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Carbon dioxide emissions from tillage of two long-term no-till Canadian prairie soils

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ABSTRACT

Agricultural soils under long-term zero tillage (no-till) management have been well known to sequester atmospheric carbon (C) in soil organic matter as well as to reduce emissions of major greenhouse gases. This fact aided the development of the present C offset market around the world and is the basis for no tillage or conservation tillage agriculture as a potential low cost means of reducing greenhouse gas (GHG) emissions. The province of Alberta, Canada currently has C offset protocols under which companies that fail to achieve targeted emission reduction can purchase C credits from agricultural farms that have changed tillage management practices. Our study aimed at quantifying the major GHG carbon dioxide (CO_2) emissions from two major agricultural soil types in Western Canada (i.e., Black Chernozem and Gray Luvisol) managed under long-term (~30 years) no-till after tillage reversal. We also studied the influences of soil temperature and soil moisture, nitrogen (N) fertilization (i.e., no N vs. 100 kg N ha^{-1}) and inherent soil fertility on the magnitude of tillage reversal impact on soil CO_2 emissions. Our study revealed that the CO_2 emissions were higher after tillage reversal irrespective of N fertilizer applications, soil types and soil physical environment. Comparative study between historic soil C sequestration after the adoption of long-term no-till and the GHG emissions in the form of CO_2 fluxes after tillage reversal on these study plots showed that the short-term rates of C emissions after tillage reversal were higher than the long-term rates of C sequestration. However, since the time scales for comparing the sequestration and emission rates were so different, these results are expected and reasonable. These results, however, indicate that increased soil C storage resulting from changes in agricultural management practices are reversible and that the potential for C sequestration is dependent on the long-term trends of management practices.

1. Introduction

Conservation agriculture such as no-tillage has been speculated to have greater potential for reducing greenhouse gas (GHG) emissions at a very low cost as well as to facilitate sequestration of organic C in agricultural soils (Antle et al., 2002; FAO, 2008; Sanderman et al., 2010). Globally, adoption of no-tillage agriculture was estimated to sequester soil organic C equivalent to one-third of the current global CO_2 emissions (i.e., 27 Pg CO_2 yr^{-1}) from burning fossil fuels (FAO, 2008). Reversion of no-tillage to conventional tillage management has a high risk of releasing the stored C in soils into the atmosphere in the form of CO_2 (Antle et al., 2002). However, much uncertainty still remains about the rate of C sequestration and permanence of the sink due to the adoption of no-tillage over conventional tillage agricultural management practices (Sanderman et al., 2010).

Greenhouse gas emission trading and offset systems are currently blooming as an effective and popular green business with well-structured open market exchange like the European Climate Exchange (ECX) in the EU and the Chicago Climate Exchange in the US. The Alberta emission trading system in Canada currently allows large emitters (companies that emit more than 100,000 Mg of GHGs in a year) to achieve emission reductions by purchasing C offsets at a maximum price of CAD$ 15 per Mg of CO_2 equivalents (Alberta Environment, 2009). The Alberta agricultural sector has well positioned itself for the potential GHG offset market since agricultural soils are generally intensely managed and additional soil C sequestration in these ecosystems can be achieved by adopting no-till (NT) practices. The Quantification Protocol for Tillage System Management (Alberta Environment,

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2009) creates C offsets by quantifying changes in GHG removal due to soil C sequestration and reductions in N_2O emissions and energy use where there is a practice change from conventional tillage (CT) to NT or reduced tillage (RT) (Alberta Environment, 2009) (Eq. (1):

$$\Delta\bar{J}_C = \bar{J}_{CT} - \bar{J}_{NT/RT} \quad (1)$$

Where $\Delta\bar{J}_C$ is the change in average C emissions (kg CO_2 equivalent [CO_2E] $ha^{-1}\,yr^{-1}$) resulting from changing tillage management from CT to NT or RT, $\bar{J}_{CT}$ is the average C emissions (kg $CO_2E\,ha^{-1}\,yr^{-1}$) from CT systems and $\bar{J}_{NT/RT}$ is the average C emissions (kg $CO_2E\,ha^{-1}\,yr^{-1}$) from NT or RT systems. In the Alberta tillage offset protocol, the change in average C emissions resulting from changing management is estimated with agro-ecological region-specific emissions factors (coefficients). For example, $\Delta\bar{J}_C$ for changing from CT to NT is estimated (Eq. (2)):

$$\Delta\bar{J}_C = NT_\Delta = \frac{\Delta\bar{J}_{C,CT\ to\ NT}\cdot A_{CT}}{A} + \frac{\Delta\bar{J}_{C,RT\ to\ NT}\cdot A_{RT}}{A} \quad (2)$$

Where NT_Δ is the net CO_2 coefficient for NT management (kg $CO_2E\,ha^{-1}\,yr^{-1}$), $\Delta\bar{J}_{C,CT\ to\ NT}$ is the average C sequestration potential for a change from CT to NT for a given agro-ecological region (kg $CO_2E\,ha^{-1}\,yr^{-1}$), $\Delta\bar{J}_{C,CT\ to\ RT}$ is the average C sequestration potential for a change from RT to NT for a given ecoregion (kg $CO_2E\,ha^{-1}\,yr^{-1}$), A_{CT} and A_{RT} are the area of crop land under CT and RT in a given agro-ecological region (ha), and A is the total area of the agro-ecological region (ha).

