Agricultural Soils

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Globally, agricultural soils are being evaluated for their role in climate change regulation as a potential sink for atmospheric carbon dioxide (CO2) through sequestration of organic carbon as soil organic matter. Scientists and policy analysts increasingly seek to develop programs and policies which recognize the importance of mitigation of climate change and insurance of ecological sustainability when managing agricultural soils.

agricultural soils | soil organic carbon | crop land-use carbon inventory | CENTURY model | greenhouse gas (GHG)

1. Introduction

About 50% of the world's habitable land is used for agriculture [1] and cultivated soils encompass about 12% of the global total soil organic carbon (SOC) stock [2]. Soils can be both a net source or sink for the three principal greenhouse gases (GHGs), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Indeed, SOC changes in cultivated soils are regulated by complex interactions between the local soil environmental and climatic conditions, as well as the agricultural management practices [3]. Many studies have suggested that changes in SOC can impact atmospheric CO_2 concentrations [4]. For instance, it is well known that historical agricultural activities have resulted in a substantial decline in SOC stocks; and that soil and cropping practices are a potentially powerful tool for climate change mitigation through C sequestration [5][6][7][8][9][10]. Numerous international initiatives (i.e., 4p1000, 2015) have recognized agricultural soils as an important contributor in the mitigation of climate change suggesting that adaptability of agricultural land-use practices can play a crucial role where food security and climate change are concerned [11]. Therefore, the development of a local land use carbon inventory (LUCI) is the first step to better understand the importance of SOC in agricultural cropland and soil conservation.

Canadian agricultural soils are important for climate regulation by being either a source of GHG emissions, or by sequestering organic carbon and nitrogen as a sink in stable SOC [12]. Since agricultural soils accounted for about 8% of Canada's total GHGs emissions in 2015, the Canadian government is now considering strategies for SOC sequestration to reduce GHG emissions. In addition, Canada's policies on climate change now acknowledge the importance of soils, and require proper, comparable and reliable information to report on carbon stocks and GHGs emissions from soil [13]. The importance of the agricultural land use sector and its contribution to GHG reduction has been reinforced by the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). Thus, there is a growing interest in estimating the net GHG balance in response to land-use changes involving agriculture for national-scale reporting.

Reports on SOC stocks and GHGs emissions from agricultural soils is of special importance to the province of Ontario because it contains significant high-intensity farmland in Canada, with a total number of 49,600 farms according to the 2016 Census of Agriculture [14]. Nevertheless, Ontario does not currently include emissions and removals of GHGs from the agricultural land use sector in its GHG inventory or GHG reduction targets. Therefore, to guide the development of a carbon policy, there is a need to develop a LUCI for the province. This carbon inventory could (i) provide a better understanding of the potential role of terrestrial carbon in achieving Ontario's objectives in climate change mitigation; (ii) provide an opportunity for the province to improve data sources and reduce data gaps by aligning scientific efforts with federal government departments; (iii) develop more comprehensive estimates of carbon stored and released by landscapes; and (iv) increase understanding of the mechanisms of how agricultural lands and soils emit and store carbon. In this context, this study aimed to contribute to a better understanding of the current status of land use SOC inventories for the cropland sector in Ontario and to identify the critical information gaps and limitations in estimating agriculture management effects on SOC monitoring.

2. Synthesis of the Main Gap Analysis

In this study, we have identified four main gaps in the methodology used by the Canada's NIR for estimating GHG emissions from the cropland sector.

2.1. Modeling Approach

Computer simulation models allow prediction of different agricultural management scenarios and climate change on SOC stocks. In particular, these models can compare different soil management practices (e.g., reduced tillage), the influence of crop yield increases (i.e., residue inputs) with improved varieties, changes in agronomic practices over time (e.g., fertility, cropping systems), and changes in climate due to global warming. In Canada, the CENTURY model has been used to predict soil C stocks for the NIR. This model describes the entire agricultural ecosystem, incorporating crop growth, plant residue inputs and tillage management effects on plant residue decay and on the dynamics of the constituent pools of SOM. A modified version of the CENTURY model was selected by several countries (e.g., EU, USA, Serbia, Bosnia and Herzegovina, Croatia, Montenegro, Albania, Macedonia, Denmark, and Norway) as being most suitable because of its ability to simulate the effects of the main management practices in agricultural fields (tillage, fertilization, grazing, etc.), and to simulate mixed management systems. In addition, computational time was reduced when modeling large numbers of management combinations because of the monthly time-step.

Two other soil-only Process Models applied in Canada to predict SOC stocks in Canadian agricultural soils are Roth-C and the Introductory Carbon Balance Model (ICBM) [15]. Roth-C has an advantage in that Plant-C inputs are easy to capture as they are added externally (i.e., empirical measurement). Satellite images or drone data could be used for obtaining site-specific crop C inputs. Both Australia and Japan use their own modified versions of Roth-C. The ICBM model, which has two SOC pools, is considered too simplistic and does not consider effects of soil texture on regulating SOC dynamics.

Even though Canada and other countries use the CENTURY model to estimate an initial baseline C stocks for all cropland, this model remains too complicated to implement in most developing countries (i.e., African countries) because of the limited or inexistent required input datasets. In these cases, an alternative modeling approach for prediction of SOC changes on agricultural land can be using an improved version of the Roth-C model. This model is also promising because of its simplicity and the availability of input data.

