EVALUATING THE BENEFITS OF SHORT-TERM GRASSLAND SEST-ASIDES ON DELTA FARMLAND

FINAL PROJECT REPORT FOR INVESTMENT AGRICULTURE FOUNDATION

EVALUATING THE BENEFITS OF SHORT-TERM GRASSLAND SEST-ASIDES ON DELTA FARMLAND

Final report to Investment Agriculture Foundation of BC for the project *Demonstrating Long-term Improvements in Soil Productivity on Delta Farmland Grassland Set-asides*

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Abbreviations

AC	Annual crop
ACR	Annual crop rotation
AGB	Aboveground biomass
ALR	Agricultural land reserve
ALUI	Agricultural land use inventory
BC	British Columbia
BUBL	Built-up/bare land
DAEP	Dilute-acid extractable polysaccharides
DEM	Digital Elevation Model
DF&WT	Delta Farmland and Wildlife Trust
FFP	Forest/forest patches
FRD	Fraser River Delta
GL	Grassland
GLSA	Grassland set-aside
LULC	Land use/land cover
MWD	Mean weight diameter of water-stable aggregates
PAN	Plant available nitrogen
PC	Perennial crop
PCA	Principal component analysis
POXC	Permanganate oxidizable carbon
SOC	Soil organic carbon
SOM	Soil organic matter
TC	Total carbon
TN	Total nitrogen
WCC	Winter cover crop
WL	Wetland

1 Introduction

The Fraser River delta (FRD) of British Columbia (BC) is considered among the most fertile agricultural land in the province. However, intensive farming practices, combined with high precipitation in the fall and winter, poor natural soil drainage, and high soil salinity have led to varying levels of soil degradation in the region. Recent reports have found issues related to poor soil structure, compaction, low organic matter and high acidity and/or salinity are common in annually cropped fields in the FRD (Hermawan and Bomke 1996; Krzic et al. 1999; Principe 2001; Lui et al. 2005; Yates et al. 2017).

Due to expropriation of agricultural land by government agencies in the late 1960s, agricultural land in the FRD is operated under insecure land tenure (Fraser 2004). Additionally, land values in the FRD are highest in the province, and are continually increasing. As a result, many farmers are less inclined to implement expensive soil conservation practices (e.g., laser leveling, installation of subsurface drainage tiles, and long-term crop rotations) that can improve soil productivity and prevent soil degradation in the long- term (Fraser 2004). Instead, farmers tend to focus on annual cash-crop production with short-term crop rotations (Fraser 2004).

A local nongovernment organization, the Delta Farmland and Wildlife Trust (DF&WT), offers several programs to farmers to undertake soil conservation practices. One of those programs is the Grassland Set-Aside Stewardship Program, which provides cost-share payments to farmers for taking active agricultural land out of production and seeding it with a grassland set-aside (GLSA) mix for a period of 1–4 years (Delta Farmland & Wildlife Trust 2000). The main goals of the Grassland Set-Aside Stewardship Program are to provide habitat for wildlife and enhance soil organic matter and structure (Fraser 2004). This model of Grassland Set-Aside Stewardship Program requires a shorter commitment from farmers than more typical, long-term (>10 years) GLSA programs occurring in other parts of the world (Clarke 1992; Karlen et al. 1999; Bowman and Anderson 2002), and provides greater flexibility for farmers to integrate GLSA within their annual crop rotations (ACRs). The 2-4 year GLSAs are usually incorporated into crop rotations, but are also commonly used to transition fields into organic production. Depending on their motivations for enrolling in the Grassland Set-aside Stewardship Program, farmers of the FRD enroll fields that vary widely in soil quality, from unproductive (or degraded) to productive.

The majority of GLSA studies have focused on the effects of this practice on farmland biodiversity and wildlife habitat (Kleijn and Baldi 2005; Tscharntke et al. 2011), while evaluations of GLSA effects on soils have received less attention. An example of a program focused on the long-term improvements of soils is the Conservation Reserve Program (CRP) in the US through which farmers remove environmentally sensitive land from agricultural production for 10–15 years and seed it with perennial vegetation to improve environmental health (Karlen et al. 1999). It has generally been reported that the long-term set-asides tend to improve soil structure, eliminate compaction, and increase soil organic matter (Karlen et al. 1999; Baer et al. 2000; Guo and Gifford 2002).

Soil structure is crucial for maintaining adequate soil water and aeration as well as promoting root growth. Aggregate stability, a measurement of the average size of water stable aggregates, 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). 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. Responses of soil bulk density, an indicator of soil compaction, 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. 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 mean weight diameter (MWD) of water stable aggregates after a single season of GLSA establishment relative to an adjacent field recently managed for potatoes. 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.

Soil organic matter (SOM) is a fundamental component of a productive soil, and is often measured as total soil carbon (TC). It has generally been found that set-asides increase SOM over time, although the rate of organic matter accrual can be highly variable. A comprehensive study by Karlen et al. (1999) found a significant difference in TC 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 in the FRD by Yates et al. (2017) that found no differences in TC between 2-6 year GLSA fields and paired fields in annual crop rotations (ACR). It is possible that more labile pools of carbon, such as permanganate oxidizable carbon (POXC) and dilute acid-extractable polysaccharides (DAEP), would be more likely to show small changes in soil C. Both have been found to be sensitive to short-term effects of management practices (Weil et al. 2003; Tisdall and Oades 1982; Lui et al. 2005; DuPont et al. 2010). No study, prior to this GLSA study, has to date evaluated either of these active SOM pools under GLSA management in the FRD.

In addition to the effects on soil structure and organic matter, it is important to understand how the incorporation of GLSA biomass affects soil nitrogen (N) dynamics. Soil N dynamics can drastically affect crop yield, and as such are of great interest to the farming community. Incorporation of set-asides of grass and legumes has been shown to release N into the soil solution, reducing the amounts of synthetic N fertilizer required while increasing yields (Nevens and Reheul 2002). Increases in SOM content have also been linked with increases in soil available N, which in turn can lead to increases in crop yields (Zhao et al. 2016). At the same time, it is well known that incorporating organic materials with high (>25) C:N ratios can temporarily immobilize N (Trinsoutrot et al. 2000; Vinten et al. 2002), making it unavailable to plants. Some farmers in the region worry that GLSAs may actually be detrimental to subsequent crop production in the year following GLSA incorporation, as GLSA vegetative biomass could temporarily immobilize plant available N (PAN) (Trinsoutrot et al. 2001; Vinten et al. 2002). However, no analysis to date has been performed on soil N dynamics following GLSA incorporation in the context of the FRD.

The DF&WT Grassland Set-aside Program, established in 1994, supports local farmers to use GLSA as a management tool to enhance soil quality and provide wildlife habitat. Many farmers perceive a benefit to their soil and/or crop yields following a GLSA; however, a knowledge gap still exists regarding how quickly benefits occur in set-aside fields, what the benefits are, and how long they persist after GLSA cessation and incorporation into the soil for the subsequent crop production. This information is essential for farmers' ability to manage their rotation to maximize long-term productivity.

The recent FRD study by Yates et al. (2017), which compared 2-, 3-, 4-, and 6-year GLSAs with neighbouring ACR fields, reported varying responses of aggregate stability, bulk density, and aeration porosity, and no differences in TC. Although many soil properties did appear to be enhanced in older set-asides, it was difficult to attribute them to length of time enrolled in the GLSA program due to a lack of baseline data (condition of soil prior to set-aside establishment). Given farmers of the Fraser River delta enroll fields into the GLSA program for a number of reasons, the productivity of the fields entering the program varies widely, and the response of a productive field vs an unproductive field under GLSA is likely to differ. This recent study demonstrated the need for characterizing baseline soil properties of the enrolled fields prior to seeding to GLSA in order to accurately evaluate soil responses to GLSA.

When presented to FRD farmers, this study by Yates et al. (2017) garnered much interest and raised further questions around optimizing use of GLSA in their farming operations. Specifically, producers were interested in how quickly benefits in soil quality occur in set-aside fields, whether they persist after GLSA cessation, and the effects of GLSA incorporation on crop yield and N dynamics the following season. There remained many unknowns about how GLSA interacted with their farming operations. It is also unclear what the overall impact of the program has been on soil quality of farms across the region since its inception in 1994. Consequently, further research was deemed necessary to determine the effects of GLSA duration and cessation on soil properties.

1.1 Objectives

The overarching goal of this project was to provide farmers with detailed information about effects of integrating short- (2 year) to medium- (4 year) term GLSA into their crop rotations. The project evaluated the effectiveness of the GLSA in enhancing soil quality (or productivity) upon Fraser River delta farmland. The specific objectives of this project were to:

1 – Evaluate the effects of GLSA on soil quality of Fraser River delta fields

2 – Evaluate the effects of GLSA on soil nutrient availability and crop yields following set-aside incorporation

3 – Synthesize and communicate project's results to stakeholders throughout the Fraser River delta and beyond

1.2 Project Overview

1.2.1 Timeline of Studies

To address these research objectives, a set of complementary studies were carried out by five M.Sc. students and one PhD student over a period of 5 years (Spring 2015 to Spring 2020). Given the duration a two-year M.Sc. program, each student was responsible for designing and executing a study that would specifically address a set of research questions that would help address either Objective 1 or 2. Summaries of the individual studies conducted by each student can be found in Appendices

Appendix A – Study Summaries).

1.2.2 Study Region

All of these studies occurred in the FRD that is located in the municipality of Delta in Southwestern BC (49.0847° N, 123.0586° W). The region has temperate maritime climate, characterized by mild wet winters and warm dry summers with an average air temperature of 11.7°C and average rainfall of 1189-mm, with 80% of precipitation occurring between October and April (Ministry of Environment 2019). Soils are typically of the Gleysolic order with silty loam to silty clay texture, and are formed on medium to moderately textured fine Fraser River deltaic deposits approximately 100-cm thick. Topography is slightly undulating with slopes <3%, and elevation is 1-3 m above sea level (Luttmerding 1981). Due to its long growing season and deep, fertile soil, this region is recognized as one of the most productive agricultural areas in all of Canada.

1.2.3 Methods and Materials

The studies often sampled the same type of soil and vegetation properties. To avoid unnecessary repetition, detailed laboratory methods for each indicator are included in Appendix B – Laboratory Procedures. When the laboratory method differed between studies for the same property, a description of each is included, indicating which was used in which study. Sampling protocols and details specific to each study are included in the Methods and Materials section for each study.

2 Objective 1 – Evaluate the Effects of GLSA on Soil Quality

2.1 Field Scale Analysis

To address objective 1, two field-scale studies were conducted across the FRD by M.Sc. student Jason Lussier from 2015-2016 and M.Sc. Student Teresa Porter from 2018-2019. These studies compared soil quality (select soil properties) on adjacent fields with and without GLSA. Soil and vegetation measurements were taken during the 1st and 2nd year of GLSA establishment (Study 1.1: 2015-16), and again during the 4th and 5th growing season (Study 1.2: 2018- 2019). Jason successfully completed his M.Sc. thesis in March 2018 (Lussier 2018). Teresa is expected to complete her M.Sc. project in summer of 2020. Over a period of 4 years, these studies addressed the specific research questions: 1. What are the effects of GLSA on soil quality and 2. How do the effects of GLSA on soil quality vary with the duration of set-aside?

2.1.1 Materials and Methods

Study Sites

These studies were carried out from spring 2015 to spring 2019 on 5-8 sites located on operational farms within the Municipality of Delta and Richmond, BC. All study sites included both a GLSA field and an adjacent field managed under annual crop rotation (ACR). Due to GLSA fields being returned to ACR production during the study, 8 fields were sampled in 2015 and 2016, 7 fields in 2018 and 5 fields in 2019. The ACR fields were selected based on similar management history and soil type as their paired GLSA counterpart. The fields included in this study ranged between 2 and 11 ha 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 seeded in 2015 between 15 April and 10 May with a standard seed mix composed of 25% (by seed weight) orchard grass (*Dactylis glomerata L.*), 28% tall fescue (*Festuca arundinacea Schreb*.), 30% short fescue (*Festuca rubra subsp. commutata Gaudin and F. rubra subsp. rubra L.*), 15% timothy grass (*Phleum pratense L.*), and 2% red clover (*Trifolium pratense L.*). The study was conducted on operational farms, therefore management practices on ACR fields varied in terms of fertilizer type and quantity, and tillage practices.

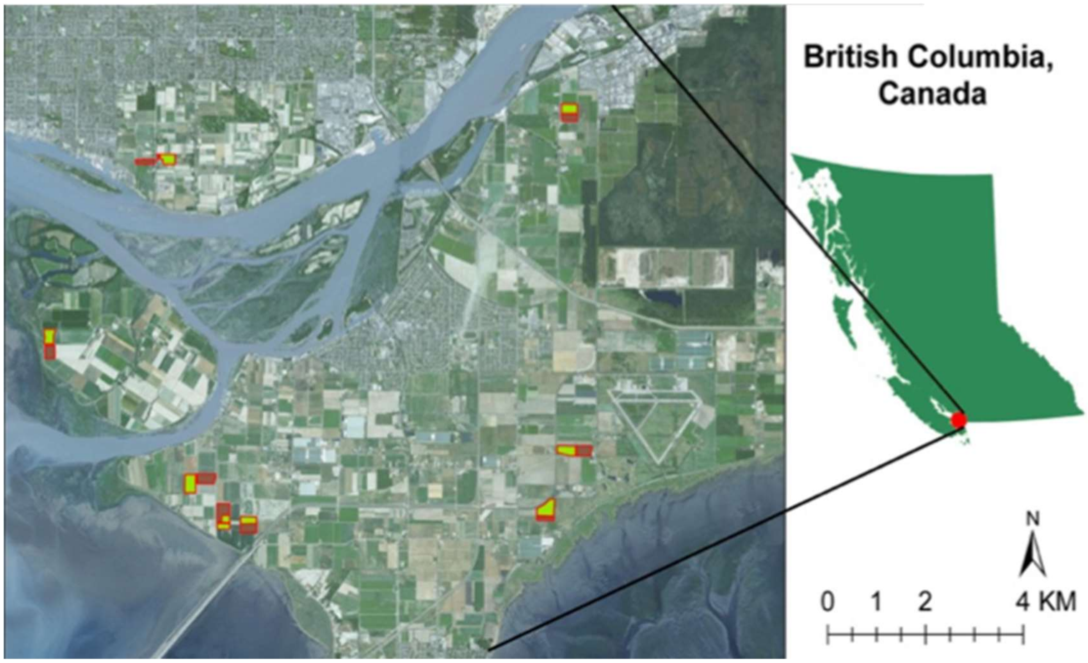

Figure 1. Map of the Fraser River delta (FRD) showing eight study sites with paired (adjacent) fields. Grassland set-aside (GLSA) fields are shown in green and paired annual crop rotations (ACR) fields are shown in brown.

Sampling and Laboratory Analysis

In spring 2015 prior to GLSA seeding, samples for baseline soil properties were collected from four randomly selected subplots per GLSA field and analyzed for exchangeable sodium (0-30 cm depth), bulk density, TC, TN, and MWD of water-stable aggregates. These subplots (with a 3 m radius) were located at least 10 m away from each other and 10 m away from field edges. Total soil carbon (TC) and TN was determined on samples collected from the 0 to 15 cm depth (using Oakfield probe) in spring 2015 and fall 2016. Samples for POXC and DAEP were collected from the 0 to 7.5 cm depth in fall of 2016, spring and fall of 2018, and spring of 2019. Aggregate stability samples were collected with a trowel at the 0–7.5 cm depth in spring, summer and fall of 2015, 2016, 2018, and again in spring 2019.

Soil bulk density was determined on samples collected in spring and fall of 2015, 2016, 2018 and spring of 2019 from 0-7.5 cm, 7.5-15 cm, and 15-30 cm depths. Aeration porosity was determined on all the samples collected for bulk density measurement, except the spring of 2015 sample time.

Aboveground vegetation biomass samples were collected in fall of 2015, 2016 and 2018, and the spring of 2018 and 2019. Samples for aboveground biomass of GLSA vegetation were collected from two locations at each subplot on GLSA fields using a 50 cm by 50 cm quadrant. Biomass was sorted into the following three broad groups: clover, grasses, and weeds (i.e., all plant species that were not included in the GLSA mix).

Statistical analysis

To determine differences in soil properties between GLSA and ACR, a linear mixed effects (LME) model was used. Site was used as a random effect in the analysis to account for difference in environmental characteristics between each of the pairs of GLSA and ACR for each study. Data were compared separately for each time of sampling as well as depth of sampling. In cases where the data was non-normal it was transformed using a log base 10 transformation to meet the assumption of homoscedasticity. A Type 3 ANOVA was used to test for significant differences ($p<0.05$) between main effects (GLSA and ACR).

2.1.2 Results and Discussion

Baseline Soil Characteristics

We found that baseline soil properties varied substantially across the eight fields sampled in the spring of 2015. Exchangeable sodium ranged from 0.07 to 2.59 $cmol_c\ kg^{-1}$, TC from 1.63% to 3.07%, MWD from 0.4 to 1.7 mm, and bulk density from 1.12 to 1.32 $Mg\ m^{-3}$ prior to GLSA establishment (Appendix C – Figures and Tables). A principal component analysis (PCA) was conducted using the baseline soil properties on the eight GLSA fields to distinguish the fields deemed productive or unproductive by farmers enrolled in the program. The PCA graph (Figure 2) displayed the main trends in soil variation among eight GLSA fields and accounted for 71.2% of the variability in the data. There was a clear separation between the fields that farmers considered productive (GLSA 1, 2, 5, 6, 7, and 8) and unproductive (GLSA 3 and 4) along the first PCA axis (i.e., horizontal spacing among transects) of soil properties (Lussier et al. 2019). The fields grouped as productive included those that were enrolled as part of a 3 year transition period for organic certification and as part of crop rotations. The unproductive GLSA fields 3 and 4 were characterized by soil properties commonly associated with low crop productivity in the FRD - high salinity, compaction, poor structure, and low soil organic matter (Paul and de Vries 1979; Coote et al. 1981; Hermawan 1995; Krzic et al. 2000; Principe 2001; Liu et al. 2005; Yates et al. 2017).

