Recruiting Soil to Tackle Climate Change:

A Roadmap for Canada

SOIL CONSERVATION COUNCIL OF CANADA
CONSEIL CANADIEN DE CONSERVATION DES SOLS

Conseil canadien du COMPOST Council of Canada

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Preface

The Soil Conservation Council of Canada (SCCC) and the Compost Council of Canada (CCC) are organizations with a deep interest and commitment to sustaining the health and productivity of Canadian soils. SCCC is a farmer-based organization that is primarily focused on the agricultural landscape to promote the use of sustainable production systems. The CCC works with a range of soil managers, such as farmers, gardeners, and turf managers, to include the use of beneficial organic amendments such as compost, in conjunction with other management practices, to enhance soil health.

Whether you work with local gardeners or large-scale crop or livestock operations, SCCC and CCC know the value healthy soils bring to Canadians. Healthy soils contribute to the health and wealth of Canadians in many ways. Food production, clean air and water, biodiversity, wildlife habitat, and climate change mitigation are all things we need and that rely on healthy productive soils.

Soil Organic Carbon (SOC) is considered the key indicator of healthy, productive, and resilient soils. So, it makes sense to increase our knowledge on how carbon moves into soils and what we can do to keep it there. Fundamentally, that is what this initiative is about.

As a first step in this project, a strategic advisory committee consisting of eight members with various backgrounds including research, policy and agricultural experience was convened to provide ongoing guidance to the project team.

Gathering stakeholder input was a key activity in developing this roadmap. Informed stakeholders were interviewed at workshops and conferences in early 2020, but due to the COVID-19 pandemic, information-gathering shifted to individual meetings using video conferencing and phone calls. A sample of the questions used in the interview is provided in Annex 1.

In addition, an extensive literature search was conducted to gather new and useful information on SOC for use in this roadmap and accompanying toolkit.

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Executive Summary

Carbon has been called the "king of the elements," and for good reason. Its unique structure and characteristics allow it to form the backbone of all organic molecules, the basis of life. Carbon is also life's energy currency, the vehicle through which the solar energy captured by photosynthesis is stored, transmitted, and utilized by all living creatures, from bacteria to humans. Carbon moves through the biosphere in regular cycles, from one carbon pool to the next, including the soil, the biosphere, and the atmosphere. Human activities over the past 10,000 years have shifted the balance between these pools, reducing carbon in soils and increasing it in the atmosphere, leading to climate instability. Burning fossil fuels has been the largest contributor, but human management of soils has also been important. The world's agricultural soils lost between 50 and 70 per cent of their carbon over this period.

Despite these historic losses, soils currently store more carbon than the atmosphere and biosphere combined, and still have the capacity to absorb and hold a lot more. But how quickly can carbon be absorbed by soils and what are the best methods for doing so? Fortunately, the science of soil-carbon sequestration has been evolving rapidly and can provide important insights into both questions. First, carbon sequestration can occur more rapidly than previously thought. The old view, that the rate is controlled primarily by the nature of the organic input, mediated by environmental conditions, has given way to the idea that sequestration is controlled by soil organisms. In this new thinking, ensuring a good flow of carbon into the system remains important, but enhancing soil health by increasing soil life (e.g., bacteria, fungi, protozoa, etc.) is an equally important factor in capturing and holding carbon in the soil.

This new scientific understanding is vital. The goal of optimizing soil carbon now has two objectives: managing carbon flows optimally; and protecting and enhancing the soil food web[a]. These complementary objectives can be best met by adopting a group of soil-health principles: keep live roots in the ground; minimize soil disturbance; optimize use of inputs; promote diversity; and ensure that the soil is always covered. These principles, in turn, lead directly to the identification of the most beneficial management practices (BMPs). The Roadmap groups these BMPs into seven categories, each with several variations and options: cover crops; organic and biological amendments; animal management; nutrient management; conservation tillage and compaction management; promotion of diversity; and the use of perennials in annual cropping systems.

Canada's soil resources represent an important and significant opportunity to sequester carbon. Canadians manage about 69 million hectares (ha) as agricultural land. In addition, another 2 million ha are managed as urban green spaces, golf courses, parks, gardens, etc. Overall, Canadian managed lands have been gaining carbon over the past few decades, largely due to the prairies, where shifts away from tillage and fallow have resulted in slow but steady gains in soil organic carbon (SOC). However, regional trends differ, and eastern Canada has been losing SOC over the same period. Overall, substantial potential still exists to build SOC, as even the prairies soils still have capacity for increase[b]. Studies conducted in Canada indicate that practices such as no-till farming, cover crops, application of compost, and enhanced management of turf systems could increase SOC at rates between 0.2 and 1.1 tonnes of carbon per hectare per year. This corresponds to a reduction in greenhouse gasses (GHGs) of between 0.7 and 4.0 tonnes of CO_{2e} per hectare per year.

We made an initial estimate of the overall potential for GHG reduction in Canada from soil-carbon sequestration by dividing the country into four regions, assuming various levels of adoption of practices or groups of practices appropriate for those regions, and applying the rates of carbon increase identified by the documented studies. The result was three scenarios: *the low projection was 21.7 megatonnes (Mt) per year, the middle was 72.7 Mt and the high was 97.4 Mt*. Canadian agriculture currently contributes about 73 Mt of GHGs annually, so our medium and high projections indicate that agriculture's GHG footprint could be completely offset by sequestering carbon. These projections would appear to be achievable, as even higher rates of sequestration (1.5 tC/ha/yr and more) have been reported by farmers using multiple practices within a systems approach to building soil health and soil carbon (see paragraph below). In addition, adoption of soil-building practices may lead to reductions in nitrous oxide emissions and fuel use, as well as other GHG benefits not included in this analysis. We conclude that a goal of eliminating Canadian agriculture's GHG footprint may be both worthwhile and realistic.

Some Canadian farmers are leading the way by applying the principles and practices documented in this Roadmap. The five growers profiled in the Roadmap include two field crop farmers (Saskatchewan and Quebec), one potato grower (Alberta), one vineyard (Ontario), and one Atlantic Canada practitioner of animal agriculture (beef, pork, chicken, etc.). All use a combination of several BMPs as part of their soil management system. The results to date have been impressive: soil-carbon rates have increased from 1.5 to 2.7 tonnes per hectare per year. All five also report maintained or increased productivity, as well as enhanced profitability.

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a "Soil food web" is the scientific term for the organisms living in the soil and the relationships between them.

b Existing SOC levels in Prairie soils are still well below the pre-agriculture levels measured in some historical documents.

However, success at the innovator or early adopter level is not enough by itself to guarantee rapid dissemination of new methods throughout society. Numerous challenges to change exist and are discussed in Section 7. These challenges significantly influence how soil managers make decisions and changes in their operations. Policies, programs and support aimed at helping soil managers in building SOC must recognize and accommodate these challenges and potential impediments. Moreover, these challenges represent individual components of what is perhaps the most significant overall challenge: expanding our collective vision of what it is to be a farmer, or, more broadly, a soil manager. Soil managers can deliver a range of products that go beyond food, fibre, fuel, esthetics and recreation to include the provision of vital services such as clean water, flood mitigation, a stable climate, and enhanced biodiversity. Our existing vision of soil management as a production system needs to expand to include the provision of a wide range of ecosystem services.

Our project team built on the challenges identified to generate a framework for potential interventions. This framework included five key areas: *making the case* (motivation and research support); *making it work* (access to the tools needed); *strengthening the business case* (providing good data and developing an incentive system); *clearing the tracks* (addressing systemic challenges); and *building the future* (creating the institutional framework necessary to support the new paradigm). From this analysis emerged the recommendations in Table ES.

Please note that this report does not recognize any specific approach to agriculture (e.g., conventional, organic, regenerative) as preferable with respect to building SOC. All approaches to agriculture can be modified to sequester more carbon through the adoption and integration of soil-health practices.

Table ES: Roadmap Recommendations

Area of Intervention	#	Recommendation
Building the Future	1	The agricultural industry and the federal government should work together to create a non-government entity (e.g., "Soil Health Roundtable") that can provide the leadership necessary to develop and achieve a vision and plan that will secure the future of soil health in Canada.
	2	Develop a Consensus National Soil Health Strategy.
Making the Case	3	Build a basic understanding among soil managers of how management practices impact soil health and soil organic carbon (SOC).
	4	Develop a mechanism to sustain communications and collaboration between farmers, other soil managers, scientists and researchers.
	5	Promote and enable leadership activities among leading edge farmers (innovators and early adopters) that will facilitate the sharing of their knowledge and experience with other farmers.
	6	Raise the public profile of soil to the same level of importance as air and water.
Making it Work	7	Build independent extension and knowledge transfer capacity to the point where it is available to all Canadian soil managers and farmers who want to adopt soil health practices.
	8	Create a program that preserves existing knowledge of our soils, gathers new information, conducts monitoring of changes, and reports to Canadians on a regular basis.
Strengthening the Business case	9	Accelerate efforts in developing tools to assess all of the costs and benefits, on-farm and off-farm, associated with improving soil health.
Clearing the Tracks	10	Identify and gradually amend government policies and programs with the goal of making them as compatible as possible with practices that improve soil health and build soil carbon.

SECTION 1: How to use this roadmap

Why is a roadmap needed to enhance SOC?

A roadmap is a strategic plan or process that sets a goal or desired outcome and identifies the major steps or milestones needed to reach it. It also serves as a communication tool among stakeholders, a high-level articulation of strategic thinking—the *why*—behind both the goal and the plan for getting there. In this case, this roadmap will help us define the actions and commitments stakeholders need to undertake to enhance carbon in Canada's soil. This roadmap will help soil carbon stakeholders to achieve their goals, which is, in the most basic terms: "putting more carbon in the soil and keeping it there."

Interest is currently strong and growing in the Canadian science community to understand the mechanisms of carbon capture and storage in soils as well as its overall benefits to soil health. A similar interest is growing among farmers and soil managers, who increasingly want to understand and capture the benefits of enhanced soil organic carbon (SOC). Lastly, a broadening interest in SOC and soil health is emerging among the other stakeholders that influence agricultural practices, including consumers. While these are all good signs, SOC and soil health in general do not stand as issues of importance on their own. Soil carbon is in a sense an orphan in our world. Notwithstanding a few notable exceptions (see below), gains in SOC and soil health are often serendipitous outcomes of initiatives that serve other priorities, such as crop production, habitat creation, and environmental protection.

SOC and soil health are by and large treated as free goods by society. They are pillars of the productivity, profitability, and resiliency of our soils, yet there is no recognition in monetary terms of their value. There has been some progress in establishing carbon markets in Western Canada and a few projects on ecological goods and services (EGS) where the beginnings of a valuation of SOC and soil health are recognized, but despite an increase in these efforts over the relatively short time period in which this document was written, most remain in a nascent or under-developed state.

Finding the path to recognizing the economic value of healthy soils and enhanced SOC are key steps to sustaining the health of our soils in the long term. To achieve a sustainable state, we are asking farmers and soil managers, who must keep their own businesses profitable, to make changes in how they use their land, labour and capital to provide other higher-level benefits to Canadians. Generally, farmers are prepared to make investments that reflect positively on the bottom line of their business, and as good stewards of the land, are often prepared to go a little further. However, there is a limit to the risk we can reasonably ask them to accept. Finding new and innovative sources of funds to support the change and adoption of new practices to build SOC and soil health need to be examined and carefully developed.

There is abundant evidence (both scientific and anecdotal) that enhancing SOC is a desirable and beneficial goal (the high tide that can float many boats). However, there is still no consensus to guide stakeholders on how to achieve this goal. The purpose of this roadmap is to identify and begin to answer several key questions, including:

- How do soils gain carbon and store it (building SOC)?
- What are the consequences of letting SOC decline?
- What are the keys to rebuilding SOC in Canadian soils?
- What are the best practices for sequestering carbon in soils?
- What is the potential?
- What additional scientific support is required?
- What are the non-technical barriers to building SOC?
- How could these be mitigated?
- How can we help stakeholders identify their commitments and contributions to the goal?

Who needs this roadmap and why?

Getting answers to the above questions and increasing the general level of knowledge and understanding of SOC is important to guide decisions in how we respond to the challenge of enhancing SOC in Canadian soils. Not all stakeholders need to become experts in the science of SOC, but a fundamental understanding of how soils can capture carbon from the atmosphere, or conversely, lose carbon back into the atmosphere, will provide informed advice and guidance to decision-making and programs that are delivered on managed landscapes in the future.

Governments at the federal, provincial, and municipal levels all make decisions that influence landscape and/or agricultural practices and management. Often, those decisions are aimed at other targets, and can have positive or negative impacts on SOC. This roadmap is intended to help inform policy and program decisions that could become barriers instead of supports for the task of increasing carbon in Canada's managed soils.

There is also an opportunity and a need for more private sector action. The long-term security of agri-business depends on a healthy, productive, and resilient soil to support profitable farms who consume their products and advice. Most large agri-businesses have commitments to sustainability written into their business plans. Some commitments are directed towards market demands while others reflect corporate concerns and reactions to environmental sustainability challenges. Regardless of the motivation, agri-business has a role to play in enhancing SOC in Canada. Examples of existing initiatives include:

- Syngenta Canada Good Growth Plan/Operation Pollinator
- A&W's commitment to grass-fed beef
- Canada's potato sector and mandatory Environmental Farm Plans
- Fertilizer Canada and the 4R Nutrient Stewardship program
- Integrated Pest Management

Enhancing SOC benefits all Canadians and not just the ag sector. The agricultural landscape is a shared landscape where hunters, fishers and recreational uses rely on soils to keep water clean, provide wildlife habitat, support biodiversity, and make rural Canada a pleasant place to be. Healthy soils are the foundation of all these benefits. This roadmap will be useful to these stakeholders by helping them learn how soil produces benefits and what actions they can take to increase SOC.

Canadians from all walks of life have a stake in soils and a responsibility to be part of future actions to keep our country's soil resource healthy and functional. Think of this roadmap as a starting point, or a crash course, for Canadians that are relatively new to the subject matter.

Without this roadmap we run the risk of stakeholder efforts remaining fragmented and less focused as individuals and organizations continue to serve their respective mandates. The coordinating power of this roadmap can help to reduce redundancy of efforts by sharing information, results and emerging challenges related to enhancing soil carbon in Canada. For example, non-agricultural lands (lawns, gardens, parks, golf courses, etc.) in Canada can contribute significantly to putting more carbon into our soils, but there is very little information and not much focused effort in this area. The potential is there, and this roadmap is a great tool to help these other soil managers as well.

It is also important to raise the commitment to manage soils for the specific outcome of enhanced SOC. Otherwise, SOC enhancement will remain a bi-product or sub-objective of other more specific objectives, such as productivity. Soil managers who do not see enhancing SOC as a primary objective of soil management may unknowingly make operational decisions that have negative effects for SOC. Knowledge, communications and understanding the importance of sustaining the health of our soils and the impacts our choices in soil management can make, for better or worse, will help those managers make more informed decisions.

Stakeholder commitments to manage soils in ways that enhance soil carbon is where the rubber hits the road. Without their individual efforts and actions, we run the risk of reducing SOC and declining soil health while losing the many benefits they provide Canadians. There is another essential element that this roadmap supports and that is the need for strong national leadership on this issue. In the long term, soil managers will need a backdrop of relevant policies that supports SOC enhancement, the science to support SOC BMP's, and programs that aid action on the landscape. Along with this, recording and reporting the results as we move forward is key.

Finally, we must acknowledge that the relationship of soils to climate goes well beyond soil-carbon sequestration. This relationship is complex and includes GHG emissions unrelated to carbon, the hydrologic cycle, and large-scale erosion – to name just three other important processes. Our scope in this report; however, is on carbon only. As stated at the beginning of this section, we focus here on how to get more people putting more carbon in the soil and keeping it there.

So, with that, let the journey begin as we get better acquainted with what soil carbon is in Section 2.

SECTION 2: What is "soil carbon" and why do we want to increase it?

The Carbon Story

King of the Elements

Carbon differs significantly from most of the other elements in the periodic table. Its ability to form polymers (long stable chains of carbon atoms, with other atoms attached as "sidekicks" – *see Figure 1a*), at a normal range of temperatures, is one of its key characteristics. These long, stable carbon chains form the backbone of sugars, carbohydrates, proteins, and even DNA – all the "stuff" of life. The most basic of these carbon chains – simple glucose (sugar) – is the initial product of *photosynthesis* (*see Figure 1b*).

In this vitally important process, all plants, and some microbes, are able to use the sun's radiant energy to break down carbon dioxide (CO_2) and water (H_2O) and then use the carbon, hydrogen, and oxygen atoms released to build sugar molecules. This conversion of radiant energy into biochemical energy, in the form of organic molecules, is what makes the enormous complexity of life on earth possible.

In fact, all life depends on carbon, and it does so in two intricately connected ways. First, as mentioned above, carbon atoms form the fundamental backbone of all organic structure. Almost one fifth of the weight of a human being, for example, is carbon. Second, and equally important, carbon-based molecules, such as sugars, carbohydrates, fats, and lipids provide all of the energy that humans and all other organisms require for both metabolism and physical activity. When organic molecules break down, as happens in our digestive tracts after we eat a steak or a tomato, the original energy that some plant used to build those molecules is released and made available to us for our own purposes.

Carbon - The Backbone of Life

Figure 1a:
A typical carbon chain, or polymer:

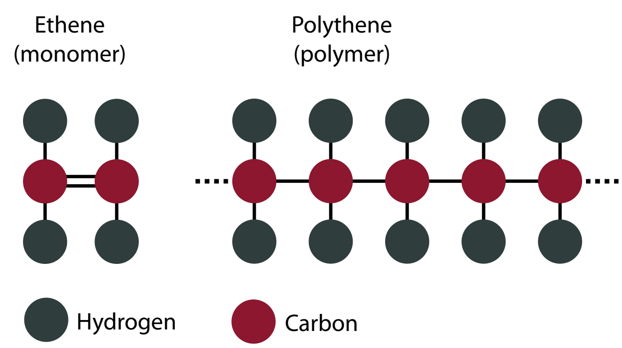
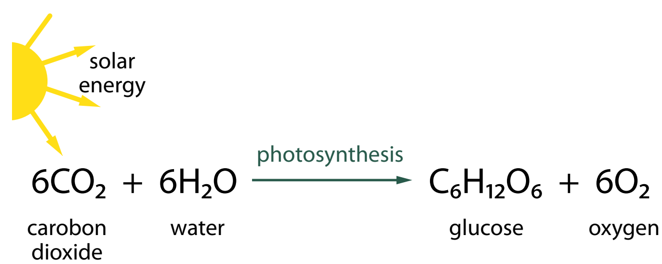


Figure 1b:
The process of photosynthesis:



Fortunately for life on Earth, carbon is ubiquitous. It is the fourth most common element in the universe (after hydrogen, helium, and oxygen) and the fifteenth most common element in the Earth's crust. We don't have to fear a shortage of carbon. However, where all that carbon is distributed on our planet – the size of the various *carbon pools* and the way that these are changing due to some of humanity's major activities – is a significant and growing cause for concern.

The Carbon Cycle(s)

Carbon actually has two cycles: one slow and the other fast. The slow cycle, dominated by physical and chemical processes, operates over millennia; the fast cycle – dominated by biological processes and initiated by photosynthesis – is measured in years and decades.

The *slow carbon cycle* consists of longer-term movement of carbon between the planet's major pools – including the Earth's crust. Carbon is released from its inorganic form, deep in the earth, primarily by volcanic activity. The enormous pressure of moving tectonic plates under volcanoes melts rock, creating primarily silicates and CO_2,

Box 2-1

Soil Carbon Measurement Units

1 Gigatonne (Gt) = 1 billion (1,000,000,000) tonnes

1 Megatonnes (Mt) = 1 million tonnes,

and thus, **1 Gt = 1,000 Mt**

which are ejected when the volcano erupts. Volcanoes emit between 130 and 380 million metric tons of carbon dioxide to the atmosphere each year[1]. While this is substantial, we will see below that it is small in comparison to the hundreds of billions of tonnes of carbon circulated annually via the fast cycle.

Further movement of carbon via the slow cycle comes from a combination of events, occurring over millions of years. Weathering of rock, wherever it is exposed to the elements, results in the release of calcium ions, which are carried to the oceans by streams and rivers. Once in the ocean, the calcium reacts with dissolved CO_2 (from the atmosphere) to form calcium carbonates. This process is largely mediated by shell-building organisms (such as corals) and plankton, which use this material to build their shells. As these organisms die, their shells sink to the bottom of the ocean and eventually consolidate into limestone rock[2].

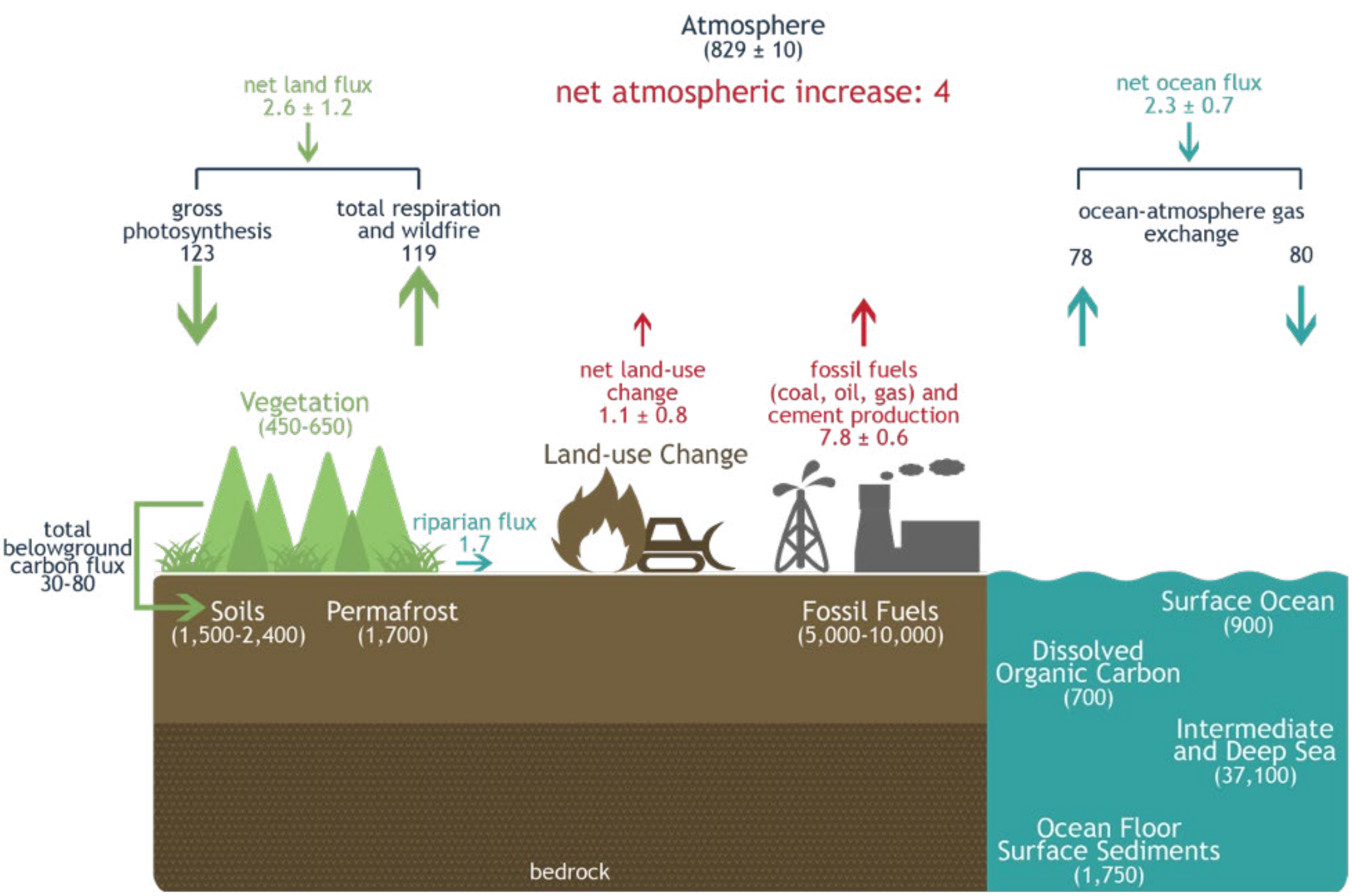
Over time, the slow cycle balances itself. If the carbon released by volcanic activity increases, it is gradually offset by an increased amount of carbon absorbed by the oceans, as the process plays out over millions of years.

The *fast carbon cycle* is a different story, and this is where our current concerns lie. Figure 2 shows the various pools of carbon in the fast, or biological, carbon cycle. It also shows the size of these pools (in brackets), and how much carbon flows in and out of each on an annual basis (associated with an arrow for *out* or *in*). The units are Gigatonnes (see box on previous page).

Two pools stand out for their sheer enormity: the deep ocean pool and sediments (combined, almost 39,000 Gt); and the fossil fuel pool (5,000-10,000 Gt). In fact, both of these could be thought of as slow-cycle processes, except for the fact that we humans have been burning fossil fuels and bringing that carbon into the atmosphere (and into the fast cycle) at an ever-increasing rate since the industrial revolution.

Looking at the other pools involved in the fast cycle, we can see that the carbon in soils (1,500-2,400 Gt) and the organic material tied up in permafrost (1,700 Gt) are each greater than the combined total of carbon in vegetation (450-650 Gt) and the atmosphere (829 Gt).

Figure 2: The Fast Carbon Cycle



The other thing to note in Figure 2 is the annual rate of loss or gain by each of the carbon pools. The combination of land-use change (which includes damaging soil management practices) and fossil fuel use releases about 9 Gt of carbon into the atmosphere every year. Increased photosynthesis and soil carbon sequestration pulls about 2.6 Gt back out of the atmosphere each year, and the oceans absorb another 2.3 Gt (a concern in itself, due to ocean acidification[c]). **The result is an increase in atmospheric carbon of about 4 Gt annually**. This is the problem, the opportunity, and the reason this roadmap exists.

Carbon in Soil: SOM and SOC

That 1,500 to 2,400 Gts of carbon in the soil organic carbon pool[d] is not there in elemental form (plain C), nor as a gas (CO_2); rather, it exists in a variety of biochemical forms, created by living organisms. In general, we call this material *soil organic matter* (*SOM*), and it is also referred to as *soil humus*. The component of SOM that is actually carbon, as opposed to hydrogen, oxygen, or any of the other elements that compose organic molecules, is what we call *soil organic carbon*, or *SOC*. The percentage of SOM that is SOC is generally in the range of 50 per cent[e].

Box 2-2

SOC vs CO_2

To convert the weight of SOC into an equivalent weight of atmospheric carbon, you must multiply by 3.67.

For example, 2 tonnes of SOC becomes 7.34 tonnes of CO_2. This is because the weight of the oxygen in CO_2 must be taken into account.

Most of the SOM in soil eventually decomposes. This is basically the same process below ground as above: living creatures consume organic matter, releasing its photosynthetic energy for their own purposes, and releasing oxidized carbon (CO_2) as the byproduct. Some organic substances last longer in the soil (e.g., are more stable) than others, and this stability characteristic is called *recalcitrance*. It has to do with how easily organisms are able to break down the substance's organic molecules, accessing the material's stored energy. This will be discussed in more detail in Section 3 (how carbon is sequestered in soil); for now, we can simply say that the amount of carbon in the soil carbon pool is determined by the differential in the rates by which it is added (e.g., residues, wastes, etc.) and by which it is lost (respiration of soil organisms, erosion, etc.).

The Historic Loss of Soil Carbon

The world's soils have been losing SOC for thousands of years, since the early days of agriculture and the advent of the plough. Turning the soil introduces oxygen into the soil, which stimulates the process of decomposition (oxygen is a limiting factor in the growth of soil microbes). As we will discuss later in this document, many of our long-term, and more modern, agricultural practices are detrimental to soil health, and result in SOC losses over time. Land-use changes, such as the burning of forests to create cropland, or the conversion of grasslands to annual agriculture, have also depleted SOC substantially.

Scientists estimate that the world's agricultural soils have lost between 50 and 70 per cent of their soil carbon stocks over the last 10,000 years[3], and the process has become more rapid over the last century. As Figure 2 shows, soils' capacity for holding carbon is very large. We will discuss the actual potential in Section 5, but the primary goal of this roadmap is to set out the various options for building higher levels of carbon in soil, thus reducing the amount in the atmosphere. Moreover, there are many other benefits associated with higher levels of SOC, and these are discussed below.

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c Excess CO_2 in the atmosphere reacts with surface ocean water to form carbonic acids. The resulting decrease in pH (acidification) is detrimental to many forms of ocean life, particularly to organisms that form shells, and generally degrades marine ecosystems.

d We are referring here to the organic carbon in soils. Inorganic carbon is also present in soils, in mineral forms, as a result of the weathering of carbonaceous sedimentary rock (see previous discussion of slow carbon cycle).

e Until recently, the generally accepted percentage of carbon in SOM was 58 per cent. However, this has changed in the past few years to be closer to 50 per cent. See: Pribyl, Douglas W. 2010. *A critical review of the conventional SOC to SOM conversion factor*. Geoderma 156(3): 75-83. April.

