University of Alberta

Greenhouse Gas Emissions Following Tillage Reversal on a Black Chernozem and a Gray Luvisol in Alberta

by

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Dedicated to

My little daughter, my sweetheart,

Saafteeha Sabil Mezbah

And to my beloved husband

Symon Mezbahuddin

Abstract

Agricultural soils under long-term no till management have been well known to sequester atmospheric carbon in soil organic matter and to reduce emissions of greenhouse gases. Our study aimed at quantifying CO_2 and N_2O emissions from Black Chernozems and Gray Luvisols managed under long-term (~ 30 years) no till after tillage reversal. Our study revealed that both CO_2 and N_2O emissions were stimulated by tillage reversal. Comparative studies showed that the short-term rates of CO_2 and N_2O emissions after tillage reversal were higher than the historical rates of sequestration after the adoption of long term no till. Since the time scales for comparing the sequestration and emission rates were so different, these results are expected and reasonable. These results indicate that increased soil carbon storage resulting from changes in agricultural management practices is reversible and that the potential for carbon sequestration is dependent on the long-term trends of management practices.

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Table of Contents

List of Tables

List of Figures

Chapter 1

1 Introduction

Conservation agriculture has been speculated to have greater potential for reducing greenhouse gas emission at a very low cost as well as to facilitate sequestration of organic carbon in agricultural soils (Antle et al. 2001; FAO 2008; Sanderman et al. 2010). Globally, adoption of conservation agriculture was estimated to sequester soil organic carbon 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). This rate can, however, vary in different parts of the world due to environmental constraints to crop production such as climate, landscapes and crop varieties (FAO 2008). Lal et al. (1998) estimated approximately 49% of agricultural soil carbon sequestration can be achieved by adopting conservation or no tillage and residue management. Reversion of conservation to conventional tillage management has a high risk of releasing the stored carbon in soils into the atmosphere in the form of CO_2 (Antle et al. 2001). Currently there is much uncertainty and debate about the total additional organic carbon sequestration potential of agricultural soils, the rate of sequestration, the permanence of the sink and how to best monitor changes in soil organic carbon stock for different 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 (Mimi Lee, Alberta Agriculture and Rural

Development). The Alberta emission trading system in Canada currently allows large emitters (companies that emit more than 100,000 tonnes of greenhouse gases in a year) to achieve emission reductions by purchasing carbon offsets at a maximum price of CAD$ 15 per ton of CO_2 equivalents (Alberta Environment 2007). The Alberta agricultural sector has well positioned itself for the potential greenhouse gas offset market (Mimi Lee, Alberta Agriculture and Rural Development). Agricultural soils are generally intensely managed and additional soil carbon sequestration in these ecosystems can be achieved by adopting no-till (NT) practices and efficient fertilizer and residue managements. The Quantification Protocol for Tillage System Management (Alberta Environment 2009) creates carbon offsets by quantifying changes in greenhouse gas removal due to soil carbon 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 2012):

$$\Delta\bar{J}_C = \bar{J}_{CT} - \bar{J}_{NT/RT} \qquad [1.1]$$

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

$$\Delta\bar{J}_C = NT_\Delta = \frac{\Delta\bar{J}_{C,CT\ to\ NT} \cdot A_{CT}}{A} + \frac{\Delta\bar{J}_{C,RT\ to\ NT} \cdot A_{RT}}{A} \qquad [1.2]$$

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 carbon sequestration potential for a change from CT to NT for a given ecoregion (kg CO_2E ha^{-1} yr^{-1}), $\Delta\bar{J}_{C,RT\ to\ NT}$ is the average carbon 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 ecoregion (ha), and A is the total area of the ecoregion (ha).

This approach of emission reduction calculation (Eq. [1.2]) targets only tillage effects on soil carbon, but coefficients for nitrous oxide reductions and energy consumption can be calculated in a similar manner to Eq. [1.1] and [1.2] (Alberta Environment 2009, 2012). It should be noted that the emissions coefficient (Eq. [1.2]) depends very much on the estimation of the average carbon sequestration potential given a change in management practices in a given ecoregion. The average carbon 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, residue management; and variability in environmental factors i.e., soil moisture and soil temperature and inherent fertility of a particular soil type (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 incorporated heavy crop residues an assurance or reserve factor (AF) for a given ecoregion is calculated as:

$$AF = 1 - \left(\frac{\#\ of\ tillage\ events}{20\ year\ period}\right) \quad [1.3]$$

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 ecoregion.

Agricultural soils under CT were reported to emit higher CO_2 than soils under NT predominantly by changing the decomposition environment through alteration of soil physical conditions and microbial contact of substrates (Larney et al. 1997; Campbell et al. 2001). CT induced CO_2 emissions can be substantially higher in agricultural soils under residue retention practices compared to residue removal because of mixing of additional soil organic matter throughout the deeper soil horizons hence facilitating higher substrate availability for the microbes (Malhi et al. 2006, 2011a,b; Malhi and Lemke 2007). Nitrogen fertilizer application can provide a boost to agricultural crop growth and a consequent increase in microbial activity in the rhizosphere facilitated by the presence of fresh carbon from increased root exudates (Havlin et al. 1999). Increased plant growth in fertilized agricultural soils can also provide the soil with higher amounts of above and below ground residues (Malhi et al. 2011a,b). Given these facts, CT-induced CO_2 emissions may vary depending on N fertilization practices. Tillage impacts on soil CO_2 emissions were reported to be enhanced in warmer soils with 50-70% water filled porosity (Grant and Rochette 1994; Rochette et al. 1995; Lal and Kimble 1997). Indigenous fertility of a particular agricultural soil was also reported to be an important control of tillage impact on CO_2 emissions from that soil. Relatively nutrient poor agricultural soils were found to sequester more carbon as a result of conversion from CT to NT than nutrient rich soils (Malhi et al. 2011a,b).

The Assurance Factor (Eq. [1.3]) which calculates average risk of reversal events also relies upon the assumption that the rate of CO_2 emissions due to tillage reversal is equal to the rate of soil organic carbon sequestration due to conversion from CT to NT (Alberta Environment 2009). Tillage reversals on long term no-till plots are expected to release large flushes of CO_2 through triggering the decomposition of accumulated light fraction soil surface organic matter over the years (Malhi et al. 2011a,b). This effect might be a transient one provided that the increased emissions rates are reduced in successive tillage events. The best protocol to test the underlying assumption of Assurance Factor is to examine the rates of soil CO_2 emissions after tillage reversals on long term NT plots of dominant Albertan soil types and to compare those with the historical soil carbon sequestration rates after the adoption of NT on the same soils. To our knowledge, this assumption has not been tested yet.

The underlying mechanisms of N_2O emissions from agricultural soils are far less understood than those of CO_2 emissions. N_2O emissions from the agricultural soils are primarily products of aerobic and anaerobic microbial denitrification as well as chemical denitrification (Venterea and Rolston 2000; Müller et al. 2006; Venterea 2007). When soil becomes waterlogged and O_2 diffusion is inhibited within the soil, nitrifiers obtain their O_2 from NO_3^- with the accompanying release of N_2O and N_2 (Eq. [1.4]) through anaerobic denitrification.

$$2\mathrm{NO}_3^- \rightarrow 2\mathrm{NO}_2^- \rightarrow 2\mathrm{NO} \rightarrow \mathrm{N}_2\mathrm{O}\uparrow \rightarrow \mathrm{N}_2\uparrow \qquad [1.4]$$

These reactions can also occur in seemingly well-aerated soil where biological O_2 demand within waterlogged microsites within soil aggregates may still exceed the supply (Havlin et al. 1999). While producing NO_3^- from NH_4^+ through aerobic nitrification, nitrifying bacteria can simultaneously use NO_2^- as an alternate electron acceptor and thereby producing N_2O through aerobic denitrification. The rate of 'aerobic nitrifier denitrification', however, increases with the increase in soil anaerobicity and consequent depletion of soil O_2 (Venterea and Rolston 2000). NO_2^- accumulation from high rates of ammonium-based nitrogen fertilizer application may also favor N_2O emissions from agricultural soils through chemical denitrification.

In cool, temperate regions N_2O emission comprises the majority of greenhouse gas emission associated with crop production (Robertson et al. 2000). Climatic factors that regulate N_2O emission include temperature, precipitation and freezing and thawing regimes (Burton and Beauchamp, 1994). Many management factors, including tillage, legume cropping, crop residue management, and type and rate of mineral N fertilizer application, also contribute to N_2O emission. There is a large uncertainty associated with current estimates of the influence of tillage practice on N_2O emissions. Many studies have indicated increases in N_2O emissions under no-tillage (Ball et al. 1999; Skiba et al. 2002; Vinten et al. 2002). The greater N_2O emissions under no-tillage have been attributed to reduced gas diffusivity and air-filled porosity, often caused by high rainfall, and having the greatest effects on N_2O emissions after fertilizer application. There are also indications that this effect of tillage on N_2O emissions diminishes after long-term practice of no tillage (Six et al. 2004).

Short term studies of tillage impacts on N_2O emissions from agricultural soils revealed reverse trends for different experiments and soil types. Few studies reported NT favoring higher soil N_2O emissions than CT (Omonode et al. 2011) while the others found no significant difference in N_2O emissions for CT vs NT (Lemke et al. 1999; Baggs et al. 2001; Boeckx et al. 2011). To our knowledge, no study so far has reported the quantification, magnitude and mechanism of N_2O emissions after tillage reversal on long term NT soils. Tillage reversal on a long term NT soil can cause rapid mineralization of soil organic matter accumulated over the years of NT practice through soil disturbance and residue mixing. This may result in an increase in soil NO_3^- concentrations exceeding crop demand through rapid nitrification and might end up with increased N_2O production through denitrification (Eq. [1.4]). Tillage reversal might also improve soil drainage and facilitate aeration thereby reducing soil anaerobicity that might partially or fully offset the additional N_2O production through higher substrate availability. So, the net impact of tillage reversal on N_2O emissions from agricultural soils should also be accounted for in the existing tillage management quantification protocol (Eq. [1.2]).

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

1. To quantify CO_2 and N_2O emissions after tillage reversal on two major soil types in Alberta (i.e., Black Chernozems and Gray Luvisols) managed

under long term (~ 30 years) NT with residue retention for different nitrogen 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 carbon 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 carbon sequestration resultant of adoption of NT" in existing Quantification Protocol for Tillage System Management of Government of Alberta.

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Chapter 2

2 CO_2 emissions from a Black Chernozem and a Gray Luvisol under long term no till management after tillage reversal

2.1 Introduction

The concentration of carbon dioxide (CO_2) in the atmosphere has been increasing during the last few decades at an accelerated rate. Its contribution to increased atmospheric radiative forcing and its influence on decreasing upper atmospheric ozone levels have raised interest in evaluating its sources and sinks (Perdomo et al. 2009). Soil is considered to be the largest terrestrial organic carbon stock which currently contains as much as twice the amount of carbon as atmospheric CO_2 and three times that of global above-ground vegetation (Powlson et al. 2011). This large carbon pool is greatly influenced by soil management (Baker et al. 2007). Agricultural soils are intensely managed and are subjected to different practices like tillage, addition of fertilizers, manure and variable cropping intensity (Ellert and Janzen 1999). Tillage may have a measurable influence on soil carbon storage through soil disturbance which stimulates soil carbon losses due to enhanced microbial growth and decomposition (Larney et al. 1997; Campbell et al. 2001). Such effects may be reflected both in immediate changes in soil CO_2 fluxes (within 7 days of tillage) as well as in the longer term (after ~50 years of tillage) alteration of decomposition environment (Kucharik et al. 2001). Conservation tillage or no-tillage has been proposed as a means of increasing carbon sequestration in agricultural soils (Six et al. 2004). Comparative field studies hypothesized no-tillage or conservation tillage to favor accumulation of organic matter in surface soils (Kern and Johnson 1993). Many soils have been reported to lose 30-50% of the carbon that they contained prior to cultivation due to tillage and tilled soils are viewed as a depleted carbon reservoir (Kucharik et al. 2001; Reicosky 2003; Baker et al. 2007). But uncertainties remain about the loss of soil organic carbon following tillage because a few field studies have reported slightly higher CO_2 emissions from no-tilled plots compared to conventionally tilled ones (Hendrix et al. 1988). Hence quantitative research is needed to understand these discrepancies. Further, nutrient management such as fertilizer application is reported to substantially improve soil organic carbon depending upon indigenous fertility of the soils (Nyborg et al. 1995; Janzen et al. 1998). The decomposition environment (e.g. soil moisture and soil temperature) also influences soil microbial activities and soil respiration (Grant and Rochette 1994; Rochette et al. 1995; Lal and Kimble 1997). Therefore, various confounding factors such as nutrient management, soil types and key environmental controls of soil respiration (e.g. soil temperature and moisture) should also be adequately addressed while quantifying the change in soil carbon storage stimulated by tillage practices.

Long term monitoring of soil carbon stocks on no-till-managed agricultural soils is a well-recognized practice aimed at evaluating the real impact of no tillage or conservation tillage on soil carbon sequestration (Six et al. 2004). Quantifying the loss of soil organic carbon upon tillage reversal on a long term non-tilled soil could therefore be a good measure of the loss of sequestered soil organic carbon. Measurement of change in soil carbon storage over time usually provides a good estimate of long term soil carbon 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). Moreover, soil carbon losses may be very high right after a tillage event and these additional carbon losses might disappear with time following tillage or consecutive tillage events in the following years (Fortin et al. 1996). Seasonal variations in soil moisture and temperature might also exert significant influences on soil carbon emissions that could obscure tillage-generated carbon losses. Nondestructive, continuous in-situ CO_2 flux measurements throughout the growing season could thus be a good estimate of short term carbon losses from long term non tilled agricultural soils upon tillage reversal that may also provide more insightful information on the mechanisms involved (Ellert and Janzen 1999; Six et al. 2004).

The government of Alberta has recently created Conservation Agriculture Protocols for Greenhouse Gas Offsets which allow large industrial emitters of greenhouse gases to offset their emissions by purchasing offset credits (Goddard et al. 2009). With this protocol, there is an Assurance Factor to account for "one-off" tillage operations that a farmer might execute to control weeds or because of crop failure, etc. This Assurance Factor assumes that the rate of carbon 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. A big question is whether rates of carbon loss following tillage reversal are the same as rates of carbon sequestration when zero tillage management was established on conventionally tilled soil.

The present study was conducted on two contrasting soil types (Black Chernozems and Gray Luvisols) located at Ellerslie and Breton respectively which were established as research plots by University of Alberta in 1979 (Nyborg et al. 1995). The experiment was designed with combinations of straw retention/removal, nitrogen fertilizer rates and conventional tillage/no-till treatments. Both treatments were managed under no-till management since their establishment with straw retained and two fertilizers i.e., unfertilized and fertilized @ 100 kg N ha^{-1} yr^{-1} since establishment. We aimed to quantify the short term impact of tillage on CO_2 emissions from fertilized (100N) and unfertilized (0N) organic matter rich black Chernozemic and relatively organic matter poor Gray Luvisolic soils. For this study we initially formulated the following hypotheses:

1. CO_2 emissions are greater following tillage reversal from both Black Chernozemic and Gray Luvisolic soils managed under long term no-till. The emissions decrease with consecutive tillage event during the following year.
2. Nitrogen fertilizer application stimulates higher CO_2 emissions following tillage reversal on both of the above mentioned soil types.
3. Tillage reversal causes greater CO_2 emissions from organic matter-rich Chernozemic soils than that from relatively organic matter poor Luvisolic soils.

2.2 Methods and Materials

2.2.1 Soils and experimental set up

The study was conducted on two soils: an Orthic Gray Luvisol (Typic Cryoboralf) of the Breton loam series located in the rolling landscape of the vicinity of Breton, Alberta, and an Orthic Black Chernozem (Typic Cryoboroll) of the Malmo loam series common to the flat lacustrine landscape near Ellerslie, Alberta. These two soils are only ~70 km apart and represent two major and distinctly different soil types found in north-central Alberta. Descriptive data of both soil types are given in Table 2.1 (Plante et al. 2010).

Parallel long-term experiments were established at each site in 1979 (Nyborg et al. 1995) and consist of 10 treatments randomized in 4 blocks for a total of 40 plots (Figure 2.1). The dimension of each small plot is 6.85 m x 2.74 m. For this investigation the tillage reversal was expressed as pre-seeding tillage for two consecutive growing seasons and was carried out on subplots on two of the original treatments: 1) no-till, 0 kg N ha^{-1} with straw retained (treatment 4); and 2) no-till, 100 kg N ha^{-1} with straw retained (treatment.6). The dimensions of the subplots were 1.37 x 6.85 m (i.e., the original plot was split lengthwise into a tilled or no-till subplots). For the purpose of this present study then, these two treatments from the original randomized block design were split into split plots with tillage regimes (referred to as no-till and conventional tillage from now on) as a main plots and nitrogen fertilizer rates (0 vs 100 kg N ha^{-1} yr^{-1}) as subplots. There are four replications of each of the subplots. Half of each of the no-till with straw plots (0N and 100N) were subjected to tillage reversal on June 3, 2009 and June 3, 2010 for the Black Chernozems and on June 4, 2010 for the Gray

Luvisols. Tillage reversal after ~30 years (1979 to 2009-10) was done by using rototiller up to 5 cm depth to mimic “one-off” tillage event by the farmer for weed controls, crop failures etc. CO_2 and N_2O emissions were then measured on those sub-plots during the growing seasons of 2009 and 2010.