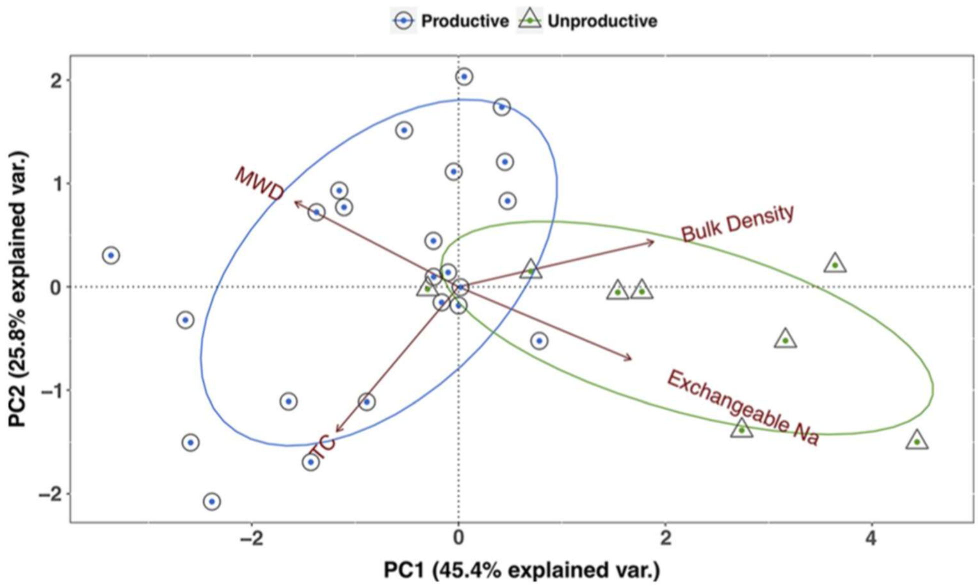

Figure 2. A principal component (PC) analysis of exchangeable sodium (exchangeable Na), total soil carbon (TC), mean weight diameter (MWD) of water-stable aggregates, and bulk density taken from subplots across eight fields prior to being seeded with the grassland set-aside (GLSA) seed mix illustrating clear separation between sets of fields deemed unproductive or productive by the farmers entering the Grassland Set-aside Stewardship Program.

Perhaps the most distinct feature of these fields was a high exchangeable sodium. These fields also had a MWD well below the 1.0 mm average observed in all other fields entering the Grassland Set-Aside Stewardship Program in this study. High levels of sodium may disperse clay particles (Agassi et al. 1981), and likely contributed to the low MWD at these sites. Furthermore, the GLSA fields 3 and 4 had a TC well below the 3% threshold suggested by Hermawan (1995) to be necessary for stabilizing aggregates in the FRD.

Vegetation Responses and Preliminary Soil Thresholds

Following the first season of GLSA establishment (i.e., September 2015), the average dry aboveground biomass across all eight sites was 3.1 t ha^{-1}. A substantial increase in biomass was observed in the second season of GLSA establishment with an average dry aboveground biomass of 8.2 t ha^{-1}, ranging from 14.1 t ha^{-1} to 1.6 t ha^{-1} by field. The unproductive fields (i.e., GLSA fields 3 and 4) not only had significantly lower aboveground biomass than most other fields, but were also characterized by a higher proportion of weeds (Figure 3).

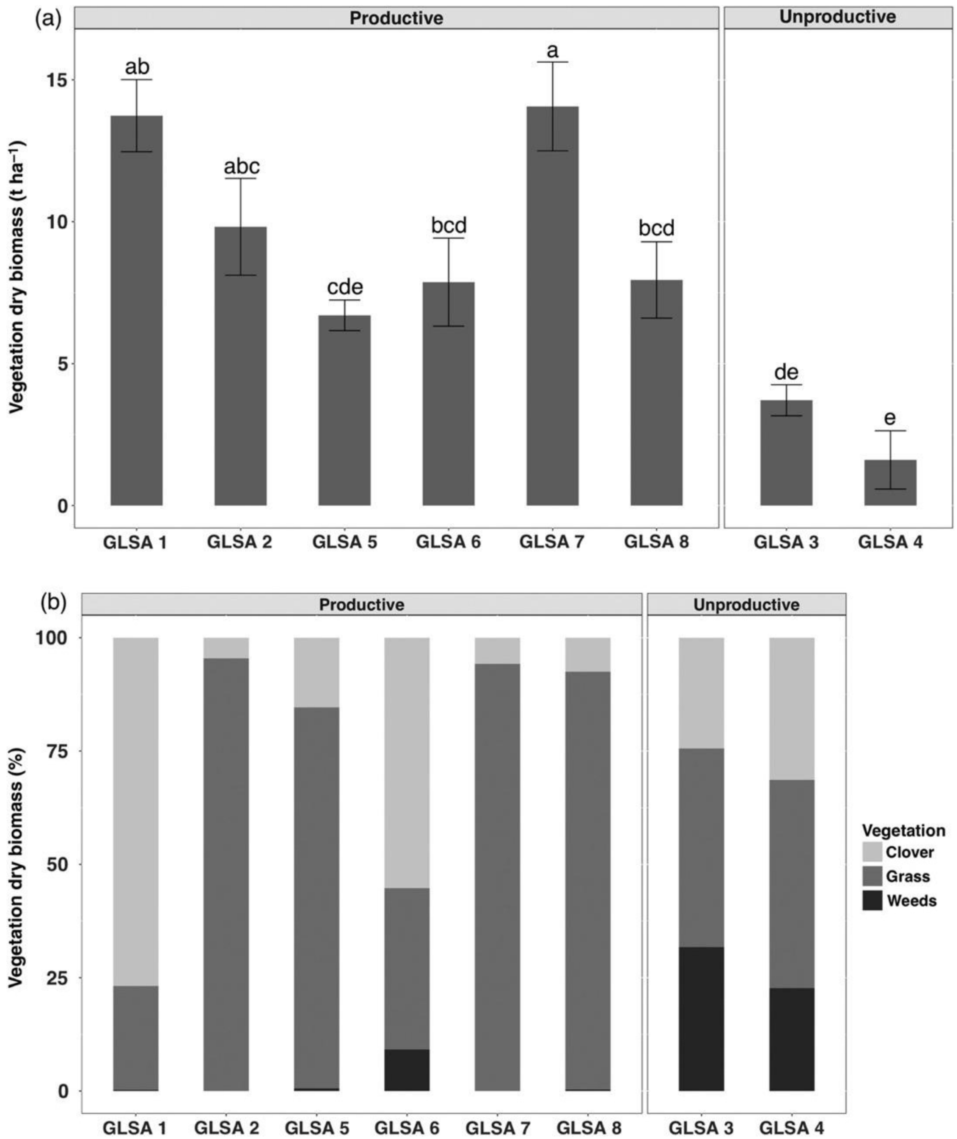

Figure 3. Total dry aboveground biomass (a) in productive and unproductive fields and (b) percentage of biomass by vegetation group (clover, grass and weeds) after two seasons of grassland set-aside (GLSA) establishment. Error bars are standard error of the mean of the four subplots within each field and significant differences are indicated by different letters.

The establishment and growth of GLSA vegetation are essential for meeting the DF&WT program goals of wildlife habitat provision and soil organic matter and structure enhancement. Therefore, a preliminary evaluation of soil thresholds for predicting GLSA vegetation responses was conducted. Of all baseline soil properties evaluated in this study, only exchangeable sodium was significantly correlated ($r = -0.61$, $p = 0.0002$) to total aboveground GLSA biomass. High levels of sodium may have a direct negative impact on plant growth (Fontenele et al. 2014), or may restrict plant growth indirectly through prevention of aggregate formation, resulting in poor aeration (Tisdall and Oades 1982). Soils with poor drainage in the FRD may be prone to sodium accumulation, making this soil property an indicator of confounding drainage issues which may further hinder vegetation growth.

To identify exchangeable sodium concentrations that may represent thresholds for plant growth, a regression tree analysis was done (Lussier et al. 2019). The exchangeable sodium values of 0.64 and 2.08 $cmol_c\ kg^{-1}$ represent thresholds associated with a significant reduction of aboveground biomass in the second GLSA season (Figure 3). Plots with exchangeable sodium below 0.64 $cmol_c\ kg^{-1}$had an average aboveground biomass of 10.4 $t\ ha^{-1}$. On the other hand, average aboveground biomass (5.5 $t\ ha^{-1}$) was lower ($p \leq 0.0001$) on plots with exchangeable sodium between 0.64 and 2.08 $cmol_c\ kg^{-1}$, whereas plots with exchangeable sodium above 2.08 $cmol_c\ kg^{-1}$ had a significantly lower average aboveground biomass of 0.9 $t\ ha^{-1}$. Future studies are needed to refine these preliminary exchangeable sodium thresholds and to determine the causes of GLSA growth reduction issues.

These preliminary thresholds, however, suggest that fields 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. 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.

Due to the differences in field productivity evidenced by the baseline characteristics and aboveground biomass responses above, the soil quality indicators were expected to respond differently to GLSA based on the initial state of the field. As such, soil quality data will be presented only for the productive fields, as they are the most representative of the average field in the FRD. Data will be included for all fields, however, in the Appendices (Appendix Table 1).

Soil Aggregate Stability

Comparisons between baseline MWD of water-stable aggregates from spring 2015 to spring 2019 illustrate improvements in aggregate stability after one to three years of enrolment in GLSA, depending on the initial state of the field. After one year of GLSA growth, MWD was significantly greater in GLSA than ACR in productive fields, and the same was true after 3 years of GLSA growth (Figure 3). The trend continued after four years of GLSA growth as well, however the difference was not significant. The addition of a 4th year under GLSA did not appear to further increase the difference soil quality between GLSA and ACR, but did maintain the relative increases in MWD that were seen in the previous year. MWD of water stable aggregates tended to be higher in productive fields relative to unproductive fields (

Appendix Table 2). Unproductive fields did not respond as quickly to GLSA growth as did the unproductive fields, and it was not until 3 years of GLSA growth that we saw increases in MWD there.

These preliminary results are indications that the short-term (1 year) GLSA is capable of improving soil aggregate stability relative to ACR in productive sites, while unproductive sites require three years to show improvements in aggregate stability. These improvements in aggregate stability were expected, as the cessation of tillage and planting of perennial vegetation has generally been found 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). 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. The slower response of MWD to GLSA in unproductive fields seen in our study could be due to high exchangeable sodium levels, higher levels of compaction and/or lower levels of organic matter, all of which negatively impact aggregation. This data suggests that barriers to aggregation can be overcome with increased time under GLSA.

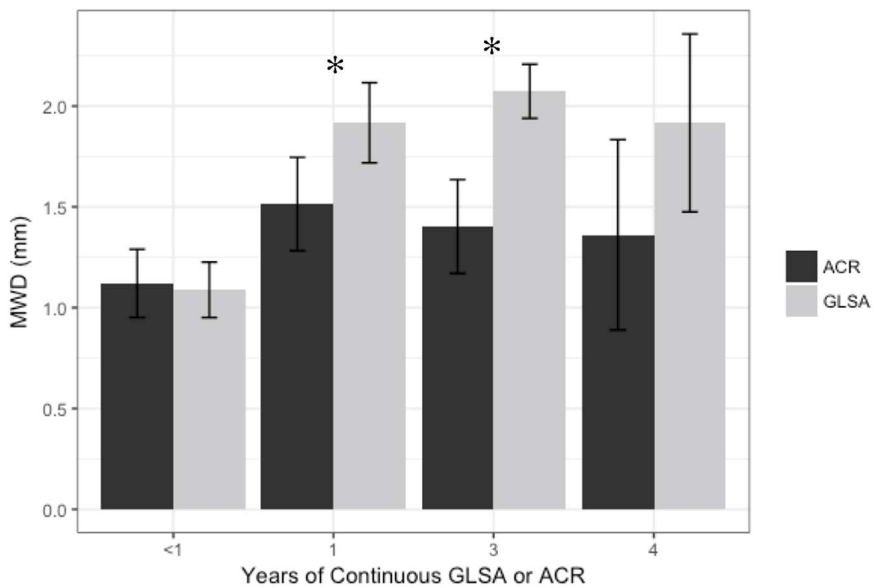

*Figure 4. Average mean weight diameter of water stable aggregates (MWD) in productive fields sampled during spring of the first 4 years under grassland set-asides (GLSA) or annual crop rotation (ACR). Error bars indicate the standard error of the mean. Significant differences indicated by * at p< 0.05.*

Bulk Density

After three years under GLSA, bulk density decreased in the 0-7.5 cm depth in the productive fields (Figure 5). This trend continued in the spring of 2019, after four years of GLSA growth, though the difference was not significant. No significant differences were seen at 7.5-

15 cm, or 15-30 cm. These data suggest a trend of improvement in soil structure under medium-term GLSA in productive fields, in the upper most soil layer. The same was not seen in unproductive fields, where no clear trend emerged (Appendix Table). Bulk density appeared to be somewhat lower under GLSA on unproductive fields as compared to ACR in spring of 2018 and 2019. Past studies in the FRD have reported harvesting and tillage practices associated with ACR management to influence soil compaction (Paul and de Vries 1979; Krzic et al. 2000). It is likely that the removal of ACR management practices in addition to the benefits of perennial root growth have contributed to the improvements in soil compaction in the 0-7.5 cm depth after three and four years of GLSA. The lack of clear trend in the unproductive field under ACR suggests that these fields have not benefitted from the same improvements to soil compaction as seen in the productive fields, after four years under GLSA.

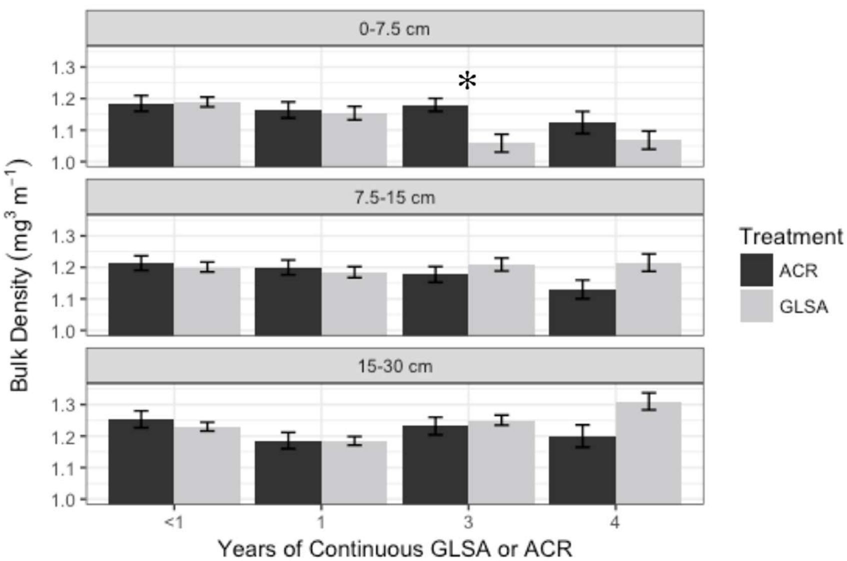

*Figure 5. Bulk density in productive fields sampled in spring of the first 4 years under grassland set-asides (GLSA) or annual crop rotations (ACR). Error bars indicate the standard error of the mean. Significant differences indicated by * at p< 0.05.*

Aeration Porosity

Aeration porosity was significantly higher under GLSA in the 0-7.5 cm depth after three years of GLSA growth in the productive fields, and this trend was continued after four years, though the difference was not significant (Figure 6). This is an indicates that, as do the bulk density results, soil compaction was improved in the uppermost soil layer after three years of GLSA establishment. However, lower depths did not follow this trend. In the 7.5-15 cm depth, aeration porosity was significantly higher under ACR after three years of GLSA growth, and this trend also was seen after four years though not significantly. The third depth, 15-30 cm, followed this trend as well. The cause for these differing responses among the different depths is unclear, but it is clear that any benefits to soil structure from the GLSAs are only being seen in the uppermost soil layers. Aeration porosity also responded somewhat differently to GLSA establishment depending on field type. In unproductive fields, aeration porosity was generally higher under ACR or showed no difference between the fields (Appendix Table).

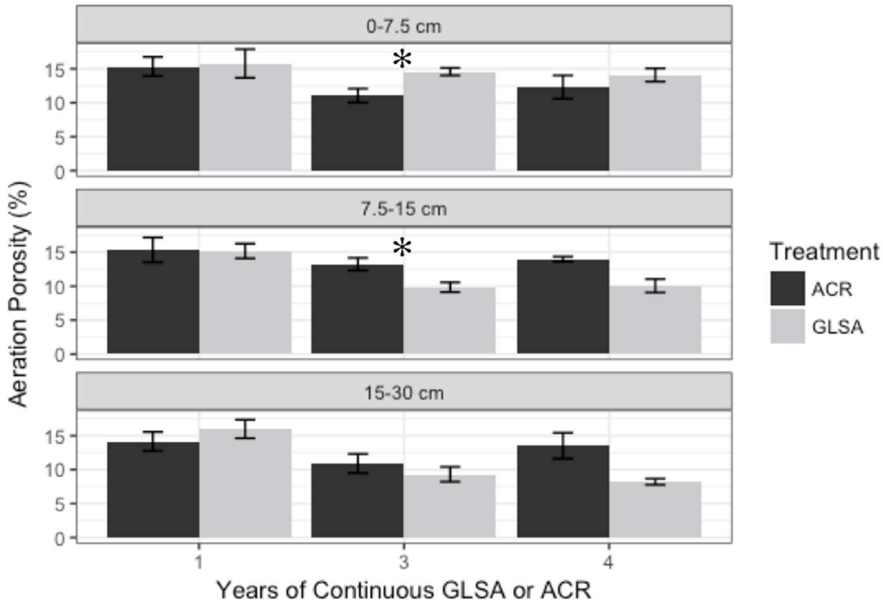

*Figure 6. Aeration porosity in productive fields sampled during spring of the first 4 years under grassland set-asides (GLSA) or annual crop rotations (ACR). Error bars indicate the standard error of the mean. Significant differences indicated by * at p< 0.05.*

The bulk density and aeration porosity results combined suggest that the upper surface of soils in GLSA fields have become generally less compacted than ACR fields, in fields that were considered productive when they entered the GLSA program. The establishment of perennial vegetation and corresponding belowground root networks have been shown to increase the number and size of soil pores (Dexter 1991), thereby reducing bulk density and increasing aeration porosity. 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). It is likely that the subtle changes we recorded over four years of GLSA establishment require a longer duration of GLSA growth to more evident.

Total Soil Carbon and Nitrogen

Total soil C and TN were assessed after two seasons of GLSA enrollment at the 0–15 cm depth (Figure 7), but no significant differences in either were found as a result of two seasons of GLSA. Similarly, there were no significant differences in POXC or DAEP, two labile C pools, between GLSA and ACR fields after two seasons of GLSA establishment. Changes in the TC or TN were not expected after two seasons, as the majority of GLSA studies have not reported significant TC increases in 1-10 year GLSA relative to paired sites under continuous cultivation (Robles and Burk 1998; Baer et al. 2000; and Yates et al. 2017). The lack of change in active C pools, however, was somewhat more surprising, as both POXC and DAEP are typically more sensitive to changes in management practices than TC, and are more likely to reflect early changes in C pools than TC. Two years, however, is still a relatively short time period to see changes in active C, and these results suggest that GLSA fields in the humid maritime climate of FRD do not accumulate significant amount of SOM following two seasons of establishment.