2.2. Model Input Data

Although this study supports and recommends continuing the use of the CENTURY model for estimating SOC stocks and SOC changes due to management, we have targeted input gaps which require solutions. The two most important gaps are manure management and soil erosion. Indeed, the effects of manure application and management on C cycling is not yet included in the Canada's NIR; manure is included in N_2O cycling but the C component is not yet considered. Soil erosion (both redistribution and deposition) also is not included in C stock changes or in GHG emissions, and these factors have a significant influence on field-level SOC stocks. There is currently a lack of understanding of the effects of animal manure management and soil erosion on net GHG emissions, so a comprehensive review of the literature is necessary for these factors to be incorporated into the CENTURY model.

In terms of existing data inputs, many of the input parameters and calibration factors are not necessarily generalized for applicability within Ontario. Model performance could be improved by tuning of input parameters specific for Ontario soil types, soil management practices, cropping systems and climatic conditions. For example, the parameters used to calibrate the crop growth sub-model in the Century model need to be specific for each crop and for each region of Ontario. Therefore, for estimations of crop C inputs, Ontario should use regionally specific crop yields, and include both the quantity and quality (chemical properties) of the residues and how they are managed (left on the field or baled and removed).

2.3. Geographic Units and Input Data

As noted above, the CENTURY model simulation in Canada is carried out for each SLC polygon. A SLC polygon is described by a standard set of attributes derived from Census of Agriculture data, with areas ranging from 1000 to 100,000 ha. Given the small scale (i.e., 1:1,000,000) described by a SLC polygon, it is not possible to obtain small/medium spatial resolution data, nor is it possible to correlate GHG drivers (i.e., topography, soil type, management practices) within a single polygon because these data are aggregated. A raster-based spatially explicit modeling approach which uses EO data (e.g., remote sensing maps) is a promising alternative. Information on agricultural soils/crops and Enhanced Vegetation Indices could be derived from satellite imagery (e.g., MODIS with moderate resolution of 250 m) and inputted to the model to produce maps of SOC stocks on a raster basis.

A recent development in digital soil mapping includes the use of remotely sensed covariates and machine learning techniques to study space-time variation of SOC stocks [16]. Because of its importance for spatial prediction of SOC in topsoil, these techniques could play a major role in LUCI implementation. The Canadian Annual Crop Inventory information published cropland cover (i.e., shown in **Figure 1**) can be of benefit LUCI implementation. We believe that a non-spatially explicit approach can impose limits on properly defining cropland areas and conversions between other land use areas and cropland. This has been acknowledged, for instance, in Australia's most recent NIR where planned improvements are underway to develop a fully spatially explicit time series of land-use maps to apply land representation to all land-uses. Such improvements would enable reporting of separate activity data and emissions estimates for all conversion categories.

The main benefit of this approach to LUCI would be its ability to represent land-use categories in the LULUCF sector in a spatially explicit way. As stated in the 2006 IPCC guidelines, "this analytical capacity can improve emissions estimates by better aligning land-use categories (and conversions) with strata mapped for classification of carbon stocks and emission factors by soil type, [and] vegetation type. This may be particularly applicable for Tier 3 emission estimation methodologies" (IPCC, 2006; [17]). We believe that the shift to a spatially explicit description of cropland area within Ontario and conversions between other land use categories and the cropland category would represent a great opportunity to improve cropland emission and removal estimates for Canada's NIR.

2.4. Ground-Truth Program and Farmer Collaboration

Given that levels of SOC stocks respond slowly to changes in agricultural management practices, several years of monitoring are required to detect changes in stocks by current analytical procedures. Compared to other countries, Canada's NIR uses a relatively small number of long-term experimental sites to calibrate and validate the CENTURY model. Ontario's LUCI will need to put in place a ground-truth program to deal with uncertainties due to spatial variability and regional climates, and to calibrate the CENTURY model. These selected sites need to be where management practices, soil conditions and cropping practices can be carefully monitored over a long period. At these sites, soil C stock sampling should be conducted every 5 years, including measurements of soil bulk density, and samples analyzed following reference procedures (i.e., high temperature combustion) after removal of inorganic C. Given the important role of nitrogen in decomposition and SOC stabilization, total N stocks should also be measured.

In addition to the existing long-term sites in Ontario [18][19], we recommend further establishment of an extensive network of long-term field sites throughout Ontario through farmer-led research initiatives. In this context, the Ontario Government should provide opportunities for farmers and farmland owners to collaborate on the data collection for LUCI by keeping detailed records of their cropping and soil management practices, and crop yields. This collaboration would provide opportunities for farmers to demonstrate to government agencies and consumers their husbandry of agricultural soils, and evidence of their individual and collective on-farm efforts to improve the environmental performance and sustainability of their land. Ultimately, this approach will lead to reductions in GHG emissions from agriculture. Financial compensation, income derived from the market carbon, or property tax reduction to farmers who use beneficial management practices (i.e., conservation tillage, crop residue return, cover crops and green manures) should be considered by the provincial government. For example, to monitor progress in reducing emissions through a range of agricultural land management practices, the Australian Government has developed a voluntary Carbon Farming Initiative (CFI) whereby landholders may generate credits for reducing emissions and/or sequestering carbon. Currently it is not clear how Ontarian C offset credits generated by farmers would be managed; nevertheless, any C offset program would require a cost-effective LUCI and GHG estimation protocol to encourage farm owner participation and to facilitate C tracking and monitoring from agricultural soils.

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