Soil Carbon's Many Benefits

Understanding the Basis for SOC's Benefits in Soils

Higher levels of carbon in soils provides many benefits, both to soil managers and society at large. The science behind this claim is based on well-established agronomic principles, as well as traditional experience. In recent years, this understanding has received a further boost from a wealth of new studies focused on the nature and functions of soil life. This work, coming from the fields of soil biology and soil ecology, has been stimulated and buttressed by the latest advancements in genomic science.

Part of the long-term accepted wisdom regarding SOC is that higher levels of organic matter are associated with better *soil structure*, which in turn results in higher *infiltration rates* of rainfall and an enhanced *water holding capacity (WHC)*. The understanding of why this is so, and how it works in detail, has been increasingly well understood as our knowledge of soil organisms expands. Good soil structure depends on "clumping," or as it is labelled scientifically, *aggregation* (*see Figure 3*). Aggregates of different shapes and sizes don't fit together perfectly, and the open spaces between the aggregates, known as pores, create a sponge-like texture. Within this soil sponge, water and air move freely, pores hold on to substantial amounts of water, roots are able to grow longer, and microscopic soil organisms have room to live and multiply.

Figure 3:
What Well Aggregated Soil Looks Like

Soils are from adjacent fields; well aggregated soil (on left) is a result of several years of cover crops.
Photo courtesy of Mel Luymes and Adam Ireland.

These microscopic soil organisms, collectively known as the *soil food web (*SFW*)*, are the key to SOC's many benefits. It all starts with soil structure. Soil aggregates are formed by a variety of factors, but their size and stability are fundamentally dependent on microbes. Bacteria secrete sticky substances, *biotic glues*, that bind together the mineral and organic elements of the smaller aggregates (*micro-aggregates*). Microscopic fungal strands and tiny plant root hairs complete the task by wrapping micro-aggregates into larger, irregularly shaped *macro-aggregates* (*see Figure 3*). Because these glues and fungal strands are not soluble in water, they don't disintegrate when it rains; they hold their structure, allowing rainfall to infiltrate the soil and fill up the pore spaces. In essence, good soil structure depends on the presence of a large and diverse population of beneficial soil microbes.

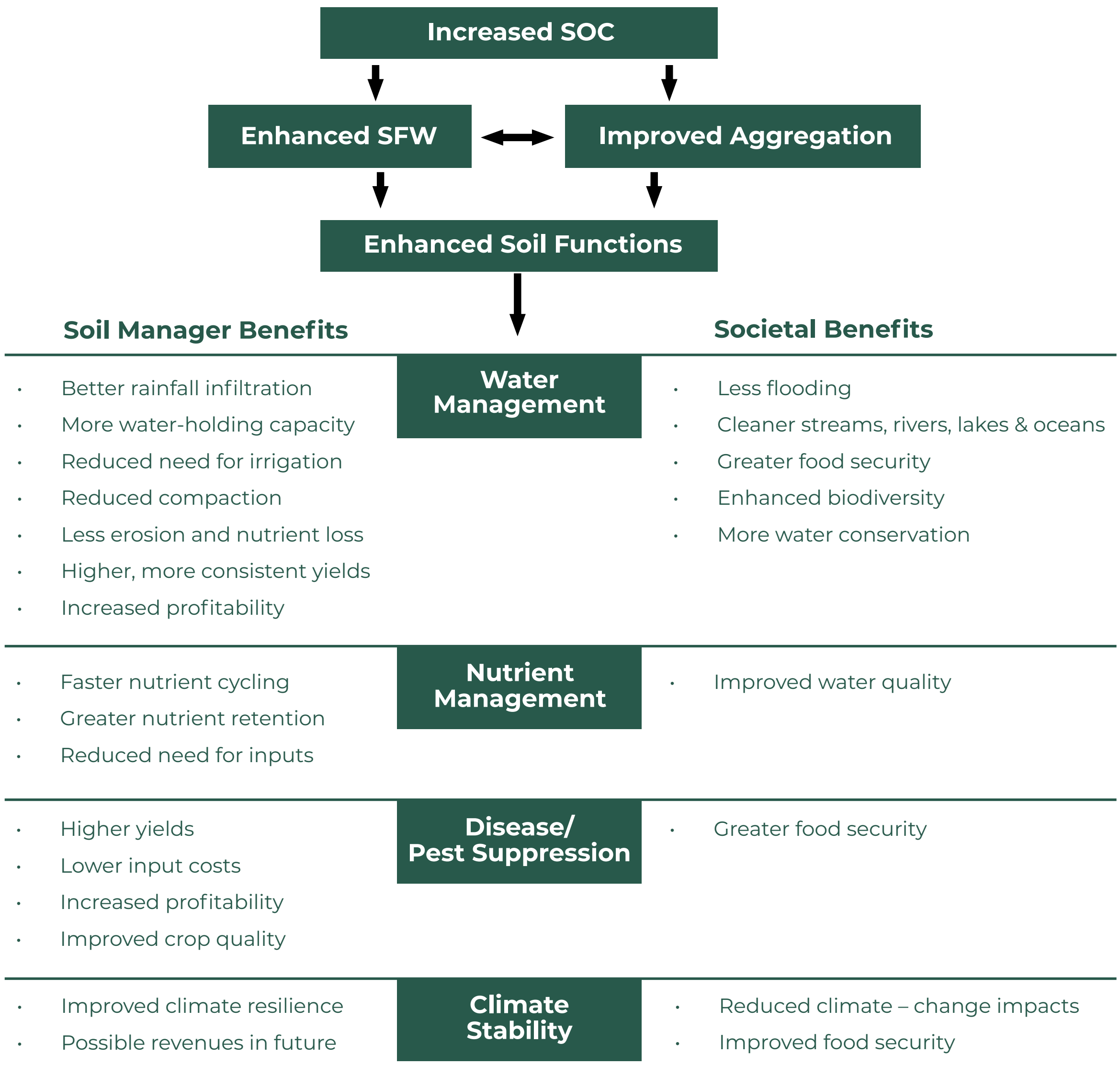
These same microbes, allowed to thrive in well-aggregated soils, are responsible for most if not all of SOC's benefits, which flow from the positive impact SOC has on the soil food web. Organic carbon provides both food and habitat for the soil food web, and the more carbon there is in the soil, the more likely it is that the soil food web will be large, diverse, and well-functioning.

Summarizing SOC's Benefits in Soils

Figure 4 shows the way in which multiple benefits, to both soil managers and society, flow from an increase in SOC. The extra carbon feeds the soil food web, which in turn helps to build good soil structure. That improved structure then allows the soil food web to expand and thrive, producing the beneficial soil functions: water management, nutrient management, disease and pest suppression, and climate stability[4]. Each of these functions results in direct benefits to both the soil manager and society at large[5]. We should also note that these functions, and the benefits they provide, are not completely independent of each other, but are closely interrelated. In particular, the better water management that comes from improved soil structure will enhance all of the other soil functions and increase the full range of benefits. For more detailed discussion of this subject, see Annex 2 (The Soil Food Web).

Figure 4:

Summary of SOC Benefits



SECTION 3: How is carbon “sequestered” in soils?

The Basic Processes

Inputs and Outputs

As discussed briefly in Section 2*, carbon input* to a soil ecosystem is the total amount of carbon that enters the soil, either as plant or animal residues (from both above and below ground), or as *root exudates*[f]. *Carbon output* from the same system is a combination of carbon loss via soil-organism respiration and, in many cases, soil erosion. These in-and-out activities are an essential part of the fast carbon cycle. As one would expect, the difference in rate by which the carbon enters and leaves an ecosystem is the primary factor in the build-up (or reduction) of SOM.

Carbon In

Soil managers have considerable influence on how much carbon enters the soil. As we will discuss in later sections, practices relating to residue and root management, crop rotations, cover crops, and organic amendments (to name some of the most obvious) go a long way in determining how much carbon enters the soil each season.

Carbon Out

How much carbon leaves the soil is also heavily influenced by soil management, although the mechanisms are not quite as obvious. This is where the concept of *soil-carbon sequestration* comes in. Earlier, we stated that the build-up or loss of carbon arises from the difference in rates of addition vs subtraction. Therefore, if you add 10 kilograms of carbon to a unit of soil, and 5 kilograms is released via respiration or lost to erosion, then your net sequestration is 5 kilograms. However, soil carbon is in a constant state of flux. For instance, what you measure in the summer will be very different from what you measure in the winter, and your 5 kilograms may be a fleeting achievement. So, when it comes to sequestering carbon in soil for the long term, scientists like to think in terms of what they call *stable carbon*. As we will see, this stable carbon is a result of the soil environment, the soil biota and also the type or quality of organic inputs.

Stable Carbon

In order to understand what "sequestered" means, we need to consider what forms carbon takes in soil and the factors that affect its stability. The science of all this has been changing significantly over the past few years, so let's start with the conventional wisdom.

For over a century, the scientific consensus was that the *rate of carbon decomposition* in soils was strictly a function of:

- the chemistry of the organic materials added (e.g., the lignin that makes up woody material takes longer to break down than the cellulose that makes up the structure of annual plants);
- environmental factors such as soil type, moisture and temperature.

Box 3-1

Labile vs Recalcitrant

The word "labile" means easily susceptible to change; while "recalcitrant" means the opposite, or not easily susceptible to change. In soil science, labile usually refers to organic substances that microbes can access quickly, whereas recalcitrant means organic substances that are to some degree resistant to microbial attack. The terms are both relative, rather than absolute, and can be considered as opposite ends of a continuum, rather than as definitive characteristics.

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f Root exudates are organic substances of various kinds exuded from the roots of plants for a variety of purposes, including feeding the soil food web. Some plants exude up to half of their photosynthate in this manner. For more information, see Annex 2**, The Soil Food Web**.

To model the process of sequestration, scientists developed, using experimental methods, formulas for decay rates for different organic substances under varying environmental conditions. These formulas were built into models for predicting carbon sequestration rates[g], which gave reasonably accurate results in most cases. If you know how much carbon is going into the soil (based on estimates of plant and root biomass, plus rates of root exudation), you know the nature of this carbon (its various levels of recalcitrance), and you have data on soil type, climate, etc., these models can predict how much carbon will increase or decrease over a given time. This approach assumes fast rates of decomposition for labile carbon, slower rates for more recalcitrant carbon, (*see Box 3-1* on defining these terms) and a resulting slow trickle of the most recalcitrant carbon into a stable pool – *soil humus*. The humus pool was thought to be all the recalcitrant leftovers, so to speak. These were thought to be extremely resistant to attack by microbes and thus highly stable. It was assumed that they would degrade only over decades or centuries.

The Product: Soil Humus

In essence, these models are based on the fundamental concept that *humus is the end product* of a gradual decomposition process – it is either the stuff left over after decomposition, left undegraded because of its recalcitrant nature; or it is *recalcitrant stuff that has been condensed* (created by soil chemistry) out of the various end-products of decomposition[6]. However, we now know that soil microbes are excellent decomposers, especially in temperate managed ecosystems, and that soil microbes can break down almost any type of carbon given enough time, regardless of its recalcitrance. Recent discoveries are suggesting that the understanding of both the nature of humus and of how carbon is sequestered in soil – the basis for these models – is incomplete, if not incorrect[7]. This means that the models are not as accurate as they could be. The new approach holds that the degree of recalcitrance of added carbon is *not* the primary key to its degradation or to its stability, and that *soil humus itself is not what we thought it was*.

The New Paradigm

The Slow Death of Soil Humus[h]

If recalcitrance of an input is not the key factor in determining how long and how much carbon stays in soil, then what is? The answer seems to arise from the day-to-day activities of the soil microbes who consume the carbon. Some of it is used for energy and is respired as CO_2. But an important question remains: what happens to the other carbon-based products of microbial activity, such as their metabolites[i], their wastes, and ultimately their dead bodies?

The older thinking was that these substances would simply be consumed again and again as energy sources, until the only C left in the soil was whatever was too tough for the bugs to eat. This viewpoint came into question when scientists began to compare the age of various samples of soil carbon with their respective level of recalcitrance. What they found was that some C in soils was very, very old -- despite the fact that it was still quite labile. They also found that, under some conditions, recalcitrant C degraded much faster than had previously been thought possible [8]. They began to question the nature of soil humus. Is it really the end product of decomposition? Or is it instead a varied mixture of organic substances with differing levels of recalcitrance, such as dead microbial bodies and their parts (called necromass), by-products of microbial metabolism (metabolites), plant-root remnants and exudates. If that is the case, what keeps the more labile materials from being consumed, as in the established models? Are there other major factors in play?

The evidence for a new version of what constitutes humus[j] has been growing and seems to have won the day. This version declares that carbon does not have to be recalcitrant to become stable in soil. In fact, labile C may become stable faster than recalcitrant forms[9].

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g The Century model and Rothamsted Soil Carbon (Roth C) model are well-known examples.

h The phrase "the slow death of soil humus" was used by Dr. Johannes Lehmann of Cornell University, one of the noted researchers behind the new model for soil carbon sequestration, at a workshop held in Ontario in 2012. It was meant to refer to the gradual change in our understanding of what constitutes soil humus.

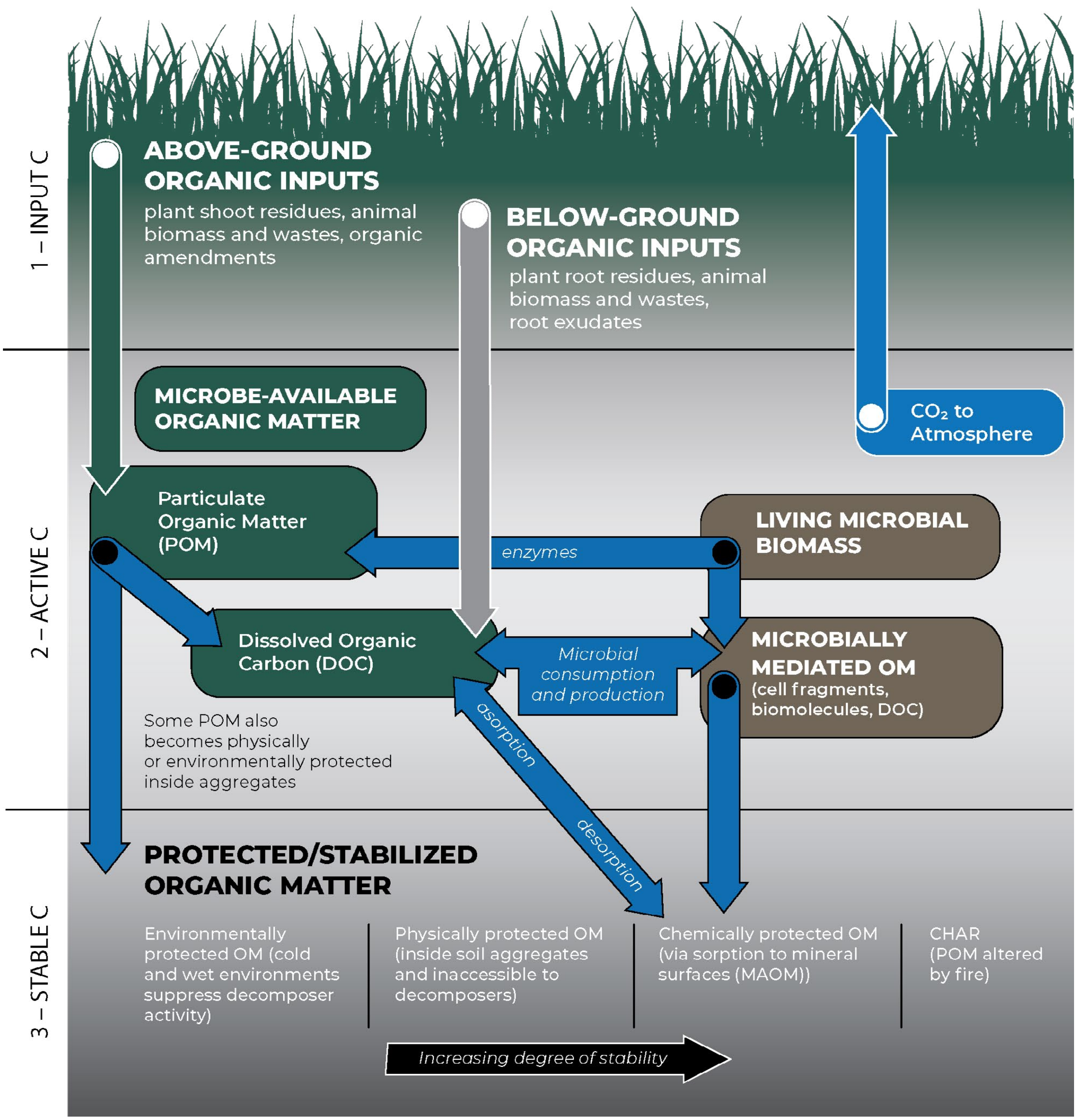
i [From Wikipedia] Metabolites are the products of a living organism's *metabolism*, which is the set of life-sustaining chemical reactions in organisms. The three main purposes of metabolism are: the conversion of food to energy to run cellular processes; the conversion of food/fuel to building blocks for proteins, lipids, nucleic acids, and some carbohydrates; and the elimination of nitrogenous wastes.

j Dr. Cynthia Kallenbach of McGill University states that… "the term humus was developed out of our prior understanding of soil-carbon dynamics, used to describe the recalcitrant material left behind that resists further decomposition. Because of the new paradigm, scientists are moving towards replacing the term humus with other terms such as persistent or stable carbon."

How it Works

Figure 5 illustrates the new model for carbon sequestration in soils. The area at the top of the figure (1 – Input C) represents carbon inputs, from both above and below the surface of the soil. These include plant residues (both shoots and roots), animal biomass and wastes (e.g., dead animals, manures) and plant-root exudates. Some of these materials enter as dissolved organic carbon (DOC) and are quite labile (e.g., plant-root exudates, residue leachates), while others enter as solids and have varying degrees of recalcitrance (e.g., shoots and roots). The carbon that goes into the DOC pool is immediately available to soil microbes as a source of energy. Alternatively, the solid material goes through two basic transformations before it becomes microbe-available: small soil-living insects shred the material, increasing its surface area and creating the pool known as *particulate organic matter* (POM); then microbes secrete enzymes that break down the larger POM molecules, releasing soluble forms of carbon into the DOC pool. The more recalcitrant the initial material (usually stuff made of larger molecules), the more resistant it is to the microbes and the longer it stays in the POM pool. This long-term POM was considered in the old model to be the principal basis for sequestration, but the new view sees it as only part of the long-term soil-carbon picture.

Figure 5: The New Science of Soil Carbon Sequestration



The middle area of the figure (2 – Active C) is where most of the action happens. This is the active carbon zone and it is dominated by soil microbes. They use the DOC for energy and as they do, a substantial portion is released as CO_2 (the product of their respiration). But a significant percentage of the carbon is transformed into other materials: cell walls, as well as internal and external metabolites, such as the sticky glues (polysaccharides) that they use to attach themselves to clay particles. These materials also have varying degrees of recalcitrance and some are used again and again as energy sources for other organisms. However, even while much of this carbon is quite labile, a significant amount of it manages to achieve stability, in various ways.

Which brings us to the third and lowest area in the diagram – long-term stable carbon, or what we have been calling soil humus (3 – Stable C). Evidence shows that this pool is comprised of carbon that is protected by four main pathways. One of those ways, of course, is *extreme recalcitrance*. A good example of that is char (*see* ***Box 3-2***). In other situations, environmental conditions (primarily low temperatures, as in northern boreal forests), slows down microbial activity, resulting in what we can classify as *environmentally protected carbon*[k]. Much of the POM that would otherwise be decomposed by microbes under more optimal environmental conditions can contribute to this pool. Most of the on-going protection of carbon in temperate regions, however, is either *chemical* or *physical* in nature. Carbon-rich materials, such as microbial necromass and metabolites, (primarily from the DOC pool), react with minerals in the soil, forming mineral complexes that decomposer microbes are unable to access. This chemical process occurs mainly inside the micro-aggregates described in Section 2. In addition, even more of that microbially processed carbon (primarily POM) is physically protected inside macro-aggregates, where conditions are such (e.g., low oxygen) that decomposer activity is low. (Note: an important point here is that the "chemically protected" process is very dependent on the existence of clay particles, which is why sandy soils are typically lower in SOM than clay soils).

Box 3-2

Char, Charcoal and Biochar

Char is organic material that has been heated in conditions with little or no oxygen. Most of the basic elements are driven out of the material as volatile gases, leaving behind a very recalcitrant form of carbon. Charcoal is one form of char, made purposefully as a fuel; biochar is another form of char, made purposefully as a soil amendment. Char also occurs naturally as a result of forest and grass fires, where heat from above chars organic materials below the surface, where oxygen levels are low.

Finally, as also shown in Figure 5, the word *stable* does not mean *irreversible*. All of the factors that provide long-term stability can be reduced or even eliminated, sending carbon back into the DOC pool or back into the atmosphere as CO_2. Factors that create and support good soil aggregation include a strong, healthy fungal population. Fungi are susceptible to significant population reduction via many management techniques, including tillage, improper pesticide use, overuse of fertilizer, and long periods without roots in the soil. Reduction in soil aggregation can expose physically protected carbon to degradation. Similarly, other changes in the soil environment can make even chemically protected or very recalcitrant carbon vulnerable. The stability of SOC depends on the management systems employed by the soil manager. This was true within the context of the older understanding of how carbon is sequestered in soil and is true under the newer version as well.

So, what is soil humus?

Carbon enters the soil in a variety of forms that range from extremely labile to extremely recalcitrant, but how much C stays in the soil for the long term (the factor that, along with the quantity of C inputs, really determines sequestration levels) is not a direct function of the chemical nature of those inputs; rather, it is a function of the size, diversity, and health of the soil food web. The bigger the microbial populations, the more necromass and metabolites produced for potential chemical and physical protection. The more diverse the microbial life, the more likely it will be that the conditions required for sequestration (e.g., good soil aggregation) will be met[l]. However, the chemistry or type of these inputs can *indirectly* influence sequestration by

k Dr. Kallenbach: "This pool of C is highly sensitive to climate changes and disturbance and could represent a large source of $\mathbf{CO_2}$ if, for example, wetlands were drained for agriculture use, or with warming of the boreal ecosystem".

l As described in Annex 2 (The Soil Food Web), good soil aggregation depends on the action of more than just bacteria. Soil fungi are critical to stable soil aggregates. Moreover, high levels of diversity means that soils are resilient to changes in environmental factors such as temperature and moisture levels, because functional redundancy is built into the system.

influencing the microbial community's composition and functions. For example, certain inputs such as corn residue may favour more fungal-dominated communities, which are better at supporting aggregation[10].

In summary, soil humus is not a pool of really stubborn (recalcitrant) carbon; rather, it is a complex conglomeration comprised of the detritus of microbial soil life, protected from further degradation by the very factors, such as good, stable aggregation, that are created and sustained by that same soil life. For those interested in delving deeper into the science of soil carbon sequestration, some of the key scientific papers on the subject are listed in Annex 3a.

What about erosion?

Figure 5 above represents the process of carbon sequestration in a "perfect world," where the landscape is flat and little soil disturbance occurs. In reality, of course, such is seldom the case. A farm (or golf course, for that matter) will have hillocks and hollows, and often incorporate streams, ponds, wetlands, etc. Practices such as tillage and leaving soil uncovered between crops have been shown to lead to significant erosion. Carbon tends to move from the high areas and concentrate in the lower areas. It also leaves the farm in drainage systems, streams and via wind erosion, ending up in larger water bodies or wherever wind movement results in soil build-up. Studies have shown that erosion is often the most significant factor in carbon loss for a farm ecosystem. These losses have major impacts on farm productivity and profitability.

From a climate-change perspective; however, carbon loss due to erosion is more complicated. The carbon lost to a farm may end up being sequestered somewhere else, which means no net loss; or it may end up in a situation where it is less protected, and more easily converted to CO_2, resulting in a net loss of SOC. Another consideration is the loss of productivity on hilltops, where erosion has reduced SOC levels to the point that crops fail or grow sparsely, reducing the carbon input from photosynthesis and slowing the process of sequestration that would rebuild SOC over time.

Fortunately, the negative impacts of erosion on overall SOC levels in soils can be mitigated through management. Section 4 discusses this benefit in more detail.

How is Carbon Measured and Accounted for in Soils?

SOC has an important role to play in climate change mitigation and adaptation. This is why establishing baseline SOC inventories and measuring subsequent changes to these inventories is increasingly important. SOC is, as mentioned above, about 50 per cent of SOM, and the latter is generally expressed as a percentage of the overall mass, or weight, of a given volume of soil. This percentage is determined as follows:

- Several soil samples are taken. These must be representative of the total area being considered. The depth of the samples is important, as it determines the overall volume of soil.
- Soil labs use various methods (e.g., loss on ignition) to calculate how much of the weight of these samples is comprised of organic matter (i.e., the concentration). This can be expressed as a percentage (e.g., 2.1 per cent SOM) and is the most common expression of a soil's carbon content (the SOC content would be about half of the SOM percentage, or 1.05 per cent).
- The bulk density of the samples is also calculated.
- Using the bulk density and the volume, an estimate of the total weight of the soil in the sampled area is calculated.
- The percentage SOM number derived from the samples can then be used to calculate the estimated SOM weight for the sampled area to the depth that the samples were taken (e.g., 100 tonnes of SOM per hectare), which would then generally be converted to SOC (50 tonnes per hectare, in this case).
- In summary, the sampling results can be expressed as a percentage SOM, as in point #2 above, or as a total weight of SOC per unit area (at a stipulated depth), as in point #5 above.

So, why are these different measurements useful?

From a soil manager's perspective, there are many benefits to knowing the level of carbon in your soil, and the agronomic literature usually sticks with SOM as a percentage of soil mass. Soil organic matter is of interest to agronomists, farmers and other soil managers for a couple of reasons: first, the extra SOM improves soil health, with all the benefits that brings (see Section 2); and second, since carbon only comprises about 50 per cent of SOM, the other 50 per cent includes many nutrients that provide benefits to growing crops. In this agronomic light, expressing carbon as a SOM percentage, rather than a carbon inventory (e.g., tonnes of SOC per hectare), has two immediate benefits: first, it uses the same terminology as the sampling, so no more calculations are required; and second, it allows for at-a-glance assessments of soil quality status and changes. SOM levels are more commonly used than SOC, as organic matter is more relevant and familiar to growers than the more basic carbon content.

From a climate change perspective, expressing changes as SOC rather than SOM is more convenient since you can easily convert units of SOC to units of CO_2. When SOC rises, it is reasonable to assume that this gain directly represents carbon that has been removed from the atmosphere. If SOC declines over time it has likely re-entered the atmosphere.

For a more detailed discussion of how soil carbon is measured, and how these measurements are used, see Annex 3b.

SECTION 4: Moving from principle to practice

What does the science tell us that we have to do, as soil managers?

Assuming that our goal is to optimize soil carbon and given the current scientific understanding of how carbon is sequestered in soils (*Section 3, above*), two fundamental *management objectives* arise.

The first, is to *effectively manage the flow of carbon* – in particular, the rate at which it comes into the soil. The more carbon that comes into the soil, the more potential there is to keep it there.

Secondly, managing the in-flow of carbon is not enough on its own. The carbon must be stabilized, or it will quickly leave as CO_2. As discussed above, the scientific consensus is that the most significant driver of carbon stability is the soil food web. The second fundamental objective, therefore, is to *manage soil in such a way that the size, diversity and overall health of the soil food web is promoted and sustained.*

What are the fundamental principles for sequestering carbon in soils?

Overview

Figure 6: Management Principles for Optimizing Soil Carbon

GOAL:
Optimize Soil C

OBJECTIVES:
Manage carbon flows optimally

Protect/enhance the soil food web

PRINCIPLES:
1. Keep live roots in the ground
2. Minimize soil disturbance
3. Optimize inputs
4. Promote diversity
5. Ensure soil remains covered

As summarized in Figure 6, some basic principles flow out of the goal and objectives. Different iterations of these principles can be found in the soil-health literature and in many online presentations by soil-health proponents. These are also considered *soil-health principles* since the health of a soil and its SOC content are closely related. SOC provides the food and habitat for the soil food web, which generates many beneficial soil functions (see Annex 2). Healthy soils build SOC and SOC contributes greatly to soil health.

The rationale for each of these prnicples, in terms of the goal and objectives, is as follows:

Keep live roots in the ground

The case for this principle is straightforward: live roots feed carbon to the soil, thus optimizing objective 1. Of course, live roots also mean living plants, which cover the soil and protect it from erosion and extreme weather, meeting objective 2.

Minimize soil disturbance

This principle's primary focus is objective 2 and it has a couple of important arguments to support it. First, disturbing the soil also disrupts microbe habitat, forcing these organisms to spend energy repairing what has been destroyed. This is particularly true of soil fungi, whose networks of fungal threads (called hyphae, or in groups, mycelia) are broken by tillage and other soil disturbances. Second, actions like tillage introduce higher levels of oxygen into deeper layers of the soil. Oxygen is often the major constraint on the growth of decomposer organisms. Once they get more oxygen, they reproduce and go to work decomposing the organic matter in the soil, releasing it as CO_2. An important consequence of both of the above is the loss of soil structure caused by the disruption of fungal threads (they hold macro-aggregates together) and the loss of organic matter.

