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Agricultural soils as a solution provider to climate change

Paper prepared for CAPI

by

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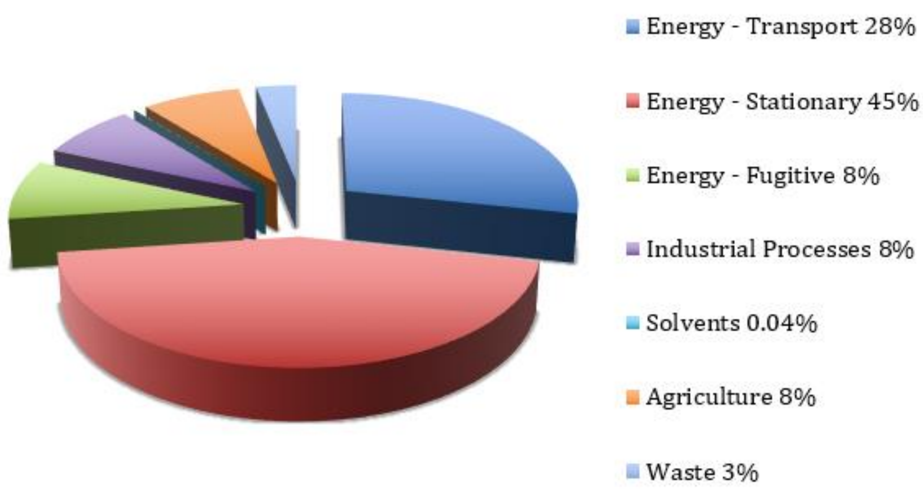
Introduction and context

Global climate experts agree that climate change, as we currently understand it, is a consequence of the emission of greenhouse gases (GHGs) resulting from human activities. Agricultural production is one of many activities that releases carbon dioxide (CO_2), nitrous oxide (N_2O) and/or methane (CH_4), and contributes to the overabundance of carbon in the atmosphere, usually through:

- Direct emissions from farming activities (N_2O from fertilizer applications, CH_4 from manure);
- Indirect emissions related to fossil fuel use in the production of agricultural inputs such as pesticides or fertilizer; and
- Activities that release soil carbon reserves (tillage, mono-cropping, deforestation).

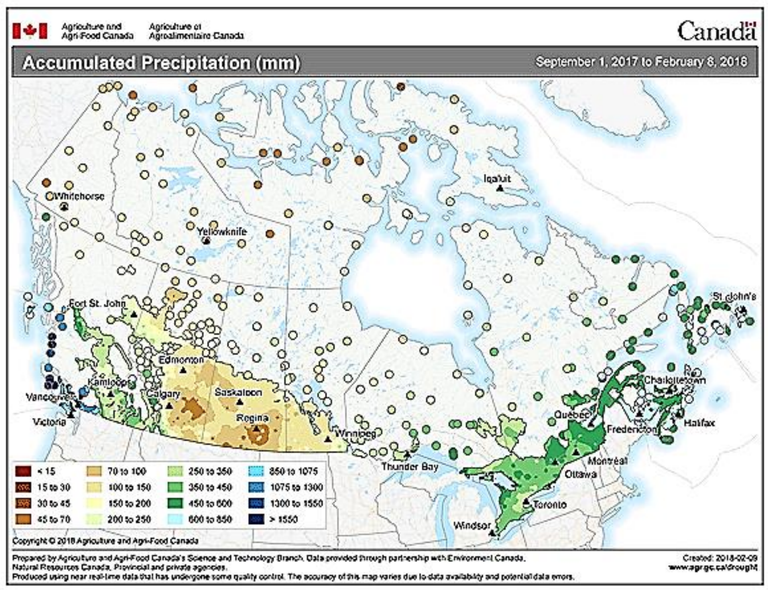
Emissions from agricultural sources contribute approximately 8% (59Mt) of Canada's total GHGs (722Mt) (Environment and Climate Change Canada (2017) Canadian Environmental Sustainability Indicators: Greenhouse Gas Emissions. Consulted on August 1, 2018). Analysis of the source data shows that slightly more than 50% of agricultural emissions arise from livestock production and manure management, with the remainder from agricultural soils and the use of nitrogen fertilizer (Prairie Climate Centre 2018)



