ACR) fields are shown in brown.
Table 2.1. Soil baseline properties of fields that entered the grassland set-aside (GLSA) program in April 2015 (n=4). Soil properties include exchangeable sodium (Na), total soil organic carbon (TOC), the mean weight diameter of water stable aggregates (MWD) and bulk density.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Site</th>
<th>Na (cmol(_c) kg(^{-1}))</th>
<th>TOC (%)</th>
<th>MWD (mm)</th>
<th>Bulk density (Mg m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unproductive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.78 (0.52)(^{a})</td>
<td>1.92 (0.08)</td>
<td>0.45 (0.03)</td>
<td>1.32 (0.03)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.59 (1.06)</td>
<td>2.02 (0.15)</td>
<td>0.55 (0.08)</td>
<td>1.21 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Productive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.07 (0.004)</td>
<td>1.96 (0.10)</td>
<td>1.18 (0.23)</td>
<td>1.23 (0.04)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.33 (0.14)</td>
<td>2.08 (0.40)</td>
<td>1.00 (0.20)</td>
<td>1.21 (0.04)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.85 (0.09)</td>
<td>2.73 (0.14)</td>
<td>1.71 (0.20)</td>
<td>1.12 (0.04)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.16 (0.03)</td>
<td>1.63 (0.07)</td>
<td>1.06 (0.10)</td>
<td>1.25 (0.03)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.20 (0.02)</td>
<td>2.67 (0.27)</td>
<td>0.78 (0.10)</td>
<td>1.14 (0.05)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.13 (0.008)</td>
<td>3.07 (0.35)</td>
<td>0.81 (0.09)</td>
<td>1.20 (0.05)</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\)SE= Standard error of the mean is shown in the brackets.
Figure 2.2. Previous management practices and inherent soil characteristics on the eight sites included in this study. Note: Site 6 was taken out of the study as the ACR field at this site was removed from agriculture production for industrial use in the Spring of 2016.
Figure 2.3. Total aboveground dry vegetation biomass in productive and unproductive fields after 2 seasons of grassland set-aside (GLSA) establishment (error bars are standard error of the mean; n=4).

Figure 2.4. Percentage of total dry biomass by vegetation group (Clover, Grass, and Weeds) in productive and unproductive fields after 2 seasons of grassland set-aside (GLSA) establishment.
Table 2.2. Pearson’s product-moment correlation coefficient (r) between all baseline soil properties and GLSA aboveground dry vegetation biomass samples taken after two seasons of GLSA establishment in September 2016 (n=32). Significant correlation indicated by *.

<table>
<thead>
<tr>
<th>Baseline Soil Property</th>
<th>r</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchangeable Sodium (cmolₑ kg⁻¹)</td>
<td>-0.61</td>
<td>0.0002*</td>
</tr>
<tr>
<td>Bulk density (Mg m⁻³)</td>
<td>-0.17</td>
<td>0.35</td>
</tr>
<tr>
<td>MWD (mm)</td>
<td>0.32</td>
<td>0.08</td>
</tr>
<tr>
<td>Total carbon (%)</td>
<td>0.10</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Figure 2.5. Non-parametric regression tree with exchangeable sodium (cmolₑ kg⁻¹) included as the only independent variable and aboveground dry vegetation biomass in GLSA fields as the response variable. Nodes are considered significantly at P< 0.05.
Figure 2.6. Principal Component Analysis of bulk density, aeration porosity and the mean weight diameter (MWD) of water stable aggregates in unproductive and productive fields after 2 seasons of GLSA establishment, and paired fields managed for annual crop rotations (ACR).
Table 2.3. Mean weight diameter (MWD) of water stable aggregates, bulk density, and aeration porosity on 2-year (productive and unproductive) grassland set-asides (GLSA) and paired fields managed for annual crop rotation (ACR) determined in September 2016 (SE= standard error; n=4). Significant differences are indicated by * for $P$-value <0.05 and + for <0.10.

<table>
<thead>
<tr>
<th>Site</th>
<th>Treatment</th>
<th>Bulk Density (Mg m$^{-3}$) Mean (SE)</th>
<th>P-value</th>
<th>Aeration Porosity (%) Mean (SE)</th>
<th>P-value</th>
<th>MWD (mm) Mean (SE)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Mean (SE)</strong></td>
<td></td>
<td><strong>Mean (SE)</strong></td>
<td></td>
<td><strong>Mean (SE)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unproductive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>GLSA</td>
<td>1.30 (0.04)</td>
<td><strong>0.008</strong></td>
<td>13.53 (1.86)</td>
<td>0.34</td>
<td>1.66 (0.09)</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.16 (0.03)</td>
<td></td>
<td></td>
<td></td>
<td>1.84 (0.08)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>GLSA</td>
<td>1.22 (0.05)</td>
<td>0.41</td>
<td>14.67 (2.81)</td>
<td>0.76</td>
<td>1.48 (0.27)</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.17 (0.04)</td>
<td></td>
<td></td>
<td></td>
<td>1.82 (0.14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Productive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>GLSA</td>
<td>1.20 (0.04)</td>
<td>0.13</td>
<td>19.05 (1.05)</td>
<td><strong>0.002</strong></td>
<td>1.95 (0.11)</td>
<td><strong>0.02</strong></td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.27 (0.03)</td>
<td></td>
<td></td>
<td></td>
<td>1.54 (0.04)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>GLSA</td>
<td>1.12 (0.05)</td>
<td><strong>0.06</strong></td>
<td>17.88 (2.21)</td>
<td><strong>0.08</strong></td>
<td>1.83 (0.26)</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.24 (0.04)</td>
<td></td>
<td></td>
<td></td>
<td>1.77 (0.16)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>GLSA</td>
<td>0.99 (0.05)</td>
<td>0.15</td>
<td>24.12 (3.08)</td>
<td><strong>0.02</strong></td>
<td>2.66 (0.06)</td>
<td><strong>0.007</strong></td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.07 (0.04)</td>
<td></td>
<td></td>
<td></td>
<td>2.00 (0.08)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>GLSA</td>
<td>1.16 (0.07)</td>
<td>0.16</td>
<td>19.46 (3.63)</td>
<td>0.49</td>
<td>2.13 (0.05)</td>
<td><strong>0.003</strong></td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.27 (0.05)</td>
<td></td>
<td></td>
<td></td>
<td>1.51 (0.07)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>GLSA</td>
<td>0.97 (0.04)</td>
<td>0.71</td>
<td>25.63 (1.95)</td>
<td>0.16</td>
<td>2.21 (0.13)</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>0.99 (0.05)</td>
<td></td>
<td></td>
<td></td>
<td>2.26 (0.17)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>GLSA</td>
<td>1.06 (0.08)</td>
<td>0.23</td>
<td>18.55 (2.83)</td>
<td>0.21</td>
<td>2.43 (0.15)</td>
<td><strong>0.005</strong></td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>1.16 (0.05)</td>
<td></td>
<td></td>
<td></td>
<td>1.68 (0.09)</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 3: What are the effects of short-term set-asides on productive soils in the Fraser River delta region of British Columbia?²

3.1 Introduction

The Grassland Set-Aside Stewardship Program in the Fraser River delta (FRD) provides cost share payments to farmers for placing fields into short-term (1-4 years) grassland set-asides (GLSA) comprised of grass and clover species. This short enrollment period is unique as most other set-aside programs around the world promote the establishment of GLSA for more than 5 years (Skold, 1989; Gebhart et al., 1994; Vaisey et al., 1996; Sotherton, 1998; Post and Kwon, 2000). While the conversion of cropland into GLSA has generally been found to improve soil structure (O’Brien and Jastrow, 2013), decrease compaction (Rosenzweig et al., 2016), and increase soil organic matter (Karlen et al. 1999), variable findings have been noted in the few GLSA studies carried out in the FRD.

A repeated measures study by Hermawan and Bomke (1996) on a single site in the FRD reported a higher mean weight diameter (MWD) of water stable aggregates after two and three years of GLSA establishment relative to paired fields under continuous cultivation. These findings were noted to be influenced by seasonal precipitation patterns and the greatest MWD difference between the treatments occurred in the early spring following the wet-season. In contrast to the improvements noted in this study, a later assessment for aggregate stability by Principe (2001)...

² NOTE: A version of this chapter will be submitted for publication in the Canadian Journal of Soil Science – J.M. Lussier, M. Krzic, S.M. Smukler, A.A, Bomke and D. Bondar. What are the effects of short-term set-asides on productive soils in the Fraser River delta of British Columbia?
on a single site in the FRD did not report a MWD difference in a one year GLSA relative to samples taken prior to GLSA seeding.

A more recent study by Yates et al (2017), which compared a 2, 3, 4 and 6 year GLSA to paired ACR fields recently managed for potatoes, also found varying soil responses under this management practice. In addition to having different periods of enrollment in the GLSA program, the fields were accompanied by a wide range of management practices and were suspected to have varying baseline conditions prior to GLSA establishment. While the study concluded GLSA management to improve bulk density and mechanical resistance, the wide range of accompanied management practices and lack of baseline information created challenges when comparing soil properties across the varying GLSA enrollment periods.

The study outlined in Chapter 2 of this thesis found extensive variability in soil physical and chemical properties in eight fields prior to GLSA seeding and supported assumptions of past studies by Principe (2001) and Yates at al. (2017) that fields entering the program had a wide range of soil properties. An additional assessment for vegetation and soil physical properties after two seasons of GLSA establishment, found unproductive and productive fields entering the program to have varying responses. Specifically, the unproductive fields were noted to have lower aboveground vegetation biomass, a lower MWD, a higher bulk density, and a lower aeration porosity relative to productive GLSA fields and paired ACR fields.

