CAPI
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TRANSLATING SCIENCE TO POLICY:

Approaches to increase soil carbon sequestration in Canada's croplands

Research Report prepared for CAPI by 2020-2022 CAPI Doctoral Fellows Lisa Ashton, Hannah Lieberman, Callum Morrison, and Dr. Marie-Élise Samson

Research Report

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This report is sponsored in part by the RBC Foundation and part of CAPI's larger environmental initiative, **Spearheading Solutions: Helping Farmers Operate Better, Smarter and Environmentally Sustainably**. This initiative aims to leverage public and private policies to aid in the rapid adoption of beneficial management practices, increase the implementation of new tools and technologies to maximize environmental and social outcomes.

To ensure the validity and quality of its work, CAPI requires all Research Reports to go through a peer review process. An Advisory Group, chaired by CAPI Research Director Dr. Al Mussell, was formed to provide input on the development, outline, and earlier drafts of this report. CAPI thanks the Advisory Group members who provided expertise and guidance to the Doctoral Fellows throughout the final year of their fellowship: Dr. Andréanne Léger, Dr. Alexandre Lillo, Dr. Lori Phillips, Dr. Grace Skogstad, Nevin Rosaasen, and Dr. Susan Wood-Bohm. The views and opinions expressed in this paper are solely those of the authors and do not necessarily reflect those of CAPI.

A Note from CAPI

In May 2021, CAPI outlined four key actions for the future sustainability and prosperity of the Canadian agri-food system: systems approaches, strategic thinking, public-private partnerships and aspirational leadership. CAPI believes that to ensure the world has sustainable and continual access to food, we must look ahead. Today's young leaders, as well as future generations, play a critical role in helping Canada's agri-food system realize its great potential.

One way that CAPI does this is through the Doctoral Fellowship Program. The CAPI Doctoral Fellows are young scholars from across Canada and across disciplines tackling some of agriculture's most critical issues. Our current cohort (2020-2022) are investigating the issue of soil health in agricultural soils.

What follows is the final report of our second cohort, a group focused on developing scientific research and data into policy surrounding climate change mitigation and the role carbon sequestration can play in Canada's croplands. This multidisciplinary research in the field of sustainability and resilience in agricultural soils contributes to some of the critical conversations CAPI is having regarding the sustainable prosperity of Canadian agriculture.

Key Takeaways

- Canadian cropland represents an opportunity for climate change mitigation through its carbon-sequestration potential. To realize this potential, strategies should reflect local context and agri-environmental conditions.
- Policies and programs can help address barriers to BMP adoption by including producers in decision making processes, providing evidence of return on investment, and ensuring access to affordable and effective measuring and monitoring tools.
- Extension related to soil carbon sequestration should provide greater clarity to producers on the state of knowledge and the opportunities and challenges in BMP adoption by utilizing science and data from multiple disciplines.

Executive Summary

OVERVIEW

The Canadian agriculture sector can be a source for solutions to climate change. One climate change mitigation strategy available for Canadian producers is soil carbon sequestration: the process of capturing atmospheric carbon and storing it long term in the soil. Canadian cropland represents a significant portion of Canadian agricultural land, with potential to sequester carbon through the adoption of beneficial management practices (BMPs). To achieve this potential, it is critical that policies and programs enable and encourage producers to adopt BMPs. In this report, we present research to help inform policies and programs that intend to enhance carbon sequestration in croplands by:

a. Explaining how and why adopting BMPs can increase soil organic carbon in croplands

b. Presenting key barriers to, and enabling conditions for scaled adoption of BMPs

c. Highlighting the latest research and existing projects that demonstrate how to improve upon the science and policy interface for soil carbon sequestration in cropland

KEY FINDINGS

Regional variation demonstrates that Canadian cropland soils do not have a homogenous history, the same potential in carbon storage, or exist within the same agri-environmental conidtions. This suggests that strategies to enhance carbon sequestration across Canada should differ to meet local needs. Below are the key findings from the four streams of research conducted to produce this report.

Foundations: Understanding soil organic carbon

Soil carbon sequestration is the process of capturing carbon dioxide from the atmosphere and storing it in the soil. The environmental drivers and agricultural practices that encourage carbon sequestration vary depending on climatic conditions and soil properties. In particular, organic matter inputs to the soil and the subsequent processing are key to understanding how to increase carbon sequestration in croplands.

Interventions: Adopting practices to increase soil organic carbon levels

There are three levers (or mechanisms) to increase soil carbon sequestration. The 1st lever is to increase the photosynthesis rate per unit of soil area both in space and time by adopting practices including cover crops and diversified crop rotations. The 2nd lever is to maximize the amount of biomass returned to soil by integrating manure and leaving crop residue on fields. The 3rd lever is to reduce soil carbon emissions outputs through organic matter mineralization by adopting practices such as reduced tillage.

Contextual factors: What's Influencing adoption

Barriers to adoption include risk and uncertainty associated with introducing new practices, high upfront costs, and environmental constraints. Enabling conditions include producer engagement in policy design, evidence of return on investment, policy and regulatory certainty, and access to affordable and effective measuring and monitoring tools and technologies.

Science and Policy: Strengthening the interface

Approaches to strengthening the science and policy interface for enhancing soil carbon sequestration should include greater integration and utilization of science and data from multiple disciplines, co-design and collaborative opportunities, and the establishment of on-the-ground test projects (e.g., pilots testing policy and market ideas).

RECOMMENDATIONS

To elevate policy's role in increasing carbon sequestration in Canadian cropland, a science-based, systems approach to policy design should be considered. In the short-term, this approach should lead to more collaborative opportunities for testing innovations in policy and market design that utilize the current understanding of which BMPs enhance carbon sequestration and the barriers and enabling conditions for adoption. In the long-term, this approach can be strengthened by investing in research and infrastructure that furthers our understanding of how to increase and measure carbon storage across pedo-climatic conditions.

WORKING AS A CAPI TEAM

As CAPI Doctoral Fellows we each specialize in different aspects of climate change mitigation in Canadian agriculture. By working as a multidisciplinary team, we were able to draw upon each other's knowledge to strengthen our own understanding of determining, designing and implementing policies to enhance carbon sequestration in Canadian cropland. We found that working as a multidisciplinary team was essential to capture the complexities of this topic.

