ASSESSING THE IMPACTS OF AGRICULTURE ON SOIL QUALITY IN A FIVE-YEAR CROP-LIVESTOCK ROTATION IN THE FRASER RIVER DELTA, BRITISH COLUMBIA

by

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Abstract

The Fraser River delta is one of the most intensively farmed agricultural regions of Canada. It is also an area of high ecological significance, providing habitat for migrating bird populations and aquatic species. To help provide habitat for bird populations, a five-year crop rotation has been developed for the Alaksen Wildlife Area. This rotation integrates perennial and annual crops and livestock production and could provide a promising alternative to intensive production in the region. A study of key soil quality indicators was conducted within the Alaksen to: i) compare key soil quality indicators to assess the impacts of land use type on soil quality, and ii) evaluate the effects of specific rotation practices (crop type, livestock) on key indicators to better understand the potential impacts of the five-year rotation on soil quality. In the fall of 2018, soil samples were taken from sixteen agricultural fields, three abandoned agricultural fields (old fields), and three relatively undisturbed forest patches and analyzed for soil organic carbon (SOC), bulk density (BD), pH and electrical conductivity (EC). Results showed that in the upper 15 cm depth agricultural and old fields, respectively, had 44% and 60% of the SOC as forest patches. Bulk density was 53% greater in agricultural fields than in old fields and 66% greater than forest in the upper 15 cm depth. There were no significant differences in soil indicators between annual and perennial crops fields, except for EC in annual crop fields, which was 52, 40 and 164% greater in the 0-15, 15-30, and 30-60 cm depth, respectively. Fields with livestock showed greater SOC and EC, and lower pH levels at some soil depths. Results of this study suggest that agriculture has negatively affected soil quality within Alaksen but these impacts varied with management. While including perennial crops in the rotation did not improve soil quality, including livestock offered some soil quality benefits, and merits further study based on its potential to improve soil quality in the region.

Lay Summary

For more than 150 years, farming in the Lower Fraser River delta, British Columbia has played a major role in the community and local economy. To date, our understanding of the extent to which agriculture has impacted the natural landscape is limited. In the fall of 2018, an observational study was conducted within the Alaksen National Wildlife Area to assess the potential impacts of agriculture on soil quality. Soil samples were taken from 16 agricultural fields, three abandoned agricultural fields, and three adjacent forest patches and analyzed for soil organic carbon (SOC), bulk density (BD), pH and electrical conductivity (EC). Results of this study suggest that agriculture has negatively affected the quality of the soil in Alaksen. The inclusion of perennial crops in the rotation did not have any effect on soil quality yet the inclusion of livestock appeared to have improved soil quality by increasing SOC. Increased EC, however suggest that grazing practices need to be examined in more detail to gain a better understanding of the extent of this practice on soil quality.

Preface

This thesis represents original, unpublished work by the author, Grace Augustinowicz. I was the lead investigator for the project and was responsible for all major areas of research question formation, data collection, data analysis, and thesis composition. Early sample collection was led by Siddhartho Paul and Lyndsey Dowell. Laboratory and field assistance for analyzing samples was provided by Siddhartho Paul and Lyndsey Dowell. Data analysis assistance was provided by Dr. Michael Bomford, from Sustainable Agriculture and Food Systems at Kwantlen Polytechnic University.

Dr. Sean Smukler and Dr. Kent Mullinix were the co-supervisors for this project and were involved in the design of the project, analysis of the data, and editing of this thesis. The project was completed in collaboration with Dr. Maja Krzic, Dr. Michael Bomford, and Courtney Albert, Canada Wildlife Service who helped with garnering background information about the Alaksen National Wildlife Area.

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List of Abbreviations

Alaksen	Alaksen National Wildlife Area
ALR	Agricultural Land Reserve
BD	Bulk density
CWS	Canadian Wildlife Services
DF&WT	Delta Farmland and Wildlife Trust
DGPS	Differential Global Positioning System
DOC	Dissolved organic carbon
EC	Electrical conductivity
GLSA	Grassland set-asides
KPU	Kwantlen Polytechnic University
LME	Linear mixed effect model
NSERC	Natural Science and Engineering Research Council of Canada
PLSR	Partial least square regression
SOC	Soil organic carbon
SOM	Soil organic matter
UBC	University of British Columbia

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I would like to respectfully thank the Coast Salish People, and unknowledge that I conducted this study in their unceded and ancestral territories.

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Chapter 1: Introduction

Soils play a critical role in maintaining healthy ecosystems and human well-being. They provide habitat for organisms, regulate climate, water and nutrient cycles and support agriculture worldwide. Despite their importance, soils are being degraded and lost at the global scale, mainly due to long-term and persistent human disturbance. Of all anthropogenic disturbances of natural soils, agriculture is by far the greatest (Oldeman, 1992). Agricultural expansion has increased at the expense of our natural environment, and the intensification of agricultural production practices geared to meet the demands of a growing population and various economic objectives has led to the degradation of arable soils worldwide (Borrelli et al., 2017; Keenan et al., 2015; United Nations Convention to Combat Desertification, 2017). As soils degrade, their capability to perform essential processes diminishes and increases the potential to contribute to a number of damaging off-site effects, such as eutrophication of water sources, sediment and nutrient runoff, air pollution, and the degradation of wildlife habitat (Steinfield et al., 2006; Withers et al., 2014).

Over the last few decades soils have become the focus of numerous initiatives that aim to ensure they are managed sustainably and degraded soils are restored. Today, sustainable soil management approaches are increasingly proposed as a key strategy for climate change mitigation via soil carbon sequestration. Despite the large number of studies being conducted in this area, our current understanding of the impacts of land use change and agricultural management practices on soil quality is limited, including in the Fraser River valley, one of the most intensively farmed regions of Canada.

For thousands of years before their first encounter with Europeans, the Tsawwassen, and Musqueam Nations inhabited the area of the Fraser River delta (Brown, 2014). These first communities tended their natural environment through selective harvesting and cultivation of culturally important plants and animals in ways that led to the enhancement and modification of their landscape (Turner and Deur, 2005). Upon their arrival, European settlers radically transformed this land through intensive logging, agriculture and urban development (Atkins et al., 2016; Balke, 2017; Boyle et al., 1997; Goldin and Lavkulich, 1990; North et al., 1979). Today, the Fraser River delta is one of the most intensively farmed agricultural regions of Canada (Crawford and MacNair, 2012). Agricultural intensification, however, has resulted in the loss of habitat and biodiversity (Goldin and Lavkulich, 1990), and has contributed to the degradation of soils and the ecological services they provide (Odhiambo et al., 2012; Principe, 2002).

Studies documenting the impacts of agriculture on the natural environment showed a relation between intensification and soil degradation at both the field scale and at larger spatial and temporal scales (Culman et al., 2010; Young-Mathews et al., 2010). Looking at a landscape gradient of increasing agricultural intensification in the Sacramento Valley of California, Culman et al. (2010) found that the effect was negatively correlated with plant and soil biota richness and diversity. The study also showed that as intensification increased, soil carbon and microbial biomass decreased. In a similar study, Young-Mathews et al. (2010) examined the effects of agricultural intensification on soil physical and chemical properties in an area of the Sacramento Valley with diverse land, soil, and vegetation types. Results indicated that areas with less intensification, such as riparian zones, supported greater plant diversity and nearly twice as much total carbon per hectare compared to adjacent lands managed for agricultural uses. Thus far, a number of studies have been conducted to investigate the effects of specific agriculture practices in the Fraser River delta (Hermawan, 1995; Liu and Bomke, 2005; Lussier, 2018; Nafuma, 1998; Odhiambo, 1998; Odhiambo et al., 2012; Principe, 2002; Yates, 2014), but much more needs to be understood if we are to address the issues of intensification, and to sustainably manage this important ecological and economic area.

1.1 Impacts of land use changes and agricultural practices on soil quality

Soil quality refers to the capability of soils to perform a number of essential processes, providing important goods and services that support the production of food and fiber, regulate air and water quality, moderate nutrient cycles (Doran and Parkin, 1994). A number of soil quality indicators have been identified, and are commonly used to assess soil quality and to monitor soil properties that are responsive to management and environmental factors. While there are no universal indicators, a good soil quality indicator will effectively reveal changes in ecosystem processes and functions, be sensitive to variations in management and environmental conditions, and be applicable to field conditions (Bünemann et al., 2018; Doran and Parkin, 1994). Soil quality indicators may be physical (e.g. penetration resistance, bulk density), chemical [e.g. soil organic carbon (SOC), pH, electrical conductivity (EC)] or biological (e.g. microbial biomass).

One of the most important soil indicators affected by land use changes and agricultural practices is soil organic matter (SOM). Soil organic matter plays an important role in the regulations of soil chemical, physical, and biological processes, and it is an important element of soil quality and fertility. Soil organic carbon is often used as an indicator of SOM and thus soil quality, as 50% of SOM consists of SOC (Brady et al., 2010). Pools of SOC, such as labile or active carbon, are also commonly used as indicators because they are more sensitive to disturbance than total soil organic matter and provide a better indication of the changes in soil quality (Bünemann et al., 2018). It has been estimated that active carbon represents 3-4% of total organic carbon (Cambardella and Elliott, 1996) and this portion has been correlated with aggregate stability and used as an important indicator of overall soil quality (Weil et al., 2003). Land use changes and agricultural practices have been found to be among some of the main drivers of changes in SOC. The conversion of forest or pasture to cropland, for instance, has been shown to decrease SOC, principally due to the loss of biomass and mineralization of carbon (Deng et al., 2016; Goldin and Lavkulich, 1990; Guo and Gifford, 2002). A reduction in SOC concentration commonly has a negative impact on important soil processes and components such as soil biodiversity, soil structure, decomposition rates, water retention and infiltration, and nutrient availability (Carter et al., 1998; Chatterjee and Lal, 2009; Steinfeld et al., 2006). Agricultural practices that reduce carbon inputs and SOC concentration can also lead to soil compaction. Intense tillage, for example, accelerates mineralization and oxidation of SOC, exacerbating soil compaction from farm machinery and thus reducing soil porosity, water infiltration, and root penetration (Chatterjee and Lal, 2009). Livestock production can also be detrimental to soil quality. Overgrazing reduces aboveground biomass, leading to soil erosion and subsequent changes in carbon and nutrient stocks and cycles (Bell et al., 2011; Steinfeld et al., 2006). In colder climates with high precipitation rates, liming to increase soil pH can enhance short-term soil biological activity, increasing SOC loss through mineralization (Leifeld et al., 2013; Paradelo et al., 2015).

Not all land use changes are detrimental to soil quality. Carter et al. (1998) found that converting forest to cropland reduced SOC in Podzolic soils, but increased SOC in Brunisolic and Gleysolic soils in the same study area. Carter’s study demonstrated an interaction between soil type and management practice. In addition, SOC stocks can experience substantial fluctuations after land conversion. Deng et al. (2016) observed a natural grassland converted to farmland and found that carbon stocks initially decreased, then progressively increased, ultimately stabilizing after 30 years.

A number of management practices have been shown to improve soil quality in agricultural systems. Highly diverse crop rotations have improved soil structure, stabilized soil macroaggregates, increased porosity, and decreased bulk density (Balota et al., 2004; Li et al., 2018; Lin, 2011). Annual crop rotations that include short-term grass leys are sometimes used to improve soil quality (Loaiza Puerta et al., 2018; Prade et al., 2017; Zhang et al., 2011). Perennial grasses have extensive root systems that increase SOM concentration, provide habitat for soil microorganisms, act as binding agents to keep soil in place, and help maintain a stable soil structure that enhances porosity and water infiltration. Livestock integration can also improve soil quality (Bird et al., 2004; Liebig et al., 2012; Franzluebbers, 2017). Grazing ruminants included in a well-planned rotation at appropriate stocking rates with resting periods can enhance soil fertility by transforming plant-bound nutrients into readily mineralizable substrates (Alves et al., 2020; Polat, 2018; Franzluebbers, 2017).

Management practices intended to improve soil quality should be selected with consideration of local biophysical conditions (i.e. climate, topography, parent material, biota, time, management) as well as economic and sociocultural factors. No-till practices, for example, can reduce soil erosion and run-off in tropical and subtropical climates. This practice however may increase erosion in northern regions by delaying growth of spring-sown crops through reduced soil temperature and increased soil water content (Soane et al., 2012). Better understanding such interactions between factors and components can help farmers maintain, or enhance, soil quality.