While the individual site analysis outlined in Chapter 2 was practical for assessing different soil responses in unproductive and productive fields under GLSA management, this experimental
design was not effective for determining the overall influence of GLSA management in the FRD region. The primary limitations of this design were a lack of true replication in the GLSA and ACR treatments (Hurlbert, 1984), and the use of only one sampling time to compare differences between the treatments. Similar limitations have been encountered in all previous GLSA studies in the FRD (Hermawan and Bomke, 1996, Principe, 2001 and Yates et al., 2017). The objective of this study was to conduct the first FRD-based replicated field experiment with repeated measures over time to evaluate the effects of GLSA on selected soil properties during the first 2 seasons of enrollment relative to adjacent fields managed for ACR. Baseline soil properties were determined before the field experiment and only productive fields were included in this study.

3.2 Materials and Methods

3.2.1 Study Sites

This study was carried out from April 2015 to September 2016 in the western part of FRD on six sites located within the Municipality of Delta and Richmond, BC (49°05’N, 123°03’W; elevation 2 m above sea level). This region is characterized by a mean annual temperature of 11.1°C and a mean annual precipitation of 1,189 mm, with approximate 80% occurring between October and April (Environment Canada, 2017). All soils included in this study were developed from surficial fluvial deltaic deposits and were classified as Humic Luvic Gleysol, Orthic Gleysol, and Rego Humic Gleysol (Luttmerding, 1981).
The six study sites included both GLSA and ACR fields (ranging from 6-25 acres in size), and all GLSA fields were established in sites containing “productive” soils. This classification is based on an assessment done in the spring of 2015 prior to GLSA seeding, as outlined in Chapter 2 of this thesis. The GLSA fields at these six sites were all characterized as having the following properties: exchangeable sodium < 0.85 cmol$_e$ kg$^{-1}$, MWD > 0.70 mm, and bulk density < 1.25 Mg m$^{-3}$. Furthermore, the GLSA fields at each of these sites were reported to have a total GLSA aboveground dry vegetation biomass > 3.71 t/ha at the end of the second season of GLSA establishment.

The GLSAs were all part of the Delta Farmland and Wildlife Trust (DF&WT) Grassland Set-aside Stewardship Program and were seeded in 2015 between April 15$^{th}$ and May 10$^{th}$ with a standard restoration seed mix composed of 25% (by seed weight) orchard grass (Dactylis glomerata), 28% tall fescue (Festuca arundinacea), 30% short fescue (Festuca rubra var. commutata and F. rubra var. rubra), 15% timothy grass (Phleum pratense), and 2% red clover (Trifolium pratense).

The ACR fields were selected based on a similar management history and soil type to the paired GLSA fields. The six sites were all located on operational farms; therefore, a variety of crops and management practices were conducted in the ACR fields. For example, the ACR fields at Sites 5 and 8 were under organic management production (Table 2.2). A standard rate of composted chicken manure of ~12.35 t ha$^{-1}$ per year was applied in the ACR fields in Sites 5 and 8, as well as in the ACR field at Site 2. Chemical fertilizers were applied in all non-organic ACR fields at typical regional rates for the select crop. A variety of tillage practices were also implemented at
each site and included several methods that are commonly utilized in the region such as disking, rotovating, plowing, and pulvi-mulching. The wide-range of management practices included in the ACR treatment were representative of common practices in the FRD.

3.2.2 Sampling and Analysis

Soil samples were collected from four sub-plots (6m radius in size) located in both the GLSA and ACR fields at the 6 study sites. Sub-plots were randomly generated in the Spring of April 2015, and were located at least 10 m apart from each other and 10 m away from field edges to avoid areas where edge effects may have interfered with the experimental treatment.

The first soil samples were collected from sub-plots in April of 2015 prior to GLSA seeding and crop planting in ACR fields. Subsequent soil sampling occurred in July 2015 (crop mid-season) and September 2015 (crop post-harvest). In 2016, soil samples were collected again in April, July, and September from the same sub-plots that were sampled in 2015. Samples from both GLSA and paired ACR fields were always collected on the same day.

3.2.2.1 Aggregate stability

Aggregate stability samples were analyzed from the 0-7.5 cm depth on all sample collection dates. Organic matter debris from the surface was removed before samples were taken and a composite of 5-7 samples were collected at each sub-plot. The soil samples were stored at 4°C
until being passed through a 6-mm sieve and collected on a 2-mm sieve. Aggregate stability was determined using a variation of the wet-sieving method (Nimmo and Perkins, 2002).

Immediately before wet-sieving, 15 g of pre-sieved 2-6-mm sized aggregates was placed on top of nested sieves with openings of 2, 1, and 0.25 mm. Aggregates were then moistened in a humidifier for 30 minutes to minimize disruption of the aggregates by the release of trapped air and samples were wet-sieved in a motorized apparatus for 10 minutes. The apparatus had a vertical stroke of 2.5 cm, an oscillating action through an angle of 30°, and a rate of 30 strokes per minute. After the sieves were removed from the water, the material retained on each sieve was oven-dried at 105°C for 24 hours and weighed. A correction was done to account for non-aggregate particles by crushing all material and washing the finer material through the sieve. Non-aggregate particles retained were weighed and their mass was subtracted from the total size fraction mass to determine the true mass of aggregates. The mass for each size fraction was expressed as a percentage of the total non-aggregate particle-free sample mass. MWD was calculated using Van Bavel's calculation as described in Kemper and Rosenau (1986) where:

\[ \text{MWD} = \sum_{i=1}^{n} W_i D_i \]

The mean diameter of each size fraction is denoted by \( x \). The proportion of the total sample weight occurring in the corresponding size fraction is denoted as \( W_i \) and \( D_i \) goes from 1 to \( n \), where \( n \) is the number of size fractions including that lost through the bottom of the smallest sieve (<0.25 mm).
3.2.2.2 Bulk Density and Aeration Porosity

Bulk density was analyzed on samples collected in April and September in both seasons, while aeration porosity was only assessed on samples collected in September 2015, April 2016 and September 2016. A double-cylinder drop hammer was used to collect a single 7.5 cm X 7.5 cm soil core from the 0-7.5 cm, 7.5-15 cm and 15-30 cm depths at each sub-plot. Once collected, these cores were sealed in bags and stored at 4°C until analysis.

Aeration porosity (i.e., soil pores having diameter > 50 µm or macropores) was determined using a water tension table technique (Danielson and Sutherland, 1986). Soil cores were removed from the sample bags and a 4-layer cheese cloth skirt was placed on the underside of cores and held with a rubber elastic. Cores were placed in a container which was gradually filled with water until the level of water was within 1 cm of the top of the core. The cores were then left to saturate for 24 hours, weighed and placed on a degassed tension table prepared with a saturated silicon carbide sand (grit 400). After placing cores on the table, tension was set to -6 kPa of matric potential. This tension corresponds to the air entry value for soil pores greater than 50 µm in diameter. The water-filled pore-space was calculated by determining the mass per volume of water that was retained in the soil at -6 kPa relative to the total soil volume.

Bulk density was determined from the same soil cores used for aeration porosity. The soil cores were dried at 105°C for 24 h and the oven-dry mass of soil was determined. A correction was made for coarse fragments by sieving the samples to remove particles >2 mm in diameter. Assuming a particle density of 2.65 g cm⁻³ of the volume, weight of coarse fragments was
calculated and subtracted from each core sample. Bulk density was calculated on a coarse fragment-free basis as the mass of oven-dry soil per volume of soil at field moisture (Blake and Hartge, 1986).

3.2.2.3 Total Soil Organic Carbon and Total Soil Organic Nitrogen

A single sample for total soil organic carbon and total soil organic nitrogen was collected from the 0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm depths at each sub-plot on April 2015 and September 2016. These soil properties were determined using the Fourier transform mid-infrared spectroscopy (FT-MIR) (Reeves et al., 2001) run on a Tensor 37 HTS-XT spectrometer (Bruker Optics, Ettlingen, Germany). Three replicates of 0.025 g each of ball mill ground soils were scanned 60 times for FT-MIR spectral reflectance between 400 and 4,000 cm$^{-1}$ at a resolution of 2 cm$^{-1}$.

Predictions for total soil organic carbon and nitrogen values were based on a pre-existing FRD regional database (n= 1,038) provided by the Sustainable Agricultural Landscape (SAL) laboratory at the University of British Columbia. The validation test for the FT-MIR calibration of total soil organic carbon provide a 0.92 coefficient of determination with a RMSE of 0.34, while the total soil organic nitrogen had a 0.96 coefficient of determination with a RMSE of 0.0221. The coefficient of determinations and RMSE were derived using a partial least squares (PLS) regression with the QUANT package in OPUS 7.5 (Bruker Optik GmbH, 2012). The optimal regression model, pre-processing methods, and spectral wavenumber ranges were chosen
using a leave one out cross-validation procedure to minimize the root mean square error (RMSE) of the model.

### 3.2.2.4 Statistical Analysis

The comparison of MWD, bulk density, aeration porosity, total soil organic carbon, and total soil organic nitrogen between GLSA and ACR treatments across six study sites were conducted with a nested linear mixed effect model using R statistical software version 3.4.0 (R Core Team, 2017). The data was analyzed with the *lme* function in the *nlme* package (Pinheiro et al., 2017) and a restricted maximum likelihood (REML) method was used. The treatment was added as a fixed effect, while sub-plots (nested within treatments and sites) were considered as random effects. The mixed model was $\mathbf{y} = \mathbf{X}\mathbf{\beta} + \mathbf{Z}\mathbf{\gamma} + \mathbf{\epsilon}$; where $\mathbf{y}$ represents the response variable vector, $\mathbf{\beta}$ is an unknown vector of fixed-effects parameters with known design matrix $\mathbf{X}$, $\mathbf{\gamma}$ is an unknown vector of random-effects parameters with known design matrix $\mathbf{Z}$ and $\mathbf{\epsilon}$ is an unknown random error vector. The models were done at individual depths for bulk density, aeration porosity, total soil organic carbon and total soil organic nitrogen. The Shapiro Wilks test was done on both marginal and conditional means and heteroscadisticity was assessed using residual plots. A post-hoc test (Tukey method) was done using the *emmeans* function to identify significant differences between treatments at the various sampling times and differences were determined to be significant for $P$-values <0.05 and < 0.10.