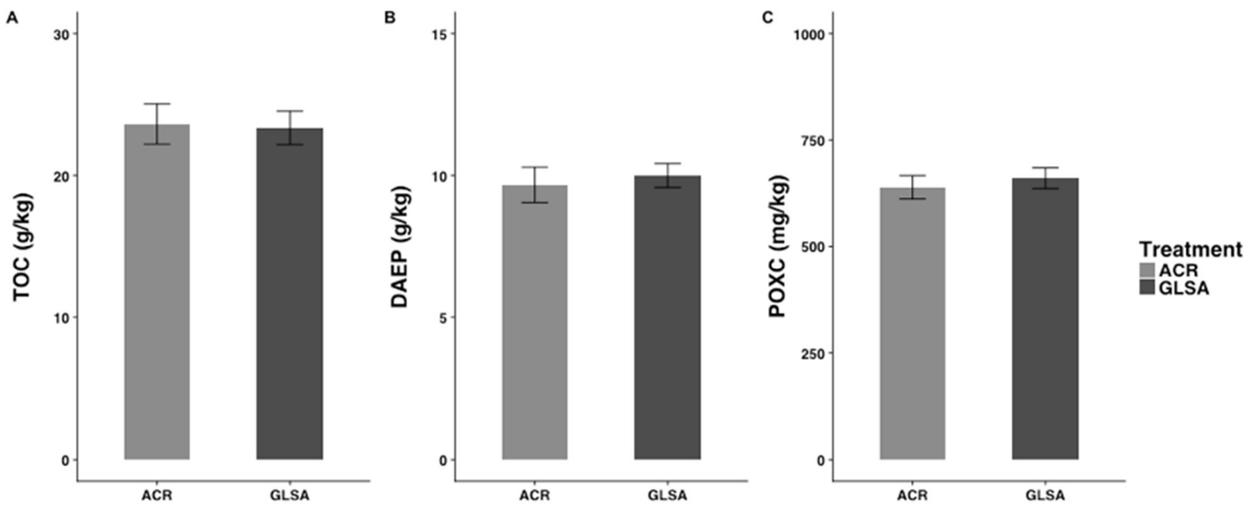

Figure 7. (A) Total soil carbon (TC), (B) dilute acid extractable polysaccharides (DEAP), and (C) permanganate oxidizable carbon (POXC) in grassland set-asides (GLSA) fields after 2-seasons of establishment and paired field managed for annual crop rotations (ACR). Error bars indicate the standard error of the mean (n=6).

In addition to the effects of short-term GLSA on C pools, we also wanted to evaluate: (i) are there relationships among soil quality indicators (i.e., POXC and DAEP) and TC (ii) whether these indicators could be used to predict the more sensitive, but more challenging to measure, indicator of aggregate stability, and (iii) if differences in soil quality after short-term GLSAs, detected with aggregate stability, could instead be detected with POXC or DAEP (Lussier et al. 2020).

We found that the three soil C fractions were significantly correlated with each other, but POXC had a stronger correlation with TC than DAEP, suggesting that it may be a better indicator of TC changes. In contrast, DAEP had the strongest significant correlation (R^2 = 0.43) with the water-stable aggregates in the 2–6 mm size fraction, followed by POXC (R^2 = 0.36) and TC (R^2 = 0.29). From these regression analyses, we can infer that DAEP and POXC are better predictors of aggregate stability than TC in the FRD and are likely more sensitive to early soil quality changes in response to on-farm land management practices. However, aggregate stability was noted to be a more sensitive indicator of early soil quality responses than either C pool as no differences were noted in POXC or DAEP between annual crop rotations in the FRD and two-year GLSA with significantly more stable soil aggregates. Several other regions have found these labile C indicators to be valuable for working with farmers to identify early soil quality responses and we still recommend that future studies in the FRD region include these indicators to better quantify and recognise beneficial land management practices.

2.1.3 Conclusions

Farmers in the FRD commonly enroll fields into the GLSA program to 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. 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 SOM, and a high exchangeable sodium at the time of baseline sampling (spring 2015). These fields were both found to have a lower amount of aboveground vegetation and a greater proportion of weeds after one year of GLSA establishment. A further assessment noted exchangeable sodium to have the strongest negative relationship with GLSA vegetation growth (r= -0.61) and critical thresholds of 0.64 and 2.08 $cmol_c\ kg^{-1}$ were associated with significant decreases in aboveground biomass in the second season of GLSA establishment. These fields would likely benefit from a more salt tolerant GLSA seeding mix, and potentially additional management practices to improve drainage and/or reduce salt levels prior to GLSA seeding.

The vegetation and soil assessments conducted in this study indicated that unproductive and productive fields respond differently to GLSA management practices. Productive fields showed increased aggregate stability under GLSA after one year of establishment, while unproductive fields did not show improvements until the 3rd year of GLSA growth. Productive fields also demonstrated improvements in bulk density and aeration porosity in the 0-7.5 cm depth after three years in GLSA, whereas unproductive fields did not show improvements in either soil quality indicator throughout four years of GLSA growth.

In contrast to the differences seen in productive fields in aggregate stability, bulk density, and aeration porosity, no differences in TC or TN were observed between treatments after two seasons of GLSA establishment on productive fields. Similarly, active C pools of POXC and DAEP did not show any significant difference between the treatments. These finding indicate that GLSA management does not significantly increase SOM relative to ACR management after two seasons of establishment on productive fields.

While no differences in soil C pools were observed, the changes in aggregate stability, bulk density, and aeration porosity in GLSA indicate that productive fields placed in the Grassland Set-Aside Stewardship Program for three years had more stable soil structure and less compaction than fields under ACR management. The findings support the use of GLSA on productive fields in the FRD for a duration of three seasons as a crop rotation practice or as transition to organic production systems. Unproductive fields, as well, are likely to benefit from a three or four year GLSA rotation in terms of aggregate stability, but longer may be required to see more substantial changes in other measures of compaction (bulk density and aeration porosity).

2.2 Regional Analysis of GLSA Duration on Soil Quality

A landscape scale study was also conducted across the FRD to help address objective 1. This study (1.3) was led by PhD student Siddhartho Paul from 2018-2019. While previous studies have observed improvements in indicators of soil quality due to GLSA it was unclear how these changes compare to other practices incentivized by the DF&WT specifically winter cover crops (WCC), typical management of the annual crops that the program targets, or of other crop types (e.g., berries) and changes to and from those crop types. In this study we used a combination of field sampling, remote sensing, and digital soil mapping to predict the impact of GLSA relative to other agricultural management impacts on soil organic carbon (SOC), a key indicator of soil quality. The specific research questions for this study were: 1. How intensively have GLSAs or WCC been used by farmers across the FRD; 2. How has land use/land cover (LULC) changed across the region from 1984 to 2018; and 3. How has SOC changed in response to GLSA and WCC relative to changes in LULC and other agricultural management practices over this period?

2.2.1 Materials and Methods

This study focused on the agricultural land reserve (ALR) areas within the City of Delta within the FRD. Some croplands, near the southern boundary of the city, which are not part of the ALR, were also included in the analysis. We utilized Landsat satellite imagery to assess the changes in LULC and predict SOC dynamics in Delta from 1984 to 2018. We used a combined pixel- and object-based classification technique to identify changes for seven LULC classes, including annual crop (AC), perennial crop (PC), grassland (GL), forest/forest patches (FFP), built-up/bare land (BUBL), water, and wetland (WL). We also evaluated the intensity of GLSA and WCC rotations using the historical GIS dataset provided by DF&WT. We then predicted SOC changes from 1984 to 2018 using the digital soil mapping approach. We applied soil and vegetation indices derived from Landsat images, topographic indices derived from Digital Elevation Model (DEM), climate variables, and existing soil survey information in a random forest model to predict SOC across the study area. We further explored the shifts in agricultural management practices using the historical data of GLSA and WCC rotations from 1992 to 2016. We also used the agricultural land use inventory (ALUI) data from the British Columbia Ministry of Agriculture to update the agricultural management classes. For detailed methods of LULC classification and SOC prediction, see Paul (2020).

We identified different agricultural management classes based on the total number of years a specific management approach was implemented in a specific crop field. Table 1 provides the threshold values of different management classes, comprising perennial berries, perennial grass, and annual crop with various rotations of GLSA and WCC.

Table 1. Description of different agricultural management classes. Annual crop rotations that also include grassland set-aside (GLSA), or winter cover crop (WCC) were identified and classified as low or high based on the total number of years the practice was utilized on a specific field.

Agricultural management classes	Total number of years
Perennial berries	Continuous
Perennial grass	Continuous
Annual crops only	Continuous
GLSA-Low	1-2
GLSA-High	> 2
WCC-Low	1-7
WCC-High	> 7

2.2.2 Results and Discussion

LULC and agricultural management practices from 1984 to 2018

Our Landsat imagery-based LULC change analysis did not detect large changes during the study period from 1984 to 2018. As expected, ACR (38%), PC (21%), and GL (12%) were the dominant LULC categories in Delta's agricultural landscape while BUBL covered 22% of the area in 2018 (Table 2). Altogether, 12% of Delta's agricultural land exhibited LULC changes during the study period.

Figure 8 shows the distribution of the intensity of agricultural management classes across Delta. The eastern part of Delta comprised the major share of perennial berries and grass production, while different types of annual cropping predominated across the whole region. We identified annual crop fields with low and high rotations of either GLSA or WCC while some annual fields had both GLSA and WCC rotations. For example, GLSA-Low-Cover-High class received 1-2 years of GLSA and >7 years of WCC during the study period. Across the region, 74% of the field area had adopted either or both GLSA and WCC for some duration. The adoption of WCC was the most common management practice covering about half of the total crop fields and 53% of the total agricultural area (Table 3). The combined rotations of GLSA and WCC were identified in 19% of the area (24% of total field count). Perennial berries were produced in 5% of the area (5% of the total field count) while perennial grass covered 11% by area and 14% by total field count.

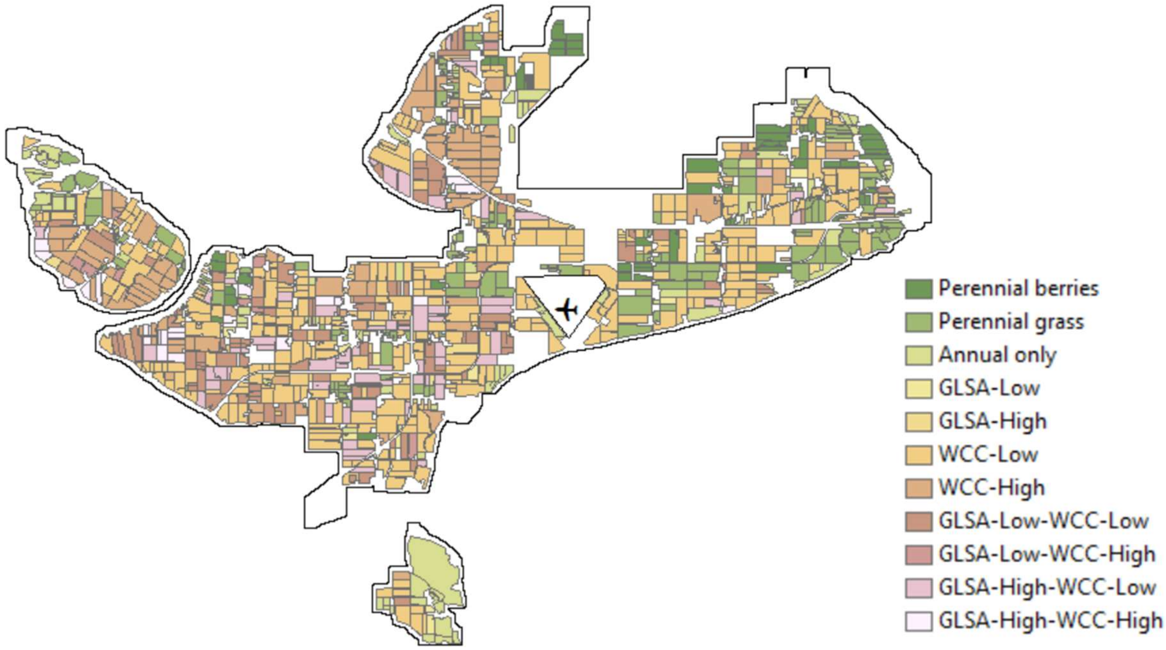

Figure 8. Various intensity of grassland set-aside (GLSA) and winter cover crop (WCC) rotations (1992-2016)

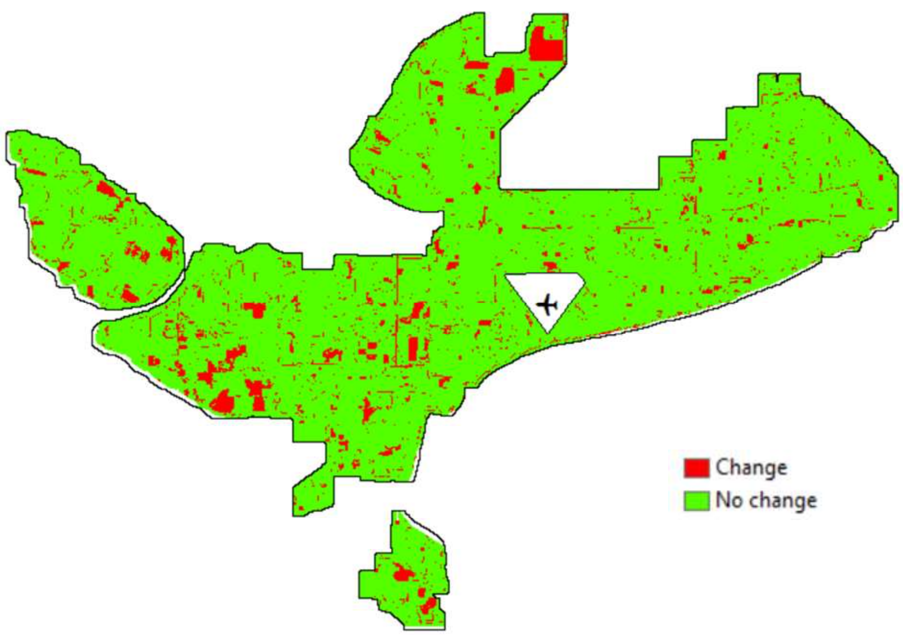

Figure 9. Land use land cover changes (1984 – 2018) derived from the classification of Landsat images

Table 2. Different land use land cover types by the % of total area (106 km²)

Land use land cover type	% of area
Annual crop (AC)	38
Forest/forest patch (FFP)	3
Grassland (GL)	12
Perennial crop (PC)	21
Built-up/bare land (BUBL)	22
Water	2
Wetland (WL)	3

Table 3. Different agricultural management classes by % of total field count and % of total area. Annual crop rotations that also include grassland set-aside (GLSA), or winter cover crop (WCC) were identified and classified as low or high based on the total number of years the practice was utilized on a specific field.

Agricultural management classes	% of total field count	% of total area
Perennial berries	5	5
Perennial grass	14	11
Annual crops only	11	9
GLSA-Low	2	1
GLSA-High	1	1
WCC-Low	35	40
WCC-High	8	13
GLSA-Low-WCC-Low	12	9
GLSA-Low-WCC-High	1	1
GLSA-High-WCC-Low	8	7
GLSA-High-Cover-High	3	2

Changes in SOC from 1984 to 2018

The distribution of SOC across Delta was fairly consistent with higher concentrations in the north-eastern corner of the region, which is located near the Burns Bog (Figure 10). This part of Delta was also dominated by perennial agricultural production. Conversely, lower SOC concentrations were observed in the western part of Delta. In much of the region, values were as low as 11.35 g C/kg.

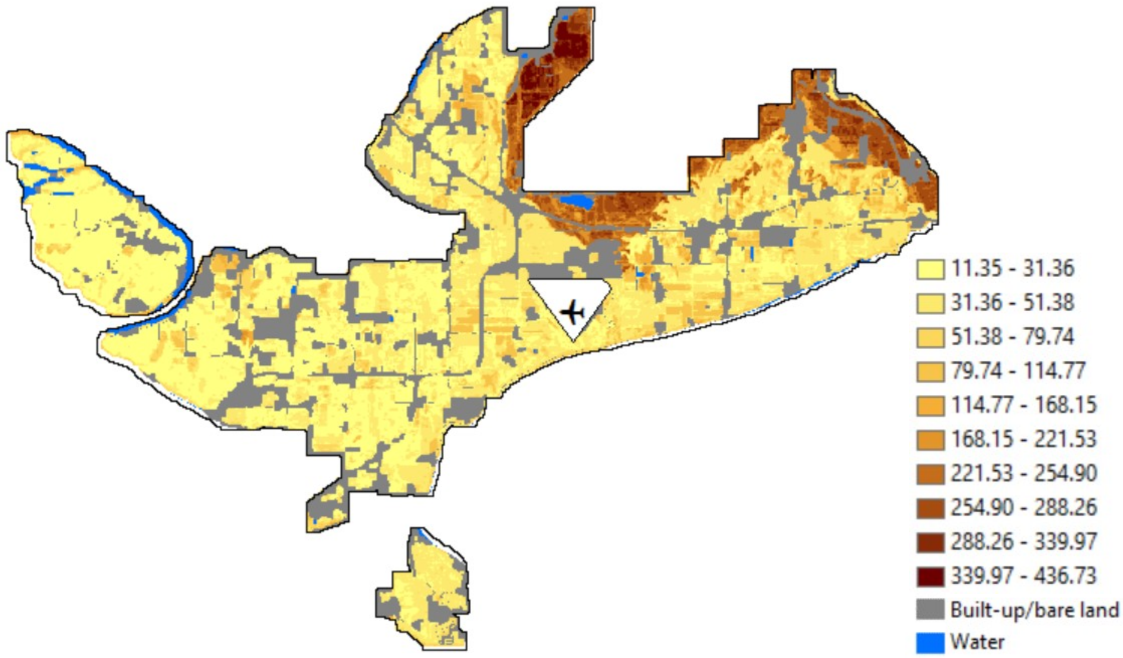

Figure 10. The distribution of soil organic carbon (g C/kg soil) across Delta in 2018

We observed that most of Delta lost SOC during the study period while SOC gains were detected in some annual crop fields, especially in the north-eastern corner of the region (Figure 11). The absolute changes (1984 - 2018) in SOC ranged from -118 to +111 g C/kg soil, with a mean value of -34 g C/kg soil. We estimated that 93% of Delta lost SOC while SOC gain was observed in 6% and 1% remained unchanged.