While agricultural production can yield substantial emissions, it can also result in the capture of carbon from the atmosphere – a process known as biological carbon sequestration or bio-sequestration. Whether focussed on food, feed, fibre or fuel commodities, agriculture is based on the production and use of plants, which uniquely rely on the biochemical process of photosynthesis to capture atmospheric carbon to support their growth. Plants can remove carbon from the atmosphere and contribute a portion of that carbon to stable pools in the soil. With careful management, the amount of carbon sequestered in the soil for longer term storage can exceed the amount of carbon emitted by the associated agricultural activities, so that soils can act as a net sink for carbons that might otherwise be emitted to the atmosphere. Thus, agricultural soils can play a part in stabilizing climate change.

The potential of agricultural soils to act as a sink has attracted considerable interest around the world. On Dec 1, 2015 France launched the "4 by 1000" initiative, which is based on the concept that a 0.4% annual growth rate in soil carbon stocks would halt the anthropogenic increase in atmospheric carbon levels, while reducing soil degradation rates and improving food security around the world. The 4 by 1000 voluntary initiative is part of the global climate action plan adopted by the UNFCCC at the Convention of the Parties 22; well over 200 signatories have pledged participation in the program in various capacities since its launch.

About Canadian soils



Of Canada's vast 9.98M Km^2 land base, only about 6.9% (626,562 Km^2 or 62,656,200 ha) is considered agricultural land, and only 4.8% is suitable for crop production. Agricultural lands are generally clustered along Canada's southern-most geopolitical boundary, where there is adequate water and sunlight, suitable heat units, and sufficient mineral soils to support agricultural activity (AAFC map, 2018).

Soils are characterized according to the parent materials and physical relief, as well as soil climate and inherent organisms. Soil survey information is used to classify soils into 7 categories according to their capability to support sustained agricultural activity; Classes 1-4 can support cultivated field crops (Canadian Land Inventory, 2018). Only 0.5% of Canada's land mass is classified as Class 1, or without any limitations for agricultural production, making best class soils a precious resource.

Soils are made up of complex mixtures of mineral particles, organic residues, and dissolved ions and water, and are highly influenced by climate and microbial activity over time. Soils are considered a living ecosystem where microbes are critical to the healthy function of soil processes. A changing climate, with expected alterations in moisture and base temperature will impact soil health and activity, and these changes may require new management strategies. Consequently, considerable focus on understanding soils and their management has occurred in recent years. The UN General Assembly declared 2015 the International Year of Soils (UN IYS), raising awareness of the vital role for soils in supporting food security, agricultural sustainability and climate change mitigation. In 2016 the federal and Ontario governments partnered to fund a soil mapping initiative in the province of Ontario, with the goals of improving soil health and conservation of some of Canada's premier soils (OMAFRA Soil Health and Conservation Strategy).

Soils are quite different across the vast expanse of Canada, varying in terms of parent materials and organic materials, and rehabilitative capacity. It is important to assess soils at the regional level because of this variable nature.