An example ANOVA for comparing the MWD of water stable aggregates between the productive GLSA and ACR treatments can be found in the appendix of this thesis (Fig.C.1).
3.3 Results and Discussion

3.3.1 Aggregate Stability

A significant difference in the MWD of water stable aggregates was noted between the GLSA and ACR treatments \((P=0.04)\). A post-hoc test found the MWD to be similar between GLSA and ACR fields prior to GLSA seeding in April 2015 (Fig. 3.1), and no difference was observed during the first season of establishment. Significant differences were, however, observed at all three sampling times in the second season of GLSA establishment. Following the wet-season, the GLSA fields had an average MWD that was 21.3\% higher than paired ACR fields in April 2016 \((P=0.08)\), while samples taken in July and September 2016 were 13.7\% \((P=0.08)\) and 18.6\% \((P=0.07)\) higher, respectively.

The findings from my study indicate that a single season of GLSA establishment in productive fields may increase the stability of soil aggregates relative to paired fields managed for ACR. A study by Hermawan and Bomke (1996) on a single site in the FRD reported similar improvements after two and three years of GLSA establishment, and also noted the largest difference between treatments in the early spring following the wet-season. The MWD improvements in both studies were not surprising as others have found the cessation of tillage and planting of perennial vegetation to protect surface aggregates (Lui et al., 2005) increase organic aggregate binding agents (O’Brien and Jastrow, 2013) and enmesh aggregates (Angers and Caron, 1998).
In contrast to my findings, a study by Yates et al. (2017) carried out on similar soils in the FRD did not find a difference in MWD when comparing 2, 3 and 4 year GLSA fields and paired ACR fields recently managed for potatoes. In addition to having a varying number of enrolment years in the GLSA program, the GLSA fields in the study by Yates et al. (2017) had a wide range of management practices and were suspected to have varying baseline conditions prior to enrolment. While the GLSA and ACR fields included in my study were also found to have varying management practices, the use of a replicated experimental design provided a more robust assessment of average trends in the FRD. Furthermore, the assessment of baseline conditions prior to GLSA seeding allowed for the exclusion of fields with poor baseline conditions (e.g., high exchangeable sodium, poor soil structure, high compaction).

In addition to treatment differences, a significant difference between sample times ($P=<0.0001$) was also noted as the MWD was found to be lower in April than in July and September in both the 2015 and 2016 seasons (Fig. 3.1). Similar seasonal fluctuations in aggregates stability have been observed in past studies in the FRD (Hermawan and Bomke, 1996; 1997, Krzic et al., 2000) and other regions (Wallace et al., 2009). These fluctuations are commonly attributed to changes in soil water content as aggregate stability has been found to have a negative relationship to this property (Hermawan and Bomke, 1996; Wallace et al., 2009). The extensive rainfall in the FRD from October to May is likely a primary cause of less stable aggregates observed on samples collected in April in both seasons of my study (Fig. 3.5).

Varying annual trends for MWD were also observed between the two years of this study. Specifically, the overall MWD was lower in April and higher in both July and September in
2015 relative to samples collected during the same time in 2016. These annual differences were likely influenced by the relatively wetter spring and dryer summer in 2015 (Fig. 3.5). A study by Principe (2001) in the FRD also noted varying annual precipitation patterns to influence the MWD of water stable aggregates and reported this to be a primary challenge in making year to year comparisons for assessing changes in aggregates stability under GLSA management. The annual changes in soil properties observed in my study, supports the need for the inclusion of an in-season comparative treatment (such as the paired ACR fields in this study) to effectively evaluate changes in soil structure under GLSA management.

3.3.2 Bulk Density and Aeration Porosity

GLSA fields had a lower bulk density (Fig. 3.2) and greater aeration porosity (Fig. 3.3) relative to paired ACR fields after two seasons of establishment. In April 2015 (i.e. before GLSA seeding), soil bulk density at all three depths of sampling was similar on GLSA and paired ACR fields, while aeration porosity was not measured at this time. A significant difference between treatments for both bulk density ($P=0.07$) and aeration porosity ($P=0.02$) was only observed in September 2016 at the 0-7.5cm depth. During this time, the GLSA treatment had an aeration porosity of $20.78 \pm 1.32\%$ and bulk density of $1.08 \pm 0.04$ Mg m$^{-3}$, while an aeration porosity of $15.85 \pm 1.43\%$ and bulk density of $1.16 \pm 0.05$ Mg m$^{-3}$ were reported on the ACR treatment.

The results indicate that the upper surface of soils in GLSA fields are less compacted than ACR fields in the fall after two seasons of enrollment. In addition to improving the stability of aggregates, the establishment of perennial vegetation and corresponding belowground root
networks have been shown to increase the number and size of soil pores (Dexter, 1991); however, the majority of studies have found significant changes in bulk density under GLSA management to take more than 10 years to occur (Rosenzweig et al., 2016). Past studies in the FRD have reported harvesting and tillage practices associated with ACR management to induce soil compaction (Paul and de Vries, 1979; Krzic et al., 2000) and it is likely that this practice may have amplified the relative differences between GLSA and ACR fields in this study.

A local study carried out by Yates et al. (2017) in the early spring noted a degraded site placed under GLSA for 6 years to have a significantly higher aeration porosity at a 0-7.5cm depth relative to a paired ACR field, and a 4-year GLSA (with sub-surface drainage and a history of laser-leveling and manure applications) to have a significantly lower bulk density. In contrast, no difference in either property was noted in a 2 and 3 year GLSA which received minimal accompanying management practices. In my study, the bulk density and aeration porosity samples evaluated in the spring after a single year of GLSA establishment also did not show differences between GLSA and ACR at this depth, while samples collected after crop harvest did. This indicates that differences in bulk density and aeration porosity between ACR and GLSA fields are more apparent in the fall after ACR fields are harvested than in the spring prior to tillage and crop planting.

A repeated measures study by Hermawan (1995) in the FRD found opposing bulk density and aeration porosity results than those observed in my study. In that study, GLSA fields had a higher bulk density and lower aeration porosity relative to ACR fields at the 0-7.5cm depth after two years of GLSA establishment on samples collected in the fall. A subtle difference in the time
of sample collection between our studies may have been the primary reason for these contrasting findings. Specifically, my samples were collected shortly after fields were harvested in September, while Hermawan (1995) collected samples in October after the ACR field was tilled in preparation for cover crop planting. It is likely that the post-harvest fall tillage in their study relieved compaction in the ACR field and lead to a temporarily lower bulk density and higher aeration porosity in this treatment. A study by Karlen et al. (1999) also noted tillage practices in cropland to influence relative difference to fields under GLSA management.

Early differences in MWD, bulk density and aeration porosity in my study support the use of 2-year GLSA rotations as a method to maintain or improve soil structure in productive fields located in the FRD. A study by Riley et al. (2008), which evaluated 4-year crop rotations with varying GLSA establishment periods over a 14-year study period on a silty loam soil (MAP 600 mm), found the constant rotation of 2-year GLSA fields with cash crops to be sufficient to maintain good soil aggregation and porosity. A similar long-term study should be established to identify optimal GLSA rotation intervals to maintain good soil structure in the FRD region.

3.3.3 Total Soil Organic Carbon and Nitrogen

Improvements in total soil organic carbon and total soil organic nitrogen are typically found to occur over a longer period of time than changes in aggregate stability, bulk density, and aeration porosity (O’Brien and Jastrow, 2013; Yate et al., 2017; Rosenzweig et al., 2016). A difference in total soil organic carbon and total soil organic nitrogen in GLSA and ACR fields was not expected in the first year of GLSA establishment; therefore, samples were only collected before
GLSA seeding (i.e. at the baseline sampling time) and after two seasons of enrollment in September 2016. The results did not show any significant difference between GLSA and ACR fields in either soil property at any depth (Fig. 3.4).

The total soil organic nitrogen results agreed with a study by Yates et al. (2017) in the FRD, which also did not find a significant difference between a 2 and 3 year GLSA and paired ACR fields. A study by Walji (2017) that evaluated nitrogen dynamics in 3 year GLSA fields in the FRD, also did not find a difference in total soil organic nitrogen relative to paired cropped fields. These studies both reported differing applications of fertilizers and manures in ACR fields as a primary challenge for comparing this soil property relative to their paired GLSA fields. It is likely that fertilizer and manure applications in the ACR fields have also limited the differences in total soil organic nitrogen between the GLSA and ACR treatments in my study.

The total soil organic carbon finding from my study were also similar to those of Yates et al. (2017) which did not find a significant difference in this property between a 2, 3, 4 and 6 year GLSA and paired ACR fields. The study by Yates et al. (2017) noted past applications of manure on some (but not all) fields to affected total soil organic carbon observations in their study. For example, a site under organic production, with a history of chicken manure applications, had a total soil organic carbon content that was almost twice as high as on all other sites included in this study. Three of the six sites included in my study received manure applications in past seasons and this may have led to varying total soil organic carbon contents across the sites. Furthermore, three paired ACR fields received manure applications during the two-year study.
period, while no manure was applied on the GLSA fields during this time. It is likely that the application of manure in ACR fields during this period influenced my findings.

Studies in other regions have noted active carbon pools to provide a better indication of early soil organic matter changes than total soil organic carbon (Burke et al., 1995; Robles and Burke; 1998; Karlen et al., 1999). It is also possible that the limited differences observed in my study, and the study by Yates et al. (2017), are related to the limited sensitivity of total soil organic carbon as an indicator of early soil organic matter changes (Weil et al., 2003). Furthermore, early increases in soil organic matter have been noted to occur in the upper depth of soils (Angers and Eriksen-Hamel, 2008) and targeting a shallower depth may provide a more sensitive indication of early soil organic matter changes under GLSA management.