Optimize inputs

This applies to the use of soil amendments, nutrients (natural and synthetic), and crop protection products. Amendments such as manure, biosolids and digestate can supply nutrition to crops and build SOC, but they need to be used properly. For example, composting these materials prior to application reduces the risk of pollution and increases soil carbon sequestration. Similarly, while nutrition is vital for building soil carbon (plants can't produce roots, shoots, and exudates without good access to nutrients), too much or improperly applied nutrition can have the opposite effect. As with the oxygen introduced by tillage, an over-abundance of nitrogen can reduce this normal constraint on decomposers, sending their populations soaring, along with their demand for soil carbon and the subsequent release of CO_2. Careful and balanced use of fertilizer, either synthetic or natural as in the 4Rs program, is a key to building SOC. Finally, crop protection products (e.g., fungicides) need to be used sparingly and carefully, as they can damage the organisms of the soil food web, reducing their numbers, and consequently, lowering the potential for SOC accumulation. Strategies such as Integrated Pest Management (IPM) are useful in mitigating unintended harm to the soil food web. 4R Nutrient Stewardship principles and IPM are important tools to ensure effective and safe use of crop inputs.

Promote diversity

Diversity above ground leads to diversity below ground. This is important because diversity brings with it resilience. As environmental conditions change in soil, due to extreme weather, for instance, diversity means that there is likely a set of organisms, dormant until now, available to take over as soil gets wetter, drier, hotter, or colder. This allows the process of carbon sequestration to proceed no matter what conditions exist in the soil, thus maintaining and building higher SOC levels over time.

Ensure soil remains covered

Keeping the soil covered protects the habitat of the soil food web and feeds the soil's biological residents. For example, cover crops feed soil organisms, both with root exudates and with their root and shoot residues. Similarly, crop residues both protect and feed the soil food web. When soil is left uncovered, it can dry out and erode via wind, water, tillage, etc. Keeping the soil covered at all times is a basic tenet of some of the world's most successful soil-health practitioners.

Common Beneficial Management Practices for Building SOC

Which carbon-sequestering practices are already used in Canada? Quite a few, although most have not reached the status of "business as usual." In Section 6, we discuss in more detail some of the most common BMPs currently employed in Canada, with a few real-world examples. Here, we take a higher-level look at BMPs and their potential to sequester carbon in soils.

The *types of SOC-building BMPs* are set out in Table 1. The eight categories organize the dozens of established and emerging practices[11]. Examples from these eight categories can be found in most, if not all regions of Canada, although some are more associated with specific regions. For instance: *minimum tillage* (specifically, no-till) is strongly associated with the western provinces; *cover crops* are more likely to be used in central Canada; while *diversity management* (specifically, *rotations*) are of specific concern in Atlantic Canada.

Table 1: Summary of Key SOC-Building Management Practices

Category	Basic Definition	Sub-Categories	Examples in Roadmap
Cover crops	Crops (commercial or non-commercial) grown primarily to cover and otherwise improve soil	• planting after harvest • frost seeding • inter-seeding • various termination options	Axten Farms Ferme Jocelyn Michon
Organic & biological amendments	Materials and/or inoculants added or retained to improve soil	• residue management • composted manure • composted food waste • compost tea • compost extract • inoculants • biosolids • raw manure • mulch	Axten Farms Perry Farm Saunders Vineyard
Animal management	Managing animals in such a way as to improve soil and build SOC	• adaptive multi-paddock grazing • grazing cover crops	Holdanca Farms
Nutrient management	Managing nutrients (synthetic or natural) in such a way as to improve soil and build SOC	• new testing methods • precision agriculture • 4Rs • legumes in rotation	Saunders Vineyard Perry Farm Axten Farms
Minimum tillage & compaction management	Minimizing soil disturbance and/or pressure	• no-till • strip-till • reducing tire pressure & equipment weight • controlled traffic • robots	Axten Farms Perry Farm Ferme Jocelyn Michon
Diversity management	Optimizing biological diversity above and below ground	• extended crop rotations • multi-species cover crops • relay cropping • intercropping • beneficial insect habitat • 60-inch corn	Axten Farms Ferme Jocelyn Michon
Use of perennials in annual cropping systems	Adding perennial plants to an annual crop rotation	• perennials (e.g., alfalfa, switchgrass, pasture) in annual rotation • agri-forestry (including alley cropping) • permaculture techniques	Holdanca Farms

The Carbon Sequestration Potential of Specific BMPs

As discussed in Section 3, both objectives – maximum carbon input and optimum management of the soil food web – are necessary to obtain high levels of sequestration. Therefore, applying a single practice or approach may not fully meet both objectives and may not maximize sequestration. In fact, the evolving science highlights that a *whole system of BMPs* is necessary to build optimum levels of SOC, especially if you want to do so as quickly as possible.

There are several practical reasons for assigning levels of sequestration potential to individual BMPs. First, it identifies the low-hanging fruit. If studies consistently show that a specific BMP results in significant sequestration, soil managers who don't want to change their approach entirely can focus on that one practice. In effect, this is what transpired in the western provinces, where no-till was the principal BMP identified, promoted, and adopted, and with good success. Second, it provides a base line for policy makers and others with an interest in building soil carbon to combat climate change. Goals can be set with some justification because credible numbers are available. And third, but not least, it allows governments and other agencies to create offsets and other payment schemes based on credible (if approximate) numbers. Of course, direct measurement of SOC gains is preferable, but for the present such methods are usually too expensive – their cost often outweighs the benefits to the soil managers (*this is discussed in more detail in Section 7*). The Government of Alberta, for instance, used modelling based on BMP research to set payment levels for farmers adopting no-till and elimination of summer fallow, two practices that have contributed to the rising carbon levels in Alberta's soils.

In that light, we have put together a list (*see Table 2, below*) highlighting some of the carbon-sequestration rates associated with various BMPs (and, in some cases, systems), as reported in the scientific literature. This is not a comprehensive list; rather, it is intended to provide a basic overview of the kinds of numbers associated with different BMPs and different soil-management approaches. Please note that the studies that yielded these numbers varied with respect to duration, depth of soil C measurement, and context. They are useful for general comparison and discussion purposes only.

Table 2: Documented Carbon Sequestration Potential of Common BMPs

Systems			
Management Practice	**Geographical Region**	**C Seq Rate**	**Reference, Notes**
		t C/ha/yr	
Conservation agriculture	Global	0.6	Review (2015)[12]
Regenerative organic	USA	2.3	Long-term trials, Rodale Institute[13]
Conventional no-till	Global	0.3	Review[14]
Convert cropland to pasture	Global	0.8	IPCC[15] (expert estimation)
Manure application	USA	2.4	Single study[16]
Cover crops	Global	0.32	Review[17]
Turfgrass establishment	USA	0.32 – 0.78	Single study[18]
Golf fairway, various BMPs	USA	0.98 – 1.05	Single study[19], 30-cm depth
Compost applied to rangeland	California	1.0	Single study[20], single application, resulting in on-going annual C additions up to 10 yrs
Compost with cover crops	California	1.15	Single study[21], 19 yrs, 2-m depth
Management intensive grazing	Southeastern US	8	Single study[22], several years, degraded land
Managed grazing	Global	2.1	Review[23]

In Section 5 that follows, we look at the potential for building SOC across Canada, if these practices were to enter the mainstream. In Section 6, we will look at how a few soil managers across Canada are using more than one BMP, or integrated approaches that include a mix of practices, to build SOC.

SECTION 5: What is the potential for building SOC in Canada?

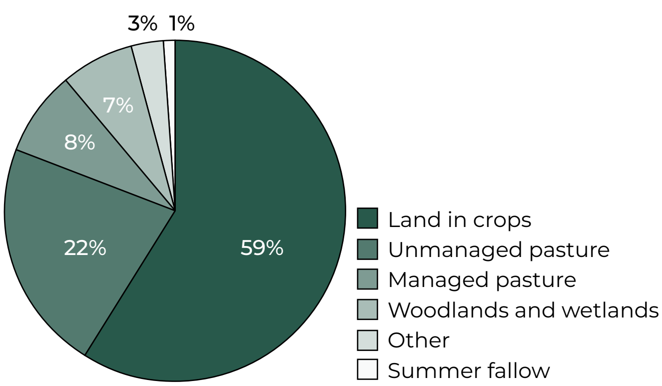
Previous sections have discussed the benefits of building SOC, the science of soil-carbon sequestration, and some of the practical aspects of how to go about it (from principle to practice). These sections were designed to lay the groundwork for the following case: *that Canada's managed soils present a real and significant opportunity with respect to climate change*. In a nutshell, the opportunity is to facilitate the replacement of some or all of the SOC lost from our soils over the past 10,000 years. By doing this, we could help to slow the rate of carbon accumulation in the atmosphere, buying some valuable time for the challenging task of switching from fossil fuels to more renewable sources of energy. The big question is…*how much can Canadian soil carbon sequestration help the world's climate cause?*

Managed Soil Uses in Canada

Canada's total land area is about 999 million hectares (Mha)[24]. Of this total, we manage approximately 68.9 Mha as agricultural land. As shown in Figure 7[25], about 59 per cent of this agricultural land is under crops (37.8 Mha) and 30 per cent (19.3 Mha) is pasture, including both managed and unmanaged grasslands. About one per cent is in summer fallow at any given time and woodlands and wetlands make up about seven per cent (4.6 Mha).

In addition, about 2 Mha are urban land[26], a portion of which has carbon sequestration potential (see *Urban Lands* below). Beyond agricultural and urban land, a large amount of managed or potentially managed soils with sequestration potential exist within large peri-urban land holdings, conservation areas, and federal and provincial parks. However, the various percentages of each of these latter sub-uses are difficult to estimate.

Figure 7: Agricultural Soil Uses across Canada



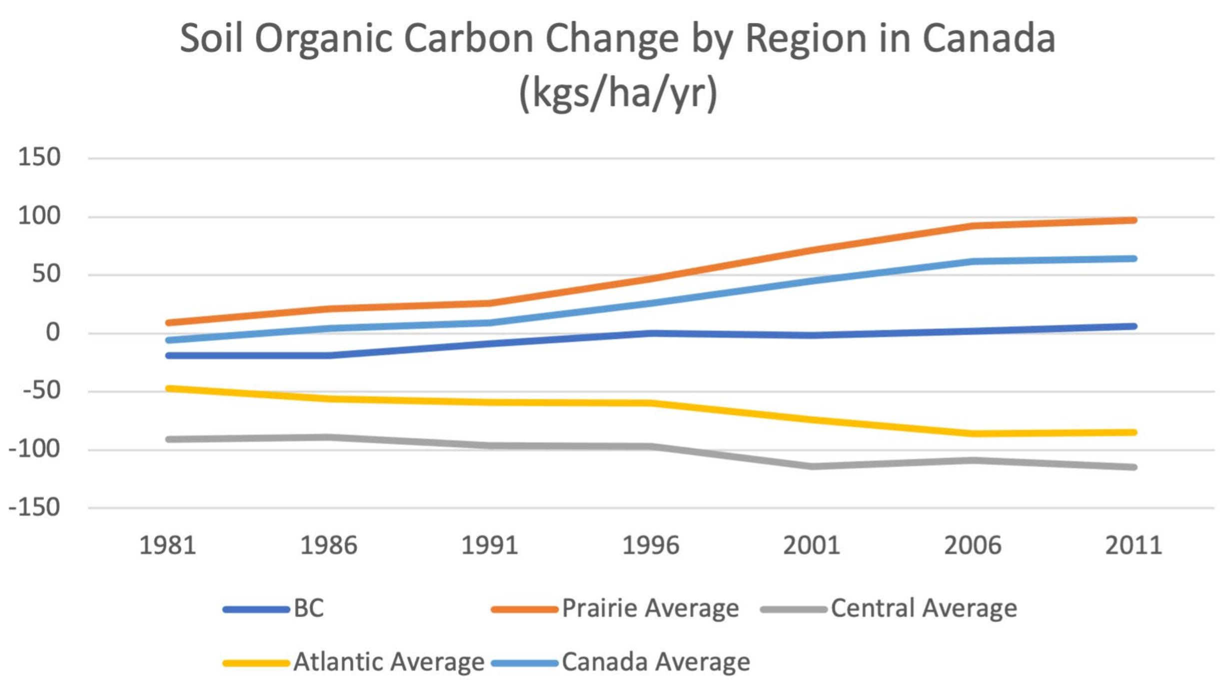
How much of this soil can be used to sequester carbon? It is hard to be anywhere close to precise, because conditions and circumstances within each category vary considerably. Moreover, the potential for Canadian soils to sequester carbon is dependent on the climate regime, topography, soil type and historical land use, making it difficult to generalize carbon storage findings for all of Canada.[27]

For practical purposes, we will focus on the two categories for which we have the most data and which may offer the most potential for SOC building in Canada – agriculture (68.9 Mha) and urban land uses (2 Mha). In the case of *agriculture*, we will look at regional differences as well as overall potential, as considerable data exist from each region of the country. The case of *urban soils* is very different. SOC data for these soils in Canada, whether regional or aggregated, is virtually non-existent. Accordingly, we will focus specifically on the potential for SOC building through turf management, a subject that has generated a fair amount of attention from U.S. scientists over the past couple of decades. This includes the management of urban parks, golf courses, the grounds surrounding industrial and commercial establishments, other municipally managed green spaces, and residential properties.

Agricultural Soils

Regional Trends in SOC

Figure 8: Soil Organic Carbon Trends in Canadian Agricultural Land, by Regional Average (adapted from AAFC, 2019)



Overall, Canadian soils are currently increasing in SOC; however, regional trends differ substantially *(Figure 8)*. The Prairie region manages 79 per cent of agricultural land in Canada, and these soils have been increasing their SOC content for decades[28]. Scientists believe this is due to three important changes in practice[29]:

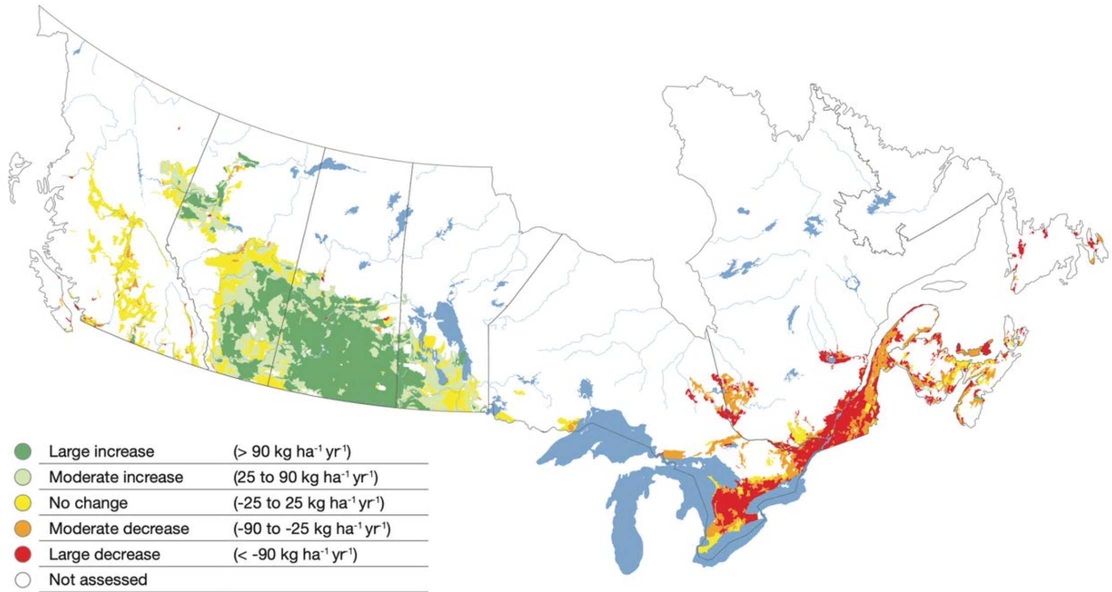
1. **Widespread adoption of no-till practices.** As discussed in Section 4, reducing tillage builds SOC by limiting the oxidation of soil organic matter by decomposer microbes while enhancing the living conditions for the wider range of organisms that are responsible for sequestering carbon.

2. **The reduction in summer fallow management.** This is the practice of leaving fields without a crop for a season, while controlling weeds with tillage or chemicals. The goal of this practice is to conserve moisture, but the lack of living roots in the soil for a season starves the soil microbial community, who instead use the soil's carbon stores for energy, lowering SOC levels and releasing CO_2 into the atmosphere.

3. **Increased conversion to perennialized systems**. Perennials, such as alfalfa and pasture grasses, sequester more carbon than annual plants, primarily because of their more extensive root systems and the lack of tillage.

Although successful long-term soil carbon sequestration has been achieved in the Canadian Prairies through these practices, there may still be room for growth, particularly with multiple BMPs, as practiced by a few regenerative farmers *(see Section 6)*.

Figure 9: Soil Organic Carbon Trends by Region (AAFC, 2019)



In other regions of Canada, specifically Central and Atlantic Canada, SOC has steadily declined for the past 40 years[30]. This is largely due to the extensive use of monoculture and other non-diverse annual cropping systems, heavy use of tillage, and a lack of carbon inputs from residue or cover crops. Only 24 per cent of land in Eastern Canada was under no-till in 2016, in contrast to 65 per cent of land in the Prairies[5]. In Prince Edward Island, for example, SOM levels have decreased since 1998 and areas of cultivation have endured the highest loss of SOM in this period[6]. Due to the steady declines, these regions have great potential for building SOC. Figure 9 shows a map of the current SOC status of Canada's soils on a regional basis.

General Overview of Potential

In general, both the scientific literature and the practical experience of many soil managers in Canada point to the significant potential of soil carbon sequestration on multiple soil uses within the country *(for a more detailed discussion of the latest science on this potential, see* Annex 5*)*.

Agricultural croplands and pastures show the greatest potential due to the substantial land area devoted to this soil use, the successes to date in Western Canada (illustrating the large-scale do-ability), and the significant carbon deficits that exist in soils in the rest of the country. However, even though there is a large body of literature devoted to research on practices that increase soil carbon, the highly variable nature of soils and climate across Canada present challenges for adopting these practices. While we have a good understanding of the many ways to improve SOC generally, in specific regions it remains a challenge to consistently store carbon long term.

Additionally, studies often target one practice and not a combination of strategies for optimal carbon storage. This shortcoming in the research has been highlighted in recent years with the growth of the regenerative agriculture movement. Sequestration rates higher than currently accepted levels *(see Section 6)* have been reported by many of these soil managers. Although these have not yet been studied thoroughly enough to be fully accepted as having real potential on a broad scale, they certainly point to the possibility that the potential ranges discussed here might be significantly higher. This research is badly needed.

In contrast to agriculture, commercial, recreational or residential land uses have not been studied in depth, with little research dedicated to Canadian soils in these categories. Research is needed to understand how much SOC is stored in managed turf-grass systems and how individual behaviours, planning guidelines, and developers are influencing carbon stocks. Although we don't have evidence from Canadian studies, the scientific work in the United States suggests that commercial, recreational and residential land uses are currently not utilized for carbon sequestration and could potentially become a net carbon sink, given that good soil management practices become widespread. This area holds potential for increased soil carbon storage. SOC BMPs are available to both commercial and residential soil managers (i.e., homeowners); however, it is important that they understand the value of these practices and how to apply them correctly. Additionally, better management of urban parks including optimal mowing, no thatch removal, compost additions, and prioritizing large growth trees will likely increase carbon sequestration, although more research in Canada is necessary to confirm this. *Again, see Annex 5 for a more thorough discussion of this topic.*

Projecting Potential in Canada

Potential Carbon Storage Rates in Canada

What does all of this mean in real, practical terms? What can we expect, or at least aim for, in terms of real reductions in GHGs through soil carbon sequestration? Here we will attempt to provide tentative and provisional answers to these questions. We simply do not have enough data to make detailed and authoritative projections, but perhaps we can offer a credible and potentially achievable range of targets.

Let's start with a summary of some of the more well-documented estimates for rates of soil carbon sequestration in Canadian managed soils, as well as two examples from U.S. golf course studies *(see also Table 2 in Section 4 for some international examples).*

Table 3: Carbon storage rate across different treatments and regions of Canada

Practice	C Storage Rate (Mg C ha-1 yr-1)	Region	Reference	Notes
Replacing annal with perennial species	0.6	Canada	VandenBygaart et al. 2010	e.g., moving from annual crops to pasture
Compost from: food waste (FW), yard waste (YW), poultry manure (PM)	0 (1.3) 0.9 1.2	Ontario	Yang et al, 2014	10-year study, with one compost application. FW compost also sequestered C (1.3), but double application rate needed
Adopting no-till	0.23	Saskatchewan	Prairie Soil Carbon Balance Project – Maillard et al. 2018.	Study conducted over 23 years
Removing summer fallow	0.23	Prairie region	VandenBygaart et al. 2010	Practice has already dropped by 50 per cent in the west over past decade[m]
Cover crops	0.32	Global (including Canada)	Poeplau and Don, 2015	Long-term effect of substituting winter fallow with cover crops as part of an annual crop rotation
Golf course: **-green** **-fairway** **-fairway** **-rough area**	0.9 1.0 3.6 2.6	Colorado Ohio	Qian and Follett, 2002 Selhorst and Lal, 2011	Sequestration rates vary by management and region, but climates comparable to many parts of Canada

m As reported by SCCC, via Stats Can -- https://www.soilcc.ca/ggmp_feature_articles/2004/2004-04.php

Projections for Agricultural Land

To develop some projections for agriculture's potential to pull carbon out of the atmosphere, we created a simple calculation matrix *(see Table 4)*. The calculations apply the following formula to a combination of regional and end-use categories:

Area (millions of hectares, or Mha) x SOC Seq Rate (tonnes C/ha/year) x adoption rate (ratio: ha adopted/not-adopted) = Total SOC increase per year

Then, to get GHG reduction equivalents: *SOC increase/year x 3.67 = GHG mitigation (tonnes* CO_{2e}*/year)*

In Table 4:

Column 1 includes nine categories: six for field crops, two for pasture, and one for wetlands and woodlands situated on agricultural land. Among the field-crop categories, we differentiated between regions (five categories) and land in fallow. In Western Canada, we differentiated between land currently managed with conservation tillage (primarily no-till) and land where conventional tillage systems are still used. The other regions of the country (B.C., Central Canada, Atlantic Canada) were treated as if there were no significant BMPs already widely in use. With pasture lands, we did not specify by region, but did differentiate between managed and currently unmanaged pasture. The other non-regional category refers to landscape-level management practices (e.g., conversion to woodland or wetland).

Column 2 indicates the type of management change(s) projected.

Column 3 lists the most appropriate carbon storage rates, as documented above and in Section 4. Because we are assuming a minimum of two BMPs being adopted in all cases[n], we used the figure of 0.6 tonnes per hectare per year as our base sequestration rate for row crops[o]. We reduced it to 0.4 t/ha/yr for Western Canada where no-till has been the norm for many years. The rationale is that these lands have been gaining carbon at 0.2 t/ha/yr[p] and bringing them up to 0.6 t/ha/yr would be an additional gain of only 0.4 t/ha/yr.

Column 4 lists the area of land managed under each of the categories in Column 1.

The other significant factor in our projections is the rate of adoption of multiple (two or more) BMPs by farmers. We used three potential rates *(box directly below column 5)*. For our lowest scenario, we adopted a 15 per cent adoption rate. This is roughly the figure for the proportion of innovators and early adopters in any given population, as per innovation diffusion theory (*see* Annex 7A). In other words, our low projection is what we could expect if only this leading-edge group adopts the SOC-building practices described in this report. In fact, this process is well underway in Canada, so one way to look at our lowest projection is that it is what will happen regardless of the level of intervention by government and/or other stakeholders.

Our medium scenario assumes a 50 per cent adoption rate. Again, referring to innovation diffusion theory, this is the outcome if the early majority also adopts these practices. Finally, our high scenario assumes a 67 per cent adoption rate. This would be the outcome if we were to make significant inroads into the group of more conservative actors that innovation diffusion theory call the late majority. This usually only happens once the new practices have become the norm (as in our medium projection).

Column 5 shows the amount of carbon (in megatons of C) that would likely be sequestered for each region/practice and under each of the three adoption-rate scenarios. As per the equation above, these figures represent the area times the sequestration rate times the adoption rate.

Column 6 shows the GHG mitigation impact (in megatonnes of CO_2). These figures are simply the figures in Column 5 multiplied by 3.67, the conversion factor for C and CO_2 *(see Box 2-2 in Section 2).*

n The assumption is that in all cases farmers would go beyond a single practice and adopt a package of (at least) two BMPs best suited for their region, soil type, crop, etc. For example, a no-tiller in Alberta might consider adding to their tool kit two or more of the innovative BMPs employed by the soil managers in Section 6, such as controlled traffic, inter-cropping, use of stripper headers, compost or compost extract, animal integration, etc.

o As per the review referenced previously, in Table 2: Srinivasrao, Lal, Kundu, and Thakur. 2015. "Conservation Agriculture and soil carbon sequestration". In Conservation Agriculture, pp. 479-524. Amsterdam: Springer. [As referenced in Toensmeier, 2016].

p See Table 3, above (Prairie Soil Carbon Balance Project – Maillard et al. 2018.).

Table 4: Theoretical Contribution of SOC to Canada's GHG Reduction Target - Agriculture

Column 1	**Column 2**	**Col 3**	**Col 4**	**Column 5**			**Column 6**		
Soil Use Category	**Management Change(s)**	**Assumed Seq Rate t/ha/yr**		**C Seq/yr in Canada**			**GHG Mitigation/yr in Canada**		
			Area Mha[q]	**Low**	**Med**	**High**	**Low**	**Med**	**High**
				Mt C			**Mt CO_{2e}**		
No-till, Western Canada	From one to multiple BMPs	0.4[r]	18.3[s]	1.10	3.66	4.90	4.0	13.4	18.0
Till, Western Canada	Adopting multiple BMPs	0.6[t]	12.9	1.16	3.87	5.19	4.3	14.2	19.0
Central Canada	Adopting two or more BMPs	0.6	5.5	0.50	1.65	2.21	1.8	6.1	8.1
Atlantic Canada	Adopting two or more BMPs	0.6	0.4	0.04	0.12	0.16	0.1	0.4	0.6
B.C.	Adopting two or more BMPs	0.6	0.6	0.05	0.18	0.24	0.2	0.7	0.9
Bare or fallow	Eliminate fallow	0.25[u]	0.9	0.00	0.11	0.15	0.0	0.4	0.6
Managed pasture	Adopt AMP Grazing	1[v]	5.1	0.77	2.55	3.42	2.8	9.4	12.5
Unmanaged pasture	Adopt AMP Grazing	0.75[w]	14.3	1.61	5.36	7.19	5.9	19.7	26.4
Woodlands, wetlands	Increase area	1	4.6	0.69	2.30	3.08	2.5	8.4	11.3
Total Ag			**62.7**	5.9	19.8	26.5	**21.7**	**72.7**	**97.4**
				Adoption Rates					
				Low	Med	High			
				0.15	0.5	0.67			

Projections for Urban Lands

The potential of urban lands to sequester carbon and provide GHG reductions appears to be real and perhaps significant, but there is a lack of data for this opportunity in Canada. Table 5 below shows some projections for golf courses and urban residences (lawns and gardens), which together make up only about a sixth of Canada's approximately 2.3 Mha of urban lands[31][32]. Although the projected benefits from urban lands are much lower than those of agriculture, and it is unlikely that they would ever be counted towards our national target, they are still worth pursuing. The co-benefits, combined with the empowerment and sense of participation they could bring to the average citizen, municipal employee, and/or golf-course manager, make these urban targets invaluable to tackle climate change.

q Statistics Canada. Table 32-10-0406-01 Land Use.

r The 0.6 figure (see Ref #6 below) was reduced by 0.2 to account for the sequestration already occurring due to no-till practices (0.23: Prairie Soil Carbon Balance Project – Maillard et al. 2018).

s Statistics Canada. Table 32-10-0408-01 Tillage practices used to prepare land for seeding.

t The 0.6 figure is for "conservation agriculture", which we have assumed to mean more than one BMP adopted. This is generally consistent with other reported figures (see Reference 12 – Srinivasrao et al.).

u The 0.25 t/ha/yr sequestration rate is from VandenBygaart et al. 2010 (see Table 3).

v There are figures in the literature that are much higher than 1.0 t/ha/yr for managed grazing (e.g: 2.1 in Toensmeier, 2016; 8.0 in Machmuller et al. 2015.). We chose a range of 0.75 to 1.0 t/ha/yr as a conservative and defensible figure that still shows the high potential involved in managing grazing for carbon sequestration, relative to cropping systems.

w See above. For our calculation purposes, the rate for currently unmanaged pasture was dropped from 1.0 to 0.75 to recognize the possibility that these lands may already have high SOC rates; alternatively, however, this number could be much higher if the unmanaged pasture has been degraded by unmanaged grazing.