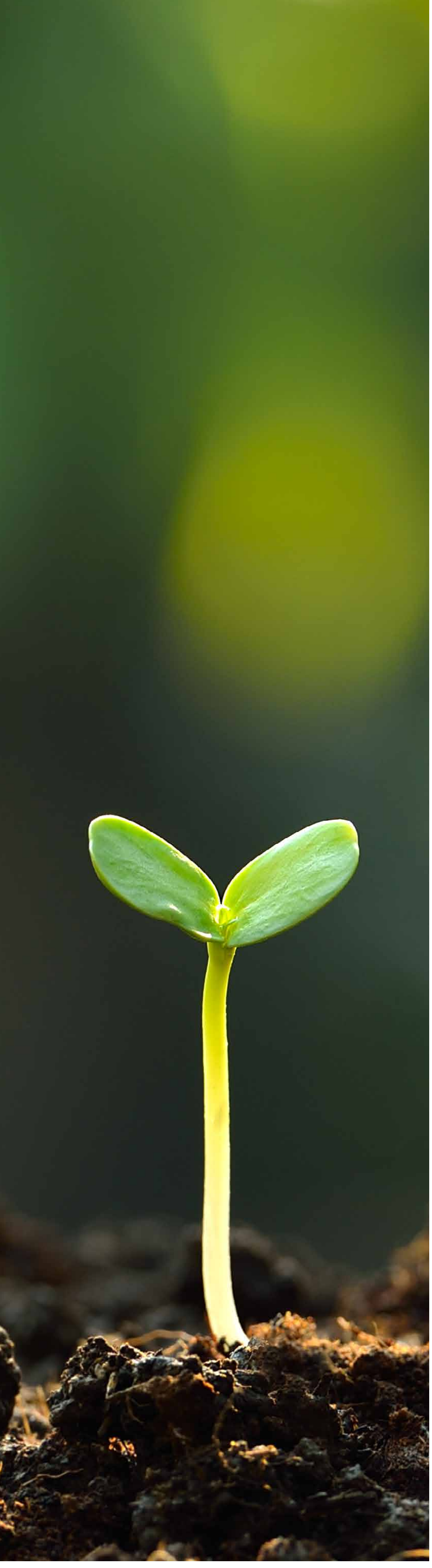
Table of Contents

CONTENTS

1. Introduction

Canada's agriculture sector plays a vital role in our day-to-day lives. Ranchers, farmers, and growers, which we collectively refer to as producers herein, produce the food we eat, fuel for our transportation (e.g., biofuels from corn, canola and sugar beet), the raw materials in the products we use, and more. Increasingly, Canada's agriculture sector is also looked at for its role in provisioning ecosystem services that can improve biodiversity, water quality and climate resilience (Drever et al., 2021). With the threat of climate change, there is an increasing need to determine, define and implement policies and programs that enhance carbon sequestration - the process of capturing atmospheric carbon into a stable carbon pool (Paustian et al., 2016). Soil is the largest terrestrial organic carbon pool, containing approximately three times the amount of carbon compared to the atmosphere, and as such can play a critical role in climate change mitigation (Paustian et al., 2016). Agricultural land presents a unique opportunity to identify and encourage beneficial management practices (BMP) that enhance carbon sequestration and produce co-benefits such as improved soil health, drought resilience, and water quality. Adopting Statistics Canada's definition, cropland herein, includes all agricultural land under crops, including annual and perennial crops, comprising of 93.4 million acres representing about 59% of total agricultural land in Canada in 2016 (Statistics Canada, 2017). Applying the '4 per mille' approach, a global blanket calculation, to Canada's croplands it is estimated that soil organic carbon stocks can increase by 0.4 percent per year (Minasny et al., 2017). This potential is not even across all lands, as soils with low soil organic carbon levels have more room to sequester carbon compared to those that are close to reaching an equilibrium (Martin et al., 2021). Nonetheless, given both the large area cropland occupies and its potential to sequester carbon, Canadian cropland provides an opportunity to provision climate change mitigation and complementary ecosystem services by adopting BMPs. The success of increasing the stable soil carbon pool in Canadian cropland is dependent on producers, researchers, policy makers and other partners working in tandem. This will help ensure that the practices adopted and the policies, programs and markets encouraging them are based on the best available science, economically viable and applicable on farms.

Canadian producers are increasingly asked to act as solution providers to climate change. To ensure that producers are well equipped to meet this societal demand, policy has a role to play in better positioning them to adopt BMPs that are practical and effective within the environmental, economic, and social context that they operate within. The BMPs that have shown to increase carbon sequestration in some regions of Canada cropland, include cover cropping, multispecies crop rotations, converting from annual to perennial crop production, reducing summer fallow and conservation tillage (Janzen et al., 1998; Bruce et al., 1999; McConkey et al., 2003; Vanden Bygaart et al., 2003; Campbell et al., 2005). Producers across Canada face different challenges and require different supports and incentives when making farm management decisions to adopt these BMPs. Therefore, policy not only needs to consider the environmental conditions, but also producers' socio-economic limitations in BMP adoption, as practices that are best for increasing carbon stocks are not necessarily feasible from an economic or farming perspective and vice versa. In addition, science is an evolving field and as such our understanding of how best to sequester carbon under different and changing climatic conditions may change.



Considering these multiple factors, enhancing carbon sequestration in Canadian croplands is an inherently multidisciplinary issue and as such requires a multidisciplinary approach. To develop policies that reach both the goal of increasing carbon stocks while being attractive and obtainable to producers, we need to consider research from soil science, economics, agronomy among others.

This report aims to provide a review of literature that contextualizes BMPs that can enhance soil carbon sequestration in croplands as well as challenges and opportunities producers face in adopting them. This report also presents best practices in translating science into policy that can be utilized in Canada, as policies and programs continue to better position agricultural producers to contribute to climate change mitigation.

To address these objectives, we first outline high-level background knowledge on carbon sequestration and where it sits within the soil health framework and the Canadian cropland context. Next, we outline the disciplines covered in our literature review. This is followed by the results where we shared what we have learned under four main streams of research: (1) foundations: understanding soil organic carbon; (2) interventions: adopting practices to increase soil organic carbon levels; (3) contextual factors: influences on adoption; (4) science and policy: strengthening the interface. These four streams of research allow for a comprehensive understanding of not only the best practices for carbon sequestration in Canadian cropland but also how to improve how this understanding is translated into policy approaches.

2. Background

2.1. SOIL HEALTH AND CARBON SEQUESTRATION

Soils across Canada inherently contain different properties and experience varying environmental conditions that impact its function. Producers, agronomists, and researchers can evaluate the state and quality of a given soil by looking at its 'soil health'. Soil health is a framework that enables us to view the complexity of soils and their role in building sustainable agriculture systems. Janzen et al. (2022) define soil health, "as the vitality of a soil in sustaining the socio-ecological functions of its enfolding land". The conditions and function of the ecosystem and the needs of the producer must be known to accurately assess the health of the soil. Janzen et al. (2022) describe how this can vary as, "a soil deemed healthy for growing grapes may not be ideal for promoting songbird habitat; soil properties favorable for sequestering atmospheric carbon dioxide may not produce good strawberries". Hence, practices that increase soil carbon sequestration are not necessarily good for all agricultural production goals or other environmental considerations (see Renwick et al. (2018) for an example of trade-offs between environmental goals). While soil health and carbon sequestration are not equivalent, soil health is critical to consider when determining practices to increase carbon sequestration. Increasingly, research evaluating cropland soil functions is done under a soil health framework and using it to evaluate carbon sequestration can be an effective approach to understand the broader environmental consequences of interventions focused on carbon sequestration.

2.2. CANADIAN CONTEXT: TRENDS, PRACTICES AND THEIR IMPLICATIONS

In the 1930s, producers of the Canadian Prairies experienced first-hand the disastrous consequences of soil degradation during the dust bowl. This event contributed to raising general awareness on the importance of soil health and created, during the following decades, a movement towards the development and adoption of BMPs in Canada. Today, carbon sequestration as an objective in BMP adoption, has come to the forefront of the conversation of agriculture's role in contributing to climate change mitigation. In Canada, according to the *National inventory report: Greenhouse gas sources and sinks in Canada*, national net carbon removals from croplands peaked between 2006 and 2011 at approximately 12 megatonnes of carbon dioxide equivalent (Mt CO2e). Since this peak in 2011, national carbon removals via croplands have steadily declined to 4.2 megatonnes of carbon dioxide equivalent (ECCC, 2021a). In the Prairie provinces (Alberta, Saskatchewan, and Manitoba), the adoption of BMPs including conservation tillage and reductions in summer fallow (i.e., leaving fields bare) were the main drivers behind the trend of relatively high carbon removals in croplands (Clearwater et al., 2016). However, since 2011, the decline in carbon removals is thought to be the result of an increasing trend of converting agricultural land from perennial to annual crops and diminishing returns on carbon storage levels from the boom in adoption of conservation tillage across the Prairies between the 1980s and 1990s (ECCC, 2021a; Paustian et al., 2019).

In other regions of Canada, particularly Eastern provinces (Ontario and eastward), Clearwater et al. (2016) found that soil organic carbon levels have experienced an overall decrease due to shifts in management practices and crop type, which is in part driven by a reduced demand for pastures and forage production for the livestock sector. In a 2018 report, The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) suggests that 82 percent of Ontario's agricultural soils are estimated to be a carbon source, and therefore a net emitter of carbon dioxide to the atmosphere. Researchers and practitioners find that drivers for the changes in practice and production systems are wide-ranging and inclusive of market demands, perverse policies, societal pressures, and the cost and time associated with different land management practices (Lark et al., 2021; WWF, 2021). To enhance soil carbon sequestration, the OMAFRA report identifies the adoption of BMPs such as crop rotations, cover crops, and no-tillage (depending on the soil type) as potential pathways to improve the quality and storage of carbon in soils.

Based on current methodologies and analysis used to inform the National Inventory Report, it appears that in general Canada's croplands are a carbon sink, but have recently trended negatively in annual carbon removals (ECCC, 2021a). The regional variation demonstrates that Canadian cropland soils do not have a homogenous history, the same potential in carbon storage, or exist within the same agri-environmental conditions, suggesting that strategies to enhance carbon sequestration across Canada should differ and meet local needs. Lastly, research demonstrates that croplands and their role in contributing to climate action targets are projected based on multiple factors, including the rate and type of BMP adoption by producers (ECCC, 2021b). Therefore, promoting the adoption of BMPs can be an impactful approach to improve carbon sequestration in agriculture (see ECCC, 2021b).