Soil temperature (°C) and Soil moisture content (cm^3/cm^3) data were collected from the official website of Agriculture and Rural development, Government of Alberta (http://www.agric.gov.ab.ca/app116/stationview.jsp) and from the micrometeorological station set in the Ellerslie Research Station, Edmonton.

2.2.2 Gas flux measurements

A non-steady state chamber system, described in details by Rochette and Bertrand (2008) was used to measure soil CO_2 fluxes. The chambers (Figure 2.2) were rectangular (65 cm x 16cm x 15cm) each of which consisted of a detachable chamber lids and collar. The whole chamber system except the bottom 5 cm of the collar was made opaque by wrapping it with bubbled aluminum foil and / or reflective tape so as to prevent penetration of sunlight during chamber deployment. The collars were inserted 5 cm into the ground leaving 10 cm above ground. The collars were kept inserted into the ground on each of the sub plots throughout the growing season. The chamber lid was attached to the collar with four rubber bands during gas flux measurements. A small fan operated with a battery was mounted under the chamber lid to maintain continuous air mixing inside the chamber between gas concentration measurements. Gas concentrations were monitored by portable, photoacoustic multi-gas monitor (Innova model

1312; www.innova.dk) (Figure 2.3) which was connected to the chambers by 2 m long plastic tubing during flux measurements. Carbon dioxide (CO_2), nitrous oxide (N_2O) and water vapor ($H_2O_{(v)}$) were measured by the gas monitor. The instrument is calibrated on an annual basis such that interference between CO_2, N_2O and $H_2O_{(v)}$ and ambient temperature are compensated for. The gas analyzer was transported from chamber to chamber in a wagon. During a concentration measurement, the gas analyzer was connected to the chamber with the plastic tubing for a 1 minute period. The gases in the chamber head space were circulated within the chamber and the gas analyzer. The digital reading of the gas (CO_2) concentration inside the chamber was recorded from the gas analyzer. The whole chamber deployment procedure like chamber selection, timing of opening and closing of lids, activation of gas analyzer and fans was operated manually. Gas fluxes were measured in sets of 4 chambers by staggering the lid attachment to the collars and gas concentration measurement in the chambers (2 minutes apart). Gas concentrations were measured at 0, 10, 20 and 30 minutes after the lid was placed on the collar. CO_2 flux measurements were carried out once a week throughout the growing season on each of the experimental sites (at Ellerslie and Breton) in 2010 and at Ellerslie in 2009. The gas flux was then calculated using the rate of change of its concentration with respect to time (dG/dt) inside the chamber during deployment (Rochette and Hutchinson 2005):

$$F = (dG/dt) * V/A \qquad [2.1]$$

Where, F = Gas flux (mg m^{-2} min^{-1}), dG/dt = change in gas concentration with time (mg m^{-3} min^{-1}), V = volume of chambers (m^3), A = area covered by chambers (m^2).

2.2.3 Statistical analyses

Data from two sites were analyzed separately since the main goal was to evaluate the differences in gas fluxes due to different management regimes in two contrasting soil types. Within and between each soil type, the difference between treatments were tested by repeated measures split-plot analysis using the Mixed Model function of SAS version 9.2 (SAS Institute 2010) with Kolmogorov-Smirnov and Levene's tests being used to check for normality and homogeneity of variances. All data were log-normally distributed.

Repeated measures ANOVA on the weekly mean CO_2 efflux rates were used to determine whether there was a significant effect on the rate of soil CO_2 fluxes for the different tillage treatments, the different Nitrogen treatments, the different soil types and for the different dry or wet growing seasons. We collected daily precipitation and soil temperature measurements at the Chernozems and Luvisols sites along with daily soil water contents at the Luvisols site to study the likelihood of any soil physical environmental effects on N_2O emissions. We performed linear correlation analyses for soil moisture and exponential growth correlation for temperature effects on soil CO_2 emissions from both soil types for different tillage treatments and N fertilizer applications. For all the analyses we assumed little or no microsite differences in soil temperature and moisture contents. Since we did not have soil moisture content measurements for the

Chernozems, we assumed changes in precipitation as analogous to fluctuations in soil moisture condition.

2.3 Results

2.3.1 Effects of tillage reversal on growing season soil CO_2 emission

Tillage reversal after ~30 years caused greater CO_2 emissions from the Black Chernozemic and Gray Luvisolic soils investigated invariably for different fertilizer treatments and weather conditions. However, the magnitude of the increase in soil CO_2 fluxes following tillage reversal from the conventional tillage (CT) plots compared to those from no-till control plots (NT) was not always consistent throughout the growing season or across different fertilizer treatments, weather conditions and soil types.

The very first tillage event after 30 years on the unfertilized (0N) Black Chernozems during 2009 did not show an observable change in weekly averaged hourly soil CO_2 effluxes with respect to those from NT plots up until 5th week following the tillage event. After 5 weeks, greater CO_2 emissions were measured for the 4 following weeks (Figure 2.4a). The fertilized Chernozems (100N), however, showed higher CO_2 emissions upon tillage reversal from the very first week following the tillage event and gradually increased up until 8th week after tillage before decreasing to levels similar to the notill treatment by the end of the growing season (Figure 2.4b). The increases in weekly averaged hourly CO_2 effluxes in the CT treatment peaked, irrespective of nitrogen fertilizer treatments, between the 6th and 8th weeks after the tillage reversal during 2009. Split-plot repeated measures analyses showed no statistically significant difference between the fluxes from the CT and NT Chernozems for both the fertilizer treatments throughout the growing season (Table 2.2) except those during 6th week after tillage ($P < 0.05$). Although weekly averaged hourly soil CO_2 fluxes did not show statistically significant differences upon tillage reversal throughout the growing season, total estimates of growing season (June-September) CO_2 effluxes from CT plots showed an increase over NT plots of 1.247 and 3.565 t ha^{-1} for 0 N ($P=0.52$; Table 2.2) and 100 N ($P=0.20$; Table 2.2) treatments respectively (Table 2.3 and 2.4).

After the second tillage event on the Black Chernozems in 2010, higher weekly averaged hourly CO_2 effluxes were observed both for the unfertilized (0 N) and fertilized (100 N) treatments from the 2nd through 8th weeks following tillage (Figure 2.4 a, b). The 0 N plots yielded an almost similar increase in CO_2 fluxes after tillage throughout the period mentioned earlier while the 100 N plots showed a peak increase in CO_2 effluxes at the 7th week following tillage (Figure 2.4 a, b). Total growing season CO_2 emissions from the CT plots following the second tillage event on the Chernozems during 2010 were greater than the NT plots by 2.221 and 2.433 t ha^{-1} for 0 N and 100 N respectively (Table 2.3, 2.4), but these differences were not statistically significant ($P=0.07$ for 0 N; $P=0.17$ for 100N; Table 2.2).

The first tillage event following 31 years of no-till on the Gray Luvisols during 2010 significantly ($P < 0.05$; Table 2.2) stimulated CO_2 emissions from the unfertilized plots throughout the growing season (Figure 2.6). The increased emissions following tillage reversal started by the 3rd week after tillage and lasted up until 13th week before it decreased at the end of the growing season (Figure 2.6). Total growing season CO_2 flux estimates in CT plots were higher than the NT plots by 2.453 t ha^{-1} (Table 2.3, 2.4).

Unlike the unfertilized plots, the fertilized plots only showed a marginal increase in CO_2 emissions following tillage reversal throughout the growing season except during 8th week after tillage when there was a two-fold increase in soil CO_2 fluxes in the conventional tillage plots compared to the notill plots (Figure 2.6). Increases in weekly, averaged hourly fluxes after tillage on fertilized plots were not statistically significant ($P=0.45$; Table 2.2) but there was still an estimated whole growing season (June-September) CO_2 emission increase of 1.067 t ha^{-1} in fertilized CT plots compared to fertilized NT plots (Table 2.3, 2.4).

2.3.2 Soil CO_2 emissions due to two consecutive tillage events after tillage reversal

At the onset of our study we expected and accordingly hypothesized that the possible acceleration in CO_2 emissions upon tillage reversal would diminish with consecutive tillage events. Even though the tilled 100N plots on the Black Chernozems had higher weekly average CO_2 fluxes in 2010 compared to 2009 (Figure 2.4b), the difference between total growing season CO_2 flux in tilled and notill plots decreased from 3.565 to 2.433 t ha^{-1} from 2009 to 2010 (Table 2.4). The unfertilized (0 N) Chernozems, however, showed the opposite trend since it yielded higher CO_2 effluxes following the second tillage event in 2010 than those during the first tillage event in 2009 (Figure 2.4a) and consequently the difference between CT and NT whole growing season estimates 1.247 t ha^{-1} in 2009 compared to 2.221 t ha^{-1} in 2010 (Table 2.4a).

These reversing trends between fertilized and unfertilized plots indicate a fertilizer treatment effect on CO_2 emissions as well.

2.3.3 Effects of nitrogen fertilizer on accelerated soil CO_2 emission upon tillage reversal

Nitrogen fertilization had varying impacts on the magnitude of soil CO_2 emissions from both soil types upon tillage reversal under different weather conditions. Although greater CO_2 emissions were observed on the 100 N plots compared to 0 N irrespective of tillage treatments (Figure 2.5a), they were not statistically significant ($P > 0.05$; Table 2.2) for the Chernozems. Even so, an estimated additional 3.110 t ha^{-1} (June-September) CO_2 was emitted over the growing season from fertilized CT plots compared to unfertilized CT plots in 2009 on the Chernozems (Table 2.3 and 2.4 b). Nitrogen fertilization appeared to stimulate CO_2 emissions from the NT plots in the Chernozems also an additional 0.993 t ha^{-1} emitted from 100N NT plots over 0N NT plots.

The second tillage event in 2010 on the Chernozems resulted in an almost identical increase in weekly averaged hourly CO_2 emissions from both fertilized and unfertilized plots in between 3rd and 8th week after the tillage event, but with no difference observed during the other weeks (Figure 2.5b). The second tillage event during 2010 was estimated to cause an increased growing season total of CO_2 emissions by 2.407 and 2.196 t ha^{-1} (CT and NT, respectively) from fertilized plots over unfertilized plots (Table 2.3 and 2.4b) but the weekly averaged hourly fluxes showed no statistically significant differences between the two fertilizer treatments irrespective of tillage treatments ($P > 0.05$; Table 2.2).

The increases of CO_2 emissions from the fertilized NT plots over the unfertilized NT plots represent the fertilizer contributions to increased soil CO_2 emissions. The increased CO_2 emissions from the fertilized CT plots over the unfertilized CT plots represents the contributions of tillage and fertilizer to increase soil CO_2 emissions. Subtracting the difference between fertilized and unfertilized NT plot CO_2 emissions from the difference between fertilized and unfertilized CT plot CO_2 emissions gives an estimate of the increased CO_2 emission due to tillage alone (assuming there is no significant fertilization by tillage interactions). Therefore, in the Chernozems, an additional 2.117 t CO_2 ha^{-1} was emitted due to tillage in 2009, but only 0.211 t CO_2 ha^{-1} in 2010 (Table 2.4b).

The Gray Luvisols, unlike the Chernozems, had a significant increase in weekly averaged hourly CO_2 emissions stimulated by nitrogen fertilization for both CT ($P<0.05$) and NT ($P<0.01$) treatments throughout the growing season (Table 2.2, Figure 2.6) during 2010. Consequently the growing season estimates of increased CO_2 emissions of the 100N plots over the 0N plots were also high i.e., 4.003 and 5.389 t ha^{-1} respectively for CT and NT treatments (Table 2.3 and 2.4b). However, unlike the Chernozems, the apparent nitrogen fertilization effect (100 N) was greater in the NT plots than the CT plots (Figure 2.6) during 2010 and showed a reduction of 1.386 t ha^{-1} CO_2 in the CT compared to NT (Table 2.4). This reduction in additional CO_2 emissions upon tillage reversal does not suggest an emission reduction due to nitrogen fertilization rather it likely happened due to increases in emissions from non-tilled (NT) fertilized plots at higher rates than those from tilled (CT) fertilized plots. The mechanism for this is unclear.

2.3.4 Effects of indigenous soil fertility on accelerated soil CO_2 emission upon tillage reversal

The organic matter-rich unfertilized Chernozems yielded significantly higher ($P<0.01$) (Table 2.2) CO_2 fluxes throughout the 2010 growing season (Figure 2.7a) than those from relatively organic matter poor unfertilized Luvisols irrespective of tillage treatments (Table 2.3 and 2.4). However, nitrogen fertilization (100N) appeared to significantly reduce the flux differences between these two soil types in terms of both hourly fluxes (Figure 2.7b) and growing season estimates (from a range of 4.904 - 5.136 t ha^{-1} for 0 N to a range of 1.942 - 3.308 t ha^{-1} for 100N) for both the tillage treatments (Table 2.2, 2.3 and 2.4d).

Nitrogen fertilization (100N) further stimulated CO_2 emissions upon tillage due to the higher inherent fertility status of the Chernozems on a weekly basis (Figure 2.7) and on a growing season basis (by 1.336 t ha^{-1}; Table 2.4). This, however, was due to reduced flux differences between CT and NT treatments apparently resulting from nitrogen fertilization of the Luvisols rather than increased emissions from fertilizing the Chernozems (Figure 2.7, Table 2.3 and 2.4). The unfertilized (0N) Luvisols, however, yielded a marginally higher (by 0.232 t ha^{-1} on a whole growing season basis) additional increase in CO_2 emissions than those from relatively fertile unfertilized (0N) Chernozems following tillage (Table 2.4d).

2.3.5 Soil carbon sequestration from long term no-till practice and the underlying assumption of “Assurance Factor”

We have done a gross estimation exercise so as to test the idea in formulating Assurance Factor that assumes carbon emissions from tillage of a conservation tillage land are equal to the amounts of carbon sequestered as a result of conversion from conventional to conservation or no tillage. For that purpose we calculated long term soil carbon storage change rates from Nyborg et al. (1999) and Malhi et al. (2011a,b) for 28 years (1979-2007) since the establishments of the long term no-till Chernozems and Luvisols plots for two different N application rates like 0 N and 100 N. The long term estimates showed a trend of additional soil carbon sequestration resultant of the adoption of no-till practice in both soil types under both fertilizer treatments except in unfertilized Luvisols that showed a deterioration of soil carbon storage due to long term no-till (Table 2.5). Gross growing season estimates from our study showed additional carbon emissions enhanced by tillage reversal for both the soil types and the fertilizer applications (Table 2.6). We found a reasonable agreement between the rates of soil carbon emission and sequestration for only unfertilized Chernozems (Table 2.5). For unfertilized Luvisols and fertilized Chernozems and Luvisols we found the emission rates due to tillage reversal were much larger than the sequestration rates as a result of conversion from CT to NT (Table 2.5). Relatively nutrient poor fertilized and unfertilized long term NT Luvisols showed greater emission vs sequestration ratio than organic matter rich Chernozems after tillage reversal (Table 2.5). However, carbon sequestration estimates and carbon loss estimates following tillage were assessed over two very different time periods. Initial rates of carbon loss over the first few tillage events are likely to be greater than the long-term average, just as the initial rates of carbon sequestration following implementation of no-till are likely greater than the long-term average.

2.4 Discussions

Pre-seeding soil CO_2 fluxes ranged from 1 – 3 kg ha^{-1} h^{-1} in our study for different tillage and fertilizer treatments as well as across soil types which is higher than other studies that reported a typical rate of CO_2 emissions from croplands ranging between 0.1 and 2.0 kg ha^{-1} h^{-1} (Raich and Schlesinger 1992; Ellert and Janzen 1999). We found an average 4 – 12 kg ha^{-1} h^{-1} CO_2 fluxes during mid-growing season for different tillage and fertilizer treatments across two different soil types which are slightly lower than the results of 15 – 25 kg ha^{-1} h^{-1} around the middle of the growing season from a European soil for different tillage treatments across sites (Regina and Alakukku 2010). These differences might be attributable to climate and management history differences between sites.

Weekly, average hourly fluxes throughout both growing seasons showed that conventional tillage (CT) stimulated higher soil CO_2 emissions with respect to those from non-tilled (NT) plots for different nitrogen fertilizer applications on two different soil types (Figures 2.4 and 2.6). The magnitude of those increases, however, varied as the growing season progressed and also with different nitrogen treatments and soil types. We found a very small (0 – 0.5 kg ha^{-1} h^{-1}) flush of CO_2 release within the first week of the tillage event for different nitrogen treatments and soil types. Ellert and Janzen (1999) reported a CO_2 flush of ~3.3 kg ha^{-1} h^{-1} within 6 hours of tillage which is higher than what our study indicated. This might be due to the fact that we had to install a larger number of chambers on the field after the tillage event which delayed the first measurement to 48 hours following the tillage event. As a result, the initial tillage induced flush of CO_2 stimulated by physical alteration of soil structure was likely missed. But this does not hinder the importance and purpose of our study since the physical release of CO_2 from recently tilled soils likely has a minimal influence on atmospheric CO_2. This is because most of the immediate CO_2 flux following tillage is from atmospheric CO_2 that was incorporated into the soil during tillage (Ellert and Janzen 1999). On the other hand, the biological release of CO_2 by the stimulation of heterotrophic decomposition upon tillage is considered to be a net contributor to atmospheric CO_2 (Ellert and Janzen 1999). Therefore, soil CO_2 flux studies during the whole growing season are recommended to examine the effects of tillage on soil heterotrophic CO_2 production stimulated by tillage-induced changes in soil architecture and environment (Ellert and Janzen 1999) which strengthens the importance of our methodology. Moreover, Regina and Alakukku (2010) did not find any significant fresh tillage induced CO_2 flush from a European soil.