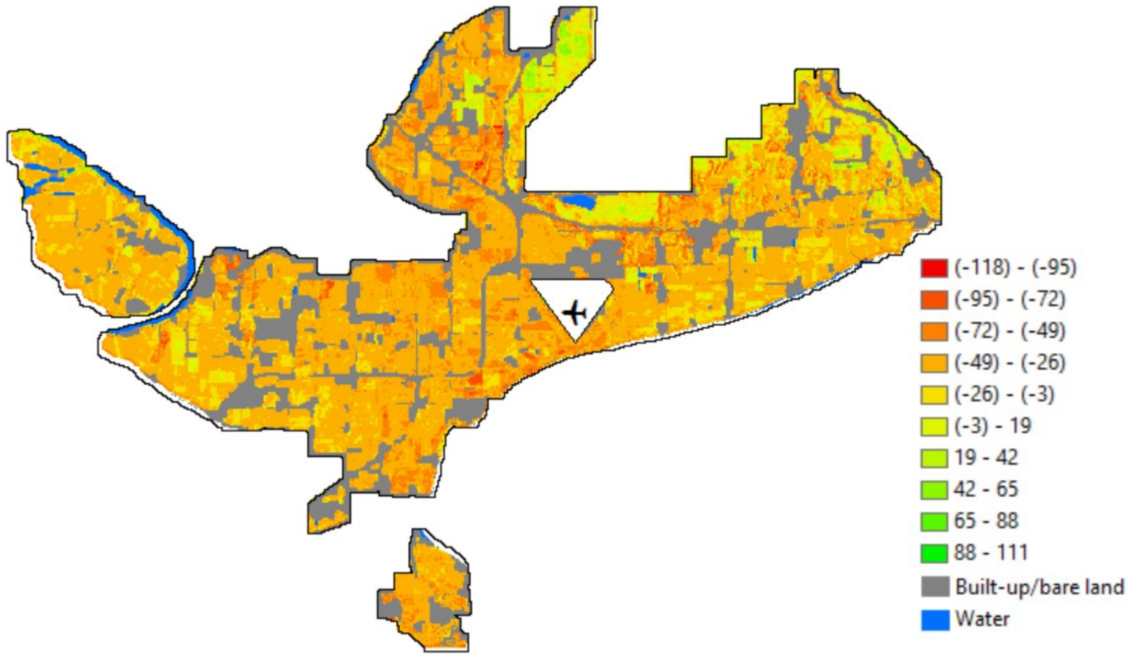

Figure 11. Absolute changes in soil organic carbon (g C/kg soil) from 1984 to 2018

SOC dynamics in response to changes in LULC and agricultural management practices

We identified several LULC change classes to explore the relationship between SOC dynamics and LULC changes. As expected, higher SOC values were observed in FFP and WL while AC fields exhibited one of the lowest SOC values. In 2018, AC fields that had not changed (AC-no change) or converted from FFP (AC-from FFP) exhibited the lowest mean SOC values (42.31 and 28.15 g C/kg soil, respectively) while rotations of AC and GL (AC-to/from GL) had a mean SOC value (121.31 g C/kg soil) substantially higher than the former two classes (Figure 11). The SOC of GL-no change and GL-from FFP were fairly similar with mean SOC of 63.67 and 50.42 g C/kg soil, respectively. Among PC fields, those converted from WL (PC-from WL) had the highest mean SOC (71.44 g C/kg soil) followed by PC-from AC (66.57 C/kg soil), PC-no change (62.71 C/kg soil), and PC-from FFP (55.97 C/kg soil). Although FFP that had not changed (FFP-no change) showed the highest mean SOC value (153.38 C/kg soil) among all LULC change classes, rotations of FFP and clear cut (FFP-to/from CC) class exhibited mean of SOC (62.45 C/kg soil). However, some fallow cropland areas might have been misclassified as clear cut due to the spectral similarity in Landsat imagery.

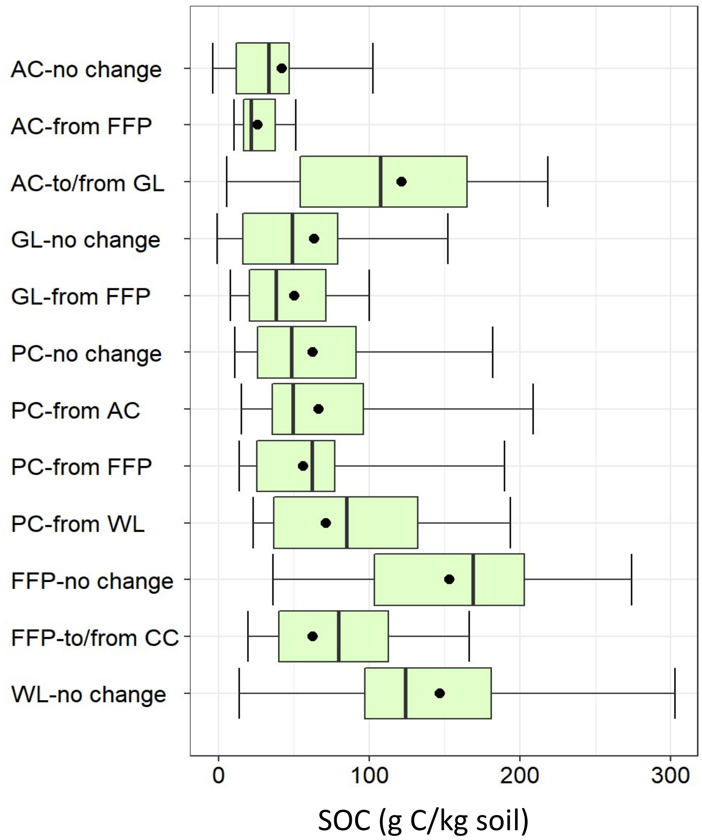

Figure 12.Soil organic carbon (g C/kg soil) in 2018 for different land use land cover (LULC) changes. Boxplots showing the first quartile, median (bar), third quartile, and mean (circles) of soil organic carbon content

When the SOC of Delta's AC-no change class was compared with the SOC of AC-no change class of other census subdivisions across the Lower Fraser Valley (Figure 13). Delta had the lowest mean (31.52 g C/kg soil) and median (23.14 g C/kg soil) SOC for AC-no change class among all the subdivisions in 2018. While these numbers are challenging to interpret on their own, given they do not indicate whether Delta soils started with lower concentrations of SOC or if there are more pockets of wetland soils in other regions, they do suggest that parts of the Delta have soils that are very low in SOC. The median value is under the 30 g C/ kg soil (or 3%) threshold identified for forming aggregates.

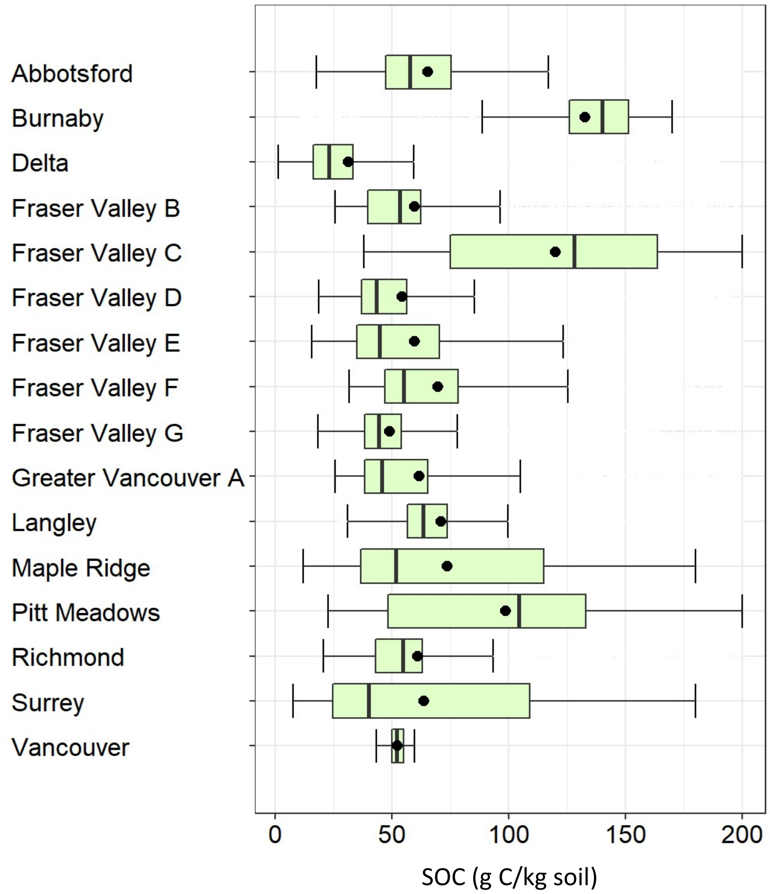

Figure 13. Soil organic carbon (g C/kg soil) in 2018 for annual crop no-chance (AC-no change) class for different census consolidated subdivisions (CCS). Boxplots showing the first quartile, median (bar), third quartile, and mean (circles) of soil organic carbon content

The relative changes in SOC (ΔSOC) from 1984 to 2018 were notably variable for different LULC change classes (Figure 14). Although we detected large variation of relative changes in SOC, ranging from +ΔSOC (i.e. gain) to –ΔSOC (i.e. loss), FFP-no change was the only category which showed a positive mean ΔSOC (+2%) during this time period. Most of LULC change classes exhibited large SOC losses during the study period with mean ΔSOC ranging from -25% to -50%. For example, AC-from FFP exhibited the largest decline with a mean ΔSOC of -52.32%. SOC decline for AC-no change was ~50% higher than the decline for AC-to/from GL. Interestingly, all no change cropland classes, i.e. AC-no change, GL-no change, PC- no change lost a substantial amount of SOC from 1984 to 2018 with their mean ΔSOC of -41.81%, -44.39%, and -31.09%, respectively. These results may indicate that croplands consistently on similar and intensive agricultural practices can also lose a significant amount of SOC due to insufficient organic matter management. Additionally, WL-no change class experienced a mean decline of 18.12%.

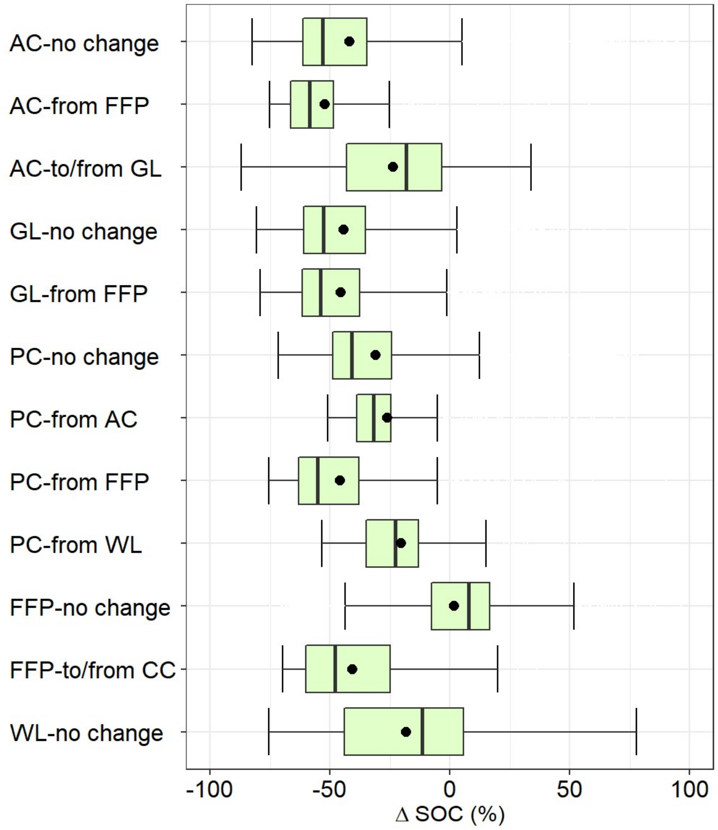

Figure 14. Relative changes in soil organic carbon (ΔSOC) from 1984 to 2018 for different land use land cover changes. Boxplots showing the first quartile, median (bar), third quartile, and mean (circles) of ΔSOC

The SOC dynamics became more striking when agricultural management classes were considered (Figure 15 & Figure 16). In 2018, perennial berries had by far the highest SOC with a mean SOC of 120 g C/kg soil. The remaining management classes all had a mean SOC values <50 g C/kg soil. The high SOC value of perennial berries class is likely attributed to cranberries which are commonly cultivated in highly organic peat soil. While the variation in SOC ranged by classes the remaining class were indistinguishable in the SOC concentrations. There were no clear differences among the annual crops with GLSA or WCC and perennial grass and annual crop only. This could be interpreted in several ways. This may imply that farmers with fields that were already highly degraded in SOC were more likely to adopt GLSA and WCC to restore the soil quality. Or that there are other practices being adopted that are maintaining equivalent SOC as GLSA and WCC. It could also mean that the GLSA and WCC is having little impact.

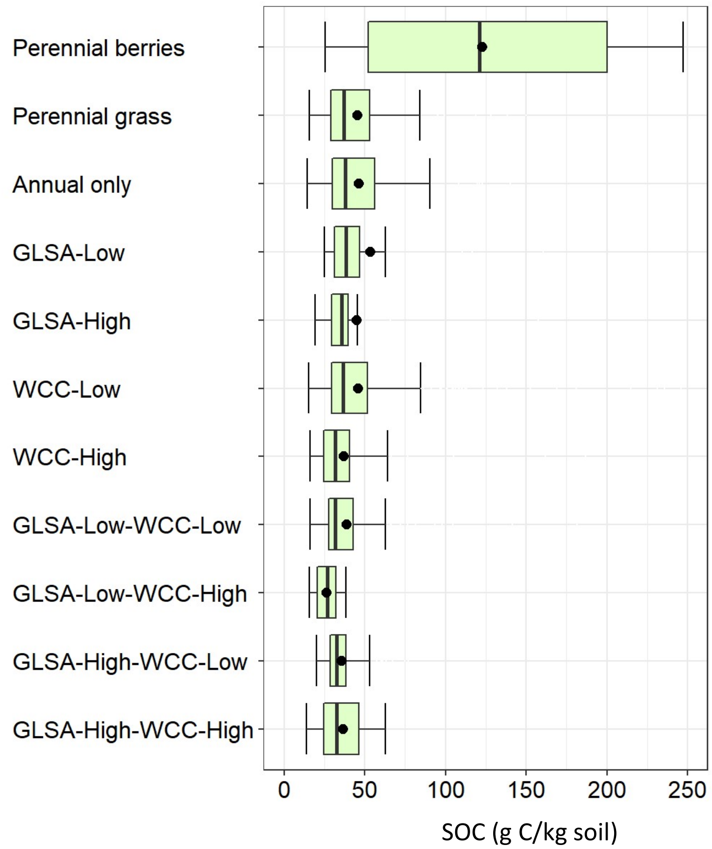

Figure 15. Soil organic carbon (g/kg) in 2018 for different agricultural management classes. Boxplots showing the first quartile, median (bar), third quartile, and mean (circles) of soil organic carbon content

As displayed in Figure 16, all management classes experienced high SOC loss, with a mean ΔSOC nearing or slightly below -50%, except perennial berries which had a mean ΔSOC value of -26%. The mean ΔSOC value of perennial berries was consistent with the mean ΔSOC of PC-no change class detected from the Landsat classification. Some high ΔSOC values of perennial berries class exhibited SOC gain as high as 28%. The high SOC decline in the fields with GLSA and WCC rotations was substantial and may be attributed to significantly intensive agricultural practices, like potato production which requires heavy tillage for planting and harvesting and may cause dramatic loss of SOC. These data, however, clearly show that the current frequency of adoption or type of GLSA and WCC is not changing the direction of ΔSOC and farm fields are continuing to degrade regardless of their management.

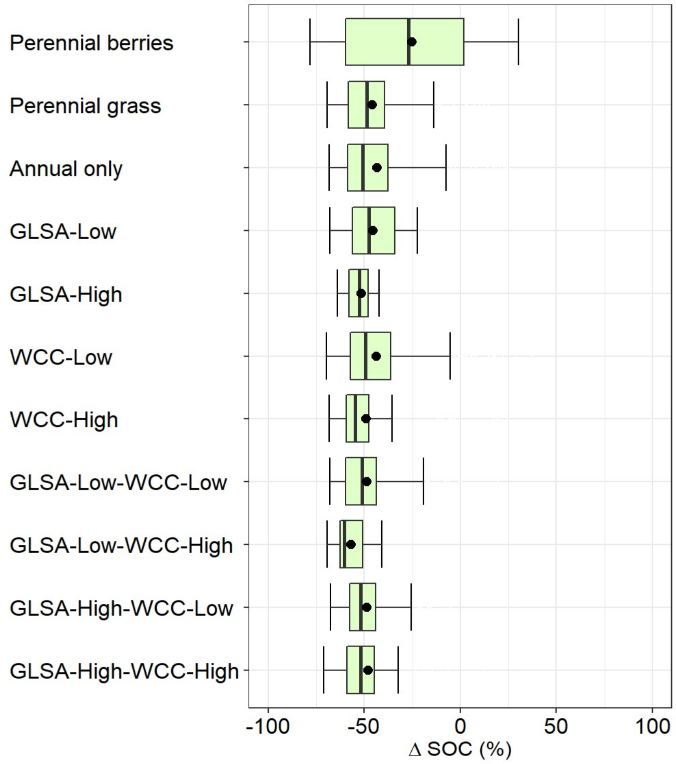

Figure 16. Relative changes in soil organic for different agricultural management classes. Boxplots showing the first quartile, median (bar), third quartile, and mean (circles) of ΔSOC

2.2.3 Conclusions

We conducted a spatiotemporal analysis of SOC dynamics in response to changes in LULC and agricultural management practices in Delta from 1984 to 2018 using remote sensing and digital soil mapping techniques. Our analysis showed that across the region, 74% of the field area had either or both GLSA and WCC for some duration. Despite this widespread adoption we captured a dramatic decline in SOC across the agricultural landscape of Delta with 93% of the area losing SOC. All agricultural management classes were observed to lose SOC while perennial berries showed relatively lower SOC decline. Fields with rotations of GLSA and WCC did show reduction in net SOC losses during our study period. It is unclear why these practices are not showing benefits over the long-term. It is possible that the benefits of GLSA, demonstrated in section 2.1 (Field Scale Analysis) are quickly lost when fields are returned to production. It is also clear from the analysis by Lussier et al. (2019 and 2020) that four years or less is too short of time to accrue detectable differences in SOC. Further research is need to determine if these practices can be improved further by combining them with other management (e.g., compost or manure applications) or need to be implemented with longer duration or increased frequency.

3 Objective 2 – Evaluate the Effects of GLSA on Soil Nutrient Availability and Crop Yields Following Set-Aside Incorporation

3.1 Field and plot-scale analysis

To better understand the impact of GLSAs on subsequent crop production we conducted a series of studies between 2015 and 2019. These studies measured nutrient dynamics and crop yield in the first and second production seasons following the incorporation of GLSAs that varied in duration from two to four years. Study 2.1 was led by M.Sc. student Khalil Walji from 2015 to 2016 and focused on 3-year-old GLSAs. For study 2.1 Khalil compared N dynamics and crop yields of fields across the region returning to crop production after incorporation of 3 -year-old GLSA to paired nearby 'control' fields that had been in continuous annual crop rotations (ACR) for the same duration of time. Khalil also conducted a plot-scale experiment in the summer of 2016 exploring soil N dynamics following the incorporation of a 3-year GLSA in combination with varying fertilizer rates, types and timing of incorporation. Khalil successfully completed his M.Sc. thesis in March 2017 (Walji 2017). For study 2.2, Lewis Fausak conducted a similar but much expanded plot-scale experiment to quantify the impacts of 2- and 3-year GLSAs on N dynamics and crop yields over two seasons, 2017 and 2018. Lewis successfully completed his M.Sc. thesis in August 2019 (Fausak 2019). In the final study for this objective, 2.3, Patricia Hanuszak, in the summer of 2019, repeated Khalil's regional analysis approach focusing on 4-year GLSAs and is expected to complete her M.Sc. project in summer of 2020. Together these studies were designed to specifically address the following research questions: 1. How does the incorporation of GLSA into a crop rotation affect soil nutrient cycling and subsequently crop yield; 2. How do differences in soil nutrient cycling and yield vary with the duration of the set-aside; and 3. If there are benefits in the first season after GLSA incorporation, will they continue in the second season?

