HETEROGENEOUS MOTIVATIONS AND CHALLENGES OF REGENERATIVE AGRICULTURE IN SASKATCHEWAN: INSIGHTS FROM CASE STUDIES AND BIOECONOMIC MODELLING

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ABSTRACT

Regenerative agriculture is an alternative farming system proposed to improve soil health, improve economic sustainability, and mitigate climate change. There are a set of principles commonly agreed upon that help guide producers: limit disturbance, armour the soil, increase plant diversity, keep living roots in the soil, integrate livestock and crop operations, and understand the farm context. Regenerative agriculture is a flexible farming system that can be adapted to producers' capabilities and conditions.

The purpose of our project is twofold. The first is to gather information about the use of regenerative agricultural practices in Saskatchewan. We interview producers throughout Saskatchewan who have experience with regenerative agriculture. We ask a series of questions about their specific practices, barriers faced, and advice for future producers. The information will be shared with the Ministry of Agriculture to support producers interested in regenerative agricultural practices.‘ The second objective is to create a renewable resource model to understand and model the economic motivations of the case studies. Regenerative agricultural practices focus on soil health management and are a large reason for why many adopt these practices. We construct a model where the representative farmer maximizes the net present value of annual net returns by choosing the amount they are willing to invest into building soil carbon stock, subject to the state of a farmer's lands, defined by soil carbon content. The purpose of the model is to better understand the fundamental trade-off between short-term economic profits and long-term improvement in soil health. We develop a framework that can be applied in the decision-making process for a producer to adopt regenerative agriculture. Our model demonstrates that only farmers in select circumstances will opt-in to regenerative farming without a

significant subsidy or cost-sharing program.

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Chapter 1

Introduction

1.1 Background

Soils are important for agricultural systems and sustainability (Kibblewhite et al., 2007; Stevens, 2018). Healthy soils can increase plant growth, reduce soil erosion, prevent pest and disease outbreak, serve as a carbon sink, increase aggregate stability, lower bulk density, increase available water capacity (O'Connor, 2020; Stevens, 2018), and regulate and increase plant nutrient availability (Magdoff, 1993). Degraded soils limit agricultural productivity, which can result in economic and environmental losses (Wu and Congreves, 2022). A producer must decide if the private benefits of improving soils outweigh the costs of soil health practices, so there are trade-offs made. The adoption of a new agricultural management strategy may result in short-term yield and profits losses before any long-term improvements in soil health emerge. Furthermore, the benefits of improved soils are not guaranteed as it is varies based on the producers' context. Soil degradation in the Canadian Prairies has come from wind erosion, which was made worse by periods of drought and heavy tillage (Wu and Congreves, 2022). More recently, soil conserving methods have been adopted to protect soils and increase agricultural productivity (Wu and Congreves, 2022).

The agricultural sector is responsible for about ten percent of Canada's greenhouse gas emissions, though, agriculture can help reduce emissions through storing carbon on agricultural land (AAFC, 2012). There are strategies that can increase the amount of carbon stored in soils, such as regenerative agriculture; which can also increase soil health, crop productivity, and water quality (Canada, 2012). According to the Government of Canada, soil carbon accumulation will continue until 2040 and then reach a steady-state at the current rate of adopting carbon sequestering practices (AAFC, 2012). Saskatchewan agriculture already has a low carbon footprint, which has been attributed to reduced/no-tillage, as well as manure management and crop residues (Bamber et al., 2023).

Regenerative agriculture is an alternative agricultural strategy to improve soils and the environment. Regenerative agriculture can be adapted to a producers' capabilities and conditions (Merfield, 2019). There are six principles that describe regenerative agriculture as there is no set list of practices or definitions. The six principles are: limit disturbance, armour the soil, increase plant diversity, keep living roots in the soil, integrate livestock and crop operations, and understand the farm context (Burns, 2021; Karaca and Ince, 2023; LaCanne and Lundgren, 2018; Moyer et al., 2020; Newton et al., 2020; Regeneration International, 2024). Regenerative agriculture can improve soil health, reduce input use, increase yields and sequester greenhouse gas emissions, although there is no guarantee that regenerative agriculture will work for every producer as there are many factors that influence the success of it. There are a variety of strategies that fall under the regenerative agriculture umbrella, many of which overlap with other forms of sustainable agricultural practices (Khangura et al., 2023). Regenerative strategies can include no/reduced tillage, diverse crop rotations, intercropping, composting, reduced synthetic inputs, rotational grazing, and using perennials (Khangura et al., 2023; Schreefel et al., 2020). There are some strategies can that fall under one or multiple regenerative agriculture principles, and have the potential to improve soil health through increasing soil carbon, improve soil moisture, increase pest and disease resilience (Khangura et al., 2023), improve soil physical quality, and improve nutrient cycling (Schreefel et al., 2020).

In this thesis, we focus on Saskatchewan farmers and policymakers. Saskatchewan producers are frequent users of soil conserving methods such as reduced tillage, no-tillage management, decreased summer fallow (Clearwater et al., 2016), direct seeding, and continuous cropping. Saskatchewan is considered to be at a low risk of soil erosion (Clearwater et al., 2016), which shows that improved soil management can reduce the risk of soil degradation (Clearwater et al., 2016), however, the increased adoption of these practices may not be enough. Saskatchewan has experienced frequent extreme weather events such as prolonged periods of drought, and increased temperature. The agricultural sector is vulnerable to climate change, which can result in reduced yields and farm income (Canada, 2012).

One principle of regenerative agriculture is reduced soil disturbance, which can be achieved through no-tillage. No-tillage is practiced on over 70% of cropland acres in Saskatchewan (Poirier, 2022), which has led to improved carbon sequestration. The widespread adoption of no-tillage throughout Saskatchewan highlights that producers practice sustainable strategies. Throughout this thesis, we are not pushing for the adoption of regenerative agriculture, but instead to understand what may lead producers to adopt more regenerative agricultural practices. The adoption of no-tillage was low at first which can be attributed to many reasons, such as lack of infrastructure and low profit margins (May et al., 2020). Throughout time, the economic benefits of no-tillage, including reduced fuel and labour costs, were realized, and improved equipment made no-tillage more appealing to producers. May et al. (2020) also attributes the uptake of no-tillage to an increased awareness of yield loss potential and environmental awareness, as well as the willingness of third-party organizations to get involved. We can learn from the adoption of no-tillage about the producer decision making process, and what plays a role on the adoption of new agricultural strategies. No-tillage is only one example of regenerative strategies that is practiced in Saskatchewan. Throughout this thesis, we will see that many other regenerative methods are used.

Regenerative agriculture is context specific, and some regenerative practices will not work on a farm. Despite the adoption of no-tillage being practiced more throughout Saskatchewan, this may not follow for other regenerative practices. There has been success with increased carbon sequestration and improved economic advantages as a result of no-tillage in Saskatchewan so there may not be a need to adopt additional regenerative strategies.

1.1.1 Objectives

There is a gap in current knowledge about regenerative agriculture in Saskatchewan. To examine the use of regenerative agriculture in the Prairies requires going to those who have firsthand experience. The first objective of this thesis is to develop a series of case studies on producers in Saskatchewan. A group of selected producers were asked about regenerative agriculture including regenerative practices, barriers, and how the Saskatchewan Ministry of Agriculture can provide assistance to regenerative producers. In order to understand and model the case studies, we present a renewable resource framework. The second objective of this thesis is to use the framework to understand the tradeoff that producers make between short-term economic losses for long-term improvements in soil health.

The case studies highlighted the different regenerative strategies used, the diverse management styles, and that there is no one size fits all. The most common regenerative strategies were cover cropping, integrated livestock, reduced disturbance and diverse crop rotations. Cover cropping and integrated livestock were commonly used together, which offers synergistic benefits as both producers and the animals benefit. Producers stated that regenerative agriculture did not cost them ‘all that much’, though there were some bad years.

Producers were mainly focused on improving their soils and making decisions for long-term improvements in soil health. For example, one producer stated the importance of soils as the building block of the whole farm, and regenerative agriculture is about meeting the needs of the soil. The decisions made on their farm fit better within their conscience and regenerative practices will make their farm successful years from now. Any improvements in soil health will not be immediate and will take some time to materialize. The improvements are not guaranteed.

Regenerative producers faced yield losses relative to previous years, and increased input costs without any improvements in soil health. Even if there are improvements in soil health over time, a producer may still face unforeseen circumstances. It is also hard to measure how any of the changes may occurs, unless discrete measurements are taken. For example there were two farms who had taken soil samples prior to implementing regenerative strategies, and both saw increases in soil organic carbon. Despite the challenges that were faced with adopting regenerative agriculture, producers experienced improved wheat yield, farm resiliency, improved biodiversity, and healthier soils.

We then present a renewable resource model that is informed by the regenerative practitioners interviewed. Our framework links how a producer builds soil health subject to biological changes in soil over time. In our conceptual framework, the representative producer maximizes the discounted net present value (NPV) of annual net returns from a hectare of land by building soil carbon stock. We analyze how a producer responds to changes in the costs of production, input efficiency, and a carbon credit program at different values of each parameter. To highlight how our theoretical framework could be used, we provide an example parameterized to Saskatchewan (Maillard et al., 2018).

The renewable resource framework can be used in any setting with the proper data requirements, which can be expensive and difficult to obtain. We used a thirty-year experiment from Swift Current, Saskatchewan to provide an example of how the renewable resource framework could be used (Maillard et al., 2018). We used the experiment to calibrate a wheat production function and a law of motion that captures the annual change in soil carbon stock. Our representative producer will build soil carbon through increasing the amount of estimated carbon input into the soil. In the example, a producer is able to increase soil carbon with methods such as retaining crop residue, manure management, cover crops, and using high producing plant biomass species.

In our renewable resource model, we focus on the individual farm level benefits of regenerative agriculture. The private benefits of regenerative agriculture may include reduced inputs, labour savings, improved crop productivity, improved biodiversity and farm resiliency. These benefits are not immediate and often take years to realize, and some producers may not experience anything.

We run our model for fifty years, and find that the representative producer responds to changes in the costs of production, and improved efficiency of practices to build soil carbon stock. We evaluated the model at a baseline and evaluated how the NPV changes with different values of costs and efficiency. When there was a 33.3% decrease in the cost per unit of soil carbon input, there was an increase of 12.5% in the NPV. If the costs per unit were to increase by 33.3%, this led to a 7.3% decrease in NPV. At a constant marginal cost of $30 per unit, an increase of 20% input efficiency to increase soil carbon stock led to a 2.5% decrease in the NPV. This highlights that a decrease in production costs makes the investment more appealing to our producer, whereas an increase in efficiency does not.

Regenerative agriculture has public benefits that extend beyond the farm. This includes improved yields, reduced greenhouse gas emissions, increased carbon sequestration, improved soil health/fertility and improved biodiversity. The public benefits of regenerative agriculture may incentivize government intervention as there are more people that benefit from it. Policies surrounding regenerative agriculture are needed in order to reverse soil degradation and improve crop productivity (Al-Kaisi and Lal, 2020). Al-Kaisi and Lal (2020) highlight several mechanisms that may have a role in regenerative agriculture: monetary incentives, reward or credit producers, carbon offset markets, and develop demand-side programs.

A carbon credit program may enhance the public and private benefits of regenerative agriculture as producers will receive an additional revenue stream, and everyone will experience the benefits from improved soil health and decreased emissions. There is an opportunity in the agricultural sector to pay producers for their ecosystem goods and services, as there are not many options available for producers. A carbon credit program would provide the chance for producers to get paid for their efforts for implementing soil conserving measures, such as regenerative agriculture. A producer will receive additional income for increased soil carbon stock.

We introduce a carbon credit program into our framework that pays a producer for the amount of carbon that is sequestered each year. The hypothetical carbon credit in our example is a voluntary outcome-based program that does not penalize producers for any carbon lost during the year. We are able to identify how a producer would respond to the addition of a carbon credit and find that it does not impact the decision making process at the values selected in our example (i.e. the amount of estimated carbon input remains relatively stable). The carbon payment gives our representative producer additional revenue, and makes investing into soil carbon stock more appealing. When the carbon payment is \$50/tonne, the NPV increases by 2.5%.

We contribute to the growing literature of renewable resource models in economic theory, with a focus on sustainable agricultural practices that improve soils. Regenerative agriculture can improve soils, though adoption is limited. Our framework is related to this broad literature that combines natural resource sciences and economics, and can be used to help understand the decision making process of a producer.

This thesis is structured as follows:

- Chapter 1: Introduction that provides a brief background and the objectives of this thesis.
- Chapter 2: Literature review with relevant information on regenerative agriculture, soil health, determinants of adoption, and renewable resource soil models.
- Chapter 3: Regenerative agricultural case studies in Saskatchewan about the experience of producers in the Prairies.
- Chapter 4: Analyzing the economic viability of regenerative agriculture through a renewable resource model that links agricultural output to soil carbon stock.
- Chapter 5: Conclusion that summarizes our key findings, limitations, and future research.

Chapter 2

Literature Review

This next chapter provides relevant background information. We start with a general introduction to regenerative agriculture, and then discuss the importance of soil health. Regenerative agriculture and soil health are closely linked, which is a main theme throughout the case studies and renewable resource conceptual framework. In order to highlight the complexity of adopting alternative agricultural strategies (e.g. regenerative agriculture), we briefly discuss the determinants of adoption. To conclude the literature review, we summarize previous renewable resource models of soil health.

2.1 Regenerative agriculture

Regenerative agriculture aims to improve soil health, build soil organic matter, and mitigate or adapt to climate change (Merfield, 2019). There is no specific set of practices for regenerative agriculture, which may incentivize producers to adopt strategies that may lead to environmental gains on their landscape (Cusworth and Garnett, 2023). Regenerative agriculture is about working with the soil, which is dependent on producer capability, topography, climate, soil, and location (Paustian et al., 2019). Producers practice regenerative agriculture differently and a range of methods are used such as cover cropping, reduced tillage, intercropping, adapted multi-paddock grazing, organic mulch, and reduced synthetic fertilizers (Newton et al., 2020).

Regenerative agriculture has been promoted for improving soils and the environment by large organizations such as the Food and Agricultural Organization (FAO) (Burgess et al., 2019; Khangura et al., 2023; O'Connor, 2020; Schattman et al., 2023), General Mills (General Mills, nd), McCain's (McCain's, nd), Nestle (Nestle, nd), Danone (Danone, 2023), and PepsiCo (PepsiCo, nd). Regenerative agriculture was introduced in the 1980s, though the principles and practices associated with it have been around long before that (Giller et al., 2021; Khangura et al., 2023; O'Donoghue et al., 2022). It has been developed to include environmental, social, and economic improvements (Giller et al., 2021; Khangura et al., 2023; O'Donoghue et al., 2022). Regenerative agriculture has competing definitions with common themes such as enhancing or improving soil health, soil carbon sequestration, improving soil physical quality, and improving soil biodiversity (Schreefel et al., 2020).

There are a set of principles agreed upon that help guide producers that focus on climate change mitigation, soil restoration, economic sustainability and preserving water systems (Al-Kaisi and Lal, 2020). The main principles are (Burns, 2021; Karaca and Ince, 2023; LaCanne and Lundgren, 2018; Moyer et al., 2020; Newton et al., 2020; Regeneration International, 2024):

1. Limiting soil disturbance
2. Armouring the soil (i.e. keeping soil covered all year long).
3. Increasing plant diversity
4. Keeping living roots in the soil.

5. Integrating livestock.

6. Understand the farm operating context.

Regenerative agriculture has agronomic, social, and economic benefits (McGuire et al., 2022), such as increased soil organic matter, increased carbon sequestration, increased biodiversity, and lower pest issues (Al-Kaisi and Lal, 2020). The advantages of regenerative agriculture are summarized in table 2.1.

Table 2.1: The benefits of regenerative agriculture.

Benefits of regenerative agriculture
Increased soil organic carbon (SOC)
Reduced farm inputs
Increased cash crop yield
Increased soil organic matter (SOM)
Resilient farms
Increased water holding capacity
Increased nutrient cycling
Increased water percolation in the soil
Increased biodiversity
Reduced GHG emissions
Increased farm profitability
Reduced pest and disease issues
Greater insect diversity
Reduced erosion risk

Sources. Al-Kaisi and Lal (2020); Burgess et al. (2019); LaCanne and Lundgren (2018); Newton et al. (2020); Schreefel et al. (2020)

We focus on the economic advantages at the farm level which are often experienced after several years of implementation (Bergtold et al., 2019). The economic benefits of regenerative agriculture may include reduced input use, lower operating costs, an increase in annual net income and more resilient cropping systems (Al-Kaisi and Lal, 2020; Morrison and Lawley, 2021; Myers et al., 2019). These advantages can come from lowering input use, a higher potential for soil nutrient supply, minimizing material loss, and greater ecosystem services (Al-Kaisi and Lal, 2020). Petry et al. (2023) found that transitioning to a sustainable practice such as regenerative agriculture can result in a 15-25% return on investment in ten years, however, there is a transition period where producers may experience lower profits from lower yields.

LaCanne and Lundgren (2018) found that regenerative systems had lower yields but were twice as profitable when compared to conventional systems. Conventional systems had higher seed and fertilizer costs, whereas regenerative systems received higher values for their crops through organic premiums, selling directly to consumers and diversifying income. Regenerative farms were able to reduce fertilizer costs by including legume-based cover crops on fields during fallow period, adopting no-till and grazing livestock. Fenster et al. (2021) also found a larger deviation in profits as farms became more regenerative in the Upper Midwest, California, and the Northern Plains indicating that profit was not as stable among regenerative farms.

There is mixed evidence on the impact of regenerative agriculture on crop yield. There are some studies that point to regenerative agriculture increasing yield (e.g. American Farmland Trust (nd); Al-Kaisi and Lal (2020); Bajzat et al. (2021); Khangura et al. (2023)), while others have contradicting results (e.g. LaCanne and Lundgren (2018); Khangura et al. (2023)). The transition to regenerative agriculture may come at the expense of short-term yield loss for the long-run improvements in soil (Obregon et al., 2023). A common regenerative practice such as crop diversification can improve yield and profit through providing nutrients to the soil, breaking pest-disease-weed cycles, improving soil quality and water use efficiency (Khangura et al., 2023). The impact of cover crops, which is another common regenerative practice, on the following cash crop varies across agricultural systems, weather and environmental conditions (Khangura et al., 2023). Cover crops can help to improve subsequent yields due to reduced compaction and soil temperature, and increased soil aggregate stability (Khangura et al., 2023), however, cover crops may have pests and diseases, or compete with cash crops for moisture (Khangura et al., 2023).

Regenerative producers throughout Ontario identified the top barriers of regenerative agriculture to be lack of time, labour, access to capital, and knowledge, and financial barriers (Organic Council of Ontario, 2020). To overcome financial constraints, respondents said cost share funding or subsidies, education and training opportunities would help. There are little subsidies offered for regenerative farming, and governments may be slow to offer that financial support (Usman, 2021). A similar survey in Ontario found that farmers faced issues with advertising and marketing support as some were unable to properly advertise their products and struggled to get new customers (Bajzat et al., 2021).

In order to adopt regenerative agriculture, it may include the need to acquire new knowledge and skills, especially when it comes to soil management (Rovný, 2022). Producers will need to learn and adapt all throughout their regenerative farming experience. Regenerative farming requires constant monitoring during every crop growth stage, and a producer must be able to identify and address a problem if it arises (Usman, 2021).

2.2 Soil health

Regenerative agriculture is about protecting and enhancing soil capacity. The principles of regenerative agriculture and soil health are closely aligned. The four principles of soil health are maximize the presence of living roots, minimize disturbance, maximize soil cover and maximize biodiversity (USDA, 2023).

Stevens (2018) provides a conceptual framework of soil health that highlights the intricacy of soil health dynamics, as shown in table 2.2. There are biological, physical, and chemical characteristics (Park, 2021; Stevens, 2018), which interact and are affected by both soil management techniques and long-term history of geographical activities (Stevens, 2018). There are challenges with measuring and defining soil health, often leading to an over-simplification of soil health (Rejesus et al., 2021; Stevens, 2018). Soils serve many roles beyond agricultural production, as it has other functions such as giving clean air and water, productive grazing lands, wildlife diversity, and beautiful landscapes (USDA, 2015).

Table 2.2: A conceptual framework for defining soil health.

