Managing Canadian Croplands to Maximize Carbon Sequestration and Minimize Other Ecosystem Service Trade-Offs

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by

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Introduction

The agricultural sector will inevitably be one of the first sectors to be hit, and to be hit hardest by the impacts of a changing climate. Although climate change will bring new challenges to most farmers around the world, it will also bring potential opportunities to others as a result of longer production seasons or the possibility of growing new crops (Smith et al. 2014). Farmers will also have the opportunity to be major players in mitigating climate change. To keep mean global temperature changes below 2 °C, cumulative greenhouse gas (GHG) emissions must be limited to less than a total of 1,000,000 Megatonnes[1] (Mt) of carbon dioxide (CO_2) between 2000 and 2050 (Frame et al. 2009). Global climate models indicate that even if GHG emissions are reduced dramatically in the short-term, it will not be possible to meet this target without drawing down current concentrations of atmospheric CO_2 (IPCC 2018). There is increasing evidence that agriculture, among other economic sectors, must be a critical component of our near-term strategy to mitigate climate change, primarily through the capture and sequestration of CO_2 in soils (Smith et al. 2014).

In December of 2015, members of COP21 initiated the “4 per mille” *Soils for Food Security and Climate* program (Paustian et al. 2016, Minasny et al. 2017). The basic concept of this initiative is to operationalize a plan to sequester carbon in soils around the world at a rate that would offset the estimated 8,900 Mt of annual GHG emissions from fossil-fuel based carbon (C). The plan is based on the idea that implementing farming practices that maintain or enhance soil organic carbon (SOC) stocks in agricultural soils and protecting C-rich soils globally by even just a small percentage could have a substantial impact on net emissions. Given the estimate that 2,400,000 Mt of C is stored in the top 2 metres of soil (Batjes, 1996), small changes in this stock can have large impacts on global atmospheric CO_2 concentrations. To calculate just how much change would be needed to completely offset annual CO_2 fossil fuel emissions, authors of the initiative took the ratio of these emissions to the total soil C stock (8,900 /2,400,000) to obtain 0.4 % or 4 ‰ (4 per mille or thousand). Thus, if the soil around the world could sequester just 0.4 % of the total pool per year, it would offset current annual fossil fuel emissions. While soil scientists have been highlighting this potential for more than 20 years (Post et al. 1982), the “4 per mille” initiative seems to have finally provided substantial traction to the idea (www.4p1000.org).

Given the vast area of land in agricultural production in Canada, our national contribution to this effort could be sizeable. It is estimated that the total 55.2 million hectares (Mha), currently in agricultural production, should contain about 4,140 Mt of C in the top 30 cm of soil and 5,500 Mt to a depth of 100 cm (Minasny et al. 2017). Applying the “4 per mille” approach to Canadian

[1] Megatonne (Mt) is equivalent to 1 billion kilograms

agriculture would mean that our agricultural land could sequester 22 Mt of C per year[2], an equivalent to 11 % of Canada's 704 Mt of CO_2 emissions (Environment Canada 2017). Much of this potential change would likely need to occur in the Prairies, which account for 80 % of Canada's agricultural land. There has, however, already been substantial changes in management practices in this region, such as the adoption of minimum or no-till and the reduction of summertime fallow (ie. summerfallow), practices that have already resulted in large increases in SOC (Cerkowniak et al. 2016). Evidence suggests that while there are some areas of Canadian farmland that are likely nearing the maximum amount of C the soil can store, there are large areas that have not yet approached this threshold. Furthermore, the soil is not the only way agriculture can sequester C. Switching to perennial crops, or integrating woody perennials into the landscape, for example, have also been shown to provide substantial opportunity for C sequestration (Huffman et al. 2015).

If, however, we are to fully operationalize Canadian agriculture to maximize C sequestration, it is critical that we do so while recognizing and assessing how these practices impact other ecosystem services. Given that sequestering C in soil, is building soil organic matter (SOM), it is often assumed that many ecosystem service co-benefits come with C sequestration practices. But there may also be potential trade-offs. Agricultural practices that might promote soil C sequestration, such as the application of fertilizers and manures to improve yields or the reduction of tillage, can also lead to increased nitrous oxide (N_2O) emissions, as an example. These emissions can in turn, offset any climate mitigation benefits. Furthermore, manure applications can lead to increased losses of nitrogen (N) and phosphorus (P) into the environment. Also, bringing additional land into agricultural production to increase the efficiency of the farming operation, can lead to increased soil C sequestration over time. But this could also result in an increase in net emissions due to the losses of C stored in woody plants. These plants also serve as habitat for a wide range of species. Thus, soil C sequestration practices may have both direct and indirect impacts on other ecosystems services, such as clean water and habitat for biodiversity. These trade-offs should be considered.