3. Methods

An extensive literature review covering multiple disciplines was conducted to produce this report. We drew from research areas including agri-environmental management, soil science, environmental governance, and science-based policy to build a comprehensive view of the factors that influence carbon sequestration in croplands. We also utilized results from our respective doctoral research projects to complement findings from literature.

This project draws on literature under four main research streams:

a. Foundations: Understanding soil organic carbon

The literature reviewed under this stream covered the foundational knowledge of soil organic carbon and the levers that can be used to enhance carbon sequestration. Attention was given to regional agri-environmental considerations that may influence carbon cycling, including soil variability, agronomic practices, climate, and extreme weather events.

b. Interventions: Adopting practices to increase soil organic carbon levels

Our team reviewed literature that presents and evaluates BMPs for cropland production systems that show promise in increasing carbon sequestration and complementary co-benefits. In many cases this literature is regionally specific and cannot be easily generalized across Canada.

c. Contextual factors: Influences on adoption

The socio-economic and policy barriers and enabling conditions that influence BMP adoption were examined in the literature covered under this research stream.

d. Science and policy: Strengthening the interface

This stream of research focused on compiling principles and best practices in improving the utilization and integration of science in policy design, while also elevating knowledge transfer among policy makers, producers, researchers, and other stakeholders.

4. Results

4.1. FOUNDATIONS: UNDERSTANDING SOIL ORGANIC CARBON

4.1.1. Soil and the global carbon cycle

The soil carbon budget is defined by the balance between carbon inputs and outputs to soil. When a natural land is first converted to arable land, a significant amount of soil organic carbon is lost to the atmosphere in the form of carbon dioxide. This loss is the outcome of arable soils containing a much lower density and diversity of plants, roots, and macro/microorganisms, both in space and time. Converting natural lands into arable soils therefore significantly reduces the annual organic carbon inputs to soil from plant growth and the resulting decomposition. Additionally, soil cultivation tends to accelerate native soil organic matter mineralization by soil microbes. This acceleration contributes to the transformation of soil organic carbon into carbon dioxide, which is released into the atmosphere, contributing to greenhouse gas emissions.

Since the advent of agriculture, it is estimated that land conversion to arable soils contributed approximately 320 billion tons of carbon to the atmosphere, whereas the use of fossil fuels from human activity released 292 billion tons of carbon to the atmosphere (Lal, 2010). Global agricultural soils therefore acted as a major carbon source to the atmosphere during the last millennia. In agriculture it is estimated that soils have lost between 20% and 70% of their initial organic content worldwide. Simultaneously, globally there has been a decline in productivity on roughly 20% of the world's arable land (FAO, 2017). Evans et al. (2020) recently estimated soil sustainability expressed as a lifespan showing that globally, about 16% of conventionally managed soils exhibit lifespans of < 100 years. The combination of reduced capacity for crop production and the increasing threat of climate change renders addressing soil carbon sequestration a pressing issue.

4.1.2. Organic Matter, Decomposition and Carbon Cycling

Carbon sequestration results from the process of decomposition where organic matter is broken down and the carbon originating from this organic matter stays in the soil instead of being lost to the system through microbial respiration (whereby microbes breathe in oxygen and release carbon dioxide), leaching or erosion. Organic matter refers to a large source of carbon-based compounds originating from living organisms, such as plants, animals and microbes, as well as their remains and organic by-products produced through their biological activity. Soil organic matter is therefore considered as a complex continuum of biochemically diverse, carbon-rich molecules, ranging from fresh and undecomposed plant residues and living macro-organisms, to earthworm feces and microbial tissues and enzymes. These diverse organic compounds all play a different role in agroecosystem functioning but are intrinsically connected. The process of organic matter decomposition lays at the crux of increasing carbon sequestration and identifying which BMPs can optimize outcomes.

When fresh organic compounds, such as plant residues, enter the soil, they act as an energy source for microorganisms (Alvarez et al., 1998). As microbes break down the new organic matter inputs and decomposition progresses, the carbon and nutrients contained in these plant residues are used by microbes. Some of the carbon is lost to the soil system as carbon dioxide via microbial respiration. Soluble plant compounds, microbial by-products and microbial necromass (dead biomass) have a strong affinity for mineral surfaces, contributing to organic matter stabilization in soil (Kallenbach et al., 2016). Organic matter also causes soil to clump and form soil aggregates, which improves soil structure and further stabilizes soil organic matter by limiting their accessibility to decomposers (Dungait et al., 2012). Soil aggregation further helps improve multiple agri-environmental conditions, including soil hydraulic conductivity, water retention capacity, aeration, resistance to compactions and erosion. The biochemistry of organic inputs, soil microbial community, soil conditions, and management practices all affect the amount of carbon that can be respired or stabilized in soil over the long-term through the formation of organic matter and soil mineral complexes and aggregates (Schmidt et al., 2011; Cotrufo et al., 2013).

Organic matter and it's processing therefore directly contributes to long term storage of carbon and nutrients. Further, soil organic matter content is considered as a key indicator of soil health due to its multiple roles in sustaining chemical, biological and physical soil quality. Understanding soil organic matter cycling processes is essential to implement strategies that maintain or enhance the multiple ecosystem services provided by soils including carbon sequestration (Palutikof, 2007).

4.1.3. Determining changes to carbon stocks

Soils are extremely complex ecosystems that still hold many mysteries. Soil morphology is shaped over millennia by parent materials, climate, topography and living organisms. They are dynamic ecosystems, that constantly evolve, shifting in response to environmental drivers, creating high variability in soils both in time and space. These differences influence soil's response to any given change in management practices. Producers experience first-hand this variability. They know which one of their soils is the best suited for wheat, corn, or soy, and what parts of their field warm up more slowly in the spring. Producers know which of their fields can be sown earlier and which field would suffer the most from a drought. This soil variability is one of the major challenges producers and soil scientists face in deter-

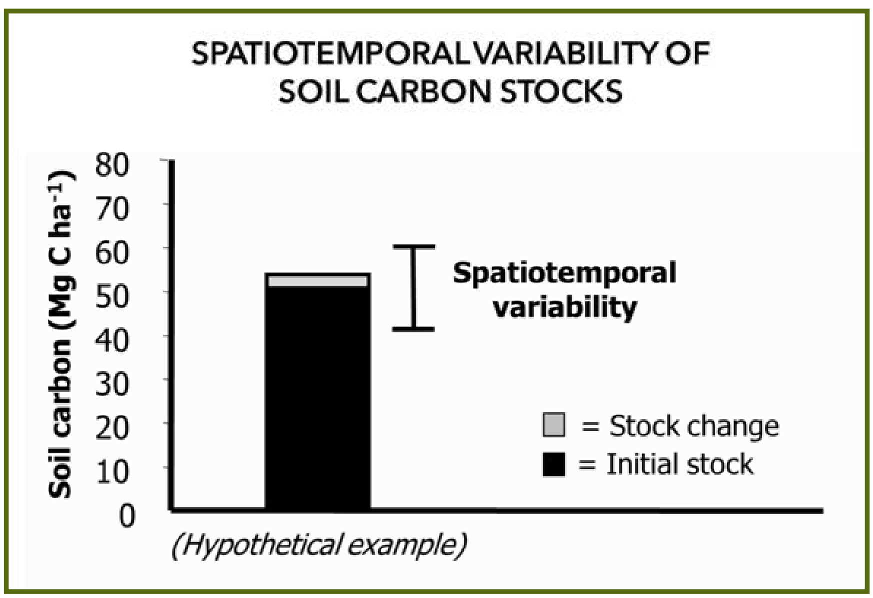


Figure 1. Challenges in measuring soil organic carbon stocks change due to large initial carbon stocks, small changes over time and high spatiotemporal variability (Source: Samson, M.E. and Angers, D.A.)

mining what BMPs would be best suited for each field. The effect of a given management practice on a specific soil cannot be generalized to all soils, nor to soils from the same country, or even to all fields from the same farm.

To accurately determine changes to carbon stocks, even within the same field, sampling intensity must account for this significant spatial-temporal variability. Further, it is incredibly difficult to detect changes in carbon stocks as changes in these stocks are at least 10 times smaller than the initial soil organic carbon content. The large background stocks, inherent spatial and temporal variability and relatively small and slow soil carbon content changes make the detection of short-term changes (e.g. 5 years) in soil organic carbon stocks very challenging.