3.1.1 Materials and Methods

Study Sites

Regional studies were conducted between the Spring 2015 until Fall 2019 in the FRD in the municipality of Delta, BC. Initially, four sites were assessed in 2015 and another four in 2016 to evaluate effects of 3-year GLSAs. At each of the study sites, a field coming out of 3 years of GLSA was paired with a nearby field that had been in ACR, specifically in vegetable production. In 2019, another four sites were selected and the analysis was repeated for 4-year GLSAs. The GLSA fields were all seeded with a DF&WT designed grass mix (described Objective 1's Materials and Methods).

All of the fields included in these regional studies were working farm operations. Each field pair was selected to be: no more than 3 km apart; on a similar soil type; planted to the same crop in the season following 3- or 4-year GLSA incorporation; and managed as similarly as possible. GLSA fields were incorporated 11-59 days before crop planting based on the weather and each farmer's schedule. Incorporation and field preparation of GLSA and ACR fields included mowing, pulvi-mulching, subsoiling and disking numerous times depending on the site. Farmers tried to keep the management of each paired field (site) as similar as possible. Nutrient management varied by site and included both organic and synthetic fertilizer being applied at various rates.

In 2017 and 2018, a portion of two fields in GLSA were used to set up a controlled, plot-scale trial. These were selected as representative of a "productive" and "unproductive" (see Objective 1) field type. Within each field, treatments were established in 3 blocks in which each treatment was replicated once. In the first week of May 2017, the 2-year GLSA plots were mowed and in the second week, the following treatments were established: (i) **AC** where 2-year GLSA aboveground biomass was removed to simulate an annual cropping system, belowground biomass was tilled in, and no N fertilizer was applied, (ii) **AC+N** was the same as above with addition of 80-kg N ha^{-1}, and (iii) **2G+N** where 2-year GLSA aboveground and belowground biomass was both tilled in with addition of 80 kg N ha^{-1}. In July 2017, garden beans were seeded.

In 2018, the experiment was continued at the same location used in 2017, which had gone through a year of annual crop production, and a 3-year old GLSA treatment was established. Hence, in 2018, we had the following treatments: (i) **AC** where 2-year GLSA aboveground biomass was removed to simulate an annual cropping system, belowground biomass was tilled in, and no N fertilizer was applied, followed by one season of bean production, (ii) **AC+N** was same as above, with addition of 100 kg N ha^{-1}, (iii) **2G+N** where 2-year GLSA aboveground and belowground biomass were both tilled in followed by one season of N fertilized bean production and application of100 kg N ha^{-1}, and (iv) **3G+N** where 3-year GLSA aboveground and belowground biomass were both tilled in and 100 kg N ha^{-1} was applied. These treatments were seeded with potatoes. In this synthesis only the treatments with fertilizer were used to compare directly to the results from the regional analysis where the fields all were fertilized.

Sampling and Laboratory Analysis

Prior to the growing season, each field entering the study was assessed for baseline soil properties. Soil samples were taken at 0-15 and 15-30-cm depths and analyzed for the following baseline properties: effective cation exchange capacity (CEC) (including cations Al, Ca, Fe, K, and Na and available P), soil pH, electrical conductivity (EC), texture, and bulk density (data not shown). Prior to GLSA incorporation, samples of GLSA aboveground biomass were collected, weighed, and analyzed for total C and N using Elemental Vario El Cube elemental analyzer. GLSA C and N concentrations were multiplied by the aboveground biomass (AGB) harvest to determine the additional C (AC) and additional N (AN) added to fields as incorporated residue.

To determine PAN, consisting of ammonium (NH_4^+ -N) and nitrate (NO_3^- -N), soil samples were collected every two to four weeks every growing season from 2015-2019, starting after crop planting and continuing until crop harvest. Soil samples were collected from 0-15 and 15-30 cm depths.

Every fall from 2016-2019, crop yield was estimated by harvesting 1-4 random samples of a predefined area (around 1 m^2) per field or plot. Crop subsamples were weighed, and then dried, either using a Labconco Model Freeze drier (Labconco, Kansas City, MO, USA) at -55ºC for between three to five days to determine dry matter content, or in some years by oven-drying at 60°C for 48 hours to obtain moisture content. Samples were then ground and analyzed for total C and N using the elemental analyzer.

Given the variation of crops and cultivars across the region and among studies crop yields were converted to a relative value to enable meaningful comparisons between GLSA and ACR. Relative yield was calculated for each field pair using the following equation:

$$RY = \frac{\sum_{n=1}^{4} \frac{SY}{MY}}{4}$$

Where the RY is the relative yield (%) for each field, MY is the maximum yield observed for a sub-plot at each site (each GLSA and ACR pair), and SY is the sub-plot yield.

Statistical analysis

To determine differences in relative yield, seasonal average of PAN and residual soil N between GLSA and ACR, a linear mixed effects (LME) model was used. Site was used as a random effect in the analysis to account for difference in environmental characteristics between each of the pairs of GLSA and ACR for each study. Both GLSA duration and depth were analyzed separately. In cases where the data was non-normal it was transformed using a log base 10 transformation to meet the assumption of homoscedasticity. A Type 3 ANOVA was used to test for significant differences ($p<0.05$) between main effects (GLSA and ACR).

3.1.2 Results and Discussion

Aboveground Biomass Characteristics

At incorporation, the GLSA biomass was composed primarily of grasses with <1% of clover present (data not shown). On productive sites during 2015 to 2017, the quantity of AGB for 2- and 3-year GLSAs were similar, the quality of biomass ranged substantially (Table 4), with C:N ratio from 25 in 2016 to 41.8 in 2017. There were also large differences in the both quantity and quality of GLSA AGB between productive and unproductive fields (Table 5). The productive field had 160% and 180% more dry GLSA biomass in 2017 and 2018, respectively. Given that the N content was fairly similar between productive and unproductive this lower biomass resulted in much lower C:N ratios in the unproductive field than for most of the observed GLSA AGB of the productive field.

Table 4. Average properties (± standard error) of aboveground biomass (AGB) from 2- and 3-year grassland set-asides (GLSA) determined between 2015 and 2018 from productive fields.

Properties	**Unit**					**2-year GLSA**						**3-year GLSA**	
			2015			**2016**			**2017**			**2018**	
		n	**=**	**4**	**N**	**=**	**4**	**n**	**=**	**3**	**N**	**=**	**3**
AGB	Mg ha^{-1}	6.02	±	6.37	5.71	±	3.45	5.08	±	0.21	5.13	±	0.75
C:N Ratio		31.0	±	2.30	25	±	2.2	41.8	±	6.89	33	±	2.5
Biomass C	Mg C ha^{-1}	2.68	±	0.03	2.54	±	0.01	2.13	±	0.08	2.07	±	0.3
Biomass N	Kg N ha^{-1}	86.4	±	12.50	101.4	±	6.6	50.8	±	2.07	62.6	±	9.16
Total C	%	44.5	±	0.45	44.4	±	0.42	41.8	±	1.43	40.3	±	0.51
Total N		1.4	±	0.20	1.8	±	0.19	1	±	0.15	1.2	±	0.1

Table 5. Average properties (± standard error) of aboveground biomass (AGB) from 2- and 3-year grassland set-asides (GLSA) determined between 2015 and 2018 from unproductive fields.

Properties	**Unit**		**2-year GLSA**			**3-year GLSA**	
		n	**=**	**3**	**n**	**=**	**3**
AGB	Mg ha^{-1}	1.95	±	0.07	1.83	±	0.31
C:N Ratio		27.6	±	3.05	26.8	±	1.19
Biomass C	Mg C ha^{-1}	0.79	±	0.02	0.74	±	0.1
Biomass N	Kg N ha^{-1}	28.8	±	0.99	23.66	±	4.01
Total C	%	40.7	±	0.22	40.8	±	0.07
Total N		1.5	±	0.15	1.5	±	0.07

Plant Available Nitrogen

When comparing the average seasonal PAN across the synthesized studies of 2-, 3-, and 4-year GLSA we found no significant differences (Figure 17 & Figure 18). Values ranged widely throughout the seasons and among fields (data not shown), but overall there were not large differences in PAN for any of the GLSA at either depth of sampling. Samples for the 4-year GLSA were not fully analyzed due to the laboratory shut-down as a result of the COVID-19. Statistical analysis for the 4-year GLSA will have to be redone once the laboratory analyses are completed after laboratory reopens.

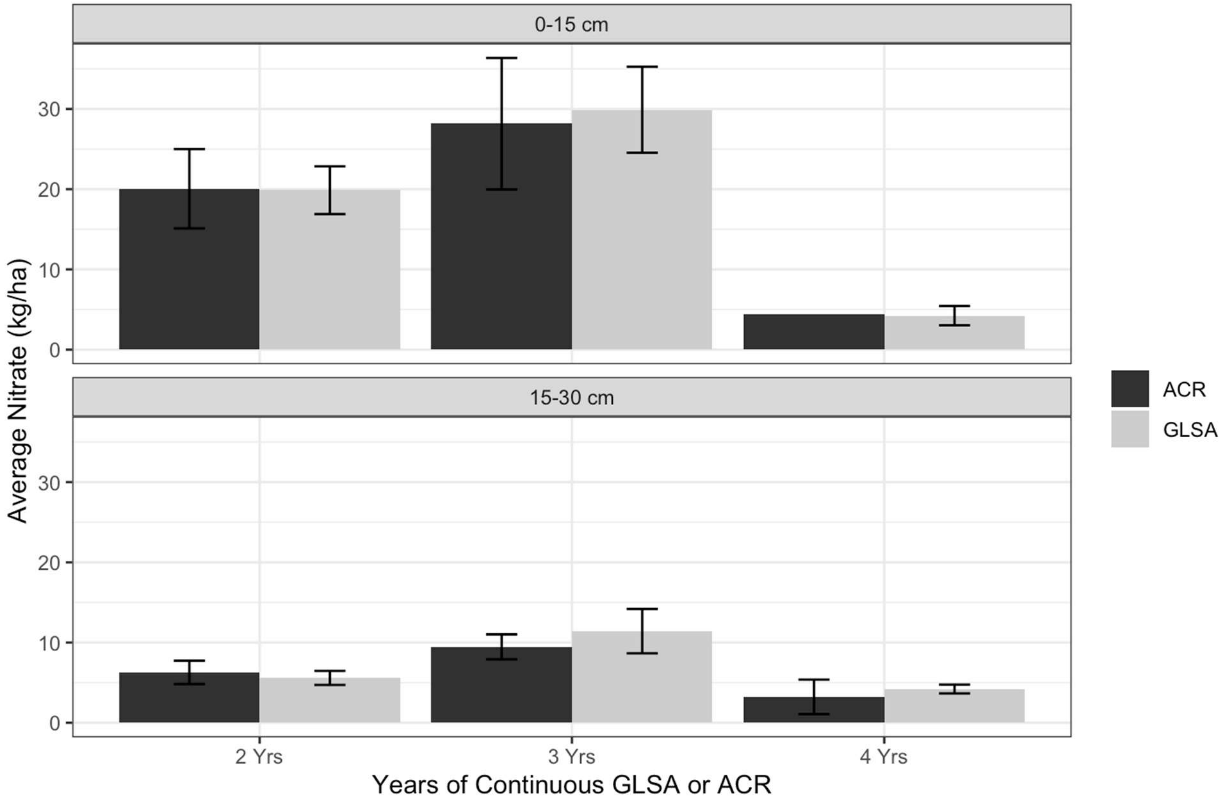

Figure 17. Average nitrate for fields following 2-, 3- and 4-year grassland set-asides (GLSA) in the season following incorporation compared to fields in annual crop rotations (ACR) for the 0-15 and 15-30 cm depths. Error bars indicate the standard error of the mean. No significant differences were found.

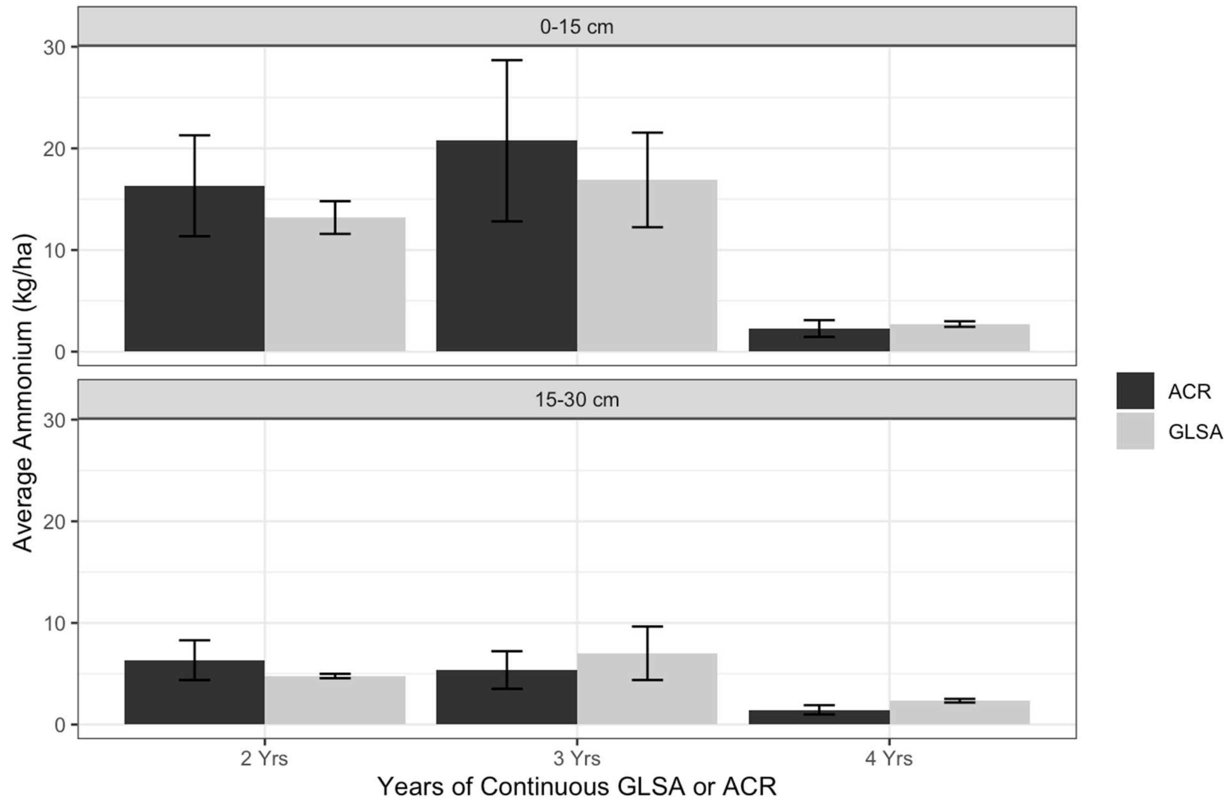

Figure 18. Average ammonium for fields following 2-, 3- and 4-year-old grassland set-asides (GLSA) in the season following incorporation compared to fields in annual crop rotations (ACR) for the 0-15 and 15-30 cm depths. Error bars indicate the standard error of the mean. No significant differences were found.

Although there were no differences in average seasonal nitrate following 2-year GLSA in the season immediately following incorporation there were differences in the second season, one year later. Both depth and treatment were marginally significant ($p<0.10$) for nitrate (Figure 19) but not for ammonium (Figure 20). This could be due to the breakdown of the biomass and roots that occurs slowly over the first season.

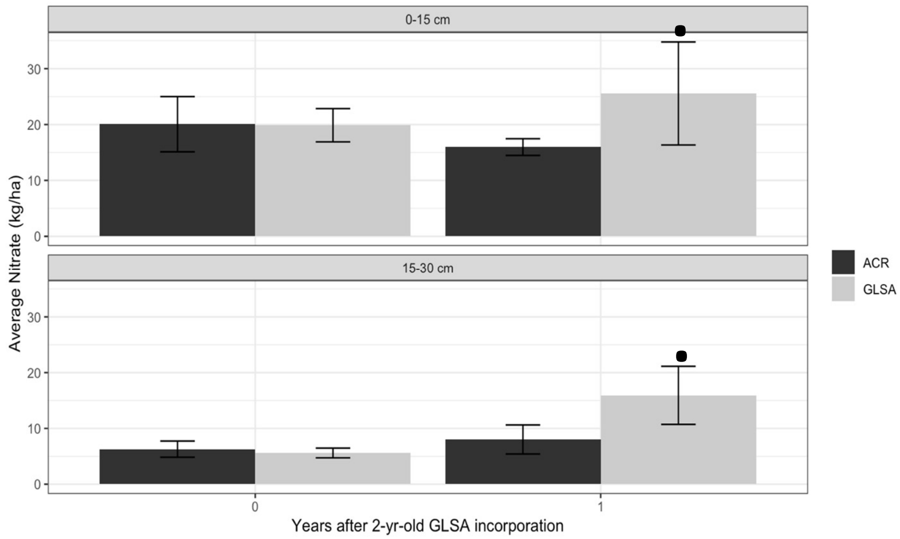

Figure 19. Average nitrate for fields following 2-year grassland set-asides (GLSA) in the year following incorporation (0) or after one year (1) compared to fields in annual crop rotations (ACR). Error bars indicate the standard error of the mean. Marginal significant differences are indicated by • at p< 0.10.

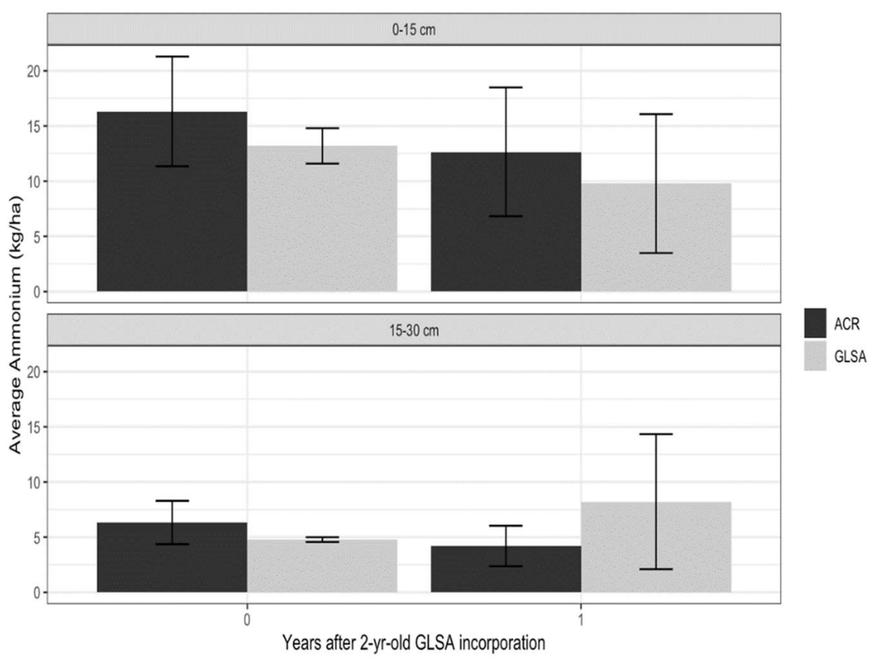

*Figure 20. Average ammonium for fields following 2-year grassland set-asides (GLSA) in the year following incorporation (0) or after one year (1) compared to fields in annual crop rotations (ACR). Error bars indicate the standard error of the mean. Significant differences indicated by * at p< 0.05.*

The seasonal averages, while indicating large overall difference between the GLSA and ACR do not reflect some of the important changes that are most likely to impact crop production. More important than the overall average is the timing of release of the PAN. While the analysis of timing is not yet possible for the 2-, 3-, and 4-year GLSAs the patterns observed in Walji (2017) are important to note. The pattern of both the timing and overall average PAN between GLSA and ACR differed in the 2015 and 2016 growing seasons (Figure 21). In 2015, average NO_3^--N at the 0-15 cm depth was significantly ($p<0.05$) higher at sampling time one and again at sampling time four and six (Figure 21A). The greatest difference was observed at sample four with the GLSA supplying 29 kg ha^{-1} more than control fields. Sampling time six, at the end of the 2015 season, was indicative of residual soil N and it showed that GLSA left 8 kg ha^{-1} more NO_3^--N. In 2015, the overall seasonal average NO_3^--N was 26% and 15% greater ($p<0.05$) in GLSAs than ACR at 0-15 cm and 15-30 cm depths, respectively (Figure 21B and D). In contrast, during the 2016 growing season, overall seasonal average NO_3^--N was 41% and 25% greater ($p<0.001$) in ACR than GLSAs at the 0-15 cm and 15-30 cm depth, respectively (Figure 21F and H).