While soil C sequestration in agricultural croplands in Canada shows great promise for helping meet global emission targets, we need to adopt a careful approach when selecting and promoting agricultural management practices to ensure we achieve the greatest benefits without unintended consequences. In this paper, data from national inventories is used to first of all, illustrate how successful Canadian farmers have been in sequestering C in cropland soils, and second of all, to identify areas where the opportunities to further increase sequestration are the highest. Using these same inventory data, I then discuss some of the potential environmental trade-offs that we

[2] One tonne of carbon is equal to 3.67 tonnes of carbon dioxide

should be aware of, and highlight the need to identify and promote beneficial management practices (BMPs) that achieve multiple objectives.

Opportunities for Increasing Cropland Carbon Sequestration

Canadian farmers have already sequestered a substantial amount of C in cropland soils since 1981, due to large-scale changes in BMPs. According to the latest Agri-Environmental Indicators Report (Clearwater et al. 2016), the indicator that tracks changes in SOC (i.e. the "Soil Organic Carbon Change Index") has gone from 48 in 1981 to 74 in 2011. In 1981, Canadian agricultural soils were a net source of 1.2 Mt of CO_2, but by 2011, based on changes in SOC, were removing 11.9 Mt of CO_2 from the atmosphere annually (Cerkowniak et al. 2016). While changes in SOC have been large on a national scale, this is mainly due to farmers adopting conservation tillage, i.e. either reducing or eliminating tillage practices in the Prairie region. To address concerns about a decline in soil health, the amount of land under conservation tillage increased by 15 Mha between 1990 and 2016 (Environment Canada 2017). By reducing the mechanical disturbance of the soil, C in crop residues and roots was incorporated into recalcitrant forms of SOM rather than released through microbial respiration back into the atmosphere. Farmers in the Prairie region have also substantially reduced the amount of land they fallow during the summertime, and instead grow crops that provide far more C inputs in the soil. Other practices that have been adopted include integrating perennial crops in rotations, improving degraded lands, and returning crop residues to the soil. These practices can increase SOC anywhere from 0.1 to 0.5 t C ha^{-1} $year^{-1}$ (VandenBygaart et al. 2003, 2008), a range that could help achieve the target of the "4 per mille" initiative (Minasny et al. 2017).

According to national inventory methods of modelling the fate of SOC, the Prairie region has increased the rate of SOC sequestration annually since 1981: by 2011 it had sequestered 97 kg^{-1} C ha^{-1} $year^{-1}$ (Figure 1) (Cerkowniak et al. 2016). Overall, by 2011, 46 % of Canadian cropland was sequestering more than 90 kg^{-1} C ha^{-1} $year^{-1}$. At the same time, however, 13% of Canadian cropland was losing more than 25 kg^{-1} C ha^{-1} $year^{-1}$ and 9 %, more than 90 kg^{-1} C ha^{-1} $year^{-1}$. Reductions in SOC have primarily been observed in Central Canada and in the Atlantic region.

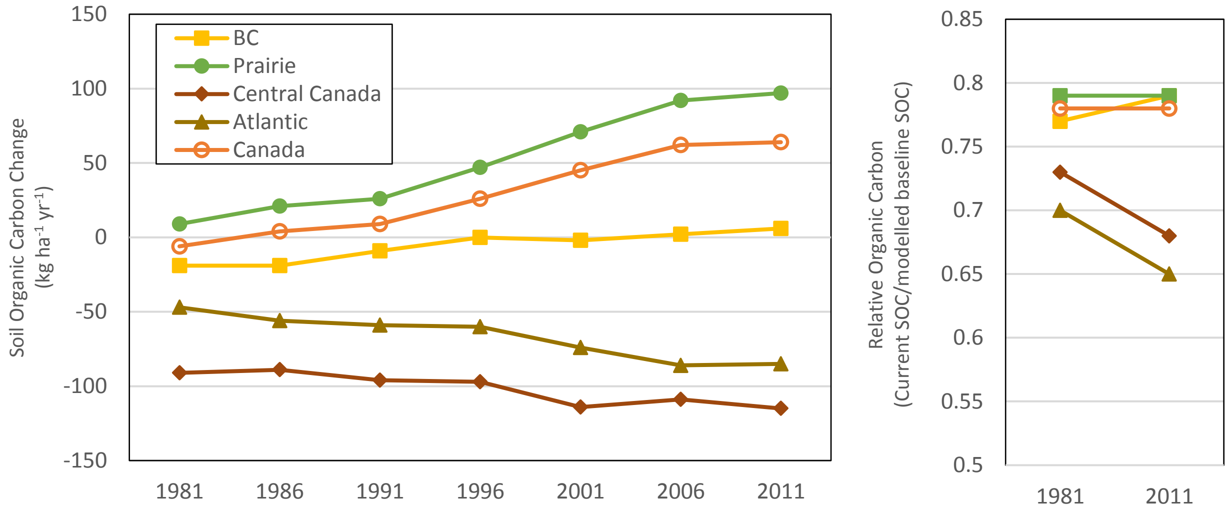

Figure 1. Average rates of SOC change (left) and relative SOC (right) for different regions of Canada from 1981 to 2011. The Prairie region includes Alberta, Manitoba, and Saskatchewan; Central Canada: Quebec and Ontario; Atlantic: New Brunswick, Newfoundland and Labrador, and Nova Scotia Prince Edward Island. British Columbia was analyzed on its own. Adapted from Cerkowniak et. (2016).