Instead of a tillage-induced initial CO_2 flush our results indicated a trend of increased soil CO_2 emissions during the middle of the growing season stimulated by tillage for different nitrogen applications. This may be due to facilitated soil aeration and nutrient status through mixing of residues which enhanced microbial activity in the rhizosphere and bulk soil. Repeated measures split-plot statistical analyses, however, showed no significant tillage induced increase in CO_2 emissions on a weekly basis throughout the growing season

(Table 2.2) except for the unfertilized (0N) Luvisolic plots. The lack of statistically significant difference between hourly CO_2 fluxes from different tillage treatments were mainly due to inter-replicate variability being higher than inter-treatment variability as apparent by the larger standard error bars (Figures 2.4-2.7). Despite subtle differences in hourly fluxes an increased 1.067 – 3.565 t ha^{-1} growing season $^{-1}$ of tillage induced-increased CO_2 emissions were estimated (Table 2.4). This can be corroborated by the decrease in light fraction organic matter (LFOM) in long-term (>20 years) conventional tillage treatments, which reflects a balance between crop residues input and their decomposition and persistence. The LFOM is readily degradable and hence is more sensitive to management practices (Malhi et al. 2011a).

Profile distributions of soil organic matter accumulation in different studies showed a higher accumulation of soil organic matter at the soil surface and a gradual decrease in carbon accumulation with depth in long term no till plots (Machado et al. 2003; Malhi et al. 2011a) due to the absence of soil mixing by tillage. This information gave rise to our first hypothesis of a substantial CO_2 flush after the tillage reversal on long term plots under no-till management stimulated by a disturbance of potentially higher top soil carbon pool accumulated over the years which will gradually decrease with consecutive tillage events. Our results, however, did not confirm a substantial CO_2 flush immediately after the inaugural tillage events during 2009 on the Chernozems. This might be due to the fact that 2009 had a drier growing season without any significant rainfall until the end of June (6th week after tillage) (Figure 2.8). Following significant rainfall, differences in CO_2 emissions between the tilled and notill subplots became more apparent. In the wetter spring of 2010, we found an increase in tillage induced CO_2 flush during the second tillage event from 0 N plots which might be attributable to favorable soil moisture status facilitated by higher rainfall in 2010 while soil temperature of the two growing seasons were almost identical (Table 2.3, Figures 2.8, 2.10). In order to reconcile the fact we performed linear correlations of hourly CO_2 fluxes vs precipitation and curvilinear correlations of the same vs soil temperatures for both of the years, tillage and nitrogen treatments. Surprisingly we found no significant correlations between CO_2 fluxes and precipitation whereas there were strong exponential growth responses of fluxes to changes in soil temperatures (Figures 2.11, 2.12). This suggests that the seasonal changes in soil moisture content had little impact on soil CO_2 emissions and the interannual variability of CO_2 fluxes were predominantly governed by the interannual variations in precipitation and hence soil moisture between 2009 and 2010. Instead of directly affecting CO_2 emissions, soil moisture variations influenced temperature responses of microbial activity since we found a stronger temperature dependence of fluxes in wetter soils during 2010 with respect to those from relatively drier soils during 2009 (Figures 2.11, 2.12). The idea was further corroborated by a similar trend of temperature dependence of soil CO_2 emissions that was found in Luvisolic soils irrespective of tillage and nitrogen treatments during 2010 when the soil water content was well above field capacity throughout the growing season and hence seasonal variations in CO_2 fluxes were less sensitive to changes in soil water content (Figures 2.9, 2.13).

The magnitudes and directions of tillage-induced changes of soil CO_2 emissions over the growing seasons were, however, found to vary widely with nitrogen applications, weather conditions and soil types. In fact, we found greater statistically significant differences in soil CO_2 emissions when we took nitrogen applications, weather conditions and soil types into consideration rather than considering the tillage treatments alone (Table 2.2). This provided us with additional opportunities to have greater insights into the processes affected by tillage reversal on a long term non-tilled plot. Eventually we ended up having the questions of how different nitrogen fertilizer applications, soil types and weather conditions actually did affect the magnitudes and directions of tillage induced CO_2 emissions. Moreover, all of our experimental plots have been managed under residue retention practices which have an additional role in soil carbon sequestration. Since all these factors have a very much additive effect on soil carbon sequestration we've tried to explain their interactive effects on the magnitudes of soil CO_2 emissions as we progress hereafter.

Tillage reversal after ~30 years on an unfertilized (0 N) Chernozems during 2009 yielded higher soil CO_2 emissions (Table 2.4a; Figure 2.4a) compared to the notill plots which might be attributed to the mixing of surface residue in tilled soils and increased soil aeration which facilitates mineralization, root respiration, and root exudation (Malhi et al. 2011a). Nitrogen-fertilized (100 N) plots, however, showed a higher soil CO_2 flush than that from 0 N plots (Table 2.4b; Figure 2.4b) since the 100 N plots might have produced higher above and below ground biomass over the years which accumulated and was available for microbial decomposition following tillage reversal (Malhi et al. 2011a). Moreover, increased soil temperature is a result of thick surface residue removal through mixing after tillage reversal (Havlin et al. 1999) and might have an additive effect on facilitating microbial decomposition on 100 N Chernozems plots. The additive effect of nitrogen applications on tillage-induced CO_2 emissions drastically reduced following the second tillage event during 2010 on the Chernozems (Table 2.4b; Figure 2.4) and that might be attributed to the absence of thick surface residue layer which created the difference after the first tillage reversal.

The inaugural tillage event after ~31 years of notill in 2010 on an unfertilized (0N) Luvisols stimulated higher CO_2 emissions compared to that from Chernozems (Table 2.4a; Figure 2.6). Tillage might have facilitated residue mixing and aeration within the soil in the Luvisolic soils, which are generally known to be very compact, and hence had an additive effect on above mentioned nutrient status induced CO_2 emissions. Reduction of soil compactness through tillage may have also facilitated root growth and hence root exudation and microbial activity in the rhizosphere. Our findings and explanations are further corroborated by a long term study on the same soil where an increase in soil organic matter is reported under no-till (NT) treatment (Malhi et al. 2011a,b).

Conventional tillage (CT) increases oxidation of soil organic matter, mixing of surface residues and hence increases microbial contact to the substrates thereby improves microbial growth and decomposition environment (Malhi et al. 2011a), especially in soils with relatively low indigenous fertility status (Thomson et al. 2006). This might cause an additional CO_2 flush after tillage on unfertilized (0N) relatively nutrient poor Luvisolic soils with respect to that from unfertilized (0 N) Chernozems (Table 2.4d; Figure 2.7a) during 2010. Nitrogen application (100N), however, reversed the situation (Table 2.4d; Figure 2.7b) since it diminished the nutrient status difference between tilled and non-tilled soils due to residue mixing by providing the non-tilled generally nutrient poor Luvisolic soils with an alternative source of nutrient.

While testing the underlying assumption of Assurance Factor to account for average risks of tillage reversal on greenhouse gas emissions, our exercise could not confirm that the sequestration rates of soil carbon due to the adoption of long term NT practice equates the carbon emission rates after tillage reversal on a long term NT soil. Our findings showed that the rates of CO_2 emissions after tillage reversal were higher than the rates of sequestration resultant from the adoption of long term NT. Rapid decomposition of light fraction soil organic matter accumulated in the top soils over the years of long term NT might have produced a higher rate of CO_2 emission after tillage reversal on a long term NT soil than the rate of sequestration after the adoption of long term NT (Havlin et al. 1999). The ratio of rates of CO_2 emissions after tillage reversal to the rates of sequestration after the adoption of long term NT are higher for Gray Luvisols with relatively poor indigenous fertility than nutrient rich Black Chernozems. This trend is consistent with other findings where they reported greater impacts of adoption of long term NT management on soil carbon sequestration of relatively low indigenous fertility soils than highly fertile soils (Malhi et al. 2011a,b).

2.5 Conclusions

Inaugural tillage events on long term notill fertilized (100 N) and unfertilized (0 N) Chernozems and Luvisols after ~30 years caused considerably higher CO_2 emissions. Our study was unable to report a big initial flush of CO_2 emissions immediately after the tillage reversal as we proposed in our initial hypothesis. In fact, nitrogen fertilization, wetter soil and indigenous soil fertility had more impact on soil CO_2 emissions than tillage as single factors. Considerable augmentation of tillage induced additional CO_2 emissions was found by nitrogen fertilization (100 N) and wetter soil physical environment. Unfertilized Luvisolic soils with relatively less soil organic matter enhanced tillage induced additional CO_2 emissions than unfertilized Chernozems with higher soil organic matter content in our short term flux study. Comparative estimation of emission and sequestration rates did not confirm the underlying idea of Assurance Factor that assumes the rate of soil carbon emission after tillage reversal on a long term notill soil equates the rate of soil carbon sequestration after the conversion of a conventionally tilled soil to no till soil. Instead we found rates of CO_2 emissions after tillage reversal on a long term NT soil were higher than that of sequestration after the adoption of long term NT. Moreover, emission vs sequestration rates are very different for different soil types with generally nutrient poor soils having a higher average risks of additional CO_2 emissions after tillage reversal. Nitrogen fertilized soils generally showed higher CO_2 emissions to sequestration ratio after tillage reversal for both the type of soils under study. The higher CO_2 emission rates in the second consecutive tillage event after tillage reversal than the inaugural tillage event on Black Chernozems indicated that this trend of the rates of CO_2 emissions after tillage reversal being higher than the rates of sequestration after the adoption of long term NT was not a transient effect. Though we presented a gross estimation exercise and included only growing season fluxes into account, our study for the first time indicates the importance of reconsidering the underlying assumption of Assurance Factor in existing quantification protocol of tillage management system of Government of Alberta as well as provides a general structure for further in depth studies in this sector.

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Table 2.1 : Descriptive characteristics (mean ± standard error) of surface soils (0-15 cm) of two study sites [source: Plante et al. 2010]

	Breton	Ellerslie
Location	Lat. 53°5°22″ N, Long 114°26°33″ W	Lat53°25°12″ N, Long 113°32°50″ W
MAT	2.1°C	1.7°C
MAP	547 mm	452 mm
Soil Classification	Orthic Gray Luvisol	Orthic Black Chernozem
Clay content	220 g clay kg^{-1} soil	360 g clay kg^{-1} soil
Total Organic Carbon (g C kg^{-1} soil)	9±1	51±1
Total Nitrogen (g N kg^{-1} soil)	0.9±0.03	4.5±0.09
C:N ratio	9.6±0.5	11.4±0.2

Table 2.2: Split plot repeated measures statistics of weekly averaged soil CO_2 effluxes (kg CO_2 ha^{-1} h^{-1}) from the Black Chernozemic and Gray Luvisolic soils under different tillage treatments, nitrogen fertilizer treatments and weather conditions

Conventional tillage (CT) vs No tillage (NT)					
Soil types	N-fertilizer treatment	Year	*n*	SE	P value
Chernozem	0 N	2009	48	0.68388	0.5226
	100 N		48	0.92592	0.2040
	0 N	2010	56	0.30312	0.0722
	100 N		56	0.58056	0.1701
Luvisol	0 N	2010	56	0.27048	0.0150*
	100 N		56	0.45780	0.4496
Unfertilized (0 N) vs N-fertilized (100 N)					
Soil types	Tillage treatment	Year	*n*	SE	P value
Chernozem	NT	2009	48	0.76254	0.6560
	CT		48	0.49686	0.0894
	NT	2010	56	0.28530	0.0644
	CT		56	0.29994	0.0583
Luvisol	NT	2010	56	0.40152	0.0025**
	CT		56	0.40788	0.0355*
2009 (total annual precipitation 171 mm) vs 2010 (total annual precipitation 558 mm)					
Soil type	N-fertilizer treatment	Tillage treatment	*n*	SE	P value
Chernozem	0 N	NT	48	0.32622	0.0181*
	100 N		48	0.42360	0.0123*
	0 N	CT	48	0.70866	0.0202*
	100 N		48	0.70440	0.0257*
Chernozems (higher SOM) vs Luvisols (lower SOM)					
Year	N-fertilizer treatment	Tillage treatment	*n*	SE	P value
2010	0 N	NT	56	0.22344	0.0034**
	100 N		56	0.62292	0.2902
	0 N	CT	56	0.19908	0.0027**
	100 N		56	0.53166	0.0600

*Significant at $p < 0.05$ **Significant at $p < 0.01$

Table 2.3: Estimated growing season (June-September) soil CO_2 effluxes from Black Chernozemic and Gray Luvisolic soils under different tillage treatments, nitrogen fertilizer treatments and weather conditions

Year	Growing season precipitation (mm)	Average growing season soil temperature at 5 cm depth (°C)	Soil type	Tillage treatment	N-fertilizer treatment	Growing season CO_2 efflux (t ha^{-1}) *
2009	171	15.11	Chernozem	CT	0 N	11.12
					100 N	14.43
				NT	0 N	9.88
					100 N	10.87
2010	558	14.10		CT	0 N	14.20
					100 N	16.61
				NT	0 N	11.98
					100 N	14.17
2010	378	16.12	Luvisol	CT	0 N	9.30
					100 N	13.30
				NT	0 N	6.84
					100 N	12.23

**Growing season CO_2 flux (t ha^{-1}) = Average measured CO_2 flux throughout the growing season (kg ha^{-1} h^{-1})× number of hours within the growing season (June – September)/1000*

Table 2.4: Estimated changes in growing season (June-September) soil CO_2 effluxes from Black Chernozemic and Gray Luvisolic soils due to different tillage treatments, nitrogen fertilizer treatments and weather conditions

(a) Change due to tillage (+/-)

Soil type	Year	N-fertilizer treatment	Change in growing season soil CO_2 efflux (t ha^{-1}) (CT – NT)
Chernozem	2009	0 N	1.247
		100 N	3.565
	2010	0 N	2.221
		100 N	2.433
Luvisol	2010	0 N	2.453
		100 N	1.067

(b) Change due to N fertilization (+/-)

Soil type	Year	Tillage treatment	Change in growing season soil CO_2 efflux (t ha^{-1}) (100 N – 0 N)	Additional growing season soil CO_2 efflux upon tillage due to N-fertilization (t ha^{-1}) (CT – NT)
Chernozem	2009	CT	3.110	2.117
		NT	0.993	
	2010	CT	2.407	0.211
		NT	2.196	
Luvisol	2010	CT	4.003	-1.386
		NT	5.389	

(c) Change due to wetter weather condition in 2010 with respect to that in 2009 (+/-)

Soil type	Tillage treatment	N-fertilizer treatment	Change in growing season soil CO_2 efflux (t ha^{-1}) (2010 – 2009)	Additional growing season soil CO_2 efflux following tillage due to wet weather condition in 2010 (t ha^{-1}) (CT – NT)
Chernozem	CT	0 N	3.078	0.975 (for 0 N plots)
		100 N	2.174	
	NT	0 N	2.103	-1.132 (for 100 N plots)
		100 N	3.306	

(d) Change due to higher inherent fertility status of Chernozemic soils than that of Luvisol (+/-)