SUBSOIL

An important consideration in soil health assessment is depth. During the last few decades, soil scientists have mostly focused on the topsoil layer, assuming that deeper soil carbon is stable and unresponsive to BMPs. This assumption was primarily based on radiocarbon dating studies, showing that carbon in the subsurface soil layers could be hundreds to thousands of years old (Hobley et al., 2017). Based on these assumptions, the Food and Agriculture Organization of the United Nations (FAO, 2020) and the Intergovernmental Panel on Climate change (IPCC, 2019) recommend sampling soil to a 30 cm depth, as a default standardized methodology for the monitoring, reporting and verification of changes in carbon stocks in agricultural soils. However, the root zone is estimated to be ~50–100 cm for wheat, maize, barley, and canola and to more than 100 cm for alfalfa (Fan et al., 2017). Further, subsoil (≥ 20 cm) contains up to 77% of total soil organic carbon making it a critical area of the soil for carbon sequestration. Recent studies show that subsoil carbon can actually be very responsive to BMPs under certain environmental conditions (Osanai et al., 2020; Samson et al., 2021). Since subsoil horizons account for more than half the global soil carbon stocks (Balesdent et al., 2018) and carbon dynamics are quite different in subsoil than topsoil (Rumpel and Kögel-Knabner, 2011), more research on the effect of management practices on subsoil will be needed before we can predict the effect of a specific BMP on total soil carbon stocks under different pedoclimatic conditions.

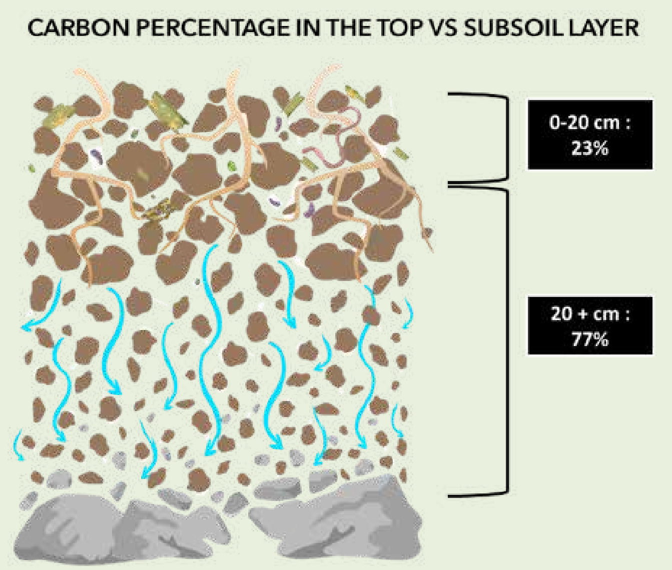


Figure 2. Distribution of soil organic carbon between the top and subsoil layers (Data source: Harrison et al., 2011)

4.2. INTERVENTIONS: ADOPTING PRACTICES TO INCREASE SOIL ORGANIC CARBON LEVELS

4.2.1. Three levers to enhance carbon sequestration in agricultural soils

Increasing organic matter inputs that are stabilized in the soil is key to increasing carbon sequestration. Here we present a three-lever approach to increasing soil organic matter. The primary carbon exchange between the atmosphere and the terrestrial ecosystem is the incorporation of carbon dioxide into plant biomass through photosynthesis. The primary lever (1st lever) to increase carbon stocks in agricultural soils is therefore to increase photosynthesis rate per unit of soil area both in space, and time. Strategies to increase soil carbon content through the 1st lever could include cover cropping, winter cereals and/or rotations that include perennial crops.

The second lever (2nd lever) to increase carbon stocks in agricultural soil is to maximize the amount of biomass returned to soil. Carbon-rich plants shoots, roots (and roots exudates) represent the primary organic inputs to soil. However, in an agricultural ecosystem, producers export and sell parts of this plant biomass (grain, shoots and/or roots).

For example, in some systems, producers harvest cereal straws for animal bedding. Broad acre producers, on the other hand, can return cereal straws to soil, which contributes to organic matter inputs to soil.

However, if a meat or dairy producer uses straw for bedding and grain to feed animals and returns manure (and straw) to the soil where these plants were produced, then both a part of the grain and the straw were returned to soil. This example shows how important it is to consider the whole system when assessing the impact of agricultural management practices on soil carbon sequestration.

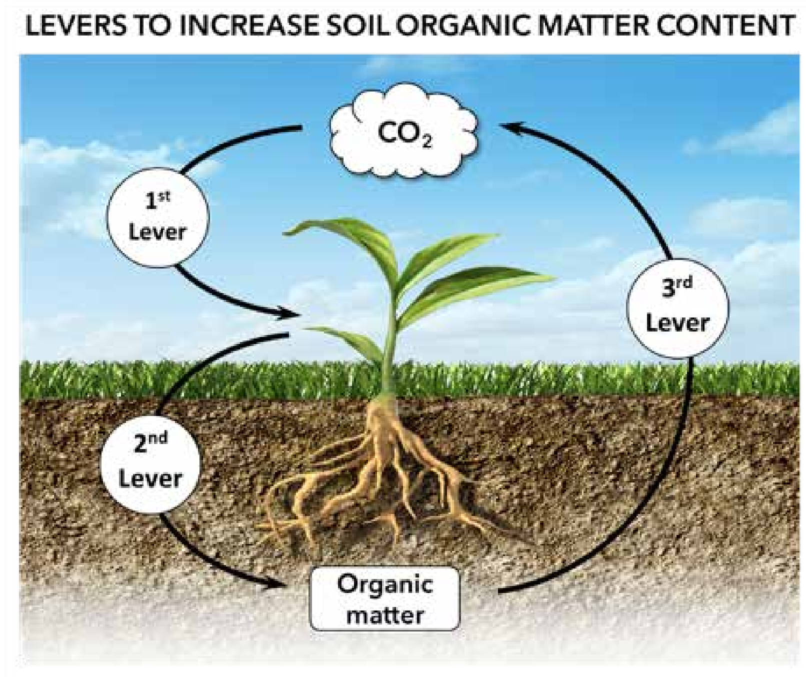


Figure 3: The three levers for carbon sequestration in soils (Source: Samson, M.E. and Angers, D. A.)

As mentioned previously, the soil carbon budget depends on the balance between organic carbon inputs and outputs. The third lever (3rd lever) is therefore to reduce soil carbon outputs through organic matter mineralization. When microbes feed on organic matter, a part of the carbon it contains is accumulated in the microbial biomass, staying in the soil and contributing to long-term carbon stabilization. However, a portion of the carbon is also respired by microorganisms and released into the atmosphere in the form of carbon dioxide. Beneficial management practices, such as tillage, can drastically affect soil organic matter dynamics by modifying its vertical distribution through the soil profile (Angers and Eriksen-Hamel, 2008). Tillage can cause aggregate disruption (Balesdent et al., 1990, 2000), enhance the contact of organic residues with soil microbes (Balesdent et al., 2000) and increase surface soil temperature and aeration status (Johnson and Lowery, 1985). These soil composition changes allow microbes greater access to previously protected soil carbon increasing mineralization rates and releasing carbon into the atmosphere.

Of these three levers, the one with the greatest potential to increase soil carbon stocks is the first lever, increasing the amount of photosynthesis per unit area of soil. For example, based on a large data set from international studies, Toensmeier et al. (2016) found that management practices such as the inclusion of perennial crops in the rotation have a much greater potential for carbon sequestration than no-till, for instance. Nonetheless, promotion of BMPs must take the regional constraints into consideration and explore how combinations of BMPS can collectively maximize carbon sequestration, other ecosystem services and production goals.

4.2.2. Beneficial management practices and soil organic carbon stocks across Canada

The BMPs that have increased carbon sequestration in some regions of Canadian cropland, include cover cropping, multispecies crop rotations, converting from annual to perennial crop production, reducing summer fallow and conservation tillage (Janzen et al., 1998; Bruce et al., 1999; McConkey et al., 2003; Vanden Bygaart et al., 2003; Campbell et al., 2005). Additionally, practices that increase crop yield can also aid in carbon storage, as carbon sequestration is influenced by plant carbon inputs (Fan et al., 2019). Research shows that the ability of BMPs to influence soil organic carbon levels in croplands also varies depending on factors including soil type, climate, and how the practice is implemented. For example, converting conventionally tilled cropland to reduced tillage does not always yield desired environmental results in Central and Eastern Canada (Angers et al., 1997). This outcome is due, in part, to the ability of different soils to build soil organic carbon following conversion to no till, where moister soils, such as those present in Eastern Canada, are less effective at than drier soils (VandenBygaart et al., 2003). Beneficial management practices also vary with regards to agronomy, as Vanden Bygaart et al. (2003) found that the crop type replacing fallow can have an impact on soil organic carbon storage, with wheat increasing storage and flax resulting in a net loss of soil organic carbon. Lastly, climate change can influence soil organic carbon as temperature and moisture impact carbon input and carbon decomposition (see Malhi et al., 2021). Understanding how the outcomes of BMPs on the soil are affected by flooding, drought and temperature changes is increasingly important as the effects of climate change results in greater frequency and intensity of extreme weather conditions.