The ability of soils to trap and hold carbon that might otherwise move to the atmosphere is related to seasonal carbon cycles. Carbon is taken from the air by the leaves and stems of growing plants through the process of photosynthesis and is used both for the metabolic processes that are needed for plant growth and for the carbon based molecules that make up the body and roots of the plant. Some 3.67 units of atmospheric $C0_2$ must be absorbed for each unit of plant carbon. If a plant is dried, about 45 - 50% of its weight is carbon; in typical grain crops, about 1/3 of the total plant material is below ground (M. Bolinder et al., 1997. Agriculture, Ecosystem and Environment 63:61). When the crop is mature and ready for harvest, much of the captured carbon is removed from the field in the form of grain and straw. The remainder, including the below ground root system, along with any remaining leaves, stems and chaff that are deposited at the soil surface are available to feed the microbial community, including bacteria, fungi, nematodes, insects, worms and others. The carbon in the residual plant materials serves as a carbon feedstock for the growth of the microbial community and is eventually transformed into humus – the non-cellular organic material so important to the water and nutrient holding capacity of soils, and that comprises the soil organic carbon (SOC) pool. The SOC pool that is in the uppermost layers of soil (<1m) increases as organic materials are added but can be lost rapidly through microbial degradation when disturbed. When output of carbon from the SOC pool exceeds input, soil degradation occurs. When inputs to the SOC pool exceed losses, biological carbon sequestration occurs and carbon is stored for the longer term. Over time, the SOC pool in the upper soil fractions can contribute to carbon pools at deeper soil layers, where degradation is less likely to occur and carbon stability improves.

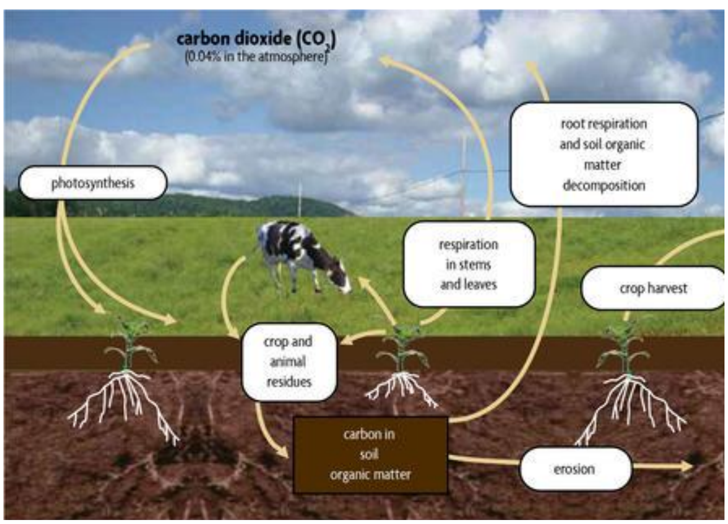


Image from: Sustainable agriculture, research and education (SARE)

Scope of the opportunity in Canada

Historic losses of soil carbon to the atmosphere resulting from the emergence of agricultural activity around the world are massive, ranging from 55 – 78 giga tonnes globally (Lal, R. 2001. Adv Agron 71:145). In largest part, this loss of carbon was related to the removal of tree cover and the cultivation or tillage of the land to facilitate the planting of crops.

Theoretically, the potential to restore soil carbons by proper management should equal the fraction already lost, however, the attainable rate of soil sequestration is limited to about 50% of the potential global capacity (Lal, R. et al. 2004. Science 304:1623). The amount of additional carbon that can be added to the soil does have limitations imposed by the soil characteristics, the extent and nature of the microbial community and the impact of local climate factors such as temperature and the availability of water. Additionally, a new equilibrium is expected to be established after a number of years of enhanced carbon sequestration, following a saturation curve that plateaus after an estimated 50 – 100 years (D.R. Sauerback. 2001. Nutrient Cycling in Agroecosystems 60:253)

In Canada, native grasslands originally covered about 61.5M ha across Alberta, Saskatchewan and Manitoba; today some 50M ha have been converted to cropland, while 1.5M ha are conserved grasslands and the remainder are used for grazing (Wang et al. 2004. Rangeland Ecological Management 67:333). The pools of SOC are quite different between soils that have permanent grass cover, those that are grazed by cattle and those that are used for crop production, and consequently they offer different potentials for carbon sequestration.