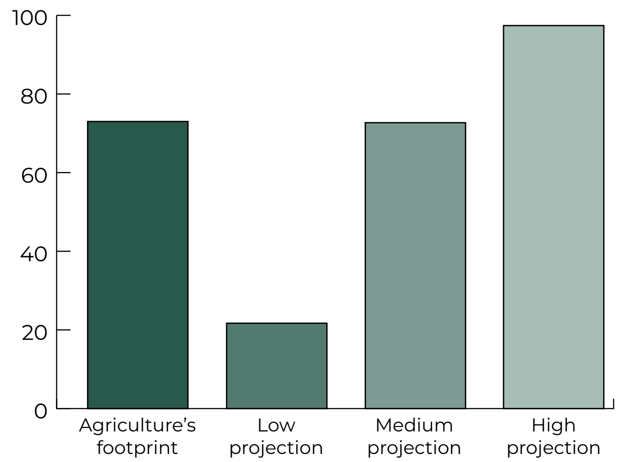
Table 5: GHG mitigation per year in Canada – Projections for urban soils

Soil use category	Seq rate	Area	Projections by % uptake		
Urban	tC/ha/yr	Mha	Low	Med	High
Golf courses	0.5	0.15	0.07	0.14	0.21
Residences	0.5	0.20	0.09	0.18	0.28
Total urban		**0.35**	**0.16**	**0.32**	**0.48**

Potential Impact of SOC on Canadian GHG Emissions

Figure 10 shows the potential impact of SOC sequestration on Canadian agriculture's contribution to the country's GHG emissions. Canadian agriculture contributes 73 Mts per annum annually to our country's total annual emissions of 729 Mt[33] (2018 data).

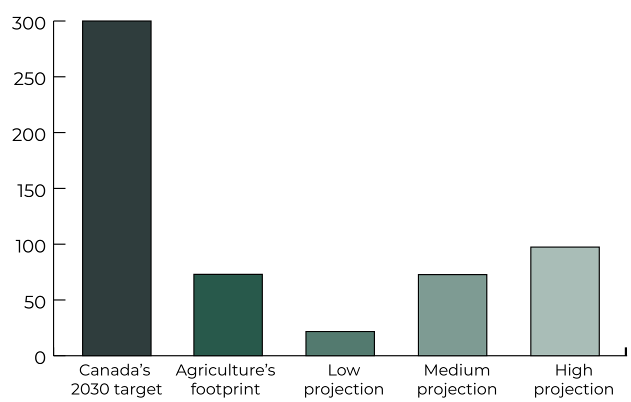
Figure 10: Potential to Offset Agriculture's GHG Footprint



- Figure 10 (Column 1) represents, for comparison purposes, Canadian agriculture's GHG footprint (as of 2018). However, please note that agriculture's total contribution is comprised of more sources than soil; it includes things like N_2O and CH_4 emissions, on-farm energy use, and the GHGs resulting from the manufacture and transportation of farm inputs.
- Column 2 shows the impact of our lowest projection, 21.7 Mt or about 30 per cent agriculture's footprint.
- Column 3 is our medium projection (72.7 Mt) and would basically offset agriculture's GHG footprint.
- Column 4 shows the impact of our high projection (97.4 Mt), which would offset agriculture's GHG contribution plus about 24 Mt.

With respect to Canada's current GHG reduction target for 2030 (about 300 Mt), our projections show that soil carbon increases could meet 7%, 24%, or 33% respectively. *See Figure 11.*

Figure 11: Potential Impact on Canada's 2030 GHG Reduction Targets



How realistic are these projections? While they are technically achievable, many objections can be raised. Some of these will have to do with the challenges involved in widespread adoption of new practices in agriculture. These are discussed in Sections 7 and 8.

Others have to do with the remaining storage potential of the 80 per cent of agricultural lands that have already been building SOC for, in many instances, two or more decades.

- How much, if any, of this area is approaching equilibrium?
- Is the equilibrium point for land managed under no-till, with no summer fallow, as high as can be achieved? Or can the introduction of a suite of additional BMPs, approached with a systems philosophy, as opposed to a single-practice focus, boost that equilibrium to an even higher level?
- Can managed systems approach or even exceed natural systems in terms of carbon storage, given optimal management?
- Will new, disruptive technologies be employed (e.g., biochar[x]), that have the potential to build SOC at higher levels more quickly?

x For a discussion of biochar and its potential as a SOC building tool, see the *Soil Organic Carbon Tool Kit*.

These questions are crucial, because the high SOC accrual levels in our projections depend on that already increasing 80 per cent of Canada's agricultural lands being able to up their game even further, even if it is only by a small increment.

Last, but not least, we acknowledge that the best way to use these projections is to treat them as aspirational, similar in nature to the goal of the 4 per 1000 initiative, rather than as a true technical assessment. For those interested in the latter, we refer you to a recently published paper entitled "Natural Climate Solutions for Canada," collaboratively authored by Drever et al (2021) in Science Advances (7). This work, which integrates economic factors with a technical assessment in estimating the potential of nature-based solutions to climate change, provides a very solid basis for the development of policy in this important area. We do note, however, that the idea of synergy between practices (the concept of a *systems approach* to building SOC), may hold considerable promise for additional SOC gains, and is not included in the Drever at al. analysis. Its absence is probably due to the lack of scientific work on this aspect of soil management. Studies looking at soil-regeneration systems as a whole are scarce to non-existent and are badly needed.

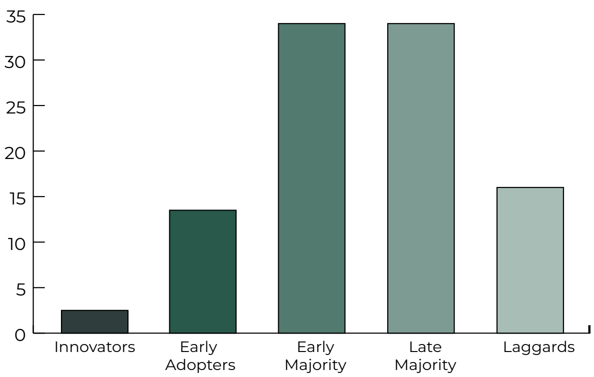
Despite these challenges, we believe that the answer to the question we posed at the beginning of this section – *how much can Canadian soil carbon sequestration help the world's climate cause?* – is this: ***perhaps enough to offset agriculture's GHG footprint, but certainly enough to justify a significant effort by all of us, from individuals to corporations to governments, to make it happen.***

SECTION 6: Innovators and early adopters lead the way

Innovation Diffusion: From leading-edge to business-as-usual

The *theory of innovation diffusion* is based on the concept that there are definable stages in the way that societies integrate new systems or technologies. This theory is not new; in fact, it has generally been accepted in many fields, including agriculture, for decades. These stages, as shown in Figure 12, are:

Figure 12: Theory of Innovation Diffusion



Stage 1, the *Innovators* – these are the people or organizations who are introducing new ideas, practices, technologies, or other types of innovations in a particular field. By definition, innovators have few peers at the beginning, at least in their own region (they may be introducing an innovation that has had significant uptake in another part of the world).

Stage 2, the *Early Adopters* – this is the group that begins the process by which the innovators' work is spread further afield. It is in this stage that word of the value of the innovation begins to spread and take root.

Stage 3, the *Early Majority* – this is the group (about one-third of the total) that are open to change, but skeptical. Once their concerns are addressed, they will adopt a new approach quickly.

Stage 4, the *Late Majority* – this group (also about a third of the total) is more conservative than the early majority and will only adopt new practices once they see that they are becoming the norm.

Stage 5, the *Laggards* – this is the relatively small group that are reluctant to change even in the presence of abundant evidence and changing norms. They usually require substantial pressure (e.g., evident competitive disadvantage, government penalties or regulation) to change their approach.

Research has shown that there are specific best practices with respect to communications, incentives, and other tools for promoting behaviour change that are best suited to each of these categories. These will be discussed further in Sections 7 and 8. *For more specific information on Innovation Diffusion see* Annex 7b.

Where do we stand currently?

Where do soil carbon practices fit in this model currently? This varies between practices and regions. For instance, no-till is probably in the late majority stage on the Prairies. Cover crops may not be much beyond the innovator stage in Atlantic Canada, but are comfortably within the early adopter stage and could be pushing into early majority status in Central Canada. Virtually all our informants told us that in general, and with respect to soil health and soil carbon, we are clearly in the early adoption stage, and the challenge is to move the process into the early majority as soon as possible.

This section provides examples of six soil managers in Canada who are in the innovator or early adopter ranges with the management practices that they employ. The intent here is to highlight both the opportunities and challenges associated with building SOC currently in this country, and provide some early evidence that the potential for building SOC in Canada is real, achievable, and can be a significant contribution to meeting Canada's climate change commitments.

Building SOC on the Prairies

As mentioned above, Western Canada has embraced conservation tillage (primarily no-till) over the past few decades. The importance of this for Canada's soil carbon sequestration efforts was discussed in Section 5. The success on increasing soil carbon in Western Canada is in part a reflection of the conservation ethic that farmers demonstrate in all parts of Canada and the fact that reduced tillage systems were shown to be profitable. Together, these influences led to greater-than-average innovation on western Canadian farms.

The two examples that follow certainly fit into the innovator mold. The first of our model farmers grows grains primarily, the second grows potatoes as a principal crop.

A Hearty Mix of BMPs

Axten Farms

Derek and Tannis Axten farm 6,000 acres in southern Saskatchewan. The climate is dry, with about 10 to 14 inches of precipitation per year, and their soil is a sandy clay loam. They grow small grains, with a lot of diversity. Their 15 to 17 annual crops include spelt, chickpeas, buckwheat, faba beans, flax, forage barley, and forage oats. They are also seed growers, producing pedigreed durum wheat, barley, and oats.

Long-time no-tillers, the Axtens' evolution into regenerative agriculture began with a couple of chance encounters at field days in the United States. The first was in 2006 when an equipment salesperson suggested that Derek visit the Dakota Lakes Research Farm in Pierre, South Dakota, headed by Dr. Dwayne Beck. The second came in 2010 when he was standing in a line at a concession booth and struck up a conversation with the fellow behind him, who turned out to be Gabe Brown, noted American soil-health advocate and rancher. Derek took Brown up on an invitation to visit the latter's ranch near Bismarck, North Dakota, and he really liked what he saw there – a soil that he says looked like dark black cottage cheese. These two meetings launched this farming family into the world of regenerative agriculture. They haven't looked back since[y].

y For more information on the Axtens, visit their website at www.axtenfarms.ca.

BMPs Employed and Planned

Table 6 summarizes 10 beneficial management practices that the Axtens have adopted over the past decade. This list will undoubtedly grow as they experiment with other opportunities.

Table 6: Beneficial Management Practices at Axten Farms[34]

Practice	Description
No-tillage	Crops direct seeded via drill, with minimal soil disturbance.
Controlled traffic	Equipment always driven over same area (known as tram lines), which reduces compaction in areas where crop is grown.
Cover crops	Crops grown as covers are planted right after harvest into standing crop stubble and include: cool-season grasses like oats or annual ryegrass; warm-season grasses such as millet; brassicas such as radish or yellow mustard; broadleaves like buckwheat; and legumes such as clover.
Relay cropping	Seeding cover crops in between crop rows gives them an early start. Experimentation includes increased row spacing to allow more light for covers.
Diverse rotations, companions	Crops are diverse (15 to 17 annually) and rotated to avoid disease issues and build diverse soil microbiome. Companions, such as red clover and alfalfa, are used where feasible to increase soil cover, build diversity, and take advantage of complementary traits.
Synergistic intercropping	Two or more cash crops grown together. Most are grown in mixed rows, but some in separate, alternating rows.
Compost extract, tea and minerals	Microbes extracted from compost into water, applied to soil with seeds to increase microbial activity in root zone; teas made from extract by adding microbe foods and brewing, applied to leaf surfaces to suppress disease and feed plant. Added minerals ensure availability of micronutrients.
Livestock integration	Cattle from neighbouring farm are brought in to graze cover crops. They trample the soil and leave manure behind, increasing fertility.
Reduced synthetic inputs	An overall 80 per cent reduction in synthetic fertilizer (100 per cent with the intercrops), with no loss in yield. Insecticides no longer used.
Stripper headers & stubble retention	Stripper headers remove heads of grain at harvest while leaving the straw behind as stubble. The stubble protects the soil, conserves moisture, and keeps the wind from blowing the snow off the high areas and into the low ones, so that there is a more even distribution of moisture in the spring.

As Table 6 illustrates, the Axtens go well beyond reduced tillage, cover crops, and more varied rotations – the three most common soil-building management practices in Canada. For a closer look at a few of these BMPs, their challenges and their rewards, see Annex 6b.

Box 6-1: Soil carbon and infiltration rates on Axten Farms

As described in Section 2, building higher carbon levels in soils is associated with better soil structure, which in turn leads to better rainfall infiltration rates. When the Axtens began their soil health journey, more than a decade ago, their soil could only infiltrate about 0.5 inch of rain per hour – the rest would run off. Now, their soil's infiltration rate has improved to 6” per hour (1” in 30 seconds). This not only reduces run-off and its potential pollution, it also increases the farm's resilience to drought as well-aggregated soils hold more water.

Results

Derek Axten considers the cornerstones of his operation to be low-disturbance farming, controlled traffic, intercropping, cover crops, and compost. Together, these practices have improved his soil's capacity to manage water (see Box 6-1), increased his yields, and made their farm more resilient and profitable.

SOC

The Axtens have increased their SOM by about one per cent over the 10 years that they have been using a regenerative approach. As outlined in Annex 6b, this corresponds to an annual increase of about 1.5 tonnes of SOC per hectare per year, considerably above the rate of about 0.2 tSOC/ha/yr ascribed to Prairie no-till on its own.

In their Own Words

The Axtens are all about their soil. The headline on their farm website is "loyal to the soil." They have gone well beyond no-till in their efforts to build soil carbon and create healthy soil and healthy plants. Derek says: *"The biggest barrier is mindset. Changing from a focus on plants to one on ecosystems is not easy. The key is to start experimenting."*

Growing Potatoes and Carbon in Alberta

Perry Farm

The Perry Farm, located near Taber, Alberta, is a fourth-generation, 5,000-acre, multi-crop operation with a focus on soil health. Brothers Harold and Chris, along with their wives and children, are the current mainstays, although their father Gerald is only semi-retired and still active. Harold was the recipient of a Nuffield Scholarship in 2006, something he experienced as "a breath of fresh air." It allowed him to travel widely for several weeks, learning about healthy soils, as well as to spend 10 months in South America, with the same purpose.

Their main crop is potatoes – 1,200 acres are devoted to spuds each year – which are sold to Frito Lay and McCain. They have another 3,800 acres of crops, which include processing peas, grains, sunflowers, seed canola, spring wheat, winter wheat, barley and grain and corn silage. All of their land is irrigated[z].

BMPs Employed and Planned

Their longest-tenured SOC-building BMP is the application of compost. They started this 30 years ago and for a long time they bought the compost from a supplier. They eventually found the quality not up to their requirements, so now they make their own – 12,000 tonnes year – from locally sourced feedlot manure. They apply the compost to fields with a green manure cover crop, then plough it in.

They ridge their potato fields in the fall, then plant covers. The ridges allow for more surface area per field (the cover crops grow up and down and over the ridges) and help the fields dry out more quickly in the spring. They use a controlled traffic system[aa] and are the only potato farmers (as far as they are aware) that use this BMP. They also do intercropping with winter wheat and multi-species covers, and make sure at least one field per year is planted to a green manure. Their potato rotations are every four years, and they have an interesting and innovative system for maintaining this rotation interval – they do land swaps with neighbouring farmers.

They also operate an anaerobic digestor (AD) on the farm. In addition to manure, the digestor takes all the potato culls. This is important, because the culls don't go back to the land unprocessed (as was previously the case), a practice that can spread disease. In addition, the digestor produces 20,000 tonnes of digestate annually, all of which is used as an amendment on the farm. Finally, the AD provides enough electrical power to meet all of the farm needs, plus three times that

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z For more information on the Perry Farm, vist their website at: https://perryfarm.ca/the-perry-farm

aa Their "tram" system is demonstrated in a YouTube video entitled "Harold Perry: New Planting Practices".

amount for sale to the power grid.

Harold and Chris have other plans for boosting soil health:

- they are experimenting with a Johnson-Su Reactor[ab], using leaf and yard waste as an input, and hope to use the resulting high-diversity, fungal-dominant compost as a seed inoculant;
- they are interested in companion cropping and are looking for the best combinations for increasing both profitability and soil health;
- they are also looking at species selection, compost extract and teas, in-season foliar application of nutrients, and mechanical weed control (Harold is hoping that robot weeders will soon be available to replace herbicides).

Results

The Perrys only use one fungicide, and only as needed, whereas most potato growers need five or six to keep diseases at bay. At the same time, their potato yields are three tonnes per acre higher than average for their region and the plants last longer into the season. The nutrient levels in their fields are always very high, allowing them to use fertilizer more efficiently, without sacrificing yields.

SOC

Their SOM levels have risen from 1.7 per cent to 2.7 per cent (averages) and their goal is to grow SOM to five or six per cent and maintain those high levels. At their current rate, the Perrys have built SOC in their fields at a rate of about 0.75 tonnes per year – an excellent achievement for an operation that focuses on potatoes, a crop notorious for lowering soil carbon stocks.

Building SOC in Central and Eastern Canada

A Biological Approach for a Perennial Favourite

Saunders Vineyard Profile

The Saunders family own and operate a 17-acre organic vineyard in Beamsville, Ontario. They grow grapes (Chardonnay, Cabernet Franc, Merlot, Riesling, and Pinot Noir) for two high-end wineries in southern Ontario. They are situated on what is known as the "Beamsville Bench," a narrow plateau between the Niagara Escarpment and Lake Ontario. The dolomitic limestone clay-loam soils on the bench are deep and hold moisture well. In addition, the microclimate associated with the bench is ideal for fruit trees and wine grapes.[ac]

Ann-Marie Saunders is now the driving force behind the business, although she has help from several family members, including her 99-year-old father, Warren[ad] (the vineyard's founder). They became certified organic and started incorporating biodynamic practices in 2013, but Ann-Marie says that the real soil improvements started a few years later, when they adopted soil-health practices.

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ab The Johnson-Su Reactor is a specialized in-vessel, zero-disturbance composting system developed by Dr. David Johnson and Hui Chun Su. The reactor is designed to age compost for a longer period, with no disturbance of the pile for one year (oxygen channels are built into the system). The goal is to increase the diversity of the compost's microbial community, particularly the fungi.

ac For a more detailed account of the Saunders operation, including its fascinating history, see "Greenbelt Farmers: Sustaining Soil Health", published by the Friends of the Greenbelt Foundation, December, 2018.

ad Warren Saunders' story is an inspiring one. You can read about it in this 2017 Globe and Mail article.

Box 6-2

Monoculture vs Diversity – An On-Going Debate

The basic tenets of "regenerative agriculture," as they apply to grazing, practiced by rancher John Duynisveld (*see John's story later in Section 6*), and promoted by soil-health advocates such as Gabe Brown and Dr. Allen Williams, include the *principle of maximizing diversity*. This is accomplished in pastures by a system of closely-managed, high-intensity grazing, which its proponents state results in a highly diverse pasture. This diversity results in many benefits, including high levels of carbon sequestration. Although these benefits have been demonstrated in practical applications all over the world, good scientific studies to corroborate these methods have either not been conducted or have been inconclusive. Proponents argue that this type of system is difficult to study using traditional scientific methods because it is so complex and adaptive. The practice depends on detailed observation followed closely by appropriate response. Accordingly, it is never done the same way twice, even though the basic principles are followed.

An alternative view is promoted by experts such as Dr. Llewellyn Manske, range scientist at the North Dakota State University Dickinson Research extension center, the developer of the "twice-over" grazing system. In this approach, animals are allowed to graze *monoculture pastures* at just the right times, physiologically, in the growth of the grass plant, maximizing both plant growth and carbon sequestration. Dr. Manske's system requires a monoculture to work properly and the science supporting his position is solid and plentiful.

This juxtaposition highlights an emerging divergence in soil carbon circles, between the "reductionist" vs "holistic" approaches to soil management. The former attempts to understand the individual components of a system, then control those components to yield an optimal result. The latter is based on the thinking that we simply cannot fully understand all the complexities of natural systems, so we should attempt to model nature as closely as possible (an approach known as *biomimicry*) in order to optimize the system's benefits.

BMPs Employed and Planned

The Saunders have modified their tillage practices to reduce soil disturbance, implemented mowing between rows to control weeds, applied manure, and brewed and applied compost teas, which included biostimulants such as molasses, black earth humates, and fish hydrolysate. Most recently (2020), they began foliar application of micronutrients as well.

They are participating in a Benchmark Study conducted by Dr. Sarah Hargreaves at the Ecological Farmers of Ontario Association (EFAO), which will measure active carbon, organic matter, water infiltration, and basic soil nutrients. This project is studying how BMPs, such as the ones that the Saunders have implemented, can improve the soil. They have also recently built a Johnson-Su Reactor[ae] and are looking forward to applying this specialized compost to their vines, either via the compost tea or as an extract.

ae See Footnote ae, above.

Results

Ann-Marie feels that it is too early to make a definitive judgement on how their use of innovative practices such as compost tea and foliar application of micronutrients is affecting the vineyard's overall productivity. She feels that it will take several years to get to that point. She does note, however, that this past season provided one of their best harvests yet.

Table 7: SOM Levels for Saunders Vineland, 2000-2019

Year	% SOM
2000	2.4
2014	2.5
2016	2.6
2018	2.7
2019	2.9

SOC

Table 7 shows SOM numbers from the tests done on the vineyard soils since 2000. Bearing in mind the unknowns here, as well as the assumptions made in calculating SOC gains (*see* Annex 6b), it appears that the rate of SOM gain is increasing substantially since the introduction of practices intended to boost the soil and plant microbiomes. The increase of an additional 0.3% of SOM in the three-year period from 2016 to 2019 is 1.5 times the amount sequestered in the 16-year period that proceeded it. And the 0.2% gain in the past year alone indicates that this impressive rate of increase is itself increasing.

In Her Own Words

"It definitely appears to be taking less time to make an impactful increase in SOM as our practices have changed and new life-promoting ones have been adopted."

Box 6-3

The Perennial Advantage

Perennial crops such as grapes have an advantage over annuals when it comes to SOC-building. This is due to several factors, including (potentially) lack of tillage and – perhaps most importantly – deeper root systems. Other perennial crops grown (or potentially grown) in Canada include: tender fruit bushes and vines (e.g., blueberries, strawberries, etc.); tree fruits (e.g., apples, peaches); tree nuts (e.g., walnuts, acorns, hazelnuts); bioenergy crops (e.g., switchgrass, willow); and perennial pasture crops such as alfalfa. Some of these crops sequester carbon at much higher rates than those documented in this roadmap. For instance: switchgrass has been measured at 6.0 and willow at 4.3 (tonnes of SOC per ha per year). For an extremely detailed and comprehensive look at the sequestration potential for perennial crops (including new types of perennial grains), see ***The Carbon Farming Solution*** by Eric Toensmeier (Chelsea Green Publishing, 2016, 480 pp.)

Improving Soil in Quebec

Ferme Jocelyn Michon

Jocelyn Michon operates a conventional regenerative farm near Saint-Hyacinthe, Quebec, where he combines field crops (soy beans, corn) with horticultural production (field peas, green beans). In general, he rotates corn and soybeans (80 to 100 ha each) with 40 to 60 ha of field peas and beans. Jocelyn is 67 years old and has been farming this land for 47 years.

BMPs Employed and Planned

He has been direct seeding (no-till) since 2003. In recent years, he has introduced cover crops: multi-species covers after the vegetable crops; cereal rye after the corn and soy. His rotations are planned so that the vegetables are planted on each part of his land every four to six years. He also adds turkey manure every few years. He adds this to the cover crops, rather than the cash crops. To avoid compaction of his soils, he has deliberately kept his equipment relatively small and has also adopted a controlled traffic approach.

Results

Jocelyn's yields are among the highest in the province – 11 per cent higher than the regional average and 40 per cent higher than the provincial average. In addition, his practices save him $100,000 per year from reduced costs for equipment and maintenance, fuel, labour and fertilizer costs. He has reduced his fungicide use to only occasionally, cut his nitrogen and phosphorus use by half, and his potassium use by one third.

His peas and beans make the top grade every year with the buyer (Bonduelle) and he raves about his earthworms, which he feels are both an indicator and a facilitator of soil health. He says that he has 20 to 30 middens per square meter, which means that overall, he probably has about 1.5 billion earthworms on his farm.

SOC

His SOM levels have improved from 1.5 per cent to 3.5 per cent over 25 years, going back before introduction of direct seeding. This represents an increase of about 1.9 tonnes of SOC per hectare per year (*see Table 8 below*).

In His Own Words

"At the beginning, my neighbours thought I was crazy, but now they invite me to speak at their production meetings."

Adaptive Multi-Paddock (AMP) Grazing in Atlantic Canada

Holdanca Farms

John Duynisveld and his family operate Holdanca Farms, 500 acres of pasture and woodland near Wallace Bay, Nova Scotia. The managed pasture occupies 250 acres, with the other 250 acres left as woodland. They raise and sell free-range meat (beef, chicken, turkey, pork and lamb) and eggs. In addition, they have recently begun to work with a company that will sustainably harvest wood from the wooded acres. John also works part-time as a research scientist for Agriculture and Agri-Food Canada.

BMPs Employed and Planned

Holdanca's most prominent BMP is AMP grazing for his beef cattle and sheep. They have done this for seven years. They move cattle as many as six times a day using solar-powered electric fencing and timed self-opening spring-loaded gates. John says that the cows hear the gates open and immediately change paddocks without his involvement. They also do bale grazing in the winter and apply manure to the land (from all of his animals). For the chickens, they use "chicken trucks" – mobile wire cages that can be moved by tractors from place to place, allowing the chickens to forage in the grass with no danger of predation by the numerous eagles that live in the region. The chickens are taken to the areas that soil tests say need the most fertility. They graze their hogs on separate pastureland where they grow a mixture of turnips and corn.

Results

John reports that his pasture soils have been improving steadily and are now full of earthworms. The grass is waist high when the cows enter and is completely flattened when they leave; however, two to three weeks later it is growing well again. The bale grazing saves about $240 per head over the winter; nevertheless, John says that he only knows three other farmers in the Maritimes that are doing it. He finds this hard to understand. His hogs also do well on his specialized pasture diet.

SOC

John has been sampling his soil for 20 years; SOM percentage has gone from low to mid-threes to between five and six (for simplicity, we have assumed here a rise from 3.5 to 5.5). This represents an annual SOC gain of 2.7 tonnes per hectare.

In His Own Words

"As a farmer, you aren't managing crops, you are managing an ecosystem. The more you can learn about how the ecosystem works, the more you will be able to work with it, rather than fight it. This greatly increases your chances of success."

"If you focus on yield, you lose out on both economic and ecological opportunities."

Building SOC – A Systems Approach

The growers in this section are definitely among the innovator and early adopters of soil health practices in Canada. Moreover, they all have one thing in common: they don't just adopt new practices; rather, they take a systematic approach to building soil health and SOC. They follow principles, not just practices, and they are reaping the rewards of this change in the way of seeing soils and agriculture. They help make the case for building SOC as a cornerstone not just to tackle climate change, but for sustainability and profitability as well.

Table 8: Summary of Case Studies

Operation	Contact	Location	# ha (acres)	Crop(s)	BMPs	Rate SOC t/C/ha/yr
Perry Farm	Harold Perry	Taber, AB	2,000 (4,900)	Potatoes	Compost	SOM: 1.7 to 2.7
Axten Farms	Derek and Tannis Axten	Minton, SK	2,400 (6,000)	Field crops	No-till, cover crops, compost, compost extract & teas, inter-cropping, controlled traffic	1.5
Saunders Vineyard	Ann-Marie Saunders	ON	7 (17)	Grapes	Biodynamic methods, compost, compost tea, foliar nutrients	2.3 (last 4 yrs)
Ferme Jocelyn Michon	Jocelyn Michon	Saint-Hyacinthe, QC	250 (620)	Corn, soy, field peas, green beans	No-till, multi-species cover crops, manure, controlled traffic	2.4 (over 25 years)
Holdanca Farms	John Duynesveld	NS	200 (500)	Animal agriculture	AMP grazing, bale feeding, manure application, chicken trucks	2.7 (over 20 years)

SECTION 7: Challenges to change

Previous sections have covered:

- the benefits of soil carbon (varied and substantial);
- the science of soil carbon sequestration (increasingly well understood);
- the principles and practices that manifest SOC's benefits (already well understood);
- SOC's potential as a climate change mitigation tool in Canada (significant); and,
- some examples of innovative, soil-carbon-oriented soil managers (all of whom are very successful).

The story so far seems clear: soil managers can help both their own operations and society in general by increasing their focus on building SOC; the supportive science and practical tools are to some degree already available; and a growing number of innovators and early adopters are proving their efficacy, productivity, and cost-effectiveness.

So why isn't everybody jumping on the bandwagon? Why is the use of cover crops not the norm in Canada? Why are SOC levels still dropping in Central and Eastern Canada? Why are some of the most innovative practices, such as intercropping, relay cropping, the use of compost and compost extracts, controlled traffic, etc. still only being used by a very small percentage of innovators, when their benefits are being demonstrated in both scientific studies and real-world practice?

This section looks at the challenges, both for the average soil manager and for our society at large, when it comes to building high-SOC soils and maintaining them.