BMPS AND THEIR EFFECT ON SOIL HEALTH PRINCIPLES

Connections between the main BMPs and the soil health principles

Selected BMPs	Soil health principles				
	Build soil organic matter	Minimize soil disturbance and soil compaction	Keep the soil covered as much as possible	Diversify crops to increase diversity in the soil	Keep living roots throughout the year as much as possible
Conservation tillage	•	•	•		
Cover crops	•		•	•	•
Organic amendments	•				
Nutrient management	•	•			
Diverse crop rotation	•			•	•
Conservation buffers	•	•	•	•	•
Prevention of soil compaction		•	•		
Integrated pest management		•		•	
Pasture management	•	•	•	•	•
Land retirement	•	•	•	•	•
Soil information collection	•*	•*	•*	•*	•*

* This practice indirectly impacts soild health principles

Source: Groupe AGÉCO.

Figure 4: Beneficial management practices and their effect on soil health principles (Source: The power of Soils, Équiterre and Greenbelt Foundation report, 2021; used with permission).

Agroecosystems are dynamic systems. Following a change in management practice, these systems evolve towards a new equilibrium. This equilibrium explains why Canada cannot solely rely on no till practices in the Canadian Prairies for carbon sequestration in the years to come. Producers massively adopted no till 30-40 years ago (Awada et al., 2014), when Prairie soils began to switch from a carbon source to a carbon sink (ECCC, 2021a). Now, these systems are starting to reach an equilibrium, meaning that sequestration rates are lower than they were in the first years after adoption of no-till and will keep declining in the years to come. For agricultural soils to keep acting as carbon sinks for the decades to come, other changes in management practices must occur. This could mean, for instance, integrating cover cropping to no till systems. This new major change in the system would cause a new disbalance and promote carbon sequestration in soil until a new equilibrium is reached. Of course, for this strategy to work, no till practices must also be maintained. Otherwise, these soils may start acting as a carbon source despite the adoption of cover cropping.

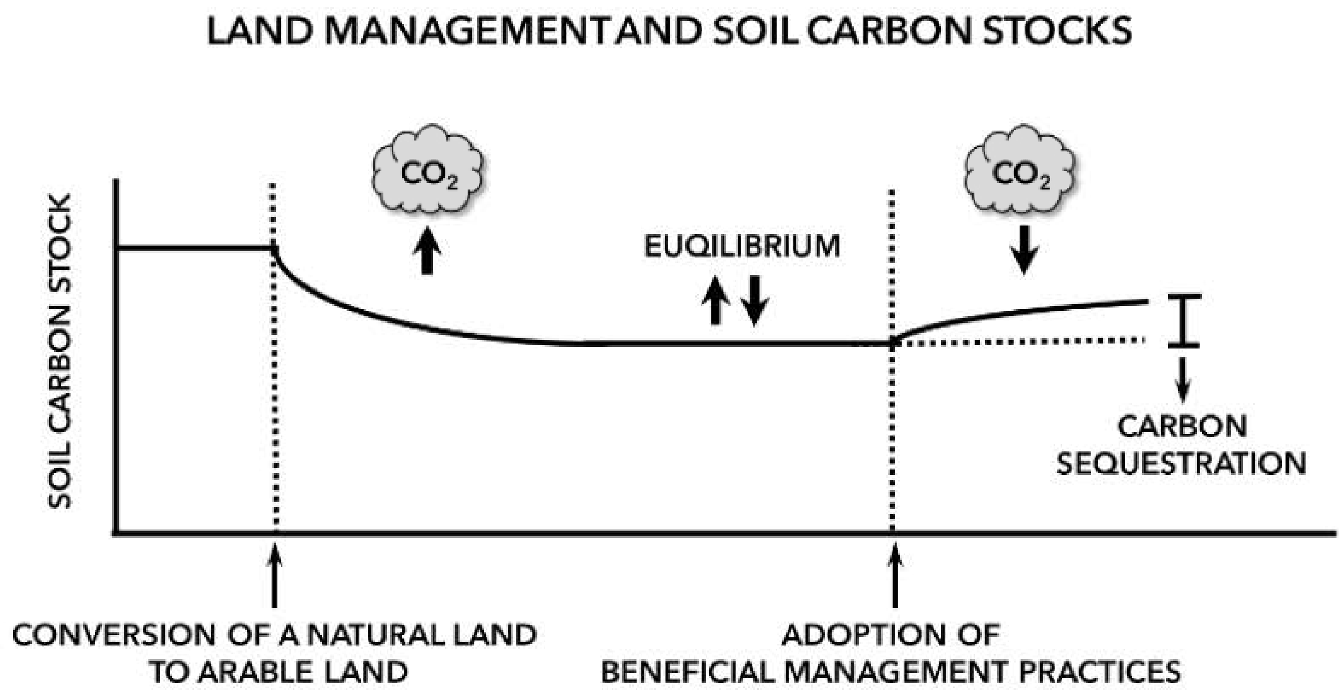


Figure 5. Carbon flux trends with land management (Source: Samson, M.E. and Angers, D.A.).

Another opportunity for the sector would be to focus on implementing BMPs in Eastern provinces. While the adoption of no till in the Prairies led to carbon sequestration in soil over the past decades, soil carbon stocks in Central and Atlantic Canada have, in general, steadily declined during the same period. Carbon loss in Eastern Canada is mainly attributed to conversion from perennial to annual crop production. Practices like non-diverse annual cropping systems, heavy tillage and a lack of carbon inputs from perennial crops, cover crops or crop residue to soils further intensify the reduction in organic carbon stocks in these soils.

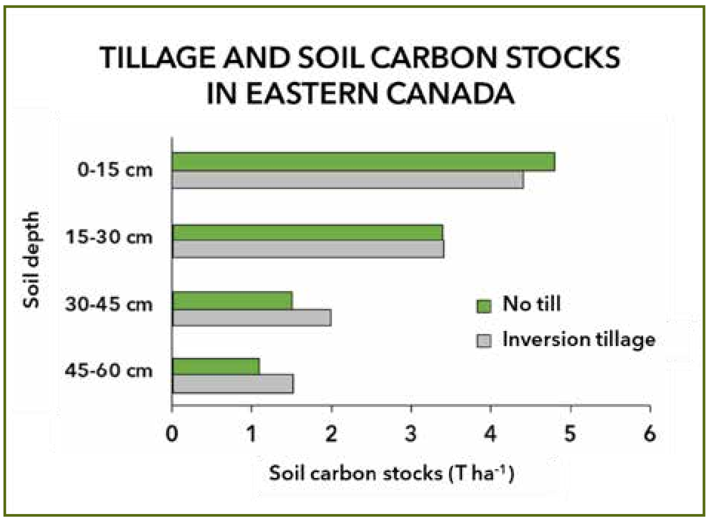


Figure 6. Effect of tillage intensity on soil organic carbon stocks at different depths in cold and humid conditions of Eastern Canada (Data source: Samson et al., 2021).

Solutions to reverse these trends should however be adapted to the specific pedoclimatic and agricultural context of these ecosystems. Indeed, in drier and warmer climates, no till provides many advantages: it can help soil retain water, improve crop yields, reduce soil erosion and foster carbon storage in soil. However, in cooler and wetter climates no till may improve surface soil health but can also result in a decrease in crop yields with no effect on soil organic carbon stocks. Indeed, under cool and humid climate conditions, no till favors the accumulation of carbon in surface soil (Angers et al., 1997; Gregorich et al., 2009), but inversion tillage increases carbon concentration at depth by placing organic matter where decomposition rates are slower, due to the cold and humid conditions that prevail in the subsoil (Angers et al.,1997; MacDonald et al., 2010; Samson et al., 2021). When the whole soil profile is considered, minimal differences are found in soil carbon stocks when different tillage intensities are compared in these regions. Diversified rotations and cover cropping might therefore be of greater interest to maintain or enhance soil carbon stocks in Eastern provinces. Given the complexity in integrating BMPs within farm systems, research is needed to better understand the multiple outcomes BMPs can produce and their net impact on ecosystem services including greenhouse gas reductions.