1.2 Land use changes and agricultural practices in the Fraser River delta

The Fraser River delta is located in the southwest portion of British Columbia, Canada. Since its formation during the retrieval of the late Pleistocene Cordilleran Ice Sheet about 10,000 years ago, the delta has been shaped by alluvial deposits from the Fraser River as it flows into the Pacific Ocean (Clague et al., 1983). Most of the area is less than 1.5 metres above mean sea level and is protected from high tides and storms by a system of dikes (Corporation of Delta, 2011). The delta is an area of high ecological significance. As part of the network of Pacific coast habitats that stretch from Siberia to South America, the delta encompasses a myriad of tidal environments and riparian buffers that provides important habitat for millions of overwintering and migrating bird populations and it is home to 80 species of fish and shellfish, 300 species of invertebrate animals and a number of endangered or at-risk species, including the western painted turtle (*Chrysemys picta*), the sandhill crane (*Antigone canadensis*), the barn owl (*Tyto alba*), and the great blue heron (*Ardea herodias*) (Flynn et al., 2006; Pacific Flyway Council, 2006). Every year, roughly two billion juvenile anadromous Pacific salmon (*Oncorhynchus* spp.) spend a month in the delta estuary in preparation for their migration to the ocean (Flynn et al., 2006; Helfield and Naiman, 2001). Upon their return, adult salmon migrate upstream to spawn, supporting numerous plant and animal populations. Salmon populations also support a multimillion dollar regional fishing and tourism industry (James, 2019). Over the last ten years, however, Pacific salmon populations have declined due to habitat degradation and loss, harvest, and climate change (Fisheries and Oceans Canada, 2020; James, 2019).

Before the arrival of colonizing Europeans, the lower Fraser River delta area was dominated by coastal vegetation that included grassland, shrub and marsh plant species (North et al., 1979). Over the years and due to agricultural and urban intensification, these natural ecosystems have been largely fragmented and converted into farmland, hedgerows, and patchy forests. Between 1897 and 1990, the Lower Fraser Basin experienced a 25% loss of forested area and a 90% loss of wetlands as urban and agricultural areas grew to encompass 26% of the region (Boyle et al., 1997). Between 1984 and 2018, the forest and wetland areas of the Lower Fraser Valley decreased by 14% and 25%, respectively, mostly due to conversion to “built up/bare land” (i.e. urban settlement, roads, farmhouses, barns, fallow farmland and forest clear-cut) (Paul et al., 2020). In 1968, private property rights became an issue to farmers in the delta when some sections were included in a new provincial Agricultural Land Reserve (ALR) that spurred land speculation outside the ALR (Principe, 2002). As a result, most farmers in the region became tenants holding short-leases, which tend to limit investment in maintaining or improving land and soil quality (Principe, 2002). Facing increasing land values, some regional producers may have prioritized cash crop production over land care.

Research in the region has shown that land use change has lead to the gradual deterioration of soil quality. Between 1943 and 1983, land use changes in the Lower Fraser Valley and adjacent Washington State were responsible for a 20% loss of SOM (Golding and Lavkulich, 1990). At the same time, increases of soil bulk density ranged from 26% and 58%. Between 1984 and 2018, 61% of the Fraser delta area studied by Paul et al. (2020) experienced SOC loss, 12% experienced SOC gain, and 27% did not change. Use of detrimental soil management practices, such as intensive tillage, working the soil under very wet or dry conditions, or shifting from integrated livestock/crop farming (mainly forage and dairy cattle) to vegetable crop production may have also contributed to the observed soil degradation (Neufeld et al., 2017; Odhiambo et al., 2012; Principe, 2002).

Adoption of regenerative agricultural practices, such as incorporation of cover crops (Hermawan, 1995; Liu and Bomke, 2005; Odhiambo, 1998; Odhiambo et al., 2012) and grassland set-asides (GLSA) can restore soil quality (Lussier, 2018; Yates, 2014). For more than 20 years, delta farmers have planted cover crops to protect the soil from erosion, improve quality and to provide food and habitat for wildlife populations. Many farmers are also active participants of the Delta Farmland &Wildlife Trust (DFWT) Grassland Set-aside Stewardship Program, a program which supports farmers maintaining a grass-legume cover for a one to four-year duration to improve soil quality and promote environmental stewardship (Lussier, 2018; Yates, 2014).

Studies conducted over the last three decades to assess impacts of cover crops and GLSA on soil quality have shown positive outcomes. Liu and Bomke (2005) found that the incorporation of certain cover crops (i.e. annual ryegrass and fall rye) improved soil quality by increasing soil aggregate stability. In a similar study, Hermawan (1995) found that the incorporation of a number of winter cover crops increased soil aeration, porosity and water infiltration, and lowered bulk density and penetration resistance when compared to bare soil. Two to six years of GLSA improved aeration porosity, aggregate stability, and mechanical resistance compared to continuously cropped land (Yates, 2014). Even a single season of GLSA improved aggregate stability, and two seasons improved mechanical resistance and aeration porosity relative to paired cropland (Lussier et al., 2019). Despite the emerging awareness of regenerative agricultural practice benefits, soil quality continues to decline across the region.

Adoption of alternative management practices commonly used in many parts of the world to maintain and enhance the quality of soils and the ecological services they provide, such as increasing crop diversity, and integrations of livestock, could be implemented to reverse this trend.

1.3 Land use changes and agricultural practices in the Alaksen Wildlife Area

This study was conducted on farmlands situated within the boundaries of the Alaksen National Wildlife Area (Alaksen) in the Fraser River delta. Since 1970, Alaksen has been managed by the Canadian Wildlife Service (CWS) with a mandate to protect the large number of deltaic habitat types and the diversity of species they support. The site encompasses a diversity of land uses, including pastures, meadows, hedgerows, wetlands, riparian areas, forest patches, and grass margins, with natural corridors between wildlife areas.

Three families have farmed at Alaksen since the 1970s. Unlike typical delta farms, Alaksen farms utilize a five-year crop rotation that includes purposeful provision of important food sources and habitat for wildlife to accomplish the ecological objectives of the site. Livestock production is an integral component of Alaksen farming and both forage production and grazing have been integrated into the crop rotation of a number of fields within the reserve. Field edge areas are a relatively ecologically complex mix of woody vegetation and grasses that serve as important habitat for small mammals, birds and arthropods (Rallings, 2016; Thiel et al., 2015). The reserve also includes a number of agricultural fields that have been abandoned since the 1980s, purportedly due to poor drainage and salinity (K. Husband, Emma Lea Farm, personal communication, September, 26, 2019). With time, these fields have been colonized by marsh plants (e.g. cattail, bulrush and sedge).

One of the primary challenges at Alaksen is timely establishment of winter cover crops. Farmers in Alaksen report that harvest has often been delayed to early or mid-October, due to increasingly wet conditions during spring planting (Augustinowicz et al., 2019). Consequently, winter cover crops are now seeded at the end of October, instead of the first week of September, when conditions for establishment are more favorable. Winter cover crops sown passed late September have underdeveloped root systems and poor biomass production (Nafuma, 1998;

Odhiambo, 1998). Field observations by Augustinowicz et al. (2019) indicated that fields that were planted with fall cover crops in late October ended up bare by the beginning of winter due to crop establishment failure. In addition, migratory and overwintering populations of waterfowl often curtail cover crop establishment and reduce forage production by severe feeding on foliage, stolons, roots and other plant parts (Zbeetnoff and McConnell, 2007). Bradbeer et al. (2012) found that waterfowl feed on winter wheat (*Triticum aestivum* L.) and fall rye (*Secale cereal* L.) early in the fall, with grazing decreasing by January and March. In a similar study conducted in the area, Odhiambo et al. (2012) revealed that fields that remained exposed during the winter as a result of poor winter cover crop establishment experienced uneven seed germination, poor crop establishment, and crop failures.

Even though farms have been operating at Alaksen over the last 35 years, there has been little study of the extent to which land use changes and agricultural practices have impacted soil quality and the natural landscape. Relatively undisturbed forest patches and old, abandoned farm fields provide an opportunity to assess how land use changes have affected soil quality at Alaksen over time. Furthermore, its distinctive five-year rotation offers a unique opportunity to examine the effects of specific management practices on selected soil properties. In addition, the proximity of these fields to the coastline and the history of using estuarine water for irrigation provide an important opportunity to observe the extent of soil salinization from surface and subsurface irrigation in the area. A baseline assessment of soil quality can help farmers and wildlife conservation managers at Alaksen and the delta area to enhance the economic performance and the ecological functions of farm operations. It could also be used as reference for the creation and development of long-term climate change mitigations and adaptation strategies for the Fraser River delta area.

1.4 Research Objectives and Hypotheses

I conducted this study to assess the effects on soil quality of the land use changes that have taken place at Alaksen as the result of the establishment of farming operations. I also aimed to explore the impacts of specific rotation practices (crop type, livestock) linked to the farms' five-year crop rotation on the soil quality in the wildlife area. While most of the discrete agricultural practices of the farming operations in this study were typical of delta region, the farms in Alaksen employ a distinctive five-year crop rotation including annual and perennial crops and livestock. In this study, I identified and evaluated the following three land use types that represent a gradient of utilization and recovery: (1) farmland in the five-year rotation (agricultural fields); (2) abandoned farm fields, unmanaged for decades (old fields); and (3) land restored to a semi-natural state (forest patches). By comparing soil quality indicators collected from land use types that shared similar attributes I aimed to assess the potential long-term impact of land use on soil quality.

The specific objectives of this research were to:

- Compare key soil quality indicators from adjacent agricultural fields, old fields and forest patches to assess the impacts of land use types on soil quality
- Evaluate the effects of specific rotation practices (perennial crops, livestock) on key soil quality indicators

Thus, in this study I attempted to answer the following questions and test their associated hypotheses:

Q1. Do soil quality indicators (SOC, BD, pH, and EC) differ among agricultural fields, old fields and forest patches?
H1. Regular disturbance of agricultural fields will result in lower SOC, and greater BD, pH, and EC compared to old fields and forested patches. Old fields no longer being disturbed will exhibit soil quality indicators somewhat improved over cultivated fields with indicator values between those of agricultural fields and forest patches.

Q2. Do soil quality indicators (SOC, BD, pH, and EC) differ between fields under annual and perennial crop production?
H2. Fields under annual production (< 1 year) will exhibit reduced soil quality than less disturbed fields growing perennial crops.

Q3. Is soil quality (i.e. SOC, BD, pH, and EC) improved by livestock integration?

H3. Fields with livestock will have higher soil quality than those without.

Results of this study will contribute to the body of knowledge that aims to provide a better understanding of how land use changes and agricultural practices might impact soil quality in the lower Fraser River area and the potential for Alaksen’s five-year rotation to maintain soil quality. Further, knowledge derived from this research can be used to help develop a long-term agricultural management plan that meets the multiple objectives of the wildlife area and the producers that farm on the reserve.

Chapter 2: Methods

2.1 Study Site

This study was conducted on farmlands in the Alaksen National Wildlife Area, located at the Westham Island, in the western Fraser River delta, British Columbia, Canada (49°06' N, 123°10' W). The region is characterized by a maritime climate with mild winters, 1869 mm average annual precipitation, and average annual temperature of 9.6°C (Metro Vancouver, 2016). Soils in this area belong to the Crescent soil management group, mostly of the Westham soil series. These soils have silt loam texture, are moderately to poorly drained, moderately acidic (pH between 5.0 and 6.0), and are prone to remain saturated within the plow layer until the late spring (Bertrand et al., 1991). Alaksen is recognized as an important ecological area under the jurisdiction of the Canadian Federal Government, and managed by the CWS. The area encompasses diverse habitats including brackish and freshwater marshes, grasslands, floodplains, riparian areas, and natural and constructed sloughs (Hatfield, 1991; Holms, 2017).

Farming has long been central to the management of Alaksen. Three separate family operations have been farming there since the 1970s. They collectively manage approximately 355 acres (143.7 ha) divided into 16 fields (of varying size, shape and characteristic) that are cultivated under a five-year crop rotation (Figure 2.1, Table 2.1). Farming in the lower Fraser area began in 1860, mainly within the most fertile, accessible, and easily cleared land (Goldin, 1996). Early operations consisted of family farms raising dairy cattle, forage, vegetables and fruit. In the 1940s, advances in the field of fruit preserve lead to a substantial increase in land area under raspberry and strawberry production. The booming in fruit production however was hampered by the devastating freezes of 1950, 1955, and 1964. In the 1950s, dairy became the dominant industry in the area as a result of a shift to silage by livestock producers, improvements in transportation and increased population. Between the 1960s and the 1980s, the introduction of improved crop varieties, greater use of synthetic chemicals, improved farming techniques and an increase in the value and demand of produce lead to a shift from integrated crop and livestock farming to intensive specialized vegetable farming.

Over the past decade, the crop rotation at Alaksen has followed a general sequence of two consecutive years of summer vegetable production, usually cultivars of potato (*Solanum* *tuberosum* L.), cabbage (*Brassica oleracea* L.) or beet (*Beta vulgaris* L.), followed by three-years of mixed grass forage, mostly orchard grass (*Dactylis glomerata* L.), tall fescue *(Festuca arundinacea* (Schreb.)), and, timothy *(Phleum pratense* L.) (Appendix A). Once forage fields are established they remain mostly undisturbed for three years, except for hay cutting (2-3 cuts per season) and/or in some fields, grazing by dairy cattle in summer. After vegetables harvest, farmers sow a winter cover crop of fall rye (*Secale cereal* L.), winter wheat (*Triticum aestivum* L.), or barley, (*Hordeum vulgare* L.), to protect the soil from erosion. Every spring, winter cover crops and fields with three-year old forage are disked and residue is plowed and incorporated into the soil at a depth of 20-30 cm, together with fertilizers and lime. Livestock is an important component of the Alaksen rotation. Every summer, a 60 to 80 head dairy herd is rotated between agricultural fields that are under forage production and those include fields 3 to 19E (Figure 2.1, Table 2.1, Appendix B). According to the rotation schedule, two fields, field 16 and 19E, have been under forage and pasture for the last ten years. After grazing freely throughout the summer in fields under forage, herds are moved indoors for the winter. Manure collected from the stables during the winter months is not used as a soil amendment on any the Alaksen fields (Kevin Husband, personal communication September 2020).

