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Increasing crop yields and root input make Canadian farmland a large carbon sink

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ABSTRACT

Soil organic carbon (SOC) in agricultural lands is vital for global food production and greenhouse gas (GHG) mitigation. Accurate quantification of the change in SOC stocks at regional or national scales, which depends heavily on reliable spatiotemporal carbon (C) input data, remains a big challenge. Here we use the process-based RothC model to estimate change in SOC stocks across Canada for 1971 to 2015, based on calculated annual C flows between cropland and livestock sectors. Total C input to 0–20 cm soils from crops, manure, and biosolids in Canada increased by 81% from 1971 to 2015, which shifted Canadian agricultural lands from a CO_2 source before 1990 (-1.1 Tg C yr^{-1}) to a small sink during 1990–2005 (4.6 Tg C yr^{-1}), and a larger sink thereafter (10.6 Tg C yr^{-1}). The increasing trend of SOC stocks is mainly driven by the increases in crop yield; the enhanced C sink since 2005 reflects increasing C input largely driven by the increasing area and yield of canola. SOC sequestration showed a potential to offset ~34% or more of agricultural GHG emission since 1990. Increasing crop yields and adopting crop mixes that input proportionately more below-ground C, such as canola and oat, showed potential additional opportunity to sequester SOC, estimated at 1.7 Tg C yr^{-1} for 2016–2030 in Canada. This study illustrates that SOC sequestration is driven largely by plant C inputs, and shows that agronomic measures which augment C input through crop choices and yield-enhancing practices can profoundly benefit climate mitigation strategies.

1. Introduction

The Paris Agreement with its nationally determined contributions call for stabilizing global warming to well below 2 °C (UNFCCC, 2015). To achieve this goal, we need to limit net greenhouse gas (GHG) emission to 36 Pg (10^{15} g) CO_2-eq yr^{-1} (Meinshausen et al., 2009). The Intergovernmental Panel on Climate Changes (IPCC) fifth assessment identified agriculture as the greatest near-term (i.e. by 2030) GHG mitigation potential among the economic sectors, which may be achieved largely by soil organic C (SOC) sequestration (Smith et al., 2014). Agricultural soil carbon sequestration has been considered as an important approach to mitigate GHG emission and global climate change, whose mitigation potential has been estimated to be as high as ~8 Pg CO_2-eq yr^{-1} (Paustian et al., 2016). Therefore, accurate quantification of the change of SOC stocks at regional or national scales is critical to support effective policies (Saby et al., 2008; van Wesemael et al., 2010). Although there have been specific opportunities to quantify the change in agricultural SOC stocks using regional repeated survey of SOC (Bellamy et al., 2005; Fujisaki et al., 2015; Sleutel et al., 2003; Xie et al., 2007), lack of measured data have compelled practical inventories of the change in SOC stocks to use process models that estimate SOC gains or losses from the difference between C input and SOC decomposition (Koga et al., 2011; Lugato et al., 2014; Ogle et al., 2010; Tan et al., 2015; van Wesemael et al., 2010). For these models to be accurate, reliable spatiotemporal C input data is essential (Wiesmeier et al., 2014).

Crop yields in many countries have shown dramatic increases since 1960s (Grassini et al., 2013; Hafner, 2003), which may increase C input

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and hence SOC change. Population growth in coming decades will fuel demand for further yield increases (Davis et al., 2017) and necessitate more intensive use of soil resources and increased GHG emissions (Howden et al., 2007; Tilman et al., 2011). Recently, increasing the use of crops with larger, deeper root systems that provide higher belowground C input, has been proposed to sequester atmospheric C to reduce net GHG emissions (Kell, 2012; Lynch and Wojciechowski, 2015; Paustian et al., 2016). Quantitative estimates of C sequestration potential from increasing root C input by changing annual crops at the regional or national scale have not yet been produced (Paustian et al., 2016).

Some studies have included crop C and manure C input to agricultural soils and their effect on SOC stocks (e.g. Koga et al., 2011; van Wesemael et al., 2010; Wang et al., 2015), but all of them estimated crop C and manure C separately either assuming all straw or a fixed proportion of straw were removed for animal bedding or assuming a constant manure application rate. The objectives of this study were to: (1) set up a whole-system C fluxes approach including varying annual C flows between cropland and livestock sectors to calculate C inputs to agricultural soil in Canada for 1971–2015; (2) estimate change in SOC stocks using the process-based RothC-26.3 model of SOC dynamics across Canada based on calculated annual C flows; and (3) evaluate change in SOC stocks for three scenarios for 2016–2030: a) continue long-term (1971–2015) yield trends, b) continue recent (2005–2015) yield trends, and c) recent yield trend with feasible increases in crops with higher relative C input from roots.

2. Materials and methods

2.1. Agricultural lands in Canada

Canadian agricultural lands are situated between 40° and 60° N and cover an area of 62 million ha, with ~80% of agricultural lands located in western Canada (Fig. S1). Soil-landscape polygons of Canada (SLC), 3403 of which containing agricultural land, were used as calculation unit (Soil Landscapes of Canada Working Group, 2010). Their area ranges from 1000 to 1,000,000 ha (Fig. S1). Crop area, crop yield, and livestock numbers from 1971 to 2015 were extracted from Statistics Canada data and then attributed annual to SLC polygons consistent with methods used for Canada's GHG inventory (NIR, 2017) (see *SI text* for detail). A remarkable crop area shift happened in Canada over 1971–2015 of an increase of 8 million ha for canola (*Brassica* spp. L.) with a concurrent decrease of 9.9 million ha of summer fallow (Fig. S2A). All major crops except hay showed significant increase of yield from 1971 to 2015, especially for maize (108 kg ha^{-1} yr^{-1}), wheat (31 kg ha^{-1} yr^{-1}), canola (21 kg ha^{-1} yr^{-1}), and legume crops (9 kg ha^{-1} yr^{-1}) (Fig. S2B). Poultry, cattle, and pig are the major livestock in Canada and their numbers increased by 54%, 34%, and 77% from 1971 to 2015, respectively (Fig. S2C).