4.3. CONTEXTUAL FACTORS: WHAT'S INFLUENCING ADOPTION

4.3.1. Barriers to adoption

Producers' might adopt BMPs for reasons, including economic benefit, regulations, the desire to remain unregulated, social influence or pressure, or they might be motivated to be good stewards of their land (OECD, 2001; Knowler and Bradshaw, 2007; Prokopy et al., 2008; Feather and Amacher, 1994). To design policies and programs that enable adoption of BMPs that enhance carbon sequestration in croplands, it is therefore imperative to understand the economic, social, and environmental barriers that producers face (e.g., Zusman et al., 2014; Nilsson and Weitz, 2019). Identifying enabling conditions presents an opportunity to address these barriers and improve producers' capacity and interest to adopt BMPs.

The barriers that limit producers' interest or capacity to adopt BMPs are found to be wide ranging and depend on the producer and the broader context they are situated within (Weber et al., 2017). These barriers can include limited access to risk mitigation mechanisms for adopting new practices, high upfront costs (i.e., due to delayed timescale before a producer sees a return on investment), and environmental constraints (e.g., lack of moisture in the fall to allow for cover crop establishment in Prairie provinces). These barriers to adoption underline the importance of recognizing that producers must consider several factors before introducing a new BMP on their farm and that farms operate as a business, and financial profit is typically a factor in farm management decisions.

Researchers find that many producers are risk averse and may be reluctant to adopt new practices that pose uncertainty in their operation, especially when the outcomes of practices are not easily evaluated (Sheeder and Lynne, 2011; Wayman et al., 2017; Barreiro-Hurle et al., 2018). Baumgart-Gentz et al. (2012) reviewed 46 studies on producers' adoption of BMPs and found that over time producers become less resistant to adopting new practices that have demonstrated beneficial outcomes as they become more widely used. As a result, innovation diffuses along the adoption curve and the perceived risk of the practice decreases, which demonstrates the need for producers to access trials that demonstrate the impacts from BMPs (Rogers, 2003). Adoption of practices can also be influenced by long-term management time horizons. Many producers, particularly those who rent the land they farm, typically operate on short timescales. This shorter timescale results in renters being less likely to adopt site specific practices like cover cropping, where it is uncertain if they will see the results from their investment (Deaton et al., 2018). According to Statistics Canada, nearly 40 percent of agricultural land is managed by non-owners, underlining the potential magnitude of this barrier in Canada (Statistics Canada, 2016). To encourage the adoption of BMPs on rented versus owned land, it is imperative to understand the timescale of returns on investment via soil health, productivity and/or profit margins as it affects producers' willingness to invest in different types of BMPs depending on the length of their rental agreements and assurance that they will see the reward (Deaton et al., 2018; Martins et al., 2021).

Case Study: Barriers and Opportunities with Cover Crops

Many producers across Canada have persisting skepticism over cover crop use. This is due in part to limited research or information on cover crop agronomy across major agricultural regions in Canada, as most cover crop research has been conducted at warmer latitudes where the benefits and challenges of cover cropping are more clearly demonstrated (Daryanto et al., 2018). Adoption of cover crops can also be limited by the difficulties experienced with implementation. Six surveys between 2013 and 2020 conducted in the United States by Sustainable Agriculture Research and Education reported that producers believed the greatest challenges for using cover crops were establishment, time and labour needed, as well as increased management and species selection. Morrison and Lawley (2021) investigated barriers to cover crop adoption in Ontario through the 2020 Ontario Cover Crop Feedback Project. The surveys determined the most common barriers limiting cover crop use in Ontario were additional costs associated with growing cover crops (41%), lack of access to equipment needed to grow cover crops (36%), the late harvest of a cash crop preventing cover crop planting (29%), not knowing where to start (24%) and the shortness of a growing season (23%).

The 2020 Ontario Cover Crop Feedback project also identified measures that could enable cover crop adoption (figure 7). Morrison and Lawley (2021) asked Ontario producers to identify their goals for cover cropping. Producers could select from multiple goals, where 20 percent of producers identified that they adopted cover crops solely for financial gains, and 85 percent of producers adopted cover crops to build soil health. This highlights that while financial gains are key factors for understanding BMP adoption, producers also value other environmental and social benefits.

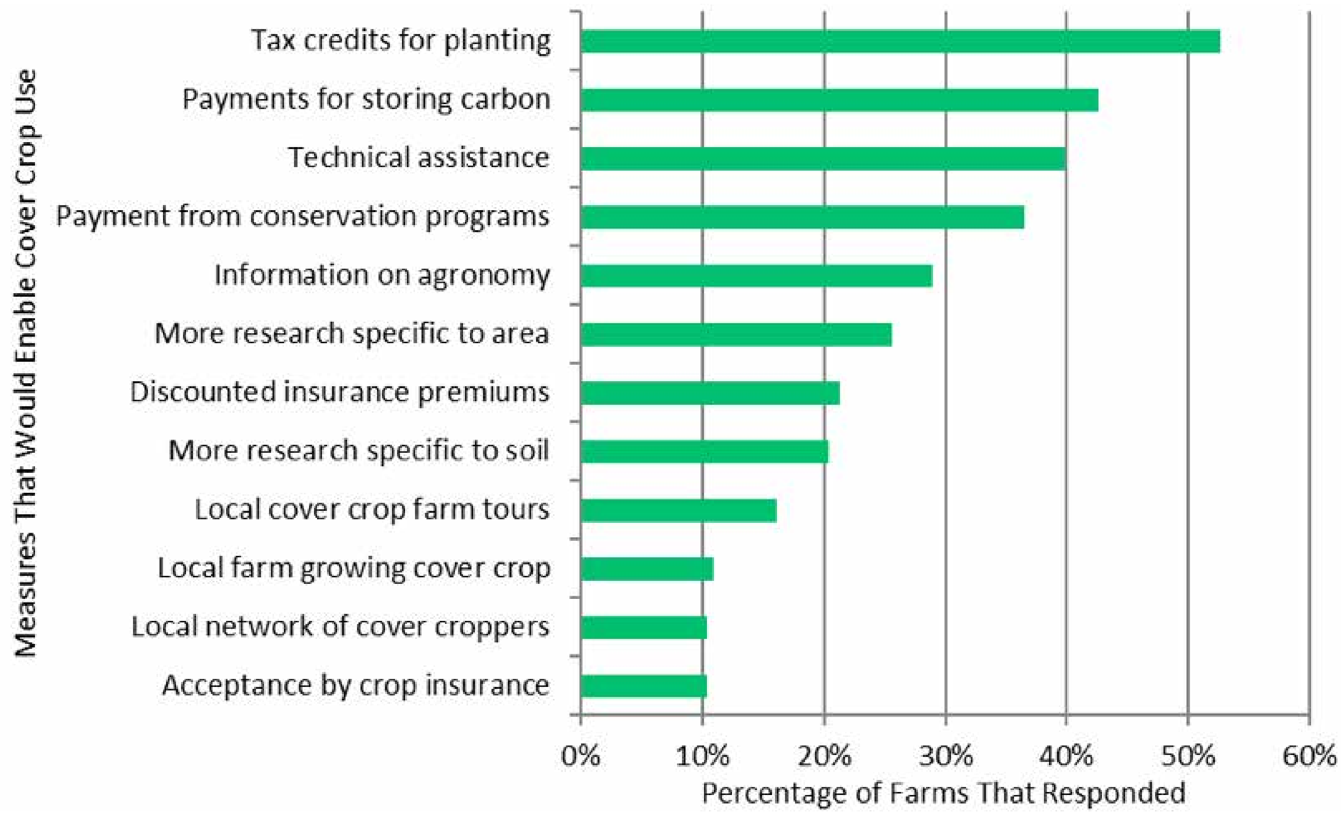


Figure 7. Ontario producers' responses when asked what measures would enable them to adopt cover crops (Source: Morrison and Lawley, 2021).

