EXPLORING HERBICIDE-TOLERANT CANOLA'S CONTRIBUTION TO THE CARBON SEQUESTERED IN SASKATCHEWAN AGRICULTURAL SOILS OVER THE LAST TWENTY-FIVE YEARS

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By

CHELSEA JOANNE SUTHERLAND

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ABSTRACT

In recent decades, Saskatchewan farmers have been progressively shifting towards practices which improve their on-farm sustainability. The adoption of two practices in particular, conservation tillage and the removal of summerfallow, improve soil carbon sequestration by minimizing soil disturbance and increasing crop residue levels. The introduction of numerous agricultural innovations and technologies facilitated the adoption of these management changes. One particular technology, herbicide-tolerant (HT) crops, played an important role in this shift by providing farmers with more efficient and cost-effective in-crop weed control. In Saskatchewan, the most widely planted HT crop is canola. This thesis quantifies the change in soil organic carbon (SOC) levels in Saskatchewan agricultural soils resulting from changes in tillage, summerfallow, and crop rotation practices following the introduction of HT canola in 1995.

Data for the analysis is gathered through a survey of 100 Saskatchewan farmers' land management practices both prior to 1995 and in their most recent crop rotations. The change in SOC between the two time periods is quantified using a carbon accounting framework adapted from the Prairie Crop Energy Model. The framework quantifies changes in SOC levels by aggregating the effects of changes in famers' tillage and summerfallow practices, crop type, crop yield, and residue removal techniques. Carbon coefficients used in the model were developed for Canada's national greenhouse gas inventory reporting. Farmers' attribution of various technologies to their changes in management practices, including HT crops and glyphosate, are also assessed using survey results. On average, participants assign a value of 9.1 out of 10 for glyphosate's contribution to reductions in tillage and summerfallow practices, and a value of 7.3 out of 10 for HT canola. An economic valuation is applied to the change in SOC using three pricing scenarios to create upper- and lower-bounds on the estimate: a carbon marketplace, a carbon tax, and the social cost of carbon. The estimated value for the increase in annual SOC gains on Saskatchewan's cropland is approximately $166 - $384 million from reductions in tillage practices and $459 million - $1.059 billion from reductions in summerfallow practices.

The objective of this study is to provide information to industry, policy makers, and the public of farm-level impacts of management changes relating to SOC gains. This information will help support agricultural representation in discussions regarding environmental and agricultural policy.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
AFOLU	Agriculture, forestry, and other land use
C	Carbon
CO_2	Carbon dioxide
CT	Conventional tillage
BMP	Best management practice
ECCC	Environment and Climate Change Canada
EU	European Union
GHG	Greenhouse gas
GM	Genetic modification
Ha	Hectare
HI	Harvest index
HT	Herbicide-tolerant
IPCC	Intergovernmental Panel on Climate Change
LMC	Land management change
LUC	Land use change
MT	Minimum tillage
NT	No-till
PSCBP	Prairie Soil Carbon Balance Project
SCC	Social cost of carbon
SCIC	Saskatchewan Crop Insurance Corporation
SSCA	Saskatchewan Soil Conservation Association
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WCED	World Commission on Economic Development

CHAPTER 1
INTRODUCTION

1.1 Introduction

Over the past 50 years, awareness of environmental sustainability and climate change have increased and have more recently moved to the forefront of policy discussions, in most, if not all, nations. Globally, governments have united through international agreements to reducing greenhouse gas (GHG) emissions and to mitigate the impacts of changing climates. Policy tools such as carbon taxes and carbon credit systems have been widely implemented with the goal of encouraging adoption of sustainable practices and technologies. In response to these policy initiatives, emission-producing industries are searching for ways to reduce their carbon (C) footprint. The introduction of innovative technologies that improve efficiencies and reduce reliance on fossil fuels helps to reduce the C footprint of many industrial operations.

In the agriculture industry, the adoption of many innovative technologies provides farmers with economic benefits, and this can contribute to environmental sustainability by facilitating the adoption of best management practices (BMPs).[1] One such technology, herbicide-tolerant (HT) canola, was approved for commercialization in Western Canada in 1995 (Smyth et al., 2011). Since its introduction, HT canola has provided producers with substantial economic benefits as indicated by its rapid adoption, which now exceeds 95% (Smyth et al., 2011). Weed control is more efficient and cost-effective, and many farmers have reported that yields have improved, especially through the use of hybrid varieties (Brewin and Malla, 2012; Brookes and Barfoot,

[1] A BMP is a management practice which ensures the long-term health and sustainability of land-related resources used for agricultural production, positively impacts the long-term economic and environmental viability of agricultural production, and minimizes negative impacts and risks to the environment (Government of Saskatchewan, n.d.).

2015). These benefits, along with high prices for canola crops, have helped to make canola an important crop on the Canadian Prairies (Brewin and Malla, 2012).

In addition to producer benefits, environmental benefits have been garnered by the adoption of HT canola through the minimization of tillage as a form of weed control (National Research Council, 2010), decrease in fuel consumption (Brookes et al., 2017), and increasing reliance on more environmentally benign chemicals, especially glyphosate, in place of more harmful chemicals (Fernandez-Cornejo et al., 2011; Hudson and Richards, 2014). One specific contribution of this technology is the improvement of soil C sequestration through the minimization of soil disturbance (Brookes et al., 2017).

Carbon sequestration is an important element of reducing net GHG emissions. It offsets positive GHG emissions by transferring carbon dioxide (CO_2) from the atmosphere into storage in plants through photosynthesis. Much of this C is then transferred into the soil when plant residues break down. Thus, the improved C sequestration achieved by Western Canadian agriculture contributes to Canada's climate change goals. However, despite the existence of literature examining the changes in C sequestration in the first decade of HT canola production, little research exists which quantifies the long-term environmental impacts.

1.2 Research Problem Statement

Since the late 20th century, grain farmers in Western Canada have been progressively shifting away from traditional farming practices, such as frequent tilling of the soil and land left uncropped for a full season, or summerfallow, towards more environmentally sustainable land and soil management practices for both their economic and environmental benefits. Two practices in particular, conservation tillage and the removal of summerfallow, have helped to improve soil organic carbon (SOC) levels through reduced soil disturbance and increased crop residue levels.

Innovative technologies such as improved crop varieties and more efficient equipment have helped to facilitate the adoption of these management practices (Young, 2006). A substantial body of literature exists documenting the role HT crops and the use of complementary chemicals, especially glyphosate, have played in facilitating the implementation of these management practices (e.g. Brookes et al., 2017; Fernandez-Cornejo et al., 2012; Smyth et al., 2011; Zhu and

Ma, 2011). The increasing affordability and availability of glyphosate in the late 1990s and early 2000s contributed to farmers' ability to control weeds effectively prior to seeding and after harvest without the need for frequent tillage. However, the complementary introduction of HT crops furthered farmers' weed control options by providing the opportunity for effective and efficient in-crop weed control. Thus, the adoption of HT canola resistant to glyphosate increased the value and flexibility of glyphosate even further for farmers. Yet, the potential contributions to Canada's climate change objectives made by the adoption of BMPs and innovative technologies in prairie crop production are often overlooked in environmental policy discussions.

It is important for agricultural representation to have a role in climate change conversations. The disconnect between consumers and agricultural production has resulted in the environmental contributions of many agricultural innovations going unrecognized by the public (Sutherland et al., 2020; Williams et al., 2021). In some cases, social concerns raise public pushback against the use of innovative technologies, such as genetically modified (GM) crops or glyphosate, and threaten their continued use (Briere, 2017; Brookes et al., 2017; Glen, 2020). Uncertainties surrounding these technologies are frequently discussed, yet the benefits they contribute are sometimes overlooked (Ryan et al., 2020; Scholderer and Frewer, 2003; Williams et al., 2021). In climate change conversations, agriculture is often perceived as an emission source, despite evidence indicating that much of Canadian agricultural land has acted as, or has the potential to act as, a net C sink (Fan et al., 2019; Smith et al., 2000; Smyth and Awada, 2018).[2] These examples suggest that the information gap between the public and the agriculture sector, and the concerns that arise from it, jeopardize the use of current and future technologies. Though many factors are considered in policy creation, public opinion plays an important role (Anderson et al., 2017).

Improved documentation of how dryland crop farms in Western Canada can assist in combatting climate change will assist in the development of policies which foster growth and innovation in agricultural sustainability. However, before significant progress towards improved agricultural and environmental policies can be made, the effects of sustainable on-farm adoptions, and the attribution of innovative technologies to these adoptions, must be quantified. This research seeks to systematically quantify the change in SOC levels over the past 25 years,

[2] A system acts as a C source when more C is released to the atmosphere than that which is photosynthesized by plants and removed from the atmosphere. A sink exists when the reverse is true (Bhatti and Tarnocai, 2009).

and explore the relationship between these changes and the introduction of HT canola in Western Canada in 1995. Providing quantified data to policy makers and the public regarding the environmental benefits of various agricultural technologies provides an opportunity for the prairie agriculture sector to contribute in a more meaningful way to national and global climate conversations.

The environmental impacts of land management changes are widespread, and warrant a complete life-cycle analysis including input production, field preparation, crop production, grain marketing, and transportation. In addition, a full emission cycle should include estimates for the other main GHGs, nitrous oxide (N_2O) and methane (CH_4). However, a full emission analysis is beyond the scope of this M.Sc. thesis. Furthermore, there are numerous technologies and advances in agriculture, including improvements in crop input technologies, farm machinery, and evolving farm demographics, which contributed to changes in Saskatchewan crop farmers' land management practices. However, these alternative factors are outside the scope of this targeted study of the contributions made by HT canola in Western Canada. So, while acknowledging that multiple factors must be considered to capture the full extent of the changes in net GHG emissions, this thesis focuses on the changes in Saskatchewan SOC levels resulting from changing soil dynamics. Using the year HT canola was introduced in Western Canada, 1995, as a baseline, allows its contribution to these changes in management practices to be explored.

1.3 Objectives of Study

The rapid adoption of HT canola and the subsequent environmental and economic impacts have been studied by many authors (e.g. Barrows et al., 2014; Brookes and Barfoot, 2006, 2017; Smyth et al., 2011; Young, 2006; Zhu and Ma, 2011). Much of this literature indicates that HT canola contributed to improvements in on-farm sustainability by assisting farmers' in reducing tillage and summerfallow. The economic benefits enjoyed by farmers from the adoption of HT canola have also been documented in the literature (e.g. Biden et al., 2018; Brookes and Barfoot, 2015; Gusta et al., 2011; Mauro and McLachlan, 2008). These insights from the literature form the hypothesis that the initial movement towards reduced tillage and summerfallow seen in the first 10-15 years of HT canola production has extended into the most recent decade.

There is also significant literature documenting the positive relationship between conservation tillage, reduced summerfallow, and C sequestration (e.g. Campbell et al., 2005;

Grant et al., 2004; Mikha et al., 2010; Rosenzweig et al., 2018). Concerns of soil erosion, soil degradation, and moisture conservation in the mid-1900s sparked the development of more sustainable farming practices, such as conservation tillage systems. These systems also benefitted from crop rotation diversification, including oilseed and pulse crop additions, as this helped to break up problem pest and disease cycles (Awada et al., 2014). The adoption of these conservation systems helped to improve soil quality and productivity, and contributed to gains in SOC levels through improved carbon sequestration (Awada et al., 2014; Government of Canada, 2021).

Based on the empirical literature, the purpose of this research is two-fold. The first goal is to determine to what extent farmers in Saskatchewan attribute the adoption of conservation agriculture practices such as reduced tillage and summerfallow to the introduction of HT canola. The second goal is to systematically quantify the net SOC changes resulting from changing soil dynamics in the 25-year period since HT canola was introduced in Western Canada. This combination of attribution and quantification will provide an assessment of Saskatchewan dryland crop farmers' shift towards improved soil sustainability. This thesis addresses these two issues by achieving the following four objectives:

1) Analyze the long-term changes in land management practices from 1994-2019;
2) Determine if, and to what extent, HT crops impacted these changes;
3) Quantify the change in C sequestration in Saskatchewan agricultural soils over the last 25 years; and
4) Calculate the economic value of the change in sequestered C.

1.4 Organization of Research

This thesis is composed of six chapters. In the next chapter, the history of climate change policies relevant to Canada are discussed, followed by a review of climate change mitigation strategies for agriculture and the role HT crops have played in facilitating the adoption of these practices. Chapter three provides the survey methodology and the carbon accounting framework used for analysis adapted from the Prairie Crop Energy Model. It also outlines the three scenarios used to calculate upper and lower bounds of the estimated economic value of the changes in SOC. The data collected by the survey and the participant demographics are also presented in chapter three. Chapter four presents and discusses the results of the analysis, including the changes in on-farm management practices seen over the past 25 years, the extent to which farmers attribute the adoption of various technologies to these management changes, the quantification of the changes in soil C sequestration between the two time periods, and the economic value of the SOC. Chapter five discusses the implications of the analysis and how the results might assist in environmental and agricultural policy development. Finally, chapter six provides a brief conclusion, and discusses the limitations of the study and opportunities for further research.

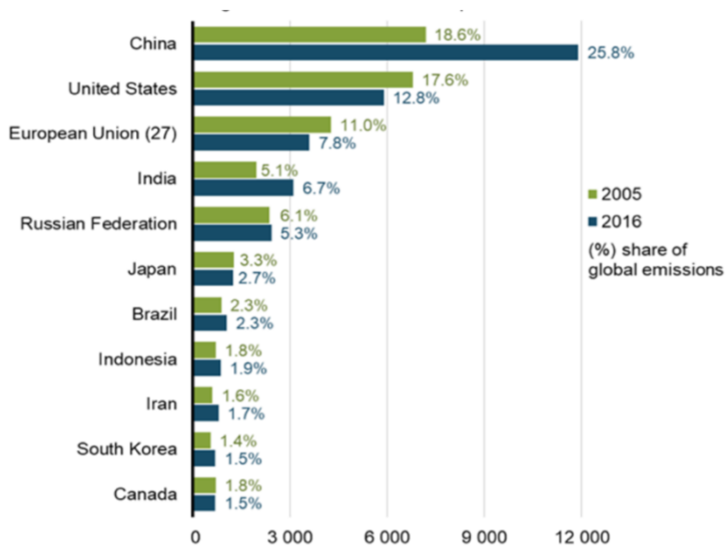
CHAPTER 2
LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

The threat of climate change has shifted the focus of many policy and regulatory decisions towards greater environmental sustainability. In the agriculture industry, this means encouragement to adopt BMPs which improve the sustainability of operations. Although agricultural production is often perceived as a net contributor to Canada's C footprint, an extensive body of literature exists, and is discussed in detail throughout this chapter, which documents the contributions of dryland cropping on the Prairies to Canada's climate change goals through reduced GHG emissions and improved C sequestration through farmers' crop input and land management changes.

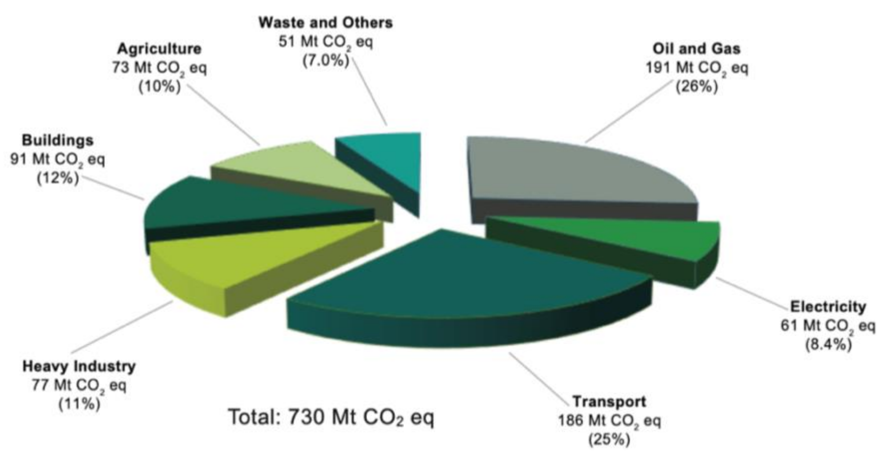
Globally, agriculture, forestry, and other land use (AFOLU) account for approximately 24% of total global GHG emissions (Intergovernmental Panel on Climate Change [IPCC] 2014; United States Environmental Protection Agency, 2019). Canada accounted for approximately 1.5% of total global emissions from all sectors in 2016, decreasing from 1.8% in 2005 (Figure 2.1); however, Canada has one of the highest per-capita emission values among industrialized countries (Environment and Climate Change Canada [ECCC], 2021a). As in most industrialized countries, CO_2 represents the largest portion of Canada's emitted GHGs, making up 80% of total emissions (ECCC, 2021b). The Canadian agriculture sector contributes approximately 10% of national emissions from all economic sectors, following behind oil and gas (26%), transport (25%), buildings (12%), and heavy industry (11%) (ECCC, 2021b) (Figure 2.2).

Figure 2.1 GHG Emissions from Canada and the Top 10 Emitting Regions



Source: ECCC, 2021a

Figure 2.2 Breakdown of Canada's Emissions by Economic Sector



Source: ECCC, 2021b

In the IPCC's fifth report on climate change, AFOLU became a combined sector (IPCC, 2019),[3] after agriculture having its own chapter in the second and fourth reports and having no

[3] The IPCC, a body of the United Nations, is the leading international authority for scientific information on climate change. Since 1990, the IPCC has been developing regular assessments on climate change summarizing current scientific research on global warming. The objective of the IPCC is to provide governments with scientific information to assist in the development of environmental policies (IPCC, n.d.). Many countries make use of the IPCC reports when conducting national climate assessments.

specific chapter allocation in the third. This combination of important sectors into one sector reduces the discussion pertaining to agriculture's contribution to only a portion of a chapter. Additionally, the IPCC Working Groups have little representation from the agriculture sector, with only a handful of vice-chairs and co-chairs of the three Working Groups having agricultural backgrounds or experience (IPCC, 2020).[4]

The IPCC's methods of calculation for agricultural GHG emissions may exclude some important considerations. For example, crops bind C in all parts of the plant including the shoots, roots, and grain (Frankelius, 2020). Yet, although the IPCC's sequestration calculations take into consideration crop residues left in the field, all harvested material is considered "lost" and equivalent to emissions. The underlying assumption is that all biomass removed from the field is emitted in the same year upon product consumption (Frankelius, 2020). Including consumption in the agriculture sector's contribution likely inflates the estimates beyond what can actually be ascribed to agricultural production. Additionally, although C exchange between soils and the atmosphere is often modelled in IPCC reports via diagrams for forestry and other ecological systems, GHG system diagrams for agriculture tend to focus on CH_4 and N_2O emissions and often minimize the net effect of CO_2 emissions and sequestration (Frankelius, 2020).

The improvement of C sequestration is achieved by increased soil C inputs and decreased soil disturbance. Two management practices, conservation tillage and elimination of summerfallow, contribute to increased SOC levels. These sustainable practices have been widely adopted in recent decades, but their adoption would likely not have occurred without the simultaneous commercialization of other innovations. Improved seed varieties, more powerful and efficient equipment, and improvements in fertilizer and chemical technologies have helped to improve the sustainability of farming operations. One innovation in particular, HT technology, assisted in providing farmers with the opportunity to adopt conservation tillage and minimize summerfallow practices as a result of more efficient and cost-effective weed control.

[4] The three Working Groups of the IPCC assess different aspects of climate change. Working Group I assesses the physical science of past, present, and future climate change. Working Group II assesses the effects of climate change on socio-economic and natural systems and identifies options for addressing these impacts. Working Group III focuses on mitigating climate change and assesses methods of GHG emission reduction and removal from the atmosphere (IPCC, 2020).

2.2 Climate Policy

Climate change has been a global concern and focus of international policy since the late-20th century. Urgent concerns regarding the long-term viability of the planet led to the World Commission on Environment and Development (WCED) being tasked with creating a ‘global agenda for change’ by the General Assembly of the United Nations in 1987. The report developed by the WCED called for countries to unite in addressing many global sustainability issues including population increase, food insecurity, urbanization, energy production, and the international economy. Within this report, sustainable development was defined as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987: 41).

In the years following the release of the WCED’s report, concern over climate change spread exponentially, and countries across the globe united to develop environmental policies and negotiate multilateral environmental agreements. In June 1992, the UN Conference on Environment and Development, also known as the Earth Summit, was held in Rio de Janeiro, Brazil (Miller, 1992). At this conference, world leaders met to discuss sustainable development and its relevance to both the environment and the global economy. A number of multilateral agreements were signed at this conference, one of the most important being the United Nations Framework Convention on Climate Change (UNFCCC). This agreement led to the adoption of the Kyoto Protocol in Kyoto, Japan in 1997 (UNFCC, 2011). The objectives of this protocol were to mitigate climate change through the stabilization and reduction of GHG emissions, and to promote sustainable development (Dumanski, 2004). Initially, the emission reduction goal was set at five percent below 1990 levels between 2008-2012. While the second round of negotiations to extend beyond 2012 are complete, this agreement has yet to be ratified by enough countries to enter into force (Smyth and Awada, 2018). This period without an agreement in place led to the negotiations and adoption of the Paris Accord in 2015 (Smyth and Awada, 2018). As part of the agreement, Canada committed to cutting GHG emissions to 30% below 2005 levels by 2030. In an effort to introduce concrete, economy-wide actions with the goal of meeting this 2030 target, Canada implemented its national climate change plan, the Pan-Canadian Framework on Clean Growth and Climate Change, in 2016. This framework is built on four pillars: (1) pricing C emissions; (2) complementary actions to reduce emissions across the economy; (3) adaptation and climate resilience; and (4) clean technology, innovation, and jobs (Government of Canada, 2019).

2.3 Soil Carbon Sequestration

An important element of reducing net agricultural GHG emissions is improving levels of soil C sequestration. Carbon sequestration offsets positive emissions by transferring C from the atmosphere into secure soil storage pools through the process of photosynthesis (Gibson et al., 2002; Lal, 2004; Smyth and Awada, 2018). The capacity of these storage pools are large, but previous studies have indicated they are finite (Powlson et al., 2011). The CO_2 that is removed from the atmosphere by plants and transferred into the soil becomes SOC; thus, increases in SOC represent increased C sequestration.[5] Capacity of the soil C storage pools are estimated to be four times the vegetation C pool and three times the atmospheric pool (Olson et al., 2017).[6] The capacity of each pool depends on soil characteristics, precipitation, and climate (Lal, 2004). Several older studies have estimated that maximum storage pool capacities will be reached 15-20 years after adoption of new management practices (Campbell et al., 2001; West and Post, 2002). However, small changes in sequestration rates can cause substantial changes in C equilibrium timeframes (Nemo et al., 2017; Wutzler and Reichstein, 2006).

More recent studies suggest that through careful management, strategies may be developed to increase the sequestration potential of storage pools (Nath and Lal, 2017; Wutzler and Reichstein, 2006). Three management practices are identified by Paustian (2000) and cited by Jarecki and Lal (2003) as contributing to increased levels of SOC: 1) minimize soil disturbance and erosion; 2) maximize crop residue levels; and 3) maximize efficiency of water and fertilizer use. Decreasing the frequency of tillage operations and increasing cropping intensity by reducing summerfallow are strategies which help to achieve these goals. Recent results from the Saskatchewan Soil Conservation Association's (SSCA) Prairie Soil Carbon Balance Project (PSCBP) suggest that SOC levels are continuing to increase beyond 20-30 years from a change in land management practices (McConkey et al., 2020).

[5] Each tonne of C in the soil represents about 3.67 tonnes of CO_2 sequestered in the past (McConkey et al., 2020).
[6] The vegetation C pool is the reservoir for C storage and release within living plants. The atmospheric C pool is the reservoir for C storage and release within the atmosphere.

2.3.1 Conservation Tillage

Reducing the use of conventional tillage (CT) practices by adopting conservation tillage assists in addressing the first two management practices defined by Paustian (2000). Soil organic matter (SOM) consists of matter from plants and animals in various stages of decomposition. It acts as a reservoir for soil nutrients and also acts as a key binding ingredient for soil aggregates. The C that occurs in this SOM is a main source of food for soil microorganisms. During the process of tillage, soil aggregates are disturbed. This process increases the availability of SOC to microorganisms, resulting in greater levels of CO_2 being released back into the atmosphere through respiration (Awada et al., 2014; Olson et al., 2017). Thus, the use of CT increases net GHG emissions from agriculture.

