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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