During the late 1800s and early 1900s, the conversion of native grasslands to croplands, and the loss of the native grazing bison herd, caused a depletion of as much as 60% of the SOC in the first meter of the soil profile (Lal, R. et al. 2004. Science 304:1623 ; A.J. Vandenbygaart et al., 2003. Canadian Journal of Soil Science 83:363). These losses of carbon and other nutrients were exacerbated by poor management practices, severe wind erosion and a period of extremely dry climate, which led to the abandonment of over 3M ha of the cultivated prairie land between 1930 and 1938 (W.D. Willms et al., 2011. In Floate, KD (ed) Arthropods of Canadian grassland. Vol 2. Biological Survey of Canada). As native vegetation returned to these lands, soil carbon levels also rose with full restoration occurring over about a 70-year period. Research has demonstrated that the sowing of perennial grasses on native grassland can also facilitate the restoration of lost soil carbon, although such gains come more slowly, and alter ecosystem biodiversity (X.Y. Wang et al., 2010. Soil Science Society of America Journal 74:1348). Canadian naturalized grasslands, currently totalling about 12.2M ha (A.W. Bailey et al., 2006. AAFC 10144) act as carbon sinks under existing management schemes (X. Wang et al., 2014. Rangeland Ecological Management 67:333) and are at or near their carbon sequestration potential.

Croplands, currently totalling 93.4M ha across Canada (StatsCan 2016 Census of Agriculture) suffered considerable depletion of SOC stocks, largely because of heavy tillage and soil disturbance. These lands offer potential for SOC enhancement, particularly where restoration is incomplete.

A detailed analysis of the potential rates of carbon gain in Canadian agricultural soils focussed on the period from 1999 to 2020 (J.P. Bruce et al., 1999. Journal of Soil and Water Conservation 54(1):382). Using both field data, and detailed soil process models, rates of both carbon loss and sequestration were determined to be quite different depending upon the initial carbon status of the soil and its use for crop production, revegetation or "set aside" lands, or as pasture or rangeland. Highly degraded soils, such as those damaged by erosion or salinity were also assessed.

Introduction and adoption of soil conservation strategies has reduced historically high carbon losses to the extent that cropland soils are now sequestering more carbon than is lost due to agricultural activity. This goal was achieved by the year 2000 as predicted by carbon cycling models (M. Boehm et al., 2004. Climatic Change 65:297). While the carbon sequestration potential of these soils is believed to be finite, sink capacity has not been reached and net carbon deposition will continue so long as management practices favour sequestration.

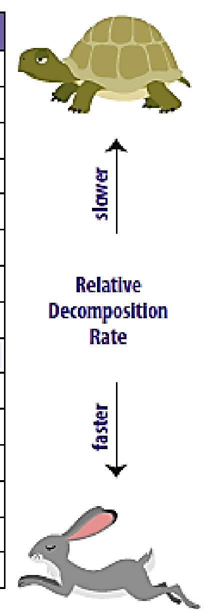
More highly degraded soils, where erosion has removed much of the organic fraction for example, have much greater sequestration potential over the longer period, but building the SOC fraction takes much longer and more intensive management strategies to restore microbial communities and natural system cycles. Pasture and rangeland have good potential for additional carbon storage provided they are carefully managed with improved practices such as rotational grazing, reseeding with improved plant species and additional nutrient inputs. Soil management and restoration has been a priority in Canada since the 1960s, yet degraded soils continue to offer restoration opportunities; models predict that at least 52% of Canadian soils will continue to accumulate additional carbon beyond 2020 at a rate of about 11kg/ha (R.L. Desjardins and R. Riznek. 2000. Agricultural Greenhouse Gas Budget, Environmental Sustainability of Canadian Agriculture: Report of the Agri-Environmental Indicator Project, AAFC). At the projected rate, croplands that have not reached sequestration capacity could sequester an additional 0.534Mt of carbon.