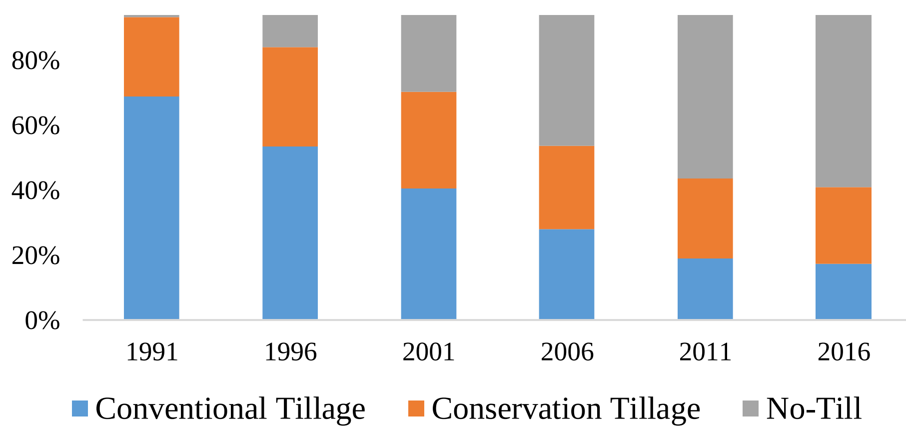
Conservation tillage is a broad term describing systems of crop residue management utilizing no-till (NT) or minimum-till (MT). However, the definition of what constitutes conservation tillage varies in the literature. One method of determining tillage classification is based on the tillage implements used. For example, the use of a moldboard plow or field cultivator traditionally constituted CT (Reicosky et al., 2011; West and Post, 2002). West and Post (2002) classify MT as any tillage operation other than plowing. Smyth et al. (2011) classify harrowing as a MT operation, while Khakbazan and Hamilton (2012) report harrowing as part of NT management. Typically, NT practices are classified as practices where the soil is left entirely undisturbed except for seeding and nutrient injection, and therefore seeding is conducted by creating a narrow slot in the soil using coulters, row cleaners, disk openers, in-row chisels, or roto-tillers (Reicosky et al., 2011).

Another method for determining tillage practice definitions is to construct a tillage index based on factors such as equipment used, number of passes made, and crop residue levels. This method was used by Khakbazan and Hamilton (2012) in their study of the economic costs of various tillage systems. They constructed an index using the residue-reducing effect of different tillage implements, taken from existing literature, and combined this coefficient with the number of passes made to assign an index value between 0-1 for each tillage operation. Based on their index, NT was classified as any value between 0.68-1, reduced-till was any value between 0.35-0.68, and CT was any value less than 0.35.

More often, the types of tillage practices are simply distinguished by their effect on crop residue levels. Widely accepted definitions of each tillage type are taken from the Conservation Technology Information Center in Indiana. These specifications define CT as practices which leave behind less than 15% crop residue cover, reduced tillage as practices that leave behind 15%-30%, and conservation tillage, which includes NT, as practices leaving behind greater than 30% crop residue (Conservation Technology Information Center, 2002). The majority of studies looking at the effects of tillage intensity and frequency use similar definitions (e.g. Awada et al., 2014; Fernandez-Cornejo et al., 2012; Perry et al., 2016; West and Marland, 2002).

As shown in Figure 2.3**,** CT practices have been declining in Canada since the 1990s. Correspondingly, the Government of Canada's SOM Indicator shows a significant increase in SOC in agricultural soils, especially in the Prairies, from the adoption of conservation tillage systems and the complimentary reduction in summerfallow (Government of Canada, 2021). Minimizing tillage also aids in water and nutrient conservation, decreases soil erosion, and contributes to increased crop yield which helps to improve residue levels (Gibson et al., 2002).

Figure 2.3 Adoption of Conservation Tillage in Canada 1991 - 2016



Source: Statistics Canada, 2016

Numerous soil science studies have examined the effects of conservation tillage adoption on C sequestration. In 2002, West and Post conducted a survey of the extensive soil science literature to quantify C sequestration rates, and found an average increase of 0.57±0.14 Mg C per hectare (ha), per year from conservation tillage adoption.[7] McConkey et al. (2003) found SOC increases ranging from 0.067 – 0.512 Mg per ha, per year across Saskatchewan, with variations

[7] One Mg represents one mega-gram, which is the equivalent of one metric tonne.

resulting from soil type and location. Liebig et al. (2005) studied emission mitigation strategies specifically in the Northwestern United States (US) and Canada, and concluded that although the effects of crop management on SOC varied, NT systems in continuous, dryland cropping resulted in an average SOC increase of 0.27±0.19 Mg per ha, per year. More recently, Aziz et al. (2013) studied the impact of tillage practices on soil quality, which was defined based on an index made up of a range of biological, chemical, and physical soil properties. Results of their study found that NT resulted in 30% higher soil C than CT. Similarly, Nath and Lal (2017) studied differences in soil aggregation and SOC resulting from changes in tillage practices. Results of their study showed that corn managed under a NT system sequestered 35-46% more C than CT corn. The SSCA's PSCBP also found conclusive evidence that SOC increased as a result of the shift towards direct seeding between 1997-2018;[8] however, their results were variable and limited by a lack of management data at most test sites (McConkey et al., 2020).[9]

Economic studies which model the effect of conservation tillage adoption on soil properties have also shown positive impacts on C sequestration. A study by Grant et al. (2004) investigated how changes in management practices affected GHG emissions using the DeNitrification and DeComposition model. They found that the average net reduction in emissions from converting to NT was 0.61 Mg CO_2 equivalents per ha, per year in Canada.[10] More recently, Awada et al. (2016) conducted a benefit-cost ratio of NT adoption on the Canadian Prairies. Their study looked at the short- and long-term benefits of NT adoption using the Prairie Crop Energy Model (PCEM). Taking into consideration the expenditures on NT R&D projects as the costs, and benefits such as reduced input costs, net GHG emissions, and wind erosion, and increased production and water use efficiency, the authors concluded that the total estimated economic benefit of NT adoption was $24.4 billion.[11] Using an estimated social cost of $5.00/tonne of C, the authors estimated the present value of C sequestration from the adoption of NT between

[8] In the PSCBP, direct seeding refers to seeding without any tillage preparation of the seed bed.
[9] Fields changed landowners frequently throughout the PSCBP. Sometimes the new landowners did not want to continue with the project, causing variation in the number of samples collected each year. It also resulted in missing management data from various years at many of the sites.
[10] GHG emissions are often discussed in terms of CO_2 equivalents. Converting all GHG emissions to the equivalent amount of CO_2, thereby giving them the same global warming potential, allows for relative comparison of emission sources. The CO_2 equivalent for each gas is calculated by multiplying the tonnes of the emission source by its global warming potential (GWP). To put the impact of each GHG into context, when considering a 100-year time horizon, N_2O has a GWP of 298 (which means one molecule of N_2O has 298 more radiative force than one molecule of CO_2), and CH_4 has a GWP of 25 (Desjardins et al., 2020; IPCC, 2007).
[11] All fiscal figures are discussed in terms of Canadian dollars, unless otherwise indicated.

1985-2012 as $915.6 million. A summary of the literature examining the effects of conservation tillage adoption on SOC is presented in Table 2.1.

Table 2.1 Summary of Conservation Tillage Adoption Literature

Study	Objective	Results
West and Post (2002)	Survey of soil science literature quantifying changes in SOC from conservation tillage adoption	Increase of 0.57±0.14 Mg SOC per ha, per year
McConkey et al. (2003)	Studied changes in Saskatchewan SOC levels from the adoption of conservation tillage	Increase of 0.067 – 0.512 Mg SOC per ha, per year
Grant et al. (2004)	Modelled changes in Canadian GHG emissions from changes in land management practices	NT resulted in net GHG emission reductions of 0.61 Mg CO_2 equivalents per ha, per year
Liebig et al. (2005)	Studied effects of NT in continuous cropping across the Northwestern US and Canada	Increase of 0.27±0.19 Mg SOC per ha, per year
Aziz et al. (2013)	Studied impacts of tillage on soil quality	NT resulted in 30% higher SOC than CT
Awada et al. (2016)	Benefit-cost ratio of Prairie NT adoption	Economic benefit of $24.4 billion from NT adoption
Nath and Lal (2017)	Studied soil quality and aggregation resulting from changes in tillage practices	NT sequestered 35-46% more C than CT
McConkey et al. (2020)	Studied changes in SOC levels across the Prairies from changes in land management practices	SOC increased from the shift towards direct seeding

The positive effects of converting to a NT system may vary based on the time-period and soil depths used for analysis. A meta-analysis by Angers and Eriksen-Hamel (2008) suggests that in the short-term, NT systems may not have a net positive contribution to SOC stocks due to accumulation of C at the soil surface. However, their results show that the benefits of a NT system likely increase with time (>10-15 years). Similar results from Blanco-Canqui and Lal (2008) indicate that gains to SOC as a result of decreased tillage are restricted to the surface soil layers. VandenBygaart et al. (2011) reported SOC increases in both the 0-15 and 15-30 cm depths in Western Canadian soils from the adoption of NT, yet improvements were higher in the 0-15 cm depth. Results from the PSCBP also found SOC changes at greater depths than predicted, reporting SOC gains at the 40 cm depth at some sites (McConkey et al., 2020). Though CT systems might re-distribute residual C throughout the soil profile better than NT in the short-term, the net C gain resulting from a NT system in the long-term offsets this redistribution of C to deeper soil levels with CT (Yanni et al., 2018).

The environmental gains from conservation tillage adoption are not necessarily permanent, and can be reversed if tillage practices revert to conventional. Govaerts et al. (2009) stated that although a high percentage of fields in the US Corn Belt region had adopted NT practices, the average time the fields were maintained in a continuous NT rotation was less than 2.5 years.[12] In Canada, factors such as moisture and climate conditions, pest infestations, and crop residue levels may constrain a farmer's ability to maintain a NT system in the long-term (Government of Canada, 2014). However, the extent to which the positive sequestration effects of conservation tillage adoption are reversed with occasional tillage applications are uncertain and depend on the frequency of tillage. Although C is released from the soil during tillage events, as the duration between tillage events increases, the resulting SOC losses decrease. Within a long-term NT system, SOC losses from a single tillage event can be as low as 1% (Conant et al., 2007). In the long-term, the negative effects of infrequent tillage within a conservation tillage system are not likely to adversely affect SOC content and soil quality (Wortmann and Blanco-Canqui, 2020).

2.3.2 Increasing Cropping Intensity

Reducing Summerfallow Acres

The shift to conservation tillage allows farmers to seed a greater portion of their crop directly into the previous year's stubble, causing a complementary opportunity to reduce summerfallow area (Powlson et al., 2011). Summerfallow is a field left uncropped for a full season. It was first discovered in 1886, and was traditionally used to attempt to conserve soil moisture and improve weed control through frequent tilling or herbicide applications (Awada et al., 2014; Boehm et al., 2004).[13] In some areas of the Prairies, it was common for farmers to employ a 50/50 summerfallow rotation, meaning that 50% of that farmer's cropland would be summerfallowed each year (Soil Conservation Council of Canada, 2004).

To obtain adequate weed control in summerfallow, a minimum of 3-4 annual tillage

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[12] Many farmers in the Corn Belt rotated their tillage practices, especially early in the NT adoption phase, with the goal of optimizing yields and managing damage from pests, disease, and weed competition.

[13] Summerfallow is thought to have been discovered accidentally by Angus Mackay in 1886, when land left uncropped during the Northwest Rebellion produced better yields the following year than adjacent land which had been cropped during both years (Carlyle, 1997).

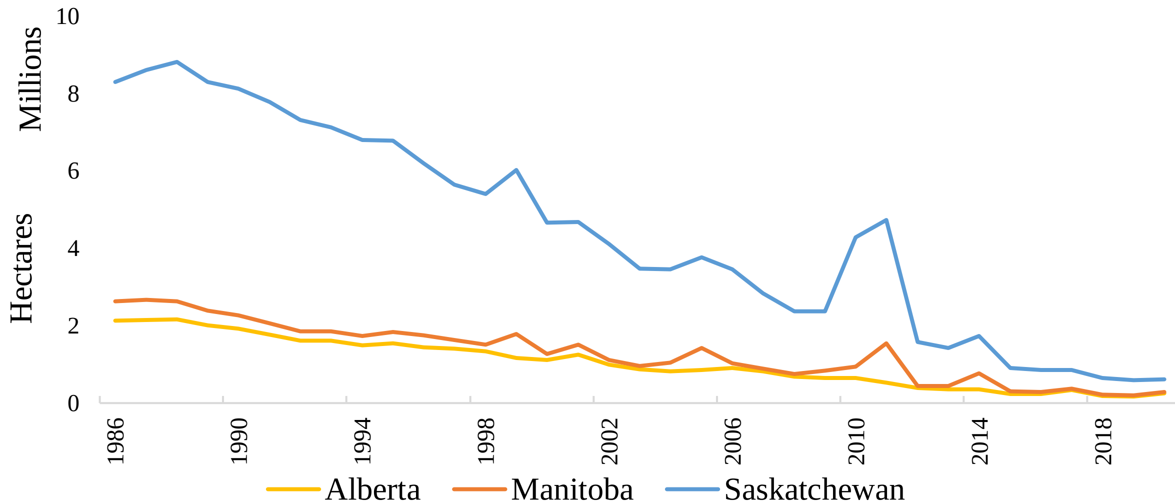
operations were required in Western Canada (Molberg et al., 1967), and often up to eight passes were made depending on the region (Carlyle, 1997). Leaving a field to fallow also results in continued microbial activity and decomposition of available residue in the soil but lacks any residue input, an important factor in increasing SOC stocks, leading to a decrease in SOM (Boehm et al., 2004; Mikha et al., 2010; Soil Conservation Council of Canada, 2004). The combined effect of the frequent tillage and lack of crop residue leads to increased soil erosion, and, in many cases, an unintended decrease in soil moisture. Consequently, SOC stocks typically decrease during fallow years (Ogle et al., 2005). Therefore, decreasing summerfallow area contributes to increased SOC levels by reducing soil emissions and, through the shift to continuous cropping, increasing crop residue levels.

The combination of improved plant genetics, fertilizer, equipment, and chemicals led to a decreased need for summerfallow practices. Statistics Canada (2020) reported that between 1986-2020, summerfallow hectares in Canada decreased by 91%. In the Prairies specifically, summerfallow hectares decreased by 93% over the same time period (Figure 2.4). Saskatchewan has seen the greatest reduction in summerfallow, dropping from 5.66 million hectares of summerfallow in 1986 to 341,000 in 2020 (Statistics Canada, 2020). Based on their cost-benefit analysis, Awada et al. (2016) reported that the rapid reduction in summerfallow area and the resulting increase in crop production represents 32% of the benefits from the adoption of NT.

A number of studies in soil science literature have investigated how reducing summerfallow affects SOC levels. McConkey et al. (2003) studied the effects of summerfallow versus continuous cropping across Saskatchewan, and found annual SOC increases ranging from 0.027-0.430 Mg per ha as a result of the shift to continuous cropping. A 15-year study comparing tillage and cropping intensity effects on SOC found that a decrease in summerfallow significantly increased SOC at the 0-15 cm depth; however, most of these increases were attributed to the 0-5 cm depth (Mikha et al., 2010). Similarly, VandenBygaart et al. (2011) affirmed that the SOC benefits from reduced summerfallow are restricted to the top 0-15 cm of the soil. A 2012 study of summerfallow frequency in spring wheat production on the Canadian prairies showed continuous wheat production gained 1.34 Mg CO_2 equivalents per ha, per year, almost double that of fallow-wheat and fallow-wheat-wheat rotations (Gan et al., 2012). In 2014, a similar study of wheat management practices found comparable, positive SOC benefits from reducing summerfallow (Gan et al., 2014). A study of 96 dryland, NT fields in the US Great

Plains looked at the effects of cropping intensity on SOC, with the results showing that at the 0-10 cm depth, SOC in continuous rotations with summerfallow completely eliminated was 17% higher than wheat-fallow rotations. At the 0-20 cm depth, SOC in continuous rotations was 16% greater than in rotations with summerfallow every 3-4 years and 12% greater than wheat-fallow rotations (Rosenzweig et al., 2018).

Figure 2.4 Change in Summerfallow Hectares in the Prairie Provinces from 1986-2020



Source: Statistics Canada, 2020

Studies looking at the impacts of reducing summerfallow have also been conducted using modelling techniques. For example, Grant et al. (2004) modelled the impact of changes in management practices on Canadian emissions between 1979-2029. They predicted that the net emission reduction from the elimination of summerfallow would be 0.56 Mg CO_2 per ha, per year. In a study of the long-term farm management effects on SOC, Sperow (2016) used 2006 IPCC estimates for SOC factors to study the effects of reducing summerfallow. His results showed that the effects of eliminating summerfallow were relatively modest, increasing SOC stocks by 0.16-0.24 Mg C per ha, per year and contributing about 3% of total potential sequestration from all activities studied. More recently, Rosenzweig and Schipanski (2019) used satellite data to study cropping patterns in Colorado, Kansas, and Nebraska. Overall, their results found a decrease in summerfallow use from 48% to 33% of dryland cropland. The authors assessed the impacts of this cropping intensification on C sequestration, concluding that sequestration increased by 38% due to the adoption of mid-intensity and continuous rotations in place of summerfallow. A summary of the literature examining the effects of the removal of summerfallow on SOC is presented in Table 2.2.

Table 2.2 Summary of Literature Examining Effects of Summerfallow Removal

Study	Objective	Results
McConkey et al. (2003)	Compared changes in SOC levels across Saskatchewan from fallow versus continuous cropping	SOC increases of 0.027 – 0.430 Mg per ha, per year from continuous cropping
Grant et al. (2004)	Modelled changes in Canadian GHG emissions from land management changes	Elimination of fallow resulted in emission reductions of 0.56 Mg CO_2 per ha, per year
Mikha et al. (2010)	15-year study of tillage and cropping intensity on SOC levels	Increase in SOC at the 0-15 cm depth (majority in the 0-5 cm depth) from continuous cropping
VandenBygaart et al. (2011)	Studied impact of sampling depth and land management practices on changes in soil depth	SOC benefits from eliminating fallow are restricted to top 15 cm of soil
Gan et al. (2012)	Studied change in SOC resulting from continuous wheat production compared to fallow-wheat rotations	Increase of 1.34 Mg CO_2 equivalents per ha, per year compared to rotations including fallow
Sperow (2016)	Studied emission effects of eliminating fallow using 2006 IPCC factors	Reducing fallow increased SOC by 0.16-0.24 Mg per ha, per year
Rosenzweig et al. (2018)	Studied effects of cropping intensity on SOC levels in the US Great Plains	At the 0-10 cm depth, SOC in continuous cropping rotation was 17% higher than wheat-fallow rotations
Rosenzweig and Schipanski (2019)	Studied cropping patterns in the US and their environmental impacts using satellite data	A decrease of 48-33% of fallow acres contributed to a 38% increase in sequestration

Increasing Crop Residue Levels

Increasing crop residue levels also contributes to increased accumulation of SOC (Campbell et al., 2002). Crop residues include any roots, stems, or other plant material left in the field after harvest (Follett et al., 1987). Accordingly, the amount of crop residue is affected by crop yield and biomass. Early in the 20th century, crop residues were considered unfavourable and farmers correspondingly took steps to remove residues from their fields. Often, residues were burned or used as livestock feed and bedding (Johnson et al., 2006). However, by 1980 the value of C sequestration and the beneficial contribution made by crop residues to reducing net GHG emissions began to be recognized. Consequently, more farmers began leaving residues in the field (Johnson et al., 2006).

Although in the past many studies assumed that the rate of C input to the soil is similar among crop types, more recent studies have shown that above- and below-ground crop biomass, varies drastically between crop types. Carbon-to-nitrogen ratios impact changes in SOM and SOC levels as well. For example, soybeans have a relatively low carbon-to-nitrogen ratio, and correspondingly, soybean crops typically result in lower C inputs to the soil (Hall et al., 2019). Therefore, crop type is an important factor to consider when estimating changes in SOC (Gan et al., 2009). Gan et al. (2009) calculated C allocation coefficients for various crops which represent how much C is returned to the soil from each part of the plant relative to total C mass. They found, on average, that pulses had the greatest allocation coefficient for seed production, and conversely, oilseeds had the greatest coefficient for straw. For all crops, the allocation coefficients for the roots were lower than for the grain or straw.

An important consideration when studying C sequestration from plant residues is the ability to separate changes in crop yield from changes in crop residue levels. Although an increase in yield means increased C above ground during the growing season, residue levels are not necessarily correlated with yield. In general, crop yields have been increasing faster than plant residues (Subak, 2000). This is because increasing yields improves farmer profitability, and therefore higher yields are selected for in breeding programs. Increasing residue levels through selective breeding might result in reduced yields for some crops, while for others residue and yield might increase simultaneously (Subak, 2000). Increased lodging resistance is another trait often selected for in the breeding process, especially for cereal crops, which led to the development of semi-dwarf varieties in the 1960s (Foulkes et al., 2011). These shorter varieties reduce the crop’s stem length, thereby decreasing the risk of crop lodging while simultaneously decreasing the level of above-ground crop biomass.

Accurate residue levels can be estimated using the harvest index (HI) for each crop (Jarecki and Lal, 2003). The HI is the ratio of the harvested grain to the total above-ground matter of the plant shoot (Unkovich et al., 2010) and is affected by environmental conditions, plant stresses, and cultivar selection (Johnson et al., 2006). The HI is commonly used in C accounting systems by calculating the difference between the C in the plant shoot and in the grain. This index varies significantly among crop types and is largely determined by how efficiently a crop produces grain from the plant matter. Typically, the HI is relatively high for cereal crops because they have high carbohydrate levels. Comparatively, oilseed crops usually have a lower HI because more energy is required to produce grain from lipids (Unkovich et al., 2010). Fan et al. (2017) established relationships between the HI and yield for major crops in the Canadian agricultural system to estimate residue inputs to soils based on the above-ground crop residue, an important element of C sequestration estimations. They found that this relationship was significantly different among most major field crops, but was not significantly affected by cultivar selection.

2.3.3 Farmer Benefits from Carbon Sequestration

Farmers are not only stewards of the land, but also business owners. Thus, changes in management practices which contribute positively to environmental sustainability must provide benefits for the farm business for adoption to occur. In the case of C sequestration, practices which contribute environmental gains have been shown to also provide economic gains for farmers through increased agronomic productivity of their soil. The adoption of many of these BMPs have facilitated the intensification of cropping systems and a complementary reduction in summerfallow acres, allowing farmers to maximize revenues on their agricultural land.

Soil C sequestration is not only an important element of reducing net GHG emissions, but it also benefits farmers' bottom lines. Soil C content is a useful indication of soil quality because in the short-term, its levels can be affected by management changes (Belcher et al., 2003). Soil productivity and agronomic yield are greatly enhanced with increased SOC, especially in soils with low clay content and when coupled with careful use of fertilizer inputs (Lal, 2006). Studies have also concluded that SOC and available water capacity are positively related (Emerson, 1995; Hudson, 1994). Lal (2006) indicates that enhancing SOC in degraded soil contributes to enhanced agronomic performance by increasing water capacity, improving soil nutrient content, and enhancing the structure and other physical properties of the soil. These benefits, in-turn, provide economic gains to farmers. Belcher et al. (2003) used a simulation model, composed of both environmental and economic sub-models, to estimate the economic value of soil quality for farmers. Their results found that the marginal user benefit of SOC increases ranged from \$3.85/tonne per ha to \$40.44/tonne per ha in the brown and black soil zones under study. [14]

[14] The marginal user benefit can be defined as the present value of the net revenue increase that can be attributed to an increase in soil quality of one unit (Belcher et al., 2003).

The reduction or elimination of disturbance to the soil layers in a MT or NT system also benefits farmers economically by reducing soil erosion, which has substantial effects on agronomic performance. Bakker et al. (2007) estimated that in mechanized agriculture, for every 0.1 m of soil loss, crop yields are reduced by 4% in the European Union (EU) and North America. No-till systems leave the majority of crop residues on the soil surface instead of incorporating them into the soil profile. The resulting increase in residues helps to increase SOM content and decrease the negative impacts of erosion. Additionally, crop residues on the soil surface will reflect sunlight and conserve moisture by lowering the temperature of the soil and protecting it from high evaporation levels (Jarecki and Lal, 2003; Sauer et al., 1996). All of these impacts have an effect on soil quality which affects agronomic performance and crop yield.

2.4 HT Canola Adoption

HT canola was introduced in Western Canada in 1995 and planted on a limited and controlled number of acres in 1995 and 1996 for seed multiplication purposes. In 1997, the HT varieties were made commercially available to farmers and were rapidly adopted, with total adoptions surpassing 95% of total canola production on the Canadian Prairies by 2004 (Smyth et al., 2011). By 2012, all varieties tested in the 2012 Canola Performance Trials were hybrid HT varieties (Manitoba Agriculture, Food and Rural Initiatives, 2013). An important reason for this rapid uptake is the benefits enjoyed by farmers resulting from the improved and more cost-effective post-emergent weed control of HT technology (Brookes and Barfoot, 2015). In a 2002 survey of farmers in the US, 65% of participants indicated that their main reason for adopting HT soybeans was increased yields from improved weed control, and 20% indicated that decreased pesticide costs was their main motivating factor (Fernandez-Cornejo et al., 2002). More than 85% of respondents in a similar post-adoption survey in Australia reported that weed control either improved or remained the same after HT canola adoption (Hudson and Richards, 2014). Correspondingly, results from the Canola Council of Canada's survey of transgenic canola use saw, on average, a 10% yield increase for farmers who planted transgenic varieties compared to farmers who planted conventional varieties. Based on system-wide estimates, Brewin and Malla (2012) estimate that average farmer benefits from the adoption of HT canola in 2012 were over $1 billion. However, farmers commonly report that their main motivation for adoption was agronomic qualities such as simplified weed control. Economic benefits, such as higher net returns, were secondary (Canola Council of Canada, 2001; Graef et al., 2007; Mauro and McLachlan, 2008).