Irrigation of summer crops at Alaksen uses water drawn from a system of sloughs and ditches filled from the Fraser River (Augustinowicz et al., 2019). Irrigation usually occurs in June and July. Because salinity of the water is tidally influenced, farmers must monitor salt levels of water going into the sloughs in the growing season. By the end of July, salinity concentration in the incoming water increases to levels toxic to crops, and slough gates are closed for the remainder of the season, precluding further irrigation.

Farmers use a combination of synthetic fertilizers in the spring to replenish nutrients lost from crop removal, leaching and soil surface runoff (Augustinowicz et al., 2019). They also apply lime once to forage fields at the beginning of the three year period, and every spring to fields with annual crops in preparation for summer vegetable production.

Three agricultural fields in Alaksen were abandoned in the 1980s. These old fields are located at the coastal edge of the reserve. According to farmers, they can no longer be cultivated due to poor drainage and excessive salinity (Augustinowicz et al., 2019). These abandoned fields have been recolonized by marsh plant species, such as cattail and sedge, and serve as important habitat to wildlife.

An extensive network of grass margins and forest patches surround most fields, they are 10-30 m wide, many running along sloughs and irrigation canals, and form a continuous belt around fields. While CWS has managed these margins since the creation of Alaksen with the mandate to enhance wildlife habitat, it is very likely that these areas were established during settlement in 1900s, and managed differently by farmers. After the creation of the wildlife area, many margins were left unmanaged and are now dominated by red alder (*Alnus rubra* Bong), Himalayan Blackberry (*Rubus armeniacus* Focke) and Black Hawthorn (*Craetageus douglasii* Lindl.) (Clausen and Smukler, 2020).

Figure 2.1. Alaksen National Wildlife. Agricultural fields, old fields, and forest patches surrounding some of the fields are indicated by field numbers and letters (E = east, FP = forest patch, N = north, S = south, W = west). Letters after hyphen denote type of ground cover/crop, A = annual/winter cover crops, F = forage, FL = forage and livestock, OF = old fields (see Table 2.1 for description).

Table 2.1. Land use types and management practice in the Alaksen National Wildlife Area showing fields and forest patches at the time the study was conducted, 2018-2019. Agricultural and old fields are indicated by field numbers and letters (W = west, E = east, N= north, S = south), and forests patches are surrounding some of the agricultural fields.

Land use type	***n***	**Species**	**Field ID** **Grazed**	**Field ID** **Ungrazed**
Perennial forage	10	Orchard grass, timothy, tall fescue	16, 19E, 5, 3, 6, 17, 4	1S, 2, 1N
Annual cropping	2	Fall rye	-	1E, 1W
	1	Winter wheat	18	-
	3	Barley	15, 14E, 14W	-
Old fields	3	Marsh vegetation (cattail, bulrush sedge)	-	8, 9, 19W
Forest patches	3	Mature trees (red alder, paper birch, holly)	-	Around fields 4, 5 & 6

2.2 Sampling and Analysis

Between September and October of 2018, 22 sites were sampled within Alaksen (Figure 2.1, Table 2.1). Soil samples were taken from four subplots within each of the 16 agricultural fields currently under production, the three abandoned agricultural fields (old fields), and three forest patches around fields 4, 5 and 6 (Appendix C). At the time of sampling, 6 out of the 16 agricultural fields were under annual crop production, and 10 were under perennial crop production (Appendix A & D). Three out of the 10 fields under perennial crop production were on their third year of forage, three on their second year, two on their first year, and two were under forage for at least 10 years.

Coordinates for each subplot were randomly generated within land use types using a geographical information software, ArcGIS 10.6 (ESRI ArcGIS. CA Environ. Syst. Res. Inst., Redlands, 2011) (Figure 2.2). The center point of each sampling area was navigated to using a Differential Global Positioning System (GNSS Pro 6H, Trimble Inc., Sunny vale, California, USA) with post-processing accuracy of 10-50 cm. A sampling area within each subplot in the fields was established by using the randomly generated point as the center sampling point, and measuring a second sampling point 16 m north (Figure 2.2). The remaining two sampling points were 120° and 240° from north, and 16 m from the center-most point (Paul et al., 2020). To sample the forest patches, a linear configuration was used to fit within a rectangular strip covering an area of ~ 900 m^2 (Paul et al., 2020) (Figure 2.2).

Soil samples were collected with a 4.4 cm diameter auger from the center of each subplot at 0-15, 15-30, 30-60, and 60-100 cm below the surface, and from the second, third and fourth points of each sampling area at 0-15 and 15-30 cm below the surface. A subsample from each depth range was weighed in the field for subsequent soil moisture content analysis. Bulk density cores were taken from the center of the first subplot sampled in each field, at 3.75-11.25 and 18.75-26.25 cm below the soil surface, using an aluminum ring, 9.4 cm high and 6.7 cm in diameter (inner), yielding approximately 331.4 cm^3 of soil for each sample.

Subsamples from each depth range were taken to the lab, oven dried at 105ºC, and weighed again to calculate the mass from soil moisture. Composite soil samples from each depth were air-dried for two weeks, pulverized, and sieve-separated into coarse fractions (>2 mm) and fine fractions (<2 mm) in preparation for analysis. Fractions were weighed separately to calculate the proportion of each. Fine fractions were used to determine SOC, pH and EC.

Two 10 g subsamples were taken from each soil sample and analyzed for EC and pH with an InLab® Expert Pro-ISM and a pH/Ion meter S220 (Mettler, Toledo) using air-dried soil in water at a 1:2 ratio pH was also measured in a 0.01M $CaCl_2$ solution at a 1:2 ratio (Whitney, 2012).

Analysis of SOC was conducted as part of a larger study by Paul et al. (2020) that aimed to track changes in soil organic carbon across the agricultural landscape of the Lower Fraser Valley of British Columbia. The study collected a total of 309 soil samples, which included samples from this study. A quarter of the total samples (n = 75) were selected using a stratified random approach that ensured an equal proportion of each land use type, and sent to the Technical Service Laboratory of British Columbia Ministry of Environment for total carbon and inorganic carbon analysis. SOC was determined by subtracting inorganic carbon from total carbon. All the samples (n = 309) were analyzed by mid-infrared spectroscopy (TENSOR 37, Bruker Instruments, Ettlingen, Germany) to predict SOC with a partial least square regression model. Data from elemental measurement were used for calibration and validation.

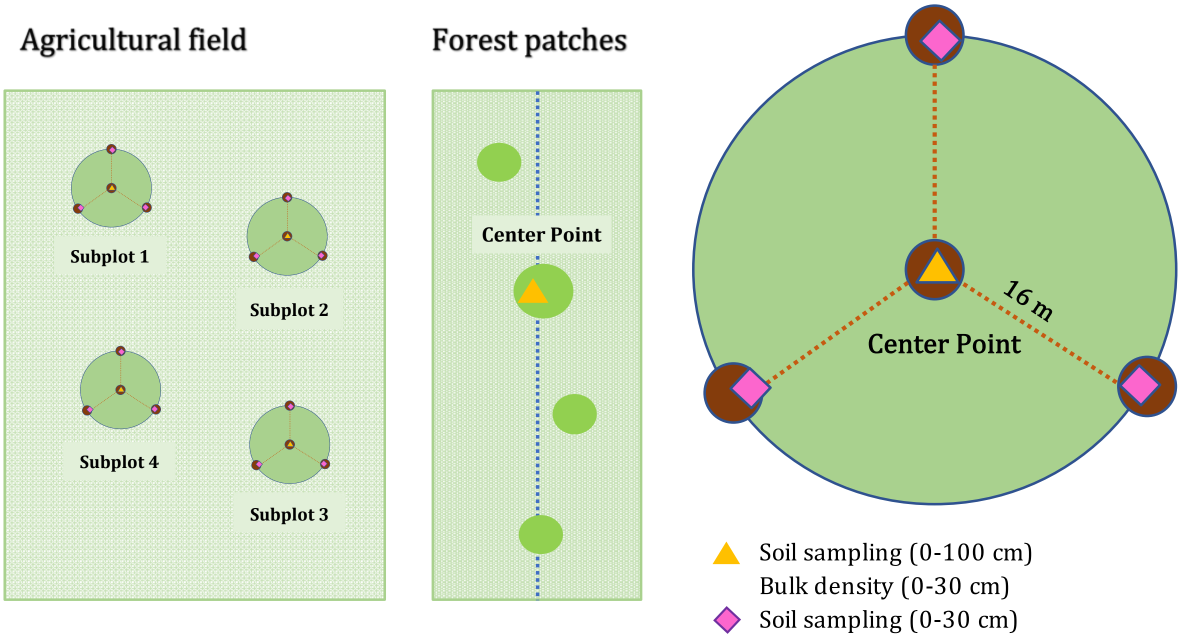


Figure 2.2. Plot sampling design for agricultural fields, old fields and forest patches. Circles in agricultural fields and forest patches represent the four randomized subplots where soil samples were taken. Triangle within subplot (right) denotes center point of subplot, where soil was sampled at four depths (0-15, 15-30, 30-60, and 60-100 cm) and bulk density was measured at two depths (3.75-11.25 and 18.75-26.25 cm). Diamonds denote sampling locations 16 m from center (0°, 120° and 240° from north) where soil was sampled at two depths (0-15 and 15-30 cm).

2.3 Statistical Analysis

All data were analyzed in the R statistical computing environment (version 3.4.2, R Development Core Team, 2020, Vienna, Austria). Linear mixed effect (LME) models were constructed to test for effects of land use type and management practices on soil quality indicators (*nlme* package version 3.1-131, Pinheiro et al., 2020). The mixed effect models included four fixed factors: land use type (agricultural field, old field, or forest patch), crop type (annual or perennial), livestock (present or absent), and soil depth (0-15, 15-30, 30-60, 60-100, or 3.75-11.25, and 18.75-26.25 cm) and the interactions between factors of land use type, crop type or livestock with depth: 1) land use type and depth, 2) crop type and depth, and 3) livestock and depth. Dependent variables were the soil quality indicators SOC, BD, pH, and EC. Field was included by virtue of geographic location and treated as a random effect.

Type III Anova was used to test for land use type, crop type and livestock effects, with a critical value of $\alpha = 0.05$ maintained throughout. When the effects of these fixed factors and the interaction between a fixed factor and depth were significant, a separate analysis was conducted for each depth. After that means were separated by a post-hoc Tukey test (*multcomp* package in R, Hothorn et al., 2020).

Chapter 3: Results and Discussion

3.1 Effects of Land Use Type on Soil Quality Indicators

Although SOC differed between land use types, the effect was inconsistent between depths (Figure 3.1, Table 3.1). SOC was greater in forest patches than in old fields, and greater in old fields than in agricultural fields at 0-15 cm depth (Figure 3.1, Table 3.2). Agricultural fields had 44% of the SOC concentration of forest patches; old fields had 60% of the SOC concentration as forest patches, but were 26% greater than agricultural fields. SOC values in agricultural and old fields were below the 30 g/kg (3%) of total soil C estimated by Hermawan (1995) as the threshold for stabilizing aggregates in the Fraser River delta. Results suggest that land conversion to agriculture reduced SOC near the soil surface. This is consistent with the findings of Deng et al. (2016) who found that conversion of forest or grassland to farmland depletes soil C stocks near the soil surface. In addition, studies indicate that some of the production practices used by farmers in the area, such as the annual cultivation of summer crops and intense tillage, have the potential to affect carbon dynamics (Hermawan, 1995; Liu et al., 2005). It is likely that some of these practices could have contributed to the deterioration of surface SOC in agricultural fields at Alaksen.

SOC declined with depth in forest patches and old fields, but not in agricultural fields. At 30-60 cm depth, SOC in forest patches and old fields, respectively, was 72 and 76% less than in agricultural fields (Figure 3.1, Table 3.2). SOC in forest patches declined with depth, going from an average 28.17 g/kg at the surface to a 5.93 g/kg average deeper in the soil profile. Differences in type of roots in forest (woody roots) and agricultural field (fine roots of grasses) could explain differences in carbon observed at this depth. The changing effect with depth may also be attributed to movement of carbon down the soil profile. Dissolved organic carbon (DOC), one of the most reactive and mobile components of soil organic carbon, is largely mineralised in the A and B horizons as it moves down the soil profile (Si et al., 2018).Topsoil with a high surface SOC concentration, as observed in the forest patches, can better retain surface DOC than topsoil with lower surface SOC concentration, like that in the agricultural fields (Si et al., 2018). Differences in SOC among land use types at the 30-60 cm depth suggest that land use change has affected carbon dynamics throughout the soil profile, not just near the surface. Dissolved organic carbon is an important component of the organic carbon pool of estuaries, and terrestrial vegetation and soils are large contributors to the pool of DOC in rivers, estuaries and groundwater (Bauer and Bianchi, 2011).