4.3.2. Enabling conditions for scaling adoption

Similar to barriers, enabling conditions span across disciplines. Enabling conditions are the conditions that should be in place to achieve a desired outcome (Choi and Fara, 2012). In this case the desired outcome is producers adopting BMPs that result in enhanced carbon sequestration. Researchers found these enabling conditions include producer engagement in policy design, evidence of return on investment, policy and regulatory certainty, and access to affordable and effective measurement and monitoring technologies (Kragt et al., 2017; Field to Market, 2022). There is an extensive body of research focused on understanding the conditions that enable BMP adoption, which has helped inform and evaluate policy design (e.g., Morris, 2004; Yiridoe et al., 2010). This research provides much needed insight into the web of conditions and factors that influence producers to adopt BMPs. Yet, this research has not conclusively identified a perfect suite of conditions that must be in place to enable all producers to adopt BMPs, nor does it appear to be the objective of many researchers, as producers are not one homogenous group and therefore their likelihood of adoption cannot be determined by a simple equation that considers a list of conditions.

Policies, similar to BMPs integrated on a farm, should also be thought of as operating within a system, where they can either function in perverse ways creating trade-offs or act complementary, enabling positive outcomes across economic, environmental, and societal objectives. Along with government policies and programs, civil society and industry-led initiatives can play a critical role in fostering an enabling policy and market landscape that facilitates BMP adoption among producers (Biggs et al., 2021). Much of the literature that explains this landscape advocates for transformational change at all scales to achieve the potential of BMP adoption in climate change mitigation. In particular, diverse stakeholders including international financial institutions, environmental non-governmental organizations and, producer associations emphasize the importance of building financial and market frameworks for agriculture that position the adoption of BMP as more economically viable compared to conventional practices and unsustainable land use change (Hallstein and Iseman, 2021; USFRA, 2021). Complementary to enhancing financial mechanisms for BMP adoption, there is a growing body of literature that highlights the need to reform existing agricultural policies and programs that have negative effects on climate change mitigation (Searchinger et al., 2020). Recent research also points to enabling conditions such as improved cross-sectoral collaboration on climate mitigation strategies to reduce trade-offs between sectors (e.g., van Oosterzee et al., 2014; Di Gregorio et al., 2017). For stakeholders, especially producers, to effectively navigate the increasingly complex and rapidly evolving policy and market landscape influencing BMP adoption, a key enabling condition is meaningful engagement at regional and local levels to inform the design of programs that ultimately seek to enroll producers to adopt BMPs (Hurlbert, 2014; Raymond et al., 2016; Lewis and Rudnick, 2019).

4.4. SCIENCE AND POLICY: STRENGTHENING THE INTERFACE

4.4.1. Knowledge transfer

Complementary to expanding research on approaches to enhance carbon sequestration in croplands, current scientific understandings need to be effectively communicated to ensure research findings are being disseminated to the right audiences. Systems approaches where researchers, agronomists, producers and others work collaboratively engaging in research development is thought to be more effective than linear models where producers are simply consumers of knowledge (Moschitz et al., 2015). Systems approaches to knowledge transfer also show promise in increasing opportunities for research to be applied in practice, and for a better understanding of research implications (Andrieu et al., 2019). A collaborative, systems model for knowledge transfer is especially relevant today as scientific knowledge in all fields (e.g., agronomy, soil science, politics, and social sciences, etc.) is so deep and broad that it is unfeasible for one person to grasp all the opportunities and challenges across all relevant disciplines to identify coherent solutions to enhance soil carbon sequestration. To build a comprehensive and systematic understanding of complex topics such as carbon sequestration in croplands collaboration in knowledge transfer should be a priority.

Concepts such as soil health provide diverse stakeholders with frameworks to conduct collaborations in multidisciplinary research that can break down silos of information and create bridges between basic and applied sciences. Multidisciplinary concepts are also foundational in the design of policies and programs that facilitate on-farm research and development. For example, in Finland the Carbon Action Platform creates a space for producers, researchers, and businesses to partner in the development and research of approaches that can accelerate carbon sequestration in agriculture (Carbon Action Platform, n.d.). So far, this program has created over 20 multidisciplinary projects, and several knowledge transfer materials including blog posts and peer-reviewed publications (e.g., Mattila et al., 2022). The development of programs that enable the co-design and implementation of research projects put into practice system approaches to knowledge transfer. This is especially important as linear forms of knowledge and technology transfer do not reflect the ways in which many producers prefer to receive and share information (Cowie et al. 2012; Wood et al. 2014). Based on 11 case studies on knowledge sharing among producers, Sumane et al. (2018) found that there is a need for more inclusive and flexible modes of knowledge transfer. This model of knowledge transfer requires greater producer engagement at the research stage, where producers can see tangible results and access local experience-based knowledge, while fostering greater confidence in BMPs and their impacts on real farms (Pannell et al., 2006). In Canada programs such as the Living Labs integrates this understanding by facilitating a co-design process for testing practice and technology innovations at the farm-level with opportunities for evaluation and refinement of innovations with researchers and other collaborators (AAFC, n.d.). Complementary to integrating producers into research and development, researchers have also found that the types of knowledge transfer channels (e.g., farmer social media networks, demonstration days, video series on research outcomes, etc.) should be diverse to better communicate research and lived experiences in BMP adoption to a wider pool of producers (Sumane et al., 2018).

4.4.2. Translating science into policy

The science and policy interface is where scientific findings are utilized to inform policy and decision-making processes. Increasingly, developing science-based policy is sought out by researchers, policy makers, and practitioners (e.g., AAFC, 2019). Similar to improving knowledge transfer, a linear model for developing science-based policy does not align with the complexity of agri-environmental stewardship and could hinder the process of developing adaptive governance frameworks based on science that are applicable to- and evolve with agricultural production systems (Cash and Moser, 2000). However, disrupting the linear model can be met with many barriers and obstacles. Researchers have identified key barriers within the process of integrating data and science into policy design such as cultural and practical differences between policy makers and researchers (Oliver et al., 2014). Beyond researchers and policy makers, there are multiple actors that engage in the science and policy interface for enhancing carbon sequestration in Canada's croplands, including producers, agronomists, not-for profits, corporations, and others. While they may share a common goal of enhancing carbon sequestration, their motivations and needs likely diverge, underlining the need for systems approaches to translating science into policy to be robust evidence-based yet adaptable and flexible. These types of approaches are increasingly advocated for as they better reflect, the complex systems producers operate within, and can be more inclusive for wide-ranging actors to effectively engage at the science and policy interface (Singh et al., 2021).

By compiling research on how to strengthen the science and policy interface we find that collaboration among diverse actors is critical to integrate and diversify the knowledge systems that inform policy design (Gluckman et al., 2021). Collaboration should be promoted within agriculture and extend outside of the sector to develop policy frameworks that are coherently aligned in achieving broader societal goals (e.g., national climate action targets), while also enhancing shared capacity and learning among sectors (Lewis and Rudnick, 2019; Singh et al., 2021). For example, as the agriculture sector increasingly becomes more data driven and engaged in climate change mitigation, collaboration and alignment across agriculture, digital and clean technology sectors may increasingly become a priority. Other key elements to consider in strengthening the science and policy interface to allow for a systems approach, include the need to build trust, transparency, and legitimacy among actors and acknowledging where actors' values and biases may influence the rigor of the interface (Gluckman et al., 2021). To build in these considerations, Singh et al. (2021) recommend integrating processes of independent and transparent assessments of knowledge that influence policy design. This may include policy design being informed and reviewed by taskforces representing diverse stakeholders (esp. including producers in the context of BMP adoption), public consultations, and open access data on performance and outcomes of programs and policies to enable evaluation of efficacy (see Boxall, 2018).

Complementary to research findings that outline why and how to improve the science and policy interface, opportunities to test different approaches are also needed. For example, in Ontario, the Ontario Soil and Conservation Improvement Association works collaboratively with producers and other partners on on-farm projects that test soil health practices, which can be used to inform improvements in their approaches to program delivery (OSCIA, 2021). In addition to informing policy there are a growing number of examples of research and development projects informing environmental market design. These examples include projects in Alberta, where the EcoServices Network is working with partners including the Western Stock Growers Association to build and test the science, data, and market infrastructure that will be foundational in implementing a market that rewards producers for adopting conservation practices (Ecoservices Network, 2021). Looking abroad, The United States Agriculture Department's Conservation Innovation Grant, similar to the Living Labs in Canada, provides opportunities to collaboratively trial innovations on-farm, but also enable testing of policy and market approaches to promote innovations. Through this program, Bayer, National Corn Growers Association, and partners developed a value chain intervention that incentivized BMP adoption and reported outcomes against climate action targets (i.e., carbon insetting). The exploration and testing in this project contribute to research needed to make value chain approaches to reduce greenhouse gas emissions replicable and scalable (SustainCERT, 2020; Viresco, n.d.). A final example of an approach to testing policy and market development informed by science is a multistakeholder collaboration led by Ecosystem Services Market Consortium. Ecosystem Services Market Consortium and its members including farmer associations, government departments, not-for-profit organizations, food and agriculture companies, and tech companies collaborate on piloting projects across the United States that test the application of protocols that enable producers to stack credits, rewarding them for improving water quality and quantity, reducing greenhouse gas emissions, protecting biodiversity and habitats, and enhancing carbon sequestration (ESMC, 2022). Learning from both academic literature and existing initiatives, greater integration and utilization of science and data, co-design and collaborative approaches, and the establishment of on-the-ground test projects (e.g., pilots testing innovations in policy design) are all key components in strengthening the science and policy interface for enhancing carbon sequestration in agriculture.