3.4 Conclusions

The findings of this study showed productive GLSA fields in the FRD to have a higher aggregate stability, lower bulk density, and greater aeration porosity relative to adjacent ACR fields in the second season of establishment. In the early spring, the MWD of water stable aggregates was 21.3% higher in GLSA than ACR, in July the MWD was 13.7% higher in GLSA, and 18.6% higher in GLSA following crop harvest in the ACR fields. A significantly lower bulk density and higher aeration porosity was only noted after two seasons of GLSA establishment in September 2016. During this time, bulk density was 6.9% lower in the GLSA relative to ACR, while aeration porosity was 23.7% higher.
In contrasts to the changes in MWD, bulk density and aeration porosity, no difference was noted in either total soil organic carbon or total soil organic nitrogen after 2 seasons of GLSA establishment. These findings supported other studies carried out in the FRD that have noted 2-3 year GLSA fields to contain similar levels of total soil organic carbon and total soil organic nitrogen relative to paired fields under ACR. Future research should evaluate active carbon pools at a shallower depth as a potential indicator of changes in soil organic matter brought by GLSA management on productive sites, especially under the short period of time (i.e., two or three years) that reflects typical GLSA duration in the FRD.
Figure 3.1. Mean weight diameter (MWD) of water stable aggregates on productive grassland set-aside (GLSA) fields and annual crop rotations (ACR) in 2015 and 2016 (n=6). Error bars represent the standard error of the mean (n=6). Significant differences indicated by * and + at $P<0.05$ and $P<0.10$, respectively.
Figure 3.2. Soil bulk density at 0-7.5 cm, 0-15 cm, and 15-30 cm depths on productive grassland set-aside (GLSA) and paired annual crop rotation (ACR) fields determined in April and September of 2015 and 2016 (n=6). Error bars represent the standard error of the mean (n=6). Significant difference at $P<0.10$ indicated by +.
Figure 3.3. Aeration porosity at 0-7.5 cm, 0-15 cm, and 15-30 cm depths on productive grassland set-aside (GLSA) and paired annual crop rotation (ACR) fields in September 2015, and April and September 2016 (n=6). Error bars represent the standard error of the mean (n=6). Significant differences at $P<0.05$ are indicated by *.
Figure 3.4. Total soil organic carbon (Total C) and total soil organic nitrogen (Total N) at 0-15 cm, 0-30 cm, 30-45 cm, and 45-60 cm depths on productive grassland set-aside (GLSA) and annual crop rotation (ACR) fields in April and September of 2015 and 2016 growing seasons (n=6). Error bars represent the standard error of the mean (n=6).
**Figure 3.5.** Total monthly precipitation during the 2014-2015 and 2015-2016 seasons relative to long-term averages taken at the Delta Tsawwassen Beach weather station.
4.1 Introduction

Soil productivity issues in the Fraser River delta (FRD) region of British Columbia are commonly associated with frequent tillage operations, which disturb soil aggregates and deplete important soil organic matter (SOM) constituents required to stabilize aggregates (Lui et al., 2005). The Grassland Set-Aside Stewardship program, run by local not-for-profit organization the Delta Farmland and Wildlife Trust (DF&WT), provides farmers with cost-share payments for placing active agricultural land under a seeded grass and clover restoration mix for a one to four-year period. The cost-share provides minimal financial incentive, and farmers have stated the perceived improvements in soil structure and increases in SOM as a primary reason for participating in the program.

The cessation of tillage and establishment of GLSA vegetation have been found to improve soil aggregate stability in the FRD after only a single season of establishment. A local study by Hermawan and Bomke (1996), found significant improvements in the mean weight diameter (MWD) of soil aggregates after two years of establishment relative to paired crop fields, while Yates et al. (2017) reported an improvement of MWD in a 6 year GLSA. Findings reported in Chapter 3 of this thesis, showed up to a 21% increase in aggregate stability in the second season.

of GLSA establishment relative to paired ACR fields. A further assessment of individual
aggregate size fractions by Hermawan and Bomke (1996) and Yates et al. (2017) reported
changes in aggregate stability to be predominantly driven by a greater percentage of water stable
aggregates (WSA) in the 2-6 mm size fraction.

Significant increases in total soil organic carbon under GLSA management have generally been
found to occur over a longer period and accrualment rates have been highly variable (Post and
Kwon, 2000). A study by Karlen et al. (1999) in the Northern plains reported a greater amount of
total soil organic carbon in a 2.5-year GLSA field relative to a paired cropland field. However,
the majority of findings in other regions have noted significant total soil organic carbon increases
to take over 10 years to occur (Post and Kwon, 2000; O’Brien and Jastrow, 2013). Studies in the
FRD have found GLSA to have similar or lower levels of total soil organic carbon than paired
ACR fields after 1-6 years of establishment (Hermawan, 1995; Yates et al., 2017).

Changes in SOM under GLSA management in the FRD have only been evaluated by assessing
total soil organic carbon; a broad measure of SOM that includes a large resistant pool and
smaller active pool of carbon. Increases in SOM (especially in a short-term) typically occur in
active pools of carbon and measurements of this pool are considered more effective at detecting
initial changes in SOM brought by a management practices (Weil et al., 2003). Permanganate
oxidizable carbon (POXC) and dilute-acid extractable polysaccharides (DAEP) are two
operationally defined active carbon pools, which have been shown to detect short-term changes
in SOM (DuPont et al., 2010; Lewis et al., 2011; Lopez-Garrido et al., 2011; Culman et al.,
2012b; Margenot et al., 2015). Furthermore, it has been reported that aggregate stability is
strongly correlated to both POXC (Weil et al., 2003; Culman et al., 2012b) and DAEP (Lui et al., 2005).

The extensive time and high-cost involved with evaluating SOM pools is often a barrier for including these indicators in soil quality evaluations. In recent years, the use of diffuse reflectance Fourier transform spectroscopy has provided a more rapid and inexpensive alternative to traditional methods for determining carbon pools (Calderón e et al., 2017). A large body of research has found Fourier transform spectroscopy calibrations with the mid-infrared (FT-MIR) region (400-4,000 cm\(^{-1}\)) to be effective in parameterizing total soil organic carbon in the FRD (Theil et al., 2015) and other regions of the world (Bellon-Maurel and McBractney, 2011; Peltre et al., 2014; Veum et al., 2014; Calderón et al., 2017). Studies have also shown the potential for FT-MIR to accurately predict active carbon pools (Veum et al., 2014; Calderón et al. 2017). For instance, Veum et al. (2014) and Calderón et al. (2017) reported the FT-MIR method to be effective for predicting POXC, while Calderón et al. (2013) observed polysaccharides to have a strong relationship to various MIR frequency regions. Further work to develop regional calibrations for these important soil indicators could provide researchers and consultants with a quick and low-cost option for assessing active SOM pools.

The main objective of this pilot study was to compare total soil organic carbon, POXC, DAEP and aggregate stability in GLSA fields after 2 seasons of enrollment, relative to adjacent fields managed for ACR. The additional objective was to evaluate the potential use of FT-MIR to predict POXC, DAEP and aggregate stability in the FRD.
4.2 Materials and Methods

4.2.1 Study Sites and Sample Collection

This study was carried out in September 2016 in the FRD region, located within the Municipality of Delta and Richmond, BC (49°05’N, 123°03’W). This region is characterized by a mean annual temperature of 11.1°C and a mean annual precipitation of 1,189 mm, with approximately 80% occurring between October and April (Environment Canada, 2017). The FRD landscape is relatively flat and contains an average elevation of approximately 2 m above sea level. Soils included in this study are predominantly developed from surficial fluvial deltaic deposits (Luttmerding, 1981) and are classified in the Gleysolic order. The primary sub-orders in the region include: Humic Luvic Gleysol, Orthic Gleysol and Rego Humic Gleysol (Luttmerding, 1981).

The study was conducted on operational farms (approximate 6-25 acres in size) and a total of six sites containing both a productive GLSA field established for 2 seasons and an adjacent field managed under ACR, were randomly selected. The six GLSA fields included in this study were all considered “productive” based on an assessment done in the spring of 2015 prior to GLSA seeding, as outlined in Chapter 2 of this thesis. The GLSA fields at these six sites were all characterized as having the following properties: exchangeable sodium <0.85 cmolc kg\(^{-1}\), MWD > 0.70 mm, and bulk density <1.25 Mg m\(^{-3}\). Furthermore, the GLSA fields at each of these sites were reported to have a total GLSA aboveground vegetation dry biomass > 3.71 t ha\(^{-1}\) at the end of the second season of GLSA establishment.
The GLSA fields were all part of the Grassland Set-aside Stewardship Program administered by the DF&WT and were all established with a standard seed mix composed of 25% (by seed weight) orchard grass (*Dactylis glomerata*), 28% tall fescue (*Festuca arundinacea*), 30% short fescue (*Festuca rubra* var. *commutata* and *F. rubra* var. *rubra*), 15% Timothy grass (*Phleum pratense*), and 2% red clover (*Trifolium pratense*). All GLSA fields were seeded between April 15th and May 10th 2015.

The ACR fields were selected based on a similar management history and soil type to the paired GLSA fields. The study was conducted on operational farms; therefore, a variety of crops and management practices were conducted in the ACR fields. The ACR fields at Sites 5 and 8 were under organic management production. A standard rate of composted chicken manure of ~12.35 t/ha per year was applied in these fields, as well as in the ACR field at Site 2. Chemical fertilizers were applied in all non-organic ACR fields at typical regional rates for the select crop. A variety of tillage practices were also implemented at each site and included several methods that are commonly utilized in the region such as disk ing, rotovating, plowing, and pulvi-mulching.

Soil samples were collected in September 2016 after two seasons of GLSA establishment and after all ACR fields were harvested. Four sub-plots (6m radius in size) were randomly selected in both treatments at each of the 6 sites. All sub-plots were located at least 10 m apart from each other and 10 m away from field edges to avoid areas where edge effects may have interfered with the experimental treatment.
Samples were collected from the 0-7.5 cm depth. Two composite samples each consisting of 5-7 sub-samples were collected from each sub-plot. Organic matter debris from the surface was removed before samples were collected. Once collected, samples were stored in a fridge at 4°C until processed. A sub-sample for aggregate stability was gently broken apart and passed through a 6 mm and 2 mm sieve and aggregates from this size fraction were used for the aggregate stability analysis. The remaining soil was air-dried, ground, passed through a 2-mm sieve and used for both permanganate oxidizable carbon (POXC) and polysaccharides analysis. Approximate 10 g was ball-mill ground and used for Fourier transform mid-infrared spectroscopy (FT-MIR) calibration of total soil organic carbon, POXC and DAEP.