Physical	**Chemical**	**Biological**
Aggregate stability	Soil pH	Organic matter
Soil compaction	Nitrogen, phosphorous, and potassium levels	Carbon content
Available water capacity	Electrical conductivity, salinity	Nitrogen cycle
Microbial ecosystem		
Soil biota		

Source. Stevens (2018).

There are private and public benefits to having healthier soils (Rejesus et al., 2021; Stevens, 2018), as summarized in Table 2.3. Private benefits are what producers experience on farm, whereas public benefits are outside the farm context and realized by others. Private benefits are important for adoption, as a producer will outweigh the advantages and costs prior to implementing a practice; however, public benefits may incentivize policymakers to develop programs or policies that help with adoption (Rejesus et al., 2021).

Table 2.3: Private and public benefits from soil health management practices.

Private benefits	**Public benefits**
Increased yields	Reduced pest and disease outbreaks
Reduced fertilizer use	Carbon sequestration
Reduced fuel costs	Improved water quality
Yield stability	Increased biodiversity
Grazing opportunities	Flood control
Erosion control	Erosion control
Reduced nutrient losses	
Better water retention	

Adapted from Rejesus et al. (2021); Stevens (2018).

2.3 Determinants of adoption

This section provides a general overview of what may affect a producer's decision to adopt an alternative management strategy such as regenerative agriculture.

2.3.1 Economic factors

Producers assess soil health management practices from an economic perspective, (Adusumilli and Wang, 2018; Carlisle, 2016; Rejesus et al., 2021; Roesch-McNally et al., 2018), as they often bear all the costs when adopting a soil health management strategy (Rejesus et al., 2021). Economics factors may include input and equipment costs, profit uncertainty, increased risk, farm size, and labour supply (Rodriguez et al., 2009).

The costs associated with soil health practices are an important factor of adoption (Carlisle, 2016; Liu et al., 2018; Rodriguez et al., 2009; Roesch-McNally et al., 2018). There are three types of costs that can be found to discourage or limit adoption: initial investment, opportunity costs, and ongoing investment (Carlisle, 2016). At the initial investment decision, there can be significant upfront costs, especially if a farmer does not have the necessary equipment. If technology is readily available, a practice is more likely to be adopted (Carlisle, 2016; Rejesus et al., 2021). With a practice such as cover cropping, the direct costs of seeding, planting and termination can become substantial (Rejesus et al., 2021; Roesch-McNally et al., 2018), with no immediate return. If a producer is not in the position to take on the high costs without knowing the results, this is a deterrent for adoption as it can put a producer in a risky situation. Producers will be responsible for the costs in the short term, as the benefits of sustainability do not appear right away (Obregon et al., 2023). An additional cost that producers face are opportunity costs (Obregon et al., 2023), which are the foregone earnings from a missed opportunity or the costs or results of choosing one alternative over another (Fernando, 2024).This may be the foregone income from a cash crop for a cover crop, or yield losses from reducing inputs (Carlisle, 2016). These costs are usually experienced during a transition to regenerative agriculture (Obregon et al., 2023).

2.3.2 Farm characteristics

Soil health practices may not be compatible with some farm settings (Rodriguez et al., 2009). The geography of a farm is important to consider as the consequences of adopting soil health practices are highly dependent on location, soil type, weather, and land characteristics (Baumgart-Getz et al., 2012; Knowler and Bradshaw, 2007). For example, a practice such as conservation tillage varies widely across region and depends on climate, soil types, crop rotation, and cropping system (Van Eerd et al., 2021). No tillage is adopted by growers in drier regions like the Canadian Prairies as water is a limiting resource for crop growth, whereas the adoption of no tillage is more limited in Eastern Canada where farmers use tillage to dry out the soils (Van Eerd et al., 2021).

2.3.3 Farmer characteristics

Farmer characteristics such as age, education, attitude, and behaviour all influence the adoption of agricultural management strategies, though these factors can be difficult to measure (Foguesatto et al., 2020; Prokopy et al., 2019).

The decision to start a new practice is complex, and the decision does not stop at adoption. Transforming a farming system includes changing beliefs, values, emotions, worldviews, structure, and shifts in mindset (Gosnell et al., 2019). The switch from conventional to regenerative agriculture requires cognitive and behavioural changes (Gosnell et al., 2019). Regenerative agriculture encourages constant innovation on the farm as there are continuous networks and different kinds of flows in a farm that determine how it operates (Gosnell et al., 2019). This may include debt, income, machinery, advice and information, social norms and expectations, traditional farming practices, consultants, peers, fuel, and inputs (Gosnell et al., 2019).

There is usually a positive relationship between education and adoption (Adusumilli and Wang, 2018; Baumgart-Getz et al., 2012; Knowler and Bradshaw, 2007; Wandel and Smithers, 2000; Wang et al., 2019). Education is often measured as the highest level of education attained or years of schooling (Baumgart-Getz et al., 2012). One study included if an individual participated in a field day or extension program as education, as they are not usually treated as formal education, though they are important for the adoption of alternative agricultural systems (Baumgart-Getz et al., 2012). For example, Baumgart-Getz et al. (2012) found that extension trainings had more of a positive influence on adoption than formal education. Field days are educational events that take place on-farm and give producers the opportunity to learn from others in their area about management practices and see it in real time.

Information is key for any sustainable agriculture practice (Carlisle, 2016; Dunn et al., 2016; Prokopy et al., 2019; Rodriguez et al., 2009). Without knowledge, "adoption is improbable" (Knowler and Bradshaw, 2007, p. 36). Information can be accessed through many avenues, such as social media, government extension, field days, neighbours, conferences, news articles, and television; not all of which are reliable or unbiased. Producers require truthful, trustful, and quality information, though there is a lack of local and accurate information, infrastructure, equipment, financial support, urbanization, and land use planning (Bajzat et al., 2021).

The attitude of a farmer plays an important role in the adoption of an agricultural practice and are linked with perceived benefits (Adusumilli and Wang, 2018; Hite et al., 2012; Prokopy et al., 2019). If producers have a positive attitude towards a practice and its' benefits, a practice is more likely to be adopted (Baumgart-Getz et al., 2012; Rodriguez et al., 2009). The benefits could include time savings, fuel savings, and more resilient farming systems. In order to adopt a new strategy such as regenerative agriculture, it will require altering current management strategies (Roesch-McNally et al., 2018).

There is a lot of risk and uncertainty that producers face with adopting an alternative strategy (Rodriguez et al., 2009). The riskiness of a management strategy varies across crops grown, crop rotations, environmental characteristics, and farmer preference (Ogieriakhi and Woodward, 2022). Farmers can be risk averse, which has been shown to have a role on adoption (e.g. Ogieriakhi and Woodward (2022); Wang et al. (2019)). Those that are more risk averse may not adopt a soil conservation practice at first, although they may perceive a practice as less risky over time, especially with experience (Baumgart-Getz et al., 2012). Uncertainty can also be a large barrier for the adoption of any practice as there are no immediate or guaranteed financial benefits from implementation (Ogieriakhi and

Woodward, 2022; Rejesus et al., 2021). There is a transition period when a producer experiments with new input mixes and equipment where they may face short-term losses (Rodriguez et al., 2009).

2.3.4 Concluding remarks

This section highlights the complexity of the producer decision making process for adopting alternative agricultural strategies. Variables that contribute to the adoption of an agricultural management strategy are summarized in table 2.4. Most variables have an inconsistent and insignificant impact on adoption (Wauters and Mathijs, 2014), and there is a lack of convergence of key independent variables (Foguesatto et al., 2020; Knowler and Bradshaw, 2007).

2.4 Dynamic optimization of soil

We will introduce a renewable resource in chapter 4.1 that will be a dynamic optimal control model to capture how a producer responds to changes in soil carbon stock. A dynamic model is able to link past management decisions to the present, which static models are unable to do. Soil is "inherently dynamic" (Stevens, 2018, p. 12), and there are foundational papers to understanding soil as a capital asset (i.e. Barbier (1990); Barrett and Bevis (2015); Berazneva et al. (2019); Burt (1981); McConnell (1983)). Earlier studies have examined the impact of agricultural practices on natural resource bases and rural livelihoods, both in static and dynamic frameworks (Berazneva et al., 2019). Soil investment can take on many forms, whether its short-term improvements or long-term prevention (Barrett and Bevis, 2015). We will now review some of the earlier models of renewable resources.

One of the earliest models was Burt (1981) who studied soil conservation in United States agricultural systems. Burt (1981) used percentage of wheat planted as a control variable to determine its effect on soil erosion, and soil fertility was measured by the depth of topsoil and percentage of organic matter. He found that high grain prices increased soil erosion problems, and that intensive wheat production was the most economic profitable farming system in the area.

McConnell (1983) followed a few years later and created a model to determine the optimal private and social utilization of soil. He specified two vectors of inputs, one with productive inputs, and one without. Productive inputs worked to prevent soil depletion and increase soil input. McConnell (1983) focused on soil depth and soil loss as state variables, which addressed soil erosion issues. Barbier (1990) built off McConnell (1983)'s work with soil depth as a state variable, and two input packages for control variables: one

Table 2.4: Determinants of adoption.

Farm characteristics	**Farmer characteristics**	**Economic factors**	**Exogenous factors**
Farm size	Farming occupation	Agricultural economy	Input prices
Diversity	Formal education Succession	Capital	Output prices
Institutional	Training	Crop value	Community agricultural practices Information
Livestock	Age	Income	Field demos, conferences, courses, meetings
Row crop	Farming experience	Income: farm	Sources of information
Tenure	Age	Labour	Extension/technical assistance
Vulnerable	Operator sex	Land value	Government regulation
Waterbody	Retired	Livestock value	
Soil quality and health	Health	Marketing	
Temperature	Attitude	Sales	
Cropping system/crop rotation	Perceived benefits	Willingness to adopt	
Distance	Gender	Yield	
Land slope	Concern for erosion	Input cost	
Program participation	Connectedness	Equipment	
Membership in organizations	Family size	Family labour	
	Skills	Hired labour	
	Environmental awareness	Access to capital	
	Farmer identify: other	Land use	
	Perception of climate	Tenure	
	Program/practice (attitude and behaviour)		
	Risk tolerance		
	Risk aversion		
	Perceived benefits		

Adapted from Adusumilli and Wang (2018); Foguesatto et al. (2020); Knowler and Bradshaw (2007); Prokopy et al. (2019); Wang et al. (2019)

conservation, and one traditional. In the short run, Barbier (1990) showed that an increase in the implicit cost of soil erosion, and an increase in the costs of traditional input package will ‘favour’ the adoption of the soil conservation package. Similar to Barbier (1990)’s framework, LaFrance (1992) had two control variables of cultivation and conservation inputs. He assumed that ‘cultivation’ and ‘soil’ were beneficial for crop production, whereas ‘conservation’ increased soil health but would be unproductive for crop production. LaFrance (1992) assumption that ‘soil conserving inputs’ reduced crop yield in the short-run, highlights an important trade-off between short-run losses for long-term improvements. This may not always be the case, as management practices intended to improve soil health do not always reduce yield.

Barrett (1991) also built off McConnell (1983) work by using optimal control to model soil erosion and soil fertility to examine the effect of pricing reforms on soil depletion and soil conservation. Barrett (1991) framework showed that pricing reforms have little effect on soil conservation, however, the cost of controlling erosion will result in decreased output, not increased expenditures.

Agriculture is characterized by risk and uncertainty, and it is important to incorporate this into renewable resource models (Pannell et al., 2000). Pannell et al. (2000) highlighted that factors such as climate, crop disease, soil types, crop species, irrigation, marketing policies and technology all interact to form and alter farming system uncertainties. There is no guarantee any agricultural system is going to work, including regenerative agriculture. It takes a lot of trial and error, which creates a time constraint as there is only growing season per year.

Graff-Zivin and Lipper (2008) introduced increased agricultural yield risk associated with transitioning to a new farming system, subject to soil carbon growth. They highlighted two potential impacts of carbon sequestration adoption on agricultural productivity: technology and productivity (Graff-Zivin and Lipper, 2008). Technology impacts are when adopting a new farming system may increase yield risk; and productivity impacts come from a change in soil carbon, which may increase agricultural output (Graff-Zivin and Lipper, 2008). The goal for a producer is to increase the productivity impact and reduce the technology impact.

Chen (2019) used a stochastic dynamic programming model to examine optimal cover crop adoption policies that considered the effects on soil fertility, uncertain future cash crop policies, partial irreversibility of sunk machinery costs, and flexibility in the timing of adoption over time. Chen (2019) found it was preferable to delay cover crop adoption with higher machinery sunk costs associated with cover crop implementation, and it was only optimal to adopt or continue planting cover crops when soil fertility was high enough. This is a contradicting result to Bevis et al. (2017) who found it optimal to invest into lower soil fertility plots. Bevis et al. (2017) built a multi-dimensional model of state-conditioned soil investments, in which farmers choose to invest labour into three categories. Their model highlighted an important trade-off on how to best allocate labour. A producer has to choose how to allocate already limited resources.

Lastly, Ouattara et al. (2018) incorporated climate uncertainty to determine the impact on the optimal path of soil conservation investment. They found that the optimal path of soil conservation investment does not depend on the existing stock of soil capital, but the current climate state, output prices, input prices, and farmer's discount rate.

Building off the insights of all these studies, there have been many that have followed (e.g. Barrett and Bevis (2015); Bevis et al. (2017); Chen et al. (2023); Clark and Furtan (1983); Cong et al. (2014); de Graaff et al. (2008); Dury et al. (2012); Louhichi et al. (2010); Schuurman

(2021); Stephens et al. (2012); Wicks et al. (2006)).

Our conceptual framework is shaped by several papers that emphasize the complexity of soil health and the farmer decision-making process. Stevens (2018) created a flexible approach using optimal control theory to bridge the gap between physical, biological, and social scientists. He presented an optimal control model of soil health in discrete time, which includes a vector of soil health characteristics, and a vector of soil health transitions that shows how future soil health characteristics depend on current characteristics and inputs. The framework captures how both the farmer's production function and soil transition function changes with input use and soil health. An extension of the model is further considered by including the external benefits of soil health, such as increased carbon sequestration, flood control, and erosion control.

Lichtenberg (2024) built off of Stevens (2018) article and created a framework to assess soil health status and evaluate actions that alter soil health. His model had four implications: (1) how soil health is assessed will depend on the soil services we want it to provide, and the value that society places on those services; (2) a universal soil health index is very unlikely to work; (3) there are trade-offs between agricultural productivity, provision of environmental services and changes in stocks of soil characteristics; and (4) when evaluating soil health, it is important to concentrate on soil characteristics and the impact of human actions that are of primary importance.

Berazneva et al. (2019) created a discrete-time optimal control model to analyze maize-production systems in Kenya. The two control variables were the proportion of maize residues left on the field after harvest, and nitrogen fertilizer applied; with soil carbon as a state variable. Optimal maize yields and soil carbon stocks were higher than those observed in the region, which they attributed to farmers heterogenous time preferences, information barriers and market imperfections. Berazneva et al. (2019) put a monetary value on soil carbon, with the steady state shadow price of soil carbon ranging from \$95/Mg to \$168/Mg, depending on the initial soil carbon level. This indicates a significant opportunity cost for soil mismanagement.

Concluding remarks

We will be contributing to this growing literature by building a general framework that could be used to analyze regenerative agriculture. The environment of farming is complex, and models can help to aid and understand the farmer decision-making process.

Chapter 3

Regenerative agriculture case studies in Saskatchewan

3.1 Introduction

Producers are at the forefront of agriculture decisions though their experiences are often missing (FOLU, 2023). Policymakers, researchers, and advocates often discuss how to innovate the agricultural sector without getting the complete picture. Without taking farmers experiences and needs into account, relevant solutions may be missed (FOLU, 2023). The producer decision process is complex and variable (Reimer et al., 2012), as farmers are heterogenous with differing values, objectives, and motivations. When considering to adopt an alternative management strategy such as regenerative agriculture, the variety of benefits may not be considered equally among producers (FOLU, 2023).

In collaboration with the Saskatchewan Ministry of Agriculture, eleven producers were selected to be interviewed for this project. For this thesis, we interviewed seven of those producers. Several attempts were made to contact the remaining four, however, we did not receive a response in time. Interviews were conducted over Zoom, lasting between forty-five minutes and two hours. All participants were given a copy of the questions prior to the interview. A copy of the questionnaire can be found in appendix 6.2. All interviews were recorded and transcribed. Each participant was given a number from farm one to farm seven for anonymity.

This study received approval by the University of Saskatchewan's Behavioural Research Ethics Board on September 13, 2022. The ethics ID number was 3569.

The sections to follow contains direct quotations from the producers or paraphrasing what was said throughout the interviews. Throughout the chapter, we have included our interpretation or views of the interviews, although otherwise much of what is written are summaries of producers' views. This chapter has been separated into five sections: a general description of regenerative agriculture, regenerative agricultural strategies, barriers and limited adoption, advice, and ministry assistance.

3.2 Regenerative agriculture

We started each interview with asking producers what regenerative agriculture is to them, and how they got into regenerative farming.

There were no formal definitions of regenerative agriculture shared or stated by participants. We called it regenerative agriculture throughout the interviews, but producers did not use it as an identifying factor for their farm. Producers said they were improving the soil and producing high quality products without having a lasting effect on the environment. For example, farm one did not love the word 'regenerative', but it was an easy way to describe how they farmed. Instead of regenerative agriculture, they used the phrase "loyal to the soil" (farm one), which was the basis for everything they did.

Farm five described regenerative agriculture as a ‘philosophy’ that encompassed many things, such as one’s values, visions, principles, practices and management.

> “Regenerative agriculture is bigger than the practices, it is about the values and the vision and what you want to see out on your land and in the community, your family, your business, all that stuff.” (Farm five).

Regenerative agriculture is a loosely defined term that can include many things, but the most important component is soil, which was relayed by all that were interviewed. Soil health is the building block for an entire farm. For instance, farm six discussed how regenerative agriculture is about meeting the needs of the soil, and they are aiming to promote a healthy environment.

When the producers that we interviewed decided to invest into building soil health, it was a long term investment that involved the continued adoption of regenerative practices. This did not mean that producers were doing the same thing every year, but instead they adapted along the way as they learnt what worked best on their farm.

Producers began and learned about regenerative agriculture through various avenues. This included thinking there was a better way to farm, fields drying out, watching loads of fertilizer being hauled in, and attending a soil health workshop or field day. For example, farm four shared there were certain things about their land that had to be realized, such as tillage history, and how to improve or repair the soils. They realized that there were more cost productive and efficient ways to improve land than what they were doing. In the grand scheme of things “you’re spending around 250 hours seeding a crop, probably should try to get as good of a crop as you can out of that costs” (farm four). Farm four did not focus on increasing the amount of bushels per acre, but instead they focused on increasing profit per acre as regenerative agriculture is about being more cost-effective and improving the land efficiently. Farm four pointed to their biggest yield years were also some of the least profitable years. They grew a monster crop one year, yet they were unable to move or sell anything due to rail backlogs. As they said: “even if there was a good dollar at the port, you couldn’t get [it]” (farm four). This was outside of their control, though highlights that going for the largest crop yield may not lead to a higher profit.

Another instance was farm two who started regenerative farming with the fundamental belief that the biological community and soils have numerous services it can offer for free.

> “A farm manager can make a decision every time they go into the field, is the decision going to be positive for soil biology or negative?” (Farm two)

Farm two went on to say that there are some circumstances that may require using synthetic inputs or spraying herbicide, as regenerative agriculture is all about balancing it out. At the end of the day, they need to make an income, grow a crop and harvest something.

Farm six shared that their current practices fit a lot better within their conscious. Doing the ‘conventional’ practices worked, but to what end? Farm six had been farming on their land for a long time and they wanted it to be successful in the future. There was no ‘aha’ moment, however someone on the farm mentioned “if we don’t change something here soon, we’re going to be hauling in more fertilizer than we haul out grain” (farm six).

There were many reasons why the producers started regenerative farming, but the common denominator was feeling a need to change and wanting to improve their soils. Regenerative farming requires a shift in thinking and going against the ‘grain’. There were farmers who went all in and changed every aspect of their farm, whereas others changed only a few aspects (e.g. only a certain amount of acres for cover cropping, mono-crop rotations, etc.). Regenerative strategies were used to improve soil health and as a long-term strategy.

3.3 Regenerative strategies

We were provided rough estimates for the costs of regenerative agriculture, although most producers stated that regenerative agriculture did not cost them 'much' to implement. It was hard to put a monetary value on how much it may cost a producer to implement regenerative practices. There were many determinants such as motivation, experience, seed costs, soil conditions, farm characteristics, product prices, neighbours, information and support available, and crop insurance. Regenerative practices were used as a tool to increase soil health and build up on-farm resiliency.