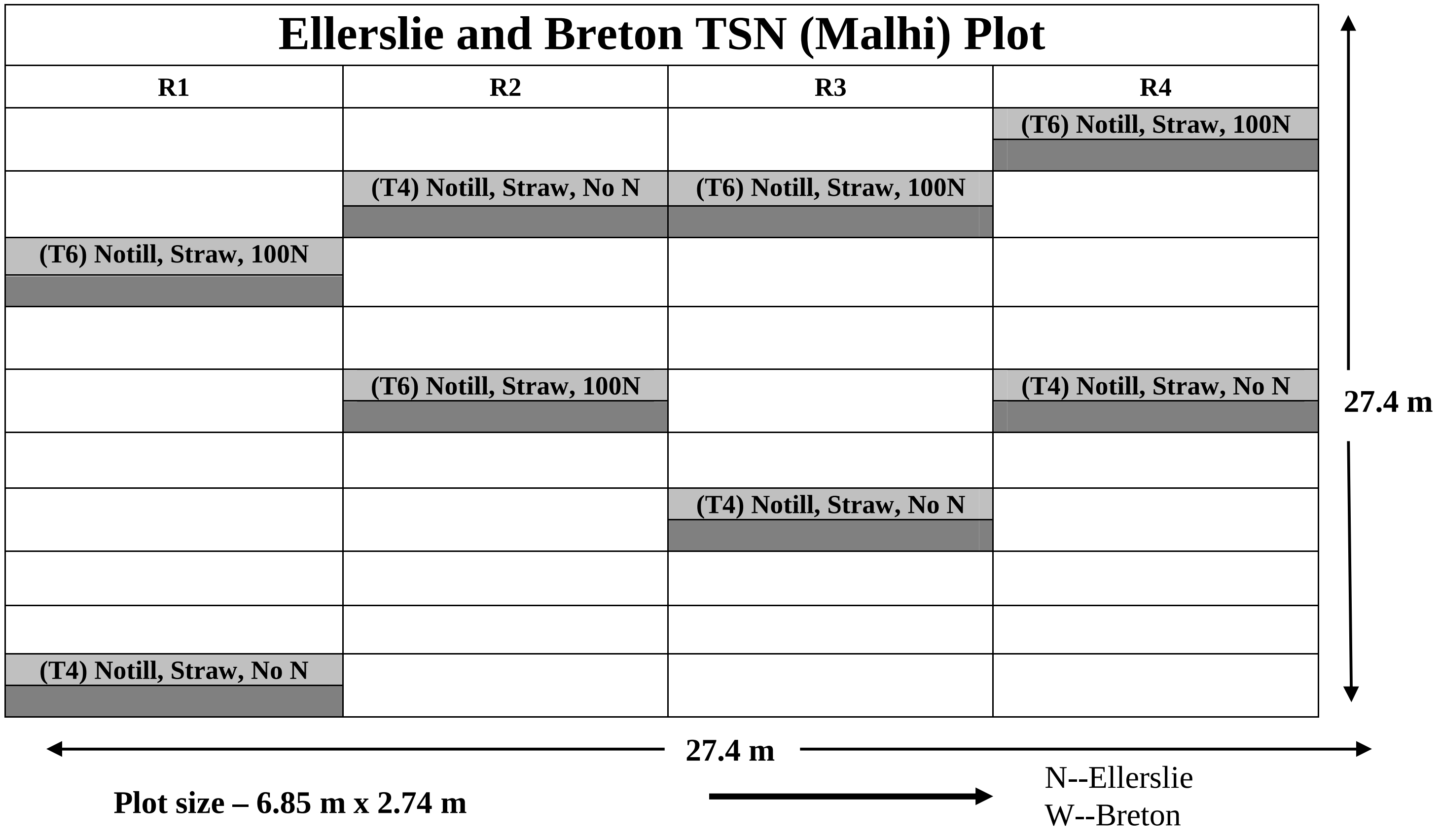
Year	Tillage treatment	N-fertilizer treatment	Change in growing season soil CO_2 efflux (t ha^{-1}) (Chernozem – Luvisol)	Additional growing season soil CO_2 efflux following tillage due to higher indigenous fertility of Chernozem (t ha^{-1}) (CT – NT)
2010	CT	0 N	4.904	-0.232 (for 0 N plots)
		100 N	3.308	
	NT	0 N	5.136	1.336 (for 100 N plots)
		100 N	1.942	

Table 2.5: Estimated soil carbon sequestration rates (1979-2007) due to adoption of long term no-till practice and emission rates (2009/2010) after tillage reversal on Black Chernozemic and Gray Luvisolic soils

Soil type	N fertilizer treatment	Carbon emission rate after tillage reversal (t C ha^{-1} growing season^{-1})	Carbon sequestration rate due to the adoption of long term no-till (t C ha^{-1}yr^{-1})♣
Chernozem	0 N	0.473*	0.411
	100 N	0.818*	0.462
Luvisol	0 N	0.669	- 0.125
	100 N	0.291	0.125

* *average of 2009 and 2010*

♣ Calculated from values using as described in Nyborg et al. (1995); Malhi et al. (2011a,b)



Ellerslie and Breton TSN (Malhi) Plot

R1	R2	R3	R4
			(T6) Notill, Straw, 100N
	(T4) Notill, Straw, No N	(T6) Notill, Straw, 100N	
(T6) Notill, Straw, 100N			
	(T6) Notill, Straw, 100N		(T4) Notill, Straw, No N
		(T4) Notill, Straw, No N	
(T4) Notill, Straw, No N			

Plot size – 6.85 m x 2.74 m

Figure 2.1: Experimental setup of TSN (Malhi) Plots at Ellerslie and Breton. The plots highlighted in gray were the subjects of the investigation. The dark gray side were tilled.

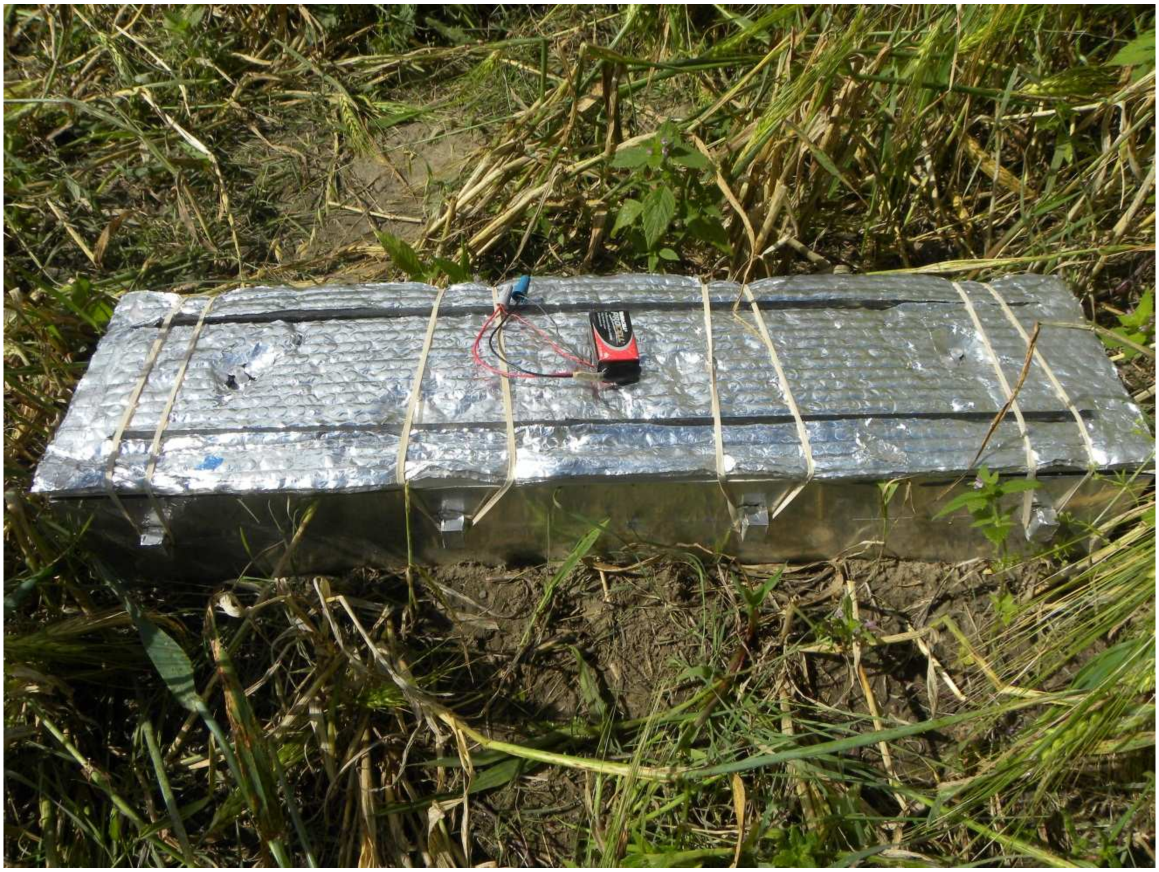


Figure 2.2: An active chamber in situ

Figure 2.3: Photoacoustic multi gas analyzer connected to the active chamber through tubing

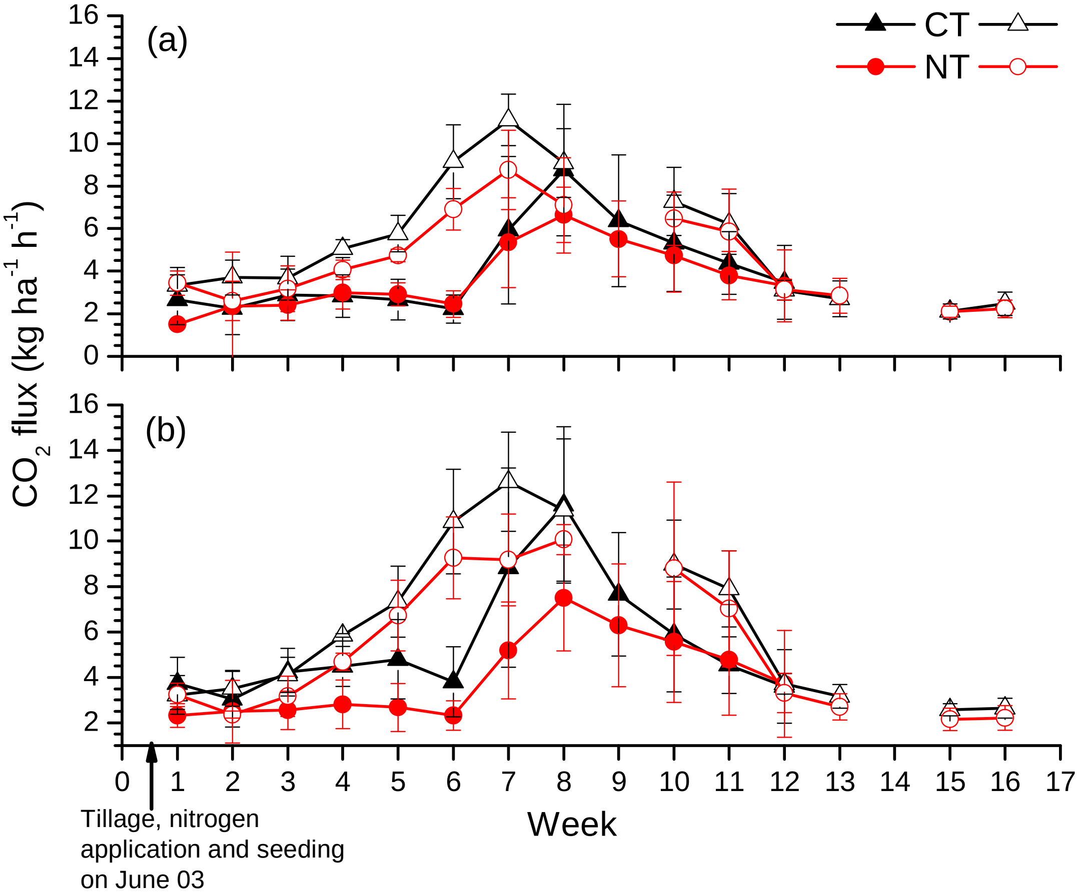


Figure 2.4: CO_2 fluxes from non-tilled (NT) and conventionally tilled (CT) (a) unfertilized and (b) fertilized Black Chernozem soils during 2009 (closed symbols) and 2010 (open symbols). Each dot represents an average of four replicates and bars represent ± standard errors

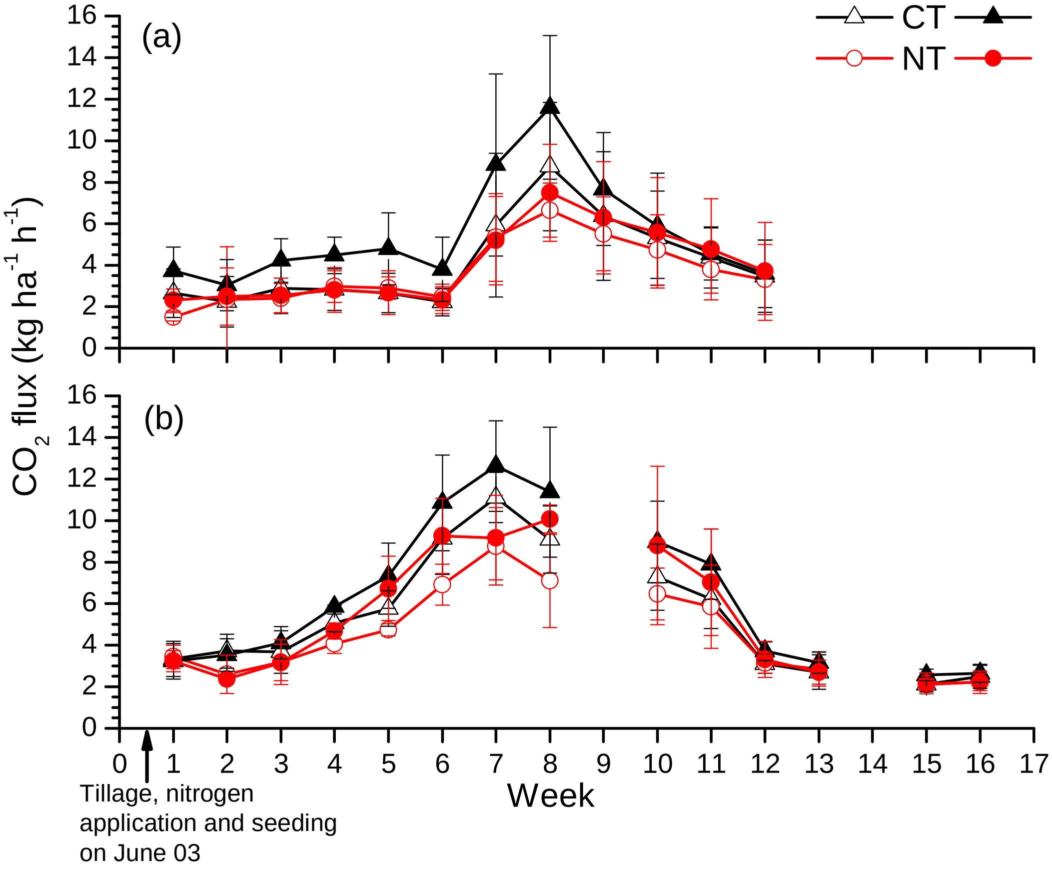
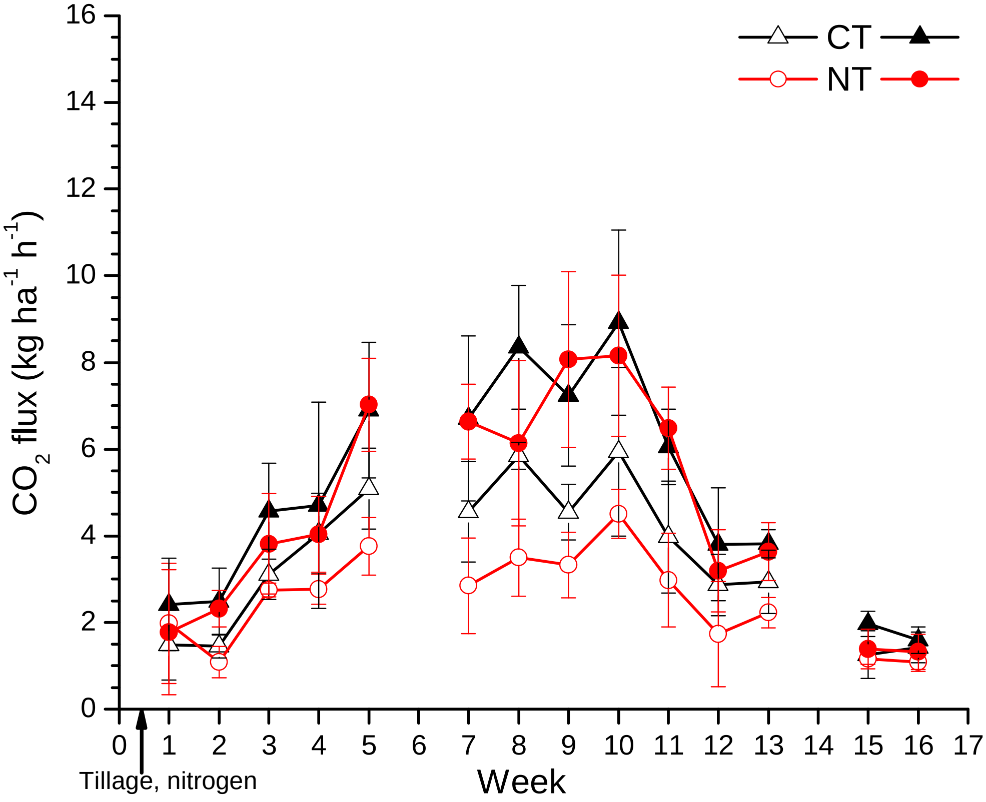
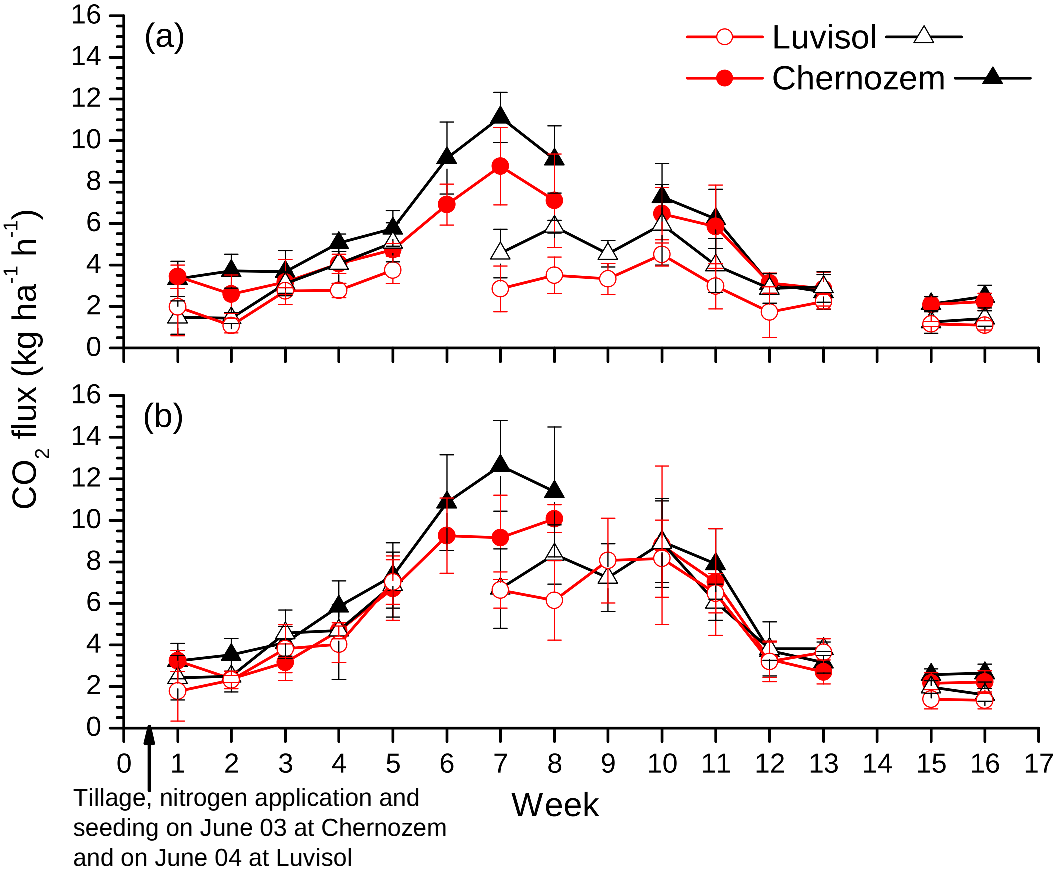