4.2.2 Permanganate Oxidizable Carbon

POXC was determined using the Weil et al. (2003) method and the detailed procedure by Culman et al. (2012a) was followed. A stock solution of 0.2 M KMnO₄ was prepared in a CaCl₂ solution at a pH 7.2. Standards of 0.005 M, 0.01 M, 0.015 M and 0.02 M were produced by diluting the KMnO₄ stock solution with various amounts of deionized water. A total of 5 grams of soil was added to 10 empty falcon tubes and 2 mL of KMnO₄ and 18 mL of H₂O was added to the soil. The tubes were then placed on an oscillating shaker set at 240 oscillations per minute for 2 minutes. Samples were then placed in the dark room and left to settle for exactly 10 minutes. Following this step, 0.5 mL of supernatant were added to new falcon tubes containing 49.5 mL of H₂O. The Falcon tubes were gently mixed and three 250 µL drops from each sample was added to a 96 well plate. Plates were run on a photometer (TECAN Group Ltd., Zurich, Switzerland) at 550 nm to determine absorbance. Deionized water blanks were then subtracted.
from all values and a standard curve was produced. The following equation was used to determine POXC:

$$POXC \text{ (mg Kg}^{-1} \text{ soil)} = [0.02 \text{ mol/L} - (B_0 + B_1 \times \text{Abs})] \times (9000 \text{ mg C/mol}) \times (0.02 \text{L solution/Wt})$$

Where:

0.02 mol/L = initial solution concentration

$B_0$ = intercept of the standard curve

$B_1$ = slope of the standard curve

Abs = absorbance of the sample

9000 = milligrams of carbon oxidized by 1 mole of MnO$_4^-$ changing from Mn$^{7+} \rightarrow$ Mn$^{4+}$

0.02 L = volume of stock solution reacted

Wt = weight of air-dried soil sample in kg

### 4.2.3 Dilute Acid-extractable Polysaccharides

Total extractable polysaccharides were analyzed with a technique outlined by Lowe (1993). In this method, 0.75 grams of soil was placed in an individual Erlenmeyer flasks and 100 mL of 0.5 $M$ H$_2$SO$_4$ was added. The flasks were then capped with tinfoil and transferred to an autoclave for 1 hour at 121°C and 103 kPa. After cooling for 30 minutes, the samples were filtered and diluted into 200 mL volumetric flasks using Whatman 42 ash-less filter paper. Working glucose standard solutions were prepared in the following concentrations: 20 $\mu$g/mL, 30 $\mu$g/mL, 40 $\mu$g/mL, 60 $\mu$g/mL, 80 $\mu$g/mL, 100 $\mu$g/mL, and 120 $\mu$g/mL. A glucose standard and 1 mL of each sample solution was pipetted into separate cuvettes. Additionally, a blank was prepared using 1 mL of distilled water. To each cuvette, 1 mL of 0.05 g/mL phenol solution and 5 mL of 18 mol H$_2$SO$_4$ was added using a pipette. To ensure proper mixing of the cuvette contents, the H$_2$SO$_4$ was added using a burette. All the cuvettes were then placed in the oven for 25 minutes at 30°C. Three subsamples of 150 $\mu$L were pipetted from the samples and standard cuvettes into a 96 well plate and analyzed using a photometer (TECAN Group Ltd., Zurich, Switzerland) at 550 nm.
4.2.4 Aggregate Stability

Aggregate stability was determined using a variation of the wet-sieving method (Nimmo and Perkins, 2002). Immediately before wet-sieving, 15 g of pre-sieved 2-6-mm sized aggregates was placed on top of nested sieves with openings of 2, 1, and 0.25 mm. Aggregates were then moistened in a humidifier for 30 minutes to minimize disruption of the aggregates by the release of trapped air. Samples were wet-sieved in a motorized apparatus for 10 minutes. The apparatus had a vertical stroke of 2.5 cm, an oscillating action through an angle of 30°, and a rate of 30 strokes per minute. After the sieves were removed from the water, the material retained on each sieve was oven-dried at 105°C for 24 hours and weighed. A correction was made to account for non-aggregate particles by crushing all material and washing them through the sieve. Non-aggregate particles retained were weighed and their mass was subtracted from the total size fraction mass to determine the true mass of aggregates. The mass for each size fraction was expressed as a percentage of the total non-aggregate particle-free sample mass. MWD was calculated using Van Bavel's calculation as described in Kemper and Rosenau (1986) where

\[ MWD = \sum_{i=1}^{4} w_i D_i \]

The mean diameter of each size fraction is denoted by \( x \). The proportion of the total sample weight occurring in the corresponding size fraction is denoted as \( w_i \) and \( i \) goes from 1 to \( n \); where \( n \) is the number of size fractions including that lost through the bottom of the smallest sieve (<0.25mm).
4.2.5 Fourier Transform Mid-Infrared Spectroscopy Calibrations and Validation

Total soil organic carbon was determined using the Fourier transform mid-infrared spectroscopy (FT-MIR) (Reeves et al., 2001) run on a Tensor 37 HTS-XT spectrometer (Bruker Optics Gmbh, Ettlingen, Germany). Three replicates of 0.025 g each of ball mill ground soils were scanned 60 times for MIR spectral reflectance between 400 and 4,000 cm\(^{-1}\) at a resolution of 2 cm\(^{-1}\). Prediction for total soil organic carbon values were based on a pre-existing FRD regional database (n= 1038) provided by the Sustainable Agricultural Landscape (SAL) laboratory at the University of British Columbia. The validation test for the FT-MIR calibration of total soil organic carbon provided a coefficient of determination of 0.92 with a RMSE of 0.34.

Soil samples which were analyzed for POXC, DAEP, and WSA were also run on a Tensor 37 HTS-XT spectrometer (Bruker Optics Gmbh, Ettlingen, Germany) for MIR calibration. Calibrations of DAEP, POXC, and WSA were derived using a partial least squares (PLS) regression with the QUANT package in OPUS 7.5 (Bruker Optik Gmbh, 2012). The optimal regression model, pre-processing methods, and spectral wavenumber ranges were chosen using a leave one out cross-validation procedure to minimize the root mean square error (RMSE) of the model.

4.2.6 Statistical Analysis

Total soil organic carbon, DAEP, POXC, and aggregate stability data obtained on the GLSA and ACR fields were analyzed in R Version 3.4.0 (R Core Team, 2017) using a nested linear mixed
effect model. The lme function in the nlme package (Pinheiro et al., 2017) was used with a restricted maximum likelihood (REML) method. The treatment was considered a fixed effect while site and sub-plots (nested within site) were considered as random effects. The mixed model is written as follows \( y = X\beta + Z\gamma + \varepsilon \); where \( y \) represents the response variable vector, \( \beta \) is an unknown vector of fixed-effects parameters with known design matrix \( X \), \( \gamma \) is an unknown vector of random-effects parameters with known design matrix \( Z \), and \( \varepsilon \) is an unknown random error vector. The Shapiro Wilks test was done on both marginal and conditional residuals and heteroscedastic was evaluated using residual plots; alpha was set at the 0.05 and 0.10 level.

Linear regressions were done to compare relationships between SOM pools and water stable aggregates using the lm function in R Version 3.4.0 (R Core Team, 2017) and alpha was set at 0.05. The Shapiro Wilks test was used to assess normality, while the Breusch-Pagan test was used to assess heteroscedasticity. Log transformations were done if ordinary least square assumptions were not met.

### 4.3 Results and Discussion

#### 4.3.1 Soil Organic Matter Pools and Aggregate Stability

The percentage of total soil organic carbon was similar between ACR fields and paired GLSA fields established on productive soils in the FRD for 2 seasons (Fig. 4.1). These results are in agreement with the majority of GLSA studies which have not reported significant total soil organic carbon increases in 1-10 year GLSA field relative to paired sites under continuous
cultivation (Robles and Burk, 1998; Baer et al., 2000; and Yates et al., 2017). In contrast, a study by Karlen et al. (1995) noted a significantly greater total soil organic matter content in a 2.5-year set-aside field relative to a paired field under continuous crop management.

The isolation of active carbon pools has been found to be an effective method to identify initial changes in SOM under management practices (Weil et al., 2003). However, significant differences in POXC and DAEP between paired GLSA and ACR fields were not found in my study after 2 seasons of GLSA enrollment (Fig. 4.1). Several studies have reported significant effects of GLSA management on active SOM pools to take 5 to 10 years (Burke et al., 1995; O’Brien and Jastrow, 2013), and it is possible that something similar might happen in the FRD.

The similar total soil organic carbon, POXC, and DAEP content between GLSA and ACR in my study suggest that GLSA fields in the humid maritime climate of FRD do not accumulate significant amount of SOM following two seasons of establishment. However, it is also possible that management practices in the ACR fields may have affected the SOM findings in this study. Most notably, my study was conducted on operational farms and three out of six ACR fields received applications of composted chicken manure in the early spring of 2015 and 2016. The application of manure in those ACR fields may have increased SOM, most likely dampening any relative increases in the GLSA treatment.

In contrast to the similar SOM content between ACR and GLSA fields, the MWD of water stable aggregates was significantly greater in GLSA fields (Fig. 4.2; Table 4.1). Other studies have also found improvements in MWD to occur before significant changes in SOM (Hermawan and
Bomke, 1996; Yates et al. 2017). A study by O’Brien and Jastrow (2013) carried out on a 35-year old restored perennial grassland chronosequence on a fine to silty soil in Illinois (MAP 975 mm), observed changes in the distribution and stability of aggregates to occur before any significant changes in active soil carbon pools.