As expected, surface SOC was greater in old fields than agricultural fields (Figure 3.1, Table 3.2). The absence of annual cultivation, and an increase in above- and below-ground vegetation and concomitant litter accumulation leads to a buildup of organic matter over time. Although the SOC average (16.9 g/kg) remains below the 30g/kg estimated by Hermawan (1995) as the threshold for stabilizing aggregates in the Fraser River delta, SOC on old fields is recovering. Deng et al. (2016) observed a similar increase in SOC 10 years after abandonment of agricultural fields. Wang et al. (2012) determined that SOC in abandoned agricultural fields increases linearly with time. The observed improvement in SOC concentration in old fields suggests that abandoning agricultural production restores carbon without management intervention.

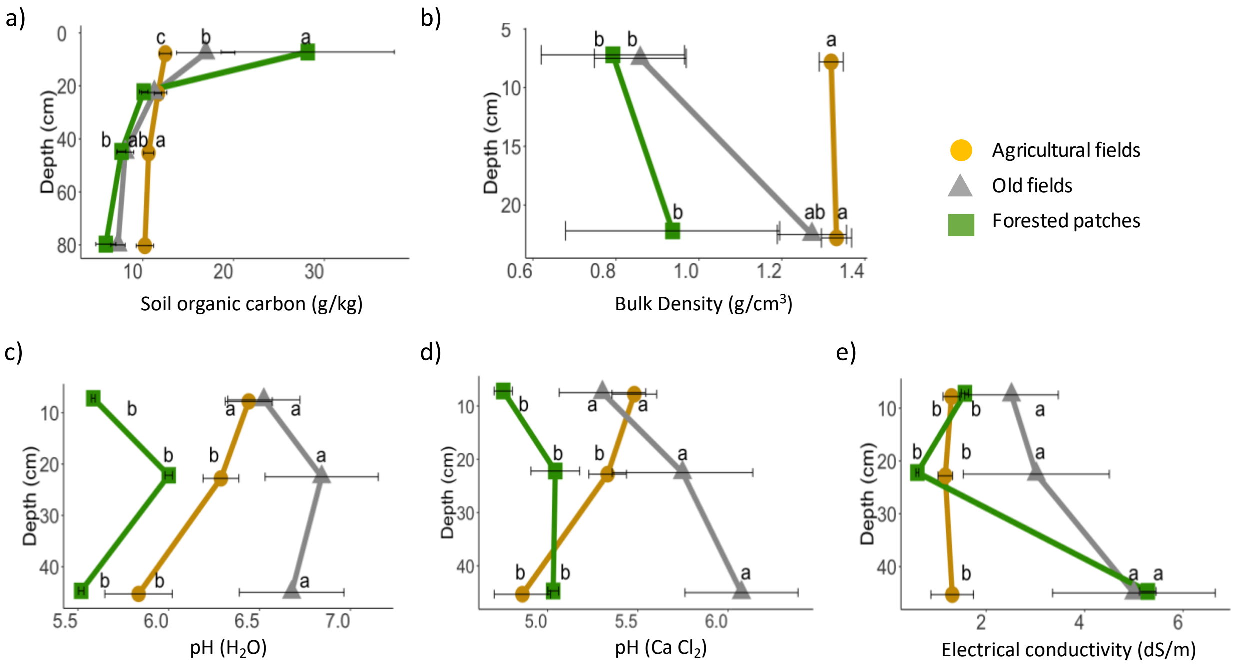


Figure 3.1. Effects of land use type on a) soil organic carbon b) bulk density c) pH (H_2O), d) pH ($CaCl_2$), e) electrical conductivity, by depth (Mean ± SE). Mean with different letters are significantly different within a depth (Tukey's HSD, $p < 0.05$)

Table 3.1. Linear mixed effect model analysis results for the effect of land use types, depth, and their interaction on soil quality indicators showing degrees of freedom (DF), F-value, and p-value. Significant results ($p < 0.05$) are shown in bold.

	Land use type			Depth			Land use type*Depth		
	DF	F-value	p-value	DF	F-value	p-value	DF	F-value	p-value
Soil organic carbon	2	2.51	0.08	3	21.37	**<0.01**	6	16.83	**<0.01**
Bulk density	2	19.82	**<0.01**	1	3.57	0.07	2	4.64	**0.02**
pH$_{H_2O}$	2	3.94	**0.02**	2	16.96	**<0.01**	4	5.04	**<0.01**
pH $_{CaCl_2}$	2	0.59	0.55	2	9.02	**<0.01**	4	11.48	**<0.01**
Electrical conductivity	2	14.45	**<0.01**	2	19.55	**<0.01**	4	29.87	**<0.01**

Table 3.2. Linear mixed effect model analysis results for the effects of land use types on soil quality indicators by individual depths showing degrees of freedom (DF), F-value, and p-value. Significant results ($p < 0.05$) are shown in bold.

Indicator	Depth	DF	F-value	p-value
Soil organic carbon	0-15 cm	2	22.11	**<0.01**
	15-30 cm	2	0.87	0.42
	30-60 cm	2	4.14	**0.03**
	60-100 cm	2	2.49	0.11
Bulk density	3.75-11.25 cm	1	11.98	**<0.01**
	18.75-26.25 cm	1	3.56	**<0.01**
pH (H_2O)	0-15 cm	2	6.63	**<0.01**
	15-30 cm	2	12.03	**<0.01**
	30-60 cm	2	5.27	**<0.01**
pH ($CaCl_2$)	0-15 cm	2	5.07	**<0.01**
	15-30 cm	2	6.58	**<0.01**
	30-60 cm	2	11.08	**<0.01**
Electrical conductivity	0-15 cm	2	14.34	**<0.01**
	15-30 cm	2	28.55	**<0.01**
	30-60 cm	2	21.02	**<0.01**

As hypothesized, BD differed between land use types (Figure 3.1, Table 3.1). BD was greater in agricultural fields than in old fields or forest patches near the soil surface (3.75-11.25 cm) (Figure 3.1, Table 3.2). Bulk density was 53% greater in agricultural fields compared to old fields and 66% greater than perennial forest patches. BD near the soil surface in agricultural (1.31 g/cm^3) slightly exceeded the 1.3 g/cm^3 threshold that can reduce root penetration, water infiltration, crop yield, and agricultural productivity in soils with silt loam texture. At deeper depths (18.75-26.25 cm) BD was also significantly greater in agricultural fields (42%), compared to forest patches.

Agricultural management practices commonly used at Alaksen, such as intensive tillage using heavy machinery, can increase soil compaction at the surface plow layer and destroy soil structure, reducing soil porosity, water infiltration and nutrient uptake by crops. Data from old fields suggest that when such practices cease, bulk density decreases substantially. This is corroborated by findings of Piché and Kelting (2015) in their study comparing changes in soil properties for abandoned agricultural lands reclaimed by trees over 60 years. They observed a rapid recovery of physical properties, such as a decrease in bulk density and increase in macro porosity, within 5–10 years after agricultural abandonment.

As anticipated, pH_{H2O} and pH_{CaCl2} differed among land use types (Figure 3.1, Table 3.1). An interaction was found between land use type and depth (Table 3.2). Both agricultural and old fields had greater pH than forest patches at 0-15 cm depth, likely because of liming. Levels of pH_{H2O} in both old fields and agricultural fields were 16% and 14% greater than perennial forest patches (Figure 3.1, Table 3.2). Following a similar pattern, levels of pH_{CaCl2} were 11% greater in old fields and 15% greater in agricultural fields compared to perennial forest patches. Holland et al. (2019) compared soil chemical properties of adjacent forest and annual crop fields over 35 years and found that long-term application of lime to the annual crop fields increased soil pH in their plow layer over time.

Contrary to expectation, pH_{H2O} and pH_{CaCl2} below 15 cm was greater in old fields than in agricultural fields or forest patches (Figure 3.1, Table 3.2). At the 15-30 cm depth, pH_{H2O} was 14% greater in old fields compared to forest patches, and 9% greater than agricultural fields. Levels of pH_{CaCl2} were 14% greater in old fields than perennial forest and 7% greater than agricultural fields. At the 30-60 cm depth, levels of pH_{H2O} in old fields were 20% greater than perennial forest patches and 14% greater when compared to agricultural fields, while levels of pH_{CaCl2} were 25% greater in old fields compared to agricultural fields and 20% greater than perennial forest patches. Even 20 years after abandonment, the pH of old fields has not returned to levels seen in the forested areas. The old fields are near the shoreline, where seawater infiltration could influence soil chemical properties. Arslan and Demir (2013) found that pH of groundwater beneath coastal agricultural fields was related to their proximity to the shoreline; seawater infiltration into the water table decreased over short distances from shore. This is an important consideration for land managers at Alaksen, as future climate change models for the area project a sea level rise (Metro Vancouver, 2016) and greater seawater infiltration would likely affect the agriculture capability of larger areas within the reserve.

As expected, EC differed among land use types (Figure 3.1, Table 3.1). Soil EC in old fields was greater than in agricultural fields at all depths, and was greater than in forested areas at 0-15 and 15-30 cm depths (Table 3.2). Soil EC at the 0-15 cm depth was 94% greater in old fields compared to agricultural fields, and 60% greater than in perennial forest. The baseline on these fields was in agreement with farmer observations regarding increased salinity. Soil EC did not differ between forested patches and old fields at the 30-60 cm depth; it was lower in agricultural fields.

The observation of greater EC in forest patches than in agricultural fields at 30-60 cm was unexpected (Figure 3.1, Table 3.2). Observed values in forest patches were well above what Luttmerding (1981) estimated for the delta's Crescent soils at this depth (2-4 dS/m). In a study designed to observe the effects of nutrient uptake by plant roots in paired coastal grasslands and tree plantations, Jobbágy and Jackson (2004) showed that exchangeable sodium in the forested stands was three to four times greater than in the native grasslands below the 50 cm depth. They suggested the observed pattern resulted from combined effects of sea water intrusion and sodium exclusion by tree roots at that depth. Many forest patches, grass margins and hedgerows at Alaksen run alongside sloughs and subsurface drainage channels. Tully et al. (2019) examined the effect of saltwater intrusion in soil profiles of farm fields in coastal areas and found that EC levels increased from the center of the fields to the ditch banks. This increase was more pronounced at 50-100 cm depth. Most importantly, the study showed how salinity can alter chemical properties of the soil over short distances within a field. My results suggest that sea water infiltration from the sloughs at Alaksen may be affecting the water table and soil chemical properties in old fields, forest patches, and some sections of agricultural fields. This is an important consideration since saline water movement from lower to upper soil horizons could compromise long-term arability of the site. Soil salinity adversely impacts soil aggregate formation and stability, resulting in a dominance of micro-pores, excessive water retention, poor drainage and aeration and reduced retention of essential cations nutrients (e.g. Ca^{2+}, Mg^{2+}, NH_4^+). Seawater intrusion could become more problematic with predicted sea level rise due to climate change.

3.2 Management in agricultural fields: effects of annual and perennial crops on soil quality indicators

Contrary to my hypothesis, SOC did not differ significantly between fields under annual and perennial crop production (Figure 3.2, Table 3.3). However, SOC decreased with depth in both annual and perennial systems. This concurs with a local study by Yates (2014), who found no significant differences in total soil C between potato fields and adjacent fields in GLSA for two to six years. Further, no effect of GLSA age was observed.

In a similar study, Lussier et al. (2019) compared soil quality indicators in GLSAs established for two years to those in fields with annual crop rotations in the Fraser River delta. No significant difference in total soil organic carbon and active organic carbon was found. Detecting short-term (i.e. 3–5 years) changes in SOC stocks is challenging because permanent increases occur slowly, over longer durations (Deng et al., 2016; Stockmann et al., 2013). Unlike the GLSAs studied by Yates (2014) and Lussier et al. (2019), forage fields at Alaksen experience plant biomass removal from hay production and livestock grazing.