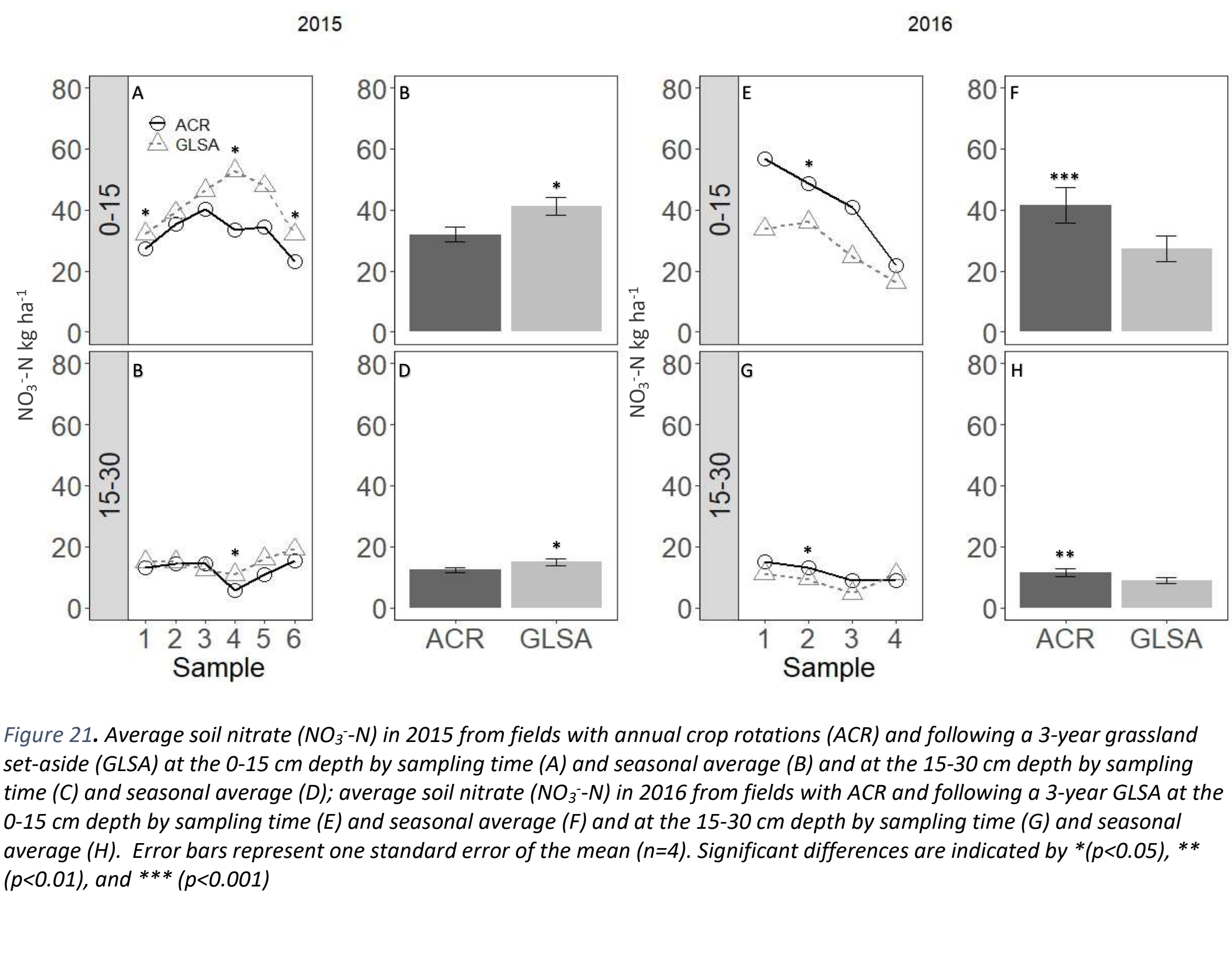

*Figure 21. Average soil nitrate (NO_3^--N) in 2015 from fields with annual crop rotations (ACR) and following a 3-year grassland set-aside (GLSA) at the 0-15 cm depth by sampling time (A) and seasonal average (B) and at the 15-30 cm depth by sampling time (C) and seasonal average (D); average soil nitrate (NO_3^--N) in 2016 from fields with ACR and following a 3-year GLSA at the 0-15 cm depth by sampling time (E) and seasonal average (F) and at the 15-30 cm depth by sampling time (G) and seasonal average (H). Error bars represent one standard error of the mean (n=4). Significant differences are indicated by *(p<0.05), ** (p<0.01), and *** (p<0.001)*

The timing of NH_4^+-N supply during the 2015 season followed a similar trend to NO_3^--N. At sampling times one, four, and five, NH_4^+-N at the 0-15 cm depth was significantly higher ($p<0.05$) in GLSA than ACR (Figure 22A) and the overall seasonal average NH_4^+-N was 20% higher ($p<0.01$) in GLSAs than ACR fields (Figure 22B). At the 15-30 cm depth, NH_4^+-N was only significantly higher in GLSA at sampling time three (Figure 22C)and the overall seasonal average NH_4^+-N was not significantly different between GLSA and ACR (Figure 22D). In 2016, there were no significant differences in NH_4^+-N either by sampling time or overall average at either depth (Figure 22BE-H).

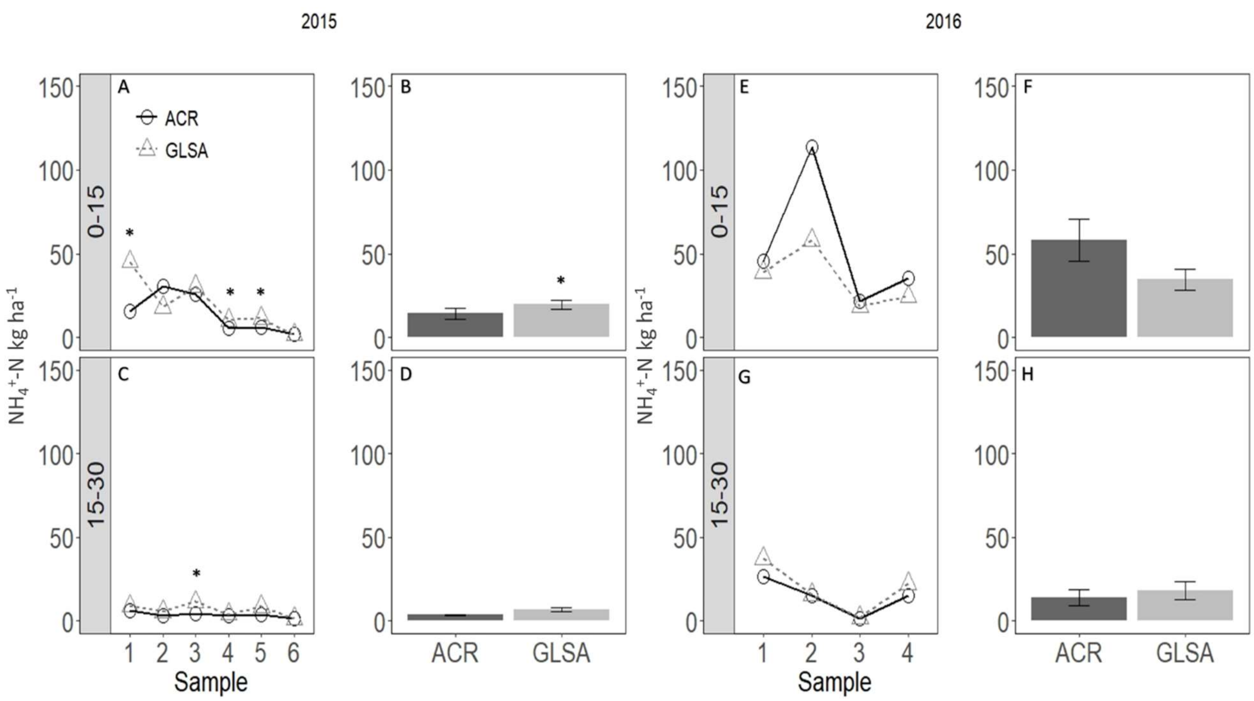

*Figure 22. Average soil ammonium (NH_4^+-N) in 2015 from fields with annual crop rotations (ACR) and following a 3-year grassland set-aside (GLSA) at the 0-15 cm depth by sampling time (A) and seasonal average (B) and at the 15-30 cm depth by sampling time (C) and seasonal average (D); average soil ammonium (NH_4^+-N) in 2016 from fields with ACR and following a 3-year GLSA at the 0-15 cm depth by sampling time (E) and seasonal average (F) and at the 15-30 cm depth by sampling time (G) and seasonal average (H). Error bars represent one standard error of the mean (n=4). Significant differences are indicated by *($p<0.05$)*

Relative Crop Yields

In the regional and plot-scale studies a wide range of crops were produced from 2015 to 2019. These included potatoes, beans, broccoli, silage corn, peas and barley. While yields varied widely within crop type across the region, there were overall no significant differences in relative yields (Figure 23). Variation varied most widely for the relative yields following 2-year GLSAs. This variation was due to the difference in the field conditions.

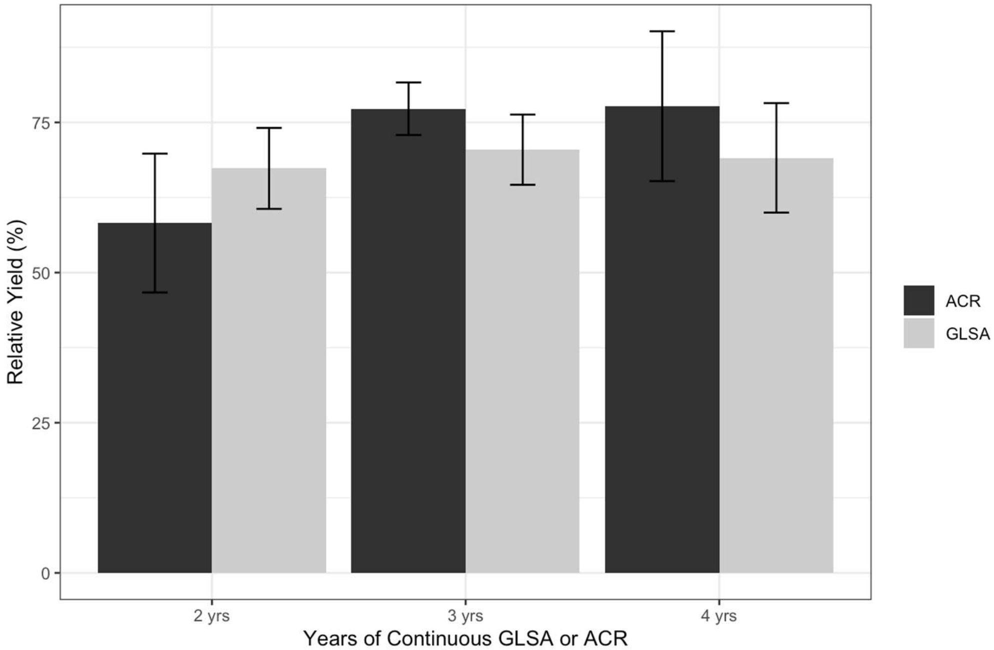

Figure 23. Average relative yield for fields in annual crop rotations (ACR) and following 2-year (n=6), 3-year (n=10), or 4-year (n=4) grassland set-asides (GLSA). Error bars indicate the standard error of the mean. No significant differences were found.

In the first season following incorporation on productive sites, relative yield was significantly different with the 2-year GLSA relative to ACR, but this was not true on the unproductive sites. In the second season following GLSA incorporation, there were no significant differences in relative yield between GLSA and ACR.

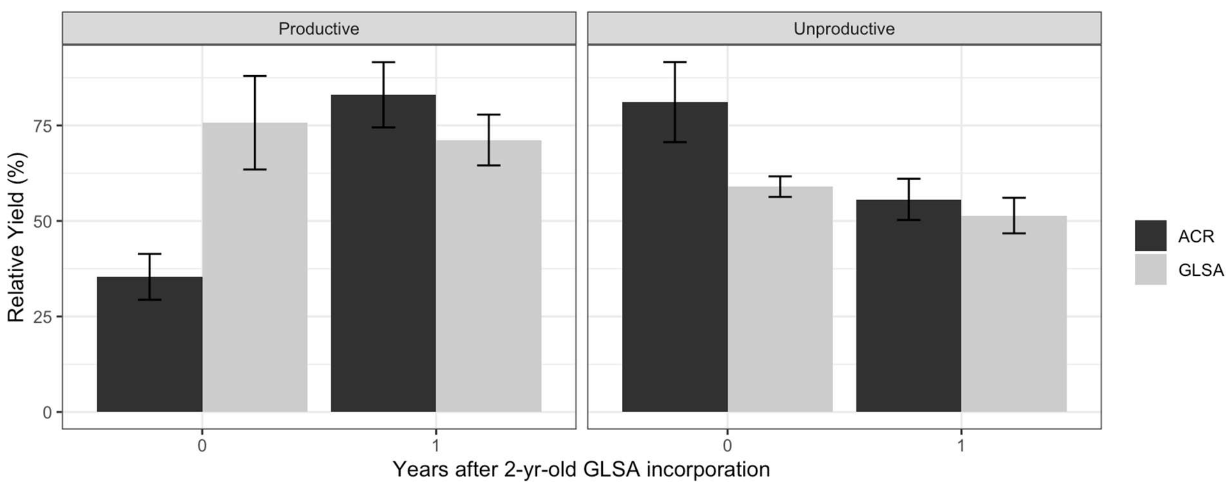

*Figure 24. Average relative yield for fields following 2-year grassland set-asides (GLSA) in the year following incorporation (0) or after one year (1) compared to fields in annual crop rotations (ACR). Error bars indicate the standard error of the mean. Significant differences indicated by * at p< 0.05.*

3.1.3 Conclusions

The results of our studies do not indicate that 2- and 3 year GLSAs increase PAN through the subsequent production season or in the post-season. There was no evidence to suggest that fields with incorporation of 2- and 3 year GLSA contained higher TC and TN compared to ACR fields, nor that they consistently supply more PAN throughout the growing season. This is likely due to the low proportion of N-fixing species (i.e., red clover) in the GLSA seed mix, among other factors.

Relative crop yields were not affected by incorporation of the 3-year GLSA in the growing season following that incorporation (Study 2.1.), likely due to the lack of differences in PAN. In Study 2.2., 2 year GLSA increased bean yield in the productive field, but not in the unproductive field. In the following season, 2- and 3-year GLSA did not improve potato yields. This suggests that the GLSA does have potential to improve crop yields after 2 years, but it likely depends on the selection of crop type as well as the soil properties at the time of GLSA establishment. A more thorough understanding of the cropping history or more detailed characterization of the status of degradation across the region could help to clarify the potential for GLSA to impact subsequent crop yields.

Farmers are often concerned with low PAN in the spring, especially when incorporating above ground biomass with high C:N ratios (such as GLSA biomass) which could immobilize PAN following incorporation. Results of Study 2.2. indicated that GLSAs could have potential to increase N mineralization earlier in the season compared to continuous cropping. This effect was only seen in the unproductive field, perhaps in part because the C:N ratio was much higher in the GLSA biomass grown on the productive field (41.8) than the unproductive field (27.6). Overall, the generally high C:N ratio of the GLSA biomass (due to it being composed mainly of grasses) does not make it susceptible to rapid breakdown or N release. The results of the field plot-scale experiment in Study 2.1. showed that farmers transitioning their fields out of GLSA and back into crop production can expect a PAN benefit between 21 and 56 DAI, depending in part on when the incorporation occurs. If incorporation and fertilization occur at the same time, the PAN benefit is likely to occur earlier than if incorporation is delayed. In this study, postponing the incorporation by 14 days, delayed the initial peak PAN to 42 DAI instead of 21 DAI, and appeared to prolong the effects of early season N immobilization until 62 DAI. Postponing incorporation by just 14 days could delay N mineralization processes and result in a mismatch of crop N needs and soil N supply.

Study 2.1. also showed that in the first production season after GLSA incorporation, fertilizer rate does impact PAN levels, but not timing of PAN release. The High fertilizer rate (double the regional average rate) did increase average seasonal PAN as compared to the Typical rate, although cumulative N levels between the two treatments were not significantly different. The results of this study indicated that doubling the application rate of fertilizer from Typical to High does not reduce the duration of immobilization or supply more PAN early in the season in either NO_3^--N or NH_4^+-N forms. This suggests farmers can apply typical rates of N fertilizer and achieve the same results as a doubled rate, thus reducing unnecessary costs and avoiding over-fertilization and potential environmental pollution. Results from this study suggest that GLSAs are not resulting in consistent PAN benefits or improved crop yields, but with further study to better quantify the impacts of timing and mineralization rates, could lead to reduced fertilizer application rates.

4 Objective 3 - Communication and Outreach Efforts

Project results were shared with stakeholders throughout the region, including farmers, policy makers, post-secondary students, and supporters of the DF&WT through a variety of communication tools and activities. Communication materials and activities included presentations, field tours, display booths, publishing of articles in various media outlets, articles in peer-reviewed academic journals, farmer bulletins, the DF&WT website, extension briefings, and a brochure.

Delta farmers were regularly updated over the duration of the project at spring and fall Delta Farmers' Institute meetings and select City of Delta councillors were kept informed of the project's progress at the City's Agricultural Advisory Committee meetings. Presentations were made at various soil conferences, a workshop for Environmental Farm Planners, and at the Horticultural Growers' Short Course - Pacific Agriculture Show. Media articles were published in various outlets including the Delta Optimist, Modern Agriculture, Something Good Magazine, UBC Faculty of Land and Food Systems homepage, UBC Faculty of Forestry's Branchlines magazine, and DF&WT's Farmland & Wildlife newsletter. Field tours that featured the project were delivered to various audiences including student classes from the UBC Faculty of Land and Food Systems, British Columbia Institute of Technology Fish, Wildlife and Recreation program and Quest University. Field tours were also provided for the City of Delta's Mayor and Council, Delta's Member of Parliament, and staff with the City of Richmond, BC Ministry of Agriculture and Agricultural Land Commission.