2.2. Soil and climate data

Initial soil data (clay content, bulk density, and soil carbon content), obtained from the National Soil Database (NSDB) of Canadian Soil Information Service (CANSIS), were used to estimate SOC stocks (Mg C ha^{-1}) of the top 20 cm soil for each SLC polygons (*SI text*; Fig. S3). An area-weighted mean SOC stock for each SLC polygon was calculated for the soil types in the polygon based on their area under agriculture. The monthly precipitation and temperatures (1971–2015) were extracted from monthly weather data for the 10 × 10 km grid cell (Newlands et al., 2011) at the centre of each SLC polygon.

2.3. Carbon input from crops, manure, and biosolids

Crop C input (C_{crop}, Mg C ha^{-1} yr^{-1}) were calculated by using agricultural statistics data according to the following equation:

$$C_{crop} = \sum_{i=1}^{n} \frac{Y_i \times (1 - MC_i) \times C_p}{HI_i} \times [(1 + Y_E) \times R/S_i + (1 - HI_i) \times (1 - Rm_i)]$$

where i denotes different crops. Y_i is the crop yield (Mg ha^{-1}); MC_i is the moisture content of harvested product (g g^{-1}); C_p is C content in plant parts (assumed as 0.45 g g^{-1}); HI_i represents the harvest index; Y_E represents the ratio of C released to soil from rhizodeposition and root turnover, which is assumed as 0.50 according to Pausch and Kuzyakov (2017); R/S_i is the root to shoot ratio for different crops; Rm_i is the residue removal ratio for different crops. For perennial crops, duration of five years for alfalfa & mixture, tame hay, berries, and grapes and duration of ten years for tree fruits and nuts were assumed (Janzen et al., 2003). We also assumed that the roots of perennial crops are returned to the soil in the year the crop was terminated, and in other years, a turnover rate of 10% for belowground C was used for all perennial crops (Janzen et al., 2003).

Typical MC_i for different crops were derived from Brown et al. (2009), while HI_i was estimated to increase with increasing yield for grain crops according to HI-yield relation proposed by Fan et al. (2017) for major crops but was held constant for minor crops using values from Janzen et al. (2003). R/S_i for major crops were adjusted to 20 cm depth (Thiagarajan et al., 2018) according to their root distribution with depth (Fan et al., 2016), while the R/S_i values for other crops derived from Janzen et al. (2003). Rm_i for grain cereal, oilseeds, and maize stalks were estimated by assuming that these residues were only removed to fulfill the demand of livestock feeding and bedding (*SI text*).

Excreted manure C was estimated from the livestock number in each category and their volatile solids excretion rate, while C from livestock bedding materials was estimated by animal bedding requirement (see *SI text* for detail). Total manure C input to soils was calculated from manure C (excreted manure C + bedding C) amount by considering C lost during different management systems (*SI text*; Fig. S4).

Biosolids, produced from municipal sewage treatment processes, were applied to agricultural lands as fertilizer or amendment for soil properties. Total biosolids production were estimated by population and a production rate of 0.15 wet ton per person per year (Hydromantis Inc., 2007), and applied partially to agricultural lands according to local government restriction (*SI text*).

2.4. Rothamsted carbon model

The RothC 26.3 model (Coleman and Jenkinson, 1996) was used in this study to simulate change in SOC stocks as affected by C input change for Canadian agricultural lands. Monthly potential evapotranspiration was calculated from the minimum and maximum temperature using the Hargreaves-Samani equation (Hargreaves and Samani, 1985) and converted to open pan evaporation by dividing by 0.75 (Coleman and Jenkinson, 1996). The model partitions soil organic pools into decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), and inert organic matter (IOM). IOM was estimated by total SOC (Mg C ha^{-1}) according to Falloon et al. (1998).

A spin-up run of the RothC model of 10,000 years was used to estimate initial distribution of SOC among the different pools for each SLC polygon. This is accepted practice for the use of this model to parameterize the relative size of the carbon pools (Coleman and Jenkinson, 1996). The resulted distribution of C pools after IOM was subtracted ranged 0.1–2.3% for DPM, 13.4–21.2% for RPM, 1.8–2.3% for BIO, and 76.2–83.8% for HUM. Model runs were then carried out with the monthly data for each year from 1971 to 2015 for all SLC polygons. Plant C input from aboveground residue and roots were assumed to occur after harvest, while rhizodeposition-C input was evenly distributed over the growing season. Manure C and biosolids C were applied together in April and October equally. The perennial crops and

Table 1
Description of experimental sites and studies used for RothC validation.

Study	Location	Duration (year)	Crops	Soil texture	Growing season temperature (°C)	Growing season precipitation (cm)	Reference
1	Guelph, ON	9	Corn	Loam	14.8	48.5	Ketcheson and Beauchamp (1978)
2	Breton, AB	11	Barley, wheat, canola, triticale, pea	Loam	14.0	33.2	Nyborg et al. (1995)
3	Breton, AB	13	Barley, wheat, canola, triticale, peas	Loam	14.0	31.5	Solberg et al. (1997)
4	Ellerslie, AB	11	Barley, wheat, canola, triticale, pea	Loam	14.1	30.6	Nyborg et al. (1995)
5	Ellerslie, AV	13	Barley, wheat, canola, triticale, pea	Loam	14.1	28.8	Solberg et al. (1997)
6	Indian Head, SK	50	Wheat	Clay	15.8	23.3	Campbell et al. (2001)
7	Star City, SK	8	Barley, pea, wheat, canola	Sandy clay loam	14.7	22.3	Malhi and Lemke (2007)
8	Lethbridge, AB	104	Wheat	Loam	15.5	24.4	Karimi et al. (2017)

seeded pasture soil were treated as covered all year round, whereas croplands were covered during the growing season. The dominant crop, estimated by harvest area, was used to estimate soil cover for each SLC polygon every year.

Eight long-term experiments across Canada with 46 individual treatments covering major crops in Canada (Table 1) were used for RothC model validation. Experimental sites having both good yield and SOC data were chosen to provide a range of SOC and C input. Crop C input was estimated from grain yield, straw biomass (if available), *HI* (when straw biomass is not available), and *R/S* as described above. Model was initialized as the same procedure described above and run for different treatments by using monthly weather data and estimated C input data.