The need for nitrogen

In addition to carbon, plants and microbes require nitrogen for growth and development. The carbon and nitrogen cycles are tightly linked and cannot function independently; therefore, in order for carbon sequestration to occur, sufficient nitrogen must be available. In natural ecosystems, nitrogen stores in the soil are augmented by microbial degradation of plant refuse and by sequestration of atmospheric nitrogen by symbiotic bacteria. Nitrogen is highly mobile in the soil and is readily lost to the atmosphere and through run-off to surface and sub-surface water bodies. In agricultural systems, where nitrogen is almost always a limiting factor for crop production, additional nitrogen is added to soils as nitrogenous fertilizer and is likewise subject to potential losses, usually as N_2O, unless promptly taken up by the plant. Microbes are key in all of the transformations of nitrogen, but they require carbon to carry out their life processes. In an ecosystem where neither carbon losses nor gains

Table 1. Carbon to nitrogen ratios of crop residues and other organic materials

Material	C:N Ratio
rye straw	82:1
wheat straw	80:1
oat straw	70:1
corn stover	57:1
rye cover crop (anthesis)	37:1
pea straw	29:1
rye cover crop (vegetative)	26:1
mature alfalfa hay	25:1
Ideal Microbial Diet	**24:1**
rotted barnyard manure	20:1
legume hay	17:1
beef manure	17:1
young alfalfa hay	13:1
hairy vetch cover crop	11:1
soil microbes (average)	8:1



Carbon to nitrogen ratios of crop residues occur, the microbial fraction requires a carbon to nitrogen balance of 8:1. Where both additional carbon and nitrogen are available, microbes will mediate the storage of carbon in the soil; a C:N ratio of 24:1 is ideal to facilitate enhanced carbon storage. At this ratio, microbes will have sufficient carbon to carry out their own biological processes, and enough to allow for extra carbon storage.

Methods for managing soil carbon stores

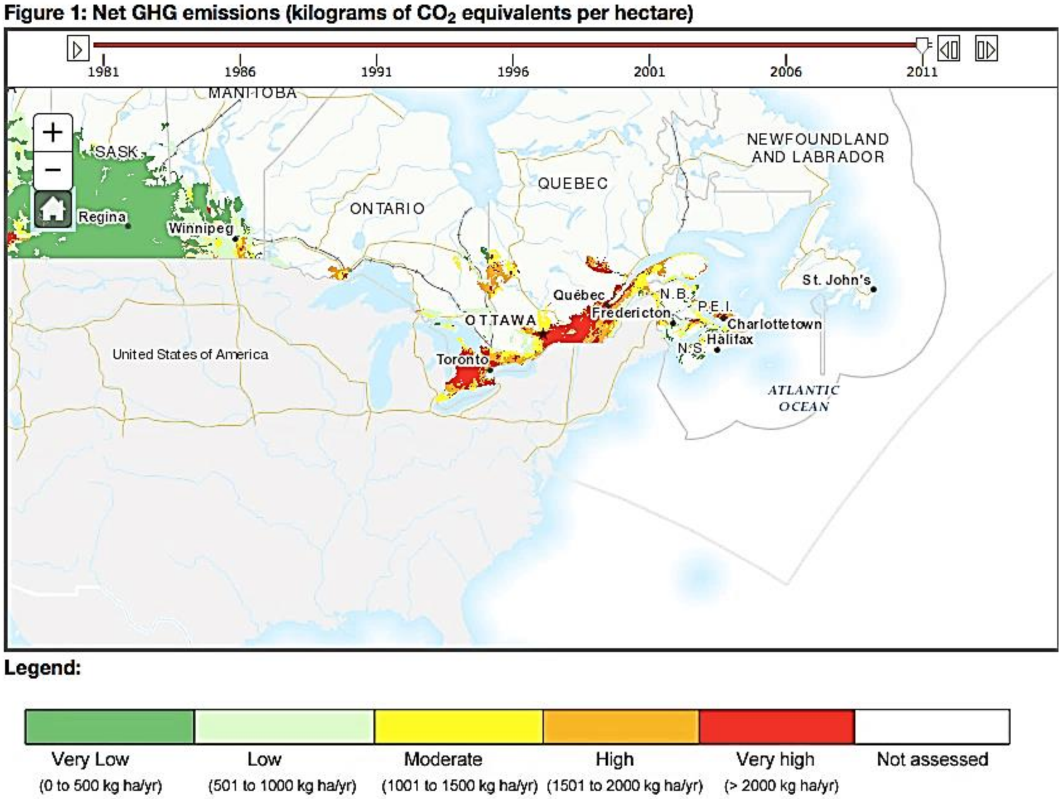
Enhancing soil carbons is managed by methods that: reduce carbon losses; enhance biological sequestration; or add stabilized carbons. Each method has specific requirements and can offer benefits when used individually or in concert.