Further investigation into the varying aggregate size fractions isolated during the wet-sieving method found differences in MWD to be predominantly driven by a greater proportion of water stable aggregates (WSA) in the 2-6 mm size fraction within the GLSA fields (Fig. 4.2). In contrast, the proportion of aggregates in the 1-2 mm and 1-0.25 mm size fractions were similar between treatments, while the proportion of soil in the <0.25 mm size fraction was significantly greater in the ACR than GLSA. Studies by Hermawan and Bomke (1996) and Yates (2014) carried out in the FRD, also found short-term changes in aggregate stability to be mainly driven by a greater portion of WSA in the 2-6 mm size fraction. Consequently, subsequent aggregates stability analysis in this study were done on WSA in the 2-6 mm fraction.

4.3.2 Relationship Between SOM Pools and Water Stable Aggregates

All three SOM pools included in this study (total soil organic carbon, POXC, and DAEP) were closely correlated to each other (Fig. 4.3). The strong correlation between POXC and total soil organic carbon observed in my study ($R^2 = 0.70$) corroborates findings by Weil et al. (2003) and Calderón et al. (2017), which reported a coefficient of determination of 0.69 and 0.71, respectively. Few studies have compared POXC and DAEP pools and the relationship observed in my study ($R^2 = 0.65$) was found to be slightly weaker than that of POXC and total soil organic
carbon. Interestingly, the total soil organic carbon and DAEP pools were found to have the weakest relationship ($R^2=0.60$). These findings indicate that POXC represents a more inclusive pool of carbon than DAEP, which is more closely related to total soil organic carbon. This was expected as POXC isolates a wide range of SOM compounds (Weil et al., 2003), while DAEP only measures labile polysaccharides.

The stabilization of soil aggregates is largely dependent on organic binding agents (Tisdall and Oades, 1982; Six et al., 2014); therefore, it was not surprising that all SOM pools were significantly correlated to WSA (Fig. 4.4; Table 4.1). With the inclusion of all samples from both the GLSA and ACR treatments ($n=48$), total soil organic carbon was found to have the weakest relationship to WSA. Of the three SOM indicators, DAEP had the strongest relationship to WSA ($R^2 = 0.43$), while POXC had a slightly weaker relationship ($R^2 = 0.36$). These findings indicate that DAEP is a SOM pools which is more closely related to aggregate stability than POXC and total soil organic carbon.

These results are in agreement with other studies which have evaluated the relationship of POXC and DAEP to aggregates stability. For example, a study by Weil et al. (2003) on soils from Honduras, noted WSA in the 1-4 mm size fraction and total soil organic carbon to have a coefficient of determination of 0.20, while a much stronger correlation of 0.45 was noted between WSA and POXC. Similarly, a study in the FRD by Lui et al. (2005) noted WSA in the 2-6 mm size fraction to have a correlation coefficient of 0.41 to total soil organic carbon, while the correlation coefficient to DAEP was 0.66.
Relationships between WSA and all carbon pools were also done separately for samples collected in fields managed for either GLSA or ACR (Fig. 4.4; Table 4.1). The results showed a stronger relationship between all SOM pools to WSA in samples taken from GLSA fields (Fig. 4.4; Table 4.2). It was, therefore, not surprising that the addition of Treatment and its interaction significantly improved the regression models between all SOM pools and WSA (Table 4.2). When comparing the linear regressions between treatments, a consistently higher WSA was noted in GLSA fields relative to ACR fields at similar SOM concentrations (Fig. 4.4).

The stronger relationship of WSA to total soil organic carbon, POXC and DAEP in the GLSA fields indicates that SOM content has a greater effect on the stability of aggregates under this management practice than in ACR. Furthermore, the consistently higher WSA in the GLSA, at similar SOM levels, indicates that factors other than SOM content may be causing aggregates to be inherently weaker in the ACR fields or more stable in the GLSA fields. It is likely that the mechanized operations which physically disrupt soils in the ACR treatment have resulted in aggregates which are inherently less stable than those in the GLSA fields at similar levels of SOM (Lui et al., 2005). On the other hand, it is also possible that some conditions in the GLSA field may inherently stabilize aggregates without any significant carbon inputs. For example, the physical enmeshment of aggregates by undisturbed root and fungal hyphae networks is a common stabilization mechanism (Angers and Caron, 1998) which may not be fully capture by the measurements included in this study.
4.3.3 Mid-Infrared Spectroscopy Calibrations for POXC, DAEP and WSA

Preliminary FT-MIR calibrations on a small data-set (n=48) in the FRD showed promising results for this method to be suitable for predicting both POXC and DAEP in this region (Fig 4.5). The validation coefficient of determination for DAEP was noted to be slightly higher at 0.93 (RMSE 0.65 g/kg), while POXC was 0.92 (RMSE 32.66 mg/kg). In comparison, the coefficient of determination on a larger data-set in the FRD (n=1038) for total soil organic carbon was 0.92 (RMSE=0.34%).

My results corroborate findings by Calderón et al. (2017) which noted FT-MIR predictions of POXC to have a coefficient of determination between 0.78 and 0.81 with a RMSE between 143.8 and 157.1. The lower coefficient of determination and higher RMSE observed by Calderón et al. (2017), is likely related to both the inclusion of soils from various locations in their study and the use of a more robust validation method. Specifically, a leave one out cross validation method was used in my study due to the small sample size, whereas a separate sample-set was used for the calibration and validation steps in the study by Calderón et al. (2017). While there is no literature on the use of FT-MIR to predict DAEP, research by Calderón et al. (2013) noted various FT-MIR spectra to be influenced by the addition of polysaccharide compounds.

Varying MIR frequency regions were used for parameterizing total organic carbon, POXC, and DAEP in my dataset (Table 4.2). The DAEP calibration had the narrowest frequency wavenumbers and predominantly included regions in the higher range between 3997.8-3317.1 cm\(^{-1}\) and 2979.6-2638.2 cm\(^{-1}\). Calibrations for POXC, on the other hand, included a wider range
of frequency regions between 3997.8-3656.5 cm\(^{-1}\), 3119.0-2298.8 cm\(^{-1}\) and 1620.0-1278.6 cm\(^{-1}\).

In comparison, calibrations for total soil organic carbon used the broadest frequency wavenumber and included regions in the higher and lower range between 3657.7-2637.7 cm\(^{-1}\) and 2300.3-940.9 cm\(^{-1}\).

The broad range of wavenumbers used for the parameterization of total soil organic carbon, relative to DAEP and POXC, was expected since total soil organic carbon includes numerous organic compounds. Interestingly, the wavenumber ranges used to parameterize this carbon pool was found to overlap by 34.7% with POXC and 28.7% with DAEP. This supports earlier findings in the correlation analysis between SOM pools, which noted total soil organic carbon to be more similar to POXC than to DAEP.

The use of wavenumbers between 3119.0-2298.8 cm\(^{-1}\) for the POXC calibrations in my study corroborates findings by Calderón et al. (2017), which observed regions between 3225 and 2270 cm\(^{-1}\) to contain spectral bands that are most positively correlated with POXC. This region is primarily organic and has low interference from minerals in soils that are low in carbonates, such as the soils included in this study. The band region between 3380-3100 cm\(^{-1}\) is associated with carboxylic acid H-bonded O-H absorbance and was also found to be important for POXC parameterization in both studies.

When considering DAEP, wavenumbers between 3997.8-3317.1 and 2979.6-2638.2 were used for FT-MIR calibrations. No study to my knowledge has assessed the use of FT-MIR to determine DAEP. However, a study by Calderón et al. (2013) found the addition of cellulose to
increase absorbance at 3400, 2970, 2800, 2200 to 2000 and 1030 cm\(^{-1}\), while Movasaghi et al. (2008) noted absorbance between 1400-1450 cm\(^{-1}\) to be associated with bending CH\(_2\) in polysaccharides. While the wavenumbers used for the DAEP calibration in my study did not include lower regions between 2200-1030 cm\(^{-1}\), significant overlap occurred in the 3400 and 2870 cm\(^{-1}\) wavenumber regions which have been reported to be closely related to active forms of carbon (Calderón et al., 2017).

In addition to predicting SOM, studies have shown the FT-MIR method to be suitable for predicting other aggregate associated binding agents such as clay particles, iron compounds, calcium and magnesium ions, and microbial biomass (Soriano-Disla et al., 2014). Further work has also been done to determine if the FT-MIR method can directly predict the stability of aggregates. When compared to SOM validations in this study, a lower coefficient of determination was reported for WSA predictions using the FT-MIR frequency region (\(R^2=0.62;\) RMSE = 5.14\%) (Table 4.2). A study by Veum et al. (2014) observed FT-MIR to provide a lower validation value of 0.42 (RMSE=11.6\%) when calibrating the percentage of WSA aggregates. However, this correlation was found to improve with the use of visible near-infrared (NIR) to a coefficient of a determination value of 0.68 (RMSE=10.6\%). The sample size used in my study was relatively small and future work should be done in the FRD to explore the use of FT-MIR and NIR methods to predict the stability of aggregates in the region.
4.4 Conclusions

There were no significant differences in total soil organic carbon, POXC, and DAEP between GLSA and ACR fields after 2 seasons of GLSA establishment. In contrast, the MWD was significantly higher in the GLSA fields, and these differences were mainly driven by an increase in the proportion of WSA in the 2-6 mm size fraction. These finding suggest that significant improvements in the stability of aggregates occurs more rapidly than changes in SOM.

The three SOM pools evaluated in this study were strongly correlated to each other, with POXC and total soil organic carbon having the strongest correlation ($R^2$ = 0.70). The weakest correlation was observed between DAEP and total soil organic carbon ($R^2$ = 0.60). While all SOM pools were noted to have a positive relationship with WSA, the active SOM pools were found to have a stronger relationship to this soil property than total soil organic carbon.