Tame pastures that are regularly reseeded were included in the present study. Natural pasture lands, primarily occurring in western Canada, have been grazed by wildlife and now livestock for ~1000 years (Janzen et al., 2003). We assumed these lands are approximately at their SOC steady state with no change or slight increase in SOC stocks under proper grazing management (Smith, 2014; Wang et al., 2016). With no detailed national management data for natural pasture in Canada to reliably estimate C input, these lands were not included in the analysis.

2.5. Scenario simulations

Three future projection scenarios for 2016–2030 kept total agricultural lands area the same as 2015 for each SLC polygon. The "long-term trend" and "recent trend" scenarios continued the 1971–2015 and 2005–2015 crop yield trends, respectively. The "higher root input" scenario continued the recent yield trend with increased area of canola and oat, two crops with higher relative C input from root than other crops (Thiagarajan et al., 2018). The "higher root input" scenario met the industry production target of 26 Tg of canola by 2025 (Canola Council of Canada, 2017) by increasing the area of canola at expense of summer fallow, small grain cereals and other minor crops within SLC polygons that had increased canola production from 2005 to 2015. The trend of these area changes were continued to 2030, resulted in canola production of 28.9 Tg, which was 5 Tg yr^{-1} higher than that in the "recent trend" scenario. The scenario also increased oat production (1.8 Tg yr^{-1} in 2015) to again meet the higher average domestic oat consumption levels of the 1970s (4.0 Tg yr^{-1}), assuming that this amount could be consumed with modest feed adjustments by the larger Canadian human and livestock populations, plus the continuation of positive 2005–2015 oat export trend to 2.4 Tg yr^{-1} by 2030. The scenario increased oat area within any SLC polygon that had oat during 2005–2015 at the expense of area of barley and spring rye; if more oat area was still required, this additional area was taken from spring wheat area. For both crops, the required additional area for each polygon was set proportionately the 2005–2015 production within that polygon compared to total 2005–2015 production. We believe the scenarios could be realized. The changes in SOC stocks under different scenarios were estimated by RothC model by using calculated C input for each scenario and averaged climate data (2005–2015) for each SLC polygon.

To estimate the net effect of manure C input on change in SOC stocks, RothC model runs were carried out by calculated C input data hypothetically-without manure in 1971–2015. The difference of annual SOC change rate between with and hypothetically-without manure in 1971–2015 was then calculated and presented in Fig. S5.

3. Results

3.1. Carbon input change

C input to Canadian agricultural land is primarily derived from plant residue C with important contributions also from livestock feed

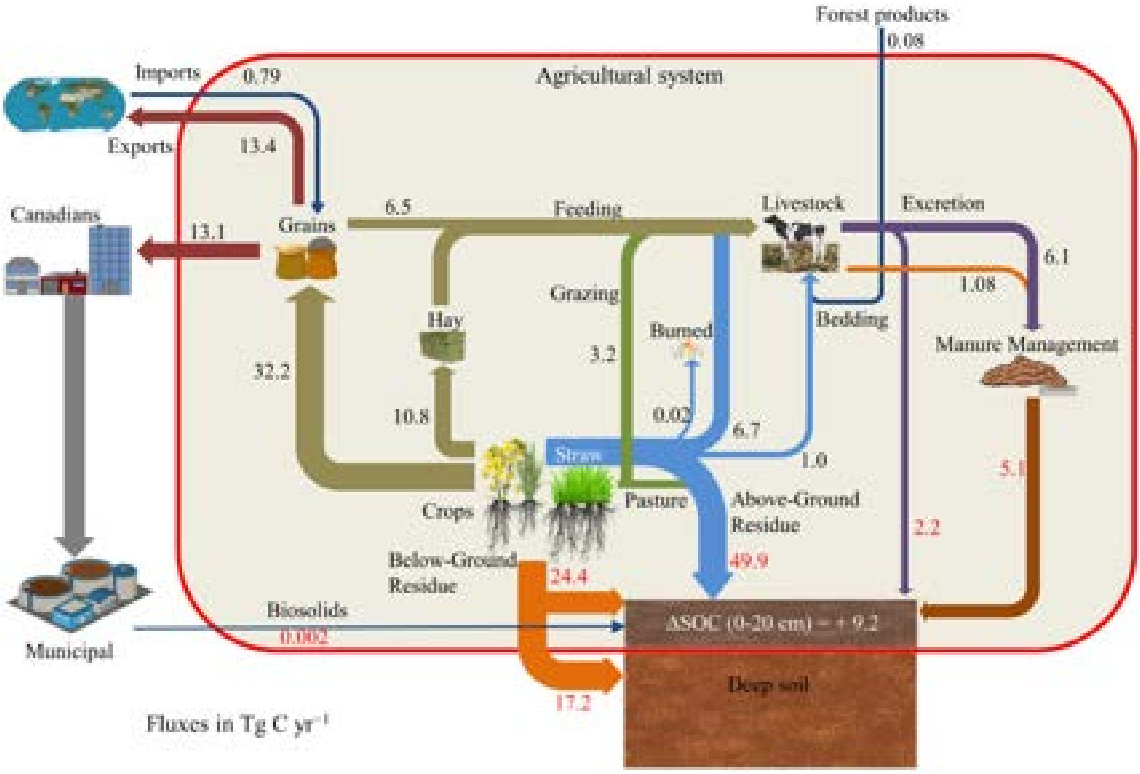

Fig. 1. Carbon fluxes in Canadian agroecosystem (2005–2015 average).

and bedding diverted to the soil as manure (Fig. 1). There are negligible external inputs to the agricultural soil C system from human sewage treatment and from forest products used as livestock bedding. Total C input to 0–20 cm soils increased by 81% from 1971 to 2015 (Fig. 2), where crop C input accounted for 82–92% of total C input compared to only 8–18% from manure C and $< 0.1\%$ from external sources. Annual compound rate of C input change from 1971 to 2015, including both area and yield, was highest for canola (7%), followed by legume crops (4%), maize (2%), and wheat (0.5%). Total C input from other crops, including small grain cereals, flax, potato, and all other field crops, showed a slight decrease from 1971 to 2015 with an annual rate of -0.4%. No significant change in hay C input was observed (Fig. 2).