An important complementary technology to HT canola is the chemical, glyphosate. Glyphosate was introduced in Western Canada in 1976 under Monsanto's trade name, Roundup™ (Beckie et al., 2019; Holm and Johnson, 2009). The chemical was initially expensive for farmers, ranging from \$65-\$130 per acre (Holm and Johnson, 2009). In 2000, the expiry of Monsanto's patent resulted in more affordable, generic versions of the chemical, and correspondingly, glyphosate usage increased (Beckie et al., 2019). Glyphosate provides superior weed control through its high level of phytotoxicity to plants, making it a valuable tool for use in pre-seed and post-harvest burn-off applications. Its effective and efficient weed control, coupled with its decrease in price upon patent expiration, helped farmers to reduce their need for tillage applications (Awada et al., 2014). Prior to the introduction of HT crops resistant to glyphosate, attempts were made to use the chemical in row crops by avoiding contact with the crops, but unacceptable levels of crop damage constrained its use for in-crop applications. This constraint was lifted with the introduction of HT crops resistant to glyphosate (Duke, 2018).

Genetically-modified HT canola varieties resistant to the chemical glufosinate (LibertyLink varieties) and mutagenic varieties resistant to specific imidazolinone herbicides (Clearfield varieties) were also introduced in the late 1990s. In the first ten years of HT canola production on the prairies, however, varieties resistant to glyphosate (Roundup Ready) were the most commonly planted. In 2000, Roundup Ready varieties composed 40% of Canada's canola acreage, compared to 15%, 25%, and 20% of acres planted to LibertyLink, Clearfield, and conventional varieties, respectively. By 2005, 93% of canola acres in Canada were planted to HT varieties, with 45% of these acres planted to Roundup Ready varieties, and 34% and 14% planted to LibertyLink and Clearfield varieties, respectively. By 2010, however, improvements in LibertyLink varieties closed the gap between the acres devoted to the HT systems, with Roundup Ready varieties making up 47% of Canada's canola acreage and LibertyLink varieties making up 46% (Canola Council of Canada, n.d.).

Herbicide-tolerant technology contributes many environmental benefits including a reduction in fuel use (Brookes and Barfoot, 2017; Smyth et al., 2011), a reliance on more environmentally-benign chemicals such as glyphosate (Egan, 2014; Fernandez-Cornejo et al., 2011), and a decrease in total chemical active ingredient applied (Brookes and Barfoot, 2017). Yet, one of the most notable contributions of HT technology is the opportunity it provides for farmers to move away from CT practices due to its enhanced in-crop weed-control options (Barrows et al., 2014; Brookes and Barfoot, 2017; Carpenter, 2011; Thomson, 2018; Zilberman et al., 2013). The facilitation of these changes in management practices has helped to increase soil C sequestration and reduce net GHG emissions from prairie dryland crop production.

2.4.1 HT Canola and Sustainable On-Farm Practices

The adoption of HT canola in Saskatchewan assisted farmers in adopting a number of conservation agriculture practices. The HT trait allows farmers to control a broad spectrum of weeds through in-crop applications without damaging crops, reducing the need for tillage operations. Correspondingly, farmers who grow HT canola are more likely to adopt conservation tillage practices (Hudson and Richards, 2014; National Research Council, 2010). Similar results have been seen in HT soybean production. In 1997, soon after the introduction of HT soybeans, twice the number of acres under NT were planted with HT soybean than those with conventional soybean in the US (Fernandez-Cornejo and Caswell, 2006). Results from a 2006 survey of 1,195 US farmers across six states (Iowa, Illinois, Indiana, Mississippi, North Carolina, and Nebraska) found a complementary relationship between the adoption of conservation tillage and HT crops. Of farmers in the survey who had previously used CT, 56% adopted MT or NT systems following the introduction of HT crops, and 25% of farmers who had been practicing MT shifted to NT (Givens et al., 2009). Similar results from a 2009 survey of US farmers showed 80% of respondents believed there was less tillage in HT production than in conventional production (Harrington et al., 2009). The complementary relationship between these technologies has also been studied using economic and econometric modelling techniques. Many studies have concluded in favour of this relationship (e.g. Fernandez-Cornejo et al., 2012; Fernandez-Cornejo et al., 2002; Mensah, 2007; Perry et al., 2016).

The reduction in frequency of tillage practices may have been facilitated by additional factors such as changes in farm and equipment size, reductions in the cost of glyphosate, and improved crop genetics (Awada et al., 2014; Carpenter, 2011; Young, 2006); however, extensive literature suggests that HT crops contributed to the widespread adoption of conservation tillage systems (Beckie et al., 2006; Fernandez-Cornejo et al., 2012; Graef et al., 2007; Zhu and Ma, 2011). Although the frequency of tillage practices was decreasing moderately prior to 1995, difficulty in applying herbicide mixtures which controlled weeds effectively without damaging crops constrained this trend (Brookes, 2014; Egan, 2014; Perry et al., 2016). The rapid and widespread adoption of conservation tillage after 1995 illustrates how HT technology assisted in lifting these previous constraints (Egan, 2014).

The opportunity to reduce or eliminate tillage assists farmers in minimizing soil disturbance and maximizing crop residue levels, two of the three key management practices identified by Paustian (2000). Conservation tillage adoption and reduced summerfallow acres are complementary management changes. Thus, the shift towards conservation tillage facilitated by HT canola also facilitated the opportunity for farmers to reduce summerfallow. Results from the Canola Council of Canada's (2001) report, which shows that the number of summerfallow acres approximately doubled in their sample of farmers planting conventional canola relative to those planting transgenic canola, supports this assumption.

The complementary relationship between the rapid adoptions of HT canola and conservation tillage practices resulted in corresponding changes in GHG emissions. Brookes and Barfoot (2006) studied GHG emissions in the first ten years of HT canola production by comparing HT production with a conventional alternative. Their study concluded that the potential soil C sequestration savings from the adoption of HT canola in Canada was 1.08 billion kg of CO_2. In 2017, they updated these results to represent 20 years of HT canola production, and estimated that 2.51 billion kg of CO_2 were sequestered between 1996-2015 from a reduction in fuel use and additional C sequestration related to conservation tillage adoption (Brookes and Barfoot, 2017). Smyth et al. (2011) conducted a similar study looking specifically at the environmental impacts in the first decade of HT canola production in the Canadian Prairies. Their results showed over 3.3 million hectares were produced under NT in 2006, corresponding to 436,000 tonnes of annual C sequestration relative to CT production. Assuming a market value of \$5.00/tonne of C, the economic value of the sequestered C was \$2.18 million.

Twenty years after the introduction of HT canola, Shrestha et al. (2014) conducted a GHG inventory analysis of canola production between 1986-2006. The authors found that canola production had increased rapidly on the Canadian Prairies since 1986. Their results showed an overall decrease in the C footprint of canola production due to land management changes.

Specifically, they found that an annual reduction in summerfallow sequestered 0.4 Mg CO_2 equivalent per ha, while a shift towards conservation tillage sequestered 0.2 Mg CO_2 equivalent per ha. Two years later, MacWilliam et al. (2016) compared the environmental effects of canola production between 1990 and 2010 on the Canadian Prairies. The results of their study showed that GHG emissions from one tonne of canola production were reduced between this time period in all of the soil zones when land use changes (LUCs) and land management changes (LMCs) were considered.[15] They attribute these changes to reduced fossil-fuel use from a decrease in tillage applications and other management changes in fertilizer and pesticide use.

2.5 Summary

This review of the literature highlights some key components of the move to increased sustainability in dryland crop farming on the Canadian Prairies, the improvement of C sequestration and its contribution to reducing net GHG emissions, and the role played by the adoption of HT crop varieties. The widespread adoption of conservation tillage practices has increased C sequestration by minimizing soil disturbance and retaining crop residues after harvest. Both of these practices increase the level of SOC remaining in the soil, thereby decreasing the C released back to the atmosphere. Additionally, conservation tillage allows for increased moisture retention in the soil, providing farmers the opportunity to reduce or eliminate summerfallow in their rotations, increasing crop residue levels and reducing soil C losses. Together, these practices make up a key component of conservation agriculture, the widespread adoption of which has allowed prairie dryland farming to contribute in a meaningful way to Canada's climate change goals.

The adoption of HT crops has provided environmental benefits including a reduction in herbicide active ingredient applied and a reduction in fuel use. Notably, however, HT crops facilitated the adoption of conservation tillage by providing enhanced, flexible weed control opportunities for farmers through the use of post-emergent pesticide applications. Although conservation agriculture practices were increasing incrementally since the late 1990s, their rapid uptake after 1995 illustrates that the introduction of HT crops was a contributing factor. Although

[15] LUCs refer to land being converted from one use to another and LMCs refer to changes in the management of agricultural lands, such as reducing tillage or summerfallow acres (MacWilliam et al., 2016).

it is difficult to separate the effects of HT crops from improvements in farm machinery, farm size, fertilizers, pesticides, and other management practices, much literature exists which indicates that HT crops, coupled with the use of complementary chemicals such as glyphosate, facilitated the adoption of these practices.

Although many studies have looked at the changes in farm management practices in the early years of HT crop adoption, few studies have looked at management practices beyond ten years after adoption. Furthermore, few studies exist which attempt to both investigate the attribution of HT canola to management changes, and subsequently quantify the environmental impacts of these changes. Thus, the novelty of the present thesis is the combined objectives of attribution and quantification, as well as the 25-year time period which allows for investigation of the long-term impacts of HT crop adoption.

CHAPTER 3
DATA AND METHODOLOGIES

3.1 Introduction

This thesis provides quantified estimates of SOC changes in Saskatchewan agricultural soils resulting from changes in crop production practices over the past 25 years, corresponding with the introduction of HT canola in 1995. The quantification is calculated through the use of a C accounting framework modelled after the PCEM. The economic value of the SOC changes is also calculated using three different pricing scenarios. An additional analysis gauges to what extent farmers attribute the adoption of various innovative technologies to the adoption of sustainable management practices.

Data for the analysis was collected through the Saskatchewan Crop Rotation Survey, conducted through the University of Saskatchewan. This survey collected on-farm management data from Saskatchewan farmers between the periods of both 1991-1994 and 2016-2019. The survey is broken into four sections: seeding, fertilizer, tillage, and chemical use. Data from the survey provides a comprehensive overview of participants' on-farm operations during the years under study.

The PCEM accounting framework is used to provide an estimate of the net change in on-farm SOC levels resulting from the adoption of NT and MT systems, minimization of summerfallow, and changes in crop rotations. Analyses are conducted on both provincial and in-province regional scales to provide snapshots of the changes in environmental sustainability related to C sequestration. Three separate C pricing scenarios, a carbon market, a carbon tax, and the social cost of carbon (SCC), provide upper and lower bounds of the economic value of the SOC.

3.2 Survey Methodology

3.2.1 The Crop Rotation Survey

The Crop Rotation Survey is broken into four components. The first section follows the seed from planting to harvest, examining the practices, equipment, and inputs used for seedbed preparation, planting, and harvest. The second section documents application rates, methods, and timings of fertilizer use. The third section examines tillage and summerfallow practices by documenting the number of tillage applications, tillage depth, and implements employed. The final survey section focuses on chemical use, and asks respondents to record the timing, application rates, equipment used, and chemicals applied for all chemical applications. Farmers chose one single field to report on throughout the survey, and if possible are asked to report on the same field for both the 1991-1994 and 2016-2019 time periods. The questions are open, closed, and partially-open, and space is provided for farmers to include more information, if necessary, to clarify their answers. Each of the four survey components took participants approximately 45 minutes to one hour to complete, resulting in an average of three to four hours to complete the survey in its entirety.

An additional questionnaire at the end of the survey addresses the important question of attribution. Questions in this section ask farmers to comment on to what extent they believe each of HT crops, GM crops, and glyphosate can be attributed to the adoption of conservation tillage and reduced summerfallow. First, participants are asked to assign a factor from one to ten for each of the three technologies, representing its role in facilitating the adoption of NT and the removal of summerfallow. A factor of one means the technology did not at all facilitate the adoption and a factor of ten means the technology played a major role. Next, participants are asked to estimate what percentage of their land would include summerfallow management in the absence of HT crops. Finally, participants are given the opportunity to comment on what would be different about their operation today without the use of HT crops, other GM crops, and glyphosate. The cumulative responses from these attribution questions provide an overview of to what extent Saskatchewan farmers attribute the adoption of sustainable management practices to the introduction of various technologies over the past 25 years.

Though responses are optional for the majority of questions in the survey, a number of questions require participant responses. Questions in the screening section are required to ensure that participants are eligible to participate in the survey, including farm location and the years in which they actively farmed. The demographical questions also require responses, including whether or not participants accessed farm records to complete the survey. Other required questions include the number of years in their respective crop rotations, if they use global positioning systems, precision or automatic sensing technology, or drones in their operations, if they are collecting, storing, or using on-farm data to improve productivity or marketing, if their topsoil depth had increased, decreased, or stayed the same over the past 20 years, and if dockage had changed between the two time periods. Both of these final questions included a required follow-up question asking by how much these metrics had changed (if applicable).

Questions relevant for this analysis include factors that affect changes in SOC levels. The location of a farmer's field is used to segment the responses into regions, and the seedable acres of the field is used to quantify the relative impact of the change in farm management practices per ha. The crops planted and their yield are used to calculate the HI, an important factor for determining crop residue levels. In addition, the residue management practices identified determine whether the crop residues have a positive effect on soil C sequestration.[16] The reported frequency and timing of tillage applications, as well as the tillage implements used, help to classify tillage practices as NT, MT, or CT. Finally, the reported frequency of summerfallow in a four-year rotation is important for identifying those farmers, in both time periods, who have removed summerfallow from their crop rotations.

The University of Saskatchewan requires all surveys to be reviewed and approved by an ethics committee. However, the Research Ethics Board has indicated that if human subjects are not the direct focus of an intended survey and that the objective of the survey is to gather non-human data, faculty are able to apply for an exemption from ethics approval. The objective of this survey is non-human data. Dr. Smyth submitted the full survey for ethics review, requesting an exemption. The Research Ethics Board quickly reviewed the survey, agreeing that the objective of the survey was non-human data and granted an official exemption from ethics approval.

The Crop Rotation Survey will continue to be circulated in the future to collect consistent

[16] Although chopping and spreading crop residues is the most commonly practiced form of residue management, some farmers may bale crop residues for livestock use, or burn them. If residues are removed from the field, they will not have the same positive effect on soil C sequestration.

data on farm management changes. Due to the opportunity for future application, this survey has intellectual property value. Therefore, the survey itself cannot be publicly revealed to the full extent. However, the specific survey questions from which responses were taken for this thesis analysis are presented in Appendix A.

3.2.2 Farmer Recruitment

To gather the data for this study, Saskatchewan farmers were surveyed on their production practices both prior to the introduction of HT canola (1991-1994) and in their most recent crop rotation (2016-2019). A series of focus groups consisting of approximately 25 farmers each were planned across Saskatchewan at 19 locations between November and December of 2020. Six of these locations were within a 150 km radius of Saskatoon and the rest were located across the province. When choosing locations for the focus groups, the aim was to ensure that at least one event was held within each Census Agricultural Region in each of the nine regions of the province.

In October 2020, the number of active Covid-19 virus cases in Saskatchewan increased substantially. This increase threatened the safety of workshop participants as well as the researchers if in-person meetings were to go ahead across the province. At this time, the provincial government made the first of several reductions in the maximum number of people allowed to participate in public gatherings. In light of the increased number of positive Covid-19 cases, the decision was made in late October to move all Crop Rotation Survey participation online. Online delivery of the survey allowed Saskatchewan farmers to complete the survey online, from home. Participants were given the choice of which week throughout November to January they would prefer to complete the survey. The survey link was emailed to them on Monday morning of the week they selected, and they had until Friday afternoon to complete all survey components. Additional time was provided if necessary. To incentivize farmer participation, financial compensation of up to $200 was provided to participants by way of e-transfer or cheque upon completion of the survey. As there were four components in the survey, farmers earned $50 for each component completed. Thus, if they completed all four survey components, they received $200.

Farmer recruitment efforts included a social media campaign promoted with the help of the

Saskatchewan Ministry of Agriculture, Saskatchewan commodity groups, the Saskatchewan Agricultural Grads Association, and various industry contacts. The main social media channels used for promotion were Facebook and Twitter. An article about the Crop Rotation Survey and its importance to Saskatchewan farmers was published in the Western Producer on December 3, 2020. Announcements about the survey were made on local radio stations, in local newspapers, and on local community Facebook pages and events calendars. In addition to these communication channels, word of mouth from friends, family, and other farmers in the community helped to promote the survey.

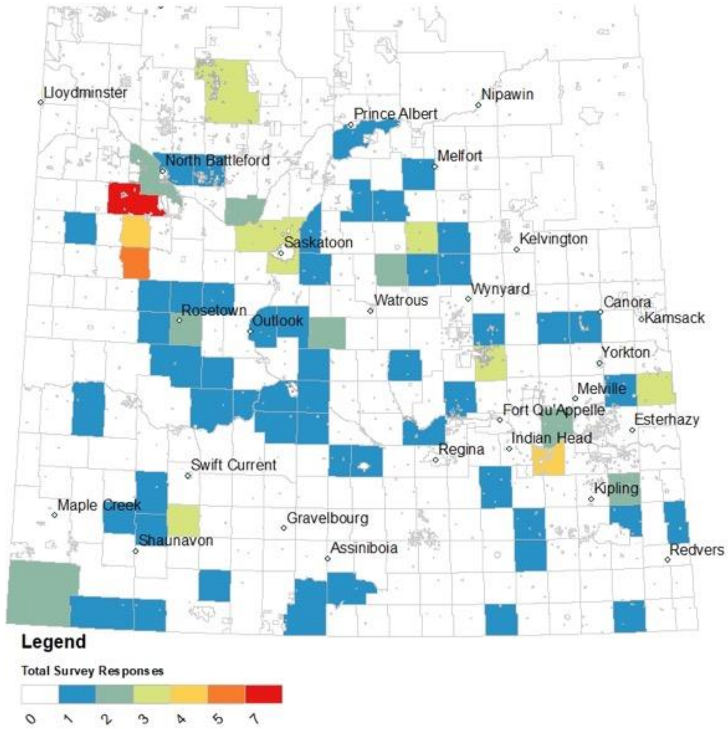
3.3 Data

3.3.1 Survey Responses

The survey was completed by 107 Saskatchewan farmers by the end of January. After removing responses that lacked complete information or were duplicates from the same farm operation, the remaining sample size was 100 responses. Fifty-two of these participants fully completed the sections corresponding to the 1991-1994 production period, and 99 completed the sections corresponding to the 2016-2019 production period. Fifty-one participants successfully completed all questions corresponding to both time periods. Given the sample size of 100, and using the population of 21,505 Saskatchewan grain and oilseed farmers taken from the 2016 Canadian Census of Agriculture, results from the survey sample have a 95% confidence level with a 10% margin of error. When considering the length of the survey, and the level of detail involved in its completion, the sample size of 100 provides sufficiently robust results for the analysis. The sample size of those who farmed in the 1991-1994 time period (n=52) out of the population of 58,650 Saskatchewan crop farmers in 1991 provides a 95% confidence level with a 14% margin of error for responses from this time period only (Statistics Canada, 2009).

Survey participants were located across the province with relatively even distribution. Participants provided representation from each of the nine provincial regions, ranging from Southwest to Northeast. Figure 3.1 shows a map of Saskatchewan indicating where the survey participants were located, grouped by rural municipality. The colours on the map indicate how many participants were located in each rural municipality, as shown in the map legend. The highest number of participants were located in the Northwest region of the province, and the fewest in the Southcentral region.

Figure 3.1 Map of Provincial Survey Participant Locations



Based on the low sample size of survey participants, it is important to benchmark participant demographics against other sources to determine how accurately the sample reflects the population of Saskatchewan farmers. The demographics of the total sample population align with the demographics from the Saskatchewan participants of the 2016 Canadian Census of Agriculture (Table 3.1). The survey sample population, overall, is younger, has a higher level of education, and operates larger farms than the Census of Agriculture sample. These distinctions are likely the result of participants who pursued post-secondary education themselves being more interested in contributing to academic research such as this project. In addition, younger farmers might be more comfortable with completing surveys online, and therefore might have been more likely to participate in the online delivery of this survey. Overall, however, the sample is representative of Saskatchewan farmers and provides a sufficient dataset to analyze further.

Table 3.1 Total Participant Demographics Compared to Saskatchewan 2016 Census of Agriculture Data

	Crop Rotation Survey	2016 Census of Agriculture
Age		
Under 35	25%	10%
35-54	44%	34%
55 +	31%	56%
Education		
Post-secondary education (diploma or degree)	64%	48%
Highschool diploma	31%	35%
No highschool diploma	3%	17%
Prefer not to say	2%	-
Collect Off-Farm Income		
Yes	40%	42%
No	60%	58%
Farm Size		
Under 399 acres	5%	30%
400 - 759 acres	10%	15%
760 - 1,119 acres	8%	10%
1,120 - 1,599 acres	9%	10%
1,600 - 2,239 acres	12%	10%
2,240 - 2,879 acres	13%	7%
2,880 - 3,519 acres	5%	5%
3,520 acres or more	37%	13%
Prefer not to say	1%	-

3.3.2 Conversion from Imperial to Metric Units

In the survey, farmers were asked to report their answers in terms of the imperial unit, including acres for area under each crop activity and bushels per acre (bu/ac) when reporting crop yield. All analyses in this thesis, however, are conducted using metric units. It is therefore necessary to convert all response data from imperial units to metric units. To complete the conversion from acres to hectares, an additional column was added in the Excel spreadsheet containing the relevant data. One acre is equivalent to 0.404686 hectares. Each cell in the additional Excel column is formatted to contain the multiplication factor of 0.404686 for the data in the acres column, automatically converting all field size data from imperial units to metric units.

The conversion of the yield data from bu/ac to metric tonnes per ha (t/ha) is more complex, as the conversion factor from bushels to metric tonnes varies among the crop types. This is because bushels are based on the test weights of the crops, which means that high-density crops weigh more than low-density crops. Therefore, it is necessary to have a separate conversion factor to calculate tonnes from the reported bushels for each crop type. The factors used to convert bushels to tonnes in this analysis are taken from the Alberta Agriculture and Forestry's online Bushel/Tonne Converter tool and the online Grain Unit Converter from FarmLead (Table 3.2).

Table 3.2 Bushels to Tonnes Conversion Factors

Wheat[1]	36.744
Oats[1]	64.842
Barley[1]	45.93
Rye[1]	39.368
Flax[1]	39.368
Canola[1]	44.092
Soybeans[1]	36.744
Peas[1]	36.744
Lentils[2]	36.744
Canary Seed[1]	44.092
Mustard[1]	44.092

Source: (Alberta Agriculture and Forestry, n.d.[1]; FarmLead, n.d.[2])

Inserting these conversion factors, as well as the factor used to convert acres to hectares, into Equation 3.1 results in conversion factors for bu/ac to t/ha for each crop type (Table 3.3). All reported yields are multiplied by the corresponding crop type's bu/ac to t/ha conversion factor within the Excel spreadsheet containing the data to complete the unit conversion.

Equation 3.1 Conversion from bu/ac to t/ha

$$\frac{1\ bu}{ac} = \frac{1\ tonne}{crop\ specific\ conversion\ factor} * \frac{1\ ac}{0.404686\ ha} = \frac{t}{ha}$$

Table 3.3 Bu/ac to t/ha Conversion Factors

Wheat	1 bu/ac = 0.06725 t/ha
Oats	1 bu/ac = 0.03811 t/ha
Barley	1 bu/ac = 0.05380 t/ha
Rye	1 bu/ac = 0.06277 t/ha
Flax	1 bu/ac = 0.06277 t/ha
Canola	1 bu/ac = 0.05604 t/ha
Soybeans	1 bu/ac = 0.06725 t/ha
Peas	1 bu/ac = 0.06725 t/ha
Lentils	1 bu/ac = 0.06725 t/ha
Canary Seed	1 bu/ac = 0.05604 t/ha
Mustard	1 bu/ac = 0.05604 t/ha

3.3.3 Data Assumptions

A number of assumptions have to be made about the data in order to produce consistent results from the model. First, previous research has suggested that the initial level of SOC affects the amount of C sequestration that can occur. This variability in sequestration potential is related to the concept of SOC saturation, which suggests that the closer soil is to its SOC saturation point, the less SOC it will continue to sequester. However, no conclusive evidence of this saturation point exists, as observations exist both of soils with high levels of SOC gaining further SOC and soils with low SOC losing SOC. In addition, there does not exist sufficient base level SOC estimates across Saskatchewan for 1995 in existing literature. Therefore, in this analysis all soils are assumed to have the same initial SOC levels, resulting in the same sequestration potential.