The benefits that producers experienced were due to many factors, and a combination of everything they did. At the time of the interview, farm two had grown wheat that was ten bushels an acres better than the previous record. Farm two noted this led to better applied nitrogen utilization, which is "certainly a step in the right direction" (farm two), though this could not be solely attributed to regenerative agriculture. Similarly, farm seven had cover crops that grew waist high and yielded over two bales an acre.

> "I'm seeing, like stuntedness and all the stuff, and then they walk over to our field across the field that with hairy vetch. So the hairy vetch and winter wheats growing in synergy with each other and one giving nitrogen, ones giving phosphorous and sourcing it. And when we came to time to combine it, it yielded 8 bushels an acre more."
> (Farm seven)

Producers used the regenerative agriculture principles to help guide their management strategies. Recall that the principles are limit soil disturbance, keep living plant roots in the soil, increase plant diversity, armour the soil, integrate livestock and understand the farming context (Burns, 2021; Karaca and Ince, 2023; LaCanne and Lundgren, 2018; Moyer et al., 2020; Newton et al., 2020; Regeneration International, 2024). Practices that are commonly associated with regenerative agriculture such as crop diversification, reduced synthetic fertilizers, reduced or no-till, cover cropping, intercropping and integrated livestock, all of which were used by those we interviewed. Cover cropping and integrated livestock operations were the most common regenerative strategies, often used in combination with each other. Regenerative agriculture took a lot of trial and error, and producers gained knowledge through direct practice.

3.3.1 Cover cropping

Cover crops are also known as service crops, green manure, living mulch, catch crops or forage crops (Bergtold et al., 2019; Van Eerd et al., 2023). They can be a grain, grass, legume, Brassica, or a mixture that are grown in between regular cash crop production periods where the soil would have otherwise been left bare (Bergtold et al., 2019; Morrison and Lawley, 2021). Cover crops were designed to cover and protect the soil but can also provide livestock forage (Blanco and Lal, 2023).

There are many reasons that a producer may grow cover crops such as soil compaction management, soil fertility improvement, erosion control, soil carbon sequestration, and soil health improvement (Blanco and Lal, 2023). Canadian producers grew cover crops to build soil health (Morrison and Lawley, 2021), however, other reasons included to slow erosion, enhance water availability, smother weeds, help control pests and diseases, and increase biodiversity (Chen, 2019). The decision to adopt cover crops depends on soil, primary cash crop, livestock density, outreach and training availability, conservation technical assistance and financial incentives (Wallander et al., 2021). The benefits from cover cropping will be realized through yield benefits, soil protection, weed control and herbicide savings, reduced tillage operations and biofuel feedstock potential. Cover crop management is complex as it involves planting and termination methods, cover crop biomass production, cover crop species, seeding rate, tillage systems, years after introduction/experience, and climate, all of which influence the success of cover crop management (Plastina et al., 2020).

All regenerative producers used cover cropping with diverse cover crop species and strategies. Farm one used cover cropping as a tool where the lowest performing fields or those with weed problems were planted with full season cover crops. They used a simple mix, which allowed for a clean slate for the upcoming cash crop, or they terminated more complex mixes with glyphosate. Previous experience showed that cover crops increased the production of the following cash crop. Similarly, farm three had different blocks of land they put into full season cover crops for five years. After the five years, those acres were put back into the normal cropping system in hopes of seeing some benefits in the following cash crops. Their strategy was to take out 10% of the acres that were the lowest producing or most risky to plant with a cash crop (i.e. areas that flooded easily or had salinity issues). Farm three saw large differences in soil structure since they implemented cover crops. When conducting soil health tests on the two fields, the hand probe went in ‘like butter’ for cover crop fields whereas it almost had to be jumped on in the mono-crop field after four inches.

Farm four found that cover cropping lessened the workload in the spring as there were less acres to seed, and they did not have to spray or harvest it. Farm four had a seed mixture that was designed for their soil conditions, topography, water and pests. The mix was tweaked to see what cover crop species worked best, which follows for many regenerative producers. Their cover crop mix contained oats and yellow peas at variable rates, as well as sugar beets, Italian ryegrass, sweet clover, sunflowers, buckwheat, millet and chicory. A cover crop mix helped to solve multiple problems in one pass as different areas of their land required different solutions. If they had four cover crops in a mix, at least one established.

Farm five planted their first cover crop with a government program that gave producers funding to demonstrate projects. Farm five benchmarked their soils prior to cover crop implementation and said

> "...in 5 years, if we don't increase organic matter by 1%, maybe this isn't the way we should go".

They resampled five years later and there was exactly a 1% increase in soil organic matter. In the same way, farm seven also saw an increase in 1.5% of soil organic matter in five years of implementing cover crops.

Cover cropping and integrated livestock have separate advantages but have synergistic benefits when combined. This was true for another study that found producers only saw a net return on cover cropping when combined with livestock (e.g. Plastina et al. (2018)).

> "The longer there's a living plant in the soil, the more biological activity you'll have, and then an added bonus is that it can also provide feed for the cows in the fall, a high quality feed for the cows in the fall, and again as a cattle go through it. It's not a net loss, because they drop out the back what they put in the front." (Farm six)

Farm seven also explained that cover cropping did not have substantial costs as they saw a return from improved soil fertility, soil health and animal health on their farm. The increased diversity added by cover cropping allowed the plants to thrive and the “cows [had] all the groceries they needed” (farm seven). Farm seven put 200 cows on 88 acres, and there was approximately a $400 return per acre, and they also experienced super ovulation at a 97% conception rate.

3.3.2 Integrated livestock and crop operations

Integrating livestock into farming systems is a principle of regenerative agriculture (Burns, 2021; Newton et al., 2020; Karaca and Ince, 2023; LaCanne and Lundgren, 2018; Moyer et al., 2020; Regeneration International, 2024). Integrated crop and livestock operations focus on minimizing synthetic inputs and using manure to maintain soil nutrient levels (Burgess et al., 2019).

Grazing farmland may have the largest potential to sequester carbon if it is managed properly (Moyer et al., 2020). Regenerative grazing is an umbrella term for many forms of grazing management such as adaptive multi-paddock grazing, holistic grazing, and mob grazing (Moyer et al., 2020). Integrating livestock involves understanding ecological processes and needing a new set of skills that are related to monitoring and moving livestock and feeding soil microbiome (Gosnell et al., 2010). Livestock have an important role in nutrient cycling, especially nitrogen and phosphorous (Martens et al., 2015). The benefits of these systems will depend on crops, livestock, soils, local conditions, and management (Sekaran et al., 2021).

There were two participants that did not own cattle, however they had neighbours with cattle who would graze their fields. For example, farm one used a diverse crop mix where they put in a fall crop, let it grow over the winter, and then graze it. Their neighbours were large-scale beef producers interested in grazing. Farm one did not have to worry about the cows and the neighbours were excited to graze. When integrating cows onto their land, communication was necessary. There was no formal contract with their neighbours, however, they get together once a year to make a grazing plan. Farm one charged their neighbours an agreed upon dollar per head of cattle that worked out for both parties. Similarly, farm four had a structured partnership that was break-even from a financial perspective, and they were in it for the long-term gains that may happen. Farm four wanted cattle on their farm, but only for thirty to sixty days. They got to have the benefits of the cows coming out to graze their fields without needing to own them.

3.3.3 Concluding remarks

Participants used several metrics to measure the success of cover cropping on their farm. Some producers used quantifiable metrics to measure changes in the soil, whereas others used more subjective measurements such as changes in soil texture. There is not necessarily a better metric as both provide useful information to the producers. If a producer can see a positive change, they know they are doing is having a positive influence on their farm. They did not know if regenerative agriculture would work on their farm, but it all came down to wanting to improve their soils. There was no guarantee that producers would witness improvements in their soil, but that did not play a factor in their decision to use regenerative strategies. Other producers did not talk of seeing any change or taking any measurements, although they were still implementing regenerative strategies.

This section only focused on cover cropping and integrated livestock, although, there were more regenerative strategies used. The producers that we interviewed also practiced diverse crop rotations, reduced fertilizer, reduced soil disturbance/no-tillage, and intercropping. All of which align with the regenerative agricultural principles. Producers practiced regenerative agriculture for the long-term benefits that may appear, with no guarantee. Many trialed different practices on their farm to see what worked best, whether it was one regenerative practice, or multiple ones. This goes back to the regenerative agricultural principle “understand the farm context”. The strategies in the case studies may not be replicable on another farm, as they took the regenerative principles and figured out how to apply them to their own.

3.4 Regenerative barriers and limited adoption

We interviewed only a small subset of producers that practice regenerative strategies, although we were still able to see that regenerative agriculture has no single or simple path. Regenerative agriculture requires experience, knowledge and understanding the local conditions, and it was not always an easy transition for regenerative producers. We asked producers what barriers they faced and why they believe that the adoption of regenerative agriculture is limited throughout Saskatchewan. The section will start with a brief summary of the barriers faced by producers, followed by the reasons for limited adoption.

The first barrier that some producers experienced was a lag in regenerative agriculture benefits. There is usually no immediate gratification from regenerative agriculture. One producer also highlighted that it can be difficult to see if there are changes occurring on farm and identify how the benefits may appear on the financial side. They have to make a profit while trying to improve the land while not going bankrupt. Another farm mentioned that several cash crop acres were losing profitability, and wondered about an alternative. A cost-effective solution may be using plants and animals (i.e. integrated livestock), but the downside was figuring out how to actually make it work and pay for the practice.

Two producers highlighted the uncertainty of regenerative agriculture, as it is not always easy to make the shift or to predict what happens on farm. Farm six noted that most farms are operating on already thin margins and there is not a lot of room for mistakes. Every farm experimented with different regenerative strategies, which is risky as there is only one crop per year. A farm can try something out one year and it either works, or it doesn't. It's complex and a "bit of a hodgepodge" (farm five). Things may go well for a while but if anything goes wrong, a farm takes on all the risk. For example, farm five faced a couple of dry years. When they checked for crop insurance, there was none available because they intercropped oats and peas. It hurts on the cash flow end.

Regenerative agricultural barriers are closely related to why the adoption is limited throughout the province. Participants pointed to traditions, social pressure, extra resources, uncertainty and risk, undeveloped markets, not enough support from the government and limited local research as to why regenerative agriculture is not practiced by many in Saskatchewan.

The following paragraphs have been paraphrased from the interviews. There are direct quotes that have been inserted, but otherwise we have left our own interpretations.

3.4.1 Tradition and social pressure

Agriculture is steeped in tradition and people can be reluctant to change. Regenerative agriculture is stepping outside of a system that everybody knows, recognizes, and understands. There is a lot of fear in stepping off the path of least resistance, so people tend not to. There has been a good run on grain and monoculture grain... "how do you argue with success when these farms are doing quite well?" (farm two). Farmers are innovative and progressive, however, some may be apprehensive to change.

The social pressure producers face is closely linked to traditions as regenerative agriculture is social, but a farmer needs to find the right people to support them, otherwise, it can be isolating. Participants found that other regenerative producers were willing to talk. For example, farm five took part in a regenerative agriculture peer group, where people were supportive and open for discussion. Regenerative producers are excited to talk about what they are doing, which was very evident throughout the interviews. There are people willing to share their experience and offer advice, but there is a stigma associated with regenerative agriculture. A lot of people do not like to be 'those people' who are farming differently. Farm one stated that as they made changes to their farm, there was a period where they got excluded from social events. People like to talk about things they have in common, and if that is farming, people do not know how to talk to you anymore "because you're farming like a weirdo" (farm one). There were some 'naysayers' quick to talk, or think that regenerative farming is ridiculous, or not understand regenerative agriculture.

Farm five shared that their business may be in jeopardy. When it comes time to rent land, farm five may not get chosen as some landlords might not want to rent to farmers like 'that' (i.e. regenerative agriculture). A series of case studies by Snorek et al. (2024) in the Northern Great Plains also noted that renting farmland was a common hurdle. Some landlords encouraged regenerative practices, whereas others had to be convinced that regenerative agriculture would improve property values. Some producers were given no trial period for regenerative practices and had their lease ended (Snorek et al., 2024).

3.4.2 Extra resources

To implement regenerative practices, it may require additional labour, knowledge and equipment. One producer said that as they started looking at things differently, there can be a lot to learn and it can be hard, especially if someone does not like learning, added management workload and change. This was not the case for all producers as regenerative agriculture actually lessened the workload on farm.

The most limiting discussed mentioned was knowledge. There were some producers that had to spend a lot of time outsourcing material and information that could be used on their farm. For example, farm one spent a lot of personal time researching, going to conferences and sharing their own strategies. When it did not involve spending time learning, farm one said that the management complexity of regenerative agriculture took over.

Regenerative agriculture is physical and low technology, and the degree of management is complex. One producer stated that the management is night and day as a producer might be doing fifteen different things in a day. For example, farm four experienced a lot of weeds with cover cropping, and it became a "real mess" (farm four). At the time of the interview, they had adjusted their strategy and sprayed prior to seeding the cover crop mix. They came to the conclusion they cannot rely on biologicals to supply nutrients to the crop, and often needed a supplement.

3.4.3 Uncertainty and risk

There was a lot of uncertainty and risk with regenerative agriculture among some of those interviewed. In a bad year, risk may come from the inability to get crop insurance, the long-term wait for improvements, and yield or profit risk. It is also difficult to quantify soil health and for producers to see changes. How will they know if regenerative practices will improve their land over time? Is it helping the soil? Will it make or lose money? There are a lot of unknowns.

Participants discussed it was difficult to get crop insurance as a regenerative producer. In the last five years, Saskatchewan faced dry years that has put pressure on the agricultural sector. When there was a bad year, regenerative producers were fully responsible for the loss as crop insurance was not an option. Regenerative agriculture can help to build resiliency into a farm, but that may not always be enough as stated by one producer. Insurance companies do not know how to account for something like cover cropping or intercropping. In 2023, there was a step in the right direction as cover cropping is now compared to forage barley.

3.4.4 Research

Finding locally relevant information was difficult for regenerative producers and it makes it harder to find answers for those interested in it. There are a lot of things a producer can learn from research farms located in Saskatchewan, but applying it to their own fields was a new challenge. Getting into the field and dealing with "real world farmer problems" was a lot different (farm three). Farm seven was involved with many programs but researchers could not monitor what they were doing, especially with multi-species cover crop blends. Researchers wanted farm seven to do simple blends that were easy to monitor, though this would have resulted in losing money.

3.5 Public support for regenerative producers

There is interest in regenerative agriculture and how government bodies can support producers, however, more information is needed. We ended each interview by asking the role that the government has in supporting producers who have either adopted or are interested in adopting regenerative agriculture. Responses were grouped into three categories: education, markets and financial incentives.

3.5.1 Education

Regenerative agriculture is not a new concept, although there has been a renewed interest in it in the last few years. There are people who know the term ‘regenerative agriculture’, but may not know what it fully entails. One producer summed it up well in that “the principles are the same everywhere” (farm one). In order to implement regenerative agriculture on a farm, producers will need to learn the principles to apply on their own farm. A good starting may be about promoting regenerative agriculture and getting the idea into a farmers mind that there is an alternative out there that may be more profitable.

For producers that are already adopting regenerative strategies, there is always more out there to learn. One producer stated that regenerative farmers will never get to a point where they have learnt everything, as every year presents different conditions and challenges. Several producers mentioned that field days are a great resource as it brings people together and can get a good conversation going. There were usually agronomists available for people to learn about the chemical side of agricultural practices, and leave with a good starting point.

3.5.2 Specialized markets

Those that we interviewed discussed how the Saskatchewan Ministry of Agriculture could help regenerative producers by finding ways to promote and advertise special markets for regenerative producers. There is a demand for regenerative products and a market for them, although the markets are not always easy to come by. For example, farm five was a carbon negative market, and sold monoculture oats at a 20% premium. There are not a lot of markets developed like this, or the markets are not developed to that point where they are common. The premium for regenerative producers may also not be high enough to get traditional farmers to switch over.

3.5.3 Financial incentives

External support could also help regenerative producers through financial assistance or incentives. One producer stated that changing the adoption rate of regenerative agriculture will be primarily tied to money. In order to improve the land, the environment and ecosystems, producers have to “bank roll that” (farm five), and are often fully responsible for these charges. There are programs available to regenerative producers, although one producer highlighted that incentive programs tend to be program based, which can be disincentivizing to regenerative producers. They suggested having a system that could prove the value of soils and products and pay producers accordingly.

3.6 Concluding remarks

We interviewed seven producers in order to understand and examine regenerative agriculture in Saskatchewan. The adoption of regenerative agriculture will not yield immediate results, and producers were in it for the potential long-term gains. Producers will not know if regenerative agriculture will be compatible with their farm setting, which can create a lot of risk and uncertainty. To adopt regenerative agriculture, a producer may be intrinsically motivated, like they were in the case studies, or they may be motivated by the economic incentives that can include improved yield, cost savings, price premiums, or new revenue streams.

Chapter 4

Analyzing the economic viability of regenerative agriculture: A renewable resource model

4.1 Introduction

Agricultural producers are faced with complex and uncertain environments (Fisher et al., 2000), which may require a dynamic toolkit to help with on farm decision making. A dynamic model allows researchers to capture the value that farmers place on future productivity (Schuurman, 2021). A renewable resource is capable of growth, and viewed as a capital asset that should be managed to maximize its' value to society (Conrad, 2010; Conrad and Clark, 1987). The renewable resource in our framework is soil carbon stock, which will be used as a proxy for soil health. There are natural processes working within soils, and it is capable of increasing soil organic carbon over a feasible timeline. Soil health is complex as the physical, chemical, and biological characteristics and soil processes are all involved and interact (Rinot et al., 2019; Stevens, 2018). Static models are not able to capture soil dynamics (Stevens, 2018), and are insufficient to account for changing soil carbon stock and linking past management decisions to the present (Cong et al., 2014).

This next chapter will outline a renewable resource framework to examine the impact of regenerative agriculture on producers' profit and how they make decisions at the farm level, subject to changes in soil carbon stock. There is a strong relationship between soil organic carbon and soil fertility, and crop productivity and soil fertility (Berazneva et al., 2019). Carbon sequestration can also achieve two sustainability goals of improving agricultural productivity and climate change mitigation (Berazneva et al., 2019). The framework helps understand and model the economic motivations of the case studies, and to examine the implications of adopting regenerative agricultural practices.

4.2 State variable: Focus on soil carbon stock

Soil health is imperfectly captured by a set of physical, chemical and biological characteristics (Stevens, 2018). There is no unidimensional soil measurement that quantifies soil health, and it must be inferred from a multitude of soil attributes, processes, and contexts (Van Eerd et al., 2021). A universal soil health index would not be feasible as it would be complicated and impractical (Lichtenberg, 2024). Soils provide a lot of services that are too heterogenous for a single index, and the contribution of soil characteristics depends on many things (Lichtenberg, 2024). This is important to consider when going through this chapter as soil carbon is used as a measurement for soil health.

Many regenerative agricultural practices focus on soil management and its' ability to increase soil health (Giller et al., 2021). Soil organic carbon (SOC) has a role in soil's overall health and agricultural productivity (Cong et al., 2014). Soil carbon is the measurable component of soil organic matter (SOM) (Berazneva et al., 2019; Dynarski et al., 2020; Edwards, 2022), which has a role in nutrient retention and turnover, soil structure, moisture retention and availability, degradation of pollutants, and carbon sequestration (Edwards, 2022; Oldfield et al., 2019). SOM also contains hydrogen and oxygen, as well as small amounts of other elements such as nitrogen, phosphorous, sulphur, potassium, calcium, and magnesium contained in organic residues (Dynarski et al., 2020; Edwards, 2022). SOM is a result of inputs minus losses, and is influenced by soil type, climate, and management (Edwards, 2022). For example, soils with higher clay content have more organic matter, and will retain more carbon than sandy soils (Edwards, 2022; Giller et al., 2021).

Soils are the largest terrestrial storage of carbon (Abbas et al., 2020; Paustian et al., 2016, 2019), and restoring carbon is a win-win scenario for soil health management practices (Dynarski et al., 2020), such as regenerative agriculture. The top one meter of Canadian soils store about 20% of the global total carbon stocks (Sothe et al., 2022). About 80% of Canadian agricultural land is located in the Canadian Prairies, which is where most of Canada's soil carbon is stored (Minasny et al., 2017).