Mean annual C input to 0–20 cm soils from 2011 to 2015 was 1.87 Mg C ha^{-1} for eastern Canada and 1.76 Mg C ha^{-1} for western Canada (Fig. S6A). However, annual C input change rate (Fig. S6B) varied spatially across Canada. Western Canada had the highest change rate with a median of 1.5%, while that for eastern Canada was 0.8%. In contrast, coastal provinces (both west and east) showed a C input decrease, with annual rate of -0.5% to -0.3%. The coefficient of variation of C input from uncertainty analysis ranged from 3.3 to 16.9% for subnational regions (Table S1; *SI text*).

3.2. Change in SOC stocks

Overall, there was a very good relationship between estimated SOC by RothC and observed SOC for the validation sites (Fig. 3). There was a significant linear relationship between modeled and observed SOC ($y = 0.92x$, $R^2 = 0.974$, $P < 0.001$). However, the underestimation indicated by the regression was only strongly evident for one of the 8 sites (Fig. 3).

The annual rate of change of SOC stocks varied across Canada (Fig. 4) in response to the pattern of C input, initial SOC stocks, temperature, and precipitation. The mean rate of increase in SOC stocks was 0.23% under the cold and dry climate of western Canada, while SOC stocks mainly decreased in the milder, more humid climate of eastern Canada with a mean annual rate of -0.22%.

We used regression to derive the following equation which captured 94.3% of the variation in modeled SOC stock change:

$$\begin{aligned}\Delta SOC = {} & (1.059 - 18.8 \times 10^{-3} \times MAT - 0.111 \times \log(MAP)) \times C_i \\ & - (0.106 \times \log(MAP) - 6.34 \times 10^{-3} \times MAT - 0.370) \\ & \times SOC_i, \quad R^2 = 0.943,\ P < 0.001\end{aligned}$$

where ΔSOC is the SOC stock change (Mg C ha^{-1}), C_i, is cumulative 1971–2015 C input (Mg C ha^{-1}), SOC_i is initial SOC stock (Mg C ha^{-1}) in 1971, MAT is mean annual temperature (°C), and MAP is mean annual precipitation (mm). The critical C input needed to maintain SOC stock (zero change) was calculated (Fig. 5) using the above equation. Much higher C input is needed to maintain SOC stocks for soils with higher initial SOC. Under the same initial SOC stock level, a higher critical C input was required with increasing temperature and precipitation.

The pattern of SOC change, with gains concentrated in interior western Canada and losses in interior eastern Canada are readily explained by combined effects of climate and initial SOC. In the drier climates of interior of western Canada, a critical C input of < 2 Mg C ha^{-1} was required to maintain SOC (Fig. 5). C input in this region was 1–3 Mg C ha^{-1} (Fig. S6A), and hence often sufficient to maintain or increase SOC. However, some SOC losses occur in this region largely associated with high initial SOC and high precipitation. Likewise, in the wetter interior of eastern Canada, C input of > 2 Mg C ha^{-1} is required to maintain initial SOC where it was > 60 Mg ha^{-1} (Fig. 5). There were many areas in that region where there was insufficient C input (Fig. S6A) to maintain initial SOC. Consequently, areas with SOC increase in that region were areas with low initial SOC and/or areas with high C input; other areas in that region tended to lose SOC.

Since ~80% of Canadian agricultural lands are located in the western Canada (Fig. S1), total change of SOC stocks (0–20 cm) in Canada showed a significant positive trend ($P < 0.001$) from 1971 to 2015

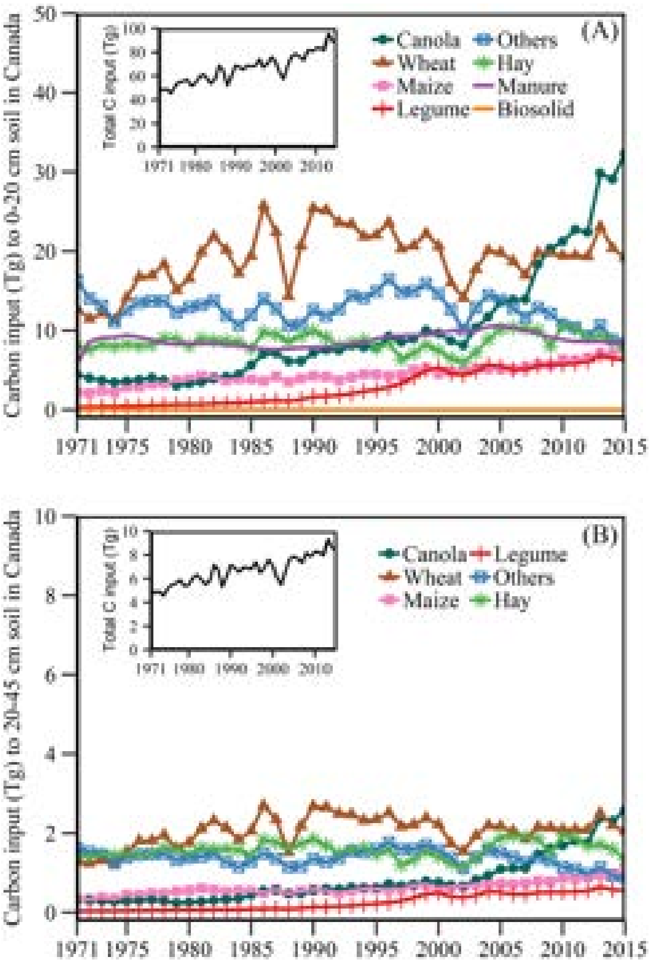

Fig. 2. Total C input from crops, manure, and biosolids to 0–20 cm (A) and crop C input to 20–45 cm (B) soil from 1971 to 2015.