Within the existing literature, classification of tillage practices as NT, MT, and CT are varied. For the present analysis, some important assumptions about tillage system classification must be made based on previous literature. VandenBygaart et al. (2008) differentiate CT and MT practices in the semiarid prairies and the subhumid prairies. According to their study, CT in the semiarid prairies is classified as any cultivator or other tillage implement used at least once per season, and more than once in the subhumid prairies, and MT is classified as one pass with the cultivator or other tillage implement in the subhumid prairies. Smyth et al. (2011) classify harrowing as MT in both regions. No-till is classified as production with no soil disturbance aside from direct injection of seed and nutrients into the soil by Reicosky et al. (2011).

Therefore, spring or fall anhydrous ammonia application is not classified as a tillage application because the nutrients are injected directly into the soil with minimal soil disturbance. Based on these assumptions, in this study, CT is classified as one or more cultivation passes in the semiarid prairies and more than one in the subhumid prairies in each year, MT in the subhumid prairies is classified as one cultivation pass, harrowing is classified as a MT operation in both regions, and NT in both regions includes no tillage or harrow applications.

In addition, the changes in management practices observed between the time periods are assumed to have occurred relatively linearly and consistently. This means that, unless the data indicates otherwise, the change in tillage and summerfallow practices is assumed to be permanent. The data only provides information on management practices that occurred in the two distinct time periods under study, but does not provide insight on the linearity or consistency of these changes between the time periods. As discussed in the literature review, reversion back to conventional practices can emit some of the C that has been sequestered from conservation practices. However, the data to determine the permanence of these practices between the time periods is not collected through this survey, resulting in the need for this assumption.

3.4 Carbon Accounting Framework

Systematic quantification of GHG emissions is often accomplished through the use of C accounting frameworks. Accounting models systematically quantify emissions and removals of GHGs by combining modelling techniques with empirical data. Similar to a financial accounting system, reductions in GHG emissions count as ‘credits’ in the accounting framework, while increases in emissions or decreases in removals act as ‘debits’ (ECCC, 2014). The net of C debits and credits results in the net GHG emissions for the period under study. Carbon accounting models have been widely used to estimate net C fluxes to and from the atmosphere in studies of the environmental effects of agricultural production (e.g. Marland et al., 2003; Smyth and Awada, 2018; Smyth et al., 2011).

Methodologies used for quantification of GHGs range from basic accounting methods using empirical emission factors to complex models using detailed, process-based calculations (Cowie et al., 2012). Under the UNFCCC, Canada is required to report its annual estimated net GHG emissions using an accounting framework. The Canadian Agriculture Greenhouse Gas -

Monitoring Accounting and Reporting System model (CanAG-MARS) is used to calculate the emissions and sequestration of GHGs resulting from LUCs and LMCs for this report (VandenBygaart et al., 2008; ECCC, 2014). Other commonly used models within the literature include the Century Model initially developed by Parton et al. (1987) and the RothC model developed by Coleman and Jenkinson (1996). Although various accounting methods are employed across the literature, the underlying assumptions, calculations, and aspects of production included in the calculations remain similar.

3.4.1 The Prairie Crop Energy Model

One specific accounting framework developed for quantification purposes is the PCEM. This model was originally developed by Nagy (1999) to estimate agricultural energy input, output, and efficiency. The PCEM separates the prairie region into 22 cropping districts as per the Statistics Canada Crop Districts. The land suitable for growing crops within each cropping district is allocated to one of 122 cropping activities based on the production system in place and the crops produced (Awada et al., 2016). Since its development, the PCEM has been adapted for a variety of studies looking at various inputs and outputs of agricultural production on the Prairies (e.g. Awada et al., 2016; Huang, 2015; Smyth and Awada, 2018).

The PCEM accounting framework was used in a benefit-cost analysis of NT adoption and the complementary reduction in summerfallow conducted by Awada et al. (2016). To calculate the benefits of NT adoption, each cropping activity was assigned a vector of coefficients representing environmental and economic factors. The aggregate hectares managed using the various cropping activities within each district were multiplied by the corresponding coefficients, summed to provide quantified cost and benefit estimates, and multiplied by output and factor prices to provide dollar value estimates. Numerous short- and long-run benefits were identified as a result of NT adoption, including increased production, reduced costs, improved soil quality, and increased water use efficiency. Costs of NT were calculated from research expenditures on the development of NT technology. Results of the study estimated that for every $1 invested by the public sector into NT technology, the agriculture sector gained $109.30.

The accounting framework used in this thesis is similar to the adapted PCEM accounting framework used by Smyth and Awada (2018) in their assessment of Saskatchewan GHG sources and sinks. One element of their study specifically calculated the C sequestration resulting from the adoption of NT and reduced land left to summerfallow, and adjusted for crop residue levels and the associated biomass. In their study, each cropping activity employed in each year within each district was assigned a coefficient representing the environmental impacts of the adopted activity, such as the adoption of NT and reduced land left to summerfallow. The C change coefficients used for these calculations were adapted from several empirical studies which estimated the rates of C sequestration on the Canadian Prairies resulting from LUCs and LMCs. Coefficients to account for increased crop residues were also included in the calculations. These values were adjusted based on the crop yield and the type of crop produced, as the HI varies between crop types. Additional factors used in the calculation of C sequestration include the rate of residual C input to the soil and the ratio of the molecular weight of CO_2 to C.

Adaption of the PCEM Accounting Framework for the Present Thesis

In the present study, the cropping activities used in the accounting framework focus on two land management changes: the change in tillage practices between CT, MT, and NT, and the elimination of summerfallow from a four-year crop rotation. The soil C change coefficients are adjusted to account for changes in crop residue levels. This adjustment is based on the HI, which is a factor of the crop type and the crop yield. Harvest index impacts changes in SOC, as crops with a higher HI have lower residue levels and therefore return lower levels of C to the soil (Yang et al., 2013). The adjustment to the C coefficients are such that above-average crop yields increase the sequestration rate while below-average crop yields reduce it (Awada and Nagy, 2020). Yields of grain crops have increased significantly over the past 25 years, with Saskatchewan wheat, canola, and barley yields increasing by 57%, 109%, and 41%, respectively, between 1995-2020 (Statistics Canada, 2020). Therefore, it is important to account for this change in crop yields, and the subsequent changes in residue levels, when calculating C sequestration.

Currently, the extent of the interactive effects between the net SOC gains from the adoption of conservation tillage and the removal of summerfallow have not been confirmed in the literature (McConkey et al., 2003). It is estimated that the SOC levels would increase by more from the combination of the two practices together than from either individual practice, but this change would likely not equal the sum of the effects (Smith et al., 2001). Therefore, in the present analysis, the changes in SOC levels from these two management practices are calculated and presented separately. Changes in SOC levels resulting from changes in tillage practices are calculated using Equation 3.2 and from changes in summerfallow, Equation 3.3.[17]

One key difference between the analysis of Smyth and Awada (2018) and this thesis is how crop residue removal is accounted for. In their analysis, Smyth and Awada accounted for the possibility of removal or burning of crop residues by only considering residue levels above 3.33 tonnes per ha. In the data collection for this thesis, respondents were asked what methods of residue removal, if any, were used in their fields. This data allows for direct estimation of remaining crop residue levels for each method of residue removal. For fields where residues were not removed, no adjustment for residue removal is needed. In cases where residues were burned or removed for livestock use, crop residues are assumed to have no positive effect on C sequestration, as the majority of residues will be removed instead of returning to the soil.

Equation 3.2 Changes in SOC from Changing Tillage Practices

$$CST_t = \sum_{i=1}^{9}\sum_{j=1}^{3} [A_{jti} * SR_{ji}] * [R_{jti} * RR] * RT_{ti}$$

Equation 3.3 Changes in SOC from Changing Summerfallow Practices

$$CSSF_t = \sum_{i=1}^{9}\sum_{j=1}^{2} [A_{jti} * SR_{ji}] * [R_{jti} * RR] * RT_{ti}$$

Where:

CST_t = the change in SOC resulting from a change in tillage practices and adjusted for crop residue levels in each year *(t)*.

$CSSF_t$ = the change in SOC resulting from the inclusion or removal of summerfallow from crop rotations in each year *(t)*.

$\sum_{i=1}^{9}$ = summation of cropping practices in each of the nine crop regions *(i)*.

$\sum_{j=1}^{3}$ = summation of sequestration effects from the three tillage systems *(j),* NT, MT, and CT.

[17] Only sequestration coefficients for cropping activities that contribute positively to sequestration, NT, MT, and the elimination of summerfallow, are adjusted for crop residue levels and residue removal techniques. Coefficients for practices that emit carbon, CT and the inclusion of summerfallow, are simply multiplied by the area under that cropping practice, as positive soil emissions are not affected by post-harvest crop residues.

$\sum_{j=1}^{2}$ = summation of sequestration effects from the inclusion or removal of summerfallow *(j)*.
A_{jtj} = area under each form of tillage or summerfallow *(j)* in each year *(t)* in each region *(i)*.
SR_{ji} = the rate of SOC change from each cropping practice *(j)* in each region *(i)*.
$R_{jti} = \left(\frac{Y_{ti}}{HI_{ti}}\right) * (1 - H_{ti})$, where $HI_{ti} = \alpha_i + (\beta_i * Y_{ti})$, = the post-harvest crop residues from each cropping activity *(j)* in each year *(t)* in each region *(i)*, calculated using the total biomass and returned crop residue. Y_{ti} is the crop yield (Mg/ha) in each year *(t)* in each crop region *(i)* and HI_{jti} is the HI of the cropping activity *(j)* in each year *(t)* in each crop region *(i)*. The HI is calculated using the relationship between crop yield and HI, where α_i denotes the intercept and β_i denotes the coefficient for each region *(i)* in this relationship (Fan et al., 2017).
RR = 0.3 = rate of C input to the soil from crop residues (Maillard et al. 2018; Smyth and Awada, 2018).
RT_{ti} = dummy variable for the residue removal technique used by the farmer in each year *(t)* in each region *(i)*. If residues are removed from the field upon harvest, this variable is assigned a value of zero, indicating that no positive sequestration occurs. If the residues are chopped and spread in the field, the variable is assigned a value of one.

3.4.2 Soil Carbon Change Factors

Soil C change factors are an important element of studying agricultural GHG emissions through modelling techniques. Though measuring changes in SOC through soil sampling techniques is the most accurate quantification method, it is often not possible or practice to physically measure SOC changes, especially over large regions and long time periods. Carbon change factors are used in most national GHG inventory systems to produce annual estimates of net emissions. These coefficients can be developed by synthesizing estimates from the empirical literature or through the use of modelling techniques. In the C sequestration equation found in Smyth and Awada (2018), coefficients were adapted from empirical studies of C sequestration in Western Canada. However, the coefficients found in empirical literature are quite variable and depend on factors such as soil quality, baseline SOC levels, sampling depths, and time period under study. Their application to accounting frameworks are also limited because few studies have sufficient measurements of SOC changes over time (VandenBygaart et al., 2008).

In 2001, Smith et al. used the Century Model to develop C coefficients for a number of on-farm management strategies for the major soil zones in Canada. Their estimates range from 0.06-0.194 Mg C per ha, per year for the adoption of NT, 0.02-0.085 Mg C per ha, per year for the adoption of MT, and 0.085-0.177 Mg C per ha, per year for the removal of summerfallow. More recently, the Century Model was used by McConkey et al. (2007) to derive C coefficients for use in Canada's CanAG-MARS model. These coefficients were used to produce estimates of the changes in SOC levels resulting from changes in LUCs and LMCs for Canada's 2006 GHG Inventory Report. To this day, the coefficients developed by Agriculture and Agri-Food Canada (AAFC) in 2007 remain the most up-to-date factors used in Canada's GHG reporting (Cerkowniak, D., personal communication, April 24, 2020).

In 2008, VandenBygaart et al. compared the C factors derived by McConkey et al. (2007) to estimates calculated using the IPCC's tier 1 methodology and from estimates in the existing empirical literature.[18] Results of their comparison showed that the 2007 modelled factors were comparable, but consistently lower than the IPCC factors. The authors attributed this partly to different management practices and partly to the cold Canadian climate slowing the sequestration process. The Century modelled factors also fell within the confidence limits created from the synthesis of empirical estimates from long-term studies of LUCs and LMCs. Based on the results of the analysis, the C factors adapted from McConkey et al. (2007) are used in the present analysis as they are more targeted to the Canadian climate under study, they fall within confidence limits of the IPCC factors and the existing empirical literature, and they provide more conservative estimates for the sequestered C (Table 3.4).

The coefficients in Table 3.4 represent changes in management practices. They were developed assuming constant management practices, as would be the case in small-plot studies of changing SOC levels. In studies such as these, each plot of soil is assigned a consistent treatment for the duration of the study.[19] However, as discussed in the literature review, deviations from farmers' typical management practices are common in real-world scenarios for

[18] The IPCC has three methodologies for using change factors to estimate SOC fluxes from agricultural land. The tier one approach uses default SOC factors for general LMCs estimated from a large body of literature. The tier two calculation is similar, but incorporates country-specific SOC factors and soil types. The tier three approach is more complex, and makes use of dynamic models to compute annual SOC changes in response to LMCs (VandenBygaart et al., 2008).

[19] In small-plot, replicated studies, each plot of soil is assigned a treatment, such as one cultivation prior to seeding and one post-harvest, which remains constant throughout the duration of the study. One plot within each replication is designated the 'check', and is typically treated using the current production status quo. The results from each of the treatments are compared to the 'check' plots to determine the effects of the differences in treatment.

reasons such as atypical weather conditions, necessary residue management, or problem weed infestations. Therefore, the application of these C coefficients to real-world data must take into consideration small deviations in farmers' management practices. Positive coefficients for NT and MT practices and the negative coefficient for CT (representing C emissions rather than sequestration) are applied based on the tillage practices used each year; therefore, within the four-year period under study, the sequestration rate per year from tillage practices might fluctuate. This would occur, for example, if a farmer practiced NT in year one and then practiced MT in year two before switching back to NT management in years three and four.

Table 3.4 Carbon Change Coefficients

Carbon Change Factors (Mg/ha/yr)	
Semiarid Prairie	
NT	0.1
MT	0.04
CT	-0.1
Removal of Summerfallow	0.3
Inclusion of Summerfallow	-0.3
Subhumid Prairie	
NT	0.15
MT	0.07
CT	-0.15
Removal of Summerfallow	0.3
Inclusion of Summerfallow	-0.3

Source: McConkey et al., 2007; Smyth et al., 2011; VandenBygaart et al., 2008

The coefficients representing the inclusion or elimination of summerfallow practices, however, are not assessed on a year-by-year basis. Instead, they represent long-term increases or reductions in summerfallow area. Therefore, these coefficients cannot be used to determine the difference in SOC changes between fallow years and crop years within a four-year rotation containing summerfallow. Instead, they can only be used to determine differences in SOC gains between rotations containing summerfallow every two-three years and rotations in which summerfallow has been eliminated. For this reason, the positive coefficient for the removal of summerfallow (0.3 Mg per ha, per year) is only applied to hectares on which summerfallow management has been completely eliminated.

3.5 Economic Value of the Sequestered Carbon

Though the previous calculations will provide quantified estimates of the change in SOC levels between 1991-1994 and 2016-2019, it is also important to consider the economic implications of this sequestration. Providing the economic value of the environmental impacts of the adoption of sustainable on-farm practices serves to put the results into a context suitable for policy makers. However, it is difficult to choose only one method to apply an economic value to the SOC, as numerous C pricing and valuation techniques are in place today. Thus, for the purpose of this study, three separate scenarios are used to calculate upper and lower bounds for the estimates of the economic value of the SOC changes:

1. A carbon removal marketplace
2. The Canadian carbon tax
3. The Canadian estimate for the SCC

3.5.1 Carbon Removal Marketplace

A Seattle-based company, Nori, recently created the world's first carbon removal marketplace. On this market, carbon removals, representing one ton of CO_2 removed from the atmosphere, are bought and sold. The framework behind this marketplace is composed of three steps: 1) farmers remove C from the atmosphere and store it in their soils by adopting sustainable on-farm management practices, 2) a third-party verifies the farmers' carbon removals, and 3) buyers in the marketplace purchase these farmers' removals and receive a certificate of purchase from Nori (Nori, 2021).[20] Recently, US farmer Trey Hill became the first farmer to sell carbon removals for his cover- and root-cropping strategies on this marketplace. His carbon credits sold for $16.50 USD/ton (Corbley, 2021).

This market price of $16.50 per ton of CO_2 serves as the valuation for the carbon removal marketplace scenario. Prior to its application, however, it must be converted to 2019 CAD/tonne to remain consistent with subsequent valuations. The Bank of Canada's 2019 exchange rate is

[20] Buyers of carbon removals include businesses who wish to offset their own C emissions, or individuals who want to support and encourage environmental sustainability through the removal of C from the atmosphere (Nori, 2021).

$1.3269 CAD = $1.00 USD. This results in $21.8938 CAD/ton of CO_2 removed. Next, the price must be converted from imperial tons to metric tonnes. One imperial ton is equal to 0.9072 metric tonnes. Therefore, the Nori market price per tonne of CO_2 removed is $19.86 2019 CAD.

3.5.2 Carbon Tax

A carbon tax policy allows governments to set the price of GHG emissions. In response to the tax, emitters will attempt to reduce their emissions to avoid paying the tax. This policy differs from a market system in that it allows for certainty and stability in the price of C, but not in the level of emissions. In this sense, a carbon tax provides a simple incentive for emission reduction and a steady stream of tax revenues which can be redistributed or invested in beneficial projects. Typically, C is priced low when the tax is first implemented and gradually increased to encourage emission reductions over time.

The Canadian federal carbon tax, which came into effect in 2018, initially priced emissions at $10/tonne. This price was set to rise by $10 each year, reaching $50/tonne in 2022 (Statistics Canada, 2017). Canadian provinces and territories were given the option to implement their own C pricing mechanism. Saskatchewan released its C pricing plan in 2018 which applied mainly to large industrial facilities. Emissions from the industries not covered under the province's plan are priced under the federal pollution program. Therefore, for the purpose of this study, the C price for agricultural producers under the carbon tax scenario is the 2019 federal carbon tax value of $20/tonne of CO_2.

3.5.3 Social Cost of Carbon

The SCC is a different valuation system than a carbon tax or carbon market. In Canada, this measure is an important tool for cost-benefit analysis of regulations which pose to reduce or increase GHG emissions. According to ECCC (2016), the SCC represents the monetary value of the damage resulting from one additional tonne of CO_2 being emitted in a given year. Calculation of the SCC involves determining the impacts of the assumed global path of CO_2 on elements of the climate including temperature, precipitation, and weather events, as well as the physical impacts of these changes. After these physical impacts are determined, they must be assigned a monetary value. After deliberation by the Canadian Group in 2010-2011 on the best way to implement an SCC,[21] it was decided that given the extent of work devoted to the US SCC and the technical expertise involved, it would be best to simply adapt the US values for Canada (ECCC, 2016). Furthermore, because the economies of Canada and the US are integrated in many ways, it was decided that the integration of this metric may actually be beneficial.

The estimated SCC values were initially established in 2011 for the period from 2010-2050. In 2013, the US released updated SCC estimates reflecting new insights from scientific and economic research. Correspondingly, the Canadian Group updated their estimates to reflect these changes (Table 3.5). The Canadian estimates use a discount rate of 3% unlike the US estimates which are calculated at three separate discount rates.[22] Because the rates are listed in terms of 2012 CAD, they need to be updated to reflect monetary inflation rates. Using the Bank of Canada's Inflation Calculator,[23] the value of $40.70 in 2012 equates to $45.89 in 2019. Thus, for the purpose of this thesis, a value of $45.89/tonne of CO_2 is used to estimate the economic value of the sequestered C under the SCC scenario.

Table 3.5 SCC Estimates 2010-2050 (In 2012 CAD Using a 3% Discount Rate)

Year	Previous central	Updated central	Previous 95th percentile	Updated 95th percentile
2010	27.6	34.1	108.6	131.5
2013	29.4	37.4	116.5	149.3
2015	30.7	39.6	121.8	161.1
2016	**31.3**	**40.7**	**124.5**	**167.0**
2020	33.9	45.1	135.1	190.7
2025	38.1	49.8	151.2	213.3
2030	42.2	54.5	167.4	235.8
2035	46.4	59.6	183.6	258.9
2040	50.5	64.7	199.6	281.9
2045	54.2	69.7	213.9	300.9
2050	57.8	74.8	228.0	319.8

Source: ECCC, 2016

[21] The working group for Canada's review of GHG valuation approaches was a Government of Canada Interdepartmental Working Group known as the Canadian Group (ECCC, 2016).
[22] Discount rates are used to place present value on future costs, as the effects of climate change will occur well into the future. The use of a positive discount rate places a lower value on future costs, while the use of a lower value places a higher value on future costs. A discount rate of zero, alternatively, would equivalate future costs to present costs.
[23] The Bank of Canada's Inflation Calculator can be found at: https://www.bankofcanada.ca/rates/related/inflation-calculator.

3.5.4 Summary of the Economic Valuation Scenarios

Table 3.6 summarizes the economic values to be assigned to the SOC based on the three scenarios considered in the analysis. The values present upper and lower valuation bounds. The carbon removal marketplace scenario represents the lowest value for each tonne of CO_2 sequestered and the SCC represents the highest. The wide range of these upper and lower bounds results in a high confidence level for the estimated economic value of the sequestered carbon.

Table 3.6 Estimated Economic Values Per Tonne of Sequestered CO_2 Equivalents

Valuation Scenario	**Economic Value/tonne CO_2 (2019 CAD)**
Carbon Removal Marketplace	$19.86
Carbon Tax	$20
SCC	$45.89

3.6 Summary

Carbon accounting frameworks are commonly used to quantify net emissions of GHGs to and from the atmosphere. One such framework, adapted from the PCEM, was used by Smyth and Awada (2018) to quantify the net GHG emissions in Saskatchewan resulting from changes in on-farm management practices. This thesis analysis uses a similar accounting framework to quantify net SOC changes resulting from changes in tillage, summerfallow, and crop rotation practices. Soil C coefficients used in this analysis are those developed by AAFC in 2007 for conducting Canada's National Inventory for GHG Reporting.

The data for this analysis is collected through a survey of Saskatchewan farmers' management practices during the periods of both 1991-1994 and 2016-2019. Additional questions at the end of the survey ask farmers to comment on their perception of the attribution of various technologies to sustainable management adoptions. Responses from a sample of 100 Saskatchewan farmers provides a sufficiently robust dataset to perform analysis on. Demographics of this sample are comparable to those of the 2016 Canadian Agricultural Census; however, the average survey participant is slightly younger, has achieved higher education, and operates a larger farm than the average participant in the census data.

Providing an estimation of the economic value of the change in SOC is an important additional element of this analysis. Economic valuations help to provide context for the results of the analysis, especially from a policy-making standpoint. Three different valuation scenarios are identified to provide upper and lower bounds on the economic value of the SOC. These scenarios are: 1) a carbon removal marketplace, 2) the Canadian carbon tax, and 3) the Canadian SCC.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Introduction

Over the past 25 years, farmers have shifted towards more environmentally sustainable on-farm management practices. Specifically, the widespread adoption of conservation tillage, the removal of summerfallow practices, and the complementary increase in cropping intensity has impacted agricultural soil dynamics, leading to changes in SOC levels. However, the long-term changes in SOC seen over the past 25 years have not yet been quantified at the farm level. The following sections address four objectives in order to quantify the change in Saskatchewan agricultural SOC levels since HT canola was introduced: 1) identify the changes in on-farm management practices, 2) discuss farmers' attribution of innovative technologies, including HT canola and the complementary chemical, glyphosate, to the adoption of sustainable management practices, 3) quantify the changes in SOC resulting from these management changes, and 4) apply an economic valuation to the sequestered C.

The changes in on-farm management practices are quantified and aggregated to both the regional and provincial level to determine how the adoption patterns changed and if these trends differ by provincial region. In addition, a cross-tab analysis identifies any farm characteristics that impact the likelihood of a farmer's decision to adopt conservation tillage or remove summerfallow from their operations. Farmers' perceived attribution of innovative technologies, including HT canola, glyphosate, and other GM crops, to the adoption of sustainable agricultural practices is then assessed on both a quantitative and qualitative scale to provide some insights into how important these innovations were in farmers' decisions to change on-farm practices.

After determining the extent of the management changes and farmers' attribution of various technologies to these changes, the resulting changes in SOC between the time periods is quantified using an adapted C accounting framework. A sensitivity analysis of these results identifies the significant variables in both time periods, and indicates how sequestration levels would change with varying changes in input levels. Finally, three different C pricing scenarios are applied to the SOC gains to estimate the economic value of the changes. This economic valuation helps to put the results of the analysis into an economic context for policy makers.

4.2 Changes in On-Farm Management Practices

Results from the survey show that on-farm management, including tillage and summerfallow practices in Saskatchewan, changed dramatically in the 25 years following the introduction of HT canola in 1995 (Table 4.1). During 1991-1994, the most commonly practiced tillage system across all provincial regions was CT, followed by MT. On average, only 13% of hectares were managed under a NT system annually in 1991-1994. Just over half (54%) of hectares were in a crop rotation that did not include summerfallow at least once in a four-year period. Twenty-five years later, during 2016-2019, 61% of hectares were being managed under a NT system, and only 3% of hectares were being managed under CT, on average. Hectares that included summerfallow as part of their crop rotations decreased by 45% during this time period.