It should be noted that the emissions coefficient (Eq. (2)) depends very much on the estimation of the average C sequestration potential given a change in management practices in a given agro-ecological region. The average C sequestration potential is based on the best scientific evidence available. But it is still an average, so a specific field may have a higher or lower sequestration potential since the magnitudes of CO_2 emissions can be largely affected by other agricultural practices (i.e., fertilizer application), variability in environmental factors (i.e., soil moisture and soil temperature) and inherent fertility of a particular soil (Nyborg et al., 1995; Lal and Kimble, 1997).

To account for the risks of "one-off" tillage events that may occur to control weed infestations or to incorporate heavy crop residues an assurance or reserve factor (AF) for a given agro-ecological region is calculated (Eq. (3)).

$$AF = 1 - \left(\frac{\text{number of tillage reversal events}}{\text{20year period}}\right) \quad (3)$$

The net CO_2 coefficient NT_Δ is then adjusted through multiplication by the assurance factor (AF) which ranges between 0.8 and 0.925 depending on the agro-ecological region. The range in assurance factors for different agroecological regions is based on a region- and management-dependent number of tillage reversal events (e.g., for the Eastern Alberta region under no till management, the assurance factor is calculated assuming 4 tillage reversal events, and for the West region under reduce till management, 1.5 tillage reversal event is assumed; Alberta Environment, 2009).

This assurance factor assumes that the rate of C loss from tillage of a conservation tillage soil is the same as the sequestration rate following conversion from conventional to conservation tillage. However, this assumption has not been tested. Hence a scientific testing of the underlying hypothesis (the rates of CO_2 emissions after tillage reversal = the rates of soil C sequestration resultant of adoption of NT) in this AF is essential.

Long term monitoring of soil C stocks on no-till agricultural soils is a well-recognized practice aimed at evaluating the real impact of no tillage on soil C sequestration (Six et al., 2004). Quantifying the loss of soil organic C following a tillage reversal on a long term NT soil could therefore be a good measure of the loss of sequestered soil organic C. Measurement of change in soil C storage between two points of time (often called "stock change method") is a common practice to estimate long term soil C losses following tillage but unfortunately this technique often fails to capture large but fleeting CO_2 effluxes as a result of episodic tillage events (Ellert and Janzen, 1999) and fluctuations in soil moisture and temperature. Nondestructive, continuous in-situ CO_2 flux measurements throughout the growing season could thus be a good estimate of short term C losses from long term non tilled agricultural soils following tillage reversal that may also provide more insight into the mechanisms involved (Ellert and Janzen, 1999; Six et al., 2004).

Given the potential significance and research needs as discussed above our study focused the following objectives:

1. To quantify CO_2 emissions after tillage reversal on two major soil types in Alberta (i.e., Black Chernozem and Gray Luvisol) managed under long term (~30 years) NT with residue retention for different N fertilizer applications and weather conditions i.e., soil temperature and soil moisture.
2. To compare the rates of CO_2 emissions after tillage reversal with those of historical soil C sequestration after the adoption of long term NT over those two soil types so as to test the underlying assumption of "the rates of CO_2 emissions after tillage reversal = the rates of soil C sequestration resultant of adoption of NT" in existing Quantification Protocol for Tillage System Management of Government of Alberta.

2. Methods and materials

2.1. Soils and experimental set up

The study was conducted on two soils: an Orthic Gray Luvisol of the Breton loam series located in the rolling landscape of the vicinity of Breton, Alberta, and a Black Chernozem of the Malmo loam series common to the flat lacustrine landscape near Ellerslie, Alberta (Alberta Agriculture and Rural Development, 2014). The Breton and Ellerslie soils roughly correlate to Typic Haplocryalf and Albic Agricryoll, respectively, according to the USDA Soil Taxonomy. These two soils are ~70 km apart and represent two major and distinctly different soil types found in North-central Alberta (Table 1).

Parallel long-term experiments were established at each site in autumn 1979 (Nyborg et al., 1995) which included 10 treatments randomized in 4 blocks for a total of 40 plots. The dimension of each plot was 2.74 m × 6.85 m. For this investigation, the tillage reversal was expressed as pre-seeding tillage on those long-term no-till plots. This tillage reversal was carried out on subplots of two of the original treatments: (1) NT, 0 kg N ha^{-1} with straw retained, and (2) NT, 100 kg N ha^{-1} with straw retained. The dimensions of these subplots were 1.37 m × 6.85 m (i.e., each of the original plots was split lengthwise into a tilled and a no-till subplots). These two treatments from the original randomized block design were again split into plots with tillage regimes (referred to as NT and CT from now on) as main plots and N fertilizer rates (0 N vs. 100 kg N $ha^{-1}\,yr^{-1}$) as subplots. Each of those subplots was replicated four times. Half of each of the NT with straw plots (0 N and 100 N) was subjected to tillage reversal on June 3, 2009 and June 3, 2010 for the Black Chernozem and on June 4, 2010 for the Gray Luvisol after ~30 years (1979 to 2009–10) of no-till management. Thus we had measurements from two consecutive growing season following tillage reversal on Chernozem and one growing season following the inaugural tillage after ~30 years on Luvisol to include in this study. The tillage was done by using rototiller up to 10 cm depth to mimic "one-off" tillage event by the farmer for weed controls, crop failures etc.