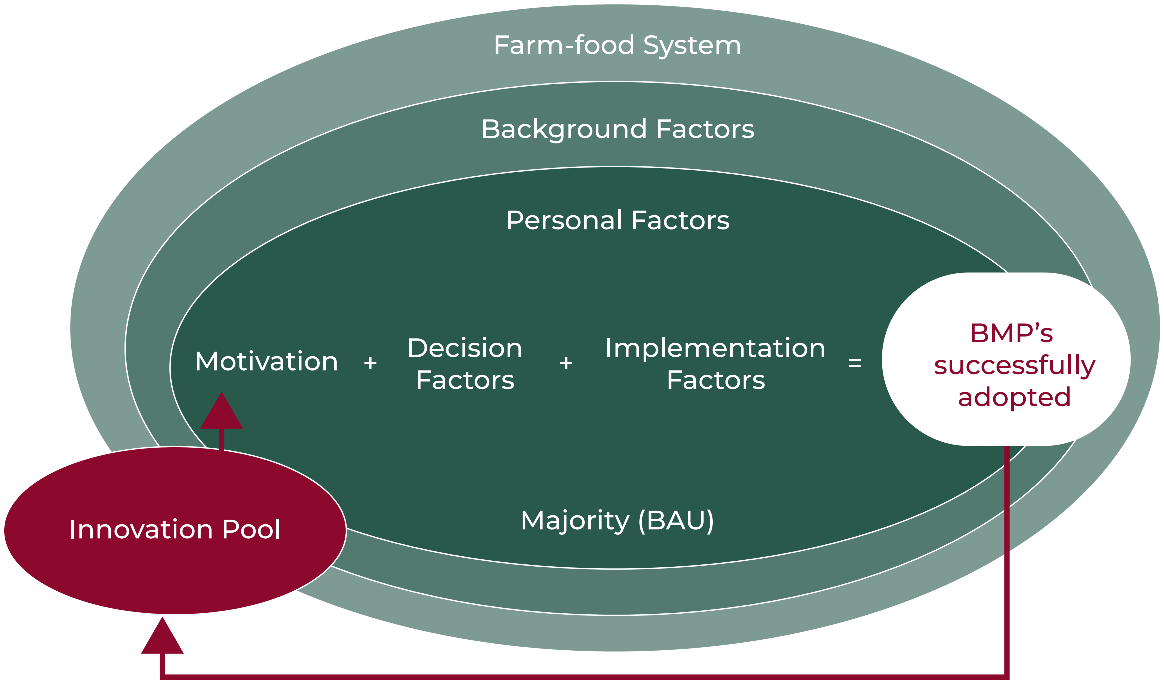
A Framework for Understanding Change

We begin by presenting a theoretical framework for mapping the process of change in soil management, including the decisions required, from a behaviour-change perspective *(see Figure 13 below).* The framework in Figure 13 is an integration and adaptation of three theories of social change found in the scientific literature: *Innovation Diffusion Theory* (*discussed briefly at the start of Section 6*); the *Multi-Level Perspective Framework*; and the *Reasoned Action Approach (RAA).* For a more in-depth discussion of the three component theories, please see Annex 7a.

The purpose of this framework is to facilitate an analysis of key factors affecting the pace of innovation diffusion among Canada's soil managers. Some factors are extremely personal to the farmer, gardener, or landscaper; others are societal in nature, such as markets, government policy, and research focus. We follow the theoretical diffusion pathway that any innovation takes. It begins in the innovation pool (which lies partly outside Canada). The next stage consists of the various decision and implementation factors faced by an individual soil manager. This stage being successful results in the adoption of the innovation by a member of the "business-as usual (BAU)" pool, converting that individual into a member of the innovation pool, closing the circle. Finally, during this process, other levels of influence need to be considered. These are the factors at the personal background and the farm-food system, or societal level. Box 7-1 below describes this analysis framework in more detail with specific references to Figure 13.

The goal of this section is to integrate the technical components of our goal (which is to increase SOC in Canada's managed soils) with its socio-economic-cultural components. Just because something can be done does not mean that it will be done. The challenges to significant change are always in themselves significant. Here we try to provide an overview of those challenges, set within a framework that we hope provides a degree of clarity and understanding to what is a rather complicated mix of factors. Then, in Section 8, we use this framework to organize and present our project's conclusions and recommendations.

Figure 13: A Framework for Understanding Change



Box 7-1

Explanation of Figure 13

The decision to implement SOC-building practices is made by each individual soil manager, but influenced by many factors. We have organized these factors within an overall framework, as shown in the diagram. ***Personal factors*** are comprised of ***motivation*** (desire to make improvements on existing approach, access to knowledge of alternative management practices, and their costs/benefits), ***decision factors*** (things that a soil manager takes into account in deciding to proceed) and ***implementation factors*** (things that can make or break the result once the decision to proceed has occurred and implementation begins). ***Background factors*** are also personal in nature (e.g., size of farm, land tenure, debt load, etc.), but unlike the ***personal factors***, are already in place prior to the decision process, but may influence it. The ***food-farm system*** provides the landscape-level factors (e.g., markets, government regulation, processing options, public perception, etc.) that can also throw up significant barriers to change. The ***innovation pool*** represents the existing practices of the innovators and early adopters, which are a subset of the Food-Farm System, and provide much of the stimulus for change to other soil managers, starting with the early majority.

Challenges to Change

This framework was used to generate a list of challenges that need to be addressed to facilitate an increased rate of diffusion of SOC-building practices among Canadian soil managers. The list our project team developed presents some of the key challenges faced by both soil managers and society at large in the process of incorporating innovative SOC-building practices and their supporting principles throughout the farm-food system and beyond. These challenges were drawn from the literature as well as from our key-informant interviews.

For a full list of challenges, organized by category in table form, see Annex 7b.

Innovation pool

This group comprises the innovators and early adopters in any given region of the country. Our focus here is not specifically on the challenges faced by this group of soil managers, past or present, but rather on the challenges to innovation diffusion, in the broader sense, that are associated with this group. In that light, the main issues have to do with *profile*, *credibility*, and *knowledge transfer*. These are the people (*see Section 6 for examples*) who have broken new ground in Canada with respect to soil health and the building of SOC. But for their innovation to continue to spread rapidly, others must know about the innovators, believe that their good results are real and achievable, and have reasonable access to their hard-won knowledge and experience. Solutions to these challenges are already emerging (e.g., soil-health profiles in agricultural media, on-farm BMP research projects, workshops and conferences with innovators as speakers), but the impetus has largely been bottom-up, with limited support to date.

Personal background factors

The challenges at this level are difficult and some may be intractable. Personality, for instance, may fit the latter category. Some people are more open to change than others, and in fact, it is generally thought that the last group on the innovation diffusion spectrum – the laggards – are mostly people who resist change vigorously, no matter what evidence is presented. This can be associated with age, with younger people often more open to change, but it is not necessarily a direct relationship[35]. Other types of challenges at this level may be more accessible to intervention. These include things like debt level (higher debt can reduce risk tolerance) and, perhaps most importantly, tenure. Many farmers rent some portion of the land that they manage – as of 2016, about 37 per cent of Canada's farmland was rented[36], either from government, other landowners, or as part of a crop-sharing arrangement. In some cases, this could lead to less motivation to improve soil on land that may no longer be available to work in the foreseeable future.

Personal decision factors

These are the challenges faced by an individual farmer, or other soil manager, when considering whether to embrace some level of change in the way that they operate. There are four sub-categories of challenge: *motivation, efficacy, norms, and capacity*.

Under *motivation*, we should consider what motivational elements might be lacking, when a soil manager thinks about whether to change practices. For instance, a lack of awareness of the availability of credible and beneficial alternative approaches to soil management would certainly be a barrier to motivation. Similarly, a lack of local demonstration sites, where you can see the benefits for yourself, and of convincing role models, to provide symbolic leadership, might dampen any desire to try out new methods. Lastly, a lack of personal knowledge of the latest soil science, and its relationship to productivity, cost efficiency, and sustainability, might be one of the most important missing pieces in the motivational puzzle.

With respect to *efficacy*, the question becomes "do these new methods really work?" This is closely related to motivation, but the issues assume awareness of viable alternatives and the questions are more specific. For instance, a grower might be interested in cover crops to increase natural fertility, but uncertain as to how well they do the job, and at what cost. Similarly, a lawn management company might be interested in using compost, but may be unsure whether the overall benefits justify the added expense. In general, a lack of credible data regarding the impact of new practices on yields, profitability, and other benefits can make the decision to proceed very difficult. A lack of data on the costs of implementing new practices also makes it difficult to do a proper risk assessment. In addition, a farmer may consider the lack of marketplace recognition (e.g., a labelling program) and/or options for getting paid for provision of societal benefits to be efficacy issues. Overall, for a practice to make sense, it must pay for itself, at the very least, and hopefully provide added benefit.

The issue of *norms* is in a larger sense about personal beliefs, values, and culture. This is a new area of study in the literature, but a growing one, and it applies particularly well to farmers. For instance, a study done in Ontario a few years ago found that a farmer's self-image can be a major barrier to change[37]. If he/she sees themselves as a very hard worker (as most do), the picture of their fields all messy with multi-species cover crops, as opposed to looking neat and tidy with rows of green crops set against dark soil, can be a tough sell. Even when they have gotten over this hurdle themselves, friends, neighbours, and family members may not be convinced. One progressive Ontario farmer reports getting angry phone calls from his mother, telling him to get out there and clean up his fields[38]. Norms are expressions of cultural values and in many rural areas, these values can clash with new practices and philosophies.

The final sub-category of personal decision factors is capacity. "Do I have the resources available to make this type of change?" The most basic concern here is knowledge, both scientific and practical. Some of the SOC-building BMPs can be complex in their implementation; for instance: knowing the right mix of plants for a multi-species cover in a specific region, following a specific crop; knowing how to understand and operate low-disturbance seeders and other specialized equipment; understanding how to optimize crop nutrition and balancing inputs with increasing natural fertility; or knowing how to make and use compost extract. Other concerns under the capacity category include the concern that financial resources are insufficient to buy new equipment and supplies and to pay for any additional labour**,** the related question of whether current equipment can be adapted to meet the challenge, and concern that the time required to manage the extra work might be overwhelming. Finally, there may be concern that a soil manager's existing knowledge base is insufficient, particularly with respect to the evolving world of soil science.

Personal Implementation Factors

After a soil manager becomes aware of possible innovations in their field, becomes motivated to look at adopting them, determines that they are almost certainly going to generate more benefits than costs, decides that the cultural cost, if any, is acceptable, and calculates that they have the resource capacity to undertake the change, then comes the hard part….they have to actually implement the innovative practice(s), with all of the risk that this entails. Implementation challenges include: *capacity* (unforeseen draws on finances, labour, equipment, etc.), *technical issues and support* (lack of information on specific BMPs, lack of knowledgeable, independent extension support), and *measurement* (lack of a cost-effective method for credibly documenting results, such as SOC increases). The difference between these implementation factors and the earlier decision factors is simply a matter of timing. What can seem straightforward when deciding to proceed can become much more complicated in implementation. Problems encountered in implementation can cause a soil manager to reverse their decision and go back to business as usual, so it is important to consider these challenges separately.

Farm-Food System Factors

Farms don't operate in a bubble; they are part of a complex farm-food system that includes input *suppliers*, *processers*, *markets*, *sources of financing*, *regulators*, *insurance*, and *research*. All these elements of the system impact farmers in many ways, and the adoption of new practices is no exception. Table 9 in Annex 7B summarizes these challenges. Here we look at them in a bit more detail.

Supply chain

In general, farmers need inputs. These include, but are not limited to: seeds (cash and cover crops); nutrients (fertilizer, synthetic or natural); crop protection products; equipment (from tractors to GPS); and, last but not least, expertise. As they move to soil-health practices, the type of inputs may change, creating potential issues in sourcing (availability, selection, quality), price, and lack of information on alternatives. Often, the entire supply chain will have developed around an agricultural system based on high-input levels and low diversity, and dependent on economies of scale. A grower who is moving toward a diversified farming system may not experience the same economies and may find the appropriate inputs hard to find or expensive. In some cases, technological innovation may be part of a farmer's approach to building SOC (e.g., precision farming) and the conversion to this approach may be expensive or require new expertise[af].

Processing

While this category may not be an issue for most, it may be a very big challenge in some situations. As an example, a blueberry grower in Prince Edward Island was not able to get his crop to market in 2019 because the processer demanded that he apply a certain pesticide to prevent worms in the fruit. Although this grower is not certified organic, he had chosen to use different methods to prevent worms, to avoid negatively affecting his carefully nurtured soil microbiome[39]. This type of challenge may lessen as more growers move to soil-health-based methods, but could be extremely problematic for growers in transition, particularly in areas of the country where alternative processing options do not exist.

Markets

Farmers need to sell what they produce, and the markets where they sell their products vary from individuals buying at the farm

af The conversion to a higher-tech approach may not proffer the same extent or severity of challenge as those experienced by farmers moving to lower-tech, low input models, simply because the suppliers of high-tech equipment can also supply the necessary training and support as part of the package.

gate or in farmers' markets to multi-national wholesalers. This is an extremely complex and important category when considering challenges to change because its members have so much power and influence over growers. This influence can be positive with respect to change, but its attitude toward new approaches can also range from indifferent to negative. This challenge usually boils down to economics. For instance, potato growers in Atlantic Canada used to grow wheat in their rotations because it helped rebuild SOC (potatoes are notorious for depleting soil carbon, while wheat is known for its opposite effect). However, various factors (including federal government subsidies and extremely large western acreages) have made wheat from the Prairies so inexpensive that Atlantic farmers can't afford to grow it profitably. As a result, wheat has disappeared from crop rotations in New Brunswick and PEI and soil-carbon levels have been continuously dropping[40]. The same factors have made wheat a problematic crop in Ontario and Quebec as well[ag], although the larger farm sizes in these provinces mitigate the problem to some extent. Similarly, a lack of established markets for some other SOC-building crops makes it difficult to build diversity into a farm's rotation.

Financing

Many farmers depend on financial institutions for loans to purchase land, equipment, supplies, etc. One concern is that financing may not be available for costs associated with transition to new practices, or to a proposed new approach to farming and soil management, if the institution believes that the changes may increase risk. In the same vein, proposed revenues from the sale of soil carbon offsets or ecosystem services may not be given credit as legitimate farm revenue in loan applications. Also, farmers who are consciously adopting practices that build SOC would appreciate seeing the increased SOC levels of their soils reflected in the appraised value of their land. So far, this is not the case.

Regulators

By this term, we mean all government agencies, at any level, that *restrict* (e.g., environmental regulations, drainage regulations), *promote* (e.g., cost-share programs, carbon offsets), *tax* (e.g., municipal property tax, carbon tax), or in any way directly *influence* farmers and/or farming behaviour (e.g., extension, education, training, etc.). Obviously, both the obstacles and the opportunities in this category have significant impacts.

Restrictions can become obstacles to progress when they preclude more innovative solutions to problems. For example, a requirement for an impermeable pad beneath a compost pile to prevent leaching of nutrients to the environment can also prevent the natural inoculation of the pile by beneficial soil organisms, resulting in an inferior product. A more flexible regulatory approach might simply require adequate testing to ensure that the environment is protected. This would allow the composters to find ways to manage the risk that would also allow the compost pile access to rich soil life. Regulations that are focused on specific methods, rather than results, can be serious barriers to innovation.

Programs that *promote* soil health (e.g., incentives such as cost-sharing, subsidies, grants, etc.) can also become barriers to creativity, if they prescribe specific methods rather than promoting objectives. But that is not the only potential drawback to incentives. Some experts feel that paying farmers or other soil managers to adopt a practice (either directly, or via the subsidy of a particular piece of equipment) sends the message that this practice is uneconomic or in some other way undesirable to the farmer. It can look as though the farmer is being bribed to do something that he or she would otherwise not rationally choose to do. Finally, there is evidence that paying farmers to adopt a practice or implement a strategy often fails over the long term, as the payee returns to previous methods when the payment goes away[41].

Influencing soil managers via education, extension, and training is essential to progress, but the challenge in organizing this set of endeavours is to keep the messaging unified. Progressive farmers in Ontario have complained that both OMAFRA and the University of Guelph provide mixed messages. Some people at both institutions are strong soil-health advocates, while others still advise methods that can be detrimental to building SOC and conflict directly with the advice of the soil-health advocates. This can cause confusion among soil managers and set up significant barriers to innovation diffusion.

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ag Some Ontario farmers are experimenting with relay cropping, which allows them to grow a wheat crop closely followed, in the same season, by soybeans (the beans are planted early in the spring, between wheat rows, then grow rapidly after the wheat has been harvested in mid-summer). The revenues from the soybeans can theoretically offset the financial losses from the wheat.

Insurance

In Canada, each province has its own crop insurance program, with premiums and administration partially funded under the federal government's AgriInsurance Program. Provincial organizations, such as Agricorp in Ontario and the Saskatchewan Crop Insurance Corporation (SCIC), work to help stabilize a producer's income by "…minimizing the economic effects of primarily production losses caused by severe but uncontrollable natural hazards"[42]. Eligible hazards include drought, flood, wind, frost, excessive rain, heat, snow, uncontrolled disease, insect infestations, and wildlife. From a SOC-building or soil-health perspective, the main concern with crop insurance programs is how well they accommodate change. To protect their programs from abuse, Canada's various insurance programs require that farmers use "standard" agricultural practices. This has led to a concern among some growers that the adoption of new practices, such as multi-species cover crops, could invalidate their insurance coverage. Similarly, some are concerned that they will not be covered when they grow novel crops, simply because the insurance agency has no way to determine whether the yield was in some way reduced or limited. An analysis of the specific challenges within each of Canada's 10 crop-insurance programs is beyond the scope of this project; however, what is clear is that potential exists for both problems and opportunities. The crop-insurance system needs to be flexible enough to both accommodate innovation in agricultural practices on the one hand, and to integrate formal recognition of the resilience SOC brings to soils and farming on the other.

Research

Good scientific research, conducted at universities and research stations, tends to be expensive and realized only over the long term. Practical, on-farm research, conducted by farmers with help from government or academia, can be somewhat less expensive and provide more short-term benefits, but it can also be less rigorous and detailed. Both are required if we are to better understand how to capture carbon in soils, keep it there, and fully realize SOC's many benefits. This challenge will require serious financial commitments from various levels of government. Although private-sector research, in support of specific products, equipment, analysis, etc., also has value, it is important that the *foundation of SOC research* be independent, so that on-going arguments regarding the basic principles and the science that underlies them are generally precluded.

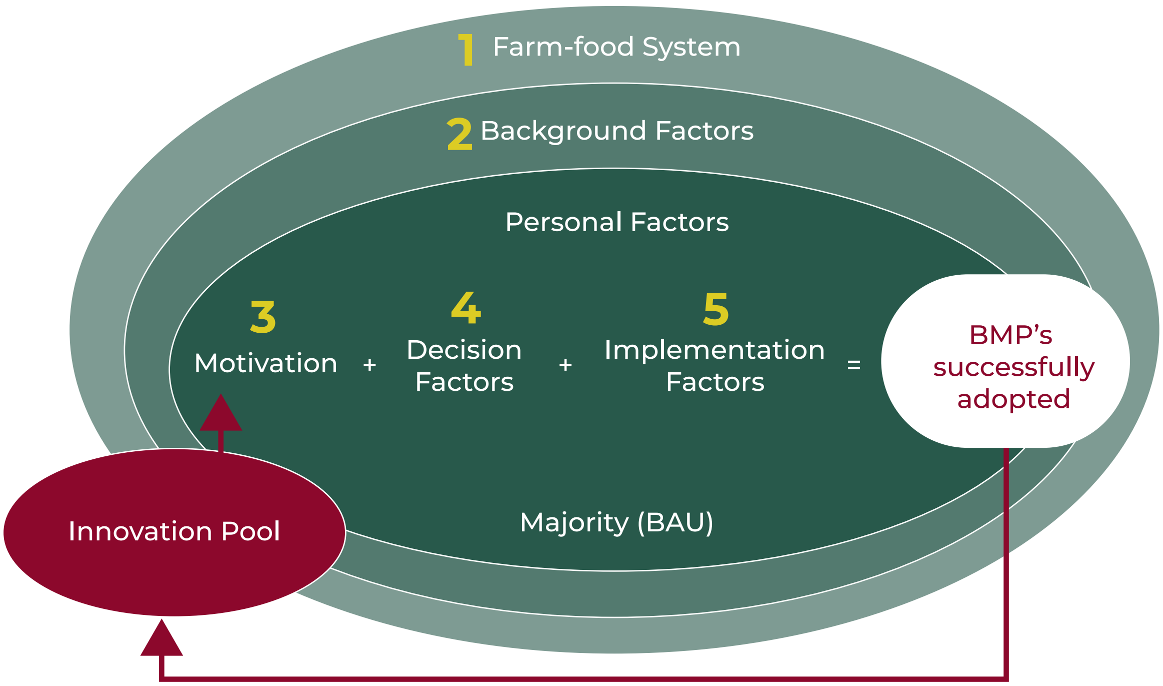
But funding independent and useful research is not the only challenge. Much of what we are beginning to understand about soils is pointing towards the need for a shift in emphasis from reductionist to holistic research. *Box 6-2* in Section 6 discussed the apparent contradiction between two systems of grazing, one based in reductionist science, the other in a holistic approach. This dichotomy between two management systems reflects a similar dichotomy in fundamental research. Do we examine individual components, such as BMPs, while holding all other factors constant, or do we study whole systems? Can we really understand the value of multi-species cover crops if we only compare systems that use them with those that do not (holding all other factors constant), without looking at how all the other factors, each of which might be synergistic or antagonistic, operate within a full functioning ecosystem? The value of applications of compost to soil is a good example of this problem. Many of the benefits of compost, such as carbon sequestration and disease resistance, have proven to be inconsistent in studies. However, once we realize that compost's benefits come from its support and enhancement of the soil microbiome, we can begin to understand the inconsistency. Compost applied to a field where tillage is consistently used, perhaps accompanied by fungicides, will likely not provide the same benefits as compost applied to a no-till field where fungicide use is absent, or very carefully applied to avoid damage to beneficial fungal populations. In fact, it may be that achieving optimal benefit from any BMP is dependent upon the extent to which all the soil-health principles *(see Section 4)* are followed.

Key Challenges

Summary of Challenges by Stage & Level

Figure 14 summarizes the challenges discussed above, organized by this project's conceptual framework for change. This summary; however, begs the question of the identification of *key challenges*, which are those that, if solved, could go a long way to unlocking barriers to swift diffusion of SOC BMP adoption throughout Canada's soil management ranks.

Figure 14: Challenges to Change



1. Farm-food System

Research needs (BMPs, holistic systems); **markets** (novel crops, SOC-building crops); **supply chain issues** (availability of inputs, technology); **financing** (SOC as asset); **insurance** (novel crops, BMPs); **government** (unintended impacts, privacy concerns, supportive policy & regulatory framework, incentive infrastructure)

2. Background Factors

Tenure (no incentive to improve rented land); **debt** (less risk tolerance, less access to capital); **personal disposition** (resistance to change, incompatibility with personal values)

3. Motivation

Awareness (majority unaware of successes of IP, or of presence locally); **research** (no documented and credible proof of success); **knowledge transfer** (no mechanisms for creating awareness or transferring knowledge and experience)

4. Decision Factors

Efficacy (majority needs credible proof of efficacy of BMPs and systems approach); **norms** (cultural support needed for those who break with traditional methods); **capacity** (financial resources, knowledge, equipment, labour, complexity)

5. Implementation Factors

BMPs (implementation issues); **equipment** (availability of specialized equipment or custom services; ability to adapt equipment); **technical support** (availability of independent advice, scientific info); **measurement** (accuracy, cost)

As suggested above, the challenge framework allows a detailed look at the range of possible challenges to the adoption of BMPs, via the integration of three established theories of change: diffusion innovation (societal progress), reasoned action (individual decision-making), and the multi-level perspective (societal context). But the framework does not differentiate between the challenges in terms of importance, or priority (i.e., what should be addressed first). Nor does it necessarily identify challenges that are more diffuse in nature, in that they arise from our shared view of soil and farming (i.e., the nature of our agricultural paradigm). So, with respect to these concerns, what do the experts say?

A fair amount of literature exists about behaviour change in farming with respect to adoption of conservation practices. However, there is little consensus as to the most important factors to either driving or inhibiting change[43]. While many of our project informants indicated they felt that financial and technical matters were primary, the results of various pilot projects and studies in the western world seem to indicate that cultural factors may be just as important. In fact, the following statement appears to capture the complexity rather well: "…while favorable external conditions may be necessary for behavior change, they are not sufficient[44]." In other words, while farmers require that any change must make sense financially ("if it pays, it stays"), and (*usually*) need to feel that both knowledge and technical support are available if required, these external factors in themselves will not result in rapid diffusion.

Why would a farmer not move forward quickly on adopting new practices if all the external factors (productivity, profit, technical support) were reasonably assured? One suggestion for understanding 'innovation hesitancy' is to try to see the world as a farmer sees it. This approach[ah] suggests that farmers see themselves as primarily as producers of food, sometimes even at the expense of profit, an identity described in the literature as "productivist." This identity is strongly reinforced by family, friends and rural culture in general. While a productivist mind-set does not preclude innovation in general, it tends to be narrow, and focus an individual farmer's attention on innovations that promise to increase yield, as opposed to those that promise environmental improvements, higher SOC levels, or even improved profitability. Given the constraints the average farmer faces, in terms of personal time requirements, financial risk, etc., it is not surprising that the amount of time and energy devoted to considering innovation on the farm is limited, and that innovation not tied to increasing yield (food production) is not given time.

In fact, many soil-health proponents, such as Gabe Brown, suggest that the biggest obstacle to the adoption of SOC-building, soil-health practices lie in farmers' attitudes. They call for the adoption of a new paradigm, where farming is seen (by both the farmer and society at large) as an ecological process, as opposed to a production process (i.e., production agriculture). While this critique is valuable, and more and more supported by science, it begs the question of how to make such a fundamental change happen. Such a change is, in effect, an innovation in awareness, and it may be the most important, timely, and most difficult challenge of all.

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ah For a detailed, interesting and very useful discussion of this approach, see: Luymes, M. 2017. "Innovator to Influencer: A network-leadership approach to growing Ontario's soils". Rural Ontario Institute

SECTION 8: Wrapping it all up

In the beginning of this project's journey, we laid out the rationale for a roadmap (*Section 1*) and argued that we needed such a document to help us reach our goal of optimizing SOC in Canada's managed soils. We felt then, and feel even more so now, that building SOC in soils is a key element of meeting Canada's climate goals. As a bonus, we argued, enhancing SOC is also closely related to soil health, which brings benefits such as increasing soil resiliency, productivity, and environmental and economic stability.

We recognized the complicated road we had set out to define. This path includes important considerations, including the circumstances of individual soil managers, the science that helps us understand carbon balances and SOC in our soils, and the impacts of programs and policies at the national and local levels, to name a few. The early work in this project focused on gathering findings that we believe create an essential and firm foundation of knowledge for moving forward.

In Section 7, we surveyed the challenges we face in working toward the goal of optimizing SOC in managed lands. We developed a framework for organizing these challenges *(Figure 13)*. The approach we have taken in developing our conclusions and recommendations flows from this same framework. We have identified five key areas of potential intervention *(see Figure 15)*. These are summarized below, then used to organize the project recommendations, as set out in Table 9.

Five Key Areas of Intervention (toward a soil-health/SOC strategy for Canada)

Making the Case [providing motivation]

For soil managers to adopt SOC enhancing practices, they need to understand why that change is important and how it will work for them. From a policy perspective, the work to create this motivation needs to include: identifying and supporting the innovators, then enlisting them as leaders and mentors; doing the necessary research to support change; and creating the opportunities for all soil managers to better understand the importance and benefits of change.

Making it Work [providing the tools]

Support for on-going research is needed, as well as significant education, outreach, training, demonstrations, and access to research data. In addition, support will be required for technical innovation (equipment, testing, data management, etc.).

Strengthening the Business Case [providing incentives]

To ensure the timely adoption of SOC-building practices by most soil managers, incentives will be required.