Table 4.1 Changes in On-Farm Management Practices

	1991-1994 Average	**2016-2019 Average**	**Change**	**p-value**
Hectares with fallow completely eliminated	54%	99%	44.7%	0.001
CT Hectares	55%	3%	-51.7%	3.24E-05[24]
MT Hectares	32%	37%	4.6%	0.530
NT Hectares	13%	60%	47.1%	7.56E-09

Fifty-one survey participants completed questions regarding both the 1991-1994 and 2016-2019 time periods, compared to 100 total participants. Therefore, it is important to compare results from the total sample between only those that completed both sections to determine if any differences in management practices exist between these two participant samples. As shown in

[24] The scientific notation, *n*E*x,* is used when values are either very large or very small. For example, 3.24E-05 means 3.24 times ten to the minus five power, or 0.0000324.

Table 4.2, the changes in management practices followed similar trends for both the total sample of participants and for only the sample of participants who farmed during both time periods. T-tests are used to test the significance of the difference in the percentage of hectares under each cropping system in each time period between the total survey sample and the sample of participants who completed questions regarding both time periods. Results of the t-tests reveal no statistical differences in the tillage and summerfallow practices between the sample of respondents who farmed during both time periods and the total survey sample at the 95% confidence level (Table 4.3).

Table 4.2 Changes in On-Farm Management Practices of Those Who Farmed in Both Time Periods

	1991-1994 Average	**2016-2019 Average**	**Change**	**p-value**
Hectares with summerfallow eliminated	55%	100%	45%	0.006
CT Hectares	55%	1%	-54%	1.74E-05
MT Hectares	32%	29%	-3%	0.766
NT Hectares	13%	70%	57%	1.96E-06

Table 4.3 Differences in Management Practices Between Participants Who Farmed During Both Time Periods and Total Survey Sample

1991-1994 Average			
	Those Who Farmed During Both Time Periods	**Total Survey Sample**	**p-value**
Hectares with summerfallow eliminated	55%	54%	0.883
CT Hectares	55%	55%	0.977
MT Hectares	32%	32%	0.963
NT Hectares	13%	13%	0.769
2016-2019 Average			
	Those Who Farmed During Both Time Periods	**Total Survey Sample**	**p-value**
Hectares with summerfallow eliminated	100%	99%	0.118
CT Hectares	1%	3%	0.103
MT Hectares	29%	37%	0.778
NT Hectares	70%	60%	0.132

4.2.1 Farm Characteristics Impact on Tillage and Summerfallow Practices

To further investigate the factors driving the changes in on-farm management practices, a cross-tab analysis studies the interactive effects between farm characteristics, and the adoption of conservation tillage practices and the removal of summerfallow. The farm characteristics used in this analysis include farm size, percent of land owned, crop rotation length, farmer education level, and the inclusion of pulse, canola, organic, and GM crops in rotations. All of these factors are compared against the tillage and summerfallow practices used to identify any trends. An analysis of variance is conducted on each interaction to determine statistical significance at the 95% confidence level (Table 4.4). Details of each analysis of variance test can be found in Appendix B.

In 1991-1994, the inclusion of pulses in crop rotations is associated with a lower number of annual tillage applications and a lower frequency of summerfallow in a four-year crop rotation ($p<0.05$). This aligns with research from Boame (2005) which suggests that farmers who grow pulses are more likely to adopt NT practices. The inclusion of canola is also associated with a lower frequency of summerfallow in a crop rotation during 1991-1994 ($p<0.05$).

In the 2016-2019 results, a larger farm size is associated with fewer tillage applications and a lower frequency of summerfallow ($p<0.05$). This is also supported by research from Boame (2005) which indicates that larger farms may be more likely to adopt NT practices in an effort to cut costs. Farmers who grow GM crops have lower frequencies of summerfallow in their crop rotations, and organic farmers have higher frequencies between 2016-2019 ($p<0.05$).

Results of the analysis are statistically insignificant at the 95% confidence level for crop rotation length, percent of farmland owned, and farmer education level during both time periods ($p>0.05$). In the 1991-1994 analysis, results are insignificant for farm size, inclusion of GM crops in crop rotations, and organic production. In the 2016-2019 time period, results are insignificant for inclusion of pulses and canola in crop rotations.

Overall, the results suggest that farmers who are more likely to adopt alternative crop options, including pulses and GM crops, are also more likely to adopt more sustainable soil management practices. In addition, larger farmers might have more economic capacity to adopt new technologies, or might be more incentivized by the efficiency and cost-savings associated with NT than smaller farms.

Table 4.4 Interactions Between Farm Characteristics and Tillage and Summerfallow Practices

	Average Number of Annual Tillage Applications		**Frequency of Summerfallow in 4-Year Rotation (Years)**	
	1991-1994	**2016-2019**	**1991-1994**	**2016-2019**
Farm Size (Acres)				
130 - 399	3.13	0.50*	1.50	0.25*
400 - 759	1.65	0.00*	0.20	0.00*
760 - 1,119	1.43	0.19*	0.86	0.00*
1,120 - 1,599	1.03	0.03*	0.44	0.00*
1,600 - 2,239	1.61	0.04*	0.67	0.00*
2,240 - 2,879	0.63	0.04*	0.75	0.00*
2,880 - 3,519	1.75	0.07*	2.00	0.09*
3,520 or more	0.75	0.09*	0.60	0.00*
Inclusion of Pulse in Rotation				
Yes	0.73*	0.10	0.24*	0.03
No	1.67*	0.05	0.87*	0.00
Inclusion of Canola in Rotation				
Yes	1.23	0.08	0.39*	0.02
No	1.41	0.15	1.13*	0
Minimum Years Between Planting Same Crop				
1	1.34	0.29	0.50	0.14
2	1.50	0.06	0.91	0.00
3	1.44	0.10	0.25	0.00
4	0.82	0.08	0.43	0.04
Percent of Farmland Owned				
<35%	1.04	0.04	0.71	0.00
35-65%	1.20	0.12	0.50	0.02
>65%	1.38	0.08	0.67	0.02
Inclusion of GM Crops in Rotation				
Yes	1.29	0.09	0.40	0.00*
No	1.28	0.09	0.67	0.08*
Organic Production				
Yes	*No Responses*	0.25	*No Responses*	0.40*
No	*No Responses*	0.07	*No Responses*	0.00*
Farmer Education Level				
Some High School	1.33	0.00	0.67	0.00
High School Graduate	0.72	0.08	0.38	0.00
Some College	1.53	0.08	1.18	0.06
College Graduate	1.26	0.11	0.40	0.02
Some Graduate School	*No Responses*	0.00	*No Responses*	0.00
Post-Graduate Degree	2.15	0.00	0.75	0.00

** Indicates statistical significance at the 95% confidence level (p<0.05)*

4.2.2 Regional Differences in Farm Management Practices

Survey responses are also analyzed on a regional basis to determine if the adoption of on-farm management practices varies across the province. The province of Saskatchewan can be divided into two ecoregions: the semiarid prairie and the subhumid prairie. Based on the ecoregion maps provided by the University of Saskatchewan's Virtual Herbarium, the southern regions along with the Westcentral and Central regions make up the semiarid region of the province, and the Eastcentral and northern regions are classified as subhumid prairie (University of Saskatchewan, n.d.). The semiarid prairies are typically drier, and therefore more prone to erosion events. In addition, moisture conservation becomes more important for farmers in the semiarid prairies where moisture might be limited. Typically, subhumid soils have higher soil productivity as a result of greater soil moisture (VandenBygaart et al., 2008).

Based on the climatic differences between the two ecoregions, it is helpful to look at the differences in on-farm management practices and how they changed over the past 25 years (Table 4.5). Farmers in the semiarid prairies are more likely to adopt strictly NT systems, while MT systems are more commonly observed in the moister subhumid regions of the province. This trend has continued into the most recent crop rotations of 2016-2019. Presently in both regions, less than 5% of hectares are managed under a CT system. In the early 1990s, summerfallow was more commonly practiced on the semiarid prairies, and correspondingly the frequency of summerfallow in a four-year crop rotation was higher in this region. Farmers in the drier regions of the province traditionally practiced summerfallow to control weeds and to attempt to conserve soil moisture for subsequent crops (Awada et al., 2014; Carlyle, 1997). However, by 2016-2019, the practice of summerfallow was almost entirely eliminated regardless of the region, with less than 3% of total hectares in crop rotations which include summerfallow.

In the early 1990s, farmers in the subhumid prairies were more likely to include a variety of crops in their rotations, including pulses and canola, and had longer crop rotations, which is represented in this analysis by the minimum number of years between planting the same crop on one field. Farmers in the semiarid prairies were often limited by climatic conditions, especially low moisture, and were therefore limited in their crop selections. However, by 2016-2019, pulses became more commonly planted in the southern regions of the province, and the majority of farmers in both regions commonly include canola in their rotations.[25] In addition, farmers in the semiarid region have larger farms, on average, than farmers in the subhumid prairies. This aligns with the higher proportion of farmers in the semiarid prairies who adopted NT practices, as larger farm size is commonly associated with earlier adoption of NT practices (Boame, 2005; Davey and Furtan, 2008).

Table 4.5 On-Farm Management Practices in Semiarid and Subhumid Prairie Regions

	1991-1994		2016-2019	
	Semiarid Prairie	**Subhumid Prairie**	**Semiarid Prairie**	**Subhumid Prairie**
NT hectares	16%	9%	71%	45%
MT hectares	14%*	54%*	24%*	55%*
CT hectares	70%	37%	5%*	0%*
Hectares without summerfallow in rotation	39%*	72%*	99%	100%
Average number of annual tillage applications	1.3	0.9	0.1	0.1
Frequency of summerfallow in rotation (years)	0.8*	0.4*	0.0	0.0
Minimum number of years between planting same crop	2.3*	2.9*	2.7	2.4
Inclusion of canola in rotation	50%*	92%*	86%*	100%*
Inclusion of pulses in rotation	29%*	54%*	79%*	44%*
Average farm size (acres)	2,309*	1,234*	4,291	3,320

**Indicates statistically significant difference at the 95% confidence level ($p<0.05$)*

4.2.3 Management Data Compared to Other Data Sources

Due to the small sample size used for this analysis, it is important to compare the on-farm management data collected with other data sources.[26] This benchmarking ensures that the sample data gathered through this survey is representative of the management trends seen in the provincial population during both of these time periods. The Canadian Census of Agriculture, conducted every five years by Statistics Canada, collects on-farm management data similar to the

[25] The expansion of pulse crops in the semiarid regions of the province is partly due to the expansion of the chickpea, lentil, and soybean markets. These pulse crops are better suited to warm climates, and therefore are most successfully grown in the southern regions of Saskatchewan (Saskatchewan Pulse Growers, 2017).
[26] Of the respondents who completed the 2016-2019 section of the survey, 81% report accessing farm records to answer questions, and of those who completed the 1991-1994 section, 80%. This high number of farmers who accessed farm records to respond to survey questions increases the confidence in survey responses.

data collected through this survey. Data from this census is available to benchmark both the early 1990's data and the 2016-2019 data. The Saskatchewan Crop Insurance Corporation (SCIC) also collects on-farm management data through their Saskatchewan Management Plus Program; however, only select data is available from this source and only extends as far back as 1995.

Metrics compared between the datasets include the percent of total farmland under NT, MT, and CT management, as well as the hectares that include summerfallow in their rotation. Data from the 1991 Canadian Census of Agriculture for Saskatchewan producers and SCIC data from 1995 is used to benchmark the 1991-1994 survey data (Figure 4.1). Tillage data is not available during the 1990s from SCIC, and therefore only the summerfallow data from SCIC is used as a benchmark for this time period. The 2016 census data and SCIC data from 2016-2019 are used to benchmark the 2016-2019 survey data (Figure 4.2).[27]

The adoption trends of MT and NT practices and the removal of summerfallow from crop rotations follow similar trends in all of the datasets. The higher proportion of farmers using MT as opposed to NT in the 2016-2019 Crop Rotation Survey dataset might be the result of a number of factors, the main factor likely being the classification of tillage systems used in this analysis. As described in Section 3.3.3, tillage system classifications vary throughout the literature. In this study, a number of assumptions regarding tillage system classification are made based on the survey data provided, including the classification of harrowing as a MT operation and the distinction between tillage system classifications in the semiarid and subhumid prairie regions.

In addition, as discussed in Section 3.3.1, survey participants were, on average, younger and operated larger farms than the average Saskatchewan farmer. Previous literature suggests that younger farmers and larger farms are more likely to adopt agricultural innovations (Boame, 2005; Davey and Furtan, 2008; Fernandez-Cornejo et al., 2002), such as the adoption of conservation tillage practices and the removal of summerfallow. Therefore, the slightly lower percentage of hectares operated under CT and summerfallow management in this sample compared to the Census of Agriculture and SCIC data would be expected based on the participant demographics. Overall, however, the adoption trends are sufficiently similar between the survey data and the other data sources to conclude that the management practices reported by

[27] SCIC tillage data from 2016-2019 was only collected on 0.5% of hectares included in the Saskatchewan Management Plus program, and therefore only represents data from a sample of Saskatchewan farmers.

the survey participants represent the adoption trends of Saskatchewan farmers.

Figure 4.1 1991-1994 Tillage and Summerfallow Practices Compared to Census of Agriculture and SCIC Data

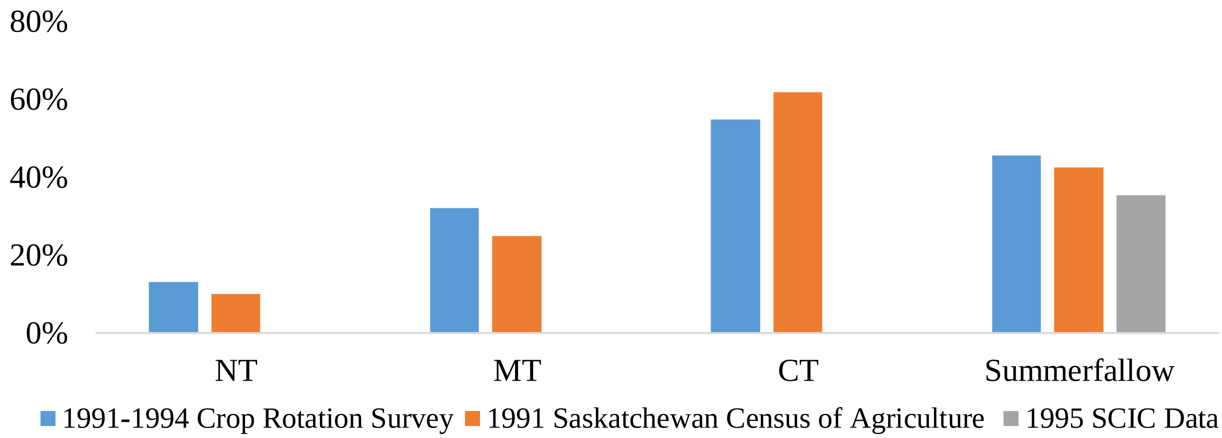
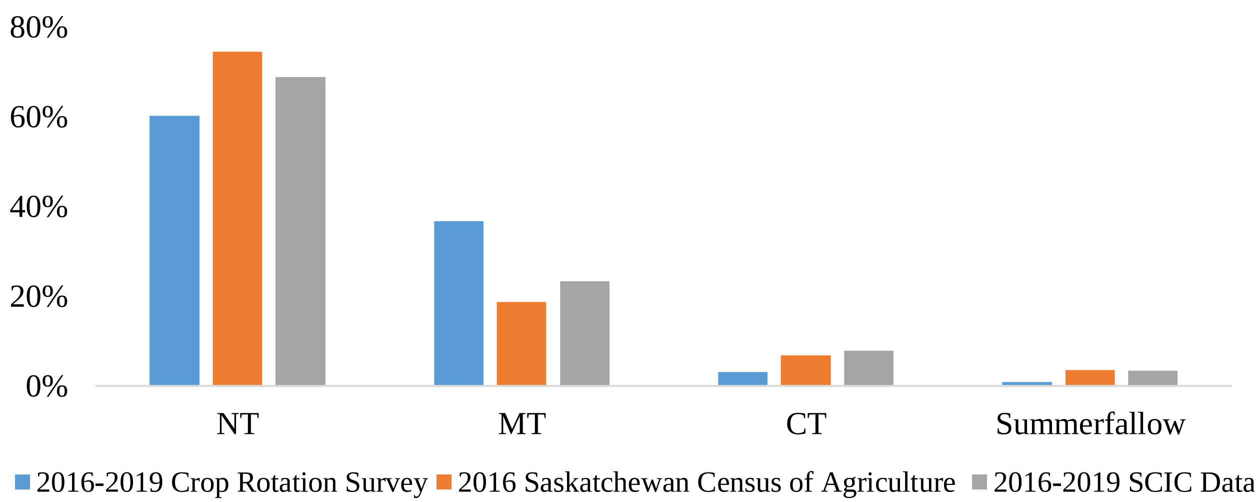


Figure 4.2 2016-2019 Tillage and Summerfallow Practices Compared to Census of Agriculture and SCIC Data



4.3 Attribution of Various Technologies to the Adoption of Sustainable Management Practices

As discussed in Section 4.2, long-term changes in management practices were substantial in the 25-year period following the introduction of HT canola. However, before the resulting changes in SOC can be quantified, the question of how the adoption of innovative technologies, including

HT crops and the complementary chemical, glyphosate, impacted these management changes must be addressed. As discussed in Section 3.2.2, survey participants were asked to comment on to what extent they believe the introduction of innovative technologies contributed to the widespread adoption of NT, MT, and the removal of summerfallow. First, the provincial and regional averages of the attribution factors assigned by farmers for each of HT canola, glyphosate, and HT crops are presented. These average factors provide a generalized overview of farmers' perceptions of the facilitation of sustainable adoptions by various innovative technologies (Table 4.6). A similar average is taken for the percentage of land which would include summerfallow management in the absence of HT crops. Finally, common themes are identified in the comments regarding how differently farms would operate in the absence of these technologies (Table 4.7).

Table 4.6 Attribution of Various Technologies to Sustainable On-Farm Management Practices

To what extent do you believe each of these technologies facilitated the adoption of reduced tillage and summerfallow? (1 = did not at all facilitate, 10 = played a major role in facilitating)			
	HT Canola (n=95)	**Glyphosate (n=95)**	**Other HT Crops (n=90)**
Mean	7.3	9.1	5.3
Standard Deviation	2.73	1.56	3.21
Margin of Error (95% Confidence Level)	0.56	0.32	0.67

As shown in Table 4.6, participants report that glyphosate facilitated the reduction of tillage and summerfallow practices to the greatest extent. This is to be expected, as in addition to its use within HT cropping systems, glyphosate is an effective and affordable weed control option for pre-seed and post-harvest applications. However, responses indicate that HT crops contributed to these adoptions as well. Based on responses from 95 participants who completed this question, the mean contribution factor of HT canola to a reduction in tillage and summerfallow was 7.3 out of 10, compared to a contribution factor of 9.1 out of 10 for glyphosate.

Regarding summerfallow management, on average, participants report that 24% of their land would include summerfallow in the absence of HT crops, with a standard deviation of 27.3% and a margin of error of 5.9%. This hypothetical 24% of land under summerfallow management compared to the average 1% of land currently under summerfallow management reported in the 2016-2019 time period in Table 4.1 indicates that HT crops facilitated the removal of summerfallow from crop rotations at least to some extent. Furthermore, it indicates that if HT canola was not available to Saskatchewan farms, the lack of viable alternatives would result in a significant step backwards in the sustainability of farmers' land management practices.

When looking at responses to what might change in their operation in the absence of various technologies (Table 4.7), about one-quarter of respondents mentioned that their tillage practices would change without HT canola, and 11% indicated that they would have to revert to summerfallow. Other common responses to what would change in the absence of HT crops include a decrease in profitability and/or yields, changes in chemical use, and changes in crop rotations.

Comparatively, over half of participants reported that tillage practice would change without the use of glyphosate and 15% said they would revert to summerfallow. About 4% of farmers indicated that they would no longer be farming without the use of glyphosate. In all questions, responses indicate that GM crops other than HT canola had lower impacts on the facilitation of these sustainable technologies. This is to be expected, as canola is planted on greater acreage in Saskatchewan than any other GM crop.[28] Examples of participants' comments in response to these questions are presented in Appendix C.

Table 4.7 Changes to Farming Operations in Absence of Various Technologies

What would be different about your farming operation today without the use of the following technologies?			
	HT Crops (n=95)	**Other GM Crops (n=89)**	**Glyphosate (n=96)**
Tillage	24%	7%	58%
Summerfallow	11%	3%	15%
Profitability/Yield	28%	40%	35%
Change in Chemical Use	31%	15%	24%
Change in Crop Rotation	22%	28%	9%
*Other Environmental Effects	9%	2%	16%
Wouldn't be Farming	1%	0%	4%
Not Much Would Change	5%	18%	3%

**Other environmental effects include mentions of increased soil erosion, changes to moisture conditions, and decrease in overall soil health.*

[28] In Saskatchewan, other GM crops available to farmers include soybeans, corn, alfalfa, and potatoes.

The results of the attribution questions are also analyzed by provincial region to determine whether some technologies were more advantageous for farmers in certain regions. When results are analyzed between the nine provincial regions, none of the results are statistically different at the 95% confidence level ($p>0.05$). When the regions are aggregated to the semiarid and subhumid prairies, results are once again insignificant for all questions except for the attribution of HT canola to the reduction in tillage and summerfallow practices (Table 4.8). The mean value for participants who farmed in the semiarid prairies is 6.8 and for farmers in the subhumid prairies, 8.1 ($p<0.05$). This result suggests that HT canola played a larger role in facilitating conservation tillage and the reduction of summerfallow in the cooler and moister regions of the province where canola might compose a larger share of the acreage. This aligns with results from Table 4.5 which show that from 1991-1994, only 50% of farmers in the semiarid prairies included canola in their crop rotations compared to 92% in the subhumid prairies.

Table 4.8 Attribution Results in the Semiarid and Subhumid Prairie Regions

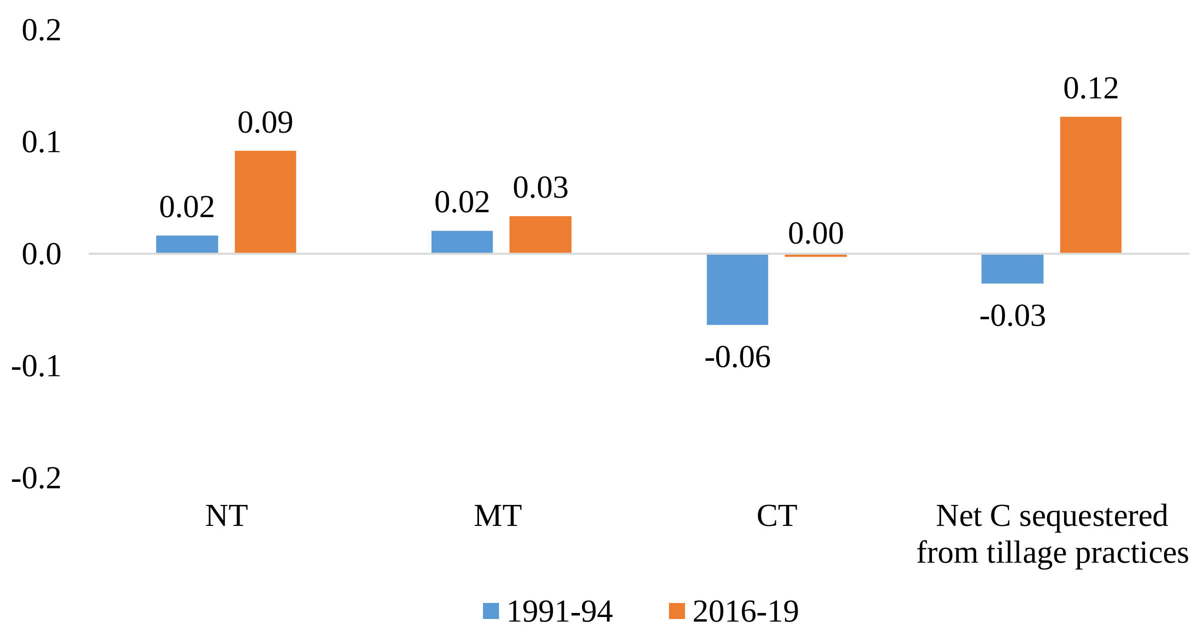
	Contribution Factor			**Percentage of Land That Would Include Summerfallow Management Without HT Crops**
	HT Canola	**Glyphosate**	**Other HT Crops**	
Semiarid	6.8	9.2	5.5	24.8
Subhumid	8.1	8.9	5.1	22.9
P-value	0.017	0.388	0.502	0.763

Based on the attribution results, participants in this survey indicate that HT cropping systems benefited their farm operations in a number of ways, both economically and environmentally. Compared to the high attribution to reduced tillage and summerfallow that farmers report for glyphosate (9.1 out of 10), HT canola was assigned a relatively high contribution factor (7.3 out of 10), highlighting its importance to these adoptions as well. The introduction of HT canola may have been more significant for farmers in the subhumid regions of the province who planted canola more frequently, especially in the early 1990s. Though many factors facilitated the adoption of sustainable on-farm management practices over the past 25 years, the results from this survey further support the assumption that the introduction of HT crops, especially canola in Saskatchewan, and the production systems associated with these crops, including the increased use of glyphosate, played a role in facilitating the adoption of conservation tillage practices and the removal of summerfallow from farmers' fields.