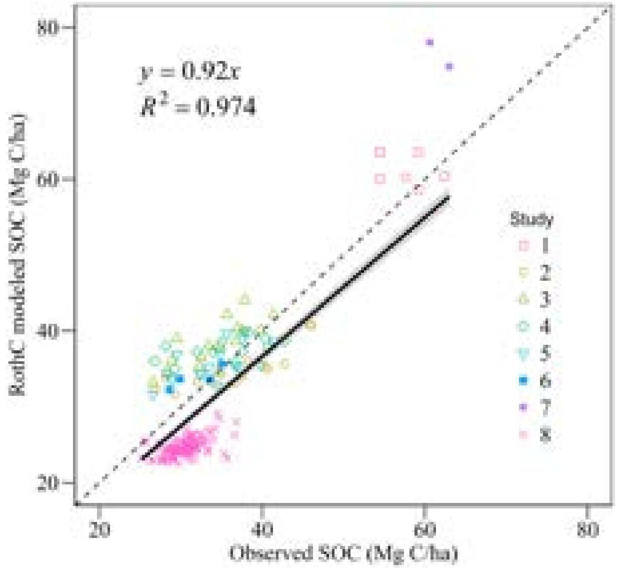

Fig. 3. Observed and RothC modeled SOC for long-term experiments across Canada. (see Table 1 for detailed information of study sites).

with a large inter-annual variation (Fig. 6). Inter-annual variability in climate affects SOC decomposition rates and C input via yields. Canadian agricultural lands mainly lost SOC stocks before 1990 (-1.1 Tg C yr^{-1}), turned to a small gain during 1990–2005 (4.6 Tg C yr^{-1}), and increased noticeably thereafter (10.6 Tg C yr^{-1}). Assuming the long-term (1971–2015) yield trend is continued until 2030, the projected average soil C sink would be 13.5 Tg C yr^{-1} from 2016 to 2030. If the higher recent (2005–2015) yield trend is continued, the projected average sink increased to 17.8 Tg C yr^{-1}.

4. Discussion

4.1. Effect of C input change on SOC stocks

The general trend of increasing SOC stocks is attributable to increases in C input. This is mostly driven by the significant increases in crop yield observed for all major crops except hay (Fig. S2B). The much increased C sink since 2005 is from higher increasing C input rates with much of that increase driven by the increase in area and yield of canola (Fig. 2). Several studies have reported the yield stagnation of different crops all over the world since 1990s, particularly for cereals (Grassini et al., 2013; Olesen et al., 2011; Ray et al., 2012), which would have severe consequences for the C balance of agricultural soils (Wiesmeier et al., 2015). However, there is no evidence of stagnation of yield in Canada with possible exception of hay crops (*SI text*; Table S2). In fact, the Canadian canola industry believes that the rate of yield increase for that crop can be increased well beyond recent rates through steady incremental improvements in both crop genetics and agronomic practices (Canola Council of Canada, 2017).

The impact of the development and adoption of crops with larger root systems to provide higher belowground carbon input has been proposed to be an efficient way to sequester atmospheric carbon (Kell, 2012; Lynch and Wojciechowski, 2015). Our results show that there is a potential opportunity to exploit differences of crop root depth and distribution (Fan et al., 2016) and root to shoot (R/S) ratios (Thiagarajan et al., 2018) to increase C input. In particular, canola and oat have higher R/S ratios (~1.5 and ~1.7 times, respectively) than those of the average grain crops (Thiagarajan et al., 2018). Annual belowground C inputs to 0–20 cm soils from canola and oat were 1.9–4.4 and 1.4–3.2 times, respectively, those of other annual grain crops excluding maize. The recent increase in canola yield and area is accounting for 70% of the increase in C input to agricultural soils since 2005. The higher relative root C input of canola is an important contributor to its effect on total C input (Fig. 6A). Our scenario having greater production of canola and oat to realize their benefit of greater root mass, increased the total estimated sink from 2016 to 2030 by an additional 1.7 Tg C yr^{-1} (Fig. 6B). Our results were supported by field observation of higher C input from canola and its root derived ^{13}C to soil (Comeau et al., 2013). However, below-ground C input remains the most uncertain part of the soil C cycle (Pausch and Kuzyakov, 2017), where further study is highly warranted. Recently, Paustian et al. (2016) estimated an increase of ~1 Pg CO$_2$-eq yr^{-1} for global cropland with a sustained increase in root C inputs. Our study supports the contention that increased root C inputs have been and can be an important factor for increasing C sequestration.

Since our scenarios only projected 15 years in the future, we did not consider the effects of projected climate change itself. Several studies suggested that climate warming might cause a loss of SOC due to enhanced decomposition of SOM (Conant et al., 2011; Davidson and Janssens, 2006; Smith et al., 2007) with temperature control on soil carbon turnover being more sensitive in cold climates than in warm climates (Koven et al., 2017). However, climate change (and higher atmospheric CO$_2$ concentrations) could also increase crop yields substantively in many parts of Canada, where crop production is constrained by low temperatures and short growing seasons. Modelling studies show cereal yields could increase by 37 to 60% by mid-21st century (Smith et al., 2013) although the increase from current levels could be less than half that amount by end of the century (Qian et al., 2016). Such yield increases, however, may be vulnerable to potential shifts in precipitation which is more difficult to predict than