Soils play an important role in the global carbon cycle (Abbas et al., 2020). There is a lot of potential for agricultural soils to store carbon and serve as a carbon sink, however, whether soils will serve as a sink or source will depend on its use and management practices (Abbas et al., 2020). There are continuous changes in soil organic carbon through losses from soil erosion and respiration, and gains by the incorporation of carbon containing biomass in terrestrial ecosystems

(Abbas et al., 2020). The amount of soil organic carbon that is captured by soils will vary with climate, time, soil texture and vegetation (Abbas et al., 2020).

Carbon is actively exchanged within the atmosphere through photosynthesis and respiration (Paustian et al., 2019). The soil carbon cycle is shown in Figure 4.1. Carbon uptake in crops occurs through photosynthesis and enters soils as a residue of above or below ground biomass (Govaerts et al., 2009). Carbon is then transferred to soils through the release of organic compounds by plant roots or the decay of plant material or soil organisms when they die (European Commission, 2011). During the process of decomposition, carbon is released as carbon dioxide back into the atmosphere, referred to as soil respiration or carbon mineralization (Keenor et al., 2021; Govaerts et al., 2009).

Soil carbon sequestration is the "removal of atmospheric CO_2 by plants and storage of fixed carbon as soil organic matter" (Lal, 2004, p. 9), which is done through increasing soil organic carbon (SOC) density in the soil, improving depth distribution of SOC and stabilizing SOC (Lal, 2004). This can be accomplished by agricultural management systems that add high amounts of biomass to the soil, and cause minimal soil disturbance (Mrabet, 2006). Soil carbon sequestration methods can offer the least expensive and most readily implementable near-term options relative to other emission reduction strategies (Paustian et al., 2019). The ability to sequester soil carbon will depend on many factors including management strategies, crop rotations, carbon input quantity, climate conditions and soil texture (Chahal et al., 2020).

Increasing the amount of soil carbon by even a small amount can have a large impact on improving soils (American University, nd; Ma et al., 2023; Paustian et al., 2019). The benefits of increasing soil organic carbon can include greater nutrient capacity, climate change

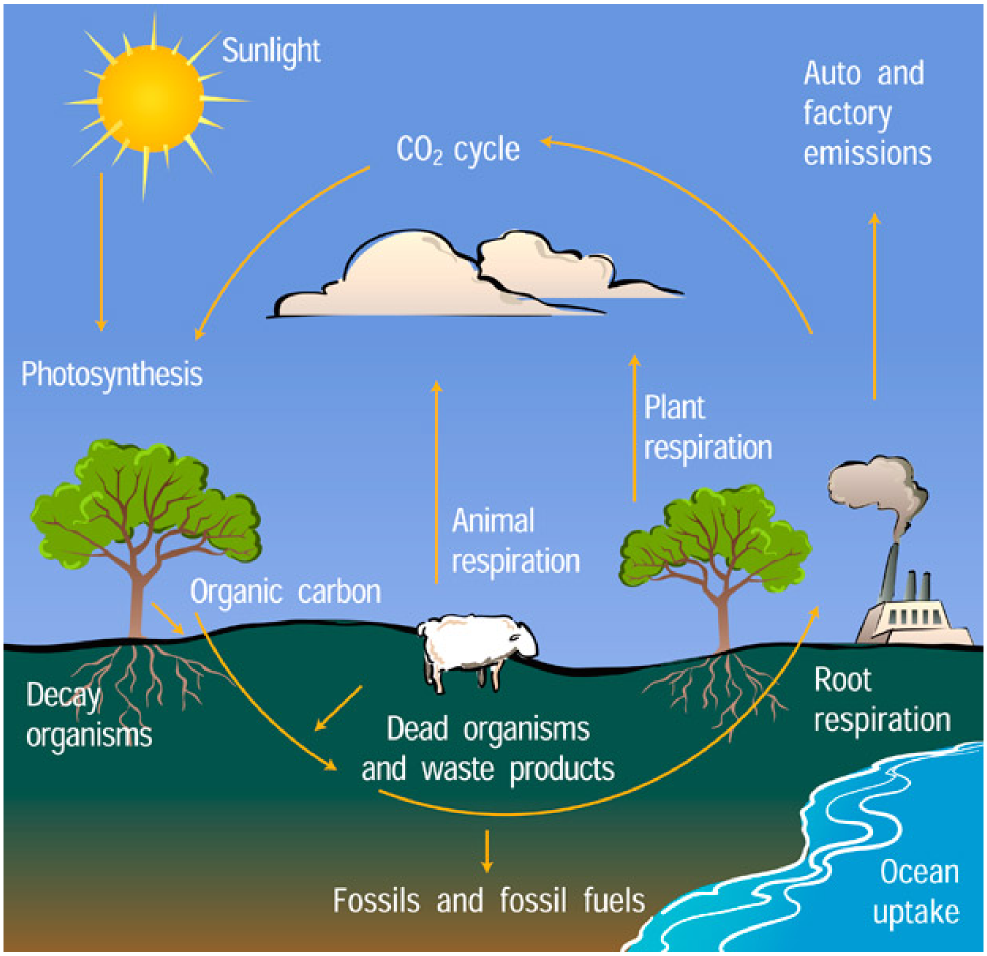

Figure 4.1: A basic carbon cycle diagram. Source: https://scied.ucar.edu/image/carbon-cycle

adaptation, increased soil aggregate stability and porosity, decreased soil bulk density, increased water infiltration rates, and reduced soil erosion (Al-Kaisi and Lal, 2020).

4.3 Theoretical framework

We now introduce a conceptual framework to examine regenerative agriculture. An empirical example in Saskatchewan follows.

The conceptual framework was built in a general setting without specifying a production function or law of motion. The framework is meant to highlight how we could examine how a producer decides to improve their soil with regenerative agricultural practices using optimal control theory. We present a discrete optimal control model that could be modified for a researchers purpose.

The representative farmer will choose the amount they are willing to invest into building soil carbon stock, which will be referred to as soil carbon investment. Let a_t represent soil carbon investment, and w represents the constant marginal cost for soil carbon investment. We do not specify a regenerative practice or how a producer will invest into building soil carbon stock. This gives flexibility into the model and allows for a future user to specify how to build soil carbon. Regenerative agriculture does not have a blueprint, and it is all about what works best for the farming context.

Agricultural practices that build soil carbon are closely aligned with regenerative agricultural practices. Regenerative agricultural practices such as conservation tillage, cover crops and diverse crop rotations can enhance soil health and food quality when compared to conventional agricultural practices (Montgomery et al., 2022). Montgomery et al. (2022) found that regenerative farms had more soil organic matter and higher soil health scores on a more consistent basis. Regenerative strategies increased soil organic matter and enhanced soil health in less than a decade of fully adopting regenerative practices. In addition, regenerative farms had greater nutrient cycling (Montgomery et al., 2022). The costs to implementing soil carbon sequestering methods may include labour, capital, structural requirements and any opportunity costs associated with the investment.

We will assume that only one cash crop is being grown per season. Let c_t denote the state of a farmer's land in year t, defined by soil carbon content. Crop production will therefore be a function of soil carbon stock and soil carbon investment:

$$q_t = f(a_t, c_t) \tag{4.1}$$

where q_t is crop yield, $f(\cdot)$ is the cash crop production function, c_t is soil carbon, and a_t is soil carbon investment. In our framework, both soil carbon (c_t) and soil carbon investment (a_t) have been included in the production function, however, this could be altered to the availability of data, specified production functional form, and research methods.

Oldfield et al. (2019) did an extensive analysis of soil organic matter and global yields by using soil organic carbon (SOC) as a proxy for soil organic matter. They found that the largest gains in yield occurred between SOC concentrations of 0.1% and 2.0%, but the gains levelled off at 2%. This study highlights that SOC can affect yield, although only up to a certain point. Increasing soil carbon infinitely will not increase yield at the same rate, nor can soil carbon stock keep growing forever.

A key component of any optimal control model is the law of motion that connects two consecutive periods. The law of motion relates the state variable to the control variable as it changes over time (Chiang, 1999). The change in soil carbon stock will depend on current soil carbon content and the farmers decision to invest into building soil carbon stock:

$$c_{t+1} - c_t = g(ka_t, c_t) \tag{4.2}$$

Where $g(\cdot)$ is the law of motion that describes soil carbon dynamics, and k will be a scalar for how much carbon is sequestered from an investment strategy or the efficiency of a practice. We introduced this parameter to represent research and development into regenerative agriculture and the ability to increase soil carbon sequestrating abilities. This parameter could also be used to differ regenerative strategies as certain practices provide more carbon input. There will be a 'sink saturation effect' where soils reach a new equilibrium, and the rate of change decreases. When soil carbon reaches its saturation point, there will be no further increases (West and Six, 2007). Soil carbon saturation occurs when soil is not able to accumulate and stabilize any more carbon (West and Six, 2007). At lower levels of initial soil carbon levels, there will be a greater response to increases in carbon input. Carbon sequestration is often a non-linear process, which implies that carbon sequestration is highest after a land use or management change is implemented (Ragot and Schubert, 2008). There will be a large response in soil carbon growth at first to an increase in soil carbon input, especially for fields with low initial levels of soil carbon. Low yielding areas have the highest opportunity to increase soil carbon in which yields will be increased from available biomass stock and organic matter inputs (Giller et al., 2021).

Let π_t denote profit in time t, where $\pi_t = \pi(a_t, c_t) = pf(a_t, c_t) - wa_t$, where p is cash crop output price, which will be taken as given. All other inputs will be held constant. This is an assumption held throughout the conceptual framework and example. The input decisions to build soil carbon stock will not influence other input decisions.

The farmer's objective is to maximize the discounted net present value of annual net returns from a hectare of land over an infinite horizon by choosing the amount to invest into building soil carbon stock, with a discrete time discount factor of $\rho = \frac{1}{(1+\delta)}$ for the discount rate (δ). The initial level of soil carbon (z), $c_0 = z > 0$ is given.

$$\max_{a_t} \sum_{t=0}^{\infty} \rho^t [pf(a_t, c_t) - wa_t]$$

$$\begin{aligned} \text{subject to: } c_{t+1} - c_t &= g(ka_t, c_t) \\ c_0 &= z > 0 \text{ given} \end{aligned}$$

The objective function can be rewritten with the discrete-time current value Hamiltonian and applying the maximum principle. The current value Hamiltonian contains two values: the net benefit flow in year t, and the discounted value of the change in soil carbon stock, which can be viewed as a capital gain if soil carbon increases (Conrad and Rondeau, 2020). The maximum principle gives a series of necessary first order conditions, which is defined by the partial derivatives of the current-value Hamiltonian (Clark, 1976; Conrad, 2010). The solution to the first order conditions is a time path that shows how the optimal soil carbon investment rate depends on soil carbon stock size (Conrad, 2010). The discrete-time current value Hamiltonian (H) can be written as:

$$H = pf(a_t, c_t) - wa_t + \rho\lambda_{t+1} g(ka_t, c_t) \tag{4.3}$$

Where λ_{t+1} represents the current value shadow price of soil carbon stock at time *t + 1*. The maximum principle states that the following conditions must hold to guarantee a solution (Léonard and Long, 1992):

$$\begin{aligned} \frac{\partial H}{\partial a_t} = p\frac{\partial f(\cdot)}{\partial a_t} - w + \rho k \lambda_{t+1} \frac{\partial g(\cdot)}{\partial a_t} = 0 \\ \Rightarrow p\frac{\partial f(\cdot)}{\partial a_t} + \rho k \lambda_{t+1} \frac{\partial g(\cdot)}{\partial a_t} = w \end{aligned} \tag{4.4}$$

$$\begin{aligned}\rho\lambda_{t+1} - \lambda_t = -\frac{\partial H}{\partial c_t} &= -\{p\frac{\partial f(\cdot)}{\partial c_t} + \rho\lambda_{t+1}\frac{\partial g(\cdot)}{\partial c_t}\} \\ \Rightarrow \lambda_t &= p\frac{\partial f(\cdot)}{\partial c_t} + \rho\lambda_{t+1}(1 + \frac{\partial g(\cdot)}{\partial c_t})\end{aligned} \tag{4.5}$$

$$c_{t+1} - c_t = \frac{\partial H}{\partial[\rho\lambda_{t+1}]} = g(ka_t, c_t) \tag{4.6}$$

Equation (4.4) states that the marginal contribution from investing into building soil carbon stock must equal the marginal costs of soil carbon investment. The first term ($p\frac{\partial f(\cdot)}{\partial a_t}$) is the marginal value product of soil carbon investment, which shows how much profit will change when soil carbon investment increases (or decreases). The second term ($\frac{\partial g(\cdot)}{\partial a_t}$) is the marginal contribution of soil carbon investment to soil carbon dynamics, which is then multiplied by the current-value shadow price. All of this must be equal to the marginal costs of soil carbon investment, w. Equation (4.5) shows how the marginal value of soil carbon stock is changing over time, or the adjustment of the shadow value over the optimal path. This is influenced by the marginal value product of soil carbon stock. The first term on the right-hand side is the marginal value product of soil carbon stock ($p\frac{\partial f(\cdot)}{\partial c_t}$). The last term is how soil carbon stock in the next period is affected by soil carbon stock in the current period ($\frac{\partial g(\cdot)}{\partial c_t}$) where $\rho\lambda_{t+1}\frac{\partial g(\cdot)}{\partial c_t}$ is the value of an increase (or reduction) of soil carbon stock. Equation (4.6) is restatement of the law of motion which shows how the state variable evolves between period t and period $t+1$.

4.4 Empirical example

We now provide an example to highlight how our framework could be used as a tool to examine regenerative agriculture. The framework introduced in the previous section will now be parameterized to examine how a producer makes decision on farm subject to changes in soil carbon stock. The example does not show that regenerative agriculture will be profitable to our representative farmer, nor does it show why a producer would invest into building soil carbon stock. Our example is meant to be demonstrative of how the general conceptual framework could be used to analyze regenerative agriculture.

The framework is used to understand the decision making process of a regenerative producer. We introduced two parameters in the conceptual framework: the constant marginal cost (w), and carbon sequestration scalar (k). A range of values for w and k will be used throughout the example to see how our representative producer responds to changes in costs and input efficiency. We also add a carbon credit extension later on.

4.4.1 Experimental design

A framework such as ours requires an extensive dataset that connects regenerative agriculture to soil carbon stock and crop yield. The experimental dataset came from a field site located at the Agriculture and Agri-Food Canada Research and Development Centre near Swift Current, Saskatchewan, Canada (50 16'N, 107 44'W). The research site is within a cool temperate and dry climatic zone, with a mean annual temperature of 3.3° and mean annual precipitation of 334 mm (Maillard et al., 2018). The soil is silt loam clay that belongs to Swinton series, and is classified under the Canadian system as an Orthic Brown Chernozem, and Haplic Kastanozem under the Food and Agriculture Organization system (Maillard et al., 2018). The initial soil characteristics were: 32.6% sand, 27.6% clay, 1.19g/cm^3, 6.5 pH, and 27.72 C Mg/ha at the 0-15 cm depth (Maillard et al., 2018).

The land was previously managed in a fallow-wheat rotation using conventional tillage methods for 70 to 80 years prior to the experiment starting in 1981 (Maillard et al., 2018). In 1981, the experiment initiated on wheat stubble as a randomized block design with four replicates. The plots were 15 meters wide by 76 meters long. There were five cropping systems implemented in a randomized block design in 1982 with four replicates. There was wheat-fallow rotation under three levels of tillage: no-tillage, minimum tillage, and conventional tillage. The other two cropping systems were continuous wheat rotations under no tillage and minimum tillage. In 1997, all the plots were split in two where one was maintained as the previous cropping system and the other half with a new cropping system. In the dataset that we obtained, only included two new cropping systems. The fallow-wheat conventional tillage and fallow-wheat no-tillage was split into a pulse crop-wheat rotation under two levels of tillage (no-tillage and minimum-tillage). Pulse crops rotated between pea, chickpea, and lentil.

The continuous wheat no-tillage cropping system was used to parameterize the wheat production function and the law of motion for our example. For this cropping system, wheat was direct seeded and included post-harvest herbicide. The continuous wheat no-tillage plot received annual glyphosate application for initial weed control. Hard red spring wheat was sown at 67 kg/ha, and harvested at full maturity using a conventional, direct-cut header combine and the crop residues were returned to the soil.

All of the steps to parameterize the model can be found in appendix 6.3. For each plot, they collected wheat yield, grain yield, and biomass yield every year, whereas soil carbon stock and bulk density every four years at different soil depth levels.

There were several steps taken to estimate our representative farmer's objective function. The first is to specify and estimate a yield production function for hard red spring wheat. Wheat production (Mg/ha) is a function of soil organic carbon stock (to a depth of 0.15 meters) (c_t), and plant biomass carbon input (a_t). The second step is to specify and calibrate the law of motion for soil carbon stock. This approximates the annual change in soil carbon stock from the addition of carbon input. The production function and law of motion describe the dynamics of our system, and provide the parameters for use in an optimal control model. The two equations will interact and determine how a producer will optimize annual net returns from a hectare of land through the amount of estimated carbon input. The numbers that we obtained were not significant, and should be interpreted with caution. We use the coefficients for the production function and law of motion to provide a working example of the conceptual framework that is purely representative. The experiment did not show a significant relationship between soil carbon and wheat yield. All parameters are summarized in table 4.1.

4.4.2 Control variable: estimated carbon input

Our representative producer in the example will build soil carbon stock through the amount of estimated carbon input (Mg/ha) added to the soil. This will be a_t as previously defined in the conceptual framework. The main sources of carbon input come from crop litter which includes straw, roots and root rhizodeposits (Gan et al., 2009). There have been attempts to measure the amount of carbon in each component of a crop, though there are errors that can occur in estimates. There are differences between crop species in how plant carbon is allocated and the carbon distribution in the soil profile (Gan et al., 2009). The primary source of carbon in ecosystems is carbon fixed in plants through photosynthesis that is added to the soil (i.e. Bolinder et al. (2007)). There are several methods to estimate annual carbon inputs to the soil that can be approximated from agricultural yields using published or approximated values for the harvest index, shoot:root ratios, plant carbon in root exudates, and carbon concentrations in plant parts (Bolinder et al., 2007). The method used to estimate carbon input from plant biomass is straight-forward and easy to calculate (Bolinder et al., 2007). Annual carbon input from plant biomass was calculated using hand grain and biomass yield for the harvest index, and the method brought forward by Bolinder et al.

(2007).

Soil organic carbon can be built by increasing the amount of carbon input, decreasing decomposition, or both (Paustian et al., 2016). Increasing the amount of carbon input can be done though intensifying crop rotations, reducing tillage, and retaining crop residue or optimizing agronomic inputs; whereas decomposition is slowed by altering tillage practices or including crops with slowly decomposing residue into crop rotations (Govaerts et al., 2009). For example, cover cropping builds soil organic carbon, reduces nitrogen losses, increases the yield of the following cash crop, and improves overall soil quality (Chahal et al., 2020). Other practices that can enhance soil organic carbon accumulation is decreased tillage and increasing crop diversity (Peng et al., 2023). Decreased tillage helps to mitigate soil aggregate breakdown and protect soil organic matter from biodegradation, whereas increasing crop diversity gives diverse carbon inputs and increase soil properties such as soil aggregate stability and soil microbial activity (Peng et al., 2023).

The amount of soil carbon is a result of carbon additions minus losses (Blanco-Canqui et al., 2013). Carbon inputs into Canadian agricultural land is usually derived from plant residue carbon, and from livestock feed and bedding (Fan et al., 2019). There are other ways to increase carbon input that may include: returning more crop residue to the soil than before, manure application with integrated crop and livestock operations, cover crops in combination with cash crops, and crop diversification.

In sections 3.3.1 and 3.3.2, cover cropping and integrated livestock were the most common methods used by those we interviewed, and are two methods of increasing carbon input.

Cover cropping

Cover crops are an important tool for carbon sequestration (Lal, 2015b; Clark, 2017), and are a promising method to increase soil carbon, especially relative to the alternative of leaving fields fallow (Vendig et al., 2023). There is a positive relationship between the change in soil organic carbon and plant biomass carbon input (Lal, 2015a). Cover crops provide ground coverage, and produce plant biomass which is returned to the soil (Lal, 2015a,b). If a producer were to build carbon input through increasing cover crop plant biomass, it may also offset any losses from removing harvest crop residues (Lal, 2015a). Cover crop roots and shoots also feed bacteria, fungi, earthworms and other soil organisms (Clark, 2017), which can improve soil biodiversity supporting improved carbon sequestration. When a cover crop is used in place of a cash crop, which we saw with some of the producers in the case studies, there may not be more carbon input from the cover crop than if there was a cash crop (B. Helgason, personal communication, October 17, 2024). If a cover crop is grown in addition to a cash crop, and there is no competition between the crops, then a net increase in carbon input occurs (B. Helgason, personal communication, October 17, 2024).