Increasing Annual Production

The continued decline in SOC in Central Canada and the Atlantic region is likely a result of farmers converting perennial production, such as pasture and hayland, to more intensive annual crops (Environment Canada 2017). Annual cropping systems are not only more reliant on intensive tillage and disturbance to the soil, but generally, they produce less crop residue to incorporate into the soil. Even in the Prairie region, there is evidence that there have been SOC losses due to the conversion of native grassland to cropland. Across all regions, the clearing of trees and shrubs to increase cropland area, as well as the conversion of orchards and vineyards to other types of production, continue to be sources of SOC losses. These losses are both from C stored in the soil and in the woody biomass of these trees, shrubs and perennial crops. Huffman et al. (2015) estimated that between 1990 and 2000, 0.07 Mt of biomass C per year alone, was lost to the atmosphere, from clearing trees and shrubs in the Prairie region. This does not include the SOC lost from under trees and shrubs, that can be up to 40 % higher, compared to neighboring agricultural fields (Thiel et al. 2015). Much of this SOC is lost when converted to crop production (Guo and Gifford 2002)

The regions of Canada that continue to lose SOC, clearly, should be targeted to improve SOC. It is not as clear, however, how much more can be gained in regions that have already adopted C sequestration practices. Soils inherently have a maximum capacity to store C that is largely determined by their texture and growing climate (VandenBygaart 2016). To address this, the Agri-Environmental Indicators Report (Clearwater et al. 2016) tracks a second SOC indicator- the Relative Soil Organic Carbon (RSOC) Indicator- which provides an estimate of how SOC levels are changing in a particular area, compared to a soil-specific baseline. This baseline level is predicted from a model of the SOC of extensively grazed permanent grass pasture in the region. While this is not necessarily the maximum attainable SOC for the region, it gives a relative value for what a healthy SOC might be, given the regional climate and soils. This indicator suggests that even in regions that have been sequestering C, such as the Prairies, current stocks, although improving, are still below this theoretical baseline (Figure 1). In the regions where we see SOC losses over time, the ratio is far below the baseline and also continues to fall. In 2011, 9 % of Canadian cropland was in the “Very low” category for RSOC, indicating they had much lower SOC than their modelled baseline. In Central Canada, 42 % of the cropland was in this category, and in the Atlantic region, 20 % was in this category. This points to those areas of the country with the highest potential capacity to increase SOC.

Practices that Increase Soil Organic Carbon

A recent analysis by Fan et al. (2019) supports theories that C sequestration in cropland is mainly influenced by the amount of C input (Kell 2012, Lynch and Wojciechowski 2015, Paustian et al. 2016). In their analysis, Fan et al. (2019), showed the importance of C inputs from crop roots, crop residues, manure and biosolids for increasing SOC. They also identified critical thresholds of C inputs required to maintain SOC, based on the climate and on initial SOC for various regions of Canada. In drier areas of Western Canada, they estimate that a C input of <2 Mg C ha^{-1} is required to maintain SOC, whereas, in the wetter interior of Eastern Canada, SOC maintenance requires >2 Mg C ha^{-1}. Modelling SOC changes from 1971 to 2015 are consistent with other Canada-wide inventories (Cerkowniak et al. 2016, Environment Canada 2017) showing a large increase in SOC. Crop inputs are the main reason for this change. During this period, there was not only a shift to conservation tillage and a decrease of 9.9 million ha of summerfallow, but an increase of 8 million hectares of canola (*Brassica spp. L.),* a crop with a high root to shoot (R/S) ratio, ~1.5 times that of the average grain crop (Thiagarajan et al. 2018). During the period 1971 to 2015, there were also significant increases in crop yields, particularly for canola and other major crops, including maize, wheat, and legumes, that were largely responsible for sizable increases in C inputs. In addition, C inputs from manures increased as the population of poultry, cattle, and pigs increased by 54 %, 34 %, and 77 %, respectively, over this time period. Adding manure and biosolids not only improves SOC, but also soil fertility and thus, productivity as well. The modeling by Fan et al. (2019) showed that if recent trends (2005-15) of increasing carbon inputs to Canadian cropland continues, we could expect to maintain a sink of 17.8 Mt C year^{-1} from 2016 to 2030.