Figure 2.5: CO_2 fluxes from conventionally tilled (CT) and non-tilled (NT) regimes of unfertilized (open symbols) and fertilized plots (closed symbols) on Black Chernozem soils during (a) 2009 and (b) 2010. Each dot represents an average of four replicates and bar represent ± standard errors



Tillage, nitrogen application and seeding on June 04

Figure 2.6: CO_2 fluxes from conventionally tilled (CT) and non-tilled (NT) regimes of unfertilized (open symbols) and fertilized plots (closed symbols) on Gray Luvisolic soils during 2010. Each dot represents an average of four replicates and bars represent ± standard errors



Tillage, nitrogen application and seeding on June 03 at Chernozem and on June 04 at Luvisol

Figure 2.7: CO$_2$ fluxes from non-tilled (circles) and conventionally tilled (triangles) (a) unfertilized and (b) fertilized Gray Luvisolic and Black Chernozemic soils during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

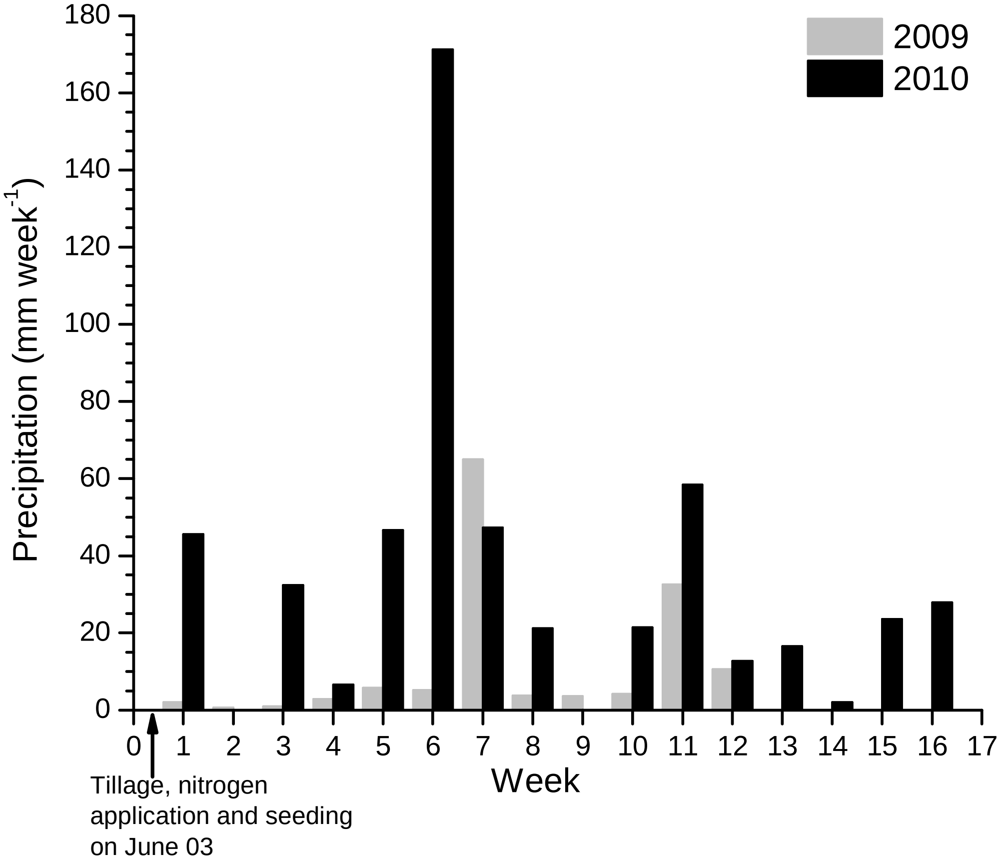


Figure 2.8: Weekly precipitation in Black Chernozem soils in 2009 and in 2010

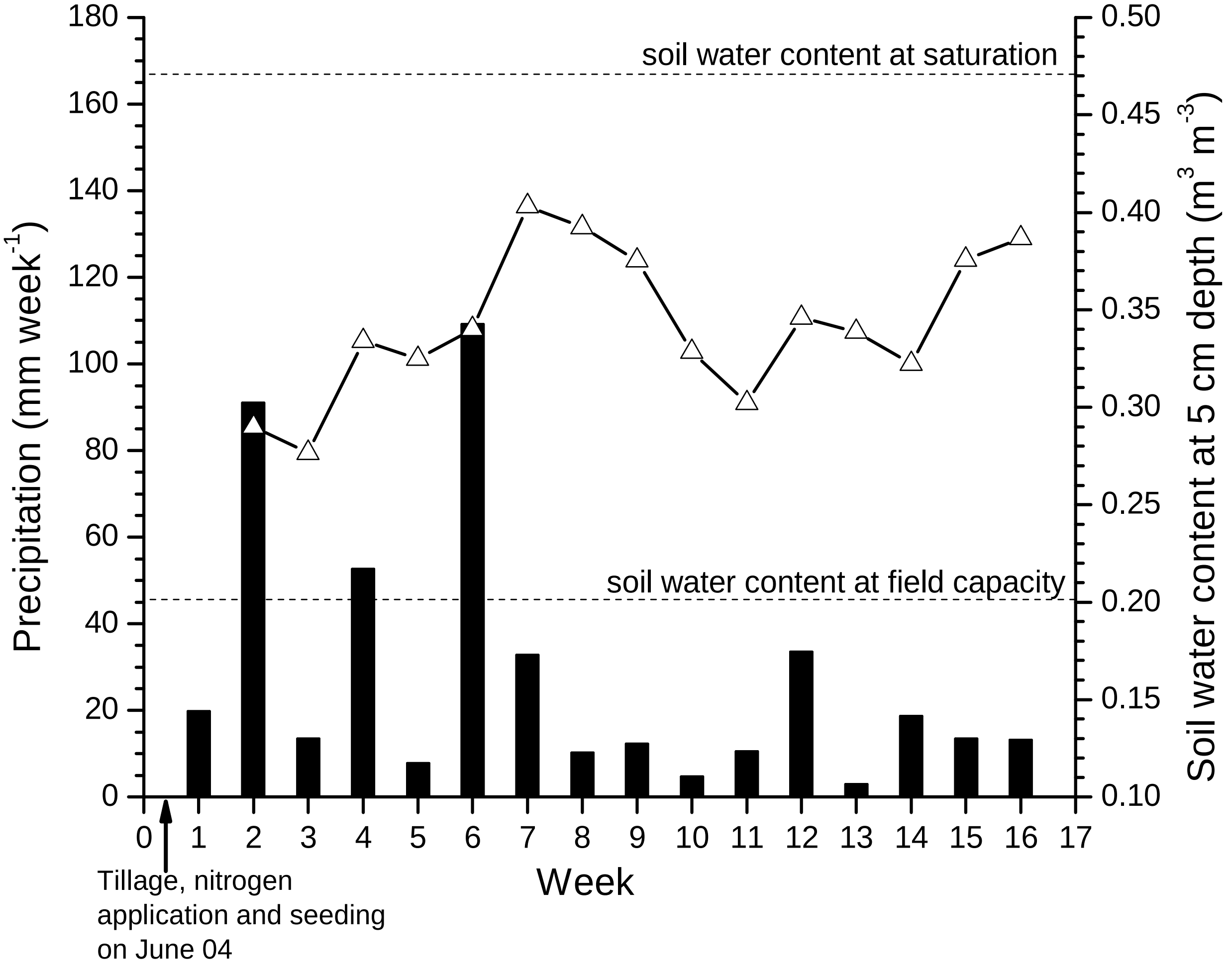


Figure 2.9: Weekly precipitation (left y-axis) and daily soil water content (SWC) at 5 cm depth (right y-axis) in Gray Luvisolic soils in 2010

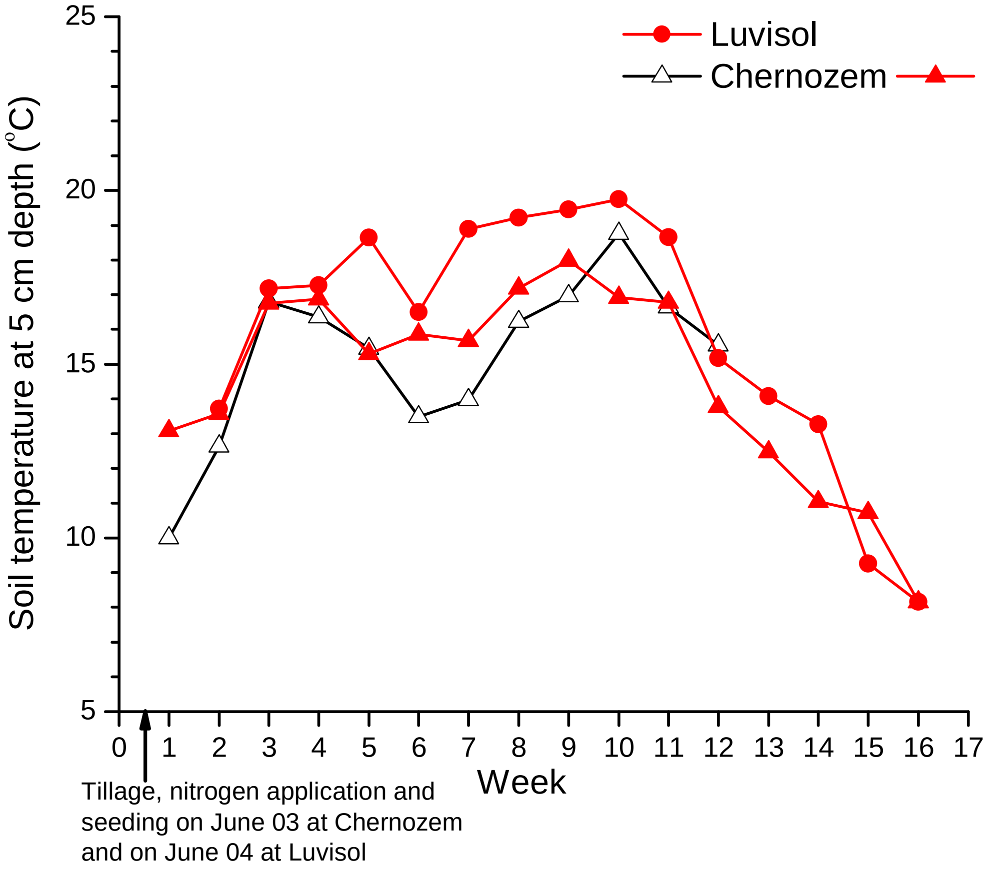


Figure 2.10: Daily soil temperature at Black Chernozems during 2009 (open triangles) and 2010 (closed triangles) and Gray Luvisolic soils in 2010 at 5 cm depths

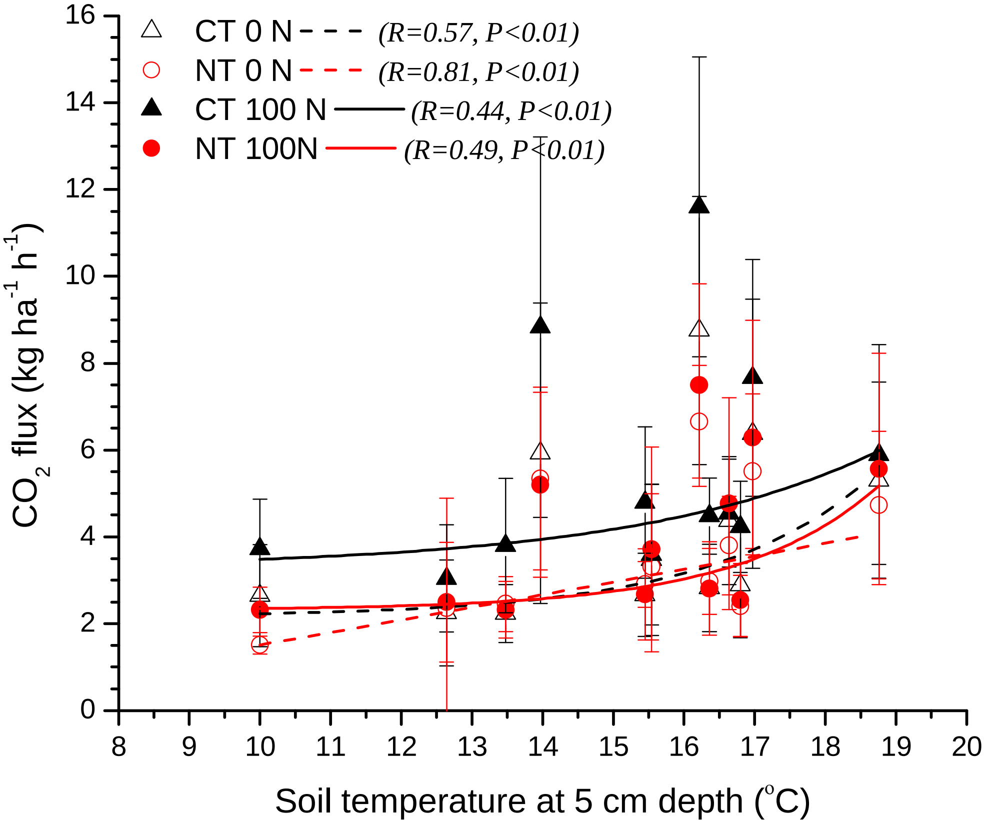


Figure 2.11: Relationships between weekly averaged hourly soil CO_2 fluxes and daily soil temperature at 5 cm depth over Black Chernozems during 2009. Each dot represents an average of four replicates and bars represent ± standard errors

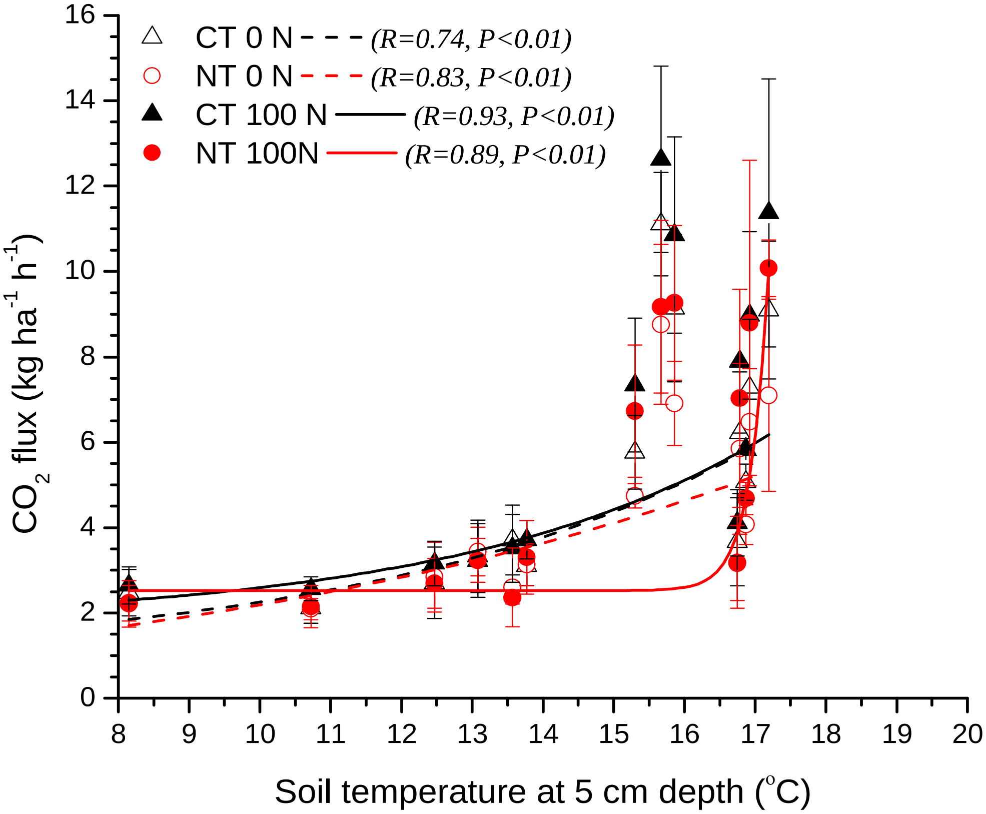


Figure 2.12: Relationships between weekly averaged hourly soil CO_2 fluxes and daily soil temperature at 5 cm depth over Black Chernozems during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