4.4 Changes in Soil Carbon Levels

After identifying the changes in management practices between the two time periods, and discussing farmers' attribution of the innovative technologies to these changes, the change in SOC levels between the time periods can be quantified. Using the PCEM framework described in Section 3.4.1, the changes in SOC levels resulting from each management practice and adjusted for crop residue levels, are estimated. Results are calculated at both the regional level within the province of Saskatchewan and the provincial level. In addition to the sequestration results from each cropping practice, the change in SOC from each cropping practice is presented as a net amount per average hectare. The net sequestration for tillage practices is calculated by summing the positive sequestration per ha resulting from NT and MT practices and subtracting the negative sequestration from CT per ha (Figure 4.3). Similarly, the net change in SOC for summerfallow practices is the difference between the change in SOC from the removal of summerfallow per ha and the C emitted from the inclusion of summerfallow (Figure 4.4).[29]

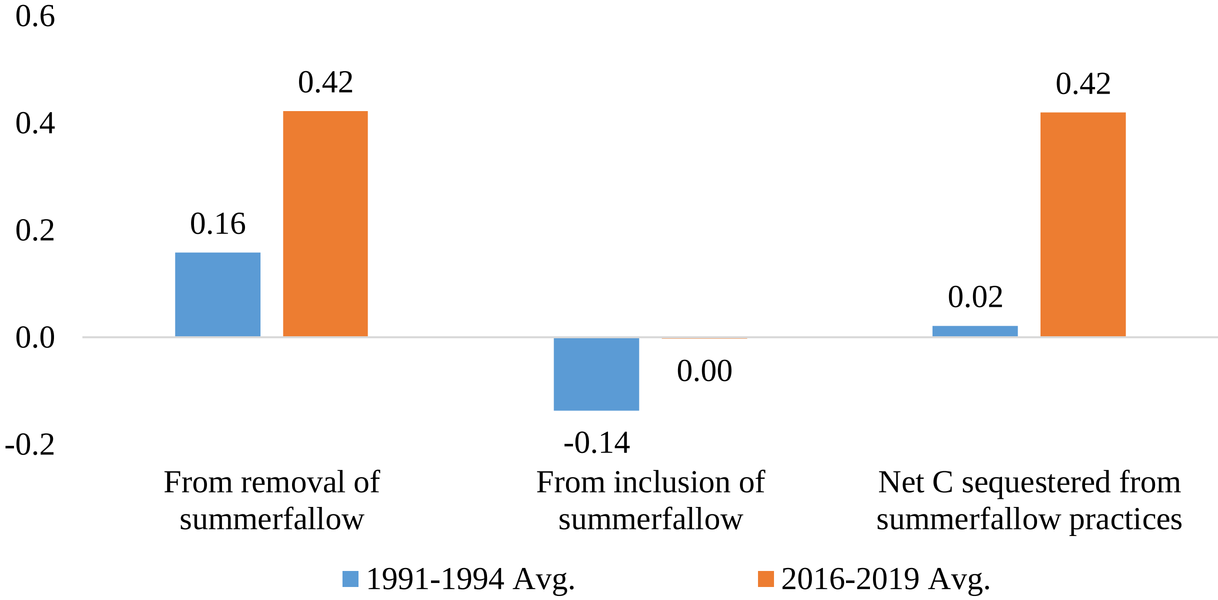
Figure 4.3 Change in SOC (Mg) from Tillage Practices per Ha, per Year[30]



[29] Net SOC gains per ha are affected in two ways from the removal of summerfallow. The first effect is the reduction of C emissions from the soil resulting from reduced soil disturbance and decomposition. The second effect is the positive increase in crop residue levels from the increase in cropping frequency. The combination of these two effects results in net positive increases in SOC levels.

[30] Due to rounding, totals may not correspond with the sum of the separate figures.

Figure 4.4 Change in SOC (Mg) from Summerfallow Practices per Ha, per Year



The net change in SOC from tillage in 1991-1994 was negative, meaning that the average hectare of crop production in Saskatchewan was releasing more C than it was sequestering each year from tillage practices. However, by 2016-2019, the net sequestration from changes in tillage practices had increased to 0.12 Mg per ha. Similarly, between 1991-1994, annual SOC gains from changes in summerfallow practices for an average hectare of crop production, although not negative, were negligible (0.02 Mg). This is to be expected, as results from Section 3.1 show that just over half (54%) of farmers had removed summerfallow from their crop rotations during 1991-1994, and the remaining 46% still included this practice in their rotations. By 2016-2019, however, net SOC was increasing by 0.42 Mg per ha, per year from the removal of summerfallow.

To put the results of the analysis into context, it is helpful to apply the change in SOC per ha to various geographical regions (Table 4.9).[31] This comparison provides an illustration of the substantial SOC gains seen at the farm level. If the average change in SOC per ha from this analysis is applied to a 1,000 ha farm in 1991-1994, this farm would have released 26.5 Mg C per year from tillage practices and gained 21.6 Mg C per year from the removal of summerfallow. By 2016, however, this same farm would be sequestering 122 Mg C per year

[31] To apply these values to larger geographical areas, the values per ha are multiplied by the corresponding number of hectares in the geographical area being examined.

from the adoption of conservation tillage practices and 420 Mg per year from the removal of summerfallow. This results in an increase of 149 Mg C from changes in tillage practices and 398 Mg C from changes in summerfallow practices over the 25-year period. The next row in Table 4.9 shows the SOC gains from the total hectares in the survey sample (7,463). The bottom row shows the change in SOC gains from all hectares under crop production in Saskatchewan. This analysis uses the estimate of 15,202,159 ha of crop production in Saskatchewan from the 2016 Canadian Census of Agriculture (Statistics Canada, 2021a).

Table 4.9 Change in Annual SOC from Aggregated Hectares in Saskatchewan Resulting from Changes in Tillage and Summerfallow Practices

	Net Change in SOC from Tillage Practices (Mg/Year)		**Net Change in SOC from Removal of Summerfallow Practices (Mg/Year)**	
	1991-1994	**2016-2019**	**1991-1994**	**2016-2019**
1,000 Ha Farm	-26.5	122	21.6	420
Total Hectares in Survey Sample (7,463 ha)	-198	913	161	3,131
Total Saskatchewan Crop Production (15,202,159 ha)	-402,372	1,858,785	328,146	6,378,274

To provide some context for these figures, the average Canadian vehicle, which burns 2,000 litres of gasoline each year, emits roughly 4,600 kg of CO_2 annually (Natural Resources Canada, 2014). Using the ratio of CO_2 to C (3.667), the average Canadian vehicle emits 1,254.4 kg of C each year, or 1.25 Mg. A 1,000 ha farm in 1991-1994 would be releasing 21 times more C than the average car from tillage practices each year, and by 2016-2019 would be sequestering the emissions from 98 cars from conservation tillage practices. Similarly, the annual SOC gains from this farm were equivalent to the emissions from 17 cars in 1991-1994 from the removal of summerfallow, and by 2016-2019, from 336 cars.

The bottom row of Table 4.9 can be compared to results from Smyth and Awada's (2018) estimation of Saskatchewan soil C sequestration between 1985-2016. There are a number of key differences between the methodologies of their study and of this thesis. The results from their 2018 analysis combine the effects of conservation tillage and the removal of summerfallow due to the C coefficients chosen for their analysis. Furthermore, the coefficients used in their analysis are synthesized from the empirical literature, while those used in the present analysis were developed using modelling techniques. Data for Smyth and Awada's study was synthesized from a number of sources, including various industry studies and Statistics Canada data. In addition, as the authors did not have access to data on the crop residue removal techniques used by farmers, they assumed only residue levels over 3.33 Mg/ha have positive sequestration effects to account for the potential of residue removal, likely overestimating the negative effects on sequestration to remain conservative. However, their study contains the most similar analysis to the present one, and therefore provides the best benchmark.

Assuming infinite C storage in Saskatchewan's agricultural soils, Smyth and Awada estimate that between 1991-1994, 0.64 - 1.14 million Mg CO_2 equivalents were sequestered annually from conservation tillage and the removal of summerfallow, and by 2016 the annual C sequestered was 8.94 million Mg CO_2 equivalents. Using the ratio of CO_2 to C (3.667), this equates to 0.17 million - 0.311 million Mg C sequestered annually in 1991-1994 and 2.44 million Mg C by 2016. The estimated net SOC changes from conservation tillage practices alone in the present study, -0.40 million Mg per year between 1991-1994 and 1.86 million Mg per year between 2016-2019, align closely with Smyth and Awada's estimates for both time periods. However, the SOC gains from the removal of summerfallow, 0.33 million Mg per year between 1991-1994 and 6.38 million Mg per year between 2016-2019, are much higher than Smyth and Awada's estimates.

There is no evidence in the literature to suggest what the interactive effects on SOC levels from the removal of summerfallow and tillage are, as these practices are complementary. No evidence suggests that the net SOC gains from the adoption of conservation tillage and from the removal of summerfallow can simply be summed to provide the total SOC gains. Therefore, due to the separate presentation of the changes in SOC levels resulting from the two management practices in this thesis, a direct comparison between Smyth and Awada's (2018) results and the results of this thesis is not possible. However, even while considering the methodological differences between the studies, the results of this thesis estimate much higher annual total SOC gains from changes in management practices than Smyth and Awada (2018).

4.4.1 Impact of Summerfallow Management on SOC Gains from Tillage

As discussed previously, the adoption of conservation tillage and the elimination of summerfallow are typically complementary practices. As tillage is an important part of weed control in summerfallow fields, when farmers shift towards continuous cropping, they are often able to simultaneously minimize or eliminate their tillage practices. To determine the extent of this complementarity in the survey sample, tillage practices and the resulting annual SOC changes can be analyzed and compared between hectares which include summerfallow management within a four-year crop rotation, and those with summerfallow management removed (Table 4.10).

Table 4.10 Comparison of Tillage Practices and Resulting Annual SOC Gains (Mg/ha) from Hectares With Summerfallow Management versus Hectares Without

1991-1994	**Hectares With Summerfallow**	**Hectares Without Summerfallow**	**p-value**
Total Hectares	1601	1910	-
NT Hectares	9%	16%	0.11
MT Hectares	20%	42%	0.4
CT Hectares	70%	42%	0.17
SOC gains from NT	0.01	0.02	0.03
SOC gains from MT	0.01	0.03	0.12
SOC loss from CT	0.07	0.05	0.37
Net SOC gains from Tillage	-0.05	-0.01	0.06
2016-2019	**Hectares With Summerfallow**	**Hectares Without Summerfallow**	**p-value**
Total Hectares	69	7394	-
NT Hectares	12%	61%	1.33E-05
MT Hectares	0%	37%	1.28E-08
CT Hectares	88%	2%	0.03
SOC gains from NT	0.02	0.09	1.14E-06
SOC gains from MT	0.00	0.03	5.87E-07
SOC loss from CT	0.09	0.00	0.03
Net SOC gains from Tillage	-0.07	0.12	2.17E-05

Results from the above comparison show that CT is more commonly practiced on hectares which also include summerfallow management. Conversely, NT and MT are more commonly practiced on hectares that have had summerfallow management completely eliminated. The resulting change in annual SOC gains per ha from the adoption of conservation tillage are, correspondingly, higher on hectares that have had summerfallow management eliminated. In the 1991-1994 period, each hectare managed without summerfallow was still a net source of C rather than a net sink from tillage practices; however, the average hectare without summerfallow management would emit less C per year from tillage than a hectare with summerfallow management. By 2016-2019, a typical hectare that included summerfallow as part of its rotation was actually a net source of C from tillage practices, while a typical hectare with summerfallow removed was a relatively large net C sink.

In general, only the results from the 2016-2019 time period are statistically significant at the 95% confidence level in the above analysis. This is likely due to the smaller sample size from the 1991-1994 time period, as well as the nearly complete elimination of summerfallow in the 2016-2019 time period. However, despite the higher p-values from the 1991-1994 time period, these results support the assumption of complementarity between the two practices. Therefore, they also support the presentation of annual SOC gains from changes in tillage and summerfallow practices separately as the extent of the interaction between the sequestration effects from the two practices are still largely unknown.

4.4.2 Regional Differences in SOC Gains

As discussed in Section 4.2.2, farmers in the semiarid and subhumid regions of the province have differing management practices due to the variations in soil and climatic conditions. Therefore, it is important to look at the differences in the net SOC gains between these regions during both time periods. As shown in Figure 4.5, rates of SOC gain per ha are higher for all time periods and all crop practices for farmers in the subhumid region. There are a number of reasons for this difference. The first reason is that the soils in the subhumid regions are more productive overall on account of their higher moisture content (VandenBygaart et al., 2008). In addition, farmers in the subhumid regions were more likely to use MT or NT rather than CT during both time periods. They also did not need to rely on summerfallow practices as heavily as farmers in the drier, semiarid region, especially in the early 1990s.

Using the difference in annual SOC changes per ha for each of the prairie regions, the annual change for a 1,000 ha farm in both regions over the past 25 years can be illustrated (Table 4.11). From a 1,000 ha farm in the semiarid prairie, annual SOC changes would have increased by 142 Mg from a shift in tillage practices, compared to an increase of 164 Mg for a farm in the subhumid prairies. Similarly, annual SOC gains from the removal of summerfallow practices would have increased by 441 Mg for a farm in the semiarid prairies, and by 365 Mg for a farm in the subhumid. Though these results do not suggest that farmers in the subhumid prairies are 'better' at soil sustainability management, they do indicate that the soils in the subhumid prairies are more conducive to increasing SOC levels, and also that farmers in the subhumid prairies are less limited by soil moisture conditions in their on-farm management decisions. These differences impact the resulting soil C sequestration.

Figure 4.5 Change in SOC (Mg) per Ha, per Year from Tillage and Summerfallow Practices in the Semiarid and Subhumid Regions

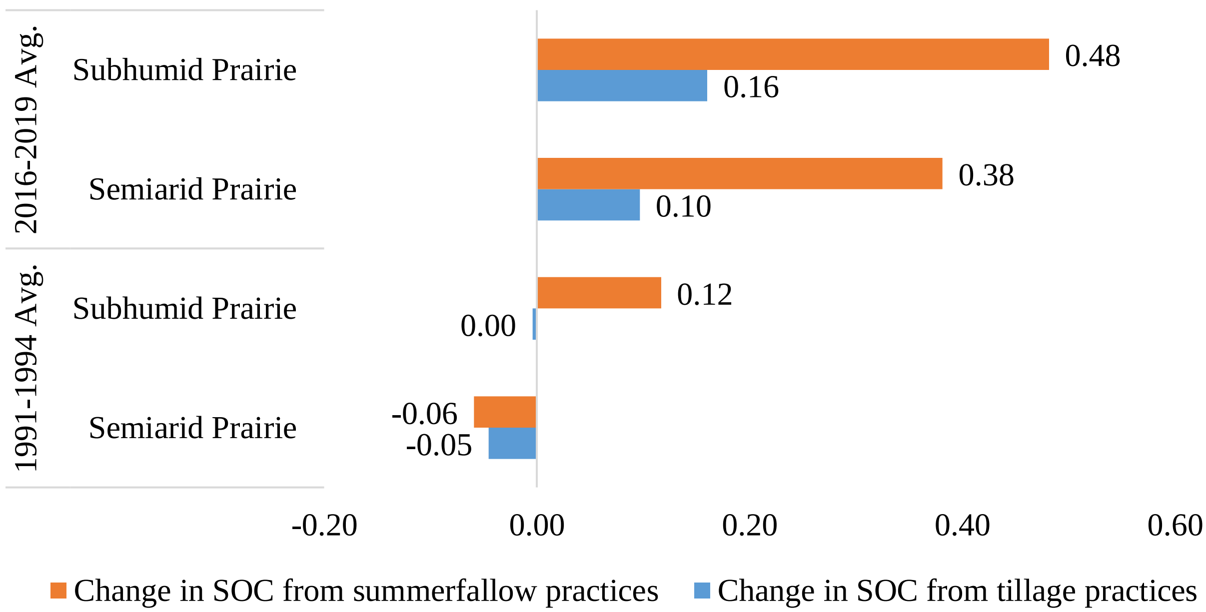


Table 4.11 Net SOC Gains from a 1,000 Ha Farm in the Semiarid and Subhumid Regions

		Annual Changes in SOC from Changing Tillage Practices (Mg)	**Annual Changes in SOC from Changing Summerfallow Practices (Mg)**
Semiarid Prairie	1991-1994	-45	-59
	2016-2019	97	381
	Difference	142	441
Subhumid Prairie	1991-1994	-4	117
	2016-2019	160	482
	Difference	164	365

4.4.3 Sensitivity Analysis

To assess the robustness of the results, a sensitivity analysis is conducted to determine the impact and significance of the input variables. The sensitivity analysis is performed on the average change in SOC across the provincial regions by taking the weighted average of the SOC changes in each of the regions studied in each year. Each of the following variables, percent of hectares under conservation tillage practices, hectares without summerfallow management, crop yield, and rate of residue input into the soil, are decreased by 10%, 20%, and 30% and the effects on net changes in SOC levels are evaluated (Table 4.12).

Table 4.12 Net SOC Gains Sensitivity Analysis

Average Change in SOC (Mg/ha/year)			
		From Tillage Practices	**From Summerfallow Practices**
1991-1994			
Original Analysis		-0.03	0.02
Decrease in hectares with conservation tillage summerfallow eliminated**	10% 20% 30%	-0.03 -0.04 -0.04	-0.03 -0.04 **-0.08***
Decrease in crop yields	10% 20% 30%	-0.03 -0.03 -0.03	0.01 0.00 -0.2
Decrease in rate of crop residue input to soil	10% 20% 30%	-0.03 -0.03 -0.04	-0.01 -0.01 -0.04
2016-2019			
Original Analysis		0.12	0.42
Decrease in hectares with conservation tillage and summerfallow eliminated**	10% 20% 30%	0.11 0.10 **0.09***	0.33 **0.28*** **0.21***
Decrease in crop yields	10% 20% 30%	0.12 0.11 0.10	0.40 0.37 0.34
Decrease in rate of crop residue input to soil	10% 20% 30%	0.11 0.10 **0.08***	0.36 0.33 **0.28***

** Indicates mean is statistically different from original mean at the 95% confidence level ($p<0.05$)*
***Each of NT and MT hectares were decreased by 5%, 10%, and 15% to result in a total reduction in conservation tillage hectares of 10%, 20%, and 30%.*

As shown in the sensitivity analysis, changes in the input values ranging from 10-30% have no significant effect on the change in SOC per ha in 1991-1994, other than a 30% increase in summerfallow hectares. However, as shown in Figure 4.1, the percent of hectares under summerfallow management reported in this survey only differ from the 1991 Census of

Agriculture data by about 6%. The likelihood of the results from this survey being 20-30% different from the actual summerfallow hectares in production during 1991-1994 is minimal. Therefore, the sensitivity analysis supports the robustness of the results from the 1991-1994 time period with a 95% confidence level.

Results from the 2016-2019 sensitivity analysis are more variable. A 30% decrease in hectares under conservation tillage, and both 20% and 30% decreases in summerfallow hectares have significant impacts on the net SOC change during this time period. A decrease in the rate of crop residue input to the soil also has significant impacts at the 30% level. One reason for the increased sensitivity of these results is that such a small percentage (<5%) of cropland was under CT and summerfallow management between 2016-2019. Therefore, even small increases in these practices cause significant swings in SOC gains. In addition, crop yields have increased by roughly 40% during this time period, with greater yield increases seen for canola and wheat. Higher yields typically lead to higher crop residue levels. Therefore, a 30% reduction in the rate of C input to the soil from these higher residue levels impacts sequestration levels more than during the early 1990s when crop residue levels were generally lower. However, the lack of significant impacts at the 10% level for all three categories does support the robustness of the results during the 2016-2019 time period.

The results of this sensitivity analysis show how far on-farm sustainability has come over the last 25 years. The insignificant changes in net SOC changes resulting from changes to the input variables in the 1991-1994 time period show how unsustainable traditional agricultural practices were at this time. When CT and summerfallow were being practiced on over half of the hectares under study, even a 30% decrease in NT and MT hectares, and 20% increase in summerfallow area, do not significantly impact SOC gains. However, more recent results show that farming has had a positive impact on SOC levels to the extent that even small changes in management practices can have major impacts on SOC gains. The results indicate that if farmers were to decrease their conservation agriculture practices by even a small amount, the negative impacts on their SOC levels would likely be significant.

4.5 Economic Valuation of SOC gains

After quantifying the SOC changes in Saskatchewan agricultural soils over the past 25 years, it is important to discuss the economic implications of these changes. The economic valuation of the sequestered C is especially important when considering the policy implications of these results. As discussed in Section 3.5, the SOC is valued based on three economic scenarios: a carbon removal marketplace, a carbon tax, and the SCC. Before applying these valuations to the SOC gains, the results in Section 4.4, currently reported in Mg C, need to be converted to CO_2 equivalents. Applying the ratio of CO_2 to C (3.667) to the SOC gains in Figure 4.3 and Figure 4.4 provides the estimated sequestration in terms of CO_2 equivalents (Table 4.13).

Table 4.13 SOC Gains (Mg/ha) in CO_2 Equivalents per Year

	1991-1994	**CO_2 Equivalent**	**2016-2019**	**CO_2 Equivalent**
NT	0.02	0.06	0.09	0.34
MT	0.02	0.08	0.03	0.12
CT	-0.06	-0.24	0.00	-0.01
Net SOC gains from changes in tillage practices	-0.03	-0.10	0.12	0.45
From removal of summerfallow	0.15	0.55	0.42	1.55
From inclusion of summerfallow	-0.15	-0.53	-0.00	-0.01
Net SOC gains from changes in summerfallow practices	0.01	0.02	0.42	1.54

Next, using the valuation scenarios discussed in Section 3.5, the economic value of the SOC gains can be estimated. The economic value (2019 CAD) per tonne of CO_2 in a carbon removal marketplace is $19.86, $20.00 in the Canadian federal carbon tax, and $45.89 for the Canadian SCC scenario. Applying these valuations to the annual net SOC gains per ha from changes in tillage and summerfallow practices provides the economic valuation of C sequestered per ha, per year for both the 1991-1994 and 2016-2019 time periods (Table 4.14). The three C pricing scenarios provide upper and lower values on the estimated economic value of the SOC gains.

Table 4.14 Economic Value (2019 CAD) of CO_2 Sequestered per Ha, per Year

	1991-1994	2016-2019	Change
From Changes in Tillage Practices			
Carbon Marketplace	-$2.03	$8.90	$10.93
Carbon Tax	-$2.04	$8.97	$11.01
SCC	-$4.69	$20.58	$25.26
From Changes in Summerfallow Practices			
Carbon Marketplace	$0.39	$30.56	$30.17
Carbon Tax	$0.40	$30.78	$30.38
SCC	$0.91	$70.62	$69.72

When the results presented in Table 4.14 are applied to a 1,000 ha farm, the total hectares included in the survey sample (7,463), and the total hectares of crop production in Saskatchewan (15,202,159), the change in the estimated economic value of the SOC gains can be seen more clearly (Table 4.15). The economic value of the annual SOC gains from changes in tillage practices from the 7,463 ha under study increased by between $82,578 - $190,810 in the past 25 years. Similarly, the economic value of the annual net SOC gains from the 7,463 ha under study increased from between $283,968 - $656,158 from the removal of summerfallow. For the total hectares of crop production in Saskatchewan (15,202,159), the economic value of annual SOC gains from the adoption of conservation tillage practices increased by between $166.2 million - $384.0 million over the past 25 years, and from the removal of summerfallow practices, by $458.7 million – $1.06 billion. These large changes in economic valuation provide context for the contributions made by Saskatchewan farmers to Canada's climate change goals.