There are a number of other strategies that could be employed across Canadian croplands to further enhance their potential as a C sink. Growing a cover crop, either during a fallow period, such as the winter, or during the production season, can increase organic inputs, protect the soil from erosion, improve nutrient cycling and increase soil fertility through nitrogen fixers. In a meta-analysis using 139 plots at 37 different sites from around the world, cover crop treatments were shown to have significantly higher SOC stock than reference croplands, with a sequestration rate of 0.32 ± 0.08 Mg C ha^{-1} $year^{-1}$. There are some who argue that organic farming has a greater potential to build SOC, since it is more reliant on organic inputs for fertility. In a review of 20 studies that compared organic and conventional farming practices for a mean period of 14 years, Gattinger et al. (2012) found that organic systems, on average, sequestered 0.45 ± 1.05 Mg C ha^{-1} $year^{-1}$. Others, however, point out that this analysis mainly illustrates the benefits of increased organic inputs in the soil, which is not inherently a distinction between organic and conventional production (Leifeld et al. 2013). Other practices that have shown promise for increasing sequestration rates, include the conversion of annual cropland to perennial production. Studies conducted in the semiarid Prairies show that sequestration rates after conversion from reseeded annual cropland to grassland or perennial forage range from 0 to 1.4 Mg C ha^{-1} $year^{-1}$, while studies in Eastern Canada range from 0.6 to 1.07 Mg C ha^{-1} $year^{-1}$ (VandenBygaart et al. 2008).

Increasing SOC and soil health may have important implications for the sustainability of our agricultural lands and C accounting on a landscape scale. Increasing productivity is critical for ensuring that it is not necessary to bring additional lands into production to increase current regional yield levels. Preventing further conversion of forest and grasslands are essential if we want to increase croplands' role as a net sink. In a global meta-analysis, Deng (2016) found that on average, the conversion of grassland to farmland resulted in a loss of 0.89 Mg C ha^{-1} $year^{-1}$, and the conversion of forest to farmland, led to a loss of 1.74 Mg C ha^{-1} $Year^{-1}$. Thus, it is critical that we not only increase yields and apply C sequestration practices on already productive lands, but also that we target the areas that are already depleted, as they are most likely to have the greatest response (VandenBygaart 2016). Minasney et al. 2018 suggest targeting the 2.8 Mha of croplands that are severely degraded in SOC and the 3.4 Mha that are moderately degraded, without showing signs of improving. These lands should be the highest priority for targeting sequestration practices. They comprise 11.2 % of Canada's agricultural land, representing a sizeable area. More specifically, the focus could be on croplands in Central Canada, where more than half are considered at “High” or “Very High” risk of degradation, or in Atlantic Canada, where 38 % of cropland is in these higher risk classes. Focusing sequestration efforts on these regions is important, not just because they have most to gain in terms of carbon sequestration, but also in terms of soil health.

Tradeoffs and Synergies Between Carbon Sequestration and other Ecosystem Services

Maximizing the sequestration of C in cropland soil is not only important for mitigating climate change, but also for building SOM and soil health, which is central to many of the ecosystem services provided by agriculture. SOM provides the basic substrate required to fuel soil food webs, which in turn are critical for functions like soil aggregation, nutrient retention and cycling, water holding capacity and water infiltration. These function together, not only to help improve the productivity and health of the crop, but also to help increase the efficiency and resilience of the farm while reducing other environmental impacts, thus ensuring the provisioning of ecosystem services. Practices such as conservation tillage, increasing yields of high R/S crops and increasing manure and compost inputs, can increase the amount of C inputs in the soil and reduce C losses. They can also concomitantly enhance a number of other ecosystem services. Alternatively, agricultural practices that are overly focused on sequestering C in cropland soil can also lead to unintended impacts on these services. Therefore, when considering the development and/or recommendation for C sequestration practices, it is important to consider their multiple outcomes. It is also important to identify practices that are most likely to provide synergies to maximize ecosystem service benefits rather than produce trade-offs.

Greenhouse Gas Emissions

Probably the most important trade-offs to consider when developing C sequestration practices are other agricultural GHGs, besides CO_2. Specifically, the emissions of methane (CH_4) and nitrous oxide (N_2O), which both adversely impact the climate, can compromise any mitigation potential. Both of these agricultural GHGs are large contributors to climate change. CH_4 is 25 times more powerful a GHG than CO_2 and N_2O is 298 times more powerful (IPCC 2012). It is important to recognize that while Canadian farmers have been increasing the amount of C sequestered in their soils, they have also been increasing emissions of these powerful GHGs. In fact, between 1990 and 2016, emissions from Canadian agriculture increased by 26 %. While agriculture in Canada sequestered 14 Mt CO_2 eq. in 2016, it also contributed 60 Mt CO_2 eq., or 8.5 % of the total national emissions (Environment Canada 2017). The primary source of emissions is CH_4 from livestock digestion (enteric fermentation), accounting for 41 % of agriculture's contribution, followed by soil management, which accounted for 40 % of the total (Environment Canada 2017). Emissions from this latter activity originate from N_2O emissions from nitrogen (N) fertilizer, which is used on cropland. These emissions more than doubled across Canada, from 1.2 Mt N in 1990 to 2.6 Mt N in 2016 (Environment Canada 2017). Much of this increase can be attributed to the Prairie provinces, where annual crop production increased dramatically over this period, requiring greater N inputs. When N fertilizer is applied, there are a number of pathways by which it can be lost, including through microbial transformation of nitrification and denitrification. It is generally assumed that at least 1% of applied N is lost as N_2O, but this can vary widely by agricultural practice, soil, and climate (Rochette et al. 2008).