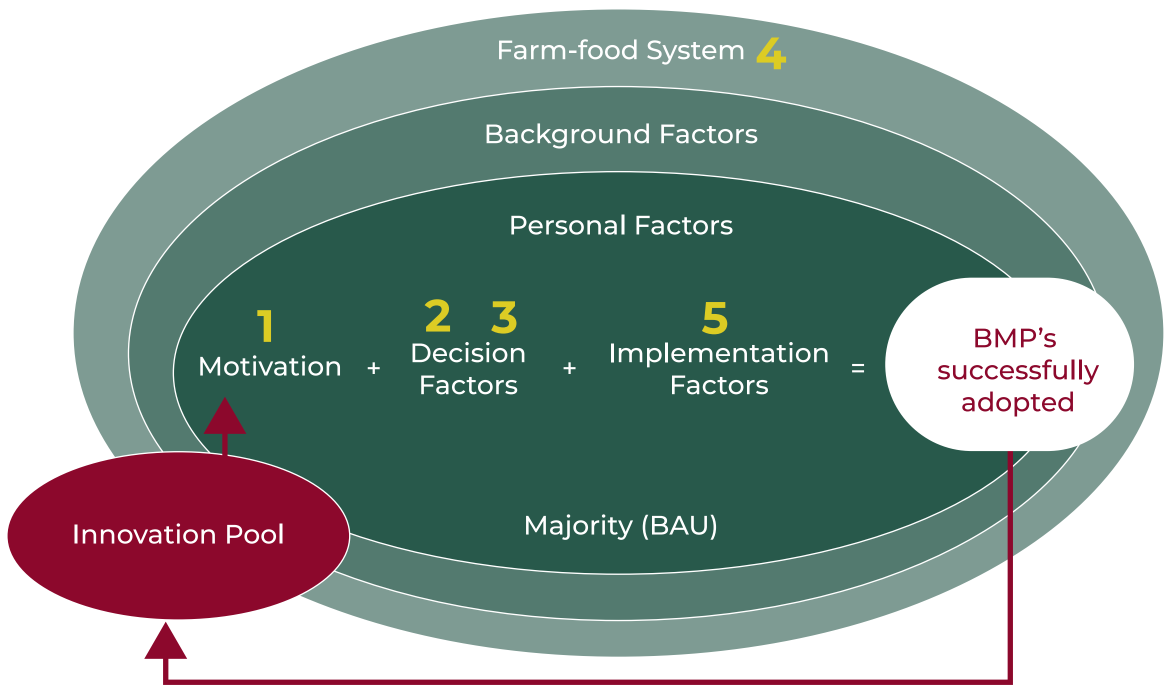
Clearing the Tracks [addressing the remaining challenges]

The current farm-food system evolves around the goals of productivity and efficiency. We now understand that agriculture has much more to offer society, not the least of which being the ecological benefits associated with healthy soils. To accommodate this broader mandate, many elements of the current system need to adapt.

Building the Future [creating the institutional framework]

Change can be temporary or permanent in nature, as in fads vs systemic change. The latter is required in this case and so the institutions that support soil management in Canada will need to be adapted, and in some cases, created.

Figure 15: Five Key Areas of Action



1. Making the case
research; education; training

2. Making it work
develop new tools and provide better information about and access to existing tools

3. Strengthening the business case
Create/facilitate an effective incentive system

4. Clearing the tracks
Address farm-food system barriers, including regulation, markets, supply chains

5. Building the future
develop implementation support infrastructure (e.g. independent extension, custom service providers)

Recommendations

Table 9 below summarizes the project team's recommendations and key actions, organized by area of potential intervention, as described above. The order of the recommendations puts area 5 (Building the Future) first, before areas 1 to 4 (as in *Figure 15*, above). This is because the recommendations arising from area 5 are more comprehensive in nature and form a foundation for many of the other recommendations. For a more detailed description of the report's findings and conclusions and how they relate to these recommendations, please see Annex 8.

Table 9: Recommendations and Priority Actions

Intervention Area	Rec #	Recommendations	Lead Entity
Building the Future [institutional framework]	1	The agricultural industry and the federal government should work together to create a non-government entity (e.g., "Soil Health Roundtable") that can provide the leadership necessary to develop and achieve a vision and plan that will secure the future of soil health in Canada. **Action:** Senior government should initiate a process where stakeholders work together to develop consensus on the ways and means of creating, funding, and maintaining such an entity.	Federal Government
	2	Develop a consensus-based National Soil Health Strategy. **Action:** Stakeholders and senior governments should task the Roundtable with developing a National Soil Health Strategy via a multi-stakeholder process.	Soil Health Roundtable
Making the Case [motivation]	3	Build a basic understanding among soil managers of how management practices impact soil health and soil organic carbon (SOC). **Action:** The Roundtable should be tasked with the design and implementation of a five-year, program with the goal of reaching 100,000 farmers with soil health education and training.	Soil Health Roundtable
	4	Develop a mechanism to sustain communications and collaboration between farmers, other soil managers, scientists, and researchers. **Action:** Establish a National Soil Carbon Science Advisory Board, in collaboration with the Living Labs Program, Canadian universities, and other relevant stakeholders. The board's mandate should be to convene annual meetings for the review of existing research and the establishment of common priorities for research investment. The focus should be projects that are targeted at farm-level issues and result in usable and practical solutions for farmers.	Soil Health Roundtable
	5	Promote and enable leadership activities among leading-edge farmers (innovators and early adopters) that will facilitate the sharing of their knowledge and experience with other farmers. **Action:** Support 200 soil champions in one-to-one and group mentoring of their colleagues with respect to practices that increase SOC.	Soil Health Roundtable
	6	Raise the public profile of soil to the same level of importance as air and water. **Action:** Launch a public engagement initiative (over five years) to raise and sustain the key role soil plays in providing multiple important benefits to all Canadians.	Soil Health Roundtable

Intervention Area	Rec #	Recommendations	Lead Entity
Making it Work [tools]	7	Build independent extension and knowledge transfer capacity to the point where it is available to all Canadian soil managers and farmers who want to adopt soil health practices. **Action:** Invest over five years to make soil-health related extension and knowledge transfer available across Canada (this would ideally be delivered by the provinces).	Federal Government
	8	Create a program that preserves existing knowledge of our soils, gathers new information, conducts monitoring of changes, and reports to Canadians on a regular basis. **Action:** Establish a national government agency/department charged with preserving and managing existing and new information relevant to soils, including beneficial management systems and practices.	Federal Government
Strengthening the Business Case [incentives]	9	Accelerate efforts in developing tools to assess all the costs and benefits, on-farm and off-farm, associated with improving soil health. **Action:** Identify/create a formal set of tools for integrating ecological services into cost-benefit analysis related to soil management.	Federal Government
Clearing the Tracks [obstacles]	10	Identify and gradually amend government policies and programs with the goal of making them as compatible as possible with practices that improve soil health and build soil carbon. **Action:** Senior governments should systematically review agricultural policies and programs on an ongoing basis, with the goal of removing obstacles to the adoption of improved soil management practices.	Governments at all levels in Canada

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Annex 1: Questions Used in Consultation Process

Questions Used in Personal Interviews

1. Respondent background (personal or organizational)

    a. For organizations, briefly describe:

        i. type
        ii. size
        iii. mandate
        iv. who you represent

    b. For individuals: indicate which of the following best describes you:

        i. producer
        ii. ag professional
        iii. gardener
        iv. turf manager
        v. ag industry
        vi. government
        vii. other (please specify)

2. Identify your key interest in soil carbon (you can select more than one):

    a. Soil heath and productivity
    b. Environment/climate change
    c. Biodiversity
    d. Other (specify)

3. How do you rate your level of awareness of the need and benefits resulting from higher soil carbon levels in Canada? (0=no awareness 10=very aware)

4. For organizations: indicate the areas in which you have capacity to promote soil carbon initiatives (select all that apply):

    a. Staff resources
    b. Collaborative partnerships
    c. Funding
    d. Information/data

5. Briefly summarize, in point form, the areas of scientific/technical information and/or experience you have that could contribute to increasing soil carbon (maximum 5 points)

6. Do you consider your scientific/technical information and/or experience to be (choose one only):

    a. in the public domain
    b. protected or proprietary
    c. a mix of both

7. Are you willing to share this scientific/technical information and or experience with other stakeholders interested in soil carbon?

8. What gaps in scientific/technical information and/or experience do you see as being high priority constraints to increasing carbon in Canadian soils? List five maximum.

9. What do you see as key solutions to filling those gaps?

10. Which of the following do you see as significant barriers to the adoption by soil managers of practices that increase soil carbon? (please rank, with 1 being the most important)

    a. financial risk
    b. insurance issues
    c. government policy
    d. extension services
    e. attitudes
    f. research
    g. new technology
    h. knowledge
    i. other

11. Based on your experience are there other potential stakeholders that this project should be in contact with? If so, can you provide contact information?

12. Would you agree to being named as a stakeholder with an interest or commitment to participate in efforts to increase carbon levels in our soil resources?

13. Any other thoughts on the potential and/or constraints associated with optimizing carbon in Canada's managed soils? [Prompt full discussion, if possible].

List of Interviews Conducted (52)

Name	**Occupation/Affiliation**
Axten, Derek	Farmer, Saskatchewan
Bambrick, Amanda	Government of Alberta (Carbon Offsets)
Burton, David	Agricultural Scientist, Dalhousie University
Carmichael, Ray	New Brunswick Soil and Crop Improvement Association
Carver, Kevin	Blueberry Grower, Prince Edward Island
Comeau, Louis-Pierre	Scientist specializing in soil carbon, AAFC, Fredericton, New Brunswick
Cowan, Dale	Agronomist, Ontario
Davison, Trevor	Agronomist, Nova Scotia Environmental Farm Plan
Duhem, Koenraad	Agricultural Input Supplier (HumaTerra), Ontario and Saskatchewan
Duynisveld, John	Farmer, Nova Scotia
Farrell, Richard	Agricultural Scientist, University of Saskatchewan
Fitzsimmons, Ananda	Chair and co-founder, not-for-profit (Regeneration Canada)
Fyk, Anastasia	Farmer, Manitoba
Geesing, Dieter	Soil Specialist, Government of British Columbia
Goyer, Claudia	Scientist (soil ecologist), AAFC, Fredericton, New Brunswick
Gray, Alanna	Agronomist, Keystone Agricultural Producers (KAP), Manitoba
Helgason, Bobbi	Agricultural scientist, University of Manitoba
Paul Hoekstra	Government and Industry Relations, Syngenta Canada
Kallenbach, Cynthia	Environmental scientist (carbon cycling), McGill University
Kerr, Bob	Farmer, Ontario

Name	Occupation/Affiliation
Kiely, Bob	Composter, Envirem Organics Inc., New Brunswick
Krzic, Maja	Scientist (soils), University of British Columbia
Landry, Jim	New Brunswick/Prince Edward Island Landscape Association
Lishman, Mike	Former farmer, agricultural consultant, Ontario
Lobb, David	Scientist (soils, biophysical processes), University of Manitoba
Luymes, Melisa	Agricultural consultant, Headlands AgroEnvironmental
MacLean, Maxine	Policy Analyst, Nova Scotia Federation Of Agriculture
McConkey, Brian	Scientist (soils), formerly AAFC, Viresco Solutions
Ménard, Odette	Agronomist, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec
Michon, Jocelyn	Farmer, Quebec
Munroe, Jake	Soil specialist, Ontario Ministry of Agriculture, Food and Rural Affairs
Ogilivie, Cameron	Soils at Guelph, University of Guelph
Paul, John	Compost scientist, consultant, British Columbia
Phillips, Lori	Soil scientist, AAFC, Harrow, Ontario
Qualman, Darrin	Director, Climate Crisis Policy and Action National Farmers' Union, author
Riekman, Marla	Soil specialist, Government of Manitoba
Rivers, Nicholas	Scientist (environmental management), University of Ottawa
Roberts, Cory	Agronomist, Nova Scotia Federation of Agriculture
Robinson, Mary	Farmer, PEI, also Chair, Canadian Federation of Agriculture
Samson, Marie-Elise	Doctoral student, soils and carbon sequestration, Laval University
Saunders, Ann-Marie	Vineyard operator, Ontario
Smith, McKenzie	Fertilizer Canada
Smukler, Sean	Scientist, applied biology and soils, University of British Columbia
Styles, Kyra	Soil specialist, Government of Prince Edward Island
Tenuta, Mario	Scientist, applied soil biology, University of Manitoba
Toner, Pat	Soil management specialist, Government of New Brunswick
Van Eerd, Laura	Scientist, sustainable soil management, University of Guelph
Verhallen, Anne	Soil specialist, Ontario Ministry of Agriculture, Food and Rural Affairs
Wagner-Riddle, Claudia	Scientist, climate change and agriculture, University of Guelph
Watson, Paul	Environmental Farm Plans coordinator, government of Alberta
Wiens, Matt	Climate change analyst, Manitoba Agriculture
Wilcox, Doug	Manitoba Agricultural Services Corporation (crop insurance)

Literature Search

The literature search had two components. The first consisted of ongoing internet searches using key terms (e.g., soil carbon sequestration, soil health, soil organic carbon, etc.). New searches were conducted throughout the project, as the research revealed new areas of interest. The second component consisted of follow-up from the personal interviews, during which our informants were asked for references. Many of the people interviewed referred our team to important papers and/or articles, which then often led to further internet searches. Overall, several hundred papers, articles and reports were identified and scanned for relevance. The most important are identified in the footnotes and reference section of the Roadmap.

Annex 2: The Soil Food Web

The following is an excerpt from *Soils at Work: The Biology of Soil Health*, copyright 2019 by the Compost Council of Canada. For more information, visit www.compost.org.

The Soil is Alive!

Introduction

The story of "soil health" starts with the realization that soil is alive -- not like an individual is alive, but in the sense of a community, or ecosystem. A single handful of healthy soil will contain thousands of species of organisms and millions of individuals. So, when we speak of heathy soil, we are not referring to the physical elements, such as particles of clay, silt or sand; we are actually speaking of the health of a community of organisms, living in the physical environment we call "soil".

But what does the health of such a "community" really mean? What does a living community of organisms require to be healthy? And what are the implications of these needs for us, as human beings? This primer attempts to answer some of these questions. We will be basing our answers on the latest science, but we will be presenting them in a more user-friendly and practical manner than you will find in a scientific paper or textbook. We will be referring to this underground community as the **soil food web** and using the following as a working definition of soil health:

> Soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans.
>
> - Natural Resources Conservation Service, USDA.

What is the "Soil Food Web"?

The "soil food web" is a term used by scientists to describe the various life forms in the soil and the relationships between them. Like the above-ground food web, the soil hosts a hierarchy of organisms, with those at higher trophic levels[1] consuming those in the lower levels. This "who eats whom" story is very important (particularly for fertility). However, it is only part of an even greater story. Just as in our own communities, "who does what, and how they do it" really matters, not just to the organisms in the soil food web, but to those of us above ground as well.

Figure 1 illustrates the various levels of the soil food web. Plants are the original (primary) energy producers, and the creatures below ground are fed by that energy, beginning with the bacteria and fungi at the lowest level (the decomposers) and continuing up to the insects and worms at the top of the underground world.

Here, we will look at the various members of the soil food web, describing in general terms what they look like, where they get their energy and resources, and what their primary roles are within the soil food web.

Key Members of the Soil Food Web

Classifying Life Forms

Before we jump into descriptions of the organisms in the soil food web, we should pull back for a quick look at how scientists have classified life forms in general (see **Figure 2**). Classifications such as this are always in flux and may not be accepted by all scientists at any given point in time. However, the basic set of three domains described below, although fairly recent, appear to be the current consensus on the subject.

Figure 2 shows the basic classifications of our planet's life forms organized by the highest category, known as domains. Until recently, scientists recognized two domains, which they named prokaryotes (bacteria) and eukaryotes (everything else). Prokaryotes are defined as single celled organisms with no nucleus or other internal organs. The eukaryotes consist of all single celled organisms that do contain a nucleus and defined "organelles", such as amoebae, plus all multi-celled organisms (such as you, your dog, your potted plant, the tiny aphid eating your plant).

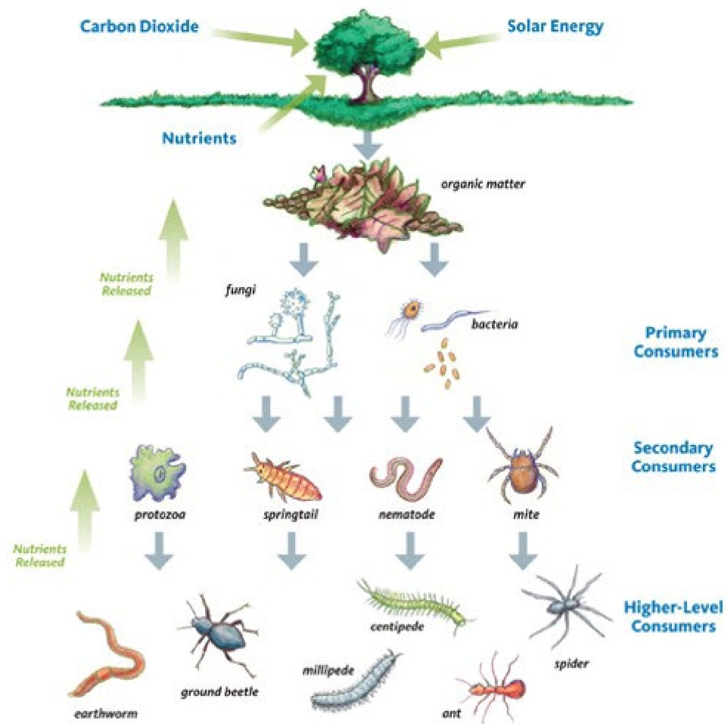
With the advent of better methods of assessing genetic material, a new domain was born – the archaea. These are also prokaryotes and are pretty much indistinguishable from bacteria under the microscope; however, genetically, they are as different from bacteria as they are from plants and animals. They tend to live in extreme environments, such as undersea vents and salt marshes, as often they can withstand extreme conditions. Archaea are also present in soils but their contributions to the functions of the soil food web are not significantly different from those of bacteria.

So, for all intents and purposes, and to make the discussion less complicated, the two domains we will consider are the bacteria and the eukaryotes. Within these two domains are five kingdoms: bacteria comprise the sole kingdom in their own domain, whereas the eukaryotes boast four kingdoms. These are: protists, fungi, plants, and animals. Of particular note in **Figure 3** is the fact that fungi are more closely related to plants and animals than to either protists or bacteria.

Bacteria – the Resilient Workforce

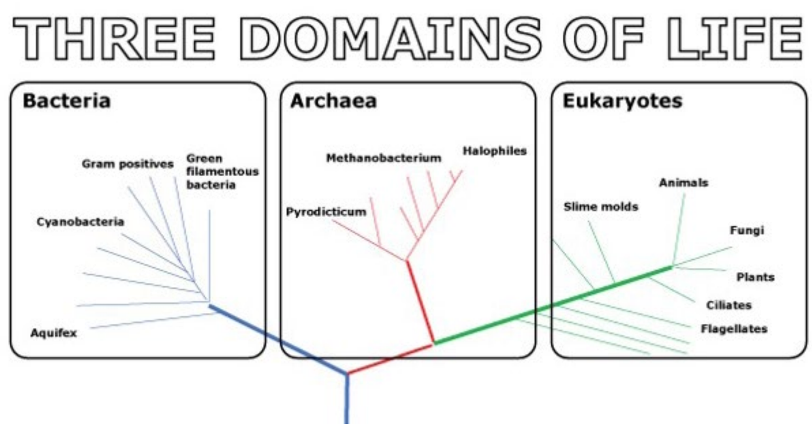
Bacteria are the smallest members of the soil food web, but the most numerous. You can think of them as the boots-on-the-ground workforce because they can "take a licking and keep on ticking". In part, this resilience is because they reproduce very quickly, so knocking their populations back is usually a temporary phenomenon. However, like all the other underground organisms, they do need a regular source of energy to thrive and perform their various functions effectively.

Figure 1: The Soil Food Web



Credit: Wikipedia Commons

Figure 2 Classification of Life Forms



Source: Figure by Compost Council of Canada, adapted from NASA

The most obvious fact about them is that they are very, very small. In general, they are a fraction of a micron in diameter and up to a few microns in length (a micron = one millionth of a meter). How small is this? If you lined them up side-by-side in one row on one of your fingernails, like a military unit, you would need between 10,000 and 20,000 of them to stretch from one side to the other (depending on the size of your nail).

The total weight of bacteria in the soil can amount to 1 - 2 tonnes per hectare in temperate grasslands, so there must be a lot of them in the soil. In fact, as little as one gram of healthy soil (about a teaspoon) will contain millions of individual bacteria and thousands of different species. They also come in a variety of shapes and sizes, with spheres, rods, and spirals among the most common types. One of the characteristics scientists use to categorize soil microbes is by how they get their energy. A few types are what scientists call autotrophs. Like plants, they are able to photosynthesize, thereby getting their energy (in the form of carbon) from sunlight and the air. However, for the majority of soil microbes, there are three main routes.[2] They can get energy by:

- consuming organic residues – these are called decomposers;
- forming a mutually beneficial relationship with another organism, usually a plant – these are known as mutualists; and,
- feeding off living organisms – commonly called parasites or pathogens.

Figures 3, 4 and **5** are microphotographs of examples of each of these types of bacteria. **Figure 3** shows *actinomycetes*, a decomposer commonly found in compost as well as soils, and known for secreting a chemical that gives soil its pleasant, "earthy" odour. **Figure 4** shows the nodules on the roots of a leguminous plant that house the mutualist *rhizobium* bacteria (see below). Finally, **Figure 5** shows *Pseudomonas syringae* bacteria, a plant pathogen, entering a plant leaf through a stoma.

Figure 3: *Actinomycetes*

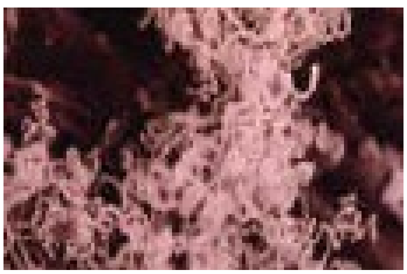
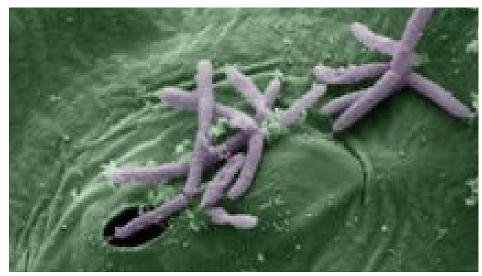


Figure 4: *Rhizobium*

Figure 5: *Pseudomonas syringae*



Source, Figures 3 and 4: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

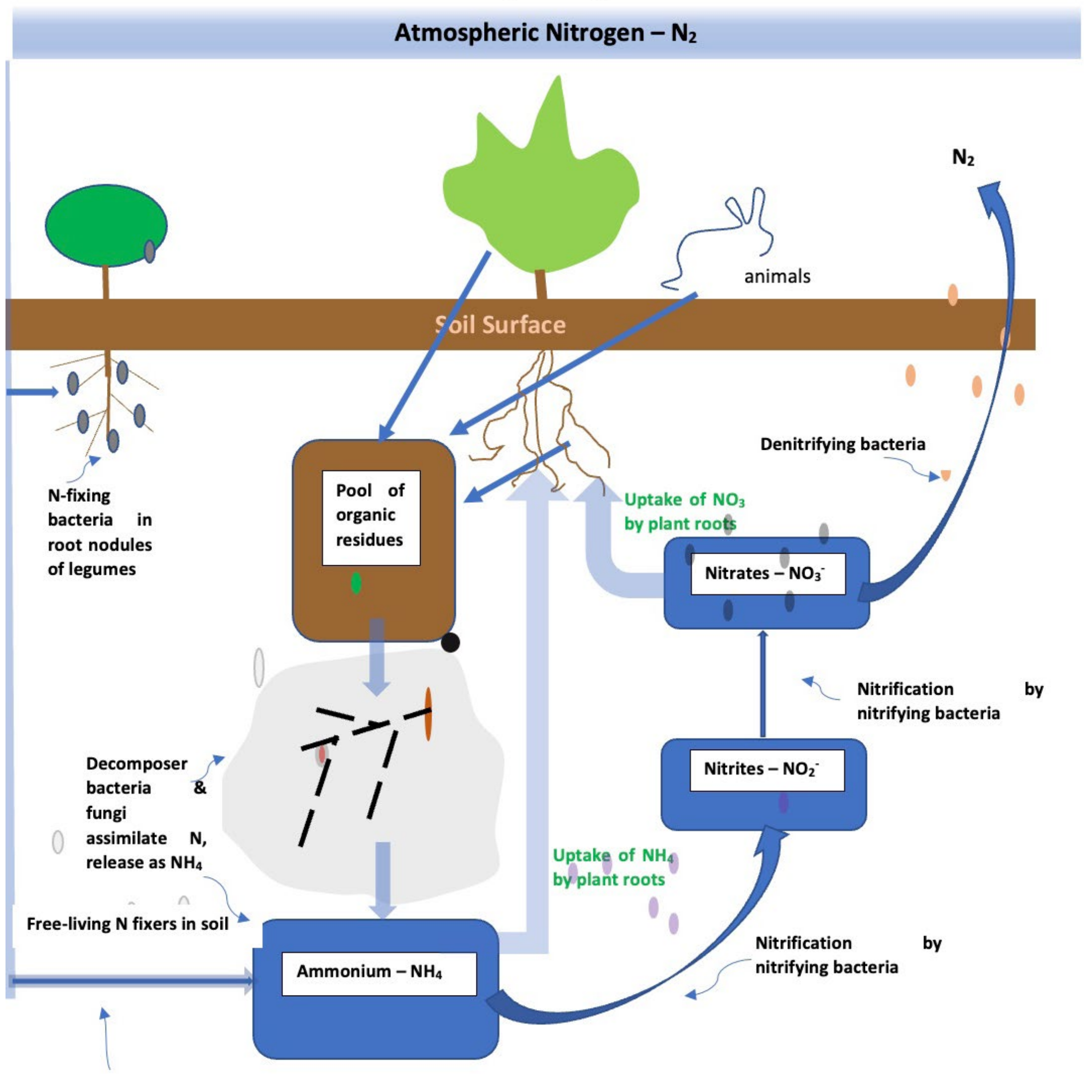
Figure 5: James Kremer and Sheng Yang He. Reproduced with permission.

There are many types of pathogenic or parasitic bacteria; fortunately, the first two categories greatly out-number the last one, at least in healthy soils.

In general, decomposers are the most well-known bacteria. It is common knowledge that bacteria cause rot and decay. In addition, the bacteria that colonize the roots of legumes (*Rhizobium*, Figure 5) and fix nitrogen from the atmosphere into a form useable by plants are also well known and appreciated, especially by farmers. Not so well known, however, are the several types of free-living nitrogen fixers, who perform the same function while working as freelancers, as opposed to being "under contract" to specific plants. These are also mutualists, as they do their work in return for payment in the form of plant root exudates.

Bacteria are also fundamental to the nitrogen cycle in soil, as described in "Bacteria and the N Cycle" (see Box below, including **Figure 6**).

Figure 6: The Nitrogen Cycle



Bacteria and the N Cycle

Nitrogen (N) is an essential element of life. It is required by all living organisms since it is a key ingredient in the synthesis of proteins, nucleic acids and other compounds basic to living processes. The Earth's atmosphere is fortunately very rich in nitrogen -- it is almost 80 per cent nitrogen gas. However, as a gas N is unusable by most living organisms. It must first be converted into a different form, called ammonium, a process we refer to as "fixing nitrogen".

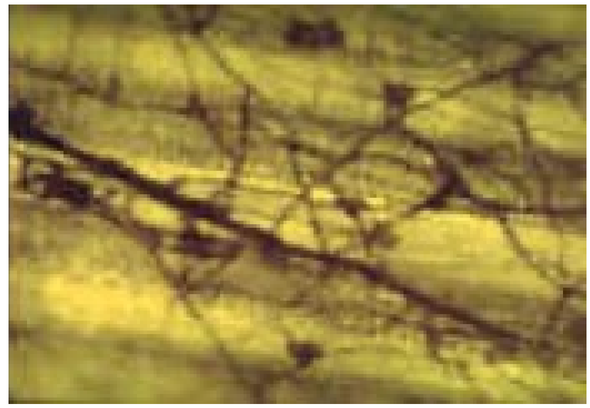
The N cycle is a series of natural processes that convert nitrogen gas to organic substances and back as part of a continuous cycle. This cycle is maintained by the decomposers and nitrogen bacteria. The N cycle can be broken down into four types of reaction and micro-organisms play roles in all of these, as the above diagram shows.

Bacteria perform many other functions in soil as well. They secrete chemicals that can break down minerals, releasing nutrients that they then take into their bodies. Some can produce antibiotics that kill other organisms, including pathogenic bacteria. Also, given the proper conditions, they out-compete the destructive organisms in soil, ensuring overall ecosystem health.

Fungi – the Networkers

The other organisms sharing this important decomposer niche at the base of the soil food web are the fungi. As mentioned above, fungi are more closely related to plants and animals than they are to bacteria. They are more complex than bacteria, beginning with the fact that most types have many cells, rather than just one[3]. They spread through the production of long, thin filaments, known as hyphae, which can have considerable length but are only a few microns in width. When we see their white strands in soil, particularly forest soils, we are not seeing individual hyphae, which are microscopic. We are actually looking at mycelia, which consist of many intertwined hyphae, numerous to the point of being visible to the naked eye.

Figure 7: Decomposer fungi



Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev.ed. Ankeny, IA: Soil and Water Conservation Society

Like bacteria, when classified by energy source, there are three main types of fungi: decomposers, mutualists, and pathogens. The decomposers are important because they break down some of the tougher organic materials, things that resist bacterial breakdown, such as lignin (one of the main components in woody material). Fungi and bacteria are therefore complementary factions of the decomposition process of organic residuals; you need both in most soils to get efficient nutrient turnover. **Figure 7** shows decomposer fungi hard at work attacking the veins of a dead leaf.