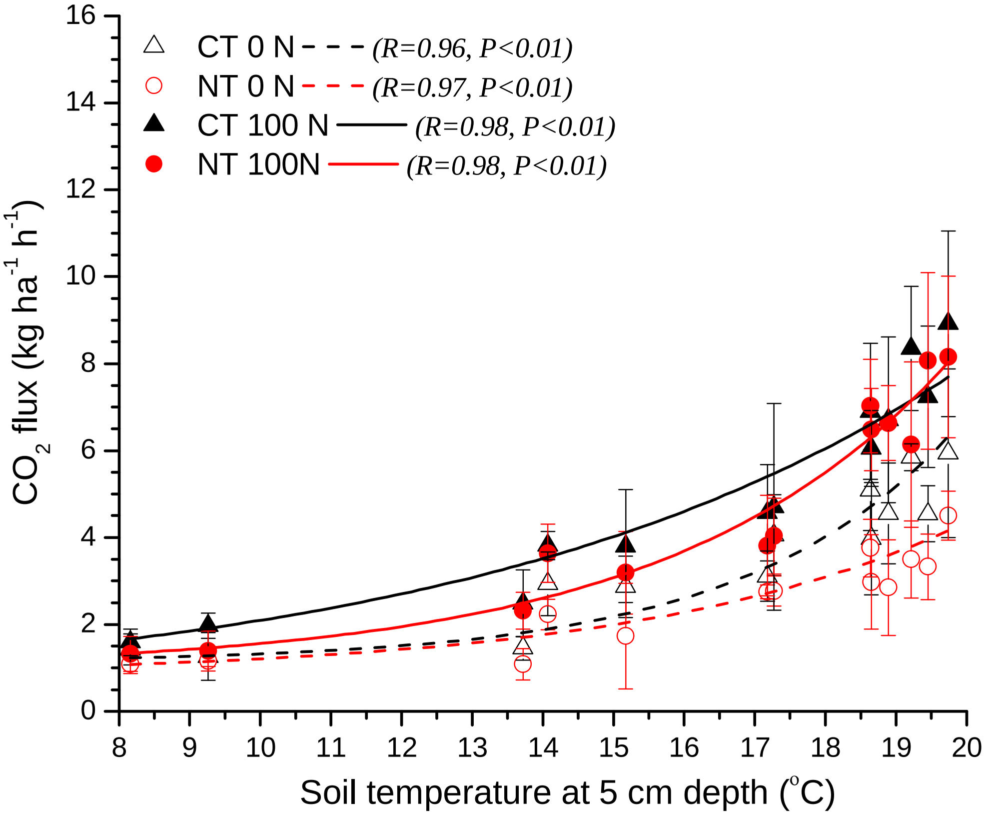


Figure 2.13: Relationships between weekly averaged hourly soil CO_2 fluxes and daily soil temperature at 5 cm depth over Gray Luvisols during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

Chapter 3

3 N_2O emissions from a Black Chernozem and a Gray Luvisol under long term no till management after tillage reversal

3.1 Introduction

Nitrous oxide is an important greenhouse gas because of its contribution to radiative forcing and its detrimental effects on the ozone layer (Boeckx et al. 2011). Though atmospheric concentration of N_2O is much less than that of CO_2 it has a greenhouse gas potential of about 310 times CO_2 (Omonode et al. 2011). Unlike CO_2, N_2O does not have a prominent atmospheric sink other than deposition which makes it more difficult to mitigate once in the atmosphere. Agriculture is a big player in atmospheric N_2O emission dynamics since agricultural soils were estimated to constitute about 38% of the total global anthropogenic N_2O emissions (IPCC 2007). N_2O from agricultural soils is primarily a product of aerobic nitrifier denitrification and anaerobic microbial denitrification as well as chemical denitrification (Venterea and Rolston 2000; Müller et al. 2006; Venterea 2007). Agricultural practices such as tillage, mineral N fertilizer applications and crop residue management, either individually or by interactions, may have a substantial impact on denitrification in different magnitudes and directions (Boeckx et al. 2011). Soil characteristics including texture, degree of compaction and water filled porosity influence the magnitude and variability of denitrification mediated N_2O emissions (MacKenzie et al. 1997; Baggs et al. 2003).

Theoretically conventional tillage (CT) can improve soil aeration that may lead to suppression of N_2O emissions by reducing anaerobicity required for denitrifiers. On the other hand, aerobic nitrifying bacteria can also utilize NO_2^- as an alternate electron acceptor and this aerobic 'nitrifier denitrification' proceeds readily under improved soil O_2 levels as facilitated by CT (Remde and Conrad 1990). Moreover, increased aerobic decomposition of soil organic matter through nitrification enhanced by tillage adds to the NO_3^- in soil solutions, the substrate for denitrification, thereby facilitating N_2O emissions (Davidson et al. 2000). Some experiments noted reduced N_2O emissions under conventional tillage (Ball et al. 1999; Skiba et al. 2002; Vinten et al. 2002) but others reported reduced N_2O emissions under no-tillage (Lemke et al. 1999; Chatskikh and Olesen 2007; Gregorich et al. 2007). Some studies showed no effect of tillage on N_2O emissions (Grandy et al. 2006; Boeckx et al. 2011). Such contrasting findings of how tillage affects denitrification makes it difficult to attribute tillage as a sole factor of either increased or decreased N_2O emissions from agricultural soils and suggests that the effects are either site- or ecoregion-specific.

Conservation tillage or no-tillage has been proposed as a means of increased carbon sequestration in agricultural soils which is gaining popularity within Western Canadian farming communities (Six et al. 2004). Reduced CO_2 emissions or increased soil carbon sequestration achieved by no-tillage, however, might be offset by an increase in N_2O emission (Li et al. 2005; Xu et al. 2008) from the same. This is not an obvious fact though since some studies revealed that the increase in N_2O emissions as a result of adoption of no-till might be minimized in the long term (Gregorich et al. 2008; Rochette et al. 2008). The government of Alberta has recently created a Conservation Tillage Protocol for Greenhouse Gas Offsets which allows large emitters of greenhouse gases to offset their emissions by purchasing offset credits for sequestering carbon (Goddard et al. 2009). With this protocol, there is an Assurance Factor to account for "one-off" tillage operations that a farmer might execute to control weeds or because of crop failure, etc. This Assurance Factor assumes that the rate of carbon loss from tillage of a conservation tillage soil is the same as the sequestration rate following conversion from conventional to conservation tillage. However, existing tillage management quantification protocol does not take any potential risks or gains of additional N_2O emissions after tillage reversal on long term NT soils. Hence, studying the impact of tillage reversal on N_2O emissions from a long term no-till plot could provide us with an excellent opportunity to examine whether there are any potential risks of additional N_2O emissions or any potential gains in N_2O emission reduction after tillage reversal on long term NT soils.

Tillage often changes soil moisture regimes and soil aeration that largely govern the production of NO_3^- through nitrification in soils and subsequent losses in the form of N_2O through denitrification. Saturated conditions generally facilitate flushes of N_2O losses through rapid denitrification in warm and biologically active arable soils. N_2O loss can however continue on a longer term basis in seemingly well aerated soils where biological oxygen demand in microsites within soil aggregates may still exceed the supply (Havlin et al. 1999). Based on this assumption, adoption of no-till practice in warmer, humid regions has a higher potential of N_2O losses through denitrification over tilled, arable land (Grant et al. 2004) and it might not have the similar effect under drier climates as we have in Western Canada. On the contrary, higher long term soil carbon sequestration in no-tilled plots may suggest lower degrees of microbiological activity that supress soil NO_3^- production through nitrification which eventually hinders denitrification (Janzen et al. 1998). Field studies examining the net impact of tillage on soil N_2O emissions from long term no-tilled plots would, however, have been more insightful in this regard.

Nitrogen fertilizer application and crop residue management may also affect soil N_2O emissions (Bavin et al. 2009; Synder et al. 2009). Increased N_2O emissions have been observed with the application of N-fertilizer, assuming conditions are suitable for denitrification (Synder et al. 2009; van Groenigen et al. 2010; Pelster et al. 2011). In dry Western Canadian soils, plant uptake of mineral N applied is sometimes minimal due to low availability of water, thus leaving more mineral N available for chemical denitrification (Grant et al. 2004). However, mineral N application is positively related with carbon sequestration that is also influenced by tillage and consequent crop residue incorporation and mixing (Pelster et al. 2011). Soil N_2O emission is, therefore, worthy to be studied as a function of multiple controls – tillage, nitrogen fertilizer application, crop residue mixing and soil drainage so as to reveal the governing factors of it.

Our study aims at studying soil N_2O emissions after tillage reversal on two dominant Western Canadian soils like Black Chernozems and Gray Luvisols. These soils differ from each other in terms of soil organic matter content and drainage status and managed under long term (~ 30 years) no-till with crop residue retention practices and different mineral N application rates at Ellerslie and Breton plots of University of Alberta. We hypothesized:

1) No tillage (NT) facilitates higher N_2O emissions than conventionally tillage (CT) for different mineral N application rates across soil types.
2) Mineral N application @ 100 kg ha^{-1} (100 N) stimulates higher N_2O emissions than no nitrogen fertilizer application (0 N) for both CT and NT across soil types.
3) Luvisols with denser subsoil and consequent lower water permeability emit higher N_2O than Chernozems for both unfertilized (0 N) and fertilized (100 N) CT and NT.

3.2 Methodology

Field sites and gas flux measurement methods are identical to those in Section 2.2.

3.3 Results

3.3.1 Effects of tillage reversal on soil N_2O emissions

Tillage reversal after ~ 30 years had been found to cause consistently higher soil N_2O emissions throughout the growing season from the unfertilized (0 N) Black Chernozems (Figure 3.1). Split-plot repeated measures analyses, however, could not detect a statistically significant difference between weekly average hourly fluxes from unfertilized (0 N) CT and NT plots throughout the growing season except those in 7th week after tillage (Figure 3.1, Table 3.1).

Despite no statistically significant flux differences, the growing season estimates suggested that CT was responsible to emit an additional 1.792 kg of N_2O ha^{-1} (1.14 kg N ha^{-1}) from the unfertilized Chernozems that appeared to be non-negligible (Tables 3.2 and 3.3). Like the unfertilized (0 N) Chernozems, the fertilized Chernozems (100 N) showed a similar trend of slightly higher N_2O emissions from NT than CT plots, but this trend reversed after the second week after the tillage event (Figure 3.1). Again, there was no statistical significance between fertilized CT and NT Chernozems N_2O fluxes except during 7th week (Table 3.1). The growing season estimates of N_2O emissions, however, showed an additional N_2O emission of 2.514 kg N_2O ha^{-1} (1.59 kg N ha^{-1}) from the fertilized (100 N) Chernozems in response to CT (Tables 3.2 and 3.3). Overall soil N_2O fluxes were, therefore, found to be stimulated by the tillage reversal in both fertilized and unfertilized Chernozems.

Tillage reversal after ~ 31 years on the unfertilized (0 N) Gray Luvisols stimulated significantly ($P < 0.01$) higher N_2O emissions throughout the growing season (Figure 3.2, Table 3.1). Consequently an additional growing season emission of 2.658 kg N_2O ha^{-1} (1.69 kg N ha^{-1}) was attributed to the CT treatment (Tables 3.2 and 3.3). The fertilized (100 N) Luvisols showed more of an inconsistent response to tillage reversal with statistically non-significant higher weekly averaged hourly N_2O fluxes in most of the weeks (Figure 3.2, Table 3.1). In some weeks, NT showed higher N_2O emissions than CT. This can be explained by higher intra-treatment differences among replicates that are apparent in large standard error bars of these fluxes (Figure 3.2). Despite the noise in fluxes, growing season estimates in the 0N plots showed additional N_2O emissions of 2.757 kg N_2O ha^{-1} (1.75 kg N ha^{-1}) in response to CT over fertilized Luvisols (Tables 3.2 and 3.3). Our findings, therefore, provide an impression that both fertilized and unfertilized Luvisols showed a higher emission of N_2O in response to tillage reversal.

3.3.2 Effects of nitrogen application on soil N_2O emissions

The 100 kg N ha^{-1} fertilizer treatments on both CT and NT showed higher N_2O emissions than the 0 kg N ha^{-1} treatments (Figure 3.1). Overall differences in weekly averaged hourly fluxes were not statistically significant except those during the middle of the growing season i.e., 8th and 9th week after N fertilization (Table 3.1). An additional 2.361 kg N_2O ha^{-1} (1.50 kg N ha^{-1}) was estimated to be emitted in response to N fertilizer application over NT Chernozems (Tables 3.2 and 3.3). N fertilizer application, however, was found to significantly ($P < 0.05$) stimulate N_2O emissions from tilled (CT) Chernozems throughout the growing season (Figure 3.1, Table 3.1). An additional growing season N_2O emission of 3.083 kg N_2O ha^{-1} (1.96 kg N ha^{-1}) was estimated as a result of N fertilizer application (100 N) over CT Chernozems (Tables 3.2 and 3.3).

Weekly averaged hourly fluxes showed significantly higher ($P < 0.05$) N_2O emissions resulted from N fertilizer application (100 N) over NT Gray Luvisols throughout the growing season (Figure 3.2, Table 3.1). CT Luvisols subplots showed an even higher level of significance ($P < 0.01$) in N_2O emission stimulation by N fertilization (Figure 3.2, Table 3.1). Substantial additional N_2O emissions of 13.785 and 13.884 kg N_2O ha^{-1} (8.8 kg N ha^{-1}) were observed on the fertilized subplots on the NT and CT treatments, respectively (Tables 3.2 and 3.3). Our results thus inferred N application (100 N) as a significant booster of soil N_2O emissions from Gray Luvisols regardless of tillage treatments.

3.3.3 Effects of soil type on soil N_2O emissions

The unfertilized (0 N) organic matter-rich Black Chernozems and relatively organic matter-poor Gray Luvisols with denser subsoil horizon and consequent lower water permeability emitted almost similar amount of N_2O up until 4th week of tillage and N fertilizer application for both the tillage treatments after which the Black Chernozems started to produce more N_2O than the Luvisols (Figure 3.3a). The increased soil N_2O emissions from the unfertilized (0 N) Chernozems was not statistically significant for the NT plots whereas they were significant ($P < 0.05$) in the case of CT plots (Table 3.1). The unfertilized Chernozems was, however, estimated to produce additional N_2O of 3.333 and 4.199 kg ha^{-1} on the growing season basis for CT and NT (Tables 3.2 and 3.3) over the emissions from the Luvisols. Our study overall suggested that unfertilized, organic matter rich Chernozems was likely to emit more N_2O than the unfertilized organic matter poor Luvisols irrespective of tillage.

In the early part of the growing season (from right after the tillage and N application up to 5th week), the fertilized Luvisols showed a flush of N_2O higher than the Chernozems for both CT and NT (Figure 3.3b). These differences were not observed after the 8th week of tillage on both N fertilization treatments (Figure 3.3b). Analyses showed a highly significant difference ($P < 0.01$) between weekly averaged hourly N_2O fluxes throughout the growing season over NT-fertilized

Chernozems vs Luvisols (Table 3.1). CT fertilized Chernozems and Luvisols were, however, not statistically significantly different in terms of weekly averaged hourly N_2O fluxes except during the 3rd and 4th weeks after tillage and N fertilization (Table 3.1). Growing season N_2O estimates revealed substantial emissions from the fertilized Luvisols in comparison to the fertilized Chernozems by the amounts of 7.468 and 7.225 kg N_2O ha^{-1} for CT and NT plots respectively (Tables 3.2 and 3.3). We thereby infer from our findings that organic matter poor fertilized Luvisols might lead to increased N_2O emissions with respect to organic matter rich fertilized Chernozems regardless of tillage.

3.3.4 Interactive effects of tillage reversal, N fertilizer application and soil types on soil N_2O emissions

Interactive statistical analyses of tillage × N fertilizer application, tillage × soil type and tillage × N fertilizer application × soil type showed no significant differences among weekly averaged hourly N_2O fluxes throughout the growing season. We thus found a meagre augmentation of CT stimulated N_2O emissions by 0.722 kg ha^{-1} growing $season^{-1}$ from Chernozems with the addition of 100 N (Table 3.3). The Luvisols showed even lower tillage × N fertilizer interaction as only 0.099 kg ha^{-1} N_2O emission was estimated from the 100 N (Table 3.3). The Luvisols showed a small increase in N_2O emissions by 0.866 kg ha^{-1} for unfertilized plots (0 N) and 0.243 kg ha^{-1} for fertilized (100 N) plots over the Chernozems (Table 3.3).