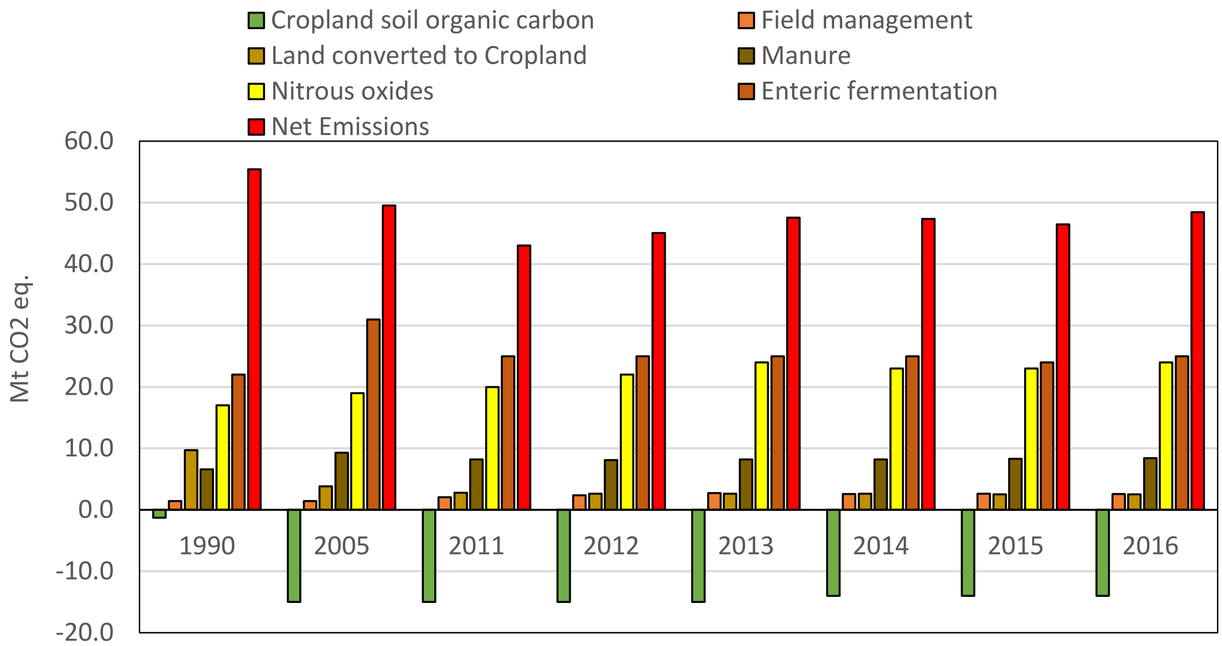

Figure 2. Carbon dioxide removals (Mt CO_2 eq.) from: sequestration in cropland soils remaining cropland; emissions from: field management which includes the application of lime and burning of crop residues; land converted from natural and semi-natural areas to cropland; manure management; nitrous oxides from soils; enteric fermentation from livestock production; and net emissions (emissions minus removals). Adapted from Environment Canada (2017).

While much of the increase in SOC between 1990 and 2016 in Canada is attributed to an increase in the amount of land under conservation tillage and high R/S crop yields, the climate change mitigation benefits of these practices have not been uniform. Conservation tillage, for example, has been shown to result in reduced N_2O in the Prairies (Malhi and Lemke 2007), but increased N_2O emissions in wetter regions of the country (Rochette et al. 2008). Since 1990, N_2O emissions have risen gradually from 17.0 Mt CO_2 eq. to 24.0 Mt CO_2 eq. in 2016 (Figure 2). In addition to accounting for N_2O emissions, it is important to quantify the CO_2 that is lost when natural or semi-natural areas, such as forests, grasslands, and other patches of land covered with woody and non-woody perennials are converted to crop production. In 1990, emissions from this conversion to cropland were 9.7 Mt CO_2 eq. And although they declined dramatically to 2016, they were still a sizeable 2.5 Mt CO_2 eq. Together, when accounting for both the amount of C sequestered in soils and the amount of CO_2 eq. emissions lost to the atmosphere from the various pathways, Canadian agriculture had net emissions of 48.5 Mt. CO_2 eq. in 2016 (Environment Canada 2017). It should be noted that this figure does not include the additional 19.4 Mt. CO_2 eq. of emissions associated with fossil fuel combustion and on farm energy use, related to agricultural production (Worth et al. 2016). These emissions are produced specifically from machinery manufacturing, agrochemical production (e.g. the manufacturing of fertilizers), field operations (ploughing, planting, spraying, harvesting), heating, farm transport, and farm electricity. The 22 % increase in these emissions between 1981 and 2011 can largely be attributed to the increased use of N fertilizers, which is produced in the energy-intensive Haber-Bosch process, reliant on natural gas (Worth et al. 2016). Although these emissions are normally reported as part of the energy and transportation sectors, it is important to recognize that crop management practices, crop selection, and farm technologies directly impact the quantity of these emissions that together, are equivalent to 40 % of the net emissions reported for agriculture. This illustrates why a more holistic net accounting of emissions is essential if we are to develop practices that truly lead to climate change mitigation benefits.