Figure 8: Mycorrhizal fungi

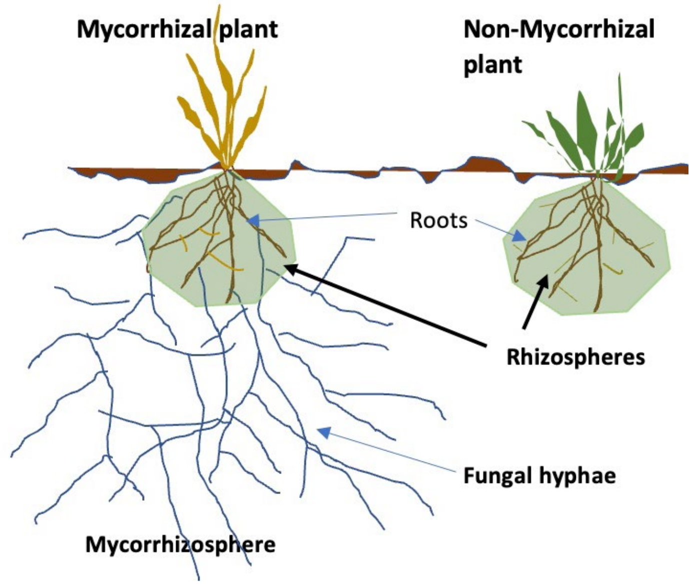


Image Credit: Compost Council of Canada

Again, like bacteria, fungi also include an important group of mutualists. These are known as mycorrhizal fungi and there are many different species. The word "mycorrhiza" means "fungus root" in Greek, referring to the fact that these fungi form an association with plant roots that is beneficial to both parties. The plants feed the fungus directly, through these root contacts, providing it with the energy-rich products of photosynthesis. In return, the fungus uses its spreading network of hyphae to scavenge for nutrients and water, which it uses to "pay" the plant for its sugar. These fungi are also able to solubilize nutrients out of minerals, so they have a complex, vital set of roles in the underground community. Mycorrhizal fungi are more than just recyclers – they are also miners, truck drivers, traders, and water managers. **Figure 8** shows how Mycorrhiza extend the range of a plant's root system.

Of course, pathogenic fungi are also extremely important, but for all the wrong reasons. Fungal species of both *Verticillium* and *Fusarium*, for instance, are the cause of major crop losses every year. **Figure 9** shows a microphotograph of *Fusarium verticillioides*, a plant pathogen.

Fungi have an enormous impact on soil functions, with these impacts growing stronger as soils become healthier. Like bacteria, fungi are very important for nutrient cycling, soil building, and certain symbiotic activities. However, fungi are much more complicated organisms than bacteria. The list of the ways they impact soil and soil health is impressiv: the following is a quick summary of some of the benefits fungi bring to soil.

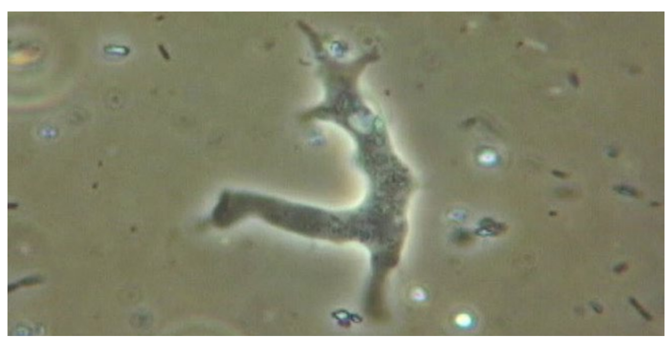
- Approximately 80 to 90 per cent of all plants form symbiotic relationships with mycorrhizal fungi, which assist the plant in acquiring nitrogen, phosphorus, micronutrients and water in exchange for sugars produced by the plant through photosynthesis.
- Some fungi help control diseases.
- Fungi can also help to control predators (e.g., nematode-trapping fungi help to control root-feeding nematodes).
- Many fungi can be used as biological controls.
- Beneficial fungi benefit most plants by suppressing plant root diseases and attacking plant pathogens with fungal enzymes.
- Some fungi produce vitamins that promote plant growth.
- Fungi also protect plants by supplying both water and phosphorus to the plant roots during droughts.

Figure 9: Fusarium verticillioides

Photo credit: Wikipedia, public domain

Protozoa and Nematodes – the Predators

Protozoa inhabit the next trophic level up in the soil – they are the smallest predators. Like bacteria, they are one-celled organisms; however, they are larger than bacteria and their cells have a nucleus and organelles (in other words, a higher level of organization than bacteria). This makes them eukaryotes (see **Figure 2**), more closely related to plants and animals than bacteria (but less closely related than fungus).



Top Left: Figure 10: Protozoa – Flagellates
Top right: Figure 11: Protozoa – Amoeba
Left: Figure 12: Protozoa – Ciliate

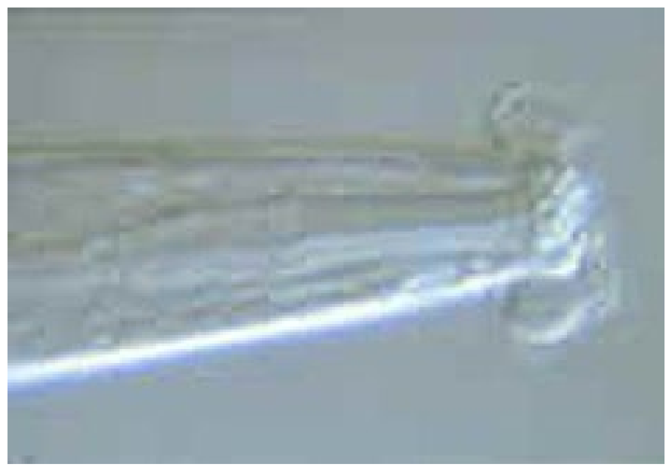
Source: Tim Wilson, Microbe Organics

They eat bacteria – lots of them. They scoop them up and assimilate the nutrient-rich bacterial bodies, creating their own larger pool of nutrients, many of which are secreted (in plant-available form) in their wastes (or when they die). There are three basic categories of protozoa in soils: flagellates, amoebae, and ciliates. They are differentiated by their structure (see **Figures 10, 11, and 12**). Bacteria are the primary diet of protozoa; fungi are a much less common food source.

Nematodes are the other major microscopic predators of the soil food web, but they are very different from protozoa. Full-fledged, multi-cellular eukaryotes, nematodes are non-segmented, microscopic worms. While they do not make up the largest organism (as measured by biomass) in the soil, they are very common in all environments, and they are the most abundant multi-cellular organism on the planet.

The agricultural perspective on nematodes has generally been coloured largely by the damage done by the pest variety, that is, root feeders (see **Figure 13**). However, that is only one type, and most nematodes are beneficial in soils. The beneficial nematodes get their energy by consuming other organisms: bacteria, fungi, protozoa, and other smaller nematodes. In doing so, they perform a similar function to protozoa: collecting and releasing nutrients (textbooks call this nutrient cycling). **Figure 14** shows a type of nematode that feeds on bacteria.

Some nematodes are also useful for controlling insect pests. These are the type that are available commercially and sometimes used by turf managers. They burrow into the larvae of insect pests and eat them from the inside out – a form of parasitism. Other predatory nematodes attack smaller nematodes, including the root feeders (see **Figure 15**).



Top Left: Figure 13: Parasitic Nematode Cysts (eggs) on Roots

Top right: Figure 14: Bacteria-feeding nematode

Left: Figure 15: Predatory Nematode Eating Another Nematode

Sources:

Figure 13: Bonsak Hammeraas, Bioforsk—Norwegian Institute for Agricultural and Environmental Research.

Figure 14 and 15: Soil and Water Conservation Society (SWCS). 2000. Soil Biology. Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

Arthropods – the Facilitators

Arthropods comprise a group of organisms that includes insects, arachnids (spiders and scorpions), and myriapods (centipedes and millipedes). They are numerous in healthy soils, although being higher trophic level organisms that are quite large relative to microbes, they do not have anywhere close to the same total numbers as bacteria, fungi, protozoa or nematodes. They are not microscopic — they are easily visible to the naked eye and range in size from barely visible (mites) to hard-to-miss (spiders, centipedes, etc.).

These creatures perform many valuable services in the soil, including:

- reducing the size of organic matter by chewing, making more surface area available to bacteria and fungi;
- excreting nutrient-rich material in their wastes (again, making more food available for further processing by the smaller members of the food web);
- keeping pathogenic organisms under control through predation and competition;
- loosening the soil, making air and water passages by means of their burrowing;
- providing "transportation services" to microbes, who will hitch a ride to other areas of the soil, either on arthropod surfaces or inside their digestive systems (they are then excreted in the fecal pellets).

As with other members of the soil food web, these creatures thrive when the environment is good for their movement, reproduction, etc. The beneficial ones are usually much more numerous than the pests when the soil is healthy. As conditions deteriorate (compaction, reduced oxygen, etc.), their numbers tend to drop relative to pest numbers, resulting in more crop damage. **Figure 16** (springtail) and **Figure 17** (pill bug) illustrate two very common soil arthropods.

Figure 16: Microarthropod - springtail

Photo Credit Michel Vuijlsteke

Figure 17: Arthropod - pill bug

Photo Credit: Franco Folini

Earthworms – the Soil's Heavy Hitters

Earthworms are generally considered to be at the very top of the underground food web. They perform all the benefits listed above and are particularly prized for their ability to both improve soil structure and enhance fertility.

Earthworms are synonymous with healthy soil, and for good reason. They are both important indicators and promoters of soil health. According to Dr. Jill Clapperton, one of North America's leading experts on soil health and the soil food web, a farmer should have five or more earthworms per spade or shovel full of topsoil. Moreover, this is a minimum – the more the better.

Farmers often state that one of the ways they can tell that the health of their soil is improving is the appearance of worm middens (see **Figure 18**), which are little piles on the soil surface made up of a mixture of organic residues and worm casts (feces). It appears as though the worms magically appear as the soil gets better but in fact it is a virtuous circle: the worms are also improving the soil as they migrate in and reproduce.

Figure 18: Earthworm middens on an Ontario no-till farm

Source: Glenn Munroe

Worms turn the soil, but not in the destructive way that tillage often does. The worms' turning is gentle and slow, not destroying soil structure but, in fact, improving it. Worms' burrows provide roots with easy channels for growth. These same channels also allow easier infiltration of water during rainfalls and better infiltration of air (and thus oxygen) all the time.

Last, but not least, worms fertilize soils. Their casts are rich not only in nutrients but also in beneficial microbes. When worms consume organic matter, it goes into their intestinal tracts, which act like hothouses for beneficial soil microbes. The casts they release hold orders of magnitude more beneficial microbes than the ambient soil. As they travel through the soil, they inoculate it with microbial activity. By doing this, they spread the greatly increased numbers of beneficial organisms all around the farm field, increasing its fertility significantly.

How do worms know to come to farms with healthy soils? From how far away do they come? Or are the increased number of worms that farmers soon see when they apply soil-health practices simply a result of increased levels of reproduction of the worms already there? Or perhaps an increase in hatching of cocoons (i.e., worm eggs) that have been in the soil for some time? We don't know for sure, but it certainly seems to be that if you build a good soil, they will come.

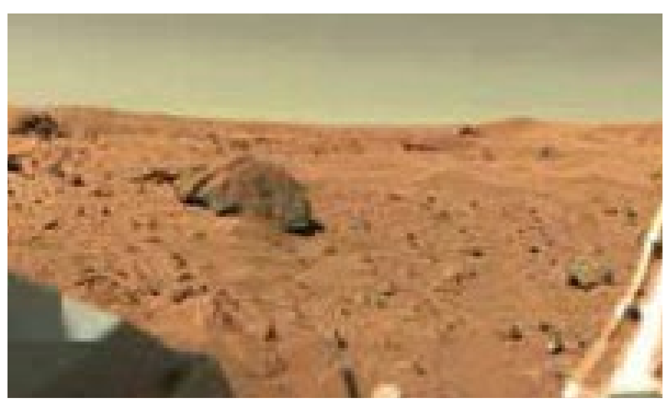
What are "soil functions"?

Healthy soils provide humans (and in fact all life on the planet) with many benefits. These include: clean and abundant water; the fertility necessary to grow our food; enhanced above-ground biodiversity; clean air; and last but not least, a moderate climate. If you think these claims may be extreme, think about the planet Mars (see **Figure 19**). The soils there (as far as we can tell) are dead, and almost certainly, as a consequence, the planet has no life above ground either. As those of you who read science fiction will know, any future plan to "terraform" Mars (i.e., make it like Earth, holding abundant life), will probably begin with the parachuting in of carefully selected varieties of soil microbes. Get the soil working and the rest of the planet will follow.

Back on Earth, we can define soil functions as simply the processes through which the soil supplies a number of specific benefits, of value both to the creatures living in the soil and those above ground (including us). From an agricultural perspective, there are four important functions:

- soil structure and its importance to water management;
- soil fertility;
- pest and disease suppression;
- soil carbon, along with its relationship to climate.

Figure 19: Surface of Mars



Source: NASA and NSSDCA

Annex 3a: The New Paradigm for How Carbon is Sequestered in Soil: Key Scientific Papers

For those who want to explore this topic further:

Bach et al. 2018. *Greatest soil microbial diversity found in micro-habitats.* Soil Biology and Biochemistry, 118: 217-226.

Cotrufo et al, 2012. *The microbial efficiency matrix stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter?* In: Global Change Biology.

Editorial Review. 2020. *Microbial necromass on the rise: the growing focus on its role in soil organic matter development.* Soil Biology and Biochemistry. September.

Kallenbach et al. 2019. *Managing Agroecosystems for microbial carbon-use efficiency: ecological unknowns, potential outcomes, and a way forward.* In: Frontiers in Microbiology

Kallenbach et al. 2016. *Direct Evidence for microbial-derived organic matter formation and its ecophysiological controls.* In: Nature Communications.

Kravchenko et al. 2019. *Microbial spatial footprint as a driver of soil carbon stabilization*. Nature Communications.

Lavallee, Jocelyn and Cotrufo, Francesca. 2020. *Soil organic carbon is a valuable resource, but all soil organic carbon is not created equal.* The Conversation, September.

Lehmann and Kleber. 2015. *Contentious Nature of Soil Organic Matter*. In: Nature Communications.

Lehmann et al. 2020. *Persistence of soil organic carbon caused by functional complexity.* Nature Geoscience, 13: 529-534.

Schmidt et al, 2011. *Persistence of soil organic matter as an ecosystem property*. In: Nature 478 (7367): 49-56.

Annex 3b: Measuring and Accounting for Carbon in Soils

At the most fundamental level, SOC is generally expressed as a *percentage of the total weight of soil within a given volume*. At the sampling level, this means that the SOC is a percentage of the total weight of the sample. If sampling is done correctly, this number can then be extrapolated to represent larger volumes of soil, such as a farm or sports field.

The key here is that the SOC percentage is *a relative weight for a given volume of soil*. For example, consider sampling that is done within a defined area, such as one hectare, and to a given depth, such as one metre. When extrapolating the resulting percentage (let's use two per cent for this example), the following calculations apply:

- One hectare of soil is 10,000 square meters (m^2);
- therefore, the volume of one hectare of soil to a meter in depth equals 10,000 x 1 = 10,000 cubic meters (m^3);
- for this example, we can assume that one m^3 of soil weighs 1500 kgs, or 1.5 tonnes (see Box Annex 3b-1 on *bulk density*);
- therefore, the weight of one hectare of soil, one meter deep, is 15,000 tonnes.

A sampling that determines that the soil is two per cent SOC by weight means that this volume of soil contains 300 tonnes of organic carbon (15,000 tonnes x 0.02).

Box A3b-1

Bulk Density is the ratio of weight to volume. Soils typically range from about 1.4 to 1.8 tonnes per cubic meter, with clay soils at the low end and sandy soils at the high end.

In our example on the left, we have used 1.5 tonnes/m_3 as a "typical" bulk density. This yields a weight of 15,000 tonnes for one hectare, measured to a depth of one meter (see Table A3b-1). If we were dealing with a sandy soil, that figure might be closer to 18,000 tonnes. For a sampled SOM concentration of 2%, the difference would be 30 tonnes of SOM, or about 25 tonnes of SOC – this is quite a substantial amount of carbon.

This illustrates the point that bulk density must be accounted for in the calculation of carbon stocks.

When considering potential changes in SOC, this number would represent the *existing stock of carbon for the sampled area, one meter deep*. If we only consider the top 10 cm (commonly done when measuring SOM and SOC levels), the total weight of that volume of soil is one-tenth of that amount, or 1,500 tonnes, and the amount of SOC would be 30 tonnes (for more examples, see Table A3b-1 below).

Table A3b-1: How SOM Levels are Calculated

Area of land	Depth of sampling (cms)	Weight of soil (tonnes)	Amount of SOM @			Amount of SOC @		
			0.5%	2%	5%	0.5%	2%	5%
One hectare (ha)	100	15,000	75 t	300 t	750 t	37.5 t	150 t	750 t
	30	4,500	22.5 t	45 t	225 t	11.5 t	22.5 t	112.5 t
	10	1,500	7.5 t	30 t	75 t	3.75 t	15 t	37.5 t
One square meter (m_2)	100	1.5	7.5 kg	30 kg	75 kg	3.75 kg	15 kg	37.5 kg

The percentages in Table A3b-1 are only one of a number of ways in which carbon levels (and changes in these levels) are expressed. Table A3b-2 below summarizes the most common methods.

Table A3b-2: Accounting for Soil Carbon: Terms in Use in Literature & Practice

	1	2	3	4
	Context	Existing Stocks (i.e., carbon already in soil)	Change in soil carbon (additions & subtractions)	Examples
A	Climate-related terms	t C/ha	t C/ha/yr	Conservation agriculture adds to soil 0.6 t C/ha/yr
B			t CO_2/ha/yr (tC/ha/yr x 3.67)	Conservation agriculture removes from atmosphere 2.2 t CO_2/ha/yr
C		% SOC (SOM x 0.5)	Change in percentage #	0.1% increase -> SOC rises from 2.0% to 2.1% (add 0.1 to 2.0)
D			Change in percentage of existing stocks (Note: 4/1000 initiative uses this method)	0.1% increase in existing stocks -> SOC rises from 2.0% to 2.002% -- (multiply 2 by 0.001, add to 2.0)
E	Agronomic term	% SOM (SOM x 0.5 = SOC, or SOC x 2 = SOM)	Change in percentage #	Same as with SOC, above.

Rows A - D show the terminology used most often in the scientific literature relating to soil-carbon sequestration and climate. In climate-related literature, changes in soil carbon (Row A) are typically given as *metric tonnes per hectare per year (Mt/ha/yr), added (gained) or subtracted (lost to the atmosphere or erosion)*. This is because the information of most importance from a climate perspective is how much carbon is being removed from the atmosphere. Using this measure allows any changes in existing stocks to be easily translated into tonnes of CO_2 added to, or removed from, the atmosphere, simply by multiplying by 3.67 (as in Row B). For example, if conservation agriculture can add 0.6 tonnes of carbon per year per hectare (see Table 2 in Section 4), then each hectare so managed is removing 2.2 (0.6 x 3.67) tonnes of CO_2 from the atmosphere on an annual basis.

Climate literature also refers to carbon as a percentage of soil, but it is usually as SOC, not SOM (Rows C and D). Changes in SOC are shown in two ways. Row C is the most common form used: if SOC percentage goes from 2.0 to 2.1 per cent, the increase is 0.1 per cent. However, sometimes the increase is expressed as a *percentage of existing stocks*. This is the approach taken by France's *4 per 1,000 Initiative*. (www.4p1000.org)

Agronomic literature, on the other hand, usually refers to changes in soil C by means of the percentages that result from sampling (Row E). This is because the focus of agronomy is not climate, but agricultural productivity. As discussed in Section 3, higher SOM levels are associated with many benefits, so changes are important. Expressing them as a percentage has two immediate benefits: first, it is the same terminology as the sampling, so no more calculations are required; and second, it allows for at-a-glance assessments of soil quality status and changes. SOM levels are more commonly used than SOC, as organic matter is more relevant and familiar to growers than the more basic C content.

The differences in expression illustrated in Column 3 of Rows C and D are particularly important because of the *4 per 1,000 Initiative*, which uses the *percentage of existing stocks* approach (Row D). How do these two approaches differ? Let's say that baseline sample measurements indicate that the SOC content of a hectare of soil to one meter in depth is 2 per cent, or 300 tonnes of C per hectare (see Table 1). If, 10 years later, measurements show an increase to 2.1 per cent, this means an increase in the existing C stock from 300 to 315 tonnes. This change can be expressed in one of two ways.

First, we can stay with the same terminology as used in the testing results: SOC increased from 2.0 to 2.1 per cent, an absolute increase of 15 tonnes. On converting to an annual basis, this is an increase of 0.01 per cent or 1.5 tonnes each year, on average.

Alternatively, we can use the **4 per 1,000 accounting method**, and say that SOC increased by five per cent of existing stocks (0.1 is five percent of two, 15 tonnes is five per cent of 300). The new SOC content is still 2.1 per cent, or 315 tonnes, but the rate of change is expressed differently. On an annual basis, the average increase would be five per cent over 10 years or an average annual increase of 0.5 per cent of existing stocks. This is slightly higher than the 0.4 per cent goal of the 4 per 1,000 Initiative, and if we work backwards, we can calculate that at 0.4 per cent per annum proposed by the initiative, the approximate level after 10 years would be 2.08 per cent.[a]

a Explains why the average is different from the actual increase each year – the cumulative change would result in a new level of 2.0813.

Annex 5: Scientific Support for the Overall SOC-Building Potential of Soils

Agricultural Soils

Agricultural soils represent the largest managed soil use in Canada, almost 70 million hectares. For Canada to do its part in achieving soil carbon sequestration that will be significant on a global scale, agricultural soils must be a priority. This potential is not up for debate; many studies[1,2,3] have concluded that depleted agricultural soils can recover lost soil organic matter and sequester carbon as a biological negative emissions strategy. Moreover, as discussed in Section 2 and summarized in Figure 4, increases in soil organic matter and carbon content are also beneficial to soils from an agricultural perspective, as soil carbon improves soil health and fertility. To focus on building SOC in our farmlands is truly a "no regrets" strategy[b].

In agriculture, management practices that have the potential to increase carbon sequestration include (but are not limited to):

- improved crop rotations;
- cover cropping;
- reduced or no-tillage;
- eliminating summer fallow;
- conversion to perennial grasses or legumes;
- manure and compost additions;
- organic soil rewetting;
- improving grazing management; and,
- land set aside[4].

Some of these practices have already been identified as tools to increase carbon storage in Canada by many long-term agronomic studies[5,6]. Improving crop rotations can be done through perennializing monoculture as well as by adding new crops to existing simple crop rotations. Adding winter varieties, removing summer fallow land, and using cover crops have been shown to improve yield stability, SOC and soil structure[7,8]. Consistent reductions in summer fallow management in the Prairies has led to significant increases in SOC storage since 1990 [9,10] Compost and manure additions increase carbon inputs and can add to long term SOC, with the amount depending on compost type and addition rate. For instance, in southwestern Ontario, a single compost addition of either household food waste, household yard waste or wheat straw and pig manure compost increased SOC in the top 30cm by 0%, 12.3% and 16.6%, respectively, during the 10 years after addition[11].

Switching from continuous corn to continuous alfalfa (a perennial) in Elora, ON increased SOC stocks by 8 Mg C/ha [12]. This was further observed in Breton, AB, where switching to fescue from barley led to a 14 Mg C/ha increase in SOC[13]. In general, replacing annual crops with perennial species could increase SOC stocks by 0.6 Mg C/ha/yr throughout Canadian sites, but this ranges based on region.

Adding winter varieties and cover crops also build SOC [14]. In Elora, the addition to a corn-based rotation of winter wheat after soybean and red clover under seeded in barley added 2-9 Mg C/ha, as compared to four other corn-based rotations over the 20-year period[15]. In this case, the addition of winter wheat or red clover increased SOC comparable to the continuous alfalfa rotation, indicating that optimizing an annual rotation can be just as beneficial as switching to a perennial forage crop. It is important to note; however, that in the above study, red clover increased SOC content when added to a barley rotation but increased the rate of carbon mineralization when added to a rotation after winter wheat[16]. This highlights the importance of understanding and optimizing the crop rotation if annuals are present.

b In climate change circles and the literature, a "no-regrets" strategy is one that is seen to deliver a range of benefits, which in total deliver savings greater than the costs of implementation; therefore, regardless of the extent of its eventual impact on climate-change mitigation or adaptation, such an action should still be considered worth doing.

Although SOC gains from no-till practices in Canada have increased, they are generally limited to the Prairies. In a meta-analysis of 36 Canadian long-term tillage studies, conversion to no-till practices consistently increased SOC in the Prairies. In Eastern Canada, carbon storage declined shortly after tillage changes, and impacts of no-till were inconsistent across 27 different sites[17]. Although it is well documented that no-till practices can increase carbon storage in agricultural soils[18,19], these results are not guaranteed. Certainly, no-till practices alone have not shown to be effective in storing carbon in Eastern Canada[20]. Additionally, no-till adoption does not necessarily increase productivity or carbon input, and some studies suggest productivity will decline if no-till is adopted in cooler and wetter climates[21].

However, we still have much to learn about the relationship of tillage to SOC storage. For instance, benefits from implementing no-till practices in Eastern Canada may take more time than previously thought. A long-term tillage study in Ontario found soils had 14 per cent higher SOC under no-till, 11 and 15 years after implementation[22]. In addition, no-till in wetter soils may work better when it is combined with other BMPs, such as cover crops or compost applications. In fact, combining several BMPs, in a systems approach, as implemented by regenerative soil managers (see Section 6), may turn out to be the optimal approach for building SOC in most if not all regions of the country, making most no-till debates moot.

Urban Lands

While regional trends in SOC for agricultural soils are striking, the same cannot be said for other managed soil uses within Canada, including residential land, commercially managed soil, and recreational land. Little is known for these uses because virtually no work has been done on this topic in this country. Accordingly, our discussion of SOC potential below draws heavily on work done in other jurisdictions, primarily the United States. We have organized the research findings under residential soils (lawns and gardens) and commercial turfgrass systems (primarily golf courses and sports fields).

Residential Soils

Much of the scientific work described in the literature on residential soil carbon and lawn management has taken place on large land parcels in regions outside of Canada. In Canada, there is a poor understanding of not only the amount of carbon that exists in residential soils, but how individual management plays a role in soil carbon sequestration. However, the available literature presents an opportunity to evaluate residential soil management and residents' behaviour as it pertains to the Canadian context.

This literature reveals that carbon storage on residential land is influenced by a variety of factors, but one of the most important is the size of the parcel[23,24]. Parcel size is determined by a combination of the management decisions of developers and the choices (and budgets) of those who purchase it and become residents, making these actions of particular interest. Categories of residential land based on the size of the land parcel are as follows:

- urban or suburban (one housing unit per < 0.2 ha);
- exurban (one housing unit per 0.2-16.2 ha);
- rural (one housing unit per > 16.2 ha).

Rural Residential Lands

Larger parcel sizes usually result in greater carbon storage, since residents often leave larger areas of land unmanaged. Unmanaged spaces allow for forest expansion, seed dispersion and secondary succession to occur, contributing to higher per-unit-area carbon storage on large land parcels[25]. Similarly, forest patches on properties increased with parcel size. This was also found in Michigan, where dense woody vegetation like trees were the highest contributor to soil carbon[26]. Therefore, there is potential for more carbon storage in residential lands if residents and ecological conditions allow for trees to grow larger. Other major sources of carbon in residential land were grass growth, leaf litter and wood residues from trees, all of which led to increases in SOC over time[27]. In contrast, residential lawn management without these larger inputs, but with grass cuttings intentionally left on the turf, saw more modest SOC increases, and these became SOC decreases when those cuttings were removed[28].

Urban and Exurban Residential Lands

Medium parcels of land (1-2 ha) have potential for building SOC due to the opportunity for reforestation[29]. Parcels larger than approximately 0.4 ha are typically managed in ways that challenge social norms such as neatness and lawn care and that are therefore more likely to increase soil carbon storage[30]. In contrast, residents on smaller land parcels were more likely to remove leaf litter and grass clippings and have a higher proportion of yard area devoted to turf[31]. These practices reduce the potential for greater SOC storage.

Developers provide an early influence on the management of urban and some exurban residential lands through practices such as tree removal, soil grading, drainage management, and vegetation establishment (e.g., turf grass and horticultural plants[32]). Larger parcels of exurban residential land, on the other hand, are managed solely by individual households. Both developer practices and human behaviour are important in considering how soils store carbon on residential land. Developers are often associated with high density suburban housing. When land is being developed, modern excavation and construction provide significant soil compaction and disturbance[33]. This was observed in residential yards where bulk density was significantly higher than field and forest soils to 40cm depth[34].

Factors Influencing SOC Potential in Residential Soils

Overall, developer and resident decision making are important aspects of lawn care and management. Practices that favour SOC increases include:

- planting trees and horticultural plants;
- reducing soil disturbance and compaction;
- reducing leaf litter and grass removal;
- applying compost.

Commercial and Recreational Turfgrass Systems

Golf courses and other managed turfgrass systems, such as urban parks, remain unutilized for soil carbon sequestration because there is a lack of research on this topic in Canada. Commercially managed turfgrass systems tend to have higher accumulation rates of soil organic matter than grassland systems and have lower rates of soil disturbance due to consistent soil cover when compared to agricultural systems[35]. Similar to residential land, managed turfgrass systems could provide significant long-term carbon storage through soil management improvements.