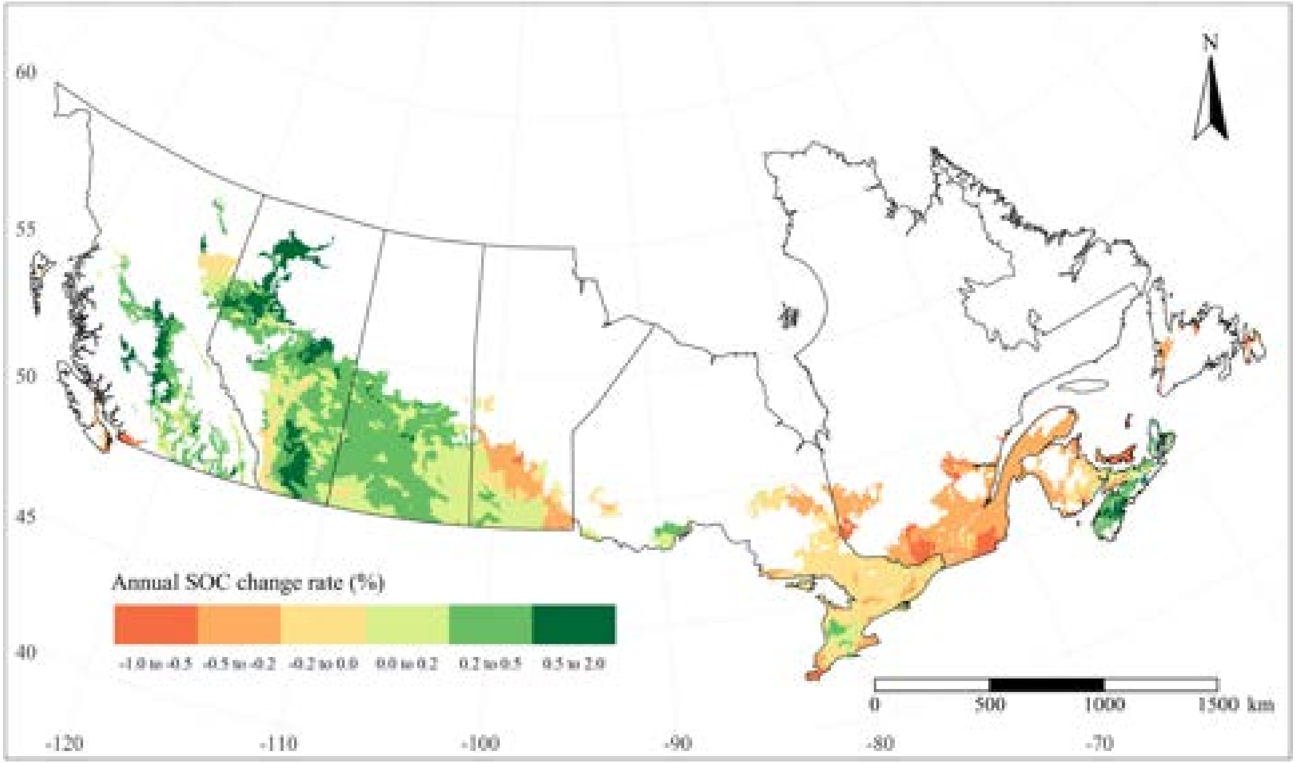

Fig. 4. Annual rate of change of SOCs (%) from 1971 to 2015 in 0–20 cm soil depth across Canada.

temperature alone. Further study is warranted to incorporate the effects of global change on C losses and gains.

4.2. Potential of agricultural land in mitigating greenhouse gases

To assess the impact of agriculture on global climate change requires considering all greenhouse gas (GHG) emission, including the N_2O and CH_4 emissions incurred in growing the crops and producing the manure. Based on the National Inventory Report (NIR, 2017), calculated using IPCC Tier 2 methodology (IPCC, 2006), Canadian agricultural CH_4 emission increased from 27.0 in 1990 to 28.9 Tg CO_2-eq in 2015 and N_2O emission increased from 21.3 in 1990 to 28.1 Tg CO_2-eq in 2015 (Fig. 7). Canadian agricultural soil showed a small SOC increase from 1990 to 2012, which offset ~34% of agricultural GHG emission and acted as a net carbon source so that the average net GHG emission for the period was 36.4 Tg CO_2-eq. With the increase in SOC change after 2013 induced by higher C input, SOC sequestration offset all agricultural GHG emissions and acted as a net carbon sink with an average net GHG emission of -16.2 Tg CO_2-eq. In 2013, other additional GHG emissions from Canadian agricultural land totaled 7.8 Tg CO_2-eq consisting of land converted to cropland (2.7 Tg CO_2-eq), land application of lime and urea (2.3 Tg CO_2-eq), residual emissions from land converted to cropland before 2013 (1.8 Tg CO_2-eq), wildfires on natural pasture (0.7 Tg CO_2-eq), and cultivation of organic soils (0.3 Tg CO_2-eq) (NIR, 2017). Therefore, in 2013, the cropland sink due to increased C input put Canadian agricultural sector into an overall carbon negative position after including these additional emissions from agriculture. However, the estimated GHG emissions for field machinery operation, on-farm transport, heating, electricity, and for those attributed to machinery manufacture and agrochemical (mostly N fertilizer) manufacture totalled 19.4 Tg CO_2-eq in 2011 (Worth et al., 2016). Assuming the latter value is representative for 2013, the large sink in that year was not sufficient to make overall Canadian agricultural production carbon negative. The C sequestration for the three scenarios estimated a carbon sequestration of 13.5–19.5 Tg C yr^{-1} from 2016 to 2030 (Fig. 6B), which would offset 85–100% of CH_4 and N_2O emissions, assuming CH_4 emission keeps same as 2015 and N_2O emission keeps the 1990–2015 trends linearly to reflect greater N intensity needed to support increase in the crop production (Fig. 7). Our result is in line with Lamb et al. (2016), which stated that increasing agricultural yields is one important means to achieve reduction in GHG emissions.

4.3. Limitations and implications

This national scale analysis clearly indicates the opportunity for soil carbon sequestration via enhanced carbon input arising from increasing crop yield and expanding the area of crops with higher below-ground C input. However, there are two important limitations that arise from the RothC model. First, change of SOC stocks could only be modeled for the top soil (0–20 cm depth). There are relatively few studies in Canada that have investigated how changes of land agricultural land management affect SOC for depths below 15 to 30 cm. The focus on shallow depths is understandable as VandenBygaart et al. (2011) measured SOC for long-term field experiments across Canada and determined that the minimum detectable difference increases rapidly and non-linearly as the depth over which SOC stock is measured increases. Nevertheless, they found detectable SOC differences for change in crop rotation or type, which would presumably reflect the effects of change in C input, to 45 cm. These differences were the same direction as for surface depths but magnitude was generally higher. Congreves et al. (2014) did an exhaustive meta-analysis of long-term field experiments in East-Central Canada, and also determined that SOC changes due system changes reflecting changes in C input (i.e. rotation or N fertilizer) were generally detectable to only 45 cm and that the SOC stock change was same direction and generally higher magnitude for 0–45 cm as for 0–20 cm. Based on these empirical studies, we concluded that there will significant SOC change to at least 45 cm and so the 0–20 cm estimates from RothC underestimated the actual SOC change. Our estimated C input for 20–45 cm layer for the major crops based relationships from