3.3.5 Effects of soil physical environment on N_2O emissions

Our analyses found no significant correlations between N_2O fluxes and soil temperature at 5 cm depth in the Chernozems regardless of N fertilization and tillage. Fluxes from both unfertilized (0 N) and fertilized (100 N) NT Chernozems were found to be significantly positively correlated ($R \sim 0.70,\ P < 0.01$) with precipitation (Figure 3.6). Multiple correlations suggested no significant interactive effects of precipitation and soil temperature on soil N_2O emissions in the Chernozems for both of the tillage and fertilizer treatments. Unlike the Chernozems, the Luvisols showed significant exponential increases ($R \sim 0.90,\ P < 0.01$) in N_2O emissions with increases in soil temperature at 5 cm depth for fertilized CT and NT plots (Figure 3.7). We, however, did not find any significant correlation between the fluxes and soil water content at 5 cm depth in the Luvisols for both of the tillage and fertilizer treatments except for unfertilized CT Luvisols where we found a significant increase ($R = 0.76,\ P < 0.01$) in N_2O fluxes with an increase in soil water content (Figure 3.8). No significant soil moisture content × soil temperature interaction effects on soil N_2O was indicated by multiple correlations regardless of tillage and fertilizer application. These sorts of correlation analyses are inadequate to draw firm inferences about soil environmental impact on N_2O emissions due to the inadequacy of measured data and consequent various underlying assumptions, but they provide us with an excellent opportunity in explaining our major hypotheses of tillage, N fertilizer and soil type effects on soil N_2O emissions to at least some degree of confidence rather than merely speculating the processes.

3.4 Discussions

Increased bulk density, decreased air-filled porosity, low O_2 diffusion through soil and consequent low microbial O_2 availability had been attributed to higher soil N_2O emissions from no-tilled agricultural soils in many previous studies (Smith et al. 2001; Grant et al. 2004; Six et al. 2004; Grandy et al. 2006). This underlying idea drove our first hypothesis of increased N_2O emissions in response to the adoption of long term (~ 30 years) no-tillage (NT) instead of conventional tillage (CT) on both unfertilized and nitrogen applied Black Chernozems and Gray Luvisols. Our findings apparently did not confirm this hypothesis. Rather we found opposite responses of higher N_2O emissions on CT over NT for both soil types and N fertilizer application rates. Microbial O_2 demand in the waterlogged microsites exceeding the supply might have been still producing N_2O through NO_3^- mediated denitrification in apparently well drained conventionally tilled soils (Havlin et al. 1999). NO_2^- mediated aerobic 'nitrifier denitrification' might also have been taking place simultaneously to cause higher N_2O emissions from better aerated CT soils (Venterea and Rolston 2000). In two long term soil carbon and nitrogen storage change studies over the same two soil types under our study, Malhi et al. (2011a,b) reported increases in mineralizable and light fraction top soil organic nitrogen in response to NT adoption. This sort of accumulation was attributed to the absence of surface residue mixing and less rapid mineralization through soil disturbances in response to the adoption of NT. Our results of higher N_2O emissions after tillage reversal thus can be corroborated by the absence of top soil accumulation of mineralizable nitrogen in CT plots and consequent higher soil NO_3^- concentrations that ensured frequent substrate (NO_3^-)

availability for denitrification (Malhi et al. 2006). Similar observations of N_2O emission stimulations under CT were reported in different studies on drier Western Canadian soils (Lemke et al. 1999; Malhi et al. 2006) and also on a Danish soil (Chatskikh and Olesen 2007). Accumulation of topsoil mineralizable and light fraction organic nitrogen is often accompanied by an accumulation of similar forms of carbon (Malhi et al. 2006, 2011a,b). Keeping that in mind, one would expect CT to give a fair boost to CO_2 emissions as well as N_2O. Higher N_2O emissions stimulated by CT as found in our study hence can further be corroborated by simultaneous increases in CO_2 emissions in response to tillage reversal as described in our CO_2 flux studies in Chapter 2. Our findings, therefore, strongly suggest that tillage reversal on long term no-till Black Chernozems and Gray Luvisols stimulates soil N_2O emissions regardless of N fertilization rates. This might be because of rapid mineralization and higher substrate availability of organic C and N built up from previous decades of NT following tillage.

Mineral nitrogen application was reported, in many studies, to stimulate N_2O emissions by raising the level of soil NO_3^-N and hence fueling denitrification (Baggs et al. 2003; MacKenzie et al. 1997; Malhi et al. 2006, 2011a,b; Pelster et al. 2011). Increased soil NO_3-N level was found in same soil types under present study as reported by Malhi et al. (2006, 2011a, b) during years of high N fertilization. This might cause increased N_2O emissions from the fertilized (100 N) Chernozems and Luvisols in comparison to unfertilized (0 N) plots. This suggests that there is extra N in the soil above crop requirements or an inability for the crop to efficiently take up mineral N before it is denitrified. Local NO_2^-

accumulation through nitrification followed by N-fertilizer application might also be another cause of higher N_2O emissions resultant of NO_2^- mediated biological and chemical denitrification from fertilized (100 N) Chernozems and Luvisols (Venterea and Rolston 2000). Our findings, however, revealed different degrees of N_2O emission response over two different soil types. The Gray Luvisols showed more than a 4-fold increase in N_2O emissions over the Black Chernozems for the 100N treatments. The soil physical environment comes into play in explaining such variations. N_2O emissions from the fertilized (100 N) Black Chernozems was governed by soil moisture content rather than soil temperature as indicated by the significant correlations between soil N_2O emissions and precipitation (Figure 3.6) and non-significant correlations between the emissions and soil temperature. Since the Chernozems have lower bulk densities, the excess water after heavy precipitation might have drained rapidly through macropores and that created fewer anaerobic microsites than the Luvisols for a given amount of precipitation. Moreover, characteristic dense subsoil horizon of Luvisols generally has low water permeability which can cause extended periods of water logging in wet years like 2010 (Dyck et al. 2012). So, even if the fertilized Chernozem had higher NO_3-N levels, it had lower degree of anaerobicity to facilitate denitrification (Figure 3.6). On the other hand, the volumetric water content of the Luvisols was much higher than field capacity during most of the 2010 growing season (Figure 3.4) and consequently the seasonal changes in denitrification rate from fertilized (100 N) Luvisols was almost completely independent of soil moisture variation. Instead like any other chemical reaction,

N_2O production through denitrification from the fertilized Luvisols exponentially increased with soil temperature (Figure 3.7) since higher levels substrate availability and anaerobic microsites were present. Hence from our results we can infer that nitrogen fertilizer application (100 N) enhanced soil N_2O emissions from both the Chernozems and the Luvisols by facilitating denitrification through substrate availability. N_2O emissions from the water logged Luvisols had a greater response to nitrogen application than the Chernozems.

The Gray Luvisols at the Breton Plots is known for its compactness and poor drainage in comparison to the Black Chernozems at Ellerslie. One would thus expect the Luvisols to emit higher N_2O than Chernozems due to lower microbial O_2 availability irrespective of tillage and nitrogen fertilizer applications. We, however, found two contrasting trends of N_2O emissions in response to these soil types. The fertilized (100 N) Luvisols with low water permeability emitted more N_2O than the fertilized Chernozems and the trend is reverse in the case of no nitrogen application (0 N). Better inherent soil fertility and aeration of the unfertilized (0 N) Black Chernozems might have resulted in higher mineralization and nitrification and consequently higher N_2O emissions than the relatively less fertile unfertilized (0 N) Gray Luvisols when soil environment was favorable for denitrification (Malhi et al. 2011 a,b). The fertilized (100 N) Luvisols, however, caught up and produced more N_2O than the fertilized Chernozems mostly due to the favorable soil physical environment for denitrification as discussed in earlier paragraph. One would argue that the higher N_2O emissions from fertilized Luvisols might be a transient effect of timing of N fertilization. Previous studies showed that there were peak flushes of N_2O emissions right after mineral N application that lasted four weeks at the longest (Pelster et al. 2011). The increased N_2O emissions from the Luvisols in our study, however, did not seem to be a transient effect of timing of fertilizer application since it stayed the same throughout the growing season. Instead, N fertilizer application with straw retention might have enhanced accumulation of organic nitrogen over the years and hence nitrogen supplying power of relatively less fertile Luvisols than Chernozems with higher initial fertility (Malhi et al. 2011 a,b).

CT induced N_2O emission was increased in the Chernozems in response to nitrogen fertilization (100 N). All of our experimental units were managed under straw retention and N fertilization was observed to increase above and below ground residue inputs to the soil (Malhi et al. 2011a,b). This additional residue, after being mixed and incorporated into the soil by CT, could have facilitated mineralization, nitrification and hence triggered additional denitrification. We, however, could not find a similar response of CT induced N_2O augmentation through N application in the Gray Luvisols. The reason for that is quite unclear and we remain inconclusive on that. Unfertilized Gray Luvisols produced an additional positive effect on CT induced N_2O emission. This can be explained by the fact that relatively less fertile Luvisols gained more soil NO_3-N from rapid mineralization and nitrification stimulated by additional residue incorporation through CT (Malhi et al. 2006; 2011 a,b). The fact is further corroborated by a reduction in tillage induced N_2O production from N fertilized (100 N) Gray Luvisols in comparison to 0N (Table 3.3c).

3.5 Conclusions

Tillage reversal caused higher N_2O emissions from long term notill Chernozems and Luvisols independent of nitrogen fertilizer application and soil types. Nitrogen fertilizer application and soil types, however, modified the relationships between tillage and N_2O emissions. Tillage induced N_2O emissions were augmented by the application of 100 N in both Chernozems and Luvisols. Unfertilized Luvisols exhibited higher tillage induced N_2O emissions than unfertilized Chernozems. Nitrogen fertilizer application (100 N) was found to be the strongest single factor to augment N_2O emissions especially in Luvisols. Our findings here pointed out an important fact that additional CO_2 emissions after tillage reversal on a long term notill soil were not offset by a simultaneous reduction of other greenhouse gas like N_2O. Instead an increase in N_2O emissions were associated with increased CO_2 emissions followed by tillage reversal. Therefore, average risks of N_2O emissions upon tillage reversal on a long term NT soil should also be accounted for in quantifying carbon offset resulting from adoption of long term NT.

3.6 Literature cited

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Table 3.1: Split plot repeated measures statistics of weekly averaged soil N_2O fluxes (kg ha^{-1} h^{-1}) from Black Chernozemic and Gray Luvisolic soils under different tillage treatments and nitrogen fertilizer treatments

Conventional tillage (CT) vs No tillage (NT)				
Soil types	N-fertilizer treatment	*n*	SE	P value
Chernozem	0N	55	0.3618	0.0962
	100N	56	0.6264	0.1566
Luvisol	0N	56	0.2418	0.0065**
	100N	56	1.1934	0.4543
Unfertilized (0 N) vs N-fertilized (100 N)				
Soil types	Tillage treatment	*n*	SE	P value
Chernozem	CT	56	0.2532	0.0178*
	NT	56	0.3288	0.0727
Luvisol	CT	56	0.6432	0.0052**
	NT	56	1.0356	0.0201*
Chernozems vs Luvisols				
Tillage treatment	N-fertilizer treatment	*n*	SE	P value
CT	0N	56	0.381	0.0329*
	100N	56	0.8802	0.0531
NT	0N	56	0.1794	0.1075
	100N	56	1.1136	<0.0001**

*Significant at $p < 0.05$ **Significant at $p < 0.01$

Table 3.2: Estimated growing season (June-September) soil N_2O fluxes (kg ha^{-1}) from Black Chernozemic and Gray Luvisolic soils under different tillage treatments, nitrogen fertilizer treatments and weather conditions

Year	Growing season precipitation (mm)	Average growing season soil temperature at 5 cm depth (°C)	Soil type	Tillage treatment	N-fertilizer treatment	Growing season N_2O flux* (kg ha^{-1})
2010	558	14.10	Chernozem	CT	0 N	11.988
					100 N	15.071
				NT	0 N	10.196
					100 N	12.557
2010	378	16.12	Luvisol	CT	0 N	8.655
					100 N	22.539
				NT	0 N	5.997
					100 N	19.782

**Growing season N_2O flux (kg ha^{-1}) = Average measured N_2O flux throughout the growing season (kg ha^{-1} h^{-1}) × number of hours within the growing season (June – September)*

Table 3.3: Estimated changes in growing season (June-September) soil N_2O fluxes (kg ha^{-1}) from Black Chernozemic and Gray Luvisolic soils due to different tillage treatments, nitrogen fertilizer treatments and weather conditions

<table>
<tr><th colspan="4">(a) Change in response to tillage (+/-)</th></tr>
<tr><td>Soil type</td><td>N-fertilizer treatment</td><td colspan="2">Change in growing season soil N_2O flux (CT – NT) (kg ha^{-1})</td></tr>
<tr><td rowspan="2">Chernozem</td><td>0 N</td><td colspan="2">1.792</td></tr>
<tr><td>100 N</td><td colspan="2">2.514</td></tr>
<tr><td rowspan="2">Luvisol</td><td>0 N</td><td colspan="2">2.658</td></tr>
<tr><td>100 N</td><td colspan="2">2.757</td></tr>
<tr><th colspan="4">(b) Change in response to N fertilizer applications (+/-)</th></tr>
<tr><td>Soil type</td><td>Tillage treatment</td><td>Change in growing season soil N_2O flux (100 N – 0 N)</td><td>Additional growing season soil N_2O flux upon tillage due to N-fertilization (CT – NT) (kg ha^{-1})</td></tr>
<tr><td rowspan="2">Chernozem</td><td>CT</td><td>3.083</td><td rowspan="2">0.722</td></tr>
<tr><td>NT</td><td>2.361</td></tr>
<tr><td rowspan="2">Luvisol</td><td>CT</td><td>13.884</td><td rowspan="2">0.099</td></tr>
<tr><td>NT</td><td>13.785</td></tr>
<tr><th colspan="4">(c) Change in response to soil types i.e., Chernozemic vs Luvisols (+/-)</th></tr>
<tr><td>Tillage treatment</td><td>N-fertilizer treatment</td><td>Change in growing season soil N_2O flux (Chernozem – Luvisol)</td><td>Additional growing season soil N_2O flux upon tillage due to better drainage status and higher organic matter content of Chernozems (CT – NT) (kg ha^{-1})</td></tr>
<tr><td rowspan="2">CT</td><td>0 N</td><td>3.333</td><td rowspan="2">-0.866
(for 0 N plots)</td></tr>
<tr><td>100 N</td><td>-7.468</td></tr>
<tr><td rowspan="2">NT</td><td>0 N</td><td>4.199</td><td rowspan="2">0.243
(for 100 N plots)</td></tr>
<tr><td>100 N</td><td>-7.225</td></tr>
</table>

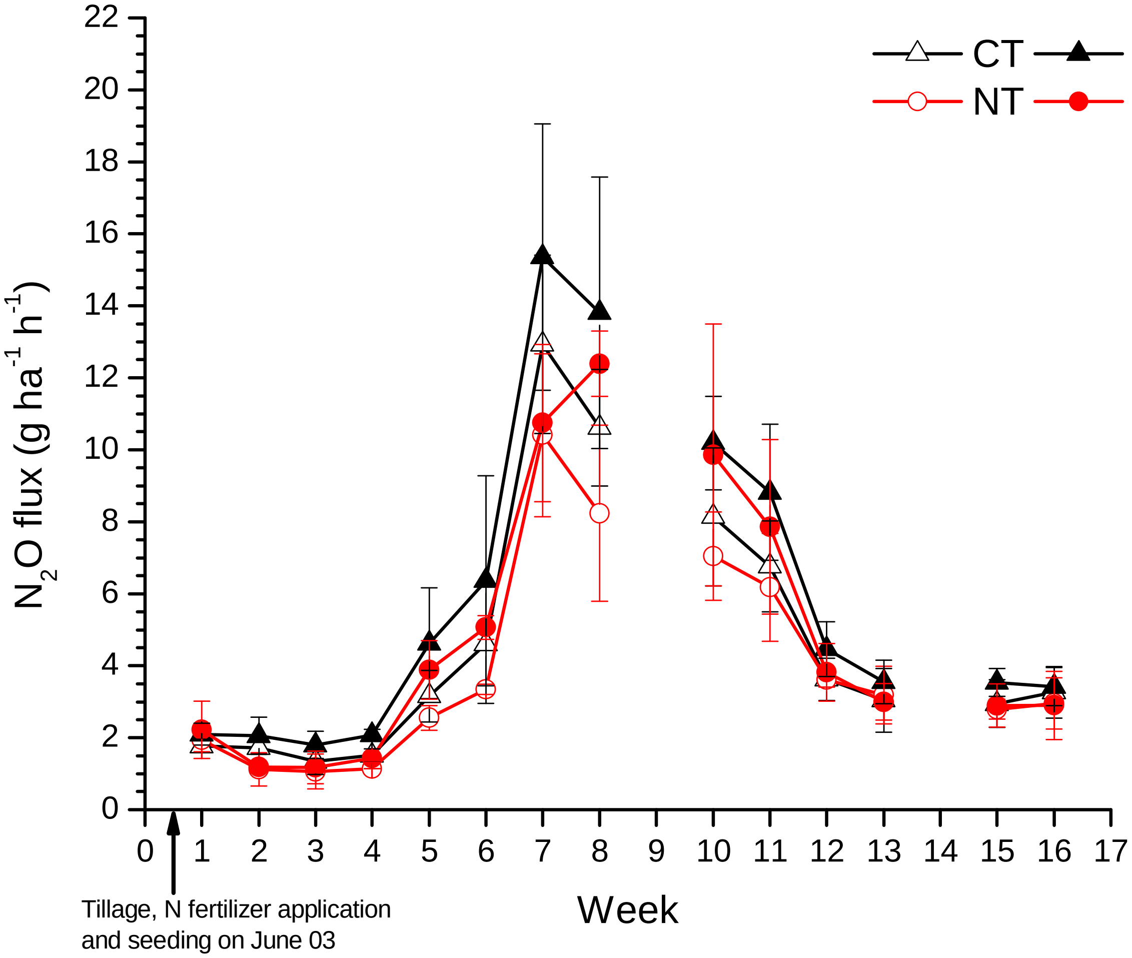

Figure 3.1: Weekly averaged hourly N_2O fluxes from conventionally tilled (CT) and non-tilled (NT) regimes of unfertilized (open symbols) and fertilized plots (closed symbols) on the Black Chernozems during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