Golf Courses

Golf courses represent a large portion of commercially managed soil in Canada. There are 2,346 public and private golf facilities in Canada as of 2015[36]. Given that the average 18-hole course can range between 60 and 80 ha in size[37], the area of land associated with golf courses in Canada likely ranges from 125,000 to 168,000 ha.

Turfgrass systems within golf courses are managed using aeration, chemical application, fertilizer application, irrigation and mowing[38]. These management practices differ over the many regions of the golf course, where highly trafficked playing areas undergo the most intensive management[39]. There is significant disruption on golf course tees and putting greens due to organic matter (thatch) removal from coring, mowing and scarification, which hinder carbon sequestration[40]. Despite these negative factors, two UK golf courses were found to be net sinks of greenhouse gas emissions, indicating that golf courses can provide carbon sequestration, even under intensive management. It should be noted, however, that the net benefit of carbon sequestration was reduced when soils reached equilibrium (20-45 years after establishment)[41].

Fairways, rough and naturalized areas (including forest and grassland) all have a net sequestration potential; however, the proportion of each varies by golf course. For example, tree cover for two golf courses in UK varied between 0.9 and 48.1 ha, greatly influencing the size of carbon sink available[42]. One study suggests turfgrass can still be a major contributor to soil carbon stocks, where turfgrass contributed 66% of the total carbon stocks over 13 golf courses[43]. Soil carbon storage differs based on the area of management within the golf course. Soil carbon content was as high as 11% and 7.8% in the top 2.5 cm for fairways and rough, respectively[44]. During the 25 to 30 years after golf course establishment in Colorado, carbon sequestration occurred at rates of 0.9 to 1.0 Mg C/ha/yr for putting greens and fairways, respectively[45]. A study conducted in Ohio found even more carbon sequestration potential, where farmland soils converted to golf course sequestered at a rate of 3.5 Mg C/ha/yr in fairways and 2.6 Mg C/ha/year in rough areas[46]. Accordingly, it seems likely that the playing area of golf courses may provide significant carbon sequestration potential, in addition to the naturalized areas.

In summary, to improve soil carbon sequestration by golf courses, managers must increase the amount of land area devoted to naturalized areas like forests and grasslands, but also optimize turfgrass management for carbon storage. One of the most important SOC-building BMPs for golf course management is reducing thatch removal[c]. Implementing planning and management guidelines that address these two issues could greatly improve soil carbon sequestration by golf courses across the country.

Other Turfgrass Systems with Significant Potential

While golf course management has been a topic of interest in the literature, other forms of commercially managed turfgrass systems, including municipal parks and conservation areas, have not been studied as much. Recreational areas are locally managed and often contain components similar to golf courses, including turfgrass, water bodies, naturalized forests, wetlands and grasslands. Additionally, municipal parks likely have similar management practices to golf course fairways and roughs in terms of mowing or foliar applications due to their use in recreational sports. Even though the amount of land allocated to parks is unknown, this soil use remains important because local government and conservation authorities can change management to improve soil sequestration.

c For other BMPs that have the potential to sequester carbon in turf, see the Roadmap companion document, the Soil Carbon Tool Kit.

Annex 6a: Further Details on Selected Axten Farms BMPs

Intercropping

This practice takes some experimentation to get right, as some crops work well together and others do not. The Axtens have found that chickpeas and flax can be grown in alternate rows, but their other combinations, such as flax with lentils, and mustard with peas, work better when seeded into the same row. Harvesting is also a challenge, as the grains or seeds must be separated – which requires specialized machinery. However, the best combinations have increased their yield by 25 per cent, on average, while allowing them to use fewer inputs (see below) and have better control over weeds. *From a soil carbon perspective*, intercropping increases diversity both above and below ground, provides more soil cover than a single crop, and reduces fertilizer requirements (when legumes are used in the mix), thus hitting three of the five principles discussed in Section 5.

Compost extract

They make their own compost, using a neighbour's beef-feedlot manure, hay, grain screenings, and wood chips. They use the compost on their crops, but they simply can't make enough compost to cover their full 6,000 acres, so they take some of their best compost, extract the beneficial microbes as a water-based liquid, then apply this extract to the furrow as they seed in the spring. How do they know which compost is best? Tannis examines samples from the compost piles, or windrows, with a microscope, looking for the richest diversity of the right kind of microbes. This practice increases the likelihood that as the seeds sprout, each plant will be able to form the microbial partnerships that it needs to thrive. *How does this increase soil carbon?* As discussed in Section 3, microbial associations with plant roots increase productivity and result in higher carbon inputs to the system. A stronger soil food web also results in a higher likelihood of increased carbon stabilization, reducing carbon losses as well.

Reduced synthetic inputs

No farmer wants to starve their crop of nutrients, limiting their yields and hurting profitability. However, *optimizing inputs* can reduce costs while maintaining yields and boosting profitability. *From a soil-carbon perspective*, optimizing nutrient use is important, because excess nutrients can result in carbon losses (see Section 3). The Axtens reduce the use of synthetic inputs by maximizing natural fertility via the development and maintenance of good soil biology, coupled with the use of legumes, compost, minerals, and manure from grazing animals.

Stripper header and stubble retention

Derek Axten says that his purchase of this equipment has made an enormous difference in terms of moisture retention and distribution. The high stubble catches the snow in winter and prevents it from being blown off the high spots in his field and into the low spots. The result is a reduction in yield loss due to patchy dry areas. With respect to soil carbon, this means higher carbon inputs due to increased productivity, as well as reduced carbon losses from erosion.

Annex 6b: Assumptions and Methods Used in Calculating SOC Increases in Section 6

In all cases, we assumed a bulk density of 1.5 tonnes per m^3 of soil. Using this figure, one square metre of soil, to a depth of 30 cm , would be a volume of 0.3 m^3 and would weigh about 0.45 tonnes, or 450 kgs. Expanding this to one hectare, or 10,000 m^2, would result in a volume of 3,000 m^3 weighing about 4,500 tonnes. Accordingly, to calculate the number of tonnes of carbon (SOC) added per hectare per year, we first multiply the percent of SOM increase by 4,500 tonnes. For example, if the initial SOM percentage was 1.6, that means that this volume of soil included 4,500 x 0.016 = 72 tonnes of SOM. If the SOM percentage went up from 1.6 to 1.8 over five years, the calculation would be as follows:

- Multiply 4,500 tonnes by 0.018 to get the new total for SOM, which is 81 tonnes
- Therefore, the increase over 5 years was 81-72 = 9 tonnes of SOM
- Divide by two to get tonnes of SOC, which would be 4.5
- Divide by 5 years to get the average increase in SOC per ha per year = 0.9

Annex 7a: Three Models Integrated and Adapted for Framework for Change

Our summary and discussion of the barriers to adoption of SOC BMPs by soil managers has been organized into a framework that draws on three models of human behaviour with respect to change. These are:

1. *innovation diffusion theory*, which attempts to model how innovation is gradually adopted by more and more actors, until it becomes the norm. This model divides potential users of the innovation into five categories, based on the time it takes each group to adopt the innovation.

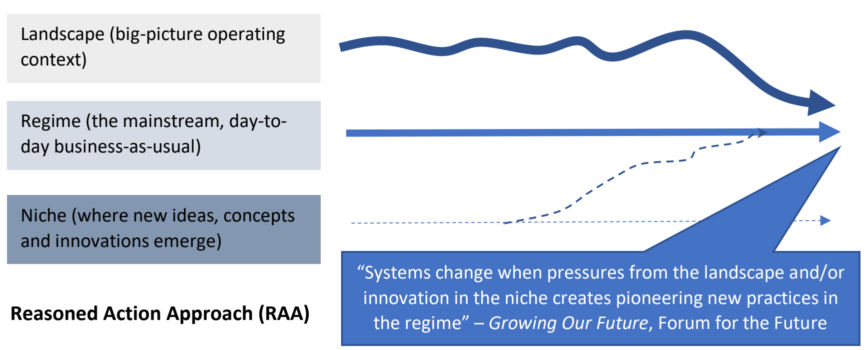
2. the *multi-level perspective framework*, which posits that the "regime" (those utilizing standard practices) are influenced from two directions – from the "niche" (those introducing the innovation, or the innovators and early adopters of innovation diffusion theory) and from the "landscape" (the overall societal context within which we all operate).

3. the *reasoned action approach*, which posits that the actions of each individual, in deciding whether or not to adopt an innovation, can be analyzed in terms of the innovation's perceived efficacy, its impact on social norms, and personal capacity of the actor to adopt it effectively.

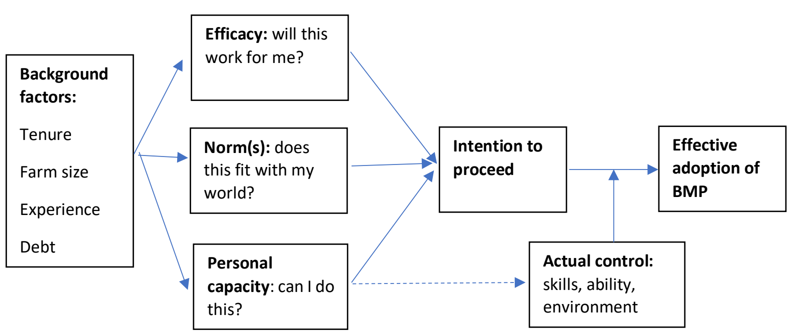
Multi-Level Perspective Framework

From Wikipedia: "Multi-level perspective (MLP) framework as the name implies, the MLP posits three analytical and heuristic levels on which processes interact and align to result in socio-technical system transformations; landscape (macro-level), regimes (meso-level) and niches (micro-level)."

Using this framework means that we need to analyze the factors affecting change from all three perspectives.



Reasoned Action Approach (RAA)



From Wikipedia: **The reasoned-action approach (RAA)** is an integrative framework for the prediction (and change) of human social behavior. The reasoned-action approach states that attitudes towards the behavior, perceived norms, and perceived behavioral control determine people's intentions, while people's intentions predict their behavior.

Annex 7b: Detailed Summaries of Challenges to Change

Table A: Summary of Substantive Challenges to Change, by Level and Process

Innovation Pool	
Profile, Sector Perception, Research, Knowledge Transfer	• lack of awareness of the accomplishments of this group by other farmers and soil managers • lack of the independent research necessary to corroborate these accomplishments and give them credibility • lack of mechanisms for on-going knowledge transfer between IP and other soil managers (including demonstration sites)
Personal Background Factors	
Tenure (future control over land)	• lack of any real incentive to improve rented land by building SOC
Experience and/or age	• unwillingness of older farmers to change an approach that has worked for a long time
Debt	• high debt may create an inability to access needed capital and/or an aversion to financial risk
Disposition	• some personalities will be less open to change and/or have less tolerance of risk
Personal Decision Factors	
Awareness (are there different ways of farming that could improve the bottom line?)	• lack of info re: benefits of implementing various BMPs • lack of local demonstration sites • lack of knowledge of latest soil science and its relationship to productivity, cost efficiency, and sustainability • lack of role models
Efficacy (is it worth it to change?)	• lack of proof re: impact on yields, profitability and other benefits • lack of credible info on costs involved with changing practices • lack of marketplace recognition • lack of ability to do an accurate risk assessment • lack of relevant information on options for recouping costs or getting paid for societal benefits (local programs available or planned)
Norms (how does this approach fit with a soil manager's sense of self and their role in the community)	• lack of awareness of local champions or members of IP • concern re: negative opinions of friends, neighbours, family • perceived poor fit with past experience and current views of farming • perceived poor fit with personal moral framework (values)
Capacity (does the grower feel that they have the ability and the tools?)	In general, fear that this new approach is too difficult or complicated. More specifically: • concern that financial resources are insufficient to buy the necessary equipment and supplies and to pay for any additional labour • question of whether current equipment can be adapted to meet the challenge • concern re: the extra time required to manage the extra work involved • concern that soil-science knowledge is insufficient

Personal Implementation Factors	
Capacity	• concern re: unforeseen draws on available resources
Technical issues	• concern re: problems with implementation due to climate or other factors beyond individual's control • concerns re: difficulties in adapting my equipment for (a) new practice(s) • concerns re: the difficulties associated with specific BMPs
Technical Support	• concern re: ability to access technical support (e.g., extension) during early days of implementation • concern re: ability to easily access good data and advice during implementation
Measurement	• concern re: availability of consistent and practical metrics for monitoring and reporting soil benefits • concern that the cost of measurement be too high vis-à-vis any financial benefit
Farm-Food System Factors	
Supply chain	• availability and affordability of supplies such as cover crop seed • availability of affordable equipment such as no-till drills • availability of scientific and technical advice when needed
Financing	• no support from banks and other lending institutions with respect to changes in soil management practices
Markets	• lack of market recognition (e.g., labelling, advertising) • lack of markets for SOC-building crops • lack of appropriate processing facilities
Insurance	• concern whether insurance programs cover novel crops • impact of the adoption of new practices on crop insurance
Environmental policies & regulation	• government regs, policies and programs that work against new practices • concern that the adoption of SOC BMPs require the grower to provide private information to government, making the grower vulnerable to existing environmental regulations
Research needs	• concern as to whether government-sponsored research is focused on the right things • need for clear and understandable data on innovative practices/approaches to be made available regularly to farmers

Table B: Barriers Aggregated by Category

Category	Barriers
Cultural	PERSONAL ATTITUDE: • unwillingness to change an approach that has worked for a long time (most common in older farmers) • personality is less open to change • personality has less tolerance for risk • perceived poor fit with past experience and current views of farming • perceived poor fit with personal moral framework (values) NORMS: • lack of role models • lack of awareness of local champions or members of innovation pool (no innovators/first adopters among friends and neighbours) • concern re: negative opinions of friends, neighbours, family (reputation)
Economic	RISK: • high debt may create aversion to financial risk • lack of proof re: impact on yields, profitability and other benefits • lack of credible info on costs involved with changing practices • lack of ability to do an accurate risk assessment • concern re: the extra time required to manage the extra work involved • concern re: unforeseen draws on available resources • availability and affordability of supplies such as cover crop seed • no support from banks and other lending institutions with respect to changes in soil management practices • concern whether insurance programs cover novel crops • impact of the adoption of new practices on crop insurance (LACK OF) INCENTIVE: • lack of markets for SOC-building crops • lack of any real incentive to improve rented land by building SOC • concern that the cost of measurement be too high vis-à-vis any financial benefit • lack of market recognition (e.g., labelling, advertising) • lack of relevant information on options for recouping costs or getting paid for societal benefits (local programs available or planned) CAPACITY: • concern that financial resources are insufficient to buy the necessary equipment and supplies and to pay for any additional labour • high debt may create an inability to access needed capital • availability of affordable equipment such as no-till drills
Government	UNINTENDED BARRIERS • government regs, policies and programs that work against new practices (outdated goals and/or unintended consequences) • concern as to whether government-sponsored research is focused on the right things PRIVACY CONCERNS • concern that the adoption of SOC BMPs require the grower to provide private information to government, making the grower vulnerable to existing environmental regulations

Category	Barriers
Information & research	AWARENESS: • lack of awareness of the accomplishments of innovators and early adopters by other farmers and soil managers • lack of local demonstration site • lack of knowledge of latest soil science and its relationship to productivity, cost efficiency, and sustain-ability • fear that this new approach is too difficult or complicated RESEARCH: • lack of independent research necessary to corroborate innovator accomplishments and give them credibility • lack of info re: benefits of implementing various BMPs ACCESS TO DATA: • lack of mechanisms for on-going knowledge transfer between IP and other soil managers (including demonstration sites) • concern that own soil-science knowledge is insufficient (need for training, education) • concern re: ability to easily access good data and advice during implementation (need for qualified extension)
Technical	EQUIPMENT: • question of whether current equipment can be adapted to meet the challenge • concerns re: difficulties in adapting equipment for (a) new practice(s) KNOWLEDGE: • concern re: problems with implementation due to climate or other factors beyond individual's control • concerns re: the difficulties associated with specific BMPs • concern re: ability to access technical support (e.g., extension) during early days of implementation INFRASTRUCTURE: • concern re: availability of consistent and practical metrics for monitoring and reporting soil benefits • lack of appropriate processing facilities for novel crops or non-traditional agronomic methods

Annex 8: Conclusions

Building the Future [institutional framework]

Conclusion 1:

Strong, focused leadership on soil health is needed to: build awareness of the benefits Canadians receive from healthy soils; sustain and enhance our national commitment to soil health; and inform the development of new policies and programs that deliver, measure, and report on programs aimed at soil health.

Desired Outcome

Leadership emerges in Canada to guide the future of soil health.

Key Elements for Success

It is critical for the agricultural industry and governments to work together toward a common vision for the future of soil health in Canada. Leadership at both levels is essential.

Recommendation 1

The agricultural industry and the federal government should work together to create a non-government entity (e.g., "Soil Health Roundtable") that can provide the leadership necessary to develop and achieve a vision and plan that will secure the future of soil health in Canada.

Action:

Senior governments should initiate a process ($2 million over two years) where stakeholders work together to develop consensus on the ways and means of creating, funding and maintaining such an entity.

Conclusion 2:

A vision for soil health and SOC is urgently needed, as the foundation for future plans, and to build consensus on key challenges and opportunities related to soil health.

Desired Outcome

Future actions to maintain and enhance soil health and the benefits derived from it are based on a national strategy for soil health outcomes.

Key Elements for Success

Interest in soil health and its many benefits to Canadians has never been greater than it is presently. The growing awareness and interest also create expectation for action by governments and the industry. A national strategy will provide a reasoned and transparent approach to managing soil health in the future.

Recommendation 2

The Government of Canada should task the entity identified in Recommendation 1 with developing a National Soil Health Strategy via a multi-stakeholder process.

Making the Case [motivation]

Conclusion 3

A basic understanding of soil mechanisms is necessary if soil managers are to select practices beneficial to soil health and soil carbon.

Desired Outcome

Soil managers are making informed decisions on how they treat their soil.

Key Elements for Success

Soil managers need to be supported in gaining a working understanding of the fundamental processes that effect SOC. This enhanced knowledge allows producers to evaluate soil management decisions with consideration to soil health and SOC, just as they consider other decisions in their overall farm operations. Knowledge is the key to good decision making.

Knowledge is also fundamental to innovation. For example, zero-till equipment was largely the result of farm level innovation of existing principles of design in tillage and seeding equipment. Farmers have a good understanding of how these machines are designed and what functions they can perform, or not perform. When the functional knowledge of farmers is combined with the need to solve a problem, innovation happens in abundance.

The key element to success in this case is strengthening and enhancing the knowledge base of farmers and agricultural professionals on the fundamentals of soil health and on which management practices will increase or decrease SOC.

Recommendation 3

Build a basic understanding among soil managers of how management practices impact soil health and soil organic carbon (SOC).

Action

The Roundtable should be tasked with the design and implementation of a five-year, $20 million program with the goal of reaching 100,000 farmers with soil health education and training.

Conclusion 4

Sound science, practised at all scales, from lab to working farm, must remain the foundation of all efforts to build SOC.

Desired outcome

Innovative soil managers are full partners alongside academics, scientists, ag professional, and others in moving discovery science to the field.

Key Elements for Success

Soil management practices used on Canadian farms have always been based on sound science and that must continue. Bringing farmers into the cycle of scientific discovery is the best approach to ensuring that science is being focused on significant areas of concern and is providing practical solutions to challenges that farmers and soil managers face.

In addition, the basic scientific understanding of soil has evolved in recent years. Scientific disciplines such as ecology, which focus on soil as an ecosystem, rather than on its individual physical, chemical, and biological processes, have added new dimensions to our understanding of soil functions. It is important that scientific research going forward includes more inclusive and integrated approaches in assessing the value of soil management practices.

Recommendation 4

Develop a mechanism to sustain communications and collaboration between farmers, other soil managers, government, and scientists and researchers from the full range of relevant disciplines.

Action

Establish a *National Soil Carbon Science Advisory Board*, in collaboration with the Living Labs Program, Canadian universities, and other relevant stakeholders. The Board's mandate should be to convene annual meetings for the review of existing research and the establishment of common priorities for research investment. The focus should be projects that are targeted at farm-level issues and result in usable and practical solutions for farmers ($2.5 million over five years).

Conclusion 5

We need to create the opportunities for leading innovative farmers to be seen as champions of soil health.

Desired Outcome

A network of leading innovators and organizations emerges that are recognized for their knowledge, experience, and success in sustainable soil management.

Key Elements for Success

Leading innovative farmers can contribute significantly to the goal of "more carbon in our soil" by speaking out, mentoring, demonstrating success and failure, and creating a more attractive and supportive environment for new adopters. Peer-to-peer learning has always been effective in extending knowledge and success stories in agriculture. Innovative managers will be credible sources of support for those earlier in the adaptation process.

Relying on volunteerism is a failing strategy. If we are asking leading innovators to do this work, they need support in the form of information, logistical support, and compensation for their time.

Conservation organizations such as Compost Council of Canada, Soil Conservation Council of Canada, Canadian Forage and Grassland Association, and others can also provide leadership and capacity to support events that raise awareness and share knowledge about SOC.

Recommendation 5

Promote and enable leadership activities among leading-edge farmers (innovators and early adopters) that will facilitate the sharing of their knowledge and experience with other farmers.

Action

Support 200 soil champions in one-to-one and group mentoring of their colleagues with respect to practices that increase SOC ($10 million over five years).

Conclusion 6

Soil needs to be included with air and water as a fundamental requirement for a healthy environment.

Desired Outcome

Canadians are aware of the value and importance of soil to their wellbeing. Soil must become as important to Canadians as air and water.

Key Elements for Success

Canadians who understand the environment, ecological and economic benefits of healthy soil, and enhancing SOC levels are more likely to support, encourage, and acknowledge the efforts of famers and other soil managers who are increasing SOC.

We have a strong story to tell in terms of the benefits of enhancing SOC.

Recommendation 6

Raise the public profile of soil to the same level of importance as air and water.

Action

Launch a $100 million public engagement initiative (over five years) to raise and sustain the key role soil plays in providing multiple important benefits to all Canadians.

Making it Work [tools]

Conclusion 7

Ag professionals in the private and public sector can play a significant role in motiving producers to build SOC. An organized, co-ordinated, independent, and unbiased system of providing technical and professional advice to soil managers will help them to increase and maintain their soil carbon levels.

Desired Outcomes

A renewed effort is undertaken to rebuild our knowledge transfer capacity for the agriculture industry in Canada, resulting in training and education opportunities for farmers and agricultural professionals in soil health practices. The goal should be that building SOC and improving soil health are routinely considered in planning and day-to-day operations.

A similar effort is made to bring enhanced knowledge and training to managers of soil in other areas, such as municipalities, golf courses, and the landscaping industry.

Key Elements for Success

Public sector capacity to provide direct advice to farmers on soil health management has declined or is non-existent in many areas of rural Canada. Most of the technical contact with farmers comes from agricultural professionals in the private sector who have limited or no training in soil-health practices. This trend needs to be reversed.

Efforts need to be directed at building the knowledge base of agricultural professionals both in the public service and the private sector so advice on soil health and SOC are part of soil management plans from the beginning and not an afterthought.

Recommendation 7

Build independent extension and knowledge transfer capacity to the point where it is available to all Canadian soil managers and farmers who want to adopt soil health practices.

Action 5

Invest $100 M over five years to make soil-health related extension and knowledge transfer available across Canada (this would probably be delivered by the provinces).

Conclusion 8

The current and future science of carbon and soil will help illuminate the principles, management practices, and systems that will enhance SOC levels despite a changing climate, market-based pressures, and other factors.

Desired Outcomes

The accepted standard for present and future recommended soil management practices continues to be based on science that is validated and calibrated to Canadian conditions.

Scientific and technical solutions are developed to ensure we adapt our responses to changing situations and maintain the resilience of our soils to manage risks.

Key Elements for Success

The current level of scientific knowledge on soils and carbon in Canada is a great asset. It has allowed us to develop soil management practices based on the available science.

Maintaining and enhancing our base of science and information is essential to our future success in maintaining and enhancing soil health in Canada. Factors like climate change, market forces and public opinion will continue to influence the demands on our soil and the range of options at our disposal to address new opportunities and challenges. Ongoing scientific investigation is needed to find a path to the future.

Recommendation 8

Create a program that preserves existing knowledge of our soils, gathers new information, conducts monitoring of changes, and reports to Canadians on a regular basis.

Action

Invest $20 M over five years to establish a national government agency/department charged with preserving and managing existing and new information relevant to soil, including beneficial management systems and practices.

Strengthening the Business Case [incentives]

Conclusion 9

Investigate ways to ensure that management designed to increase SOC makes business sense to soil managers.

Desired Outcomes

Even though the bulk of the evidence points to the value of the long-term business case for building SOC, and that this information can and should be widely shared *(Section 1: Making the Case),* we believe that more is needed to ensure a timely adoption of SOC-building BMPs by most soil managers.

Key Elements for Success

Private-sector initiatives to provide carbon payments have been springing up across North America in the past few years[d]. These programs pay farmers to store carbon using money raised from businesses who want to offset their emissions and/or individuals who want to help tackle climate change. Some of the large agricultural companies, such as Cargill and Bayer, have also introduced programs to pay farmers to adopt SOC-building BMPs, and similar programs are emerging in Europe and around the

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d Major initiatives include: ESMC (Ecosystem Services Marketing Consortium), a program of the not-for-profit Soil Health Institute in the United States; Indigo Ag (Earn Income for Enriching Your Soil | Indigo Carbon (indigoag.com)); and the Nori Carbon Removal Marketplace (US).

world. Some of these initiatives are for SOC building only, while others pay for a broader range of ecosystem services, including water quality and conservation.

These programs are innovative and leading-edge and may play an important role in getting farmers to adopt SOC-building practices. However, they are U.S.-based, not international, and may put Canadian farmers at a disadvantage, if no such systems exist in this country. A system for Canadian agriculture is needed sooner, rather than later.

On March 6, 2021, the federal government posted draft Greenhouse Gas Offset Credit System regulations, under the *Greenhouse Gas Pollution Pricing Act*, to the Canada Gazette for comment. These draft regulations include offset protocols for SOC. Hopefully, this is just the beginning of the development of a framework for integrating SOC into the economics of soil management in Canada.

Recommendation 9

Accelerate efforts in developing tools to assess and address the full range of costs and benefits, on-farm and off-farm, associated with improving soil health.

Action

Invest $20 million over five years to identify/create a formal set of tools for integrating ecological and other socially beneficial services into cost-benefit analyses related to soil management.

Clearing the Tracks [obstacles]

Conclusion 10

Farmers face a host of challenges beyond the farm gate that make progress difficult. Support for innovators and early adopters is needed, so that they can overcome these obstacles and grow successfully. In turn, this upward pressure should stimulate necessary changes in the businesses, institutions, and government agencies that make up the overall farm-food system in Canada.

Desired Outcome

A shift in the perspective of the entire farm-food system, away from a simple production model and toward a more holistic approach that sees agriculture (and all soil management) as a multi-faceted tool for delivering much more than traditional food and fibre. This vision can also go beyond soil carbon and climate change, to embrace a range of environmental services such as water quality, biodiversity, and human health.

Key Elements for Success

Section 7 outlined some of the most important challenges to the adoption of SOC-building practices at the farm-food system level. These included issues with the supply chain, processing infrastructure, markets, financing, regulation at various government levels, crop insurance, and all types of agricultural research. At a general level, the fundamental issue in all these areas is the systems are set up for a strictly production-focused model of agriculture, where yield and price are the dominant drivers, rather than a more holistic model, which puts other objectives, such as building soil carbon and related environmental benefits, at the same level as productivity.

In summary, the challenge is to effect systemic change in a variety of agents, including businesses, institutions, and government. This cannot be done overnight. Nor is it likely that it can be done effectively in a top-down manner, that is, strictly through laws and regulations. Governments can and should begin the process of change through education, communications, funding, and policy. Provincial governments can identify and support the efforts of the innovators and early adopters, helping them to navigate the system-level challenges such as crop insurance, markets, and financing. The federal government can influence research in support of change. In fact, this is already happening as Agriculture and Agri-Food Canada has made soil carbon the focus of its Living Labs program with new funding and the goal of having at least one of these farmer/researcher partnerships in each of the provinces by 2022. In addition, the 2021 budget includes more money for the acquisition of equipment and specialized services for farmers adopting soil-health BMPs. This will drive change in the businesses involved in the supply chain and end markets.

The shift from early adoption to early majority in soil health is already underway in many parts of the country, and for a variety of farming practices. The private sector has already recognized and acknowledged this, with companies such as General Mills, McDonald's, and Nature's Path devoting significant time and money to help their suppliers move to more climate-friendly practices. The term that is being adopted by these private-sector movers and shakers is "regenerative." It appears to be the label that is emerging for the most progressive growers, the ones that governments at both federal and provincial levels can identify and nourish. If they do so, promptly and effectively, it could facilitate a burgeoning demand from the early majority of growers that will stimulate a shift in the way that conventional institutions, supply-chain businesses, and markets act with respect to multiple-objective approaches to farming.

Recommendation 10

Identify and gradually amend government policies and programs with the goal of making them fully compatible with practices that improve soil health and build soil carbon.

Action

Governments of all levels should systematically review agricultural policies and programs on an ongoing basis, with the goal of removing obstacles to the adoption of improved soil management practices.

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