Increased Nutrient Use

There are other potential trade-offs beyond GHGs, that should be considered when identifying practices that sequester SOC, particularly if these practices require additional inputs or intensification of production. The increase in SOC sequestration with the expansion of annual cropping systems in the Prairies, for example, has been largely reliant on an increase in inputs of fertilizers and pesticides, both of which have important consequences for the environment, beyond their impacts on climate change.

All across Canada, the application of N and P in the form of mineral fertilizers or animal manures has increased substantially since 1981, and with that increase has come greater environmental risk. Analysis using the Canadian Agricultural N Budget (CANB) Model showed that between 1981 and 2011, average N application increased by 81 % from 44.4 kg N ha^{-1} to 80.8 kg N ha^{-1}, while outputs in the form of harvested crops only increased by 63 % (Drury et al. 2016). The difference between the application rates and output is used to calculate the residual soil N (RSN), an indicator for how much N is left in the soil profile after the cropping season. This RSN is assumed to be susceptible to leaching losses that can negatively impact drinking water quality and aquatic habitat. Nationwide, average RSN went from 9.4 kg N ha^{-1} to 23.6 kg N ha^{-1}, a 150% increase over 30 years. Over this period, the percentage of cropland that was considered “High” to “Very High” in terms of RSN risk, increased from 10 % to 28 % (Drury et al. 2016). Most of the cropland in these high-risk categories was located in southwestern Manitoba, southern Ontario, the St. Lawrence Lowlands (Quebec) and Atlantic Canada (Drury et al. 2016). These areas also tend to be the regions with declining SOC, indicating that promoting practices that improve C sequestration and N use efficiency (e.g. cover crops, precision agriculture) could have important synergistic effects for these croplands.

The increased use of manure and mineral fertilizer has also resulted in an increased risk of P losses to the environment. The use of manure, in particular, can result in an increase in soil P pools, given the mismatch in the P to N ratio between manure and crops. In general, by supplying crops with adequate manure to meet N demands, farmers are over-applying P. Excess soil P can be lost from cropland, mainly through surface run-off, leading to the eutrophication of aquatic habitat. The environmental impacts of this type of surplus have been observed in shallow lakes across the country, such as Lake Winnipeg, Lake Erie, and Missisquoi Bay in Lake Champlain (Reid et al. 2016b). The analysis of the Risk of Water Contamination by Phosphorus (IROWC-P) Indicator has shown an alarming increase in potential environmental impacts across Canada over the last 30 years (Reid et al. 2016b). Of the 280 watersheds analyzed across the country, 50 % moved to higher IROWC-P classes between 1981 and 2011. The Atlantic Provinces have maintained the highest P balances nationally since 1981, with > 16 kg P ha^{-1}, mainly because of intensive livestock and potato production. This is followed by Quebec, due to its intensive livestock production. Less than half of the P balances in the Atlantic provinces, Alberta, Manitoba, and Saskatchewan have increased since 1981, and there is no sign that this is likely to change. There are, however, a number of BMPs that can help farmers minimize the impacts of utilizing manure as a fertilizer and for sequestering C, and these should be promoted and/or developed further. For example, the separation of liquid and solid fractions of dairy manure has been shown to enable farmers to more precisely apply nutrients to match crop demands (Bittman et al. 2011, Neufeld et al. 2017). Coupling this separation approach with injection into the soil has been shown to also reduce N_2O emissions (Bhandral et al. 2005).