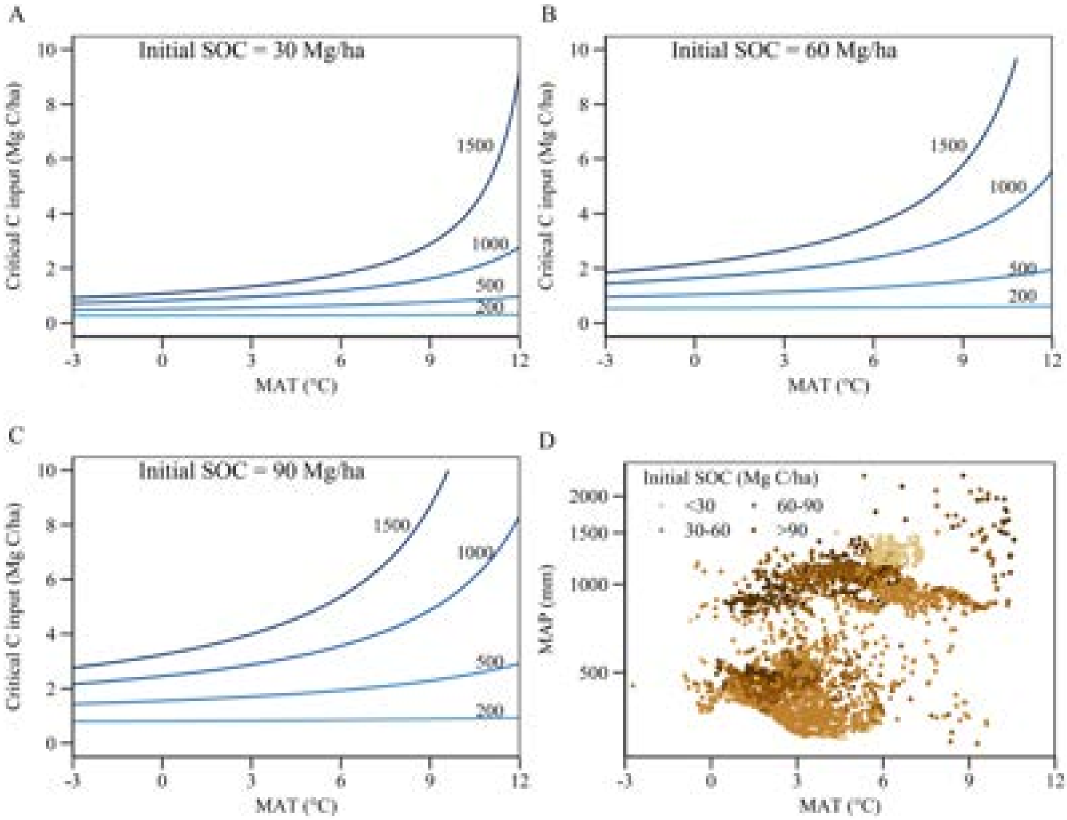

Fig. 5. Critical C input (Mg C ha^{-1}) needed to maintain the SOC stock (zero change) under different climate regions with different mean annual temperature (MAT, °C), mean annual precipitation (MAP, mm), and initial SOC stock (Mg C ha^{-1}) (A–C), and the distribution of initial SOC stock under different climate regions (D). Different gradients of blue lines represent different MAP (mm). The patterns of soil distribution correspond to particular geographical areas: soils with MAP $<$ 600 mm are located in western interior Canada with their latitude generally increasing as MAT decreases; soils with MAT $>$ 8 °C and MAP $>$ 600 mm occur in extreme southern Ontario and western coastal; soils with initial SOC $<$ 30 Mg C ha^{-1} occur mainly in eastern coastal Canada, and soils not in above geographical areas occur across eastern Canada with their latitude generally increasing as MAT decreases. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

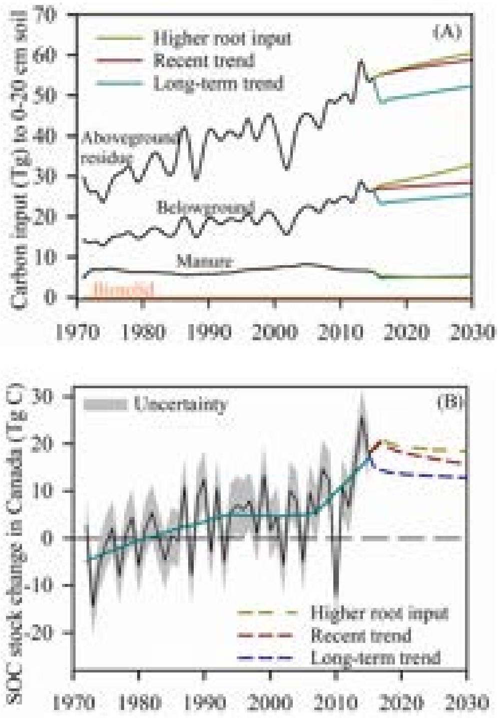

Fig. 6. C input change (A) and it induced change in SOC stocks (B) in Canada from 1971 to 2030.

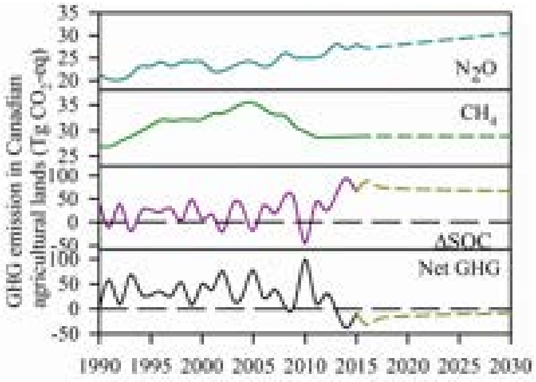

Fig. 7. N_2O and CH_4 emissions (data from National Inventory Report (NIR, 2017)), change in SOC stocks, and net greenhouse gas (GHG) emissions in Canadian agricultural lands from 1990 to 2030. Dashed lines indicate future projection (only "higher root input" scenario is included for Δ*SOC* and total GHG emission as most promising scenario).