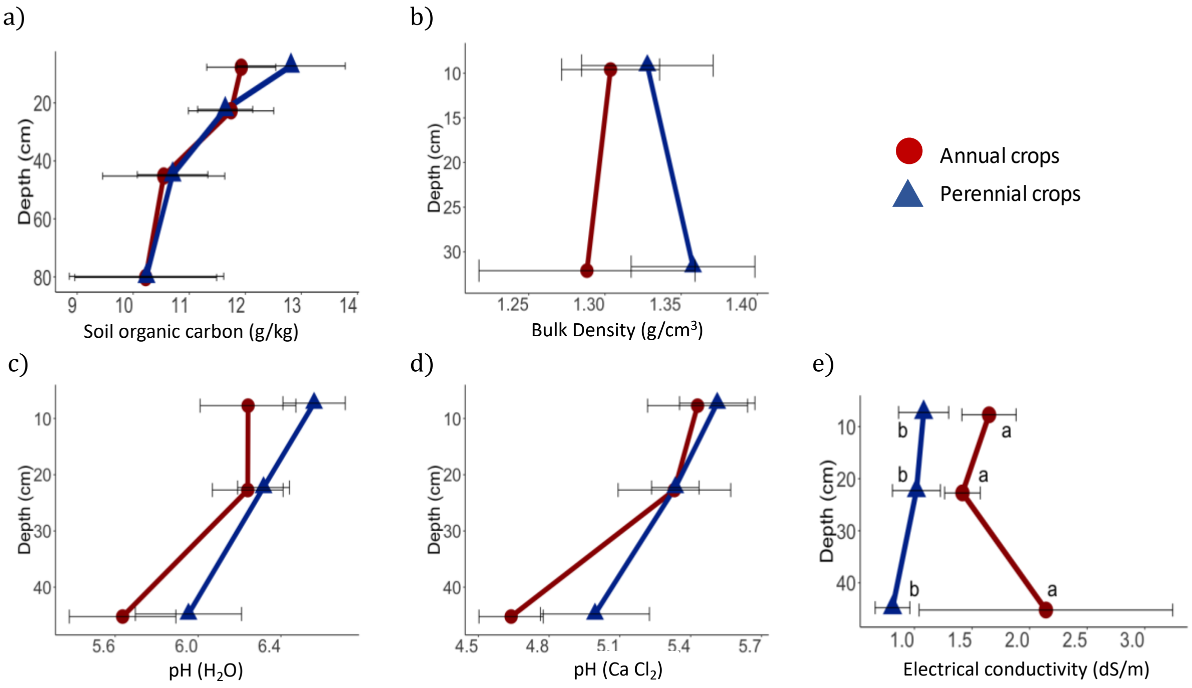


Figure 3.2. Effects of crop type (annual crops versus perennial crops) on a) soil organic carbon b) bulk density c) pH (H_2O), d) pH ($CaCl_2$), e) electrical conductivity, by individual depths (Mean ± SE). Mean with different letters are significantly different within depth (Tukey's HSD, $p < 0.05$).

Table 3.3. Linear mixed effect model analysis results for the effect of crop type (annual crops versus perennial crops), depth, and their interactions on soil quality indicators showing degrees of freedom (DF), F-value, and *p*-value. Significant results ($p < 0.05$) shown in bold.

	Crop type			Depth			Crop type*Depth		
	DF	F-value	p-value	DF	F-value	p-value	DF	F-value	p-value
Soil organic carbon	1	0.15	0.71	3	6.18	**<0.01**	3	0.54	0.65
Bulk density	1	0.63	0.44	1	0.14	0.71	1	0.41	0.53
pH_{H2O}	1	1.14	0.31	2	22.91	**<0.01**	2	2.36	0.1
pH_{CaCl2}	1	0.164	0.69	2	23.63	**<0.01**	2	1.78	0.17
Electrical conductivity	1	4.13	0.06	2	1.17	0.31	2	5.14	**<0.01**

Table 3.4. Linear mixed effect model analysis results for the effects of crop type on soil quality indicators by individual depths showing degrees of freedom (DF), F-value, and p-value. Significant results ($p < 0.05$) are shown in bold.

Indicator	Depth	DF	F-value	p-value
Electrical Conductivity	0-15 cm	1	14.19	**<0.01**
	15-30 cm	1	10.7	**<0.01**
	30-60 cm	1	5.08	**0.03**

BD did not differ significantly between fields under annual and perennial cropping. No significant interaction was observed between crop type and depth (Figure 3.2, Table 3.3). Three years of perennial crops did not improve soil physical attributes. Again, these results are consistent with those of Yates (2014) who determined that land use (2-6 years grassland versus annual) did not have an effect on soil BD over this relatively short duration. In a similar study following two years of GLSA Lussier et al. (2019) reported no significant differences between paired agricultural fields with annual crop rotations and GLSA established in fields with poor soil properties. In the same study, GLSA established in fields with good soil properties, however, showed an improvement in soil structure and a reduction in compaction when compared to agricultural fields with annual crops.

Neither pH_{H2O} nor pH_{CaCl2} differed significantly between perennial and annual cropping systems, and no significant interaction between these management approaches and depth was observed. Both pH_{H2O} and pH_{CaCl2} decreased with depth (Figure 3.2, Table 3.3). Although soils at Alaksen are not limed during the three years of perennial cropping, this interval may not be long enough to observe any permanent decrease in pH.

As anticipated, EC was greater in fields under annual crop production than those in perennial crop production across the soil profile (Figure 3.2, Table 3.3). An interaction was observed between management type and depth (Figure 3.2, Table 3.4). EC in annual fields was 52% greater at 0-15 cm depth, 40% greater at 15-30 cm depth and 164% greater at 30-60 cm depth when compared to perennial fields. Greater EC values in annual fields likely resulted from different irrigation schedules. Annual crops are irrigated over the summer months, while perennial crops are only irrigated during establishment. Salinity of water in the sloughs increases over the summer as spring freshet decreases. Soil samples in this study were collected at the end of the summer, after a period of intense irrigation of annual crops with slough water and no precipitation to leach the deposited salt deeper into the soil profile.

Sea water intrusion might be another factor contributing to greater EC. Yu et al. (2013) looked at the factors that underline soil salinity in agricultural fields along the Yellow River Delta. Their results showed that soil salinity in the sampled agricultural fields was greater near the soil surface than in subsoil due to salt in subsoil moving up and accumulating in topsoil as a function of evaporation. In a study that examined soil surface evaporation and water requirement in crops, Allen (1998) observed that low percentages of ground cover by crops lead to significant losses of water in the soil via soil surface evaporation. Conversely, high percentages of ground cover resulted in an increase in soil moisture and moisture retention, and a subsequent decrease in evaporation. The combination of a shallow water table, sea water intrusion, and a reduction in vegetative cover in fields with annual crops at Alaksen may explain the differences observed in soil EC among systems. Irrigation practices that lead to soil salinization are deleterious to crop production and agroecosystem ecological service provision.

3.3 Livestock production in agricultural fields: effects of integration on soil quality indicators

SOC concentration was affected by the integration of livestock into the Alaksen rotation, but only at some soil depths (Figure 3.3, Table 3.5). SOC in grazed fields was 12% greater than in ungrazed fields at 0-15 cm depth (Figure 3.3, Table 3.6). These findings coincide with results of a 22-year study by Hewins et al. (2018), who found that cattle grazing on pastures increased SOC concentration by 12% in the upper 15 cm of soil. Similarly, Persson et al. (2008) reported that grazing livestock for two years out of six resulted in greater soil carbon content than annual crop rotations without livestock.

SOC concentration was greater in ungrazed fields than grazed fields at the 60-100 cm depth, but this effect was only marginally significant ($p < 0.1$).

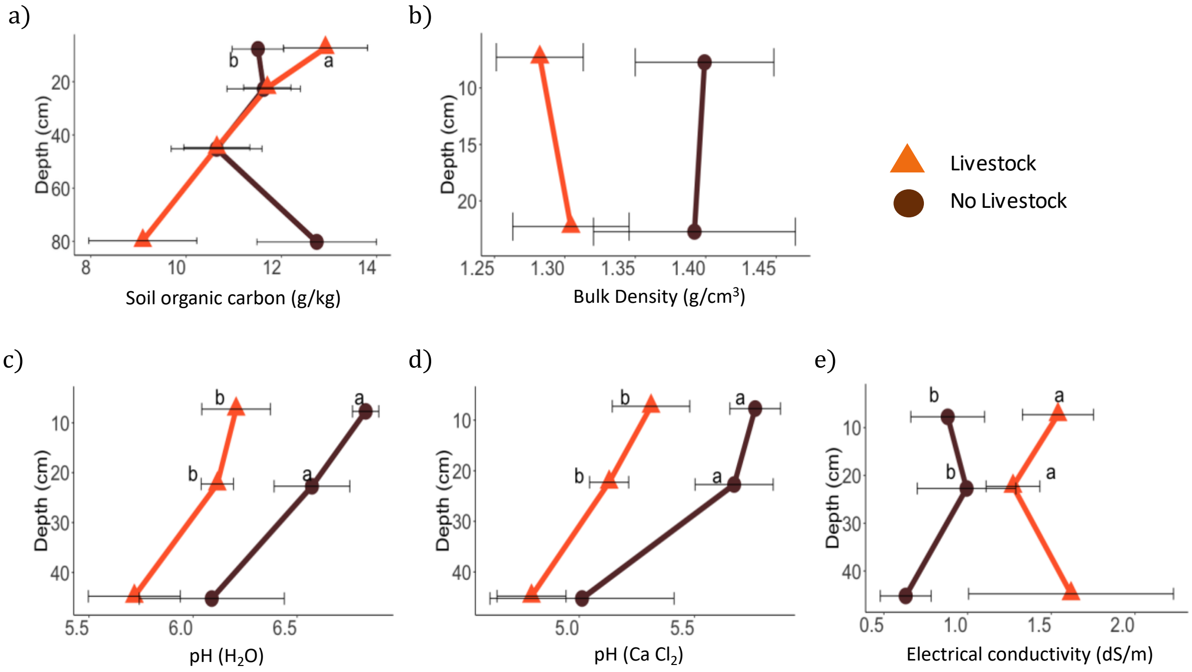


Figure 3.3. Effects of livestock (Livestock and No Livestock) on a) soil organic carbon b) bulk density c) pH (H_2O), d) pH ($CaCl_2$), e) electrical conductivity, by individual depths (Mean ± SE). Mean with different letters are significantly different within depth (Tukey's HSD, $p < 0.05$.

Table 3.5. Linear mixed effect model analysis results for the effect of livestock, depth, and their interaction on soil quality indicators showing degrees of freedom (DF), F-value, and *p*-value. Significant results ($p < 0.05$) are shown in bold.

	Livestock			Depth			Livestock*Depth		
	DF	F-value	p-value	DF	F-value	p-value	DF	F-value	p-value
Soil organic carbon	1	0.06	0.79	3	6.82	**<0.01**	3	5.37	**<0.01**
Bulk density	1	3.24	0.09	1	0.14	0.71	1	0.15	0.69
pH_{H2O}	1	6.08	**0.01**	2	22.33	**<0.01**	2	1.03	0.35
pH_{CaCl2}	1	6.96	**0.01**	2	21.59	**<0.01**	1	0.86	0.42
Electrical conductivity	1	0.38	0.54	2	1.11	0.33	2	3.11	**0.04**

Table 3.6. Linear mixed effect model analysis results for the effect of livestock integration on soil quality indicators by individual depths showing degrees of freedom (DF), F-value, and p-value. Significant results ($p < 0.05$) are shown in bold.

Indicator	Depth	DF	F-value	p-value
Soil organic carbon	0-15 cm	1	3.45	**< 0.01**
	15-30 cm	1	0.02	0.9
	30-60 cm	1	0.04	1
	60-100 cm	1	3.71	0.07
Electrical conductivity	0-15 cm	1	19.87	**<0.01**
	15-30 cm	1	4.95	**0.03**
	30-60 cm	1	2.36	**0.13**

Differences in bulk density between grazed and ungrazed fields were only marginally significant (*p*- value < 0.1) throughout the soil profile (Figure 3.3, Table 3.5, Table 3.6). Mean BD in the upper profile was 1.40 g/cm^3 in ungrazed fields and 1.28 g/cm^3 in grazed fields. Nominally lower bulk density in grazed fields might be due to greater SOC near the soil surface. These results suggest that the inclusion of livestock in the crop rotation likely improved the physical properties, but the marginal difference in bulk density between grazed and ungrazed fields must be interpreted with caution. While herd size was relatively small (60-80 animals), this could still represent an excessive stocking rate in some of the smaller fields (3.2-10.1 hectares), possibly leading to overgrazing and soil compaction. Trampling by animals can increase bulk density by reducing pore space and affecting water infiltration (Abdel-Magid, et al., 1987; Bell et al., 2011; Brock et al., 1990). Grazing rotations within and among fields (e.g. light or moderate rotational grazing, rest grazing) and management of stock densities can be designed to prevent overgrazing and compaction and improve soil quality (Polat, 2018). Farmers at Alaksen and in the delta area can benefit from gaining a better understanding of the impact of these managements approaches on soil quality and related pasture quality and composition.

As hypothesized, pH$_{H2O}$ and pH$_{CaCl2}$ were both lower in grazed than ungrazed fields, but only in the top 30 cm (Figure 3.3, Table 3.5, Table 3.6). Deposition of urine and excreta may have reduced pH and lead to animal induced soil acidification in grazed fields with high stock densities (Brock et al., 1990; Carran and Theobald, 1995; de Klein et al., 1997). Improved understanding of the relationship between stocking density and soil chemical properties could help farmers in Alaksen select sustainable grazing practices, such as moderate rotational grazing, that improve soil structure, enhance nutrient provision to crops, and maintain pH.

Soil EC in the top 30 cm was greater in grazed than ungrazed fields (Figure 3.3, Table 3.6). Fields with livestock had a soil EC that was 74 and 27% greater in the 0-15 and 15-30 cm profiles, respectively. In a similar study conducted to examine the effects of manure deposition in soil chemical properties of adjacent grazed and ungrazed plots Chaneton et al. (1996) found, just as I did, that plots that received no manure deposition experienced lower EC. Understanding the impact of pastured livestock on soil salinity may help Alaksen farmers reap the benefits of livestock integration (e.g. greater SOM and soil microbial activity) while avoiding soil quality deterioration.