Fecal Coliform and Increased Animal Concentration

Another impact of using animal manure as a fertilizer is the potential contamination of groundwater with pathogens including viruses, bacteria, and protozoa. Fecal coliforms, an indicator of manure contamination, is used in the Risk of Water Contamination by Coliforms (IROWC-C) performance index nationally. Reid et al. (2016a) showed that while only 5 % of Canada's agricultural cropland was in the "High" to "Very High" categories for this indicator, there was a general trend across the country of increasing risk. In 1981, 77 % of cropland was in the “Very Low” risk category, but this dropped to 46 % in 2011. The “Low” to “Moderate” risk classes went from 19 % of cropland in 1981 to 50 % in 2011 (Reid et al. 2016a). Much of this shift can be attributed to the intensification of animal production. More animals are being produced in smaller facilities, including cattle feedlots, and hog and poultry barns. For example, the number of dairy cows per farm increased by about 13 % since 2005 (Canadian Dairy Commission 2012). Between 2006 and 2011, the average number of pigs per farm increased by 32 % (Statistics Canada 2013). This increase in the concentration of animals raises the likelihood that the manure produced will exceed the capacity of the operation’s land base to absorb the manure. While large applications of manure may increase SOC, it should not be at the risk of contaminating waterways. There are a number of BMPs that have been developed to improve manure management and some have been shown to prevent fecal coliform runoff and to help sequester carbon. For example, riparian buffer strips can reduce fecal coliform and nutrient losses (Tate et al. 2000, Entry et al. 2010), while at the same time sequestering carbon in both the vegetation and the soil (Smukler et al. 2010). There are also a number of new technologies coming online, such as anaerobic manure digestors (Ro et al. 2010) and biochar pyrolysis reactors (Ro et al. 2010), which show promise to produce both renewable energy and to provide pathogen-free, carbon sequestering, soil amendments.

Increased Pesticide Use

Intensification of Canadian agriculture has also meant an increase in pesticide use and the potential for negatively impacting drinking water and aquatic ecosystems. Gagnon et al. (2016), in their analysis of the Indicator of the Risk of Water Contamination by Pesticides (IROWC-Pest), have shown that the risk of water contamination by pesticides increased on 50 % of cropland across Canada, between 1981 and 2011. Most of these changes occurred between 2006 and 2011. Cropland area in the "High" and "Very High" risk classes rose from 6 % in 2006 to 17 % in 2011 (Gagnon et al. 2016). The rise in the areas of high risk over this period was attributed to the expansion of the area treated, as well as wetter-than-usual weather in the Maritimes and the Prairies. The increased use of pesticides in the Prairies was largely attributed to the increased adoption of reduced tillage systems. Without the use of intensive tillage, soils are more prone to fungal disease and plant and insect pests (Gagnon et al. 2016). As a result, during this time, the area treated with fungicides doubled in the Prairies while the area treated with herbicides increased by 7 % (from 33 to 35.1 %), and the area treated with insecticides, by 47 % (from 2.6 to 3.7 %). There was also a substantial increase in glyphosate-resistant crops planted across the country, particularly genetically modified corn (Zea mays), soybeans (Glycine max), and canola (Brassica spp.). As a result, glyphosate sales increased by 24 % between 2008 to 2011 (Clearwater et al. 2016). Although glyphosate has long been considered a much more benign alternative to other herbicides, a recent ruling by the International Agency for Research on Cancer (IARC) classified glyphosate as "probably carcinogenic to humans," calling into question the extensive use of this product (Benbrook 2019).

In addition, the use of glyphosate, a phosphonic acid ($C_3H_8NO_5P$), adds a non-negligible amount of P to Canadian agricultural watersheds. In a recent study of glyphosate use, it was estimated that in regions in the United States that are dominated by glyphosate-resistant crops, P additions can exceed 20 kg P km^{-2} (Hébert et al. 2019). Glyphosate use not only contributes to the potential losses of P to water bodies, but because of its chemical similarities with phosphate ions, can bind to the same soil sites, and thus also disrupt watershed P cycling, potentially influencing soil P saturation, further exasperating losses (de Jonge et al. 2001, Vereecken 2005).

Improved Soil Cover

Another potential trade-off from increased annual cropping across Canada is the potential for soil erosion. Soil cover across the country, however, actually increased by 7.6%, between 1981 and 2011 (Huffman and Liu 2016). Improvements in soil cover were mainly due to the increase in conservation tillage and the reduction of summerfallow in the Prairie region. In some parts of the country, however, the number of soil- cover days dropped after 2006, as farmers produced fewer beef cattle and shifted their production of pasture and forage to annual crops (Huffman and Liu 2016). This pattern could be seen in areas such as the St. Lawrence Lowlands in Eastern Ontario and Western Quebec, as well as in parts of the Maritimes (Huffman and Liu 2016).

Wildlife Habitat

The decline in pasture and forages also contributed to the reduction of habitat quality on Canadian croplands. Since 1986, when the indicator of Wildlife Habitat Capacity was first introduced, it has declined by 14 % (Javorek et al. 2016). The majority of this decline can be attributed to the conversion of natural or semi-natural habitat to cropland in the Mixedwood Plains region of Eastern Canada. Small patches of natural and semi-natural habitat within agricultural landscapes are important for close to 90 % of the 600 species of mammals, birds, reptiles, and amphibians that depend on agricultural land (Javorek et al. 2016). Most of the nation's cropland generally, has low capacity as wildlife habitat, but annual cropping, due to its frequent disturbance, is particularly poor. Between 1986 and 2011, the percentage of land under annual crops in Ontario increased from 59 % to 70 %, and in Quebec from 32 % to 53 %. Across the country, over this period, there was more than a fivefold increase in the total area of annual production of canola, potatoes, and soybeans (Javorek et al. 2016). Beneficial management of farm field edges has, however, been shown to improve both habitat quality and C sequestration, even for intensively-managed annual crops (Smukler et al. 2010, Thiel et al. 2015). In analysis done by Rallings et al. (2019), highlighting the potential trade-offs between annual cropland expansion, habitat connectivity, and C sequestration, demonstrated that farm edge hedgerows can provide multiple benefits, disproportionate to their area.