Thiagarajan et al. (2018) was ~11.6% of the cumulative C input above 20 cm. Assuming SOC change below 20 cm is strongly related to cumulative C input as we showed for 0–20 cm, then the SOC change for 20–45 cm layer would be a similar proportion (~12%) of the SOC change for 0–20 cm layer as the cumulative C input for 20–45 cm to C input above 20 cm. In the above two multi-experiment studies, there were also examples of detectable SOC change to 60 cm. The SOC change below 45 cm may become more important as crop type is changed to those with greater relative root C input, such as forages and specific grain crops like canola. For one field site in eastern Canada, Carter and Gregorich (2010) found that after 7 years of perennial grass forage on land previously only having annual crops, the SOC change for 0–60 cm was 177% of the SOC change for 0–20 cm. Therefore, the likely underestimation of SOC change may be relatively larger for our high root input scenario than other scenarios. In the latter scenario has 31% more cumulative root C input for 20–60 cm for 2016 to 2030 than the recent trend scenario potentially suggesting that SOC change will also be greater below 20 cm. Further study is needed to accurately model whole profile SOC change.

RothC is based on linear first order kinetics similar to other widely used models of SOC dynamics. Carbon saturation refers to the limit of sites for physiochemical protection of organic matter from decomposition; saturation occurs when all sites are occupied and any subsequent carbon storage is of more unprotected organic matter. Stewart et al. (2007), in an analysis of SOC change in North America including several Canadian studies, concluded that including carbon saturation provided marginally better estimates of SOC change than first order kinetics alone. However, Feng et al. (2013), who included long-term manured Canadian field studies having high C input, failed to find evidence of carbon saturation is affecting SOC dynamics. The effects of carbon saturation will be most pronounced with high SOC contents that are near SOC saturation level. In our studies, according to the first order kinetics of RothC, soils with high SOC (i.e. 0–20 cm SOC > 60 Mg ha^{-1}) are predominantly (69%, data not shown) losing C based on estimated C inputs since 1971; sequestration occurs almost entirely in soils with low SOC where carbon saturation would be less important to SOC change. We do not believe that carbon saturation is significantly affecting our estimated C sequestration due to changes in C input since 1971. However, further validation of RothC is warranted to test for potential effects of carbon saturation as new empirical data becomes available, especially data for situations of high SOC and high C input.

The RothC model does not include the effect of soil disturbance. In western Canada, no-till is now the predominant tillage system and Canada reported a net sink from the reduction of tillage of 3.8 Tg C in 2015 (NIR, 2017). More research is needed to include effects of changes in soil disturbance on SOC in RothC. The Century model (Parton et al., 1988) is an example of a model that models the effect of soil disturbance but it also models the vegetation to estimate C input. The actual C input is determined by the complex interactions between crop cultivar agronomic practices, weather, and soil conditions and cannot be easily simulated with any accuracy. This study has shown that C input is critically important so it is advantageous to base C input as much as possible on measured crop production, as we did in this study.

The area of Canadian agricultural land included in the present study has been relatively stable with 54 million ha in 1971 and 52 million ha in 2015 although there have been both gains and losses of land on the basis of SLC polygons. Within the agricultural land, the area of native pasture in Canada was 12.0 million ha in 1971 and 10.5 million ha in 2015. In 2013, a detailed estimate of the SOC change for land-use change involving agricultural land is provided by the Canadian National Inventory of Greenhouse Gas Emission (NIR, 2017). The SOC change was a loss of 0.5 Tg C including residual loss of SOC occurring in that year from land conversion that happened in all previous years since 1971. Including the complexity of land-use change (LUC) processes was well beyond the scope of this study. To remove any effect of LUC in our study, we assumed that land entering agriculture had the same SOC state as land already in agriculture and land leaving agriculture had no subsequent SOC change. To obtain an estimate of SOC change including LUC, we recommend adding Canada's official estimates of the SOC change for LUC reported for national inventory reports to the change in SOC stocks reported in this study.

Crop residue (aboveground and belowground) and livestock manure were the main C sources for agroecosystem influencing the change in SOC stocks (Lal, 2004; Maillard and Angers, 2014). Our study estimated Canadian agriculture carbon balance by integrating cropland and livestock sectors into a whole agroecosystem and considering their supply-demand interaction (Fig. 1). Crop residue removal was driven largely by livestock demand for feeding and bedding, which in turn regulated aboveground crop C input and C flux going through the livestock sector. This approach successfully connected residue removal/supply with livestock demand in a national scale by assuming livestock feeding and bedding were major usage of crop residue in agroecosystem. Our results suggested that crop C accounted for most of the C input in Canadian agroecosystem, while manure and biosolids only contributed to < 20% of total carbon input (Fig. 2). However, manure C input change would significant affect regional soil C change (Sleutel et al., 2007; Taghizadeh-Toosi et al., 2014). Furthermore, manure C input and its effect on SOC stocks (*SI text*; Fig. S5) varied significantly across Canada, indicating the high importance of whole ecosystem investigation of C balance.

Agriculture is deemed to have the greatest near-term (by 2030) greenhouse gas mitigation potential among the economic sectors by the Intergovernmental Panel on Climate Changes fifth assessment, largely via SOC sequestration (Smith et al., 2014). Opportunities suggested for accomplishing C sequestration include increasing crop yields (Lamb et al., 2016) and changing crop mix to include crop types that input proportionately more below-ground C (Kell, 2012; Lynch and Wojciechowski, 2015; Paustian et al., 2016). To our knowledge, ours is the first study to quantify the past and potential future effect of these actions for a national situation, which has ramifications for other countries with increasing yields and adopting more crops with larger and deeper root systems.

In summary, our study proposed a whole-system C fluxes calculation approach by considering their supply-demand interaction between cropland and livestock sectors. Then the thoroughly validated process-based RothC model was used to estimate the change SOC stocks across Canada for 1971 to 2015, based on calculated annual C flows. SOC sequestration induced by increasing crop yield and switching crops to higher below-ground C input type showed a potential to offset ~34% or more of Canadian agricultural GHG emission since 1990. The results provide direct evidence of increasing crop yields and below-ground C input on C sequestration for a national situation.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2018.08.004.

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