The rate of carbon sequestration as a result of cover crops will depend on geographic location, soil type, cover crop species and management. For example, non-legume cover crops may be less effective than legume cover crops at increasing soil organic carbon (Vendig et al., 2023). If cover crops have longer growing seasons, they will be able to produce more plant biomass depending on the species, and have higher soil carbon stock benefits (Qin et al., 2023).

Integrated livestock-crop operations

Integrated crop and livestock operations may provide new opportunities to sequester carbon (Brewer and Gaudin, 2020). Grazing will impact landscape productivity, biodiversity, and the adoption of conservation practices, which are all important for soil organic carbon (Brewer and Gaudin, 2020). Integrated livestock systems have reported increased soil carbon relative to non-integrated systems, which has been attributed to improved rotational complexity, biodiversity, and synergistic feedbacks (Brewer and Gaudin, 2020). If a producer grazes cash crop residues or cover crops, there is an opportunity to increase net primary productivity through longer ground coverage and managing forage quality (Brewer and Gaudin, 2020). In order to optimally manage integrated livestock operations for carbon sequestration, it requires proper management of grazing stocking intensity, frequency and duration; vegetation composition and coverage; and soil disturbance levels (Brewer and Gaudin, 2020).

Manure and urine from grazing cattle can lead to local 'hotspots' of carbon and nitrogen, though this stimulates methane and nitrous oxide emissions (Franzluebbers and Hendrickson, 2024). There is a delicate balance as livestock can increase greenhouse gas emissions, but they also can counteract the emissions with improved carbon sequestration (Franzluebbers and Hendrickson, 2024). In one study, the addition of compost and manure from animals led to an average increase of 2.29 Mg C/ha/yr (Rowntree et al., 2020). Maillard and Angers (2014) also saw an overall increase in soil organic carbon as a result of manure application, which highlights the importance of integrated livestock and crop operations.

4.4.3 The production function and law of motion

Our representative farmer is growing hard red spring wheat. In our example, crop production is only a function of soil carbon and estimated carbon input, and all other inputs have been held fixed. The functional forms for the cash crop production function and the law of motion are influenced by Berazneva et al. (2019). Let c_t be the state of a farmer's land, which will be represented by soil carbon, and a_t be the amount of estimated carbon input. We used a quadratic equation to estimate the relationship between wheat yield (Mg/ha), soil carbon stock (Mg/ha), and estimated carbon input (Mg/ha):

$$f(a_t, c_t) = \gamma_0 + \gamma_a a_t + \gamma_{aa} a_t^2 + \gamma_c c_t + \gamma_{cc} c_t^2 + \gamma_{ac} a_t c_t \tag{4.7}$$

There is a positive relationship between wheat yield and both soil carbon stock and estimated carbon input, albeit at a decreasing rate. An increase in estimated carbon input and soil carbon stock will increase wheat yield, though the increases become smaller over time.

Soil carbon stock is endogenously determined within the system as a producer will increase soil carbon stock through the amount of estimated carbon input, which is captured by the law of motion. The law of motion is:

$$c_{t+1} - c_t = \beta_0 + k\beta_a a_t + \beta_{aa} a_t^2 + \beta_c c_t \tag{4.8}$$

Where k is the carbon sequestration scalar. The sequestration scalar is multiplied by the linear coefficient of estimated carbon input. This parameter represents the efficiency of the practice, research and development, education, soil capability, crop species, resources available and technology improvements.

The law of motion describes the annual change in soil carbon stock. There is a non-linear relationship between carbon input and the annual change in soil carbon stock, and a linear relationship with current soil carbon stock. Estimated carbon input will increase the amount of soil carbon stock in the next period at a decreasing rate. The coefficient attached to soil carbon stock is the natural growth rate of soil carbon, β_c. For our example, there is an annual loss in soil carbon stock that is proportional relative to the amount of soil carbon stock in that period.

4.4.4 Objective

We now define our representative farmer's objective function. Let π_t denote profit in time t, where $\pi_t = \pi(a_t, c_t) = pf(a_t, c_t) - wa_t$, p is wheat price ($/ha), $f(a_t, c_t)$ is the wheat production function as defined earlier, and w is the constant marginal cost a producer pays for estimated carbon input ($/Mg). The cash crop output price for wheat is $386.16/Mg, which is the 2023 average annual farm product price for wheat (Government of Canada, 2018). We use a range of values for w when evaluating the optimal control model. This parameter is used to help guide our discussion of how our representative producer responds to changes in costs.

Our representative farmer will maximize the discounted net present value of annual net returns over an infinite horizon through the amount of estimated carbon input to build soil carbon stock, with a discount factor of $\rho = \frac{1}{(1+\delta)}$ for the discount rate δ. Initial soil carbon stock is 27.72 Mg/ha (Maillard et al., 2018).

$$\max_{a_t} \sum_{t=0}^{\infty} \rho^t [p(\gamma_0 + \gamma_a a_t + \gamma_{aa} a_t^2 + \gamma_c c_t + \gamma_{cc} c_t^2 + \gamma_{ac} a_t c_t) - w a_t]$$

$$\text{subject to: } c_{t+1} - c_t = \beta_0 + \beta_a k a_t + \beta_{aa} a_t^2 + \beta_c c_t$$
$$c_0 = 27.72$$

The discrete-time current-value Hamiltonian can be written as:

$$H = p(\gamma_0 + \gamma_a a_t + \gamma_{aa} a_t^2 + \gamma_c c_t + \gamma_{cc} c_t^2 + \gamma_{ac} a_t c_t) - w a_t + \rho \lambda_{t+1} (\beta_0 + k \beta_a a_t + \beta_{aa} a_t^2 + \beta_c c_t) \tag{4.9}$$

Where λ_{t+1} is the current-value shadow price on soil carbon. The first order conditions require that:

$$\frac{\partial H}{\partial a_t} = p(\gamma_a + 2\gamma_{aa} a_t + \gamma_{ac} c_t) - w + \rho \lambda_{t+1} (k \beta_a + 2\beta_{aa} a_t) = 0 \tag{4.10}$$

$$\rho\lambda_{t+1} - \lambda_t = -p(\gamma_c + 2\gamma_{cc}c_t + \gamma_{ac}a_t) - \rho\lambda_{t+1}\beta_c \tag{4.11}$$

$$c_{t+1} - c_t = \beta_0 + k\beta_a a_t + \beta_{aa}a_t^2 + \beta_c c_t \tag{4.12}$$

In order to solve the empirical example, we used Wolfram Mathematica Version 13.3.1.0 (Wolfram Research, 2023).

4.4.5 Model extension: the addition of a carbon payment

Soil has the potential to sequester and store more carbon which would capture more greenhouse gas emissions (RBC et al., 2023). A carbon payment gives producers the opportunity to earn additional revenue for protecting water, land and air. This is an extension of our model into the objective function. The carbon payment is denoted by s (\$/Mg). Recall that the law of motion captures how soil carbon stock changes over time. Our producer will be paid for the amount of soil carbon sequestered each year.

A carbon credit program for agricultural producers would allow producers to get paid for the amount of carbon sequestered. In our example, the potential carbon program would be a voluntary outcome-based program that is based on the amount of carbon sequestered per year. We use the federal carbon prices, though the actual amount producers are paid would depend on market conditions and demand for such a program. Producers will not be penalized for any decreases in soil carbon stock.

To capture how much our representative producer would be paid in period t, we shift the law of motion back one period to capture the change in soil carbon stock from the period before (i.e. $c_t - c_{t-1} = g(ka_{t-1}, c_{t-1})$. If $c_t - c_{t-1} < 0$, then $s = 0$ as there is no penalty for a loss in soil carbon stock in a year. If there is a loss in carbon, our representative producer will receive nothing. The federal carbon prices are currently \$50/Mg, and increasing at \$15/Mg annually until it reaches \$170/Mg. For example, if our producer sequesters 0.4 Mg/ha of carbon at a price of \$50/Mg, our producer would get \$20/ha. The addition of a carbon payment will alter our objective function and the decision making process of our producer. Our profit function will now be $\pi_t = pf(a_t, c_t) - wa_t + s(c_t - c_{t-1})$, if $(c_t - c_{t-1}) > 0$. This will alter the first order conditions and how the producer decides to build soil carbon stock.

A carbon payment will incentivize our representative producer to sequester more carbon as it will increase revenue per hectare (if $(c_t - c_{t-1}) > 0$), and makes sequestering carbon more appealing to our producer. They will receive additional revenue beyond the potential benefits of increasing soil carbon stock on wheat yield. If regenerative strategies increase soil carbon stock, they are more likely to be adopted. We are modelling a profit maximizing producer, and therefore they will choose strategies that sequester and store more carbon if it is beneficial for both wheat yield, and the added benefit of being paid for it.

$$\max_{a_t} \sum_{t=0}^{\infty} \rho^t [pf(a_t, c_t) - wa_t + s(c_t - c_{t-1})]$$

subject to:

$$c_{t+1} - c_t = g(ka_t, c_t)$$

$$c_t - c_{t-1} > 0$$

$$c_0 = z > 0$$

There are several challenges with implementing carbon offset programs for the Canadian agricultural sector. This may include costs of implementation, system complexity, and ensuring mitigation outcomes occur (i.e. carbon sequestration) (Monahan et al., 2023). Producers will need help with the administration and practical requirements of a carbon offset program (Monahan et al., 2023). In order to finance and pay producers for sequestering carbon, it will also require proper measurement, reporting and verification (RBC et al., 2023; Murray, 2015). A carbon offset program could incentivize in the agricultural sector to adopt practices that sequester and store more carbon.

4.5 Results and discussion

4.5.1 Steady state results

In an infinite horizon problem, one question is whether or not the solution variables will converge to a set of values and remain unchanged (Berazneva et al., 2019). This is referred to as a steady or stationary state. Will the optimal management strategies remain sustained *ad infinitum*? In order for a steady state to exist, we need $a_t = a > 0$ and $c_t = c > 0$. In a steady-state, the time element is dropped and $\lambda_{t+1} = \lambda_t = \lambda$, $c_{t+1} = c_t = c$ and $a_t = a$. A new steady state is reached when soil carbon stock reaches a new equilibrium, and carbon additions and losses are balanced (Stella et al., 2019). The model extension has been ignored for now (i.e. the addition of a carbon payment). The functional forms for the steady state are implied by the following from the previously defined first-order conditions:

$$p(\gamma_a + \gamma_{aa}a + \gamma_{ac}c) - w + \rho\lambda(k\beta_a + 2\beta_{aa}a) = 0 \tag{4.13}$$

$$\rho\lambda(\beta_c - \delta) + p(\gamma_c + 2\gamma_{cc}c + \gamma_{ac}a) = 0 \tag{4.14}$$

$$\beta_0 + k\beta_a a + \beta_{aa}a^2 + \beta_c c = 0 \tag{4.15}$$

The optimal steady state values were initially evaluated at $w = 30$ and $k = 1$, with the parameters defined in table 4.1 The optimal steady state values are: $a = 1.26086$, $c = 36.6494$, and $\lambda = -305.139$. The values for carbon input and soil carbon stock are similar to what is seen in the experiment. In the experiment, the range of values for plant biomass carbon input was 0.84 Mg/ha to 12.86 Mg/ha, with an average of 6.36 Mg/ha. The range of values for soil carbon stock in the top 15cm was 23.42 Mg/ha to 40.61 Mg/ha with an average of 31.64 Mg/ha. The steady-state values are reached at approximately period $t = 35$. The negative shadow price of soil carbon is concerning, which

Table 4.1: Parameter values for optimal control model

Description	Values	Units	Source
Wheat production function			
γ_0	-15.1184	–	Experiment
γ_a	0.88035	–	Experiment
γ_{aa}	-0.01723	–	Experiment
γ_c	0.96851	–	Experiment
γ_{cc}	-0.01432	–	Experiment
γ_{ac}	-0.01976	–	Experiment
Soil carbon equation			
β_0	3.25449	–	Experiment
β_a	0.07609	–	Experiment
β_{aa}	-0.01172	–	Experiment
β_c	-0.09091		Experiment
Carbon sequestration scalar (k)	1, 1.2, 1.4, 1.6, 1.8, 2.0		
Prices			
Price of wheat (p)	386.16	\$/Mg	Statistics Canada, 2023
Constant marginal cost (w)	10, 20, 30, 40, 50, 60, 70, 80, 90, 100	\$/Mg	
Federal carbon pricing (s)	65, 95, 110, 125, 140, 155, 170	\$/Mg	Government of Canada, n.d.
Discount rate (δ)	0.05	%	
Initial soil conditions			
c_0	27.72	Mg/ha	Experiment

will be discussed later on.

The steady state conditions were evaluated at different levels of the constant marginal costs from $w = 10$ to $w = 100$ at increments of 10, with k fixed at 1. A decrease in w implies that the average cost of carbon input decreases. In order to determine the role that k has on producer's decision to increase carbon input, k was increased from 1.0 to 2.0 at increments of 0.2, with w fixed at 30. We evaluated the increases in k under the assumption that carbon input would not decrease in efficiency. An increase in k means that estimated carbon input will increase soil carbon stock at a greater rate. Realistically, increases in k will

As the constant marginal cost increases, the steady state value for carbon input decreases. This follows for most profit maximization problems as a producer will substitute away from the more expensive input. Once $w > 60$, it is too expensive for the producer to invest into building soil carbon stock as there are no steady state values for estimated carbon input. The steady state value for soil carbon stock is the highest when $w = 40$. Soil carbon stock is not as sensitive to changes in w in comparison to estimated carbon input as the steady state values remain within 2 Mg/ha of each other. There is an interesting relationship between soil carbon stock and carbon input. The highest steady state value for carbon input is at $w = 10$, though this does not translate to the highest steady value for soil carbon stock, which could imply that adding large amounts of carbon input will not result in rapid soil carbon growth.

The carbon sequestration scalar increases the annual change of soil carbon stock through increasing the efficiency of carbon input to build soil carbon. At a value of $k = 1$, this means that there have been no changes to the efficiency or ability of carbon input. The original expectation was that an increase in k would lead to steady state lower values of carbon input and increased soil carbon stock values. This is somewhat reflected in our results. The steady state values of estimated carbon input decreases substantially with an increase in k. An unexpected result was that the steady state values of soil carbon stock also decrease slightly with an increase in k.

4.5.2 Value of soil carbon

In an optimal control model, the shadow value of a renewable resource represents the marginal value of the resource stock with respect to the objective function, and the value of the resource to the producer. For our example, the shadow price represents the value of soil carbon stock to the producer.

The current-value shadow price depends on the level of carbon input and soil carbon stock in period t. It was the most sensitive variable to changes in the exogenous parameters.

At the steady-state, the shadow value of soil carbon stock was always negative. At the baseline of $w = 30$ and $k = 1$, the steady value of λ is $-\$305.14/Mg$. As the constant marginal cost of carbon input increases, the steady state values of the shadow price increase, whereas an increase in the carbon sequestration scalar will decrease the steady state value of the shadow price.

When we let the model run for fifty time periods, the current-value shadow price was negative for most of the time horizon, and decreased the more time went on (i.e. got more negative). A negative shadow value could imply that soil carbon decreases the objective of our representative producer to maximize the NPV of annual net returns from a hectare of land. By increasing the amount of soil carbon stock, there is a decrease in annual net returns.

One explanation for the negative shadow value comes from the marginal productivity of soil carbon stock to wheat yield ($\frac{\partial f(\cdot)}{\partial a_t}$). Revenue for our representative producer comes from wheat yield, which is directly influenced by the marginal product of soil carbon stock. When the model ran for fifty time periods at $w = 30$ and $k = 1$, the marginal productivity of soil carbon stock is positive for the first period only. Beyond period one, our representative producer is better off not building soil carbon stock. If initial soil carbon stock is lower, a producer will benefit more from increases in soil carbon stock as an additional unit will decrease yield at the margin. Once soil carbon stock reaches a certain level, the marginal productivity of soil carbon stock becomes negative, and the costs of building soil carbon stock outweigh the benefits of increasing it. The proof for this is found in appendix 6.4. Increases in yield will level off beyond a certain threshold of SOC increases. For example, Oldfield et al. (2019) found that increases in yield will level off beyond increases of two percent soil organic carbon concentration. A producer cannot infinitely build soil carbon in hopes of increasing yield; at a certain level, they will experience diminishing returns.

4.5.3 Optimal time paths

We let our model maximize the discounted annual net returns from a hectare of land over fifty years at a discount rate of 5%. The model was ran with different values of the constant marginal cost from \$10/Mg to \$100/Mg, different values of the carbon sequestration scalar from 1.0 to 2.0, and the carbon payment at federal carbon prices. The optimal time paths for estimated carbon input and soil carbon stock for different values of w, k, and the addition of s are shown in figures 4.2, 4.3, 4.4, 4.5, 4.6, and 4.7. This next section discusses the optimal time paths and the net present value of annual net returns through the estimated amount of carbon input.

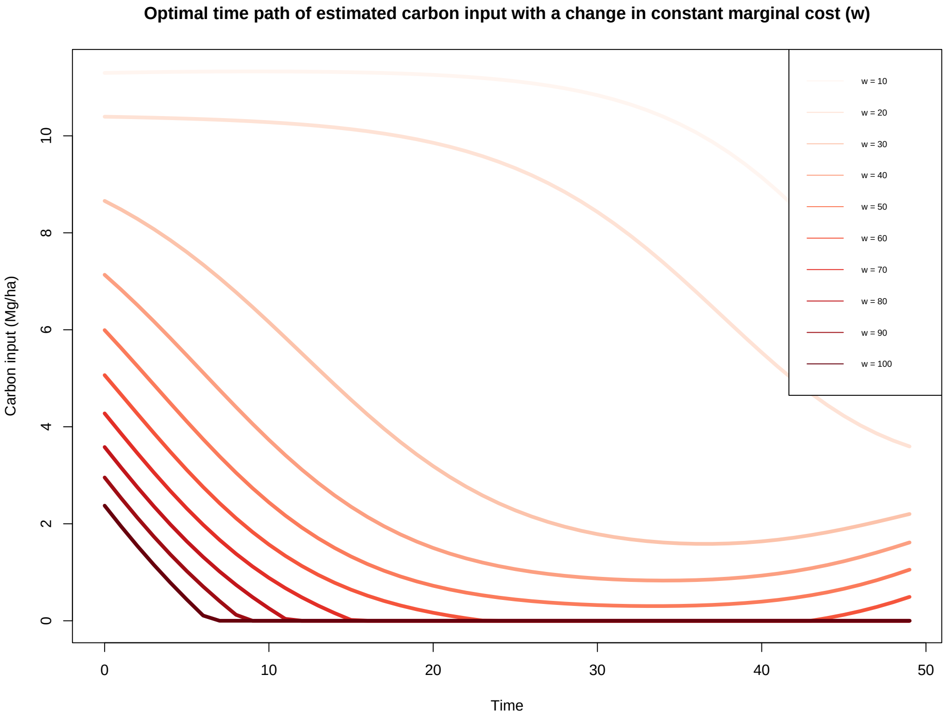

Figure 4.2: The optimal time path of estimated carbon input with a change in constant marginal cost (w)

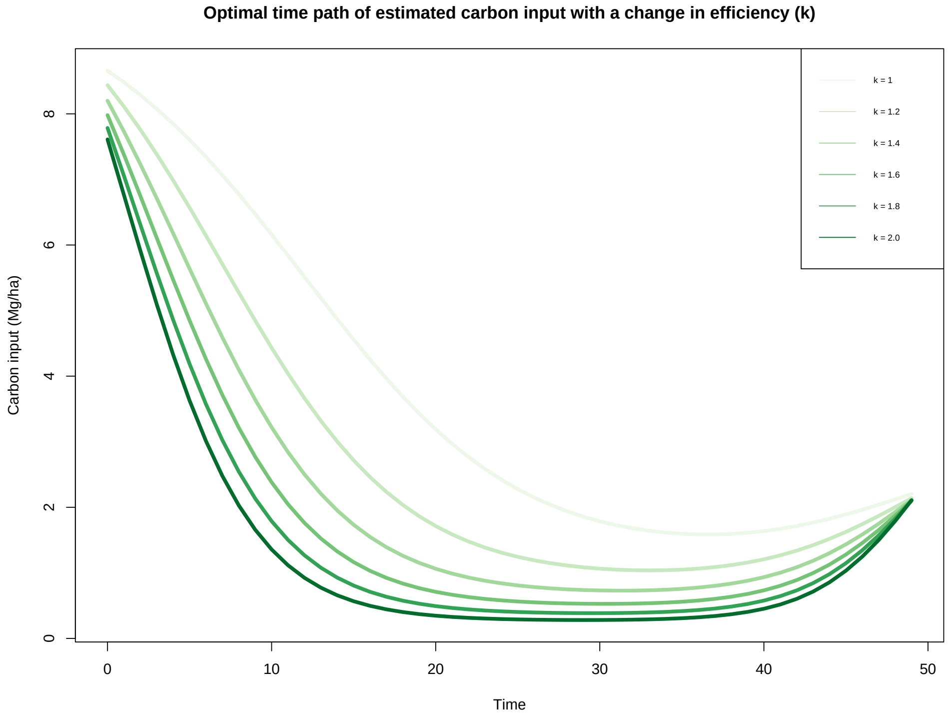

Figure 4.3: The optimal time path of estimated carbon input with a change in the carbon sequestration scalar (k).