Reducing carbon losses is achieved by ensuring that natural carbon cycles and the microbes essential for those processes are undisturbed, which is a challenging goal given the necessary operations required for planting, growing and harvesting crops. Reducing the amount of tillage in crop production has proven to be a highly beneficial management strategy, with good carbon outcomes. Historically, croplands were prepared for spring seeding by deep tillage, usually with a mouldboard plow that was drawn through the soil behind a horse or tractor, followed by cultivation to further reduce the size of soil clumps until the soil was uniform and friable. While this method does produce a smooth and weed-free seed bed, it exposes soils to oxygen that changes the ability of many soil microbes to function, dries the soil, further reducing microbial activity and enhances the breakdown and release of carbon molecules to the atmosphere. Heavily tilled soils are also at risk for wind and water erosion causing further loss of SOC (Paustian et al., 2007. Soil Use and Management 13:230). Soil conservation has been a well-established goal in Canada since the 1960s and significant rates of adoption of reduced tillage strategies have had very positive impacts, particularly on prairies soils. Reduced tillage includes methods of limiting soil disturbance to strips where crops will be planted in the field or the more aggressive elimination of tillage by planting directly through the stubble of the previous year's harvest. Other modifications to achieve reduced or zero tillage are necessary as well: typically, weed control is achieved through the use of pesticides rather than mechanical removal, and crop rotation is essential to maintain appropriate C:N balances. Benefits are not only limited to reduced carbon losses alone. Reduced tillage also protects soils from erosion, maintains soil water supplies and significantly improves yields and profitability (Soil Conservation Council of Canada).

Modified tillage strategies for reducing carbon losses have had better rates of adoption in the west, where soils are typically drier and dominant crops are canola and grains. In eastern Canada where soils tend to be heavier and slower to dry in the spring, more modest adoption has occurred. Some producers of corn remain reluctant to move to zero tillage because of slower germination in wet, cool spring soils (Soil Conservation Council of Canada).

These differential rates of adoption have contributed to regional differences in net GHG emissions (AAFC, Net GHG Emissions).

Figure 1: Net GHG emissions (kilograms of CO_2 equivalents per hectare)



Other methods for reducing carbon losses on cropped lands include reducing summerfallow and intensification of cropping, for example, through the use of winter cover crops (Dabney, S.M. et al., 2007. Communications in Soil Science and Plant Analysis 32), which increase the amount of plant materials available for building soil carbon pools.

Enhancing carbon pools can be achieved through a number of different approaches. On cultivated lands, ensuring adequate plant nutrition is key as it maximizes yield per area and generates both saleable product and crop refuse to feed carbon pools. In addition, the use of improved varieties and soil amendments as required hasten carbon stabilization. Considerable research to identify and select crop plants with the capacity for enhanced carbon sequestration has shown potential to increase the role for plants by selecting for optimal rates of photosynthesis, enhanced yield, altered allocation of plant resources to below-ground tissues and heightened production of specific plant metabolites such as phytoliths (Jansson,C. et al., 2010. BioScience 60:685). Phytoliths are silica crystals that are deposited in the cell walls of some plants (particularly grasses) through a process of biomineralization. Phytoliths are highly stable structures of encapsulated carbon that do not break down in the soil as plant material is degraded, burned or decays and remain sequestered for millennia (Parr, J.F. and L.A. Sullivan, 2005. Soil Biology and biochemistry 37:117).