Preliminary FRD calibrations for active carbon pools using FT-MIR showed promising results with a coefficient of determination of 0.92 for POXC and 0.93 for DAEP, while the calibration for WSA was not as strong ($R^2$ = 0.62). The wavenumbers associate with active carbon pools was consistent with finding from other studies. The results from this preliminary study are promising and future work should attempt to develop FT-MIR calibrations for all three soil quality indicators with a larger sample size in the FRD.
Figure 4.1. (A) Total soil organic carbon (TOC), (B) dilute acid extractable polysaccharides (DEAP), and (C) permanganate oxidizable carbon (POXC) in grassland set-asides (GLSA) fields after 2-seasons of establishment and paired field managed for annual crop rotations (ACR). Error bars indicate the standard error of the mean (n=6).
Figure 4.2. (A) Mean weight diameter (MWD) of water stable aggregates between grassland set-asides (GLSA) and paired fields managed for annual crop rotations (ACR) and (B) the fraction of water stable aggregates by individual aggregate sizes. Error bars indicate the standard error of the mean (n=6). Significant differences indicated by * at P< 0.05.
Figure 4.3. The relationship between permanganate oxidizable carbon (POXC), dilute acid extractable polysaccharides (DAEP) and total soil organic carbon (TOC) from samples collected in both grassland set-aside (GLSA) and annual crop rotation (ACR) fields in September 2016.

Figure 4.4. The relationship between water stable aggregates (WSA) and (A) total soil organic carbon (TOC), (B) permanganate oxidizable carbon (POXC) and (C) dilute acid extractable polysaccharides (DAEP) in grassland set-asides (GLSA) and annual crop rotations (ACR) from samples taken after 2 seasons of GLSA establishment in September 2016.
**Table 4.1.** The coefficient of determination ($R^2$) between water stable aggregates and total organic carbon (TOC), permanganate oxidizable carbon (POXC) and dilute acid extractable polysaccharides with the inclusion of various treatment groups.

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>n</th>
<th>$R^2$</th>
<th>$P$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC (GLSA + ACR)</td>
<td>48</td>
<td>0.29</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TOC + Treatment + Treatment $\times$ TOC</td>
<td>48</td>
<td>0.54</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TOC (GLSA)</td>
<td>24</td>
<td>0.45</td>
<td>0.0002</td>
</tr>
<tr>
<td>TOC (ACR)</td>
<td>24</td>
<td>0.36</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>POXC</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POXC (GLSA + ACR)</td>
<td>48</td>
<td>0.36</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>POXC + Treatment + Treatment $\times$ POXC</td>
<td>48</td>
<td>0.53</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>POXC (GLSA)</td>
<td>24</td>
<td>0.44</td>
<td>0.0002</td>
</tr>
<tr>
<td>POXC (ACR)</td>
<td>24</td>
<td>0.37</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>DAEP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAEP (GLSA + ACR)</td>
<td>48</td>
<td>0.43</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>DAEP + Treatment + Treatment $\times$ DAEP</td>
<td>48</td>
<td>0.64</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>DAEP (GLSA)</td>
<td>24</td>
<td>0.57</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>DAEP (ACR)</td>
<td>24</td>
<td>0.52</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

*GLSA = grassland set-aside, ACR = annual crop rotation*
Figure 4.5. Cross validation results for calibrations of (A) permanganate oxidizable carbon (POXC), (B) dilute acid extractable polysaccharides (DAEP), and (C) water stable aggregates (WSA) using Fourier transform spectroscopy from the mid-infrared (FT-MIR) region (400-4,000 cm⁻¹).

Table 4.2. Cross validation values for correlation of determination (R²) and root means squared error (RMSE) on calibrations for permanganate oxidizable carbon (POXC), dilute acid extractable polysaccharides (DAEP), water stable aggregates (WSA) in the 2-6 mm size fraction and total soil organic carbon using Fourier transform spectroscopy from the mid-infrared (FT-MIR) region (400-4,000 cm⁻¹). Wavenumbers included for the parametrization of each soil property.

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>n</th>
<th>R²</th>
<th>RMSE</th>
<th>Wavenumber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POXC (mg/kg)</td>
<td>48</td>
<td>0.92</td>
<td>32.66</td>
<td>3997.8-3656.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3119.0-2298.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1620.0-1278.6</td>
</tr>
<tr>
<td>DAEP (g/kg)</td>
<td>48</td>
<td>0.93</td>
<td>0.65</td>
<td>3997.8-3317.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2979.6-2638.2</td>
</tr>
<tr>
<td>WSA (%)</td>
<td>48</td>
<td>0.62</td>
<td>5.14</td>
<td>3997.8-3317.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2298.8-1957.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1620.0-1278.6</td>
</tr>
<tr>
<td>TOC (%)</td>
<td>1038</td>
<td>0.92</td>
<td>0.34</td>
<td>3657.7-2637.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2300.3-940.9</td>
</tr>
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</table>
Chapter 5: General Conclusions, Management Implications and Recommendations for Future Research

5.1 General Conclusions

Farmers in the FRD commonly enroll fields into the GLSA program to either restore degraded land, transition fields into organic production or maintain soil productivity. The various reasons for enrolling fields into the program resulted in extensive variability in soil baseline properties observed in this study. Specifically, the eight sites which entered the program had an exchangeable sodium concentration ranging from 0.07 to 2.59 cmol$_c$ kg$^{-1}$, a total soil organic carbon concentration from 1.63 to 3.07%, a MWD from 0.35 to 1.66 mm, and a bulk density from 1.12 to 1.32 Mg m$^{-3}$.

Of the eight fields entering the GLSA program in this study, two were considered “unproductive” due to a combination of a low MWD of water stable aggregates, low total soil organic matter and a high exchangeable sodium. These fields were both found to have a lower amount of aboveground vegetation and a greater proportion of weeds in the second season of GLSA establishment. A further assessment noted exchangeable sodium to have the strongest negative relationship to GLSA vegetation growth ($r = -0.61$) and critical thresholds of 0.64 and 2.08 cmol$_c$ kg$^{-1}$ were associate with significant decreases in aboveground biomass in the second season of GLSA establishment.

In addition to having poor aboveground vegetation growth, the unproductive fields enrolled in the GLSA program (GLSA 3 and 4) were noted to have a similar or worse aggregates stability,
aeration porosity, or bulk density to paired ACR fields. In contrast, productive GLSA fields had either a greater MWD, lower bulk density, or higher aeration porosity relative to paired ACR fields after two seasons of enrolment. The vegetation and soil assessments conducted in this study indicated that unproductive and productive fields respond differently to GLSA management practices and subsequent studies were only done on productive fields enrolled in the program.

A replicated design with repeated measures used in Chapter 3 of this thesis provided an effective evaluation of aggregate stability, bulk density, and aeration porosity between productive GLSA and ACR fields in the FRD region over the first two season of GLSA enrollment. This analysis found productive fields seeded with GLSA to have a 21.3% greater MWD than paired ACR fields in the second season of establishment on samples collected in April, 13.7% greater in July, and 18.6% greater in September. Following crop harvest, the bulk density of GLSA fields was noted to be significantly lower than ACR fields by 6.9% at the 0-7.5cm depth, while aeration porosity was 23.7% higher at the same depth.

In contrast to these differences in aggregate stability, bulk density, and aeration porosity, no differences in total soil organic carbon and total soil organic nitrogen were observed between treatments after two seasons of GLSA establishment. The lack of difference in SOM between the treatments was hypothesized to be partially related to the limited sensitivity of total soil organic carbon to initial changes in SOM. However, an additional assessment of more active carbon pools, including permanganate oxidizable carbon (POXC) and dilute acid extractable polysaccharides (DAEP), also did not show any significant difference between the treatments.
These findings indicate that GLSA management does not significantly increase SOM relative to ACR management after two seasons of establishment.

A further analysis was done to assess the relationship of POXC and DAEP to total soil organic carbon and the percentage of water stable aggregates (WSA). The coefficient of determination for POXC and total soil organic carbon ($R^2 = 0.70$) was found to be greater than that of DAEP and total soil organic carbon ($R^2 = 0.60$). While, DAEP was found to have a higher relationship to WSA ($R^2 = 0.43$) than POXC did ($R^2 = 0.36$). These findings indicate that DAEP represents a more specific carbon pool than POXC, that is more closely related to aggregate stability.

5.2 Management Implications and Recommendations for Future Research

The inclusion of soil aggregate stability, bulk density, exchangeable sodium and total soil organic carbon in the baseline assessment was effective for characterizing soil productivity prior to GLSA enrollment in this study. These soil properties should be included in future studies which evaluate soil productivity in the FRD, and the inclusion of additional indicators for soil biota and active SOM pools should be considered to provide a more complete assessment of overall soil quality.

The non-parametric regression tree analysis method used in this study (*ctree*) was useful for developing exchangeable sodium thresholds (0.63 and 2.08 cmol$_c$ kg$^{-1}$) and should be considered for future studies with similar objectives. The findings from this analysis suggest that areas with a baseline exchangeable sodium between 0.64 and 2.08 cmol$_c$ kg$^{-1}$ require a GLSA seed mix
which is more tolerant to elevated salinity and/or extended winter ponding. While fields with an exchangeable sodium above 2.08 cmol\(_c\) kg\(^{-1}\) may require accompanying management practices, such as laser leveling or the installation of sub-surface drains, to reduce salt levels and/or improve drainage prior to GLSA seeding. It is also important to note that the exchangeable sodium thresholds in this study were determined in an uncontrolled setting and should only be used as a general guide for consultants and producers in the FRD region. Future research in a controlled setting is required to develop more precise exchangeable sodium threshold values.

The varying vegetation and soil responses observed in unproductive and productive GLSA fields entering the program, indicates that short-term GLSAs may be better suited for maintaining soil productivity as opposed to restoring highly degraded sites. From a program management perspective, my findings suggest that 1 year of GLSA establishment provides enough time for some remediation (i.e. improved aggregate stability) in productive fields but that 2 seasons is a minimum to see a wider range of benefits (i.e. improved bulk density and aeration porosity). Highly degraded fields, on the other hand, may require other restorative management practices (e.g. subsoiling, laser levelling, subsurface drainage) and likely require a longer enrollment period. Future studies should evaluate the influence of GLSA management on similar properties after three and four years of establishment.