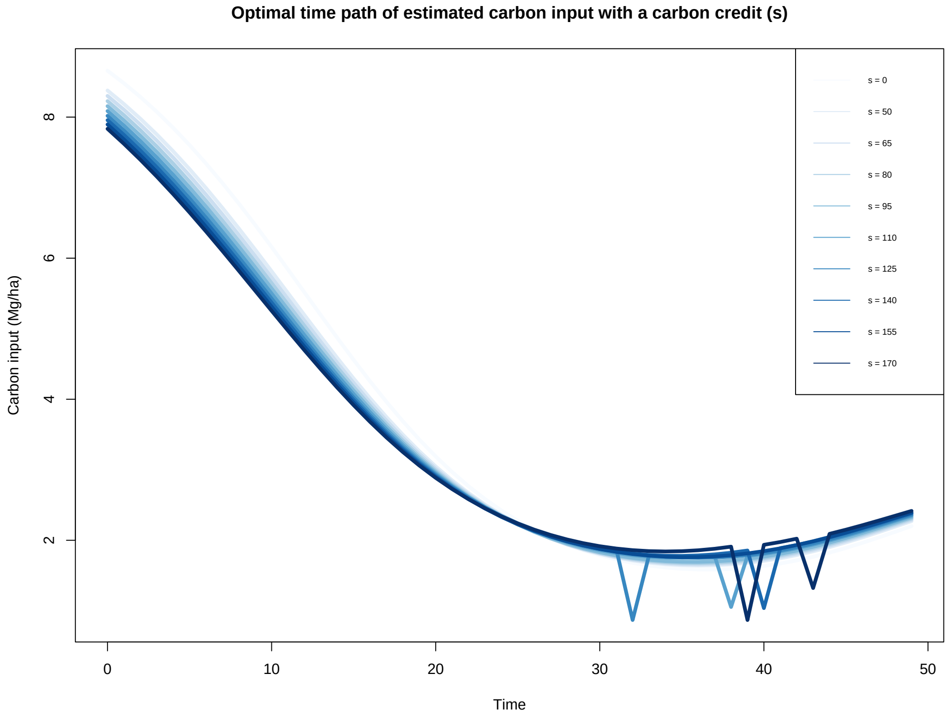

Figure 4.4: The optimal time path of estimated carbon input with the addition of a carbon payment (s).

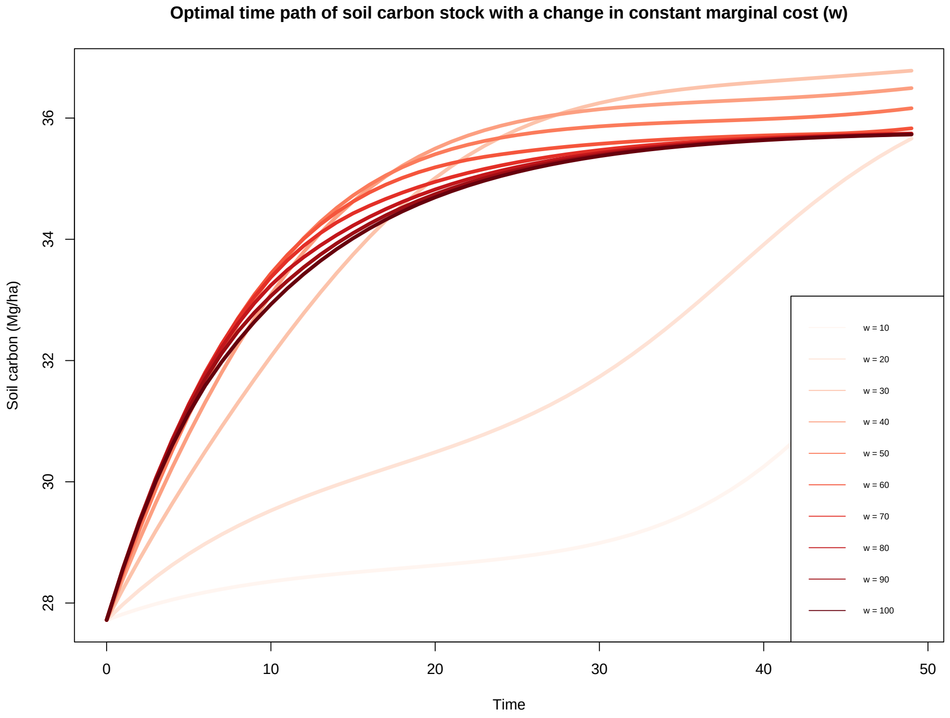

Figure 4.5: The optimal time path of soil carbon stock with a change in constant marginal cost (w).

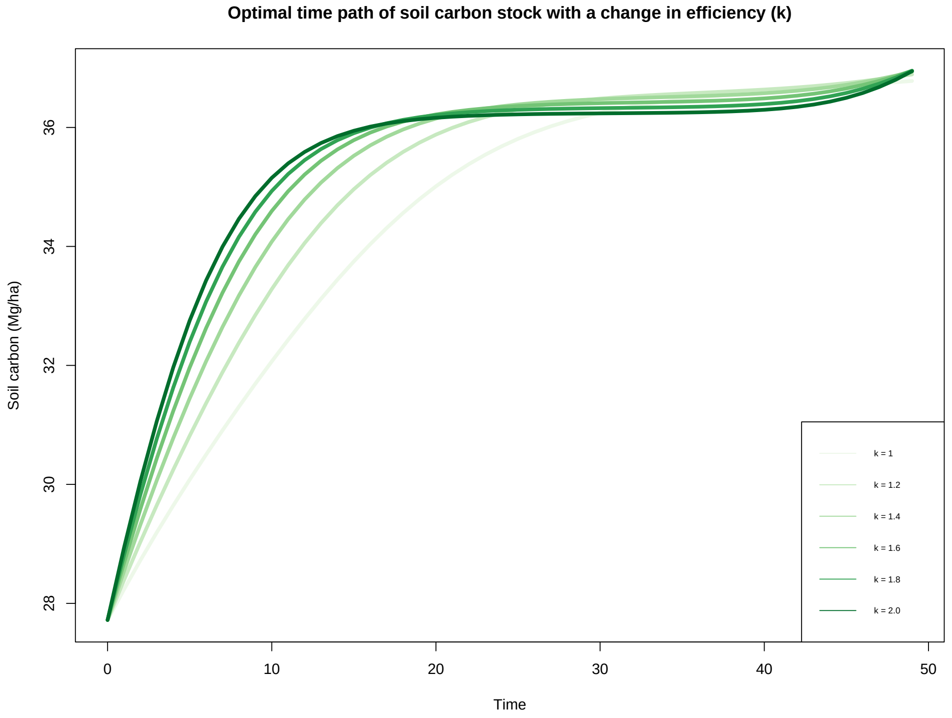

Figure 4.6: The optimal time path of soil carbon stock with a change in the carbon sequestration scalar (k).

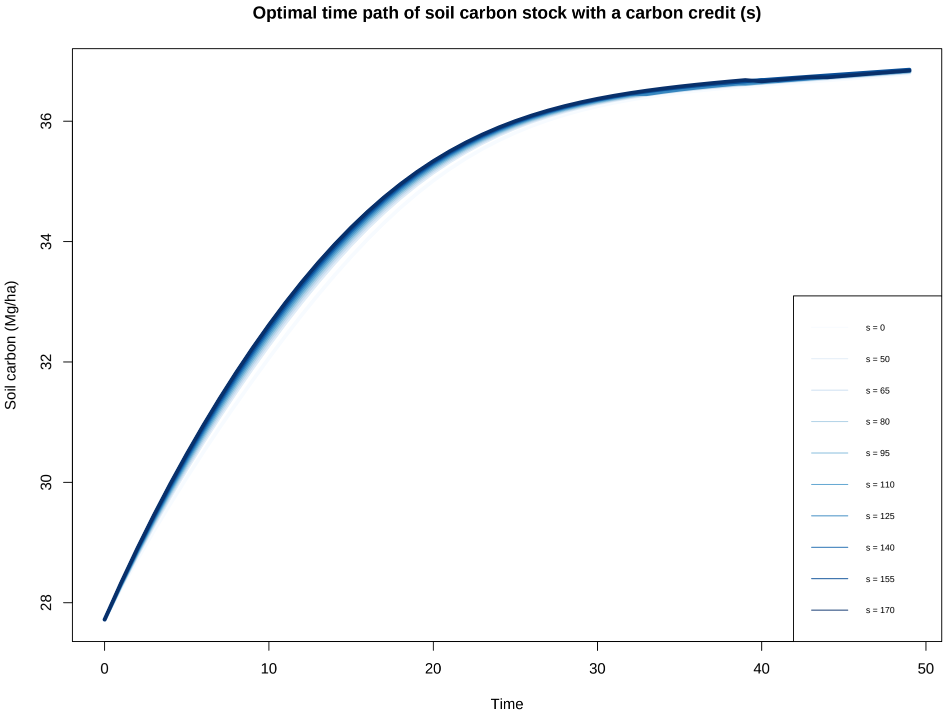

Figure 4.7: The optimal time path of soil carbon stock with the addition of a carbon payment (s).

Constant marginal cost (w)

We were able to identify how our representative producer responds to changes in costs through differences in the constant marginal cost. We did not account for returns to scale in our example, though this would be interesting to look at in future research. If the costs of an input increases, we would expect the producer to decrease the amount of estimated carbon input, which is reflected in our example. Across all increments of the constant marginal cost, carbon input starts high and steadily decreases towards the last period.

The optimal time path trends for estimated carbon input are similar across most values of w, where there is a high level at the beginning of the time horizon before it steadily decreases. There are large differences in the starting and terminal values of carbon input, with lower values the greater that w is. There is an interesting path for soil carbon stock. When $w = 10$, we have the highest amount of carbon input throughout all fifty periods, yet soil carbon stocks are lowest. The greatest increase and terminal values for soil carbon stock are when $w = 30$ and $w = 40$. This highlights a balance between inputting carbon into the soil and soil carbon growth. At $w = 10$, it is less expensive to invest and a producer increases a_t, however, soil carbon growth does not grow at an accelerated rate. Therefore, more input may not always translate to carbon growth.

In table 4.2, the NPV of the investment is summarized for different values of the constant marginal cost. As w increases, the NPV decreases as building soil carbon stock becomes too expensive. As a result, estimated carbon input decreases, and wheat yield decreases. The investment is less appealing to our representative producer the greater that w is.

Table 4.2: Comparative analysis of NPV for changes in constant marginal cost.

Constant marginal cost (w)	**NPV ($)**
10	14 495.70
20	12 513.00
30	11 119.50
40	10 307.80
50	9746.82
60	9351.42
70	9072.21
80	8872.51
90	8731.92
100	8636.33

Carbon sequestration scalar (k)

The carbon scalar (k) is multiplied by the linear coefficient of estimated carbon input in the law of motion, and will be a proportional increase in the efficiency of carbon input to grow soil carbon stock. The ideal situation for our representative producer would be an increase in k leading to less carbon input required, if the goal is to improve soil carbon stock.

An increase in k led to a decrease in estimated carbon input across the entire time horizon, when compared to the baseline of $w = 30$ and $k = 1$, which is shown in figure 4.3. The greatest decrease in estimated carbon input was $k = 1$ to $k = 1.2$, which is a twenty percent increase in efficiency (or ability) to increase soil carbon stock in the next period.

Estimated carbon input follows a convex time path, where carbon input starts high and steadily decreases before it curves up at the end of the time horizon, as reflected in figure 4.3. Recall that an increase in k will only affect the rate of soil carbon growth, not yield. Soil carbon stock grows at faster rates even with the corresponding decreases in estimated carbon input, as shown in 4.6. The marginal productivity of soil carbon is negative beyond period one, and therefore increases in soil carbon does not lead to increases in yield. Our representative producer experienced a decrease in yield following increases in k, despite there being increases in soil carbon stock.

The NPV of the investment for different values of the carbon scalar is summarized in table 4.3. The NPV decreases with each increase in k, which makes it more unattractive to our representative producer.

Table 4.3: Comparative analysis of NPV for changes in the carbon sequestration scalar.

Carbon sequestration scalar (k)	**NPV ($)**
1.0	11 119.50
1.2	10 841.70
1.4	10 631.40
1.6	10 455.20
1.8	10 332.80
2.0	10 223.00

Carbon payment (s)

We introduced a model extension of a carbon offset program that pays producers for the amount of carbon sequestered each year. The addition of a carbon payment will not burden a producer as it will not penalize them for any carbon loss and it does not cost anything to join. Stevens (2018) highlighted that policy intervention is best when there are high information search costs, which will occur with a carbon offset program. A carbon credit program would be expensive to implement and we would also need to find the market demand. The carbon credit program in our example does not account for a farmer that may purposely decrease carbon in order to increase the payment, although this would have to be accounted for

The addition of a carbon payment has a minimal impact on the optimal time paths of estimated carbon input and soil carbon stock, as reflected in figure 4.4 and figure 4.7. Therefore, a carbon payment does not have a major influence on the producer decision to build soil carbon stock.

There is a simulation anomaly at the highest carbon payment amount where there are steep drops in estimated carbon input. At these drops, there are small decreases in soil carbon stock.

The NPV of building soil carbon stock with the addition of a carbon payment is in table 4.4. The NPV slightly increases with a carbon payment, which makes it more appealing to our representative producer the greater that the carbon payment is.

Table 4.4: Comparative analysis of NPV for the addition of a carbon payment.

Carbon payment (s)	**NPV($)**
50	11400.5
65	11 485.90
70	11 571.70
95	11 657.8
110	11 744.20
125	11 830.60
140	11 918.30
155	12 006.20
170	12 093.40

4.5.4 Model implications and discussion

Our representative producer is maximizing the net present value of annual net returns from a hectare of land through the amount estimated of carbon input into soil. With our example, we identified how our representative producer responded to changes in costs, input efficiency, and a carbon payment. The representative producer was more responsive to changes in costs (w) than changes in efficiency (k) and a carbon payment (s).

The wheat production function and law of motion highlighted that there is a positive relationship between estimated carbon input, and both soil carbon stock and hard red spring wheat yield. In the production function, soil carbon has a positive relationship with wheat yield, however, the marginal product of soil carbon stock is negative. An increase in soil carbon stock will result in a decrease in wheat yield at the margin. If our representative producer decides to build soil carbon stock, there is the risk of decreasing yield identifying an important tradeoff between increasing soil health and maximizing profit.

We discussed the private and public benefits of soil health in section 2.2, which have an important role in the producer decision making. The private benefits of increasing soil health are important for adoption as a producer will outweigh the benefits and costs, whereas the public benefits may incentivize policymakers to develop programs or policies that help with adoption (Rejesus et al., 2021).

The private benefits of increasing soil carbon are directly experienced by producers on their own fields. For our producer, private benefits may include higher soil carbon levels, improved wheat yields, reduced production costs, enhanced input efficiency, more resilient farming systems, and better soil health, although we could not observe these. If farmers observe and experience the direct advantages on their land, a producer may be more willing to invest into building soil carbon stock. Recognizing the benefits can be challenging since there might be a delay in their appearance, or they may not materialize at all. The initial decision to build soil carbon starts with higher net returns, though this will decrease as time goes on. We emphasized the short-term loss for the long-term improvements of regenerative agriculture and soil health, though our example does not reflect this.

Our representative producer experienced a decrease in yield and profit over a long horizon, although soil carbon stock is improve slightly. The outcomes of increasing soil carbon and implementing regenerative strategies will depend on many factors.

In both the steady-state and infinite horizon problem, the optimal values and time paths of soil carbon stock and estimated carbon input changed with the costs of production, input efficiency and a carbon payment. The representative producer was most responsive to changes in costs, so the decision to adopt regenerative agriculture may be primarily tied to money. The constant marginal cost of regenerative strategies could be decreased by selecting regenerative strategies that are less expensive. For example, this may be selecting cover crop species that have less expensive seed, planting and/or termination costs. The costs of production could also change as a result of a producer's decision to change strategies, or from needing less carbon input as soil carbon grows. To increase the efficiency of inputs (i.e. increase k), it may involve choosing an alternative regenerative strategy at the same price point that sequesters more carbon. There are certain crops or practices that are able to sequester or supply more carbon. This includes root depth, yield, biomass capability, growing ability, and synergy of practices. As a producer gets more experience with regenerative agriculture, they may get more efficient with their practices and better able to adapt their farm conditions, and possibly decrease costs along the way too.

The public benefits of investing into soil carbon stock are those that are experienced off-farm, and are important for government intervention. By improving soil carbon stock, public benefits may include improved greenhouse gas emissions reduction, more resilient farming systems, increased food quality, cleaner air and water, and improved soils. If there are more people that can benefit from improved soils, there is more of a demand for improved soils.

We did not calculate what the public benefits of improving soil carbon are directly, though we can understand how government intervention will affect the producer choice of carbon input. The role of government intervention in our example could be a change in the costs of production from cost-share programs, subsidies, outcome-based programs (e.g. carbon payments) or tax incentives. It may also be in the form of research and development into making regenerative agriculture better able to increase soil carbon stock (i.e. increase the carbon scalar). The most relevant role for government intervention in our example would be the addition of a carbon offset program.

Regenerative agriculture is a proposed method of climate change mitigation, and may provide an incentive for policymakers to create carbon offset programs. These types of programs pay producers for the amount of carbon that is sequestered and taken out of the atmosphere. The demand for carbon markets are there, and several initiatives are available (e.g. Agriculture and Agri-Food Canada (2023); Government of Alberta (2024); Environment and Climate Change Canada (2020); Nori Inc. (2024); Government of Saskatchewan (nd)). The addition of a carbon payment would be complex, which was ignored for simplicity. The carbon payment makes building soil carbon stock more appealing to our representative producer (i.e. NPV increases), though our representative producer was not as responsive to the carbon payment.

Our example showed that increasing soil carbon stock does not result in increased yield, though this depends on soil type and conditions, initial soil carbon content, management style, weather and location. There were no increases in yield throughout the entire time horizon, which does not show the potential long-term benefits of soil health. Although there were improvements in soil health. At the initial soil carbon stock of 27.72 Mg/ha, soil carbon stock was not productive towards yield. When soil carbon goes above a certain level, the marginal productivity of soil carbons became negative. This means that an additional unit of soil carbon stock will decrease total wheat production. One implication of our example is that fields with lower levels of soil carbon will benefit more from the adoption regenerative practices, which can be seen in appendix 6.4.

4.5.5 Concluding remarks

Producers are often motivated by themselves, a specific situation or another producer to start regenerative farming. The producers that we interviewed for this thesis did not start regenerative agriculture because they were given monetary incentives; and instead started themselves, meeting someone, or attending a workshop. In order to increase soil health, the most basic opportunity would be to incentivize farmers to learn about the relationship between soil health and production dynamics, and their own soil health (Stevens, 2018). We can use the model to identify how a producer may respond to changes in costs and efficiency, though there is not a lot that the government could do to influence the adoption of regenerative agriculture.