Three extension briefs and a brochure were produced at the end of the project, which will be distributed to members of the Delta Farmers' Institute and made available to interested parties including farmers outside of the Municipalities of Delta and Richmond. The stakeholder engagement plan and corresponding deliverables is detailed in Table 6.

Table 6. Stakeholder Engagement Plan 2015 and 2020

Communications Activity	Date Completed
2015	
Article announcing project in industry media	Article entitled "Fallow Fields – Delta Soil Productivity Evaluation" published in Modern Agriculture (Nov 2015)
Article introducing project in DF&WT Biannual Newsletter (Summer edition)	Article entitled "DF&WT-UBC GLSA Soil Evaluation Commences" (Jul 2015)
Project progress report delivered to DF&WT Board of Directors	Updates provided at spring and fall board meetings
Article in the Delta Optimist newspaper (Agriculture Week edition)	Article entitled "Trust studies benefits of set-aside efforts" published on Aug 14, 2015
Feature Project in outreach activities	See table below
Present project update to Delta Farmers' Institute Fall meeting	UBC Master's graduate (Khalil Walji) presented update on Nov 27, 2015
Printed update bulletin to participating farmers	Bulletins delivered on Dec 5, 2015
2016	
Article featuring project on DF&WT website	Entitled "Soil Productivity in the Fraser River delta" was published on the DF&WT website and the Spring 2016 issue of UBC Branchlines Magazine.
Project progress report delivered to DF&WT Board of Directors	Updates provided at spring and fall board meetings
Feature Project in outreach activities	See table below
Present project update to Delta Farmers' Institute Fall meeting	Verbal update provided at meeting on Dec 1, 2016
Printed update bulletin to participating farmers	Bulletins delivered to participating farmers in Jan/Feb 2017
2017	
Project progress report delivered to DF&WT Board of Directors	Updates provided at spring and fall board meetings
Project updates in DF&WT Biannual Newsletter (Winter edition)	Article entitled "IAF Grassland Set-aside Project Update" (Jan 2018)
Feature Project in outreach activities	See table below
Present project update to Delta Farmers' Institute Fall meeting	Verbal update with printed copies was provided at meeting on Dec 17, 2017
Printed update bulletin to participating farmers	Bulletins delivered in Jan 2018
2018	
Project progress report delivered to DF&WT Board of Directors	Updates provided at spring and fall board meetings
Article in the Delta Optimist newspaper (Agriculture Week edition)	Article entitled "Grassland Set-asides support soil conservation and critical wildlife habitat" published on Aug 10, 2018
Article featuring project in online media	Article entitled "New UBC findings on Delta farms can improve soil productivity and drainage" published on UBC Faculty of Land and Food Systems website (Mar 29, 2019) and the Delta Optimist (Apr 16, 2019)
Feature Project in outreach activities	See table below
Present project update to Delta Farmers' Institute Fall meeting	Verbal updated provided at meeting on Dec 6, 2018
Printed update bulletin to participating farmers	Bulletins delivered in Jan/Feb 2019

2019	
Project progress report delivered to DF&WT Board of Directors	Updates provided at spring and fall board meetings
Project updates in DF&WT Biannual Newsletter (Winter edition)	Article entitled "Investment Agriculture Foundation Grassland Set-aside Project" (Jan 2020)
Feature Project in outreach activities	See table below
Present project update to Delta Farmers' Institute Fall meeting	UBC Masters' graduate (Lewis Fausak) and student (Teresa Porter) presented at the meeting on Dec 5, 2019
Printed update bulletin to participating farmers	Bulletins delivered in Jan/Feb 2020
2020	
Presentation of Project Results to DF&WT Board of Directors	Postponed due to COVID-19
Publications of findings in scientific journal	Detailed below

DF&WT engages in various outreach activities throughout the year. Approximately 28,200 people were informed about the project through its outreach activities including DF&WT's annual community event- Day at the Farm (DATF), display booths at various events, presentations and field tours.

DATF is an event DF&WT has hosted for 14 years that regularly sees over 4,000 people from across Metro Vancouver attend. Multiple organizations and businesses from the agricultural and environmental sectors set up displays to educate event attendees about agriculture in the Lower Mainland and the wildlife habitat it provides. UBC is an annual attendee that sets up a display including digging a soil pit to inform the public about Delta soils and how GLSA are utilized to support soil health. UBC attended DATF every year over the duration of the research project and graduate students working on the project (including Jason Lussier, Khalil Walji, Lewis Fausak and Teresa Porter) were present at the event to discuss their research results.

Research results were also provided to the general public at other events that DF&WT attended including the Orphaned Wildlife Rehabilitation Society annual open house, the Richmond Raptor Festival and Pacific National Exhibition's "Ag in the City" event. Field tours were given throughout the year to interested parties, which included site visits to GLSAs and discussions about the GLSA research project. Outreach activities conducted over the duration of the project are detailed in (Table 7).

Table 7. Project Outreach Activities from 2015 to 2020

Period	Outreach Target Group Details	Communication Tool	Number of People in Attendance
Mar 1 to Sep 30, 2015	Delta Farmers' Institute (DFI) meeting	Presentation	50
	City of Richmond staff	Field Tour	3
	City of Delta Agricultural Advisory Committee (AAC)	Presentation	15
	DF&WT "Day at the Farm" Agri-awareness Event – general public	Community Event	3,600
	University of British Columbia (UBC) Applied Biology (APBI) 260 class	Field Tour	25
	Pacific Regional Soil Science Society (PRSSS)	Field Tour	50
	South Coast Conservation Program	Presentation	50
	UBC Faculty of Land and Food Systems - Alumni night	Presentation	50
	University of Colorado and National University of El Salvador researchers	Field Tour	5
Oct 1, 2015 to Mar 31, 2016	Delta Naturalists' Society	Presentation	20
	City of Delta AAC and Delta Mayor & Council	Field Tour	20
	Nature Vancouver	Field Tour	20
	Quest University	Field Tour	30
	UBC Natural Resource Conservation students	Presentation	40
	DFI Fall meeting	Presentation	30
	Ducks Unlimited Canada (DUC) and visiting professors (from Japan)	Field Tour	20
	UBC APBI 360 class	Presentation	20
	UBC Science and Land and Food Systems	Panel Discussion	30
	UBC APBI 460 and 495	Field Tour	30
	British Columbia Institute of Technology (BCIT) Sustainable Resource Management class	Field Tour	30
	Handsworth Secondary School	Presentation	25
	Nature Trust of BC Board of Directors	Field Tour	15
Apr 1 to Sep 30, 2016	ES Cropconsult Ltd.	Field Tour	10
	BCIT Fish, Wildlife, Recreation (FWR) students	Field Tour	3
	DF&WT "Day at the Farm" Agri-awareness Event – general public	Community Event	4,525
	UBC APBI 260 class	Field Tour	30
Oct 1, 2016 to Mar 31 2017	BCIT FWR class	Field Tour	30
	City of Delta AAC meeting	Meeting	10
	DFI meeting	Presentation	20
	Vancity - assistant branch managers	Presentation	12
	BCIT FWR students	Interview	4
Apr 1 to Sep 29, 2017	DFI Annual General Meeting	Presentation	50
	ES CropConsult Ltd. summer co-op students	Field Tour	22
	Tsawwassen Vancity branch staff	Presentation	7
	Orphaned Wildlife Rehabilitation Society Open House – general public	Display Booth	3000 (Over 2 days)
	Richmond Raptor Festival – general public	Display Booth	400

	DF&WT "Day at the Farm" Agri-awareness Event – general public	Community Event	1,570
Sep 30, 2017 to Mar 30, 2018	UBC APBI 260 Class	Field Tour	20
	BCIT FWR Class	Field Tour	30
	DFI Fall Meeting	Presentation	50
	City of Delta Heritage Week	Display Booth	100
	Biodiversity Workshop for Environmental Farm Plan planners and agrologists	Presentation	30
Mar 31, 2018 to Mar 29, 2019	Pitt Meadows AAC meeting	Presentation	16
	BC Ministry of Agriculture Staff and Agricultural Land Commission staff	Field Tour	25
	ES CropConsult Ltd. summer co-op students	Field Tour	20
	Richmond Garlic Festival – general public	Display	4,000
	PNE "Ag. In the City" Fair – general public	Display	1,000
	DF&WT "Day at the Farm" Agri-awareness Event – general public	Community Event	4,000+
	Quest University students	Field Tour	20
	BCIT FWR students	Field Tour	30
	MP Carla Qualtrough & Bird Studies Canada	Field Tour	3
	DFI Meeting – Delta farmers	Presentation	25
	UBC and Simon Fraser University faculty	Field Tour	3
	BCIT FWR class	Presentation	30
Mar 30 to Sep 30, 2019	DFI meeting	Updates	30
	Journalist from the Western Producer and staff at BC Blueberry Council	Field Tour	2
	DF&WT "Day at the Farm" Agri-awareness Event – general public	Community Event	4,400
	BCIT FWR class	Field Tour	3
	BC Fuchsia and Begonia Society	Presentation	25
	Delta Chamber of Commerce	Bus Tour	45
	BC Farm Writers' Association	Field Tour	20
	UBC APBI 260 Class	Field Tour	20
	Canadian Soil Science Society Annual Meeting (Saskatoon, Saskatchewan)	Posters	210
	Dunbar Garden Club	Presentation	60
Oct 1, 2019 to May 31, 2020	BCIT FWR class	Field Tour	30
	DFI meeting	Presentation	30
	City of Delta AAC meeting	Update	12
	Pacific Agriculture Show Horticultural Growers' Course	Presentation	30
	DUC Board of Directors	Field Tour	30

Multiple articles were also published, or have been submitted for publication, in peer-reviewed scientific journals, including Soil & Tillage Research, Canadian Journal of Soil Science, Soil Research, and Agronomy. Articles published, or that have been submitted for publication, are listed below:

- Fausak, L., M. Krzic, D. Bondar, A.A. Bomke, W. Valley, and S.M. Smukler. Effects of short-term grassland set-asides on CO_2, CH_4 and N_2O emissions in subsequent annual crop production in coastal British Columbia. To be submitted to Soil & Tillage Research in May 2020.

- Lussier, J.M., M. Krzic, S.M. Smukler, A.A. Bomke, and D. Bondar. 2019. Short-term effects of grassland set-asides on soil properties in the Fraser River Delta of British Columbia. Canadian Journal of Soil Science 99:136-145. https://doi.org/10.1139/cjss-2018-0097

- Lussier, J.M., M. Krzic, S.M. Smukler, K. Neufeld, C. Chizen, and A.A. Bomke. 2020. Soil organic carbon and aggregate stability in two seasons of grassland set-aside and annual crop rotations. Soil Research 58(4): 364-370. https://doi.org/10.1071/SR19180

- Walji, K., M. Krzic, D. Bondar, and S.M. Smukler. Nitrogen dynamics following incorporation of 3-year old grassland set-asides in the Fraser River delta of British Columbia. Submitted to Agronomy in May 2020.

5 Conclusions and Recommendations

This research provides key insights to the effects of integrating GLSAs into operational farms in the FRD, and contributes to the body of scientific knowledge on the role of set-asides in agroecosystems. The overarching goal of this research project was to provide farmers of the FRD with detailed information on the effects of two to four years of GLSA on soil productivity. The research objectives of this project were to: (1) evaluate the effects of GLSA on soil quality of Fraser River delta fields, and (2) evaluate the effects of GLSA on soil nutrient availability and crop yields following set-aside incorporation. To address those study objectives, six independent, but complementary, studies were undertaken during this 5-year research project, providing a much needed information to FRD farmers regarding the effects of GLSAs.

5.1.1 Objective 1

One of the key finding for this objective is that the effects of GLSA on soil quality depend greatly on the state of the field prior to GLSA seeding. Farmers enroll fields into the GLSA program generally either to restore degraded fields that are no longer producing optimally, or to maintain soil productivity in already productive fields. In addition, some productive fields end up enrolled in the GLSA program to transition them into organic production. Before GLSA seeding in 2015, unproductive fields included in our study, were differed from productive fields by low MWD of water stable aggregates, low soil organic matter, and high exchangeable sodium. Development of the criteria, based on baseline soil properties, to distinguish between 'productive' and 'unproductive' fields allowed for a more accurate analysis of the effects of GLSA throughout the rest of the project.

Unproductive fields did not show any changes in MWD under GLSA in the first two seasons of GLSA growth, while the productive fields showed MWD improvement in their 2nd season of GLSA. By 2018, both productive and unproductive fields that had been in GLSA for three years and were in their 4th season of GLSA growth. At that time, greater MWD was observed on GLSA than the ACR fields. This difference in MWD was maintained (but did not increase) in 2019. The improvement in aggregate stability after two years of GLSA in productive fields and three years in unproductive fields indicates that the undisturbed growth of GLSA vegetation is capable of improving soil physical quality over a short period of time.

We found that bulk density was improved (became less compacted) in productive fields that had been in GLSA for two growing seasons, and this trend continued for the duration of the study. However, the same was not true for unproductive fields, which showed no improvement in bulk density after four seasons. Aeration porosity did not improve after four years GLSA growth in either productive or unproductive fields. Generally, bulk density and aeration porosity are slow to change as a result of management practices, and often require many years to show measurable improvements. Labile C pools, represented in this study by POXC and DAEP, are generally responsive to management practices. At the end of their 2nd

growing season in GLSA, POXC and DAEP were not found to be different on productive fields under GLSA as compared to ACR fields. Similarly, TC and TN also did not change after two growing seasons of GLSA.

This study established that short- to medium-term GLSAs have a positive, though limited, effect on soil quality, as seen in improvements in aggregate stability and bulk density. GLSA did not affect soil carbon or aeration porosity. The duration of GLSA was found to be important in predicting the effects of GLSA, as was the baseline condition of the field (productive or unproductive). Productive fields benefitted from improved aggregate stability and bulk density after the 2nd season of GLSA growth, while unproductive fields needed at least three years under GLSA to benefit from improved aggregate stability. It is possible that soil quality indicators such as aeration porosity, POXC, DAEP, and soil organic matter require a longer GLSA duration to show changes.

The observed lack of organic matter improvement due to short- and medium-term GLSA was in agreement with the spatiotemporal analysis of SOC dynamics in response to changes in LULC and agricultural management practices in Delta from 1984 to 2018 using remote sensing and digital soil mapping techniques. Despite the widespread adoption of both GLSA and WCC, there was a dramatic decline in SOC across the agricultural landscape of Delta with 93% of the area losing SOC. Even fields with rotations of GLSA and WCC showed reduction in net SOC losses during our study period (i.e., from 1984 to 2018). One of the possible reasons for this could be that the benefits of GLSA, demonstrated in improvements of soil aggregate stability and bulk density, are quickly lost when fields are returned to crop production. Addtional research is need to determine if these practices such as GLSA and WCC can be improved further by combining them with other management (e.g. compost or manure applications) or need to be implemented with longer duration or increased frequency.

5.1.2 Objective 2

Results for this objective showed no definitive evidence that 2- and 3 year GLSAs contribute to increased TN or PAN in the production season following GLSA incorporation. This is likely due to the low proportion of N-fixing species (i.e., red clover) in the GLSA seed mix used. However, they also found no definitive evidence that the incorporation of GLSA biomass reduces the overall amount of PAN supplied in the season following incorporation, which was of concern to many farmers given the high C:N ratio of the biomass and the risk of immobilization. Study 2.1. found that GLSA provided more cumulative PAN that the ACR fields in 2015, but found the opposite (ACR provided more PAN than GLSA) in 2016. In Study 2.2., the amount of PAN supplied by GLSA and ACR fields receiving the same fertilizer rate did not differ, and as a result had lower the risk of post-season N losses through leaching or volatilization. Otherwise, GLSA incorporation did not appear to affect the N availability of synthetic fertilizer applied.

Aside from overall amount of PAN supplied, timing of PAN release from organic residues is an important aspect to consider in crop production. Study 2.1. demonstrated that delaying incorporation of GLSA by two weeks resulted in delayed PAN mineralization, though the same overall amount of PAN was supplied throughout the season. Early season PAN, however, was not affected by fertilizer type or rate in Study 2.1. It was also observed in the on-farm assessment in Study 2.1. that GLSA fields experienced peak NO_3 several weeks after the paired Control fields. Contrarily, Study 2.2. found that GLSA incorporation could have potential to increase N mineralization early in the season compared to continuous cropping in unproductive fields, both fertilized and unfertilized. This effect was not seen in the productive field, perhaps in part because the C:N ratio was much higher in the GLSA biomass grown on the productive field than the unproductive field (41.8 vs 27.6). It is possible that if the GLSA biomass had a lower C:N ratio and was more easily broken down, N mineralization would occur more rapidly and more PAN would be supplied to crops planted post-GLSA incorporation early in the season.

Crop yield was only somewhat affected by GLSA incorporation in Study 2.2., dependant on crop and field type. Potato yield was not affected by 2- or 3-year GLSA, only by fertilization. Bean yield responded positively to two year GLSA in the productive field, but did not exhibit any treatment effects in the unproductive field. Similarly, neither potato nor broccoli yield was affected by three year GLSA in Study 2.1. Although GLSA did not lead to increases in crop yields as other set-aside studies have found, the lack of negative effects on crop yield is worth noting, given the concerns over potentially detrimental impacts of GLSAs on crop production.

Overall, short- to medium-term GLSAs were not shown to affect the amount of TN or PAN in the season after cessation, nor did they definitively affect the timing of PAN release. Crop yields showed the potential to increase following GLSA cessation, but were largely unaffected by GLSA. These effects did not appear to depend on the duration of the GLSA in these studies.

5.1.3 Objective 3

Over the course of the project various stakeholders were engaged throughout the region. Project results were shared through a variety of formats that included field tours, presentations, bulletins, display booths at various events, articles in local media sources, and publications in peer-reviewed scientific journals. Extension briefs and a brochure were completed at the conclusion of the project and will be distributed to members of the Delta Farmers' Institute as well as other interested parties. DF&WT will continue to share project results in its ongoing annual outreach activities.

5.1.4 Overall Implications for Farmers and the DF&WT

Overall, short- to medium-term (i.e., 2-4 year) GLSAs were found to positively affect soil quality, improving indicators of soil structure and compaction in productive fields after two years and in unproductive fields after three years. Given the lack of negative impacts on crop yield, and the lack of clear effect on PAN dynamics, this research supports the ongoing use of GLSA to improve soil functioning in both productive and unproductive fields.

It is recommended that farmers with fields with high levels of exchangeable sodium (i.e., unproductive fields) keep these fields in GLSA for at least three years. Accompanying the use of GLSA with other beneficial management practices (i.e., subsurface drainage, surface laser leveling, subsoiling) may yield further improvements in unproductive fields. A more salt-tolerant GLSA seeding mix could be of use for these fields as well, to establish a healthier stand of vegetative biomass. It is also recommended that the DF&WT consider increasing the proportion of N-fixing legumes in the GLSA seeding mix to increase the N benefits in annual crop rotations.