Studies in other regions have found the use of 2-year set-asides in rotation with cash crops to be sufficient for maintaining good soil structure (Riley et al., 2008). The relatively higher aggregates stability, higher aeration porosity, and lower bulk density observed in the second year of GLSA establishment (productive fields only) indicates that 2-year GLSAs, in short-term
rotations with cash crops, may be an effective management practice for maintaining soil structure in the FRD as well. In addition to evaluating soil responses after GLSA are re-incorporated back to ACR production, a long-term study should be established to identify optimal GLSA rotation intervals to maintain favorable soil properties in the FRD.

In contrast to the changes in soil physical properties, no difference in SOM between GLSA and ACR were observed in this study. Long-term improvements in soil structure are often associated with increases in organic binding agents and additional inputs of SOM during the GLSA enrollment period would likely enhance the benefits of this management practices to soils. Potential methods to increase SOM in these systems would include the application or organic amendments (e.g., manure, bio-solids, composts) in GLSA fields or the introduction of livestock grassing systems during the GLSA enrollment period. Future studies should be done to evaluate the ability of these practices to increase SOM accruement under GLSA management.

Although no SOM differences were noted between the treatments, the active carbon pools used in this study (POXC and DAEP) should be further investigate as soil quality indictors in the FRD. These indicators were noted to have a strong relationship to soil aggregate stability and future research should assess their relationship to other chemical and biological soil indicators. Furthermore, an in-field method to determine POXC has also been developed (Weil et al., 2003) and future studies should evaluate this method in the FRD. The calibrations of POXC and DAEP using the FT-MIR method also showed promising results and improved calibrations for the FRD region could provide agricultural researchers and consultants with an even quicker method to
assess active carbon pools. Further work should be done to improve regional calibrations of these soil properties by including a larger sample size with greater spatial coverage in the FRD.

Management practices which increase aggregate stability and reduce soil compaction are critical for long term crop productivity and soil quality in the FRD. While this study has shown these soil properties to improve in the second season of GLSA establishment in productive fields, it is important to note that these short-term improvements may be quickly lost under intensive tillage and harvesting practices. The use of GLSA management should, therefore, not be considered as a stand-alone practice to restore soils, but rather, as one of many management options which producers should consider when developing long-term management plans to maintain soil productivity on their farms. Future regional research which evaluates the effects of GLSA management on soil properties in concert with other practices, such as reduced tillage, cover cropping, and crop rotations, would provide important information to promote long-term soil conservation in the FRD.
References


Appendices

Appendix A  – Crop History

**Table A. 1.** Crop history for the eight sites included in this thesis.

<table>
<thead>
<tr>
<th>Season</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
<th>Site 6</th>
<th>Site 7</th>
<th>Site 8</th>
<th>Site 9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>ACR</td>
<td>GLSA</td>
<td>ACR</td>
<td>GLSA</td>
<td>ACR</td>
<td>GLSA</td>
<td>ACR</td>
<td>GLSA</td>
</tr>
<tr>
<td>2016</td>
<td>GL</td>
<td>PT</td>
<td>GL</td>
<td>C</td>
<td>GL</td>
<td>B</td>
<td>GL</td>
<td>P</td>
<td>GL</td>
</tr>
<tr>
<td>2015</td>
<td>GL</td>
<td>B</td>
<td>GL</td>
<td>B</td>
<td>GL</td>
<td>B</td>
<td>GL</td>
<td>PT</td>
<td>GL</td>
</tr>
<tr>
<td>2014</td>
<td>PT</td>
<td>PT</td>
<td>B</td>
<td>P</td>
<td>PT</td>
<td>PT</td>
<td>B</td>
<td>B</td>
<td>P</td>
</tr>
<tr>
<td>2013</td>
<td>PT</td>
<td>PT</td>
<td>PT</td>
<td>W</td>
<td>P</td>
<td>P</td>
<td>BN</td>
<td>BN</td>
<td>C</td>
</tr>
<tr>
<td>2012</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>PT</td>
<td>PT</td>
<td>PT</td>
<td>BN</td>
<td>BN</td>
<td>C</td>
</tr>
<tr>
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<td>GL</td>
<td>PT</td>
<td>P</td>
<td>BN</td>
<td>PT</td>
<td>PT</td>
<td>BN</td>
<td>BN</td>
<td>C</td>
</tr>
</tbody>
</table>

(PT=Potatoes; P= Peas; GL= GLSA; B= Barley; W=Wheat; BN= Beans; C= Corn; F=Fallow)
Appendix B – Baseline Soil Properties

Table B.1. Baseline chemical and physical properties determined in April 2015 on fields included in this study. All properties were determined at the 0-15 cm depth with the exception of the mean weight diameter (MWD) and bulk density which were determined at the 0-7.5 cm depth and Na\(^+\) which was determined at the 0-30 cm depth. Methods for total soil organic carbon (TOC), bulk density and MWD may be found in Chapter 2, and all chemical properties were determined using the barium chloride method outlined in section 2.2.2.1. Silt and clay percentages were determined using the same FT-MIR method as outlined in section 2.2.2.2.

<table>
<thead>
<tr>
<th>Site</th>
<th>Treatment</th>
<th>TOC (%)</th>
<th>Bulk density (Mg m(^{-3}))</th>
<th>MWD (mm)</th>
<th>CEC (cmol(_c) kg(^{-1}))</th>
<th>EC (S/m)</th>
<th>Na(^+) (cmol(_c) kg(^{-1}))</th>
<th>K(^+) (cmol(_c) kg(^{-1}))</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>GLSA</td>
<td>1.96 (0.10)</td>
<td>1.23(0.04)</td>
<td>1.18(0.22)</td>
<td>12.57 (1.43)</td>
<td>133.60 (17.84)</td>
<td>0.07 (0.004)</td>
<td>0.37 (0.06)</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
<td>2.14 (0.06)</td>
<td>1.19(0.05)</td>
<td>1.28(0.13)</td>
<td>15.82 (0.45)</td>
<td>166.63 (47.54)</td>
<td>0.08 (0.004)</td>
<td>0.38 (0.04)</td>
</tr>
<tr>
<td>2</td>
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<td>2.08 (0.41)</td>
<td>1.21(0.04)</td>
<td>1.00(0.20)</td>
<td>13.23 (0.49)</td>
<td>213.18 (69.78)</td>
<td>0.33 (0.14)</td>
<td>0.79 (0.08)</td>
</tr>
<tr>
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<td>ACR</td>
<td>1.32 (0.06)</td>
<td>1.24(0.04)</td>
<td>0.46(0.29)</td>
<td>15.99 (0.20)</td>
<td>137.48 (7.34)</td>
<td>0.10 (0.01)</td>
<td>1.11 (0.46)</td>
</tr>
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<td>GLSA</td>
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<td>0.45(0.03)</td>
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<td>1.78 (0.52)</td>
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<tr>
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<td>1.28(0.03)</td>
<td>0.69(0.03)</td>
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<td>201.03 (18.58)</td>
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<td>0.72 (0.05)</td>
</tr>
<tr>
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<td>18.07 (1.60)</td>
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<tr>
<td></td>
<td>ACR</td>
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<td>17.74 (1.21)</td>
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<td>0.40 (0.13)</td>
<td>0.96 (0.37)</td>
</tr>
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<td>1.71(0.20)</td>
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<td>0.23 (0.02)</td>
</tr>
<tr>
<td></td>
<td>ACR</td>
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<td>1.01(0.05)</td>
<td>1.69(0.08)</td>
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<tr>
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<td>1.33(0.07)</td>
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<td>0.89 (0.12)</td>
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</tr>
<tr>
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<td>Treatment</td>
<td>Ca(^{+2}) ((\text{cmol c kg}^{-1}))</td>
<td>Mg(^{+2}) ((\text{cmol c kg}^{-1}))</td>
<td>Mn(^{+2}) ((\text{cmol c kg}^{-1}))</td>
<td>Fe(^{+2}) ((\text{cmol c kg}^{-1}))</td>
<td>Al(^{+3}) ((\text{cmol c kg}^{-1}))</td>
<td>Silt ((%))</td>
<td>Clay ((%))</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
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<tr>
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<td>0.009(0.001)</td>
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<td>ACR</td>
<td>14.39 (0.41)</td>
<td>0.88(0.05)</td>
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<td>0.003(0.001)</td>
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<td>27.22(0.91)</td>
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<td>0.030(0.008)</td>
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</tr>
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<td>20.72(1.07)</td>
</tr>
<tr>
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<td>3.74(0.14)</td>
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<td>0.005(0.001)</td>
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<tr>
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<td>23.70(0.60)</td>
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<tr>
<td></td>
<td>ACR</td>
<td>13.01 (1.21)</td>
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<td>0.001(0.001)</td>
<td>0.01(0.01)</td>
<td>64.30(0.72)</td>
<td>23.94(0.83)</td>
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<td>6.44 (0.35)</td>
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<td>0.04(0.02)</td>
<td>61.85(0.51)</td>
<td>22.03(0.72)</td>
</tr>
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<td>2.43(0.16)</td>
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<td>0.004(0.002)</td>
<td>0.18(0.07)</td>
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<td>26.90(1.10)</td>
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<td>8.40 (0.56)</td>
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<td>0.013(0.006)</td>
<td>0.52(0.16)</td>
<td>63.70(0.79)</td>
<td>27.76(0.52)</td>
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<tr>
<td>9</td>
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<td>0.012(0.003)</td>
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<td>57.51(0.34)</td>
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</table>
Appendix C – ANOVA

Table C.1. ANOVA output example for the mixed effect model (MWD ~ Treatment*Time, random = ~1|Block/Treatment) and the post-hoc test results.

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<tr>
<td>Time</td>
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<td>50</td>
<td>56.38</td>
<td>&lt;0.0001</td>
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<td>Treatment X Time</td>
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<td>0.29</td>
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Tukey HSD post-hoc test for Treatment by Time

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<td>0.58</td>
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</tr>
<tr>
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<td>July 2016</td>
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<td>-2.16</td>
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</tr>
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<td>September 2016</td>
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<td>0.07*</td>
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