Trade-off analysis

Although SOC has increased steadily on average across Canada, it is clear from our national Agri-Environmental Indicators that there are clear trade-offs. When we account for the emissions associated with the increasing intensification of agricultural practices, the mitigation improvement of increased C sequestration in our soils is negated, and there is little net change in the impact on emissions. As a result, the agricultural sector continues to contribute 6 % of the nation's overall emissions. For agriculture to effectively serve as a sink for emissions, farmers must adopt additional practices that sequester C on their land, which may include soils and woody biomass, while at the same time reducing emissions, particularly from animal production, manure management, pesticide and fertilizer use. Adopting BMPs can help address some of the other trade-offs that have been incurred with intensification. The trade-offs are highlighted in Cerkowniak D. et al. (2016), and show that between 1981 and 2011, indicators of pesticides, N, P, and coliforms have worsened by 19%, 34%, 42%, and 10% respectively. While indicators for wildlife habitat and soil cover did not decrease over this period, they remain fairly low. Clearly, there is room for improvement across these indicators and a need to adopt practices that address them all simultaneously.

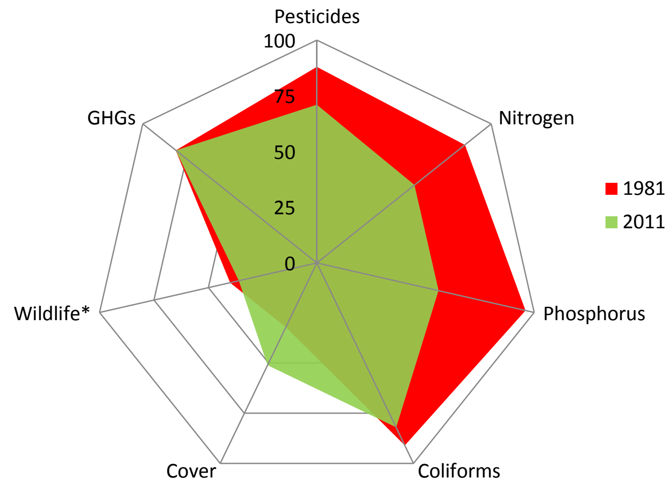

Figure 3. Radar graph illustrating the trade-offs among select Agri-Environmental Indicators reported in 1981 and 2011. Areas of the graph in red indicate declining trends, while areas in green indicate stable or increasing trends. The indicators are presented on a 0-100 index and include: Risk of Water Contamination by Pesticides (Pesticides), Residual Soil Nitrogen (Nitrogen), Risk of Water Contamination by Phosphorus (Phosphorus), Risk of Water Contamination by Coliforms (Coliforms), Soil cover (Cover), Wildlife Habitat on Farmland (Wildlife), Agricultural Greenhouse Gas (GHGs). *The index for Wildlife Habitat Capacity is from 1986 as this was the first year of analysis.

Conclusions

The "4 per mille" initiative has provided renewed impetus for the idea that agricultural soils can and should play an important role in the global effort to combat climate change. Although there are some who caution that placing too much weight on the mitigation potential of soil could take energy away from the real efforts that are needed to curb emissions (Schlesinger and Amundson 2019), there is consensus that this initiative can contribute substantively and could be important for improving soil health (Minasny et al. 2017, de Vries 2018). Canada, given its relatively large area of cropland, seems well suited to provide major contributions to this effort. National inventories suggest, that although Canadian farmers have already sequestered a large quantity of C in cropland soils, they likely can continue to sequester at least an additional 17.8 Mt C year^{-1} through 2030 (Fan et al. 2019). Focusing on developing strategies that will encourage those who farm the 6.2 Mha of moderately to severely degraded soils, mainly in Central and Atlantic Canada, are most likely to have the largest gains in terms of sequestering C, but also in improving soil health. However, for Canadian agriculture to really make contributions to climate change mitigation, we must also develop, promote and adopt practices that reduce the 60 Mt. CO_2 eq. of GHG emissions from livestock production and manure and fertilizer use, as well as the additional 19.4 Mt. CO_2 eq. of emissions from fossil fuel combustion and on-farm energy use associated with the sector. Finally, the practices that are deployed, must be ones that also reduce other environmental impacts. While we have developed BMPs that have clearly helped farmers increase C sequestration, it is time to develop practices that ensure multiple, simultaneous environmental benefits. Given the increasing economic challenges for Canadian farmers, it will be important that society help pay for the climate change mitigation and other ecosystem services that will come with their food.

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