Table 4.15 Economic Valuation of Annual SOC gains

From 1,000 ha Farm	**1991-1994**	**2016-2019**	**Change**
From Changes in Tillage Practices			
Carbon Marketplace	-$2,028	$8,905	$10,932
Carbon Tax	-$2,042	$8,967	$11,009
SCC	-$4,685	$20,576	$25,261
From Changes in Summerfallow Practices			
Carbon Marketplace	$393	$30,564	$30,171
Carbon Tax	$395	$30,779	$30,384
SCC	$907	$70,623	$69,716
From Total Hectares Under Study (7,463)	**1991-1994**	**2016-2019**	**Change**
From Changes in Tillage Practices			
Carbon Marketplace	-$15,133	$67,445	$82,578
Carbon Tax	-$15,239	$67,920	$83,160
SCC	-$34,967	$155,843	$190,810
From Changes in Summerfallow Practices			
Carbon Marketplace	$2,930	$286,898	$283,968
Carbon Tax	$2,950	$288,920	$285,970
SCC	$6,769	$662,927	$656,158
From Total Saskatchewan Crop Production (15,202,159 ha)	**1991-1994**	**2016-2019**	**Change**
From Changes in Tillage Practices			
Carbon Marketplace	-$30,825,022	$135,369,049	$166,194,017
Carbon Tax	-$31,042,522	$136,323,312	$167,365,835
SCC	-$71,227,067	$312,793,840	$384,020,907
From Changes in Summerfallow Practices			
Carbon Marketplace	$5,967,445	$464,637,662	$458,670,216
Carbon Tax	$6,009,512	$467,913,053	$461,903,541
SCC	$13,788,825	$1,073,626,500	$1,059,837,675

These values can be compared to the estimated net returns from crop production to provide further context. Values for comparison are taken from the Saskatchewan Ministry of Agriculture's 2019 Crop Planning Guide. Using the average values across all soil types for production of wheat, barley, oats, green lentils, red lentils, yellow peas, green peas, soybean, flax, and canola, the estimated average net return over all expenses is $34.16 per ha in 2019.[32] If we apply this value to a 1,000 ha farm, this results in a net return on production of $34,160. Over the past 25 years, the increase in the estimated value of the SOC gains from a 1,000 ha farm ranges from $10,932 - $25,261 ($10.93/ha - $25.26/ha) from a change in tillage practices and $30,171-$69,716 ($30.17/ha - $69.72/ha) from a change in summerfallow practices (Table 4.15). Therefore, the value of the increase in SOC gains from changes in tillage practices is 32-74% of 2019 net returns on production. Similarly, the value of the increase in SOC gains from changes in summerfallow practices are 88-204% of this farm's net returns.

The results of the economic valuation for the provincial crop production area can also be compared to the total net farm income reported in Saskatchewan. Between 2016-2019, Statistics Canada (2021b) reports that annual net farm income in Saskatchewan ranged from $1.73 - $4.45 billion, with an average value of $2.76 billion. Taking the value of the increase in SOC gains over the last 25 years from reductions in tillage practices, $166.2 - $384.0 million, this represents 6-14% of Saskatchewan's average 2016-2019 annual net farm income. Similarly, the value of the SOC increase from reductions in summerfallow over the past 25 years, $458.7 million - $1.06 billion represents 17-38% of the average annual net farm income in Saskatchewan during in 2016-2019.

4.6 Summary

The results presented in this chapter indicate that Saskatchewan dryland crop farms have made substantial improvements in their environmental impacts relating to soil dynamics and C sequestration in the last 25 years. The 52% decrease in hectares under CT and 45% decrease in summerfallow hectares during this time period has resulted in a shift almost entirely to conservation agriculture practices, which includes 97% of hectares under NT and MT management and 99% of hectares with summerfallow completely removed from crop rotations. Farm characteristics that are significantly associated with a reduction in tillage and the removal of summerfallow include larger farms and the inclusion of a wide variety of crops, including pulses and canola, in rotations.

[32] In the Saskatchewan Ministry of Agriculture's Crop Planning Guide (2019), estimates for expenses include both cash or operating expenses, such as input costs, utilities, and crop insurance, and non-cash expenses, such as building repair, land investment, labour cost, and building and equipment depreciation.

There are many factors that contributed to the widespread shift away from CT and summerfallow practices, including innovations in farm machinery, farm inputs such as seed, chemical, and fertilizer, and an increased knowledge of the impacts of farm operations on soil and land quality. However, results from this survey indicate that farmers attribute the adoption of more sustainable management practices, at least in part, to the introduction of HT canola and glyphosate. Farmers estimate that 24% of their land would include summerfallow management in the absence of HT crops, compared to the 1% of land currently managed with summerfallow in the survey results. Compared to an attribution factor of 9.1 out of 10 for glyphosate's role in facilitating reductions in tillage and summerfallow, farmers assigned HT canola a relatively high factor of 7.3 out of 10. Decreases in farm profitability and crop yield, and other negative environmental impacts are other ways in which farmers believe their operations would change without the use of these innovative technologies. Farmers in the subhumid regions of the province place a greater importance on HT canola's role in facilitating the adoption of these sustainable management practices, likely because canola was more commonly planted in the moister regions of the province in the early 1990s.

The shift in management practices towards reduced tillage and summerfallow has resulted in considerable increases in net SOC gains per ha. In Saskatchewan, the changes in tillage practices over the past 25 years have resulted in an increase of 0.15 Mg C sequestered per ha, per year. Similarly, the change in annual net SOC gains from the removal of summerfallow practices has been 0.40 Mg during the same time period. If these estimates are applied to the total number of hectares of crop production in Saskatchewan (15.2 million ha), the increase in annual net SOC gains in Saskatchewan soils between 1991-1994 and 2016-2019 is 2.26 million Mg from a change in tillage practices and 6.05 million Mg from a reduction in summerfallow. Considering the average Canadian vehicle emits 1.25 Mg C per year, these results suggest that the Saskatchewan soils are sequestering emissions from 1.81 million more cars each year now than they were during 1991-1994 from changes in tillage practices. From the removal of summerfallow practices, Saskatchewan soils are annually sequestering emissions from 4.84 million more cars now than during 1991-1994.

From a policy-making standpoint, it is helpful to place an economic value on the SOC gains. There are many different ways to value C, however, three common scenarios include a carbon marketplace, a carbon tax, and the SCC. This analysis applies 2019 CAD figures to the Nori

Carbon Marketplace evaluation (\$19.86/t CO_2 equivalent), the Canadian federal carbon tax (\$20.00/t CO_2 equivalent), and the Canadian SCC (\$45.86/t CO_2 equivalent). Applying these valuations to the C sequestered from the total hectares of crop production in Saskatchewan (15.2 million ha) results in upper and lower bounds on the economic valuation. The range of economic values for the change in annual SOC gains across the province from a change in tillage practices is \$166.2 - \$384.0 million, and from summerfallow practices, \$458.7 million – \$1.06 billion.

Overall, the results presented in this chapter illustrate the improvement in soil sustainability on Saskatchewan dryland crop farms over the past 25 years. This analysis only looks at the changes in SOC resulting from changing soil dynamics, and does not take into consideration emissions from equipment used for farm practices, not does it consider the other important GHGs (CH_4 and N_2O). However, the storage of C in agricultural soils is one key component of the on-farm GHG cycle. Therefore, though they do not present the whole picture of the farm GHG cycle, the results do show that in terms of C sequestration, agricultural soils have become important storage sites for carbon over recent decades as a direct result of Saskatchewan dryland crop farmers' widespread adoption of sustainable management practices. As shown by farmers' responses to the attribution questions, the results in this chapter also support the assumption that the introduction of HT canola in Saskatchewan, coupled with the increasing reliance on glyphosate, have played a role in facilitating this shift towards sustainable management practices.

CHAPTER 5
IMPLICATIONS

5.1 Introduction

The results presented in the previous chapter indicate that Saskatchewan dryland crop farmers have contributed to the achievement of Canada's climate change goals over the past 25 years through voluntary adoption of sustainable on-farm management practices including conservation tillage and continuous cropping. Over the past 25 years, annual changes in SOC levels in agricultural soils have increased by 2.26 million Mg from reductions in tillage practices and 6.05 million Mg from changes in summerfallow practices. The increases in SOC over this time period are valued from between $166.2 - $384.0 million from reductions in tillage, representing 6-14% of the province's net farm income, and from between $458.7 million - $1.059 billion from reductions in summerfallow, representing 17-38% of the province's net farm income.

The results also support the contribution of innovative technologies, including HT canola, to these beneficial land management changes. Survey participants indicate that on a scale from one to ten, glyphosate's contribution to farmers' ability to reduce tillage and summerfallow practices was valued at 9.1, and HT canola's contribution was 7.3. In addition, participants indicate that in the absence of HT canola, 24% of their land would likely include summerfallow management compared to the 1% of land currently managed with summerfallow. Using the results from the sensitivity analysis in Section 4.4.3, a 23% increase in land managed with summerfallow if HT crops were no longer available represents a decrease of 0.14-0.21 Mg SOC sequestered per ha, per year from the original analysis. Applying this value to total provincial crop production hectares (15,202,159), this represents a decrease of roughly 2-3 million Mg SOC sequestered annually from summerfallow reductions.

Policy discussions increasingly focus on strategies for the mitigation of climate change, including both penalties and credits for negative and positive influences on the environment. As such, members of the agricultural industry are working to become more involved in these conversations and advocate for recognition for farmers' contributions to the climate goals set out in the Kyoto Protocol and the Paris Accord. Accurate quantification of on-farm sustainability effects contributes information to the policy making process.

5.2 Contribution of Farmers' Management Changes to Canada's Climate Objectives

The data collected and results presented in this thesis provide evidence of increases in on-farm SOC gains resulting from a sub-set of farmer's management decisions, influenced by the introduction and adoption of beneficial technologies such as HT canola and glyphosate. Having quantified estimates of how SOC levels are changing is important for the creation of policy relating to C emissions. The results of this thesis, presented over a 25-year period, provide quantification of the changes in SOC levels. Though the results of this thesis only discuss a portion of the GHG cycle, they provide a crucial first step in documenting how soil sustainability is changing on dryland crop farms in Saskatchewan, and how these farms are helping Canada to meet its climate change goals set out in the Kyoto Protocol and the Paris Accord.

In 2019, GHG emissions from Canada's agricultural sector were estimated to be 73 million Mg CO_2 equivalents, representing about 10% of Canada's total national GHG emissions (ECCC, 2021b). When the ratio of CO_2 to C is applied to this estimate, this results in about 20 million Mg SOC. If we compare Canada's total agricultural emissions to the 2016-2019 annual gains in SOC in Saskatchewan presented in this thesis, 1.86 million Mg from reductions in tillage and 6.4 million Mg from the removal of summerfallow, the annual SOC gains represent 9% and 32%, respectively, of Canada's emissions from the agricultural sector. Considering that these results only represent carbon sequestration in one province, they indicate that beneficial land management practices of Saskatchewan dryland crop farmers are helping to offset a significant portion of the positive emissions from Canada's agricultural sector.

In the Paris Accord, Canada committed to reducing national GHG emissions to 30% below 2005 levels by 2030. Using the 2005 annual emission estimate of 730 million Mg CO_2 equivalents, a 30% reduction requires emissions to be reduced by 219 million Mg CO_2 equivalents, reaching 511 million Mg CO_2 equivalents by 2030 (ECCC, 2021c). Using the ratio of CO_2 to C, the required reduction of 219 million Mg CO_2 equivalents equates to 59.72 million Mg C. The results of this thesis estimate that annual SOC gains in Saskatchewan soils in 2016-2019 were 1.86 million Mg SOC from conservation tillage and 6.4 million Mg from the removal of summerfallow (Table 4.9). Based on these estimates, C sequestration in Saskatchewan agricultural soils is annually contributing 3-11% of Canada's required national emission reductions. Total positive emissions were not examined in this analysis, and therefore the results cannot be used to comment on the total changes in net emissions from prairie dryland crop production. Further research into total emissions from prairie dryland cropping is required to quantify the net contributions to Canada's emission reduction goals. However, the significant improvements in carbon sequestration play a role in lowering Canada's net emissions. The results of this thesis show the importance of including net C sinks as well as sources in emission calculations.

5.3 Carbon Credit System

The federal government implemented Canada's C pricing system in 2018 in an attempt to lower GHG emissions. Though some aspects of agricultural production are exempt from this tax, including fuel used for farm operations, the tax is still applied on fuel and electricity for drying grain, heating farm buildings, and is passed on to farmers through grain transportation and input costs. With the Canadian federal government's recent proposal to increase the tax to $170/tonne by 2030 (ECCC, 2020), concerns of economic pressures and the international competitiveness of Canadian farmers and industry members continues to rise.

Since the implementation of the carbon tax, discussions of whether Canadians who are sequestering C rather than emitting it should be compensated have been raised. The concept of carbon credits is straightforward: if those who are emitting C must pay, then those who are removing C would receive compensation. Since the C pricing policy took effect in 2019, a concrete federal carbon credit system has yet to be put into place. Recently, however, the Canadian federal government announced plans for the Federal GHG Offset Program, which will enable and fund the development of projects that offset GHG emissions in Canadian provinces and territories. This includes projects that implement "a protocol for sustainable agricultural land management activities that reduce GHG emissions and enhance soil carbon sequestration on agricultural lands" (Canada Gazette, 2021: 968).

The Saskatchewan Soil Carbon Sequestration Protocol Working Group, composed of representatives from the SSCA, the Agricultural Producers Association of Saskatchewan, the Saskatchewan Ministry of Agriculture, and the Saskatchewan Ministry of the Environment, are working to develop a Saskatchewan offset protocol for the sequestration of C in agricultural soils to be presented to the ECCC for implementation in the federal GHG offset program (Saskatchewan Soil Conservation Association, n.d.). The objective of the SSCA's representation on this committee is to help develop a science-based protocol to document data sources, coefficients, and methodologies for calculation of annual C sequestration in agricultural soils. Similarly, the Western Canadian Wheat Growers is advocating for the removal of the carbon tax on the premise that it negatively impacts farmers, who currently have no alternative energy options for their operations (Western Canadian Wheat Growers, 2019). A number of other farm groups are advocating similarly against the carbon tax or for a carbon offset program to recognize farmers for their contributions to lowering net GHG emissions through sequestration (e.g. Agricultural Producers Association of Saskatchewan, 2021; Saskatchewan Association of Rural Municipalities, 2018; SaskWheat, 2021).

The results presented in this thesis are benchmarked against 1995. The objective of using this baseline was to capture the most significant changes in management practices, which began in the mid 1990s, as well as to explore the contribution made by the introduction of HT canola to these management changes. However, the federal government's proposed GHG offset program states that only projects with a start date of 2017 or later will be eligible for credit (ECCC, 2019). This means that, although CT and summerfallow practices have been almost completely eliminated from Saskatchewan crop farmers' operations, these efforts over the past 25 years would not be eligible for credit.

5.4 Use of Current and Future Innovative Agricultural Technologies

The final implication of these results is the use of current and future innovative agricultural technologies. As shown by the results of this thesis, innovative technologies such as HT canola not only provide economic benefits to farmers, but also help them reduce their environmental footprints through a shift away from emission-intensive practices. Survey participants indicate that both HT crops and glyphosate helped to facilitate changes in on-farm management practices, including the reduction of tillage practices. They also indicate that, in the absence of these technologies, the lack of suitable alternative technologies would require them to shift away from the conservation practices they had previously adopted.

Public pushback against the use of many innovative technologies remains a concern for farmers and industry members, especially looking at the future of agricultural innovations. Health and safety regulations, consumer perceptions, media, and export markets play key roles in determining if, when, and how innovative technologies in agriculture will be developed and released (Lassoued et al., 2019). The results of this thesis support the case that the innovative technologies discussed in this thesis assisted in improving the sequestration of C on dryland crop farms in Saskatchewan. Commercialization of future technological advancements which stand to improve the sustainability of crop farms even further should therefore be supported and made available to farmers.

5.5 Summary

Discussions regarding agricultural and environmental policy changes require quantified data on the changes in farmers' management decisions and the resulting environmental impacts. Agricultural representation is currently advocating for changes in carbon policies including the federal carbon tax and the federal GHG offset program. The results of this thesis contribute quantified data to these policy discussions of the impacts of LMCs on carbon sequestration levels in Saskatchewan dryland crop farming. However, better measurement techniques of SOC levels in prairie soils are still required to improve the accuracy of C sequestration change estimates. Although the results of this thesis focus on C sequestration, and therefore cannot provide insight on total net emission changes from grain production, they do provide a first step in quantifying how the carbon footprint of Saskatchewan grain farms have changed over the past 25 years.

CHAPTER 6
CONCLUSION

6.1 Conclusion

This research identifies changes in Saskatchewan on-farm management practices undertaken by dryland crop operations, including a 45% decrease in summerfallow hectares, 52% decrease in CT hectares, 5% increase in MT hectares, and 47% increase in NT hectares, over the past 25 years. Survey participants indicate that the introduction of HT canola, as well as the complementary use of glyphosate, played a role in facilitating these adoptions. Participants report that, in the absence of HT canola, 24% of their land would be managed with summerfallow, compared to the 1% of land in the survey sample currently managed with this practice. The reduction in soil disturbance and increasing crop residue levels that accompanied these changes in management practices have resulted in net improvements in SOC levels.

A carbon accounting framework was used to quantify the changes in SOC resulting from these management changes. Over the past 25 years, the annual SOC gains from changes in tillage practices have increased by 0.15 Mg per ha. When applying this value to the SOC gains from a hypothetical 1,000 ha farm, the change in annual SOC gains is 149 Mg, which is equivalent to the emissions from about 119 cars. Annual SOC gains from changes in summerfallow practices have increased by 0.40 Mg per ha. When applying this value to the same 1,000 ha farm, the increase in annual SOC gains is 398 Mg C, the equivalent of emissions from 318 cars.

Applying economic valuations using three pricing scenarios, an online carbon removal marketplace, the Canadian carbon tax, and the SCC, results in an estimated economic value of the change in SOC from a hypothetical 1,000 ha farm. The economic valuation of the change in annual SOC gains from this farm resulting from a change in tillage practices ranges from $10,932 - $25,261, representing 32-74% of this farm’s net returns. The valuation of the change in

SOC gains resulting from the changes in summerfallow practices ranges from \$30,171 - \$69,716, representing 88-204% of this farm's net returns. A summary of the results for a hypothetical 1,000 ha farm are presented in Table 6.1.

Table 6.1 Summary of Changes in SOC gains from 1,000 Ha Farm Between 1991-1994 and 2016-2019

	From Tillage Practices	**From Summerfallow Practices**
Change in Annual SOC gains	0.15 Mg/ha	0.40 Mg/ha
Change in Annual Vehicle Removal Equivalents of SOC gains	149 cars	318 cars
Change in Economic Value of Annual SOC Gains	\$10,932 - \$25,261	\$30,171 - \$69,716

These results provide evidence that dryland crop farmers' voluntary adoptions of sustainable management practices in Saskatchewan contribute annually to the achievement of Canada's climate change goals. As policy discussions increasingly focus on environmental sustainability, the results support groups advocating for recognition of farmers' sustainability efforts in policy creation.

6.2 Limitations of Study and Areas of Future Research

This study has a number of limitations that must be considered. First, though the research quantifies the annual SOC gains from changes in soil dynamics and interactions as a result of the shift away from CT and summerfallow, it does not consider the complete C cycle, nor does it consider the other two main GHGs emitted from farms: N_2O and CH_4. The results presented in this thesis only cover one stage of the C cycle, and therefore cannot be used for inferences about net GHG emissions from grain production. In addition, agricultural emissions extend beyond the farm gate. The production and transportation of inputs such as fertilizer and chemical, and the transport of harvested grain both domestically and globally must be included in a complete analysis of agricultural emissions. Therefore, this thesis is limited to illustrating only the net C emissions from changes in agricultural soil dynamics, and even these measurements may be imperfect, as the most accurate method of measuring changes in SOC levels is through soil sampling techniques.

Secondly, the results presented in this thesis are based on broad empirical estimates. Though soil sample analysis is the most accurate method of gauging changes in SOC levels, it is difficult to physically measure SOC changes, especially over extended time periods and large regions. Therefore, estimated annual sequestration coefficients provide the best estimates of how SOC levels change in response to changes in management practices. However, numerous factors affect sequestration rates, including soil type and weather conditions. This analysis was broken down into two ecoregions, the semiarid and subhumid prairies, differing in climatic and soil conditions; however, even within these ecoregions the conditions are variable. The soil C coefficients used to estimate the changes in sequestration in this thesis are still used to conduct Canada's national GHG inventory assessments, indicating they are the most credible estimates available for C accounting studies. However, they can only be used to estimate SOC changes. The development of more robust methodologies for measuring changes in SOC levels would improve the accuracy of soil C accounting frameworks.

In addition, the survey collects farm management data from farmers both from their most recent crop rotation and from 25 years ago. Asking farmers to recall management decisions and practices from 25 years ago creates opportunity for recall bias due to farmers not remembering or having incomplete information of the practices used. In order to minimize the risk of this bias in survey responses from this time period, participants were encouraged to access farm records when responding. Eighty percent of participants indicated they used farm records to answer the questions from the 1991-1994 time period, which helps to increase confidence in these survey responses. However, despite the use of records by the majority of participants, data collected from this time period is limited to the information that farmers were able to provide.

Though the main driving factor of tillage and summerfallow reductions focused on throughout this thesis is the introduction of HT canola, there are also many other potential causes of LMCs. Some examples include innovations in other crop input technologies, including fertilizer, chemical, and seed technologies, improvements in farm machinery, especially in seeding implements, changes in input and grain prices, and increases in farm size and farm profitability. Leaving these other factors out of this study leads to a potential overstatement of the impacts of HT technology on these adoptions. Further research into the relative impacts of each of these technologies on changes in farmers' management practices is needed to determine the relative importance of each factor. Furthermore, it is important to acknowledge that HT canola and glyphosate are complementary technologies, and therefore linkages in their attribution to reductions in tillage and summerfallow exist. These linkages must be considered when discussing the attribution factors assigned by farmers to each of these technologies.

Another limitation is the relatively small sample sized of 100 farmers used for the analysis. In addition, as discussed in Section 3.3.1, the survey sample is, on average, slightly younger and operates larger farms than the average farmer in the 2016 Saskatchewan Census of Agriculture data. There is potential for the bias in the sample to lead to some bias in the results towards early adopters of technologies and farm practices. As such, it is possible that this bias in the sample leads to an overstatement of the sequestration results to some degree.

The final limitation is the time periods under study. In this thesis, two time periods are studied, 1991-1994 and 2016-2019, providing an overview of what has changed in 25 years of HT canola production. However, the data is not collected between these time periods. This means that the linearity and consistency of these management changes between the two time periods cannot be studied. The results show how many farmers are practicing conservation tillage and have removed summerfallow now compared to 25 years ago, but not how the changes were implemented. Therefore, the results of the study are limited by the assumption that the changes occurred in a relatively linear pattern, and that once a farmer adopted conservation tillage, they continued using this production system unless the data from either time period indicates otherwise.

Future research is needed in order to expand the scope of the results and to address the limitations discussed above. The continued collection of the survey data will help to build a database of changes in farm management practices in Saskatchewan. Running the survey every five years in the future will provide sufficient data to examine the continuing trends in on-farm management decisions. For future analysis, this will help to lessen the limitation of the time periods under study. Continuous data collection will allow further research to more accurately capture the trends, consistency, and rate of management changes.

The research also needs to be expanded to capture the complete GHG emission cycle from crop production to better inform policy makers of agriculture's net emission effects. As the full GHG cycle is quite complex, this additional research will need to be conducted in stages. First, the current methodology could be expanded to include CO_2, CH_4, and N_2O emissions from the soil, agricultural equipment, and use of other farm inputs including fertilizer and chemical. This will help to illustrate the complete on-farm GHG cycle. Current concerns of N_2O emissions from agricultural production make this a key priority area of future research. Beyond the farm gate, more data needs to be collected on the grain and input transportation systems, as well as the production of inputs, in order for indirect emissions to be included in agricultural estimates. This expanded research will help provide an overview of the net GHG emissions of agriculture, from input production and transport, to crop production, to grain harvest, handling, and transportation. Only at this point will the grain industry's complete emission effects be quantified.

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APPENDIX A: CROP ROTATION SURVEY QUESTIONS USED FOR ANALYSIS

Seeding - Harvest Questions

	Q1a. How many acres did you farm?	Q1b. Of the acres you farm, how many acres are owned and how many are rented in the respective years?		Q2. On your farm, how many acres are devoted to the following in the respective years?		
		Acres rented:	Acres owned:	Conventional crop production acres:	Genetically modified crop production acres:	Organic crop production acres:
Currently (2019)						
Farmed in 1994						

Q3. Throughout this survey you will report on a single field and the crop rotation(s) which you have used on this field. How many acres are in your selected field?

The field should be used in response to all questions regarding your most recent crop rotation and your crop rotation that led up to 1994 if you were farming at this time. When selecting a field, please choose one which has been used in cereal, oilseed, and/or pulse production, or summerfallow in the crop rotation. However, do not select a field which was used for hay or fodder production or pasture land during these time periods.

Acres: ____

If not all acres are seedable, please state the acres that are: ________________

Q4. What is your postal code?

Please respond using the following format **A1A 1A1**

____

Q4a. Is your field located in a Rural Municipality or a county?

- o Rural Municipality
- o County

Q4b. Please indicate the Rural Municipality number where your field is located:

- o RM# ____
- o RM Name____

Q4c. Please indicate the county name where your field is located:

- o County Name: ____

Q4d. What is the Dominion Land Survey (DLS) description of your field? Please use the standard DLS format of quarter, section, township, range, and meridian (e.g. SW 24-12-18-W3).

- o DSL description: ____

Q4e. What are the land coordinates to your field?

- o Latitude (x): ____
- o Longitude (y): ____

Q5. Screener1_Did you farm in the 1991 to 1994 time period?