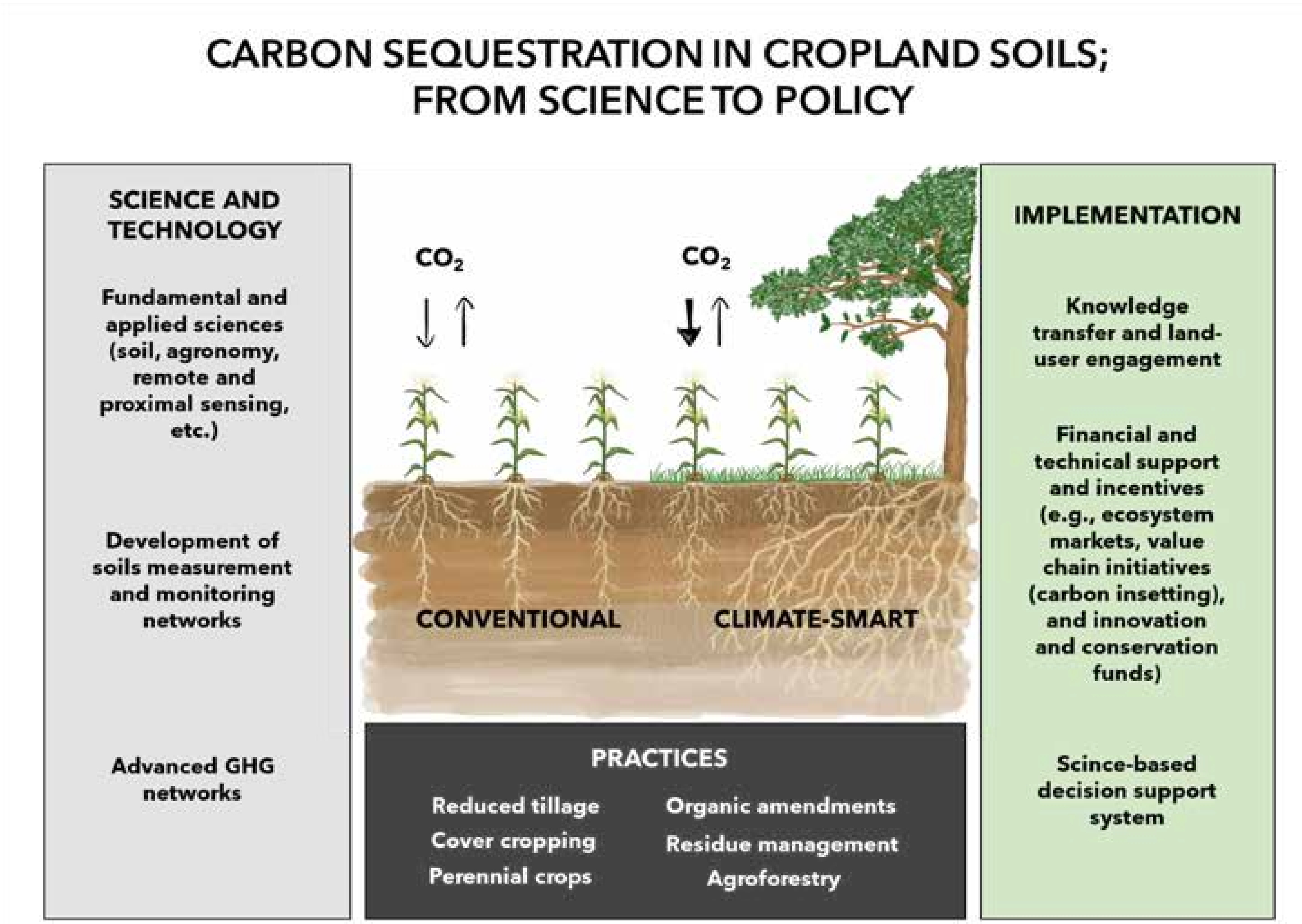


Figure 8. Translating science into policy to increase carbon sequestration in Canadian croplands. (Inspired by Paustian et al., 2016).

5. Conclusion

Fighting climate change is a daunting task that requires diverse solutions from multiple sectors. Canadian agriculture can play a critical role in mitigating climate change. In this report we present our findings on one aspect of climate change mitigation in Canada, carbon sequestration in croplands. We took a multi-disciplinary approach to this issue and considered the environmental, agronomic and socio-economic opportunities and barriers to increasing carbon sequestration across Canada.

Overall, we found that the regional variation demonstrates that Canadian cropland soils do not have a homogenous history, the same potential in carbon storage, or exist within the same agri-environmental conditions. Thus, strategies to enhance carbon sequestration across Canada should differ and meet local needs.

Under the four main research streams, we found:

a. Soil carbon sequestration is the process of capturing carbon dioxide from the atmosphere and storing it in the soil. The environmental drivers and agricultural practices that encourage carbon sequestration vary depending on climatic conditions and soil properties. In particular, organic matter inputs to the soil and the subsequent processing are key to understanding how to increase carbon sequestration in croplands.

b. There are three levers to increase soil carbon sequestration. The 1st lever is to increase photosynthesis rate per unit of soil area both in space and time by adopting practices including cover crops and diversified crop rotations. The 2nd lever is to maximize the amount of biomass returned to soil by integrating manure and leaving crop residue on fields. The 3rd lever is to reduce soil carbon outputs through organic matter mineralization by adopting practices such as reduced tillage.

c. Barriers to adoption include risk and uncertainty associated with introducing new practices, high upfront costs, and environmental constraints. Enabling conditions include producer engagement in policy design, evidence of return on investment, policy and regulatory certainty, and access to affordable and effective measurement and monitoring tools and technologies.

d. Approaches to strengthening the science and policy interface for enhancing soil carbon sequestration should include greater integration and utilization of science and data from multiple disciplines, co-design and collaborative opportunities, and the establishment of on-the-ground test projects (e.g., pilots testing policy and market ideas).

RECOMMENDATIONS

To elevate policy's role in increasing carbon sequestration in Canadian cropland, a science-based, systems approach to policy design should be considered. In the short-term, this approach should prop up more collaborative opportunities for testing innovations in policy and market design that utilize the current understanding of which BMPs enhance carbon sequestration and the barriers and enabling conditions for adoption. In the long-term, this approach can be strengthened by investing in research and infrastructure that furthers our understanding of how to increase and measure carbon storage across pedo-climatic conditions.

To build upon what the science and agriculture communities already know about carbon sequestration, scaled research efforts and soil data analyses are needed to improve predictions in soil organic carbon changes under a variety of pedoclimatic and management contexts.

a. Develop a better understanding of how individual BMPs and combinations of BMPs impact soil carbon sequestration in the whole soil profile (deep soil)

b. Increase research that evaluates how climatic conditions impact carbon sequestration across Canadian cropland as soil will face new conditions with climate change.

c. Foster greater multidisciplinary research programs, especially those that strengthen and build interpolated soil organic carbon measuring and monitoring systems (e.g., connecting experts in remote sensing, ecosystem modelling and soil sampling)

As CAPI doctoral fellows we worked as a multidisciplinary team on this report, working from of our own expertise while expanding our understandings of Canadian agriculture. Working together highlighted differences in our respective fields towards what we value as researchers, find fundamental in Canadian agriculture and even in the language we use to define key terminology. However, we also found significant common ground in our work, especially around the theme of site-specific solutions while deepening our understanding of how our research from our doctoral degrees and beyond can be used in a real-world context. The multidisciplinary nature of working together on this report allowed us to better understand the immense complexities in determining, designing and implementing just one aspect of improving Canadian agriculture for climate change- increasing carbon sequestration in cropland.

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