Chapter 5

Conclusion

Regenerative agriculture is an alternative farming system proposed to improve environmental, economic and social sustainability. It can increase carbon sequestration, increase yields, decrease costs and create more resilient cropping systems. Regenerative agriculture may not be compatible for every farm setting as it depends on many factors such as an individual's discount rate, a producer's objective, soil conditions, topography and weather.

Through the use of the case studies, we were able to better understand why producers adopt regenerative strategies, the challenges that they faced, and what the benefits are in Saskatchewan by those who have first-hand experience. There is a lot of information available to producers but having locally relevant resources and a supportive network will help aid producers who are interested in adopting regenerative strategies. Producers started regenerative agriculture on their own and were motivated by themselves or someone else sharing their experience with them. Regenerative agriculture was practiced differently among each farm, though the same principles were used. Regenerative agriculture is possible in Saskatchewan, though this does not imply that it will work for every producer. Every year will present new challenges, and producers will have to adapt along the way.

We then developed a renewable resource model to examine regenerative agriculture in a dynamic setting. We created a framework that linked regenerative agriculture and soil health, with soil carbon used as a proxy for soil health. The framework can be used to understand and model the economic motivations of the case studies, and to examine how a producer responds to biological changes in soil. We then provided an example of how a producer would respond to changes in costs, the ability of a practice to sequester carbon, and the addition of a carbon payment that is purely representative.

Our study has potential limitations. For the case studies, we only interviewed seven producers, which is a small subset of people. We also did not interview those that have stopped practicing regenerative agriculture, therefore all participants had a more positive view of regenerative agriculture. This created sample bias for the case studies. The results for the renewable resource model should be interpreted with caution. The first limitation in the renewable resource model is that we are holding all other inputs constant, and assuming that our input decision of soil carbon investment will not impact any other input decisions. The second limitation is the empirical example is parameterized for Swift Current, Saskatchewan using only one subset of the data that we were given. It would be interesting to parameterize with the other experimental plots, however, time did not allow for that. The third limitation is that in order to estimate the plant biomass carbon input, we used the Bolinder et al. (2007) method. This may bias the results as the estimation may be inaccurate. Calculating the amount of carbon input is complex and subject to criticism. Finally, due to data limitations, we did not have values for the constant marginal cost and the carbon sequestration scalar. The values chosen do not reflect the costs and efficiency of actual regenerative practices, however the increments chosen for them helped aid in our discussion of how a representative producer would respond.

Our project will shed some light on the use of regenerative agriculture in Saskatchewan by building a dynamic economic model informed by regenerative practitioners that can be used to assess the economic viability of regenerative practices. The framework can be used to understand the financial incentives for adopting any regenerative practices. All we need is the contribution of soil carbon investment to soil carbon stock, and the costs associated with each investment strategy.

Chapter 6

Appendices

6.1 Demographics of case study participants

Table 6.1: Demographics of case study participants.

Farm number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Farm size (acres)	$\sim 11,000$	4500	2200	2500	~ 5500	~ 9000	-
Net farm income	$> 150,000$	$> 150,000$	$> 150,000$	$> 150,000$	$> 150,000$	$> 150,000$	$> 150,000$
Education	B.A. and diploma	Diploma	Diploma	Certificate	B.A.	Diploma	Continuing education workshops
Experience	$\sim$ 20 years	$\sim$ 12 years	$\sim$ 20 years	$\sim$ 10 years	$\sim$ 20 years	$\sim$ 20 years	$\sim$ 30 years
Age	40s	40s	30s	30s	–	40s	40s

We interviewed seven producers who lived throughout Saskatchewan. We will not share the specific locations. Each farm has been numbered one through seven in order to keep it anonymous. This table provides a very brief description of the farms including the approximate farm size, net farm income bracket, education, farming experience, and age bracket.

6.2 Case study questionnaire

Each participant was provided a copy of the questionnaire prior to starting the interviews. They could refuse to answer any question. The questions were a starting point for the interviews though the conversations flowed in many directions.

Background

1. What is your approximate farm size?

2. What is your approximate household income?
3. Do you or anyone in the household earn off-farm income?
4. What is the highest level of education completed?
5. What is your age range?

Regenerative agriculture

1. How familiar are you with regenerative agriculture?
2. Which regenerative agricultural strategies have you implemented?
3. For each regenerative strategy from question 2, we will ask the following questions a through i. Strategy 1 is used as an example to demonstrate questions that will be asked for different regenerative strategies.
    (a) How long have/had you been implementing strategy 1?
    (b) What influenced your decision to start implementing strategy 1? Or stop strategy 1?
    (c) Have there been any benefits that you have observed since adopting strategy 1? What are they?
    (d) Have there been any barriers or constraints to adopting strategy 1? What are they?
    (e) How has implementing strategy 1 changed your revenue?
    (f) How has implementing strategy 1 changed your expenses?
    (g) What was/is the biggest expense to implementing strategy 1?

   (h) Did you require any additional resources or specific investments to implement strategy 1? What were they? (e.g., labour, knowledge, machinery/equipment, time, custom harvester, etc.).

   (i) Did you need to take on additional debt to finance strategy 1?

4. The adoption of regenerative strategies is limited and not widely spread across the prairies, why do you think that is?

5. How could the Ministry of Agriculture better support producers when it comes to implementing regenerative strategies?

6.2.1 Extra questions

There were two components of the case studies not included in the main portion of the thesis. The first section comes from regenerative strategies, where two producers shared their intercropping strategy. The second section comes from the advice that participants had for those interested in regenerative agriculture.

Intercropping

Crop diversification is a principle of regenerative agriculture, which can be accomplished with intercropping. Intercropping is planting more than one crop together (Agriculture and Agri-Food Canada, 2019).

There were three farms who practiced intercropping and shared their strategy. Farm one's plan was to find crops that were low yielding and high value, so that there would be less removal from the system in the spring, less grain to handle and less storage. Farm two planted winter triticale at a light rate into spring seeded cereals and used clover with canola and Italian ryegrass.

Farm five intercropped peas and oats, which built resiliency into their farm. There was one year when it was quite dry with only five inches of rain. They were originally going to sell the crops for seed or grain, however, they raised it as no crop insurance was available and grazed the cows on it. Farm five was able to keep their herd, and although there were winter feed costs, it could have been way worse. The alternative would have been de-stocking, and then needing to build up the genetics again of their farm.

Regenerative advice

In the case studies, we asked participants about advice they may have for producers who are interested in regenerative agriculture. There were two pieces of advice that producers had to offer.

The first was that what works on one farm will not necessarily work on another. There is no blueprint for regenerative agriculture, and it is all about finding what works best for your context.

The second piece of advice was to start small and slowly adopt regenerative practices. If a farm tries to change everything, they may risk taking on a huge financial burden. A farm may be doing something one week that works, but try something new the next week or a farm may need to change strategies quickly. For example, farm three started making changes as they realized that what they were currently doing was not working. Making the small tweaks is the biggest thing that a person can do on their farm because “you’re not going out there and trying to change the world and totally screwing it up” (farm three). Starting regenerative agriculture does not mean changing everything. You “don’t want to run before [you] start walking” (farm two).

6.3 Parameterizing the optimal control model

The experimental dataset came from a field site located at the Agriculture and Agri-Food Canada Research and Development Centre near Swift Current, Saskatchewan, Canada (50 16'N, 107 44'W) (Maillard et al., 2018). The experiment was initiated in 1981 and concluded in 2011. Soil carbon concentration levels were collected every four years from 1982 to 2011 at different depths, and yield was collected every year. There were four replicate plots sampled each year.

In order to parameterize the model for the law of motion and wheat production function, we used the continuous wheat no-till experimental plot. The first step was to extrapolate the variables required to estimate the dynamic equations.

To prepare the experiment for the production function and the law of motion, we needed a value for annual soil carbon stock as it was collected every four years. We first aggregated soil carbon stock and then conducted linear interpolation to obtain values for each experimental year. The annual averages of wheat yield and plant biomass carbon input for the four replicates were used for parameterization. Figure 6.1 shows a comparison between average soil carbon stock among the four replicates of the experiment collected every four years versus interpolated soil carbon stock.

The amount of carbon input from plant residue was estimated using agricultural yields, published or assumed values for the harvest index (HI), shoot:root ratio (S:R), plant carbon in root exudates, and carbon concentrations in the plant part (Bolinder et al., 2007). To predict the changes in carbon stocks, it will depend on reliable estimates of net primary productivity (NPP) and the proportion of residues returned to the soil. Bolinder et al. (2007) proposed a method to describe the

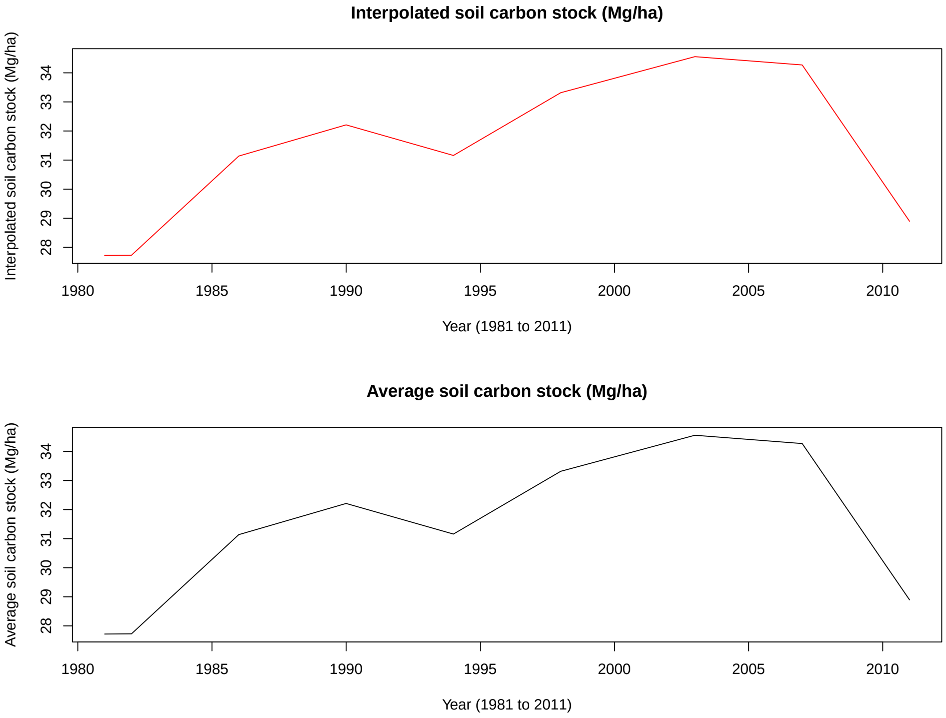

Figure 6.1: Average soil carbon stock collected every four years versus annual interpolated soil carbon stock.

annual NPP, carbon allocation and carbon input to soil that includes all carbon fractions, is compatible with readily available data, and allows for easy and direct of annual carbon input to the soil. We assumed a plant carbon concentration of 45% in the plant tissues and formulas proposed by Bolinder et al. (2007) using the harvest index (HI) and shoot:root ratio (S:R). Bolinder et al. (2007) add a parameter, S, which describes the proportion of carbon in a given fraction returned to the soil. If all residues are incorporated and only the product is harvested, then the default is $S_P = 0$, $S_S = 1$, $S_R = 1$, and $S_E = 1$ which are the proportions of carbon in product, above-ground residues, roots and extra-root, respectively. We will assume that all crop residues have been returned to the soil, as this was done in the experiment. The HI was calculated from hand grain yield (HG) and aboveground biomass (BM) for wheat according to: $HI = HG/BM$.

Bolinder et al. (2007) split the carbon in crop plants into four fractions, and then the annual net primary productivity is equal to $CP + CS + CR + CS$. The annual carbon input to soil is calculated as: $C_i = [C_P \times S_P] + [C_S \times S_S] + [C_R \times S_R] + [C_E \times S_E]$, where C_i is annual carbon input to soil. The four fractions are as follows:

- C_P: This is the plant carbon in the agricultural product, and is typically harvested. Plant carbon in agricultural product is calculated as: $C_P = HG/0.45$.

- C_S: This is the plant carbon in straw, stover and other above-ground post harvest residues, excluding the product. The above-ground plant carbon inputs from straw was calculated as: $C_S = HG(1 - HI)/HI \times 0.45$.

- C_R: This is the plant carbon in root tissue that includes all below-ground physically recoverable plant materials. To estimate the carbon input from roots, a S:R for the full rooting depth 4.37

was used

- C_E: This is the plant carbon in extra-root material that includes root exudates, and other material derived from root-turnover. The carbon input from rhizodeposition was calculated as: $C_E = C_R \times 0.45$

6.3.1 The production function

We specified a quadratic equation for hard red spring wheat yield. Figure 6.2 shows the relationship between soil carbon stock and wheat yield. There is not a strong correlation between soil carbon stock and wheat yield in the experiment. In order to better capture the relationship, annual temperature was gathered from the Swift Current weather station (Government of Canada, 2024).

The production function was calibrated using RStudio. We first created lagged variables for estimated carbon input and soil carbon stock to shift the values back one period, and created squared variables of the variables. We then ran an OLS regression of hard red spring wheat yield on lagged carbon, lagged carbon squared, lagged carbon input, lagged carbon input squared, an interaction term, and temperature. The coefficient on temperature was multiplied by the mean annual temperature throughout the experiment and added to the intercept.

The quadratic specification of the production function is as follows:

$$f(a_t, c_t) = \gamma_0 + \gamma_a a_t + \gamma_{aa} a_t^2 + \gamma_c c_t + \gamma_{cc} c_t^2 + \gamma_{ac} a_t c_t \tag{6.1}$$

The parameters for the equation are:

$$f(a_t, c_t) = -15.1184 + 0.88035 a_t - 0.01723 a_t^2 + 0.96851 c_t - 0.01432 c_t^2 - 0.01976 a_t c_t \tag{6.2}$$

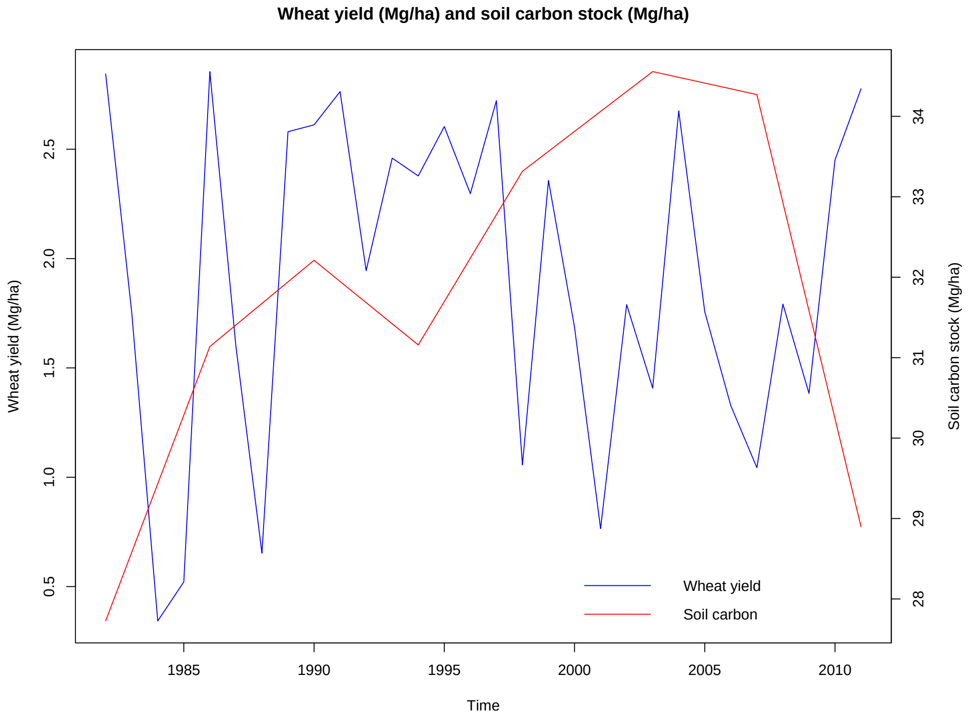

Figure 6.2: A double y-axis graph depicting the relationship between hard red spring wheat on the left vertical axis and soil carbon stock on the right vertical axis.

Table 6.2: Production function regression results.

Term	Coefficient	Std. Error	T Value	Pr (¿ — t —)
(Intercept)	-14.52888	68. 89144	-0.211	0.835
Lagged carbon input	0.88035	1.63424	0.539	0.597
$Laggedcarboninput^2$	-0. 01723	0.03967	-0.434	0.669
Lagged soil carbon	0.96851	4.40662	0.22	0.829
$Laggedsoilcarbon^2$	-0.01432	0.07026	-0.204	0.841
Lagged carbon input * lagged soil carbon	-0. 01976	0.05502	-0.359	0.724
Temperature	-0.13822	0.17703	-0.781	0.445

6.3.2 The law of motion

The annual change in soil carbon stock is represented by the law of motion, which was calibrated using RStudio.

Maillard et al. (2018) note an important decrease of soil organic carbon stocks in 2007 that was linked to the precipitation regime. The monthly mean precipitation between 2007 to 2011 was the wettest, which was linked to the highest SOC loss throughout the experiment. During this time, decomposition exceeded plant biomass carbon input, and soil carbon was lost. For this reason, we exclude soil carbon stock values between 2007 to 2011 as there were drops across all experimental plots.

To calibrate the law of motion, we created a first difference variable for carbon using interpolated carbon, which represents $c_{t+1} - c_t$. We then ran an OLS regression of the first difference variable on estimated carbon input, carbon input squared, and current soil carbon stock.

The quadratic equation of the law of motion is:

$$c_{t-1} - c_t = \beta_0 + k\beta_a a_t + \beta_{aa} a_t^2 + \beta_c c_t \tag{6.3}$$

The parameters for the law of motion are:

$$c_{t-1} - c_t = 3.25449 + k0.07609 a_t - 0.01172 a_t^2 - 0.09091 c_t \tag{6.4}$$

Table 6.3: Law of motion regression results.

Term	**Coefficient**	**Std. Error**	**T Value**	**Pr (¿ — t —)**	**Significance**
(Intercept)	3.25449	1.29124	2.52	0.0199	*
Carbon input	0.07609	0.14588	0.522	0.6074	
$Carboninput^2$	-0.01172	0.01332	-0.88	0.3889	
Soil carbon	-0.09091	0.04122	-2.206	0.0387	*

6.4 Time value of soil carbon

6.4.1 Why is the relationship between soil carbon stock and wheat yield negative?

When discussing the time value of soil carbon stock, a concerning feature was that the shadow value of soil carbon was negative. This means that soil carbon stock will decrease the objective function, and our representative producer is better off without investing into building soil carbon stock. In order to understand the relationship between soil carbon stock and wheat yield, we can look at the marginal product of soil carbon stock.

Recall that the production function is:
$f(a_t, c_t) = \beta_0 + \beta_a a_t + \beta_{aa} a_t^2 + \beta_c c_t + \beta_{cc} c_t^2 + \beta_{ac} a_t c_t$

The marginal product of soil carbon stock would be:
$\frac{\partial f(\cdot)}{\partial c} = \beta_c + 2\beta_{cc} c_t + \beta_{ac} a_t$

We can then set this equal to zero and solve for c_t.

$\beta_c + 2\beta_{cc} c_t + \beta_{ac} a_t = 0 \rightarrow \beta_c + 2\beta_{cc} c_t + \beta_{ac} a_t < 0 \rightarrow 2\beta_{cc} c_t < -\beta_c - \beta_{ac} a_t$

We then input the values for the parameters from table 4.1.

$0.02864 c_t < -0.96851 + 0.01976 a_t \rightarrow c_t > 33.8167 - 0.689944 a_t$

If soil carbon stock goes above this level, then the marginal product will be negative. When $w = 30$ and $k = 1$, the marginal productivity of carbon was only positive for one period before it became more negative over time. When we increased the value of w, the marginal product of soil carbon is positive for more time periods. At higher levels of w, estimated carbon input is lower so soil carbon stock does not increase as quickly. When we increase k, the marginal product of soil carbon stock is slightly more positive as well.

In our example, initial soil carbon stock starts high at 27.72 Mg/ha and our representative producer will not benefit as much from increases in soil carbon. The marginal productivity of soil carbon stock will also depend on the level of estimated carbon input. The value of λ_t at the original and a lower initial soil carbon level are in table 6.4. Tables 6.5 and 6.6 show the marginal productivity and discounted profit with a lower initial soil carbon level.