The use of perennial crops, particularly those in the legume (pea and bean) family are helpful. These produce extensive and long-lasting root systems in the soil that degrade slowly; legumes can also develop a symbiotic relationship with nitrogen fixing bacteria, which add organic nitrogen sources to the soil that support microbial communities and future crops (J.P. Bruce et al., 1999. Journal of Soil and Water Conservation 54(1):382). A secondary benefit of enhancing biological nitrogen reserves is the avoidance of emissions related to fertilizer production, which are not included in agricultural emissions, but contribute to the national inventory nevertheless.

On pasture and rangelands, carefully managed stocking rates (the number of animals per hectare), improved grazing and rotation regimes specific to the local conditions and needs, additional inputs such as fertilizer and irrigation and use of improved species with deep root systems have all proven beneficial (AAFC: Management of Canadian Prairie Rangeland).

On degraded lands, damaged by erosion or the disruption caused by mining or other development, carbon stores can be restored over time by the planting of perennials, especially if their growth is supported by additions of nutrients and irrigation. The rate of carbon deposition is reported to be 0.8 Mg/ha/year (Paustian et al., 2007. Soil Use and Management 13:230), which indicates that a very significant potential for these landscapes is possible.

Adding stabilized carbon is the third category of soil carbon modification. Stabilized carbons may be created in several forms, the most common being biochar, or charcoal produced by the temperature and pressure-controlled thermal degradation (pyrolysis) of biomass. Biochar may be created from any biological material with the resulting char offering different characteristics depending on the source matter and the specific treatment conditions (Tang et al., 2013. Journal of Bioscience and Bioengineering 116:653). Biochar is very stable when added to the soil and breakdown requires decades to centuries depending on soil moisture and temperature. The addition of biomass to agricultural soil has many potential benefits including enhancing carbon stores, improving soil texture, adding moisture retention capacity, enhancing nutrient availability and stabilizing contaminants (Domingues, R.R. etal., 2017. PLOS one). The amount of biomass that can be added to any particular region is dependent upon the soil parent material, the degree of carbon degradation and the costs to manufacture and apply biochar. Because biochar does not interfere with natural carbon cycling processes, carbon added in this way is considered additive to other plant refuse sources, which means that it can be added to virtually any agricultural soil across the country, even those that may be near their capacity for additional SOC. Research indicates that the adsorptive characteristics of biochar can impact the environmental fate of pesticides in highly specific ways (Safael Khorran et al., 2016. Journal of Environmental Science 44:269). In some situations biochar could reduce potentially harmful leaching of pesticides to waterways; in others effectiveness could fall due to more rapid degradation and reduced bioavailability. Where overuse of pesticides has led to soil contamination or harmful impacts on microbial communities, biochar offers benefits of soil remediation through pesticide degradation and enhanced microbial activity (Lui et al., 2018. Science of Total

Environment 15:645). Interactions between biochar, pesticides and the microbial community offer management of specific challenges and must be considered in the management of agricultural soils.

Summary

Although agriculture in Canada results in about 8% of the national emissions, the existing biological carbon sequestration and additional potential that could be realised from targeted management strategies within the sector is very positive. Biological carbon sequestration can be enhanced by management of cropped lands, grazing and pasture lands, and those degraded and requiring remediation. Specific management strategies are intended to reduce carbon losses, enhance sequestration and retention of biological carbon stocks and add stable forms of carbon on agricultural landscapes. Canada's large land mass means that even small increments of change per unit area will total to significant carbon management over the longer term. The variability in Canada's soil landscape means that management strategies must be optimized to regional opportunities.