Chapter 4: Conclusions

4.1 General Conclusions

Land use changes and agricultural practices impact soil quality, but we have limited knowledge of the extent to which agriculture has affected soil quality in the Fraser river delta. In the fall of 2018, I conducted an observational study in the Alaksen National Wildlife Area to develop a baseline of key soil quality indicators comparing three distinct and dominant land use types, agricultural fields, old fields (abandoned) and forest patches, and to assess impact of agriculture on soil quality.

By comparing soil quality indicators collected from land use types that shared similar attributes I was able to observe temporal changes caused by land use on soil properties of agricultural and old fields. These changes however were significant within the top 15 cm, where actively farmed agriculture fields showed lower SOC and greater BD than old fields and forest patches. These findings indicate that agriculture has reduced the quality of the top soil at Alaksen. An increase in SOC and concomitant decrease in BD at the soil surface in old fields compared to agricultural fields suggests that the absence of cultivation has built up surface organic matter, possibly due to increased above- and belowground vegetation and litter accumulation over time. SOC declined with depth in forest patches and old fields, but not in agricultural fields allegedly due to the retention through mineralization of dissolved organic carbon in the A and B horizons of these two land use systems. These data suggest that farmers in the reserve could benefit from employing agronomic methods that increase soil organic matter. Baseline data brought forth by this study can be used to guide future research and help both farmers and reserve managers develop a long-term agricultural management plan that meets multiple objectives, that include building agricultural soil health and enhancing the ecological integrity of the Alaksen Wildlife Area.

By examining some of the stages of the rotation and management options within the rotation, most specifically the inclusion of perennial crops and livestock, I was able to assess the potential long-term impact of the 5-year crop-stock rotation on soil properties. Contrary to what I had anticipated, soil quality was not different between fields in perennial crop production and fields in annual crop production, with the exception of EC, which was greater in the upper 30 cm for annual crop fields. The presence of greater EC values in annual fields suggest that soil salinity is likely the result of current management practices (i.e. irrigation, ground cover). In the context of predicted changes to weather patterns and anticipated sea level rise due to climate change, these data serve as a baseline to monitor and manage soil salinity levels and to guide future adaptation planning in the area.

By evaluating the effects of livestock integration into the five-year rotation I was able to examine how this practice impacts soil quality. As anticipated, SOC in fields used for livestock production was greater near the soil surface than in fields without livestock. This suggests a potential improvement in the quality of the soil from the grazing regime. However, effects on BD were only marginally significant and EC was greater in fields with livestock. Results suggest that inclusion of livestock in the crop rotation had mixed effects on soil quality. Improved grazing management through changes in stock densities, for example, may bring greater soil quality benefits.

While evidence suggests that soil quality continues to decline across the region, farmers and land managers can use these data as a reference point to re-evaluate some of the practices that are known to contribute to the degradation of soils in the delta area. Once the effects of livestock integration into crop rotations, which should also consider some of the negative effects, such as ruminant methane emissions, are well understood, this practice may be used as a regenerative tool to counteract some of the adverse impacts of land use changes and agricultural practices in our area. At the same time, these data can be used for the exploration of additional regenerative practices (i.e. reduced tillage, intercropping, precision irrigation) that aim to prevent and revert soil degradation in our region. Lastly, results of this study can be used to guide planning strategies that address climate change and to advance municipal and regional policies that support the sustainability of our food system.

4.2 Study Limitations

Through my study, I was able to assess the quality of the soil at Alaksen by comparing adjacent agricultural fields, old fields and forest patches. From information gathered from land managers at Alaksen, the perennial forest patches included in this study represent modified lots which experienced disturbance as recently as 30 years ago and thus are not an accurate representation of pre-disturbance ecosystems. Because these forest patches are going through a process of natural succession as they revert to a natural state, they have less developed horizons when compared to the highly developed and a more stable soil horizon of an ecosystem that has been undisturbed for thousands of years. Given that my reference sites are themselves disturbed, my results likely underestimate the impact of agricultural disturbance.

Another major limitation of my study was that sampling points were established randomly and thus there was spatial correlation among fields that was not entirely accounted for. Drainage in agricultural fields, for example, differed from field to field. Some fields at Alaksen were well drained, while others experienced longer periods of flooding. Some of the management challenges related to soils in the Delta area have been associated with poor drainage (Neufield et al., 2017). Factors such as soil texture, position below sea level, high water table, and high precipitation rates keep some soils saturated during the winter and early to mid-spring. Many farm operations rely on infrastructure (such as drain tiles) for saturation-free root zones during time of crop establishment (Bertrand et al., 1991), and to reduce prolonged waterlogged conditions during the spring (Hermawan, 1995). Farmers at Alaksen have not install drainage tiles and rely on a system of constructed channels to prevent waterlogging during the spring in some of the fields. Thus far, it was unclear if differences in drainage among fields were determined by field location, soil texture, or management practices. It has been well established that drainage can have a significant impact on soil quality. Not accounting for the effects of spatial variations in drainage among fields had the potential to limit our understanding of the factors that affect soil quality. Field location could also be seeing as a limiting factor. Old fields, for example, were located next to the coastline which made them prone to seawater intrusion, while fields without livestock were clustered inland and at a relative distance from major sloughs. Differences in pH and EC among some of the groups found in this study could have been the unaccounted result of field location.

4.3 Recommendations for future studies

Results from my study showed that fields with livestock production had significantly greater SOC concentration compared to fields without livestock. In the future, it would be valuable to measure additional indicators, such as mean weight diameter and water stable aggregates, nitrogen and phosphorous levels, to further explore the value of including livestock on crop rotations as a management approach to improve soil quality. A better understanding of the role livestock plays in improving soil structure and the nutrient cycles can help local farmers explore the potential of introducing livestock into their rotations as a sustainable, cost-effective, on-farm source of non-synthetic soil amendments.

In spite of having greater SOC levels, fields grazed by livestock had greater BD. In my discussion, I suggested this might be linked to the effects of animal traffic and grazing observed during sampling in some of the fields. It would be valuable, especially from a management perspective, to explore in more detail effects of different system-based approaches to grazing (i.e. moderate rotation, intensive rotation), on soil quality. Future studies can explore grazing components such as stocking density, stocking rate, stocking period, and rest period, focusing on the interaction between soil, animals and vegetation. Evaluating soil quality prior to the establishment of these management approaches and monitoring change could provide valuable management information to both farmers and wildlife area managers. Furthermore, these results can then be compared to forage fields in adjacent farming operations outside of the reserve that are not under livestock production to evaluate the potential use of some of these practices by other farmers in the delta area.

Despite the fact that farming operations are an essential tool for Alaksen Wildlife Area management to provide habitat and food for wildlife, there is limited information about the role that these operations play in delivering mission critical ecological services. As a result, our understanding of the role of soils in supporting these ecosystems and how land use changes and management practices impact ecological services is limited. Future studies could focus on developing a framework to ascertain the impacts of agriculture systems and management practices on the ecological health and function of natural lands and habitats in the delta area.

Levels of EC were greater in fields in annual crop production when compared to fields in perennial grasses, probably due to an increase in the use of brackish water for irrigation. Over the last century, the region has experienced substantial expansion of urban development which resulted in removal of forest and wetlands and the transformation of many waterways through diking, channeling and dredging. A detailed assessment of the effects of changes on water quality and the use of water from the Fraser River for irrigation in the delta area could serve as a critical reference in the near future to address some of the issues affecting agriculture, such as the expansion of Delta Port and the effects of climate change. Future studies can also explore adaptation practices that address the relationship between cover crop quality and soil salinity development, and that can be used by producers in the selection of crops that are better suited to withstand predicted changes in climate conditions in the area.

Soil microbial communities are essential components of natural and managed ecosystems. They mediate key processes that control soil carbon and nitrogen cycling, and contribute to a wide range of ecosystem services. Despite their importance, there is a large gap in our knowledge of the composition and functions of below ground ecosystems in the delta region's agricultural soils. With its diversity of natural and managed ecosystems, Alaksen provides an excellent opportunity to begin exploring the diversity and function of the soil biota that sustain these systems.

Bibliography

Abdel-Magid, A.H., Trlica, M.J. & Hart, R.H. 1987. Soil and vegetation responses to simulated trampling. Journal of Range Management, vol. 40, no. 4.

Allen, R. & Food and Agriculture Organization of the United Nations. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Food and Agriculture Organization of the United Nations. Rome.

Alves, L.A., Denardin, Luiz Gustavo de Oliveira, Martins, A.P., Bayer, C., Veloso, M.G., Bremm, C., Carvalho, Paulo César de Faccio, Machado, D.R. & Tiecher, T. 2020. The effect of crop rotation and sheep grazing management on plant production and soil C and N stocks in a long-term integrated crop-livestock system in Southern Brazil. Soil & Tillage Research, vol. 203.

Arslan, H. & Demir, Y. 2013. Impacts of seawater intrusion on soil salinity and alkalinity in Bafra Plain, Turkey. Environmental Monitoring and Assessment, vol. 185, no. 2.

Atkins, R.J., Tidd, M. & Ruffo, G. 2016. Sturgeon Bank, Fraser River Delta, BC, Canada: 150 years of human influences on salt marsh sedimentation. Journal of Coastal Research, vol. 75, no. sp1.

Augustinowicz, G., Smukler, M.S., & Mullinix, M. K. 2019. Agriculture in the Alaksen National Wildlife Area Baseline Assessment Report. Unpublished.

Balke, E. 2017. Investigating the role of elevated salinity in the recession of a large brackish marsh in the Fraser River estuary. MSc Thesis, Simon Fraser University, Burnaby, BC.

Balota, E.L., Colozzi Filho, A., Andrade, D.S. & Dick, R.P. 2004. Long-term tillage and crop rotation effects on microbial biomass and C and N mineralization in a Brazilian Oxisol. Soil & Tillage Research, vol. 77, no. 2.

Bauer, J.E. & Bianchi, T.S. 2011. Dissolved organic carbon cycling and transformation. in Elsevier Inc.

Bell, L. W., Kirkegaard, J. A., Swan, A., Hunt, J. R., Huth, N. I., & Fettell, N. A. 2011. Impacts of soil damage by grazing livestock on crop productivity. Soil & Tillage Research, 113(1).

Bertrand, R.A., Hughes-Games, G.A., & Nikkel, D.C. 1991. Soil management handbook for the lower Fraser Valley. 2d ed., Ministry of Agriculture, Fisheries and Food, Abbotsford, B.C.

Bird, P., Jackson, T., Kearny, G., Saul, J., Waller, R., & Wipp, G. 2004. The effect of improved pastures and grazing management on soil water storage on a basaltic plains site in south-west Victoria. Australian Journal of Experimental Agriculture, vol. 44, no. 6.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K.V., Montanarella, L. & Panagos, P. 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nature Communications, vol. 8, no. 1.

Boyle, C.A., Lavkulich, L., Schreier, H. & Kiss, E. 1997. Changes in land cover and subsequent effects on lower Fraser basin ecosystems from 1827 to 1990. Environmental Management, vol. 21, no. 2.

Bradbeer, D., Lansdorp, O., Travers, M., Jack,K., & Halpin, L. 2012. Winter cover crops on the Fraser River Delta: 20 years of Greenfields. Delta Farmland and Wildlife Trust. Web. https://deltafarmland.ca/wp-content/uploads/2017/07/Winter-Cover-Crops-on-the-Fraser-River-Delta-20-Years-of-Greenfields.pdf

Brady, N.C. & Weil, R.R. 2010, Elements of the nature and properties of soils, 3rd ed., Pearson Prentice Hall, Upper Saddle River, NJ.

Brock, J., Ball, P., & Carran, R. 1990. Impacts of management on leaching of nitrate from pastures. Proceedings of the New Zealand Grassland Association 52 (1990).

Brown, Jack. 2014. Surrey History. Web. https://www.surreyhistory.ca/kwantlen.html

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W. & Brussaard, L. 2018. Soil quality – A critical review. Soil Biology and Biochemistry, vol. 120.

Cambardella, C. A., & Elliott, E. T. 1994. Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. Soil Science Society of America Journal, 58(1).

Carran, R. & Theobald, P. 1995. Nitrogen-cycle processes and acidification of soils in grazed pastures receiving or not receiving excreta for 23 years. Australian Journal of Soil Research, vol. 33, no. 3.

Chatterjee, A., & Lal, R. 2009. On farm assessment of tillage impact on soil carbon and associated soil quality parameters. Soil & Tillage Research, 104(2). doi:10.1016/j.still.2009.03.006

Carter, M.R., Gregorich, E.G., Angers, D.A., Donald, R.G. & Bolinder, M.A. 1998. Organic C and N storage, and organic C fractions, in adjacent cultivated and forested soils of eastern Canada. Soil & Tillage Research, vol. 47, no. 3-4.

Chaneton, E.J. & Lavado, R.S. 1996. Soil nutrients and salinity after long-term grazing exclusion in a flooding Pampa grassland. Journal of Range Management, vol. 49, no. 2.