6.5 Comparative statics

The endogenous parameters of our system are a, c, and λ; and the exogenous parameters are p, w, and k.

Prior to introducing the example, we examined the framework in functional form. Comparative static results are sensitive to the relative size of $\frac{\partial g(\cdot)}{\partial c_t}$ and δ, which is the marginal contribution of soil carbon to building soil carbon stock, and the discount rate, respectively. G_c is the rate of soil carbon growth, or the speed at which soil carbon grows over time. If g_c is greater than the discount rate, this means that the value of sequestering carbon is more valuable to the producer. There is more weight on taking the costly soil carbon investment measures now. The discount rate has an important role in determining how a resource stock is used in renewable resource economics. A higher discount rate implies that our representative farmer values the benefits today (present) more than the future. In our example, $\frac{\partial g(\cdot)}{\partial c_t} = b_c$, which is less than the discount rate. The negative coefficient indicates that a one unit increase in current soil carbon stock will lead to a decrease in the annual rate of change in soil carbon stock. This will always be less than the discount rate, though this does not mean that our representative producer does not care about the long term benefits of improving soil health.

At different values of the constant marginal cost and the carbon multiplier, the steady state values of a, c and λ shift. The comparative

Table 6.4: The current value shadow price of soil carbon stock with different initial levels of soil carbon stock.

Time	**c0 = 27.72**	**c0 = 14**
1	10.008	1065.07
2	-22.3004	938.039
3	-51.6605	822.447
4	-78.3203	717.251
5	-102.507	621.505
6	-124.426	534.35
7	-144.266	455.007
8	-162.198	382.769
9	-178.381	316.996
10	-192.959	257.107
11	-206.068	202.575
12	-217.827	152.925
13	-228.358	107.725
14	-237.762	66.5848
15	-246.14	29.1505
16	-253.586	-4.8982
17	-260.183	-35.8482
18	-266.017	-63.9652
19	-271.162	-89.4861
20	-275.677	-112.63
21	-279.638	-133.591
22	-283.103	-152.553
23	-286.126	-169.68
24	-288.76	-185.125
25	-291.041	-199.026
26	-293.02	-211.513
27	-294.738	-222.706
28	-296.211	-232.718
29	-297.488	-241.649
30	-298.581	-249.596
31	-299.532	-256.653
32	-300.334	-262.897
33	-301.04	-268.408
34	-301.624	-273.262
35	-302.139	-277.523
36	-302.576	-281.258
37	-302.947	-284.513
38	-303.27	-287.355
39	-303.541	-289.827
40	-303.785	-291.97
41	-303.977	-293.822
42	-304.144	-295.426
43	-304.293	-296.811
44	-304.415	-298.006
45	-304.516	-299.032
46	-304.605	-299.911
47	-304.697	-300.669
48	-304.759	-301.316
49	-304.813	-301.866
50	-304.868	-302.352

Table 6.5: The marginal productivity (MP) of soil carbon stock with different initial levels of soil carbon stock

Time	**c0 = 27.72**	**c0 = 14**
0	0.00352153	0.370206
1	-0.00770763	0.32606
2	-0.0179116	0.28589
3	-0.027177	0.249334
4	-0.0355825	0.216064
5	-0.0431998	0.185781
6	-0.0500942	0.158214
7	-0.0563258	0.133119
8	-0.0619493	0.110272
9	-0.0670153	0.0894722
10	-0.0715704	0.0705366
11	-0.0756579	0.0532996
12	-0.0793179	0.0376118
13	-0.0825875	0.0233373
14	-0.0855017	0.0103534
15	-0.0880929	-0.00145095
16	-0.0903915	-0.0121769
17	-0.0924259	-0.0219158
18	-0.0942228	-0.0307511
19	-0.095807	-0.0387586
20	-0.0972018	-0.046008
21	-0.0984289	-0.0525628
22	-0.0995088	-0.0584818
23	-0.10046	-0.0638191
24	-0.101301	-0.0686254
25	-0.102048	-0.0729477
26	-0.102717	-0.0768304
27	-0.103322	-0.0803152
28	-0.103879	-0.0834422
29	-0.104401	-0.0862493
30	-0.104901	-0.0887735
31	-0.105395	-0.0910503
32	-0.105895	-0.0931146
33	-0.106418	-0.0950011
34	-0.106977	-0.0967432
35	-0.107589	-0.0983747
36	-0.108271	-0.0999285
37	-0.109039	-0.101438
38	-0.109911	-0.102933
39	-0.110902	-0.104447
40	-0.112027	-0.106006
41	-0.113298	-0.107636
42	-0.114723	-0.109357
43	-0.116304	-0.111186
44	-0.118037	-0.113129
45	-0.119913	-0.115188
46	-0.121914	-0.117356
47	-0.124016	-0.119617
48	-0.126192	-0.12195
49	-0.128411	-0.124329

Table 6.6: The discounted net returns from a hectare of land at different initial soil carbon levels.

Time	**c0 = 27.72**	**c0 = 14**
0	633.58	-320.934
1	605.984	-107.08
2	578.257	49.5885
3	550.814	162.462
4	523.929	241.934
5	497.77	296.06
6	472.426	331.071
7	447.937	351.774
8	424.307	361.87
9	401.526	364.197
10	379.576	360.921
11	358.442	353.692
12	338.116	343.752
13	318.6	332.033
14	299.907	319.225
15	282.054	305.834
16	265.062	292.218
17	248.95	278.631
18	233.734	265.24
19	219.417	252.154
20	205.996	239.436
21	193.454	227.117
22	181.764	215.207
23	170.892	203.709
24	160.793	192.615
25	151.42	181.922
26	142.722	171.627
27	134.649	161.734
28	127.15	152.249
29	120.176	143.184
30	113.681	134.551
31	107.624	126.361
32	101.966	118.625
33	96.6713	111.347
34	91.7088	104.525
35	87.05	98.1529
36	82.6694	92.2178
37	78.5439	86.7018
38	74.6529	81.5826
39	70.9776	76.8351
40	67.5007	72.4323
41	64.2065	68.3462
42	61.0805	64.549
43	58.1096	61.0137
44	55.2818	57.7146
45	52.5863	54.6282
46	50.0141	51.733
47	47.5572	49.0101
48	45.2094	46.4435
49	42.9656	44.0193

static results were calculated at w = 30 and k = 1, which are shown in table 6.7.

Table 6.7: Comparative static results values for optimal control model

Comparative static	**Result**
$\partial \bar{a}/\partial p$	0.00525247
$\partial \bar{c}/\partial p$	0.00268866
$\partial \bar{\lambda}/\partial p$	-1.22424
$\partial \bar{a}/\partial w$	-0.0676097
$\partial \bar{c}/\partial w$	-0.0346084
$\partial \bar{\lambda}/\partial w$	6.69638
$\partial \bar{a}/\partial k$	-2.30005
$\partial \bar{c}/\partial w$	-0.122047
$\partial \bar{\lambda}/\partial w$	140.837

Table 6.7 follows the same trends as what happened with the steady state results. At the steady state equilibrium, a decrease in the constant marginal cost leads to an increase in the steady state value of estimated carbon input, whereas an increase in the carbon scalar leads to a decrease in estimated carbon input. The magnitude for a change in k is greater than a change in w, highlighting that the efficiency of a practice may have more of an impact than the costs of a practice at the margin.

Our representative producer will be a price taker and make decisions based on market output prices. There is a positive relationship between wheat output price and both soil carbon stock and carbon input. These results follow for a typical profit maximizing producer in our example. If prices rise, a producer may be able to increase revenue and will increase estimated carbon input as it is productive towards crop production.

6.5.1 What about a change in p?

$$\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial\bar{a}}{\partial p} \\ \frac{\partial\bar{c}}{\partial p} \\ \frac{\partial\bar{\lambda}}{\partial p} \end{bmatrix} = \begin{bmatrix} -(\gamma_a+2\gamma_{aa}\bar{a}+\gamma_{ac}\bar{a}) \\ -(\gamma_c+2\gamma_{cc}\bar{c}+\gamma_{ac}\bar{c}) \\ 0 \end{bmatrix}$$

$$\frac{\partial\bar{a}}{\partial p} = \frac{\begin{bmatrix} -(\gamma_a+2\gamma_{aa}\bar{a}+\gamma_{ac}\bar{a}) & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ -(\gamma_c+2\gamma_{cc}\bar{c}+\gamma_{ac}\bar{c}) & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ 0 & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial\bar{c}}{\partial p} = \frac{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & -(\gamma_a+2\gamma_{aa}\bar{a}+\gamma_{ac}\bar{a}) & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & -(\gamma_c+2\gamma_{cc}\bar{c}+\gamma_{ac}\bar{c}) & \rho(\beta_c-\delta) \\ 0 & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial\bar{\lambda}}{\partial p} = \frac{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & -(\gamma_a+2\gamma_{aa}\bar{a}+\gamma_{ac}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & -(\gamma_c+2\gamma_{cc}\bar{c}+\gamma_{ac}\bar{c}) \\ 0 & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

6.5.2 What about a change in w?

$$\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c - \delta) \\ k\beta_a + 2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial \bar{a}}{\partial w} \\ \frac{\partial \bar{c}}{\partial w} \\ \frac{\partial \bar{\lambda}}{\partial w} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\frac{\partial \bar{a}}{\partial w} = \frac{\begin{bmatrix} 1 & p\gamma_{ac} & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ 0 & 2p\gamma_{cc} & \rho(\beta_c - \delta) \\ 0 & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c - \delta) \\ k\beta_a + 2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial \bar{c}}{\partial w} = \frac{\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & 1 & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 0 & \rho(\beta_c - \delta) \\ k\beta_a + 2\beta_{aa}\bar{a} & 0 & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c - \delta) \\ k\beta_a + 2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial \bar{\lambda}}{\partial w} = \frac{\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & 1 \\ p\gamma_{ac} & 2p\gamma_{cc} & 0 \\ k\beta_a + 2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa} + 2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a + 2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c - \delta) \\ k\beta_a + 2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

6.5.3 What about a change in k?

$$\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix} \begin{bmatrix} \frac{\partial\bar{a}}{\partial k} \\ \frac{\partial\bar{c}}{\partial k} \\ \frac{\partial\bar{\lambda}}{\partial k} \end{bmatrix} = \begin{bmatrix} -\rho\bar{\lambda}\beta_a \\ 0 \\ -\beta_a\bar{a} \end{bmatrix}$$

$$\frac{\partial\bar{a}}{\partial k} = \frac{\begin{bmatrix} -\rho\bar{\lambda}\beta_a & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ 0 & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ -\beta_a\bar{a} & \beta_c & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial\bar{c}}{\partial k} = \frac{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & -\rho\bar{\lambda}\beta_a & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 0 & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & -\beta_a\bar{a} & 0 \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

$$\frac{\partial\bar{\lambda}}{\partial k} = \frac{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & -\rho\bar{\lambda}\beta_a \\ p\gamma_{ac} & 2p\gamma_{cc} & 0 \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & -\beta_a\bar{a} \end{bmatrix}}{\begin{bmatrix} 2p\gamma_{aa}+2\rho\bar{\lambda}\beta_{aa} & p\gamma_{ac} & \rho(k\beta_a+2\beta_{aa}\bar{a}) \\ p\gamma_{ac} & 2p\gamma_{cc} & \rho(\beta_c-\delta) \\ k\beta_a+2\beta_{aa}\bar{a} & \beta_c & 0 \end{bmatrix}}$$

6.6 Sensitivity analysis

6.6.1 Steady states

The steady state values were initially evaluated at $w = 30$ and $k = 1$, and all parameters in table 4.1. We analyzed the steady-state values for different values of constant marginal cost, carbon scalar, wheat output price, and the discount rate. The results can be found in tables 6.8, 6.9, 6.10, and 6.11.

6.6.2 Hard red spring wheat yield and discounted profit

In our example, the representative producer is maximizing the net present value of annual net returns from a hectare of land. The trends for hard red spring wheat yield and discounted returns under different values of constant marginal cost, the carbon sequestration scalar and the addition of a carbon payment can be found in figures 6.3 and 6.4. Only one parameter was changed at a time. When w changes, $k = 1$ and $s = 0$. When k changes, $w = 30$ and $s = 0$. When s changes, $w = 30$ and $k = 1$.

Table 6.8: Steady state values for changes in the constant marginal cost.

Constant marginal cost (w)	**Endogenous variables**		
10	$a \to 11.3744$ $c \to 28.64$ $\lambda \to -220.126$		
20	$a \to 6.74191$ $c \to 35.5821$ $\lambda \to -528.83$	$a \to 2.10323$ $c \to 36.9891$ $\lambda \to -381.03$	$a \to 10.3927$ $c \to 30.5732$ $\lambda \to -323.623$
30	$a \to 1.26086$ $c \to 36.6494$ $\lambda \to -305.139$		
40	$a \to 0.673507$ $c \to 36.3043$ $\lambda \to -243.3$		
50	$a \to 0.204259$ $c \to 35.9646$ $\lambda \to -188.628$		
60	-		
70	-		
80	-		
90	-		
100	-		

Table 6.9: Steady state values for changes in the carbon sequestration scalar.

Carbon scalar (k)	Endogenous variables		
1.0	$a \to 1.26086$		
	$c \to 36.6494$		
	$\lambda \to -305.139$		
1.2	$a \to 0.898172$		
	$c \to 36.5971$		
	$\lambda \to -280.21$		
1.4	$a \to 0.659561$		
	$c \to 36.5158$		
	$\lambda \to -259.94$		
1.6	$a \to 0.490238$		
	$c \to 36.4246$		
	$\lambda \to -242.793$		
1.8	$a \to 0.364582$		
	$c \to 36.3312$		
	$\lambda \to -227.951$		
2.0	$a \to 14.0185$	$a \to 14.6893$	$a \to 0.268493$
	$c \to 33.9306$	$c \to 32.5708$	$c \to 36.2392$
	$\lambda \to -806.468$	$\lambda \to -732.549$	$\lambda \to -214.908$

Table 6.10: Steady state values for changes in the discount rate.

Discount rate (δ)	**Endogenous variables**
0.05	$a \rightarrow 1.26086$ $c \rightarrow 36.6494$ $\lambda \rightarrow -305.139$
0.10	$a \rightarrow 1.50144$ $c \rightarrow 36.7651$ $\lambda \rightarrow -242.356$
0.15	$a \rightarrow 1.63884$ $c \rightarrow 36.8245$ $\lambda \rightarrow -199.488$
0.20	$a \rightarrow 1.72562$ $c \rightarrow 36.8595$ $\lambda \rightarrow -168.988$
0.25	$a \rightarrow 1.7848$ $c \rightarrow 36.8822$ $\lambda \rightarrow -146.369$

This is where you can provide additional information about the data, including whatever notes are needed.

Table 6.11: Steady state values for changes in the wheat output price.

Wheat output price (p)	**Endogenous variables**		
200	–		
250	$a \rightarrow 0.366078$		
	$c \rightarrow 36.0882$		
	$\lambda \rightarrow -134.666$		
300	$a \rightarrow 0.74617$		
	$c \rightarrow 36.3518$		
	$\lambda \rightarrow -195.267$		
350	$a \rightarrow 1.0613$		
	$c \rightarrow 36.5421$		
	$\lambda \rightarrow -258.268$		
400	$a \rightarrow 1.3323$		
	$c \rightarrow 36.6853$		
	$\lambda \rightarrow -323.348$		
450	$a \rightarrow 1.57213$		
	$c \rightarrow 36.7962$		
	$\lambda \rightarrow -390.312$		
500	$a \rightarrow 7.61475$	$a \rightarrow 9.83356$	$a \rightarrow 0.268493$
	$c \rightarrow 34.6972$	$c \rightarrow 31.5632$	$c \rightarrow 36.2392$
	$\lambda \rightarrow -654.561$	$\lambda \rightarrow -483.504$	$\lambda \rightarrow -214.908$

This is where you can provide additional information about the data, including whatever notes are needed.

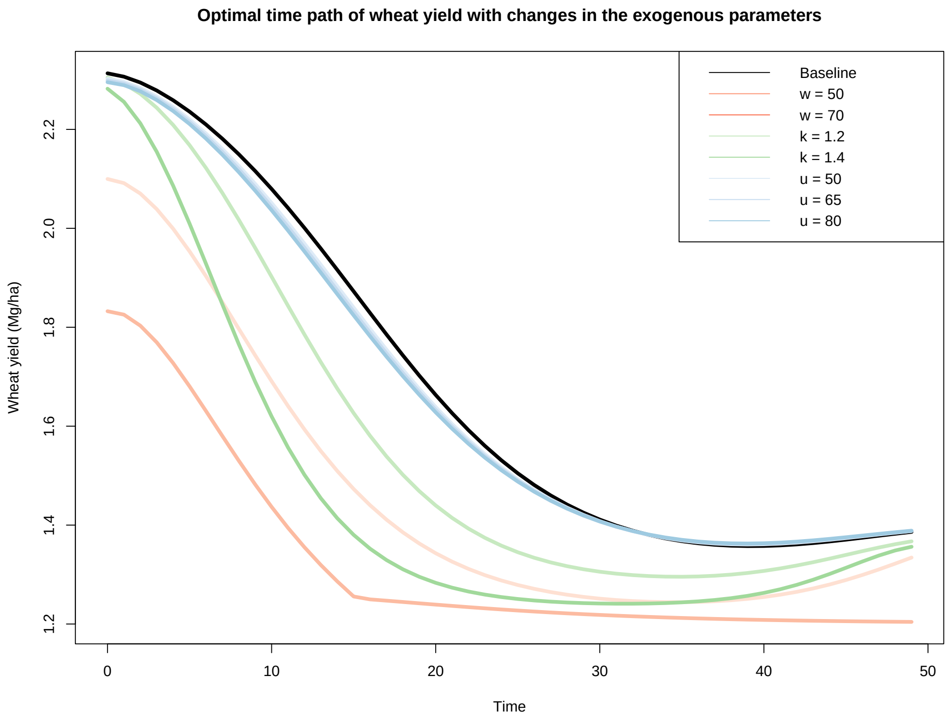

Figure 6.3: Hard red spring wheat (Mg/ha) under different values of the constant marginal cost, carbon sequestration scalar, and the addition of a carbon payment.

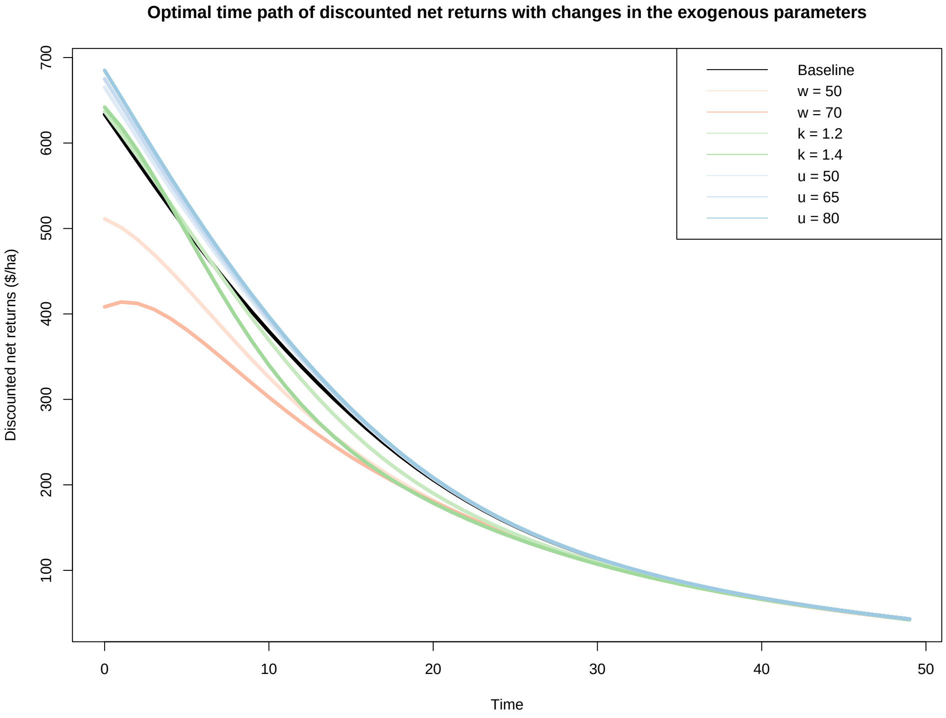

Figure 6.4: Discounted net returns ($/ha) under different values of the constant marginal cost, carbon sequestration scalar, and the addition of a carbon payment.

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