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7 Appendices

7.1 Appendix A – Study Summaries

Summaries of student studies involved in GLSA project.

Study 1.1 summary

This study was led by master's student Jason Lussier from spring 2015 – spring 2018. The objective of this 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, selected soil properties and aboveground GLSA biomass were assessed throughout the first and second growing seasons of GLSA establishment. The unproductive fields were noted to have poor GLSA vegetative growth during the first two seasons of enrollment and 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. Jason successfully completed his M.Sc. thesis in March 2018 (Lussier 2018).

Study 1.2 summary

This study was led by master's student Teresa Porter from spring 2018 – spring 2019.The objective of this research was to evaluate the effects of GLSA duration on select soil properties during the first 4 years of GLSA establishment. A total of seven fields that entered the GLSA program in 2015 were assessed for the same selected soil properties as used in Study 1. Both productive and unproductive fields were noted to have greater aggregate stability after 3 years of GLSA relative to fields managed for annual crop rotations (ACR). Productive 3 year GLSA fields appeared to have higher aeration porosity and bulk density than paired ACR fields, but unproductive fields did not. Teresa is expected to complete her M.Sc. project in summer of 2020.

Study 2.1 summary

This study was led by master's student Khalil Walji from spring 2015 – spring 2017.The objective of this research was to quantify the nitrogen benefits to crop production after incorporation of 3-year-old GLSA. A regional experiment was conducted over two years, utilizing production fields transitioning from GLSA, paired with continuously cropped fields (Control) with matching management. A controlled field experiment was also conducted on a single 3-year-old GLSA, comparing fertilizer types, rates and timing of incorporation. In each experiment, soils were sampled every 10-14 days for ammonium (NH_4) and nitrate (NO_3), while ion probes, installed near the rooting zone, tracked plant available nitrogen (PAN) throughout the season. The results from the regional experiment were confounding, in 2015 showing GLSA supplied an additional 18 kg PAN ha^{-1} compared to Control, but showing no PAN benefits in 2016. While the PAN supplied by the GSLA remained consistent each year, the amount supplied by Control in 2016 was higher than in 2015. In both years, PAN following GLSA peaked later in the season than the Control, likely due to immobilization of nitrogen due to incorporation of biomass with a high carbon to nitrogen (C:N) ratio. Immobilization also delayed NH_4 release in the controlled experiment for up to 21 days and NO_3 56 days. The controlled experiment also highlighted the importance of fertilizer type to subsequent PAN, showing synthetic treatments consistently supplied more PAN than organic amendment. Results from this study suggest that 3-year-old GLSAs can potentially improve PAN to subsequent crops; however, benefits provided by GLSA in Delta are dependent on a number of factors, which include the C:N ratios of biomass, timing between incorporation and crop planting, precipitation and temperatures, and fertilizer type, all of which impact the timing and quantity of PAN and thus its utility to subsequent crops. Khalil successfully completed his M.Sc. thesis in March 2017 (Walji 2017).

Study 2.2 summary

This study was led by master's student Lewis Fausak from spring 2017 – summer 2019. Study objectives were to quantify the effects of 2- and 3-year GLSAs on plant available nitrogen (N), crop production and soil quality. A field experiment was established in 2017 on one productive and one unproductive field with fertilizer treatments (0 and 80-kg N ha^{-1}) compared across GLSA treatments (i) AC – GLSA biomass removed and (ii) 2G – 2-year-old GLSA biomass was incorporated, and seeded with beans. In 2018, fertilizer treatments (0 and 100-kg N ha^{-1}) were compared across the same GLSA treatments and (iii) 3G – 3-year-old GLSA biomass was incorporated, and seeded with potatoes. Active carbon (POXC) and aggregate stability (MWD) were measured 3 times per growing season and plant available nitrogen (PAN) was sampled every 2 weeks from May-September. MWD increased in 2G and 3G in the year of incorporation relative to AC and POXC increased for 3G relative to AC and 2G. Average seasonal PAN did not differ across treatments but was higher earlier in the season for 2G. Bean yields were greater in 2G compared to AC in the productive field, but otherwise crop yields did not respond to GLSA. Results suggest 2- and 3-year GLSAs do not increase average PAN to subsequent crops, but increase PAN earlier in the season, and increase crop yield depending on subsequent crops. Lewis successfully completed his M.Sc. thesis in August 2019 (Fausak 2019).

Study 2.3 summary

Patricia is expected to complete her M.Sc. project in summer of 2020.

7.2 Appendix B – Laboratory Procedures

Aboveground Vegetative Biomass

Aboveground biomass was cut about 2 cm from the ground and collected in paper bags, oven-dried at 60°C for 1 week, and weighed.

Active and Exchangeable Soil pH

Study 1.1. and 2.2.: Active pH of air-dried soil was measured in water at a 1:2 ratio. Exchangeable pH was determined in a 0.01*M* $CaCl_2$ solution at a 1:2 ratio (Hendershot et al. 1993).

Study 2.1.: 25% of samples were analyzed by water suspension method (McLean 1982). All soils were then analyzed using Fourier-transformed mid-infrared spectroscopy (FT-MIR) with a Tensor 37 HTS-XT spectrometer (Bruker Optics, Billerica, MA, USA). Partial least squares (PLS) regression using Quant package in OPUS 7.2 (Bruker Optik GmbH, 2012) was used to develop predictions of soil properties from the relationship between FT-MIR spectra and laboratory results. These models were then used to predict soil properties for the remaining 75% analyzed only by FT-MIR (Yang and Mouazen 2012).

Aeration Porosity

Soil samples for aeration porosity were collected from the 0 to 7.5 cm depth using a double-cylinder drop-hammer sampler and 7.5 cm diameter by 7.5 cm deep cores. Aeration porosity (i.e., soil pores having diameter >50 µm or macropores) was determined using a water tension table (Danielson and Sutherland 1986).

Aggregate Stability

Aggregate stability samples were collected with a trowel at the 0–7.5 cm depth. Analysis was done using a variation of the wet-sieving method by Nimmo and Perkins (2002; see Wallace et al. 2009 for details). The results for aggregate stability were expressed as the MWD, which is the summation of a series of Di × Wi products where Di is the mean diameter of each size fraction and Wi is the proportion of the sample weight occurring in the corresponding size.

Bulk Density

Soil samples were collected using a double-cylinder drop-hammer sampler and 7.5 cm diameter by 7.5 cm deep cores. The cores were dried for 24 h at 105°C and soil bulk density was determined as mass of dry soil per unit volume of soil at field moisture (Blake and Hartge 1986). Coarse fragments (diameter >2 mm) within the sample were screened out, weighed, and removed from soil mass. Volume of mineral coarse fragments was also removed from soil volume, determined from dry mass, assuming a particle density of 2.65 Mg m^{-3}.

Cation Exchange Capacity (CEC) including cations Al, Ca, Fe, K, and Na and available P.

CEC was determined by inductively coupled plasma optical emission spectrometry (ICP-OES) using 0.2 *M* barium chloride solution extractions (Hendershot and Duquette 1986). Available soil P was determined using the Bray P-1 method (Bray and Kurtz 1945) and was measured on an ultraviolet visible spectrophotometer.

Cumulative Nitrogen Supply

Ion exchange membranes were used to determine in situ cumulative PAN over the growing season. Probes with a surface area of 10 cm^2, made from ion resin membranes which adsorb cations and anions, were installed vertically into the top 15 cm of the soil profile. Probes were installed and retrieved at two to four week intervals and once removed were cleaned using a brush and distilled water. Ion probes were brushed clean of soil and extracted together in 2*M* KCl. Cumulative NH_4^+-N and NO_3^--N supply were determined colorimetrically as described above. Once extracted, probes were prepared for re-use by shaking for an hour in a 0.5*M* hydrochloric acid (HCl) solution and recharged by shaking five times in fresh 0.5*M* sodium bicarbonate ($NaHCO_3$) solution (Qian and Schienau 1996).

Dilute Acid-extractable Polysaccharides (DAEP)

Total extractable polysaccharides were analyzed with a technique outlined by Lowe (1993). In this method, 0.75 g of soil was placed in an individual Erlenmeyer flasks and 100 mL of 0.5 *M* H_2SO_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 µg/mL, 30 µg/mL, 40 µg/mL, 60 µg/mL, 80 µg/mL, 100 µg/mL, and 120 µg/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_2SO_4 was added using a pipette. To ensure proper mixing of the cuvette contents, the H2SO4 was added using a burette. All the cuvettes were then placed in the oven for 25 minutes at 30°C. Three subsamples of 150 µL 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.

Electrical Conductivity

Study 1.1.: Samples were air-dried, sieved to <2 mm, and ground to a fine powder. Electrical conductivity was determined in distilled water at a suspension ratio of 1:2 (McLean 1982).

Study 2.1.: 25% of samples were analyzed by water suspension method (McLean 1982). All soils were then analyzed using Fourier-transformed mid-infrared spectroscopy (FT-MIR) with a Tensor 37 HTS-XT spectrometer (Bruker Optics, Billerica, MA, USA). Partial least squares (PLS) regression using Quant package in OPUS 7.2 (Bruker Optik GmbH, 2012) was used to develop predictions of soil properties from the relationship between FT-MIR spectra and laboratory results. These models were then used to predict soil properties for the remaining 75% analyzed only by FT-MIR (Yang and Mouazen 2012).

Exchangeable Sodium

Soil samples were collected using an Oakfield soil sampling probe to measure exchangeable sodium. Exchangeable sodium was extracted using 1:10 (v/v) soil to 0.1 mol L^{-1} barium chloride (Hendershot et al. 2008) and analyzed with an inductively coupled plasma–optical emission spectrometer (Teledyne Leeman Labs' ProdigyPlus, Hudson, NH, USA).

Permanganate Oxidizable Carbon (POXC)

POXC was determined using the Weil et al. (2003) method and the detailed procedure by Culman et al. (2012) 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 $KMnO_4$ 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 (mg Kg-1 soil) = [0.02 mol/L – (B0 + B1 x Abs)] x (9000 mg C/mol) x (0.02L solution/Wt)

Where:

0.02 mol/L = initial solution concentration B0 = intercept of the standard curve
B1 = 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+} -> Mn^{4+} 0.02 L = volume of stock solution reacted
Wt = weight of air-dried soil sample in kg

Plant Available Nitrogen (and Residual Soil Nitrogen)

Soil samples were transported in coolers to the University of British Columbia (UBC) and extracted using 2*M* potassium chloride (KCl) and then frozen until analysis. Plant available nitrogen (PAN) in terms of nitrate N (NO_3^--N) and ammonia N (NH_4^+-N) were analyzed colorimetrically using a 99 well microplate absorbance reader (Biorad iMark,Hercules, CA,USA) following the methods of Doane and Horwath (2003). A fresh 20 g subsample of soil was oven dried at 105ºC (221ºF) until reaching a stable weight to determine soil gravimetric water content (Blake and Hartge 1986). Residual soil nitrogen is the PAN contained in the final soil sample, taken at harvest or immediately following harvest, and analyzed as the soil nitrogen that would be susceptible to leaching during heavy winter rains. Concentrations were converted to content (kg ha^{-1}) using bulk density values.

Texture

Study 1.1.: Soil texture was determined on samples collected from the 0 to 15 cm depth (using Oakfield probe). Samples were air-dried, sieved to <2 mm, and ground to a fine powder. Soil texture was analyzed by hydrometer method (McKeague 1978).

Study 2.1.: 25% of samples were analyzed by hydrometer method (McKeague 1978). All soils were then analyzed using Fourier-transformed mid-infrared spectroscopy (FT-MIR) with a Tensor 37 HTS-XT spectrometer (Bruker Optics, Billerica, MA, USA). Partial least squares (PLS) regression using Quant package in OPUS 7.2 (Bruker Optik GmbH, 2012) was used to develop predictions of soil properties from the relationship between FT-MIR spectra and laboratory results. These models were then used to predict soil properties for the remaining 75% analyzed only by FT-MIR (Yang and Mouazen 2012).

Total Soil Carbon and Total Nitrogen

Study 1.1.: Samples were analyzed by the diffuse Fourier transform mid-infrared spectroscopy method (Reeves et al. 2001; see Thiel et al. 2015 for details) run on a Tensor 37 HTS-XT spectrometer (Bruker Optics, Ettlingen, Germany). Prediction for total soil organic carbon values were done using on a pre-existing regional database (n= 1,038) provided by Study 2.1.

Study 2.1.: 25% of samples were analyzed by dry combustion method (Nelson and Sommers, 1982). All soils were then analyzed using Fourier-transformed mid-infrared spectroscopy (FT-MIR) with a Tensor 37 HTS-XT spectrometer (Bruker Optics, Billerica, MA, USA). Partial least squares (PLS) regression using Quant package in OPUS 7.2 (Bruker Optik GmbH, 2012) was used to develop predictions of soil properties from the relationship between FT-MIR spectra and laboratory results. These models were then used to predict soil properties for the remaining 75% analyzed only by FT-MIR (Yang and Mouazen 2012).

Study 2.2.: Soil samples were analyzed for total soil C and N concentration using the diffuse Fourier transform mid-infrared spectroscopy (FT-MIR) method (Reeves et al. 2001) on a Tensor 38 HTS-XT spectrometer (Bruker Optics, Ettlingen, Germany). This data was parameterized and validated using an Elemental Vario El Cube elemental analyzer (EA) (Elementar Analysenysteme GmbH, Hanau, Germany) (Kirsten and Hesselius, 1983) on 25% of the samples (Thiel et al. 2017).

7.3 Appendix C – Figures and Tables

Appendix Table 1. Soil baseline properties of fields that entered the grassland set-aside (GLSA) program in April 2015 (n=4) in Study A. Soil properties include exchangeable sodium (Na), total carbon (TC), the mean weight diameter (MWD) of water stable aggregates and bulk density. Standard Error of the mean shown in brackets.

Field type	Site number	Na ($cmol_c kg^{-1}$)	TC (%)	MWD (mm)	Bulk density ($Mg\ m^{-3}$)
Unproductive					
	3	1.78 (0.52) [a]	1.92 (0.08)	0.45 (0.03)	1.32 (0.03)
	4	2.59 (1.06)	2.02 (0.15)	0.55 (0.08)	1.21 (0.06)
Productive					
	1	0.07 (0.004)	1.96 (0.10)	1.18 (0.23)	1.23 (0.04)
	2	0.33 (0.14)	2.08 (0.4)	1.00 (0.20)	1.21 (0.04)
	5	0.85 (0.09)	2.73 (0.14)	1.71 (0.20)	1.12 (0.04)
	7	0.16 (0.03)	1.63 (0.07)	1.06 (0.10)	1.25 (0.03)
	8	0.20 (0.02)	2.67 (0.27)	0.78 (0.10)	1.14 (0.05)
	9	0.13 (0.01)	3.07 (0.35)	0.81 (0.09)	1.20 (0.05)

Appendix Table 2. Average mean weight diameter (MWD) of water stable aggregates of productive and unproductive grassland set-asides (GLSA) and paired fields under annual crop rotation (ACR).

Year	Season	Depth (cm)	Productive Fields: Grassland Set-Aside (GLSA)	Productive Fields: Annually Cropped Field (ACR)	Unproductive Fields: Grassland Set-Aside (GLSA)	Unproductive Fields: Annually Cropped Field (ACR)
			MWD (mm)			
2015	Spring	0–7.5	0.87	0.91	0.45	0.69
	Summer	0–7.5	2.52	2.40	1.76	1.78
	Fall	0–7.5	2.57	2.49	1.81	1.23
2016	Spring	0–7.5	1.92	1.51	1.13	1.08
	Summer	0–7.5	2.84	2.45	1.66	2.00
	Fall	0–7.5	2.19	1.78	1.67	1.83
2018	Spring	0–7.5	2.07	1.42	1.20	0.74
	Summer	0–7.5	3.02	2.91	1.62	1.87
	Fall	0–7.5	2.89	2.17	1.60	1.09
2019	Spring	0–7.5	1.89	1.35	0.99	0.46

Appendix Table 3. Mean bulk density at productive and unproductive grassland set-asides (GLSA) and paired fields under annual crop rotation (ACR).

Year	Season	Depth (cm)	Productive Fields		Unproductive Fields	
			Grassland Set-Aside (GLSA)	Annually Cropped Field (ACR)	Grassland Set-Aside (GLSA)	Annually Cropped Field (ACR)
			Bulk Density (mg m^{-3})			
2015	Spring	0–7.5	1.19	1.18	1.24	1.28
		7.5–15	1.20	1.21	1.35	1.24
		15–30	1.23	1.25	1.30	1.29
	Fall	0–7.5	1.08	1.10	1.10	1.18
		7.5–15	1.14	1.17	1.22	1.22
		15–30	1.17	1.18	1.17	1.28
2016	Spring	0–7.5	1.15	1.16	1.28	1.31
		7.5–15	1.19	1.20	1.29	1.31
		15–30	1.18	1.19	1.24	1.28
	Fall	0–7.5	1.08	1.17	1.27	1.16
		7.5–15	1.16	1.20	1.22	1.20
		15–30	1.17	1.18	1.20	1.19
2018	Spring	0–7.5	1.06	1.18	1.20	1.33
		7.5–15	1.21	1.18	1.35	1.35
		15–30	1.25	1.23	1.36	1.38
	Fall	0–7.5	1.00	1.08	1.22	1.13
		7.5–15	1.20	1.11	1.32	1.26
		15–30	1.21	1.18	1.33	1.35
2019	Spring	0–7.5	1.07	1.12	1.28	1.34
		7.5–15	1.22	1.13	1.31	1.36
		15–30	1.31	1.20	1.38	1.34

Appendix Table 4. Mean aeration porosity at productive and unproductive grassland set-asides (GLSA) and paired fields under annual crop rotation (ACR).

Year	Season	Depth (cm)	Productive Fields: Grassland Set-Aside (GLSA)	Productive Fields: Annually Cropped Field (ACR)	Unproductive Fields: Grassland Set-Aside (GLSA)	Unproductive Fields: Annually Cropped Field (ACR)
			Aeration Porosity (m^3 m^{-3})			
2015	Fall	0–7.5	0.21	0.19	0.19	0.18
		7.5–15	0.19	0.17	0.19	0.15
		15–30	0.17	0.17	0.18	0.15
2016	Spring	0–7.5	0.16	0.15	0.13	0.13
		7.5–15	0.15	0.15	0.12	0.13
		15–30	0.16	0.14	0.16	0.15
	Fall	0–7.5	0.21	0.16	0.14	0.16
		7.5–15	0.18	0.16	0.18	0.16
		15–30	0.18	0.16	0.19	0.19
2018	Spring	0–7.5	0.15	0.11*	0.11	0.11
		7.5–15	0.10	0.13*	0.07	0.09
		15–30	0.09	0.11	0.09	0.09
	Fall	0–7.5	0.20	0.16	0.14	0.25
		7.5–15	0.14	0.17	0.13	0.22
		15–30	0.13	0.15	0.13	0.11
2019	Spring	0–7.5	0.14	0.12	0.09	0.09
		7.5–15	0.10	0.14	0.09	0.09
		15–30	0.08	0.14	0.09	0.10