Clague, J.J., Luternauer, J.L. & Hebda, R.J. 1983. Sedimentary environments and postglacial history of the Fraser Delta and lower Fraser Valley, British Columbia. Canadian Journal of Earth Sciences, vol. 20, no. 8.

Clausen, M., & Smukler, S.M. 2020. Alaksen National Wildlife Area Hedgerow Assessment Report. Faculty of Land and Food Systems. University of British Columbia.

Corporation of Delta. 2011. Official Community Plan. Web. http://www.delta.ca/home-property-development/official-community-plan. Retrieved June 2019.

Crawford, E., & MacNair, E. 2012. BC Agriculture Climate Change Adaptation Risk & Opportunity Assessment Series - Fraser Valley & Metro Vancouver British Columbia Agriculture & Food Climate Action Initiative. Victoria, Canada (2012). Web. https://bcagclimateaction.ca/wp/wp-content/media/AdaptROseries-Provincial.pdf

Culman, S.W., A. Young-Mathews, A.D. Hollander, H. Ferris, S. Sánchez-Moreno, A.T. O'Geen, & L.E. Jackson. 2010. Biodiversity and soil ecosystem functions over a landscape gradient of agricultural intensification in California. Landscape Ecology 25.

de Klein, C. A. M, Monaghan, R.M. & Sinclair, A.G. 1997. Soil acidification: A provisional model for New Zealand pastoral systems. New Zealand Journal of Agricultural Research, vol. 40, no. 4.

Deng, L., Zhu, G., Tang, Z. & Shangguan, Z. 2016. Global patterns of the effects of land-use changes on soil carbon stocks. Global Ecology and Conservation, vol. 5.

Doran, J.W., & Parkin, T.B. 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., & Stewart, B.A. (Eds.), Defining soil quality for a sustainable environment. SSSA, Madison, WI.

ESRI ArcGIS, 2011. ESRI ArcGIS. Release 10. CA Environ. Syst. Res. Inst, Redlands, 2011. Google Scholar.

Fisheries and Oceans Canada. 2020. 2020 Fraser River Chinook salmon management measures. https://www.canada.ca/en/fisheries-oceans/news/2020/06/2020-fraser-river-chinook-salmon-management-measures.html

Flynn, S., Cadrin, C., & Filatow, D. 2006. Estuaries in British Columbia. BC Ministry of Environment. ISBN 0-7726-7723-9.

Franzluebbers, A. 2017. Fostering the future with forages. the case for pasture-crop rotations. better crops. Vol. 101 (2017, No. 4).

Goldin, A., & L. Lavkulich. 1990. Effects of historical land clearing on organic matter and nitrogen levels in soils of the Fraser lowland of British Columbia, Canada and Washington, USA. Canadian Journal of Soil Science 70.

Guo, L. B., & Gifford, R. M. 2002. Soil carbon stocks and land use change: A meta-analysis. Global Change Biology, 8(4). doi:10.1046/j.1354-1013.2002.00486.x

Hatfield, J. 1991. Use of the Alaksen National Wildlife Area by waterfowl. 1973-1987. Haynes, R.J. & Williams, P.H. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Elsevier Science & Technology.

Helfield, J.M. & Naiman, R.J. 2001. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology (Durham), vol. 82, no. 9.

Hermawan, B. 1995. Soil structure associated with cover crops and grass leys in degraded lowland soils of Delta. PhD Thesis, The University of British Columbia, Vancouver.

Hewins, D.B., Lyseng, M.P., Schoderbek, D.F., Alexander, M., Willms, W.D., Carlyle, C.N., Chang, S.X. & Bork, E.W. 2018. Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Scientific Reports, vol. 8, no. 1.

Holms, C. 2017. Alaksen National Wildlife Area Management Plan. Environment and climate change Canada. Unpublished.

Holland, J.E., White, P.J., Glendining, M.J., Goulding, K.W.T. & McGrath, S.P. 2019. Yield responses of arable crops to liming – An evaluation of relationships between yields and soil pH from a long-term liming experiment. European Journal of Agronomy, vol. 105.

Hothorn T, Bretz F, & Westfall P. 2008. Simultaneous inference in general parametric models. Biometrical Journal, 50(3).

James, S.E. 2019. Foraging ecology of juvenile Fraser River sockeye salmon across mixed and stratified regions of the early marine migration. MSc Thesis, The University of British Columbia, Vancouver.

Jobbágy, E.G. & Jackson, R.B. 2004. The uplift of soil nutrients by plants: Biogeochemical consequences across scales. Ecology (Durham), vol. 85, no. 9.

Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A. et al. 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. Forest Ecology and Management 352.

Leifeld, J., Bassin, S., Conen, F., Hajdas, I., Egli, M. & Fuhrer, J. 2013. Control of soil pH on turnover of belowground organic matter in subalpine grassland. Biogeochemistry, vol. 112, no. 1.

Li, J., Hernandez-Ramirez, G., Kiani, M., Quideau, S.A., Smith, E.G., Janzen, H., Larney, F.J. & Puurveen, D. 2018. Soil organic matter dynamics in long-term temperate agroecosystems: Rotation and nutrient addition effects. Canadian Journal of Soil Science, vol. 98, no. 2.

Liebig, M.A., Tanaka, D.L., Kronberg, S.L., Scholljegerdes, E.J. & Karn, J.F. 2012. Integrated crops and livestock in central North Dakota, USA: Agroecosystem management to buffer soil change. Renewable Agriculture and Food Systems, vol. 27, no. 2.

Lin, B. 2011. Resilience in agriculture through crop diversification: Adaptive management for environmental change. Bioscience, 61(3). Web. https://doi.org/10.1525/bio.2011.61.3.4

Liu, A., Ma, B.L. & Bomke, A.A. 2005. Effects of cover crops on soil aggregate stability, total organic carbon, and polysaccharides. Soil Science Society of America Journal, vol. 69, no. 6.

Loaiza Puerta, V., Pujol Pereira, E.I., Wittwer, R., van der Heijden, M. & Six, J. 2018. Improvement of soil structure through organic crop management, conservation tillage and grass-clover ley. Soil & Tillage Research, vol. 180.

Lussier, J.M., Krzic, M., Smukler, S., Bomke, A. & Bondar, D. 2019. Short-term effects of grassland set-asides on soil properties in the Fraser River Delta of British Columbia. Canadian Journal of Soil Science, vol. 99, no. 2.

Luttmerding, H.A. 1981. Soils of the Langley-Vancouver map area, RAB Bulletin 18, volume 6. British Columbia: Ministry of Environment. http://sis.agr.gc.ca/cansis/publications/surveys/bc/bc15/bc15-v6_ report.pdf.

Metro Vancouver, the Pacific Climate Impacts Consortium, Pinna Sustainability. 2016. Climate Projections for Metro Vancouver Report. http://www.metrovancouver.org/services/air-quality/AirQualityPublications/ClimateProjectionsForMetroVancouver.pdf

Nafuma, L. 1998. Short-term effects of graminaceous cover crops on autumn soil mineral nitrogen cycling on western lower Fraser valley soils. PhD Thesis, The University of British Columbia, Vancouver.

Neufeld, K., Paul, S., & Smukler, S. M. 2017. Improving on-farm drainage management to reduce the impacts of climate change in Delta, BC Final report for the Farm Adaptation Innovator Program (FAIP), British Columbia Project.

North, M. E. A., Dunn, M.W., & Teversham, J. M. 1979. Vegetation of the southwestern Fraser lowland, 1858–1880. Lands Directorate, Environment Canada, Vancouver, British Columbia.

Oldeman, L.R. 1992. The global extent of soil degradation. In: Greenland, D.J., Szabolcs, I. (Eds.), Soil resilience and sustainable land use. Proc. Symposium, Budapest, Hungary. 28 Sept.-2 Oct. 1992, CAB International, Wallingford, UK.

Odhiambo, J. 1998. Effect of cereal/grass and legume cover crop monocultures and mixtures on the performance of fall planted cover crops, soil mineral nitrogen and short-term nitrogen availability. PhD Thesis, The University of British Columbia, Vancouver.

Odhiambo, J., Temple, W., & Bomke, A. 2012. Managing cover crops for conservation purposes in the Fraser River Delta, British Columbia, Crop Management, Cases and Tools for Higher Yield and Sustainability. Dr. Fabio Marin (Ed.), ISBN: 978-953-51-0068-3, InTech.

Pacific Flyway Council. 2006. Pacific Flyway management plan for the Wrangel Island population of lesser snow geese. White Goose Sub Commission. Pacific Flyway Study Comm. [c/o USFWS], Portland, OR. Unpublished. rept. 20 pp.+ appendices.

Paradelo, R., Virto, I. & Chenu, C. 2015. Net effect of liming on soil organic carbon stocks: A review. Agriculture, Ecosystems and Environment, vol. 202.

Paul, S.S., Dowell, L., Coops, N.C., Johnson, M.S., Krzic, M., Geesing, D. & Smukler, S.M. 2020. Tracking changes in soil organic carbon across the heterogeneous agricultural landscape of the Lower Fraser Valley of British Columbia. The Science of the Total Environment, vol. 732.

Persson, T., Bergkvist, G., Bergkvist, G., Kätterer, T. & Kätterer, T. 2008. Long-term effects of crop rotations with and without perennial leys on soil carbon stocks and grain yields of winter wheat. Nutrient Cycling in Agroecosystems, vol. 81, no. 2.

Piché, N. & Kelting, D.L. 2015. Recovery of soil productivity with forest succession on abandoned agricultural land: Soil recovery on former agricultural lands. Restoration Ecology, vol. 23, no. 5.

Pinheiro J., Bates D., DebRoy S., Sarkar D., R Core Team. 2020. *nlme:* Linear and nonlinear mixed effects models. R package version 3.1-149, https://CRAN.R-project.org/package=nlme

Prade, T., Kätterer, T. & Björnsson, L. 2017. Including a one-year grass ley increases soil organic carbon and decreases greenhouse gas emissions from cereal-dominated rotations A Swedish farm case study. Biosystems Engineering, vol. 164.

Principe, L.L. 2002. Plant species abundance, diversity and soil quality of grassland set-asides on the Fraser River delta. MSc Thesis, The University of British Columbia, Vancouver.

Rallings, A. 2016. Evaluating potential impacts of hedgerow and riparian buffer management options on habitat and carbon stocks within the Agricultural Land Reserve of the Lower Fraser Valley, British Columbia. MSc Thesis, The University of British Columbia, Vancouver.

Polat, A. 2018, Impacts of diverse crop rotations and integrated crop-livestock system on soil quality in South Dakota, ProQuest Dissertations Publishing.

Si, Y., Xiong, L., Chen, Y., Zhu, J., Xie, J., Gao, R. & Yang, Y. 2018. Contribution of the vertical movement of dissolved organic carbon to carbon allocation in two distinct soil types under *Castanopsis fargesii* Franch. and C. carlesii (Hemsl.) Hayata forests. Annals of Forest Science, vol. 75, no. 3.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F. & Roger-Estrade, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil & Tillage Research, vol. 118.

Steinfeld, H., Food and Agriculture Organization of the United Nations, & Livestock, Environment and Development (Firm). 2006. Livestock's long shadow: Environmental issues and options. Rome: Food and Agriculture Organization of the United Nations.

Stockmann, U., Adam, M., Crawford, J., Field, D., Henakaarchchi, N., Jenkins, M., Minasni, B., McBratney, A., de Remy de Courcelles, V., Singh, K., Wheeler, I., Abbott, L., Angers, D., Baldock, J., Bird, M., Brookes, P., Chenu, C., Jastrow, J., & Zimmermann, M. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agriculture, Ecosystems and Environment. Volume 164. https://doi.org/10.1016/j.agee.2012.10.001

Thiel, B., Smukler, S.M., Krzic, M., Gergel, S. & Terpsma, C. 2015. Using hedgerow biodiversity to enhance the carbon storage of farmland in the Fraser River delta of British Columbia. Journal of Soil and Water Conservation, vol. 70, no. 4.

Tully, K.L., Weissman, D., Wyner, W.J., Miller, J. & Jordan, T. 2019. Soils in transition: saltwater intrusion alters soil chemistry in agricultural fields. Biogeochemistry, vol. 142, no. 3.

Turner, Nancy J., and Deur, D. 2005. Keeping it living: Traditions of plant use and cultivation on the Northwest Coast of North America. Vancouver, BC; Seattle, WA: University of Washington Press: UBC Press, 2005. Print.

United Nations Convention to Combat Desertification. 2017. The global land outlook, first edition. Bonn, Germany. ISBN: 978-92-95110-48-9 eISBN: 978-92-95110-47-2

Wang, Z., Liu, G., Xu, M., Zhang, J., Wang, Y. & Tang, L. 2012. Temporal and spatial variations in soil organic carbon sequestration following revegetation in the hilly Loess Plateau, China. Catena, vol. 99.

Weil, R., Islam, K., Stine, M., Gruver, J., & Samson-Liebig, S. 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. American Journal of Alternative Agriculture, 18(1).

Whitney, D.A. 2012. Soil Salinity. In J.R. Brown (Ed.), Recommended chemical soil test procedures for the North Central region. NCR Publ. No. 221 (revised). Missouri Agr. Exp. Sta. SB 1001. Columbia, MO.