- o Yes
- o No

Q6. Screener2_ Did you farm in the 2016 to 2019 time period?

- o Yes
- o No

Q7. Did you plant a crop or summerfallow this crop year?

	I planted a crop	I summerfallowed
1991	•	•
1992	•	•
1993	•	•
1994	•	•

1991-1994 Seeded Crop[33]

Please answer the following questions on land management or seed/soil preparation which was performed at the same time as seeding in the years 1991-1994.

Please refer to the same field throughout this survey.

	Q8. Did you seed in the spring or fall?		Q9. What type of crop did you plant as part of your crop rotation?
	Spring	Fall (of the previous year)	○ Cereal ○ Oilseed ○ Pulse ○ Summerfallow
1991	•	•	
1992	•	•	
1993	•	•	
1994	•	•	

	Select the type of crop you seeded:		
	Q9a. Seeded in the Spring or the Previous Fall (Dropdown)	Q9b. Text for if they select other	Q9c. What variety did you plant? (text)
1991	•		
1992	•		
1993	•		
1994	•		

	Q10. Did you pack this field?	Q10a. If yes, how many times?	Q11. Did you harrow this field?	Q11a. If yes, how many times?	Q12. Did you roll this field?	Q12a. If yes, how many times?
	• Yes • No	[whole number]	• Yes • No	[whole number]	• Yes • No	[whole number]
1991						
1992						
1993						
1994						

[33] Questions are repeated for 2016-2019

	Q23. What was your crop yield?
	Yield (bushel/acre)
1991	
1992	
1993	
1994	

Tillage and Summerfallow Questions

Please answer this section of the survey on your 1991 to 1994 tillage practices for the same plot of land you previously have chosen and described.

	Q1. During this crop year, did you till/cultivate your field?	
	Yes	No
1991	●	●
1992	●	●
1993	●	●
1994	●	●

	Q2. During this crop year, did you till/cultivate your field in the following production time periods:		
	Q2a. Before seeding in the spring? ○ Yes ○ No	Q2b. Post seeding until harvest? ○ Yes ○ No	Q2c. After harvest? ○ Yes ○ No
1991	○	○	○
1992	○	○	○
1993	○	○	○
1994	○	○	○

1991-1994 Pre- Seeding

Please answer the following questions on your spring tillage practices leading up to the time of seeding. If one year you happened to summerfallow, please just leave that year blank for the following pre-seeing questions.

	Q13. How frequently did you till prior to seeding? Please list the average number of days between tilling of the field. [drop down option 0-40]
1991	
1992	

1993	
1994	

Tillage during pre-seeding in 1991

Q3. How many times did you till or cultivate your field alone, or alongside chemical, excluding contracted tillage? [drop down option 0-10]

	Q3a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q3b. What implement did you use to till this field?	Q3c. How many feet wide was this implement?	Q3d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

Tillage during pre-seeding in 1992

Q4. How many times did you till or cultivate your field alone, or alongside chemical, excluding contracted tillage? [drop down option 0-10]

	Q4a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q4b. What implement did you use to till this field?	Q4c. How many feet wide was this implement?	Q4d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

Tillage during pre-seeding in 1993

Q5. How many times did you till or cultivate your field alone, or alongside chemical, excluding contracted tillage? [drop down option 0-10]

	Q5a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q5b. What implement did you use to till this field?	Q5c. How many feet wide was this implement?	Q5d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel	Feet (‘):	Inches (“): [drop down option 1-24]

	• Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	• Subsoiler • Cultivator • Other: Please specify		
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

Tillage during pre-seeding in 1994

Q6. How many times did you till or cultivate your field alone, or alongside chemical, excluding contracted tillage? [drop down option 0-10]

	Q6a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q6b. What implement did you use to till this field?	Q6c. How many feet wide was this implement?	Q6d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet ('):	Inches ("): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○

Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

1991-1994 In-Crop Tillage Practices

Please answer the following questions with regards to your in-crop tillage/cultivation practices (post-seeding, leading up to harvest time). If one year you happened to summerfallow, please just leave that year blank for the following set of in crop questions.

	How frequently did you till in crop (post-seeding to pre-harvest)? Please list the average number of days between tilling of the field. [type in number between range 0-90]
1991	
1992	
1993	
1994	

In-Crop tilling 1991:

Q8. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q8a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q8b. What implement did you use to till this field?	Q8c. How many feet wide was this implement?	Q8d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet ('):	Inches ("): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○

Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

In-Crop tilling 1992:

Q9. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q9a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q9b. What implement did you use to till this field?	Q9c. How many feet wide was this implement?	Q9d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

In-Crop tilling 1993:

Q10. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q10a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q10b. What implement did you use to till this field?	Q10c. How many feet wide was this implement?	Q10d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

In-Crop tilling 1994:

Q11. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q11a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q11b. What implement did you use to till this field?	Q11c. How many feet wide was this implement?	Q11d. What was the average tillage depth?
	Drop down of:	Drop down of:	Feet (‘):	Inches (“): [drop down

	• Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	• Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify		option 1-24]
Pass 1		○		○
Pass 2	○	○		○
Pass 3	○	○		○
Pass 4	○	○		○
Pass 5	○	○		○
Pass 6	○	○		○
Pass 7	○	○		○
Pass 8	○	○		○
Pass 9	○	○		○
Pass 10	○	○		○

1991-1994 Post-Harvest

Please answer the following questions with regards to your in-crop tillage/cultivation practices (post-seeding, leading up to harvest time). If one year you happened to summerfallow, please just leave that year blank for the following set of in crop questions.

	How frequently did you till in crop (post-seeding to pre-harvest)? Please list the average number of days between tilling of the field. [type in number between range 0-90]
1991	
1992	
1993	
1994	

Post-harvest tilling 1991:

Q12. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q12a. If a tillage pass is the same across multiple passes, please	Q12b. What implement did you use to till this field?	Q12c. How many feet wide was this implement?	Q12d. What was the average tillage depth?

	indicate which pass this matches			
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○

Post-harvest tilling 1992:

Q13. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q13a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q13b. What implement did you use to till this field?	Q13c. How many feet wide was this implement?	Q13d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]

Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○

Post-harvest tilling 1993:

Q14. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q14a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q14b. What implement did you use to till this field?	Q14c. How many feet wide was this implement?	Q14d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○

Post-harvest tilling 1994:

Q15. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-10]

	Q15a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q15b. What implement did you use to till this field?	Q15c. How many feet wide was this implement?	Q15d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○

1991-1994 Summerfallow

Please answer the following questions in relation to the summerfallow of this field in the given year of the crop rotation. If years in which you seeded crops appear, please leave those years blank for the remainder of the summerfallow block of questions.

	Q16. How frequently did you till during summerfallow? Please list the average number of days between tilling of the field. [type in number between range 0-90]
1991	
1992	
1993	
1994	

Summerfallow tilling in 1991:

Q17. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-15]

	Q17a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q17b. What implement did you use to till this field?	Q17c. How many feet wide was this implement?	Q17d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet ('):	Inches ("): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○
Pass 11				○
Pass 12				○
Pass 13				○
Pass 14				○
Pass 15				○

Summerfallow tilling in 1992:

Q18. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-15]

	Q18a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q18b. What implement did you use to till this field?	Q18c. How many feet wide was this implement?	Q18d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○
Pass 11				○
Pass 12				○
Pass 13				○
Pass 14				○
Pass 15				○

Summerfallow tilling in 1993:

Q19. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-15]

	Q19a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q19b. What implement did you use to till this field?	Q19c. How many feet wide was this implement?	Q19d. What was the average tillage depth?

	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5 • Pass 6 • Pass 7 • Pass 8 • Pass 9	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler • Cultivator • Other: Please specify	Feet (‘):	Inches (“): [drop down option 1-24]
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○
Pass 11				○
Pass 12				○
Pass 13				○
Pass 14				○
Pass 15				○

Summerfallow tilling in 1994:

Q20. How many times did you till or cultivate your field alone, or alongside chemical? [drop down option 0-15]

	Q20a. If a tillage pass is the same across multiple passes, please indicate which pass this matches	Q20b. What implement did you use to till this field?	Q20c. How many feet wide was this implement?	Q20d. What was the average tillage depth?
	Drop down of: • Pass 1 • Pass 2 • Pass 3 • Pass 4 • Pass 5	Drop down of: • Moldboard • Disc plow • Rotary tiller • Chisel • Subsoiler	Feet (‘):	Inches (“): [drop down option 1-24]

	• Pass 6 • Pass 7 • Pass 8 • Pass 9	• Cultivator • Other: Please specify		
Pass 1				○
Pass 2				○
Pass 3				○
Pass 4				○
Pass 5				○
Pass 6				○
Pass 7				○
Pass 8				○
Pass 9				○
Pass 10				○
Pass 11				○
Pass 12				○
Pass 13				○
Pass 14				○
Pass 15				○

Q21. Are there any comments you would like to make about your tillage practices for the 1991 to 1994 time period? If so, please use the following space:
[Text box for response]

Demographics

Q24. How long have you been farming (in years)?

○ Year(s)____

Q25. Do you also collect off-farm income?

- o Yes
- o No

Q26. How long have you been involved in the decision making process for your farm (in years)?

○ Year(s)____

Q27. Please indicate in which year you were born. [drop down options]

Q28. Which of the following best describes your level of education?

- Some High School
- High School Graduate
- Some College
- College Graduate
- Some Graduate School
- A Post-graduate degree
- Prefer not to say

Q29. Is your farm incorporated?

- Yes
- No

Q29a. In what year did your farm become incorporated?

- Year: ____

Q30. Did you access any of your records to complete this survey?

- Yes
- No

Attribution Questions

Q1. We are interested to know to what extent you believe the following factors contributed to the adoption of conservation tillage practices and reduced summerfallow. Please assign each of these factors a value from one to ten corresponding to the extent you believe they facilitated the adoption of these practices.
(0 = did not at all facilitate, 10 = played a major role in facilitating)

- Herbicide-tolerant canola
- Glyphosate
- Herbicide-tolerant crops (other than canola)

Q2. What percentage of your land would include summerfallow management if herbicide-tolerant crops did not exist? [scale: 0-100%]

Q3. What would be different about your farming operation today without the use of herbicide-tolerant crops? [text]

Q4. What would be different about your farming operation today without the use of other genetically-modified crops? [text]

Q5. What would be different about your farming operation today without the use of glyphosate? [text]

APPENDIX B: ANOVA TABLES FOR FARM CHARACTERISTIC IMPACTS ON TILLAGE AND SUMMERFALLOW PRACTICES

1991-1994 ANOVA Tables

Impact of Farm Size on Number of Annual Tillage Applications

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
180-399	2	6.25	3.125	0.28125
400 - 759	5	8.25	1.65	0.70625
760 - 1,119	7	10	1.42857143	0.53571429
1,120-1,599	18	18.5	1.02777778	0.83006536
1,600-2,239	9	14.5	1.61111111	1.91189236
2,240 - 2,879	4	2.5	0.625	0.52083333
2,880 - 3,519	1	1.75	1.75	#DIV/0!
3,520 or more	5	3.75	0.75	0.6875

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.11941527	7	1.87420218	2.0127905	0.07540998	2.2315299
Within Groups	40.03928571	43	0.93114618			
Total	53.15870098	50				

Impact of Inclusion of Pulses in Crop Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
31	51.5	1.66129032	0.94499328	31
21	15.25	0.72619048	0.69315476	21

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	10.94696214	1	10.9469621	12.9663726	0.00072799	4.03430971
Within Groups	42.21289363	50	0.84425787			
Total	53.15985577	51				

Impact of Inclusion of Canola in Crop Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
No	16	22.625	1.4140625	1.4514974
Yes	36	44.125	1.22569444	0.88555308

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.39303719	1	0.39303719	0.37242836	0.54444752	4.03430971
Within Groups	52.7668186	50	1.05533637			
Total	53.1598558	51				

Impact of Crop Rotation Length on Number of Annual Tillage Applications

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	8	10.75	1.34375	0.9453125
2	22	33	1.5	1.40625
3	8	11.5	1.4375	1.12053571
4	14	11.5	0.82142857	0.37912088

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.239096841	3	1.41303228	1.38643698	0.25826551	2.79806064
Within Groups	48.92075893	48	1.01918248			
Total	53.15985577	51	53.15985577			

Impact of Percentage of Farmland Owned on Number of Annual Tillage Applications

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
<35%	7	7.25	1.03571429	0.4672619
35-65%	14	16.75	1.19642857	0.81902473
>65%	30	41.5	1.38333333	1.3404454

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.83489146	2	0.41744573	0.38294985	0.68391151	3.19072734
Within Groups	52.3238095	48	1.09007937			
Total	53.158701	50				

Impact of Inclusion of GM Crops in Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
No	42	54	1.28571429	1.11226045
Yes	10	12.75	1.275	0.83958333

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.0009272	1	0.0009272	0.0008721	0.97655839	4.03430971
Within Groups	53.1589286	50	1.06317857			
Total	53.1598558	51				

Impact of Farmer Education Level on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Some High School	3	4	1.33333333	0.14583333
High School Graduate	8	5.75	0.71875	0.54352679
Some College	11	16.875	1.53409091	1.31278409
College Graduate	25	30.625	1.225	1.18229167
Some Graduate School	0	0		
A Post-Graduate Degree	4	8.5	2.125	0.4375

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6.16612355	5	1.23322471	1.18296966	0.3325372	2.42208547
Within Groups	46.9116951	45	1.04248211			
Total	53.0778186	50				

Impact of Farm Size on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	Count	Sum	Average	Variance
180-399	2	3	1.5	0.5
400 - 759	5	1	0.2	0.2
760 - 1,119	7	6	0.85714286	0.80952381
1,120-1,599	18	8	0.44444444	0.37908497
1,600 - 2,239	9	6	0.66666667	0.75
2,240 - 2,879	4	3	0.75	0.91666667
2,880 - 3,519	1	2	2	#DIV/0!
3,520 or more	5	3	0.6	0.8

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.36998133	7	0.76714019	1.34358026	0.25382591	2.2315299
Within Groups	24.5515873	43	0.57096715			

Total	29.9215686	50

Impact of Inclusion of Pulse in Crop Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	31	27	0.87096774	0.71612903
No	21	5	0.23809524	0.19047619

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.01429753	1	5.01429753	9.91226677	0.00276817	4.03430971
Within Groups	25.2933948	50	0.5058679			
Total	30.3076923	51				

Impact of Inclusion of Canola in Crop Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	36	14	0.38888889	0.41587302
No	16	18	1.125	0.65

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.00213675	1	6.00213675	12.3472527	0.00094769	4.03430971
Within Groups	24.3055556	50	0.48611111			
Total	30.3076923	51				

Impact of Crop Rotation Length on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1	8	4	0.5	0.28571429
2	22	20	0.90909091	0.94372294
3	8	2	0.25	0.21428571
4	14	6	0.42857143	0.26373626

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

Between Groups	3.56093906	3	1.18697969	2.13016602	0.10869159	2.79806064
Within Groups	26.7467532	48	0.55722403			
Total	30.3076923	51				

Impact of Percentage of Farmland Owned on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
<35%	7	5	0.71428571	0.57142857
35-65%	14	7	0.5	0.57692308
>65%	30	20	0.66666667	0.64367816

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.32633053	2	0.16316527	0.2646349	0.76859851	3.19072734
Within Groups	29.5952381	48	0.61656746			
Total	29.9215686	50				

Impact of Inclusion of GM Crops in Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	10	4	0.4	10
No	42	28	0.66666667	0.61788618

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.57435897	1	0.57435897	0.96585029	0.33044907	4.03430971
Within Groups	29.7333333	50	0.59466667			
Total	30.3076923	51				

Impact of Farmer Education on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Some High School	3	2	0.66666667	1.33333333
High School Graduate	8	3	0.375	0.26785714
Some College	11	13	1.18181818	0.76363636
College Graduate	25	10	0.4	0.41666667
A Post-Graduate Degree	4	3	0.75	0.91666667

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.22883244	4	1.30720811	2.41220716	0.06249726	2.57403503
Within Groups	24.9280303	46	0.5419137			
Total	30.1568627	50				

2016-2019 ANOVA Tables

Impact of Farm Size on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
130-399	4	2	0.5	0.33333333
400 - 759	10	0	0	0
760 - 1,119	8	1.5	0.1875	0.13839286
1,120-1,599	9	0.25	0.02777778	0.00694444
1,600-2,239	12	0.5	0.04166667	0.02083333
2,240 - 2,879	7	0.25	0.03571429	0.00892857
2,880 - 3,519	11	0.75	0.06818182	0.01363636
3,520 or more	37	3.25	0.08783784	0.04936186

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.91732079	7	0.13104583	2.7945286	0.01118082	2.1130667
Within Groups	4.22043431	90	0.04689371			
Total	5.1377551	97				

Impact of Inclusion of Pulse in Crop Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Yes	63	6.75	0.10714286	0.06192396
No	36	1.75	0.04861111	0.03506944

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.07848575	1	0.07848575	1.50257433	0.22324343	3.93912613
Within Groups	5.06671627	97	0.05223419			
Total	5.14520202	98				

Impact of Inclusion of Canola in Crop Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Yes	91	7.25	0.07967033	0.05260989
No	8	1.25	0.15625	0.05245536

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.04312441	1	0.04312441	0.81987538	0.36746021	3.93912613
Within Groups	5.10207761	97	0.05259874			
Total	5.14520202	98				

Impact of Crop Rotation Length on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
1	7	2	0.28571429	0.23809524
2	52	3	0.05769231	0.03582202
3	17	1.75	0.10294118	0.03170956
4	23	1.75	0.07608696	0.0479249

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.32800675	3	0.10933558	2.15620911	0.09830003	2.70040906
Within Groups	4.81719527	95	0.05070732			
Total	5.14520202	98				

Impact of Percentage of Farmland Owned on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
<35%	14	0.5	0.03571429	0.00824176
35-65%	41	4.75	0.11585366	0.06905488
>65%	43	3.25	0.0755814	0.05218715

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.07655666	2	0.03827833	0.71849411	0.49011548	3.09221744
Within Groups	5.06119844	95	0.05327577			
Total	5.1377551	97				

Impact of Inclusion of GM Crops in Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Yes	73	6.25	0.08561644	0.05593607

No	26	2.25	0.08653846	0.04471154

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.6298E-05	1	1.6298E-05	0.00030727	0.98605059	3.93912613
Within Groups	5.14518572	97	0.05304315			
Total	5.14520202	98				

Impact of Inclusion of Organic Crops in Rotation on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Yes	5	1.25	0.25	0.1875
No	94	7.25	0.07712766	0.04573467

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.14187755	1	0.14187755	2.75059566	0.1004486	3.93912613
Within Groups	5.00332447	97	0.05158066			
Total	5.14520202	98				

Impact of Farmer Education Level on Number of Annual Tillage Applications

SUMMARY

Groups	Count	Sum	Average	Variance
Some High School	3	0	0	0
High School Graduate	13	1	0.07692308	0.07692308
Some College	18	1.5	0.08333333	0.05882353
College Graduate	56	6	0.10714286	0.05649351
Some Graduate School	2	0	0	0
A Post-Graduate Degree	6	0	0	0

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.10753532	5	0.02150706	0.39335258	0.85224811	2.31343059
Within Groups	5.03021978	92	0.0546763			
Total	5.1377551	97				

Impact of Farm Size on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	Count	Sum	Average	Variance

130-399	4	1	0.25	0.25
400 - 759	10	0	0	0
760 - 1,119	8	0	0	0
1,120-1,599	9	0	0	0
1,600-2,239	12	0	0	0
2,240 - 2,879	7	0	0	0
2,880 - 3,519	11	1	0.09090909	0.09090909
3,520 or more	37	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.30009276	7	0.04287039	2.32557211	0.03154132	2.1130667
Within Groups	1.65909091	90	0.01843434			
Total	1.95918367	97				

Impact of Inclusion of Pulse in Crop Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	63	2	0.03174603	0.031234
No	36	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.02308802	1	0.02308802	1.15648286	0.28486379	3.93912613
Within Groups	1.93650794	97	0.019964			
Total	1.95959596	98				

Impact of Inclusion of Canola in Crop Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	91	2	0.02197802	0.02173382
No	8	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.003552	1	0.003552	0.17614346	0.67563677	3.93912613
Within Groups	1.95604396	97	0.0201654			
Total	1.95959596	98				

Impact of Crop Rotation Length on Frequency of Summerfallow in Four-Year Crop

Rotation

SUMMARY

Groups	Count	Sum	Average	Variance
1	7	1	0.14285714	0.14285714
2	52	0	0	0
3	17	0	0	0
4	23	1	0.04347826	0.04347826

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.14593136	3	0.04864379	2.54796827	0.06044732	2.70040906
Within Groups	1.8136646	95	0.01909121			
Total	1.95959596	98				

Impact of Percentage of Farmland Owned on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	Count	Sum	Average	Variance
<35%	14	0	0	0
35-65%	41	1	0.02439024	0.02439024
>65%	43	1	0.02325581	0.02325581

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00682973	2	0.00341487	0.16616466	0.84715237	3.09221744
Within Groups	1.95235394	95	0.02055109			
Total	1.95918367	97				

Impact of Inclusion of GM Crops in Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	Count	Sum	Average	Variance
Yes	73	0	0	0
No	26	2	0.07692308	0.07384615

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.11344211	1	0.11344211	5.96043771	0.01644282	3.93912613
Within Groups	1.84615385	97	0.01903251			
Total	1.95959596	98				

Impact of Inclusion of Organic Crops in Rotation on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Yes	5	2	0.4	0.3
No	94	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.75959596	1	0.75959596	61.4006734	5.9808E-12	3.93912613
Within Groups	1.2	97	0.01237113			
Total	1.95959596	98				

Impact of Farmer Education Level on Frequency of Summerfallow in Four-Year Crop Rotation

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Some High School	3	0	0	0
High School Graduate	13	0	0	0
Some College	18	1	0.05555556	0.05555556
College Graduate	56	1	0.01785714	0.01785714
Some Graduate School	2	0	0	0
A Post-Graduate Degree	6	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.03259637	5	0.00651927	0.31131381	0.9050295	2.31343059
Within Groups	1.9265873	92	0.02094117			
Total	1.95918367	97				

APPENDIX C: EXAMPLES OF PARTICIPANT COMMENTS ON ATTRIBUTION OF VARIOUS TECHNOLOGIES TO ADOPTION OF SUSTAINABLE LAND MANAGEMENT PRACTICES

Examples of participant responses to the question: What would be different about your farming operation today without the use of herbicide-tolerant crops?

"There would be more land with wind and water erosion. There would be a lot less food."

"We would have to go back to summer fallow."

"I would still be pre-tilling my land and making more passes across my field."

"We would invest more capital in tillage equipment, we would be less profitable, weed populations would be more difficult to manage."

"Likely more tillage and additional herbicide application for weed control."

"We would be making more passes, and taking land out of rotation to deal with weeds."

"Continuous cropping would be very tough."

"Would require more tillage and more herbicides."

"We would be less sustainable, environmentally."

"Would have to summerfallow."

"Resumption of summerfallow. Increased use of alternative herbicides. Reduced crop yields and profitability."

"Probably growing little canola (or none)."

"Lower profits, more crop rotations, more hrs on machinery."

"We would most likely be cultivating to incorporate Edge to control weeds in pulse crops."

“More tillage.”

“I think we would have not made it this far.”

Examples of participant responses to the question: What would be different about your farming operation today without the use of glyphosate?

“Very different. More swathing in the fall, with greater risk of crop quality deterioration due to weather. More in-crop herbicide application, which would be more costly. Certain weeds would return with a vengeance like quackgrass, millets/foxtails, and certain thistles.”

“More herbicide applied, more tillage, more resistance weeds, less profitable, significantly more tillage, erosion. Smaller farms.”

“There would need to be a large increase in tillage.”

“Glyphosate has been essential for the use of direct seeding technology. Only once have we grown a Roundup tolerant crop, but we grow Liberty tolerant canola. Having effective pre seed applications and potential perennial weed control in fall is critical to maintaining our crop production system. Again, it's uses outside of in-crop weed control has been essential.”

“Using the cultivator not spraying.”

“Would have to use more expensive herbicides and more tillage to make up for the lost weed control.”

“If we didn't have glyphosate we would have no choice but to go back to tillage and summerfallowing.”

“I would be summer fallowing and tilling more. Thus increasing fuel costs.”

“More tillage, more labour, less yield, poorer soil quality with more tillage.”

“Could not farm the way we do. Glyphosate enables zero tillage and has reduced soil erosion to near zero. It is critical for soil health.”

“I do not expect to continue no-till cropping and would lose the soil building gains we have made by ceasing tillage. At my age I might retire rather than resume tillage practices.”

“We would never have been able to continuous crop our land. We would have more weed pressure and dockage. We would never be able to straight combine.”

“I would [be] working the land, would be watching it blow again. Would require more rain to grow a crop of equal yield. I would need to almost double the amount of rain compared to zero tillage to working the land. My organic matter would be reduced also if I went back to summerfallow and working the land.”

“I would have to till more, use more dangerous chemicals and burn more fuel.”

“We would have to till everything before we seed.”

“I don’t think we would be farming.”