Withers, P., Neal, C., Jarvie, H. & Doody, D. 2014. Agriculture and eutrophication: Where do we go from here? Sustainability (Basel, Switzerland), vol. 6, no. 9.

Yates, D.E. 2014. Effects of grassland set-asides on selected soil properties in the Fraser River Delta of British Columbia. MSc Thesis, The University of British Columbia, Vancouver.

Young-Mathews, A., S.W. Culman, S. Sánchez-Moreno, A.T. O'Geen, H.Ferris, A.D. Hollander, & L.E. Jackson. 2010. Plant-soil biodiversity relationships and nutrient retention in agricultural riparian zones of the Sacramento Valley, California. Agroforestry Systems.

Yu, J., Li, Y., Han, G., Zhou, D., Fu, Y., Guan, B., Wang, G., Ning, K., Wu, H. & Wang, J. 2013. The spatial distribution characteristics of soil salinity in coastal zone of the Yellow River Delta. Environmental Earth Sciences, vol. 72, no. 2.

Zhang, Y., Li, Y., Jiang, L., Tian, C., Li, J. & Xiao, Z. 2011. Potential of perennial crop on environmental sustainability of agriculture. Procedia Environmental Sciences, vol. 10.

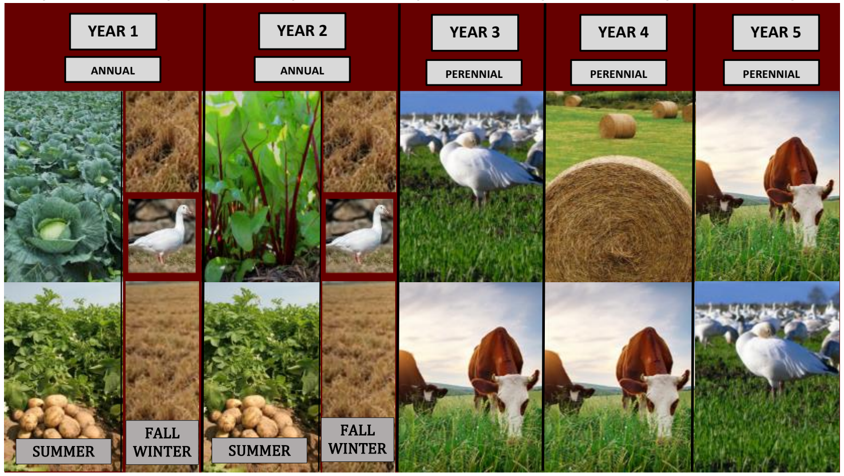
Zbeetnoff, D., & McConnell, R. 2007. Evaluation of the economic impacts from waterfowl damage. Final Report. Identification and quantification of economic losses and compensation options. BC Agricultural Council Agriculture Environment Initiatives

Appendix A - Alaksen five-year crop-livestock rotation schedule (2013 to 2018)

Table **Error! No text of specified style in document.**.1. Alaksen five-year crop-livestock rotation schedule from 2013 to 2018

Field	2013		2014		2015		2016		2017		2018	
	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall
1N	forage	forage	forage	forage	cabbage	cover crop	cabbage	cover crop	forage	forage	forage	forage
1E	cabbage	cover crop	forage	forage	forage	forage	forage	forage	cabbage	cover crop	cabbage	cover crop
1W	cabagge	cover crop	forage	forage	forage	forage	forage	forage	cabbage	cover crop	cabbage	cover crop
1S	forage	forage	potatoes	cover crop	cabbage	cover crop	forage	forage	forage	forage	forage	forage
2	forage	forage	potatoes	cover crop	cabbage	cover crop	forage	forage	forage	forage	forage	forage
3	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop	cabbage	cover crop	forage/pasture	forage/pasture
4	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop	cabbage	cover crop	forage/pasture	forage/pasture
5	forage/pasture	forage/pasture	potatoes	cover crop	cabbage	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture
6	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop	cabbage	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture
14E	potatoes	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop	cabbage	cover crop
14W	potatoes	cover crop	potatoes	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop
15	potatoes	cover crop	potatoes	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop
16	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture
17	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop	cabbage	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture
18	potatoes	cover crop	cabbage	cover crop	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	cabbage	cover crop
19E	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture	forage/pasture

Field	Field Size (acres)	2018	
		Spring	Fall
1N	20	forage	forage
1E	20	cabbage	cover crop
1W	20	cabbage	cover crop
1S	10	forage	forage
2	10	forage	forage
3	35	forage/pasture	forage/pasture
4	22	forage/pasture	forage/pasture
5	23	forage/pasture	forage/pasture
6	40	forage/pasture	forage/pasture
14E	22	cabbage	cover crop
14W	23	cabbage	cover crop
15	32	cabbage	cover crop
16	6.7	forage/pasture	forage/pasture
17	19	forage/pasture	forage/pasture
18	12	cabbage	cover crop
19E	8	forage/pasture	forage/pasture



☐ Rotation schedule at the time of sampling

Appendix B - Map of agricultural fields under crop-livestock rotation at Alaksen

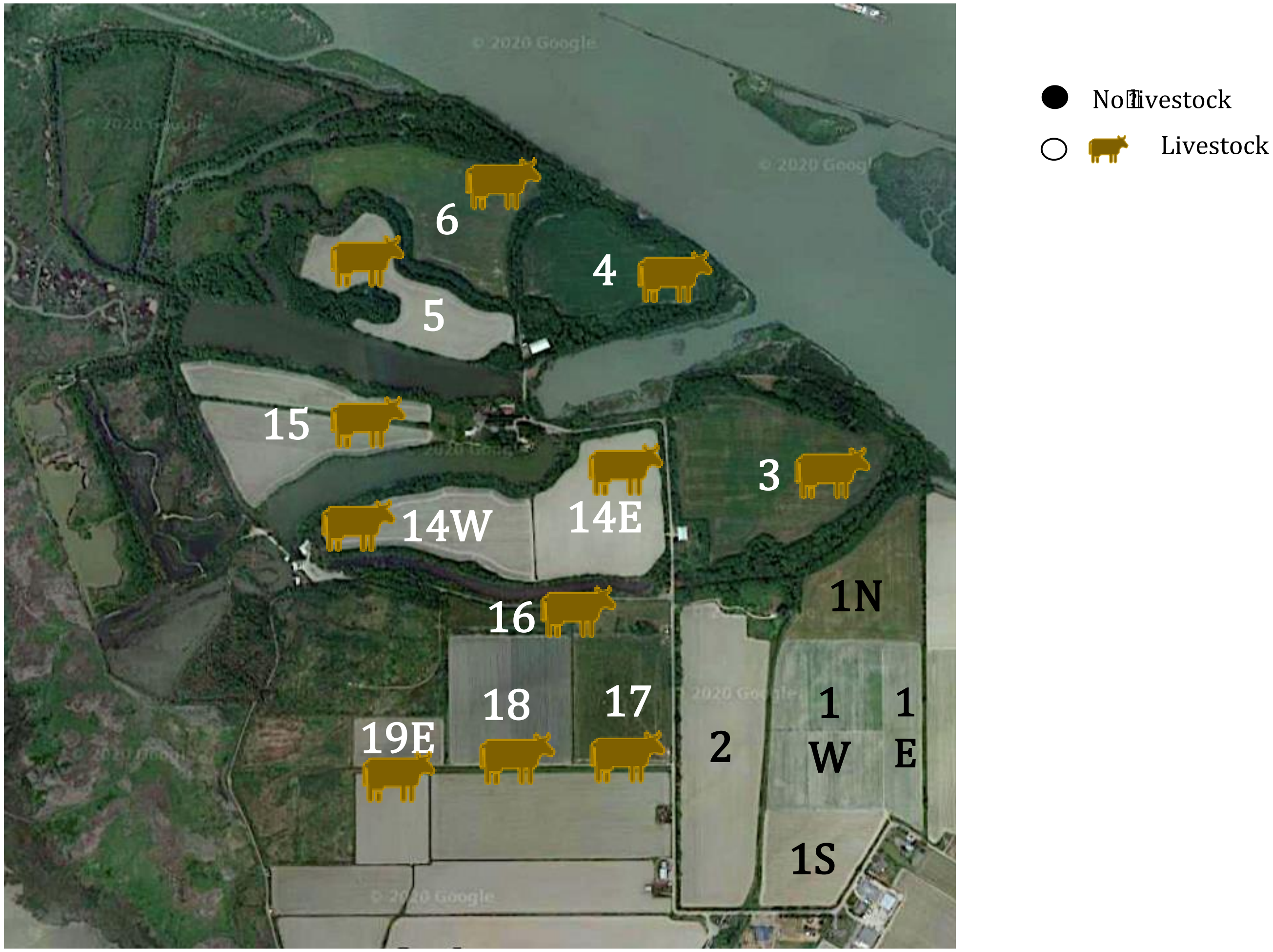


Figure **Error! No text of specified style in document.**.1. Agricultural fields under crop-livestock rotation (white) (3-19E) at Alaksen

Appendix C - Map of fields and forest patches showing randomly selected sampling points (Sep-Oct 2018)

Figure **Error! No text of specified style in document.**.1. Randomly selected sampling points in 16 agricultural fields (red), 3 old fields (yellow) and 3 forested areas (blue) at Alaksen, Sep-Oct 2018

Appendix D - Map of crop-livestock rotation in agricultural fields at time of sampling (Sep-Oct 2018)

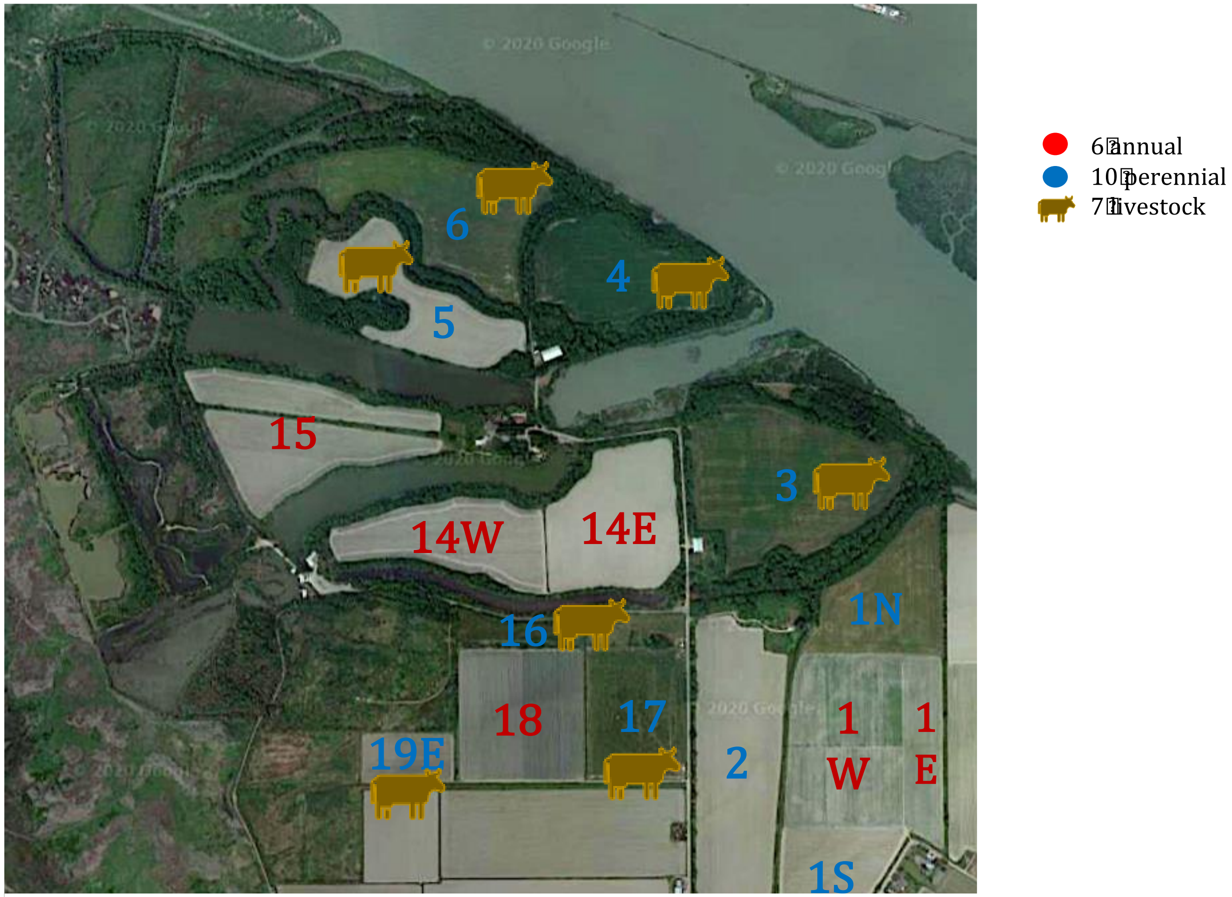


Figure **Error! No text of specified style in document.**.1. Crop-livestock rotation schedule in agricultural fields at the time of sampling (September - October 2018), colour red representing fields under annual crop production, blue under perennial crops, and cattle icon under perennial crop-livestock rotation