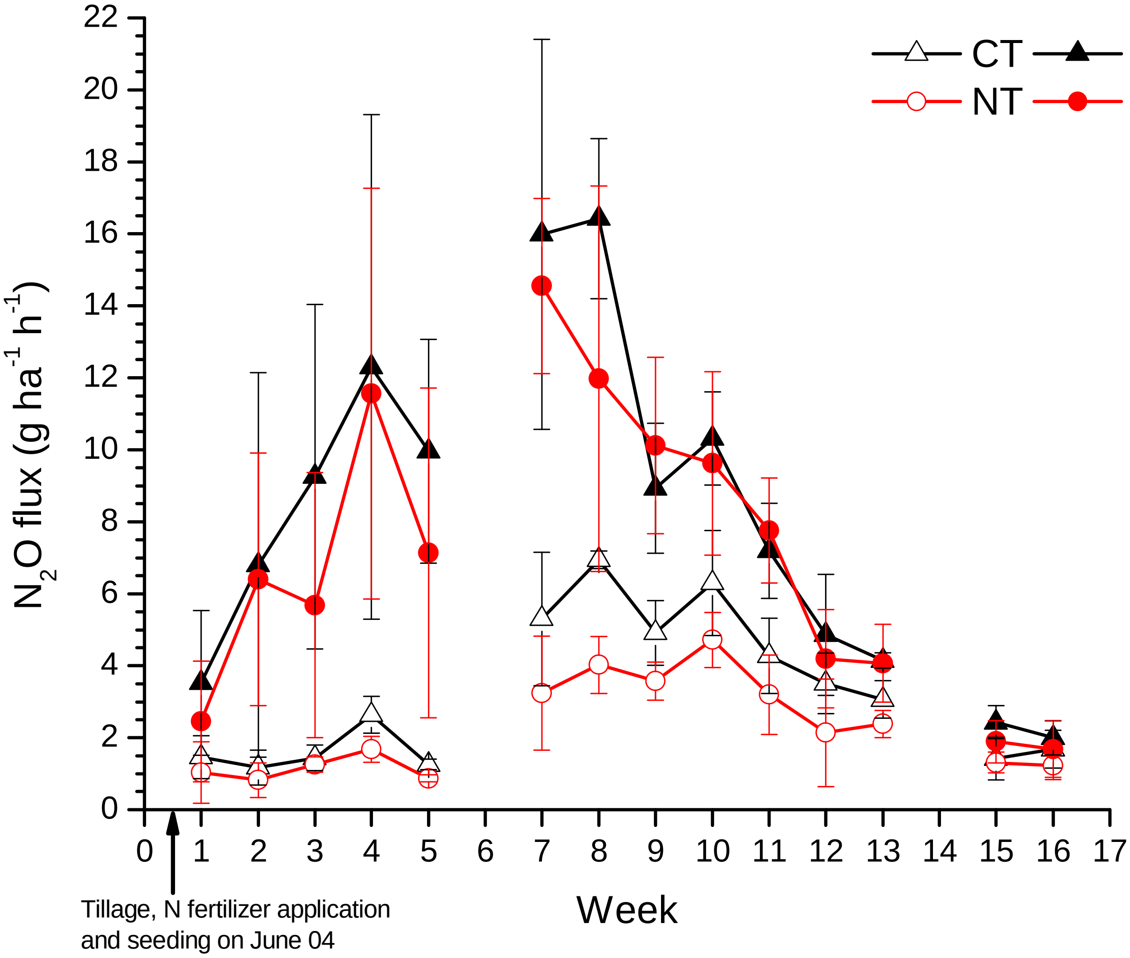

Figure 3.2: Weekly averaged hourly N_2O fluxes from conventionally tilled (CT) and non-tilled (NT) regimes of unfertilized (open symbols) and fertilized plots (closed symbols) on Gray Luvisols during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

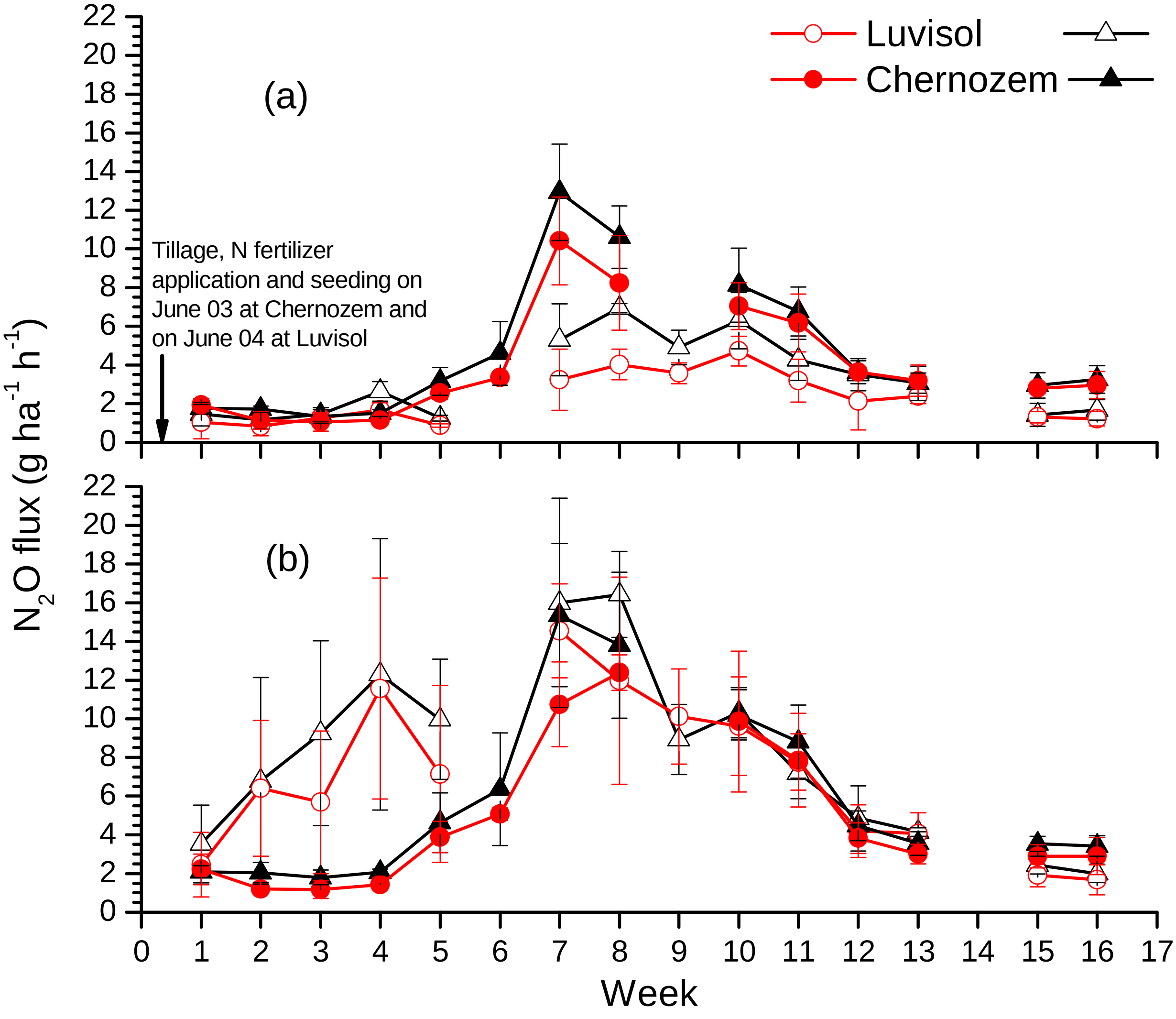

Figure 3.3: Weekly averaged hourly N_2O fluxes from non-tilled (circles) and conventionally tilled (triangles) (a) unfertilized and (b) fertilized Gray Luvisols and Black Chernozems during 2010.Each dot represents an average of four replicates and bars represent ± standard errors

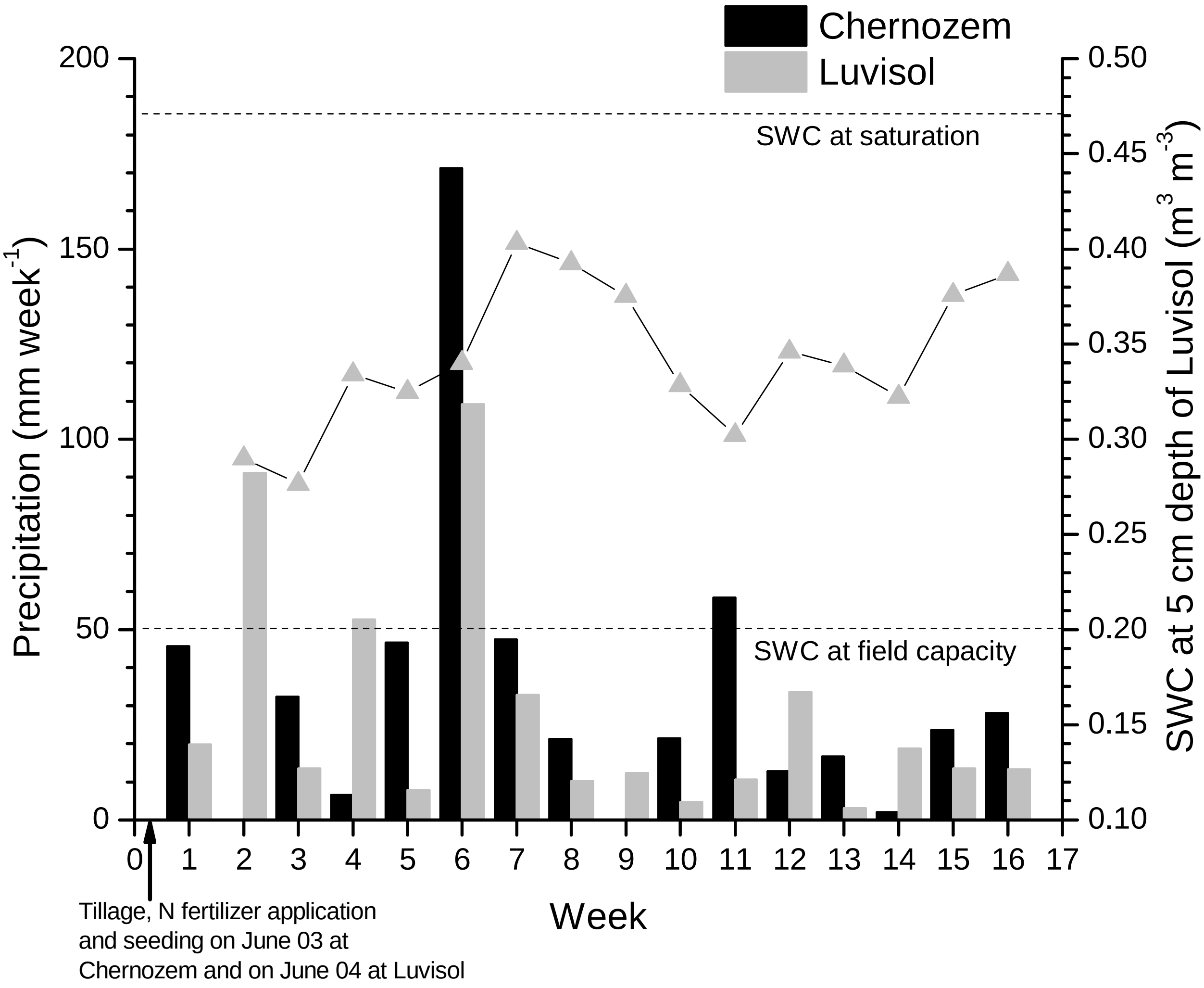

Figure 3.4: Weekly total precipitation (columns on left y-axis) on Black Chernozems and Gray Luvisols and weekly averaged daily soil water contents (SWC) at 5 cm depth of Gray Luvisols (symbols with line at right y –axis) during 2010

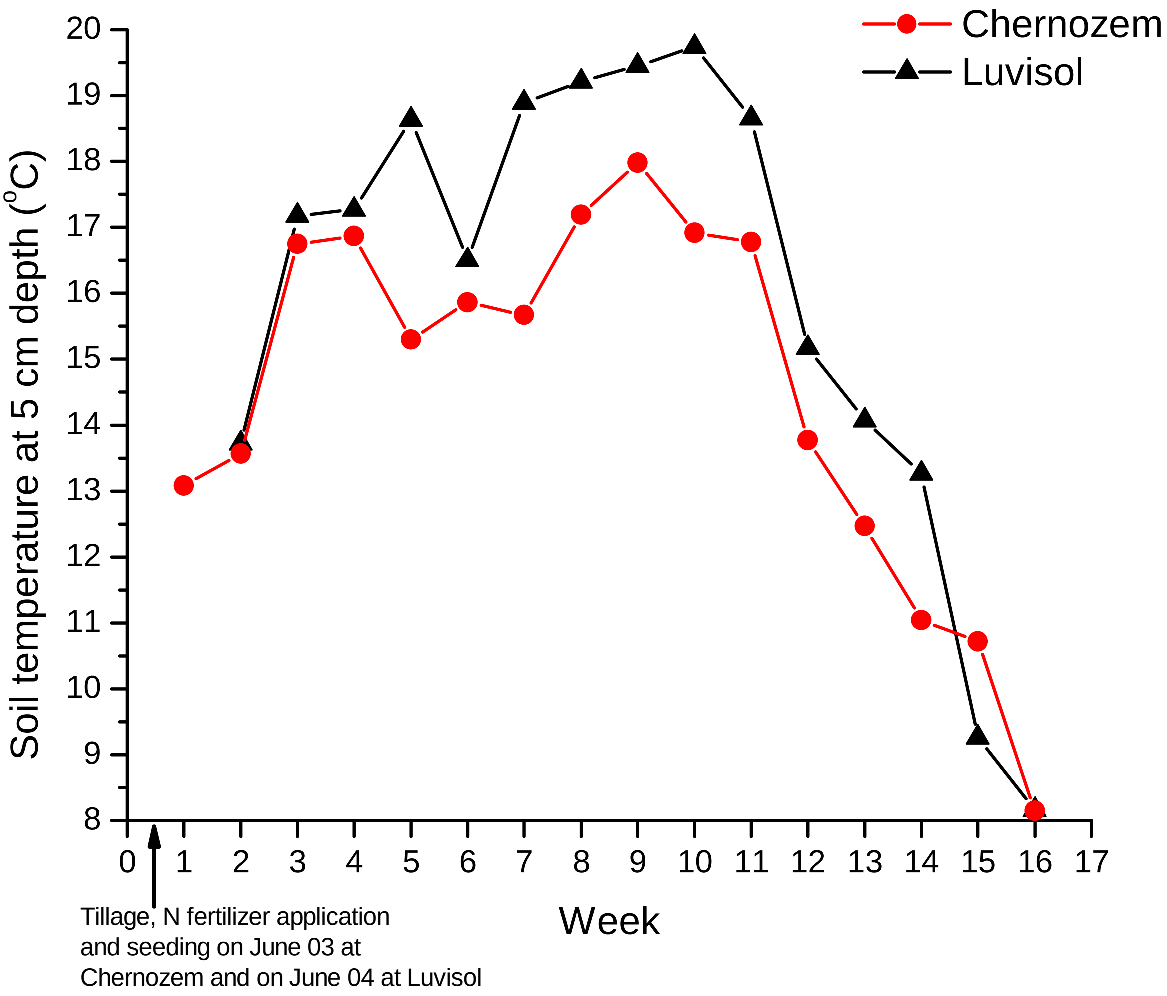

Figure 3.5: Daily soil temperature at 5 cm depth of Black Chernozemic and Gray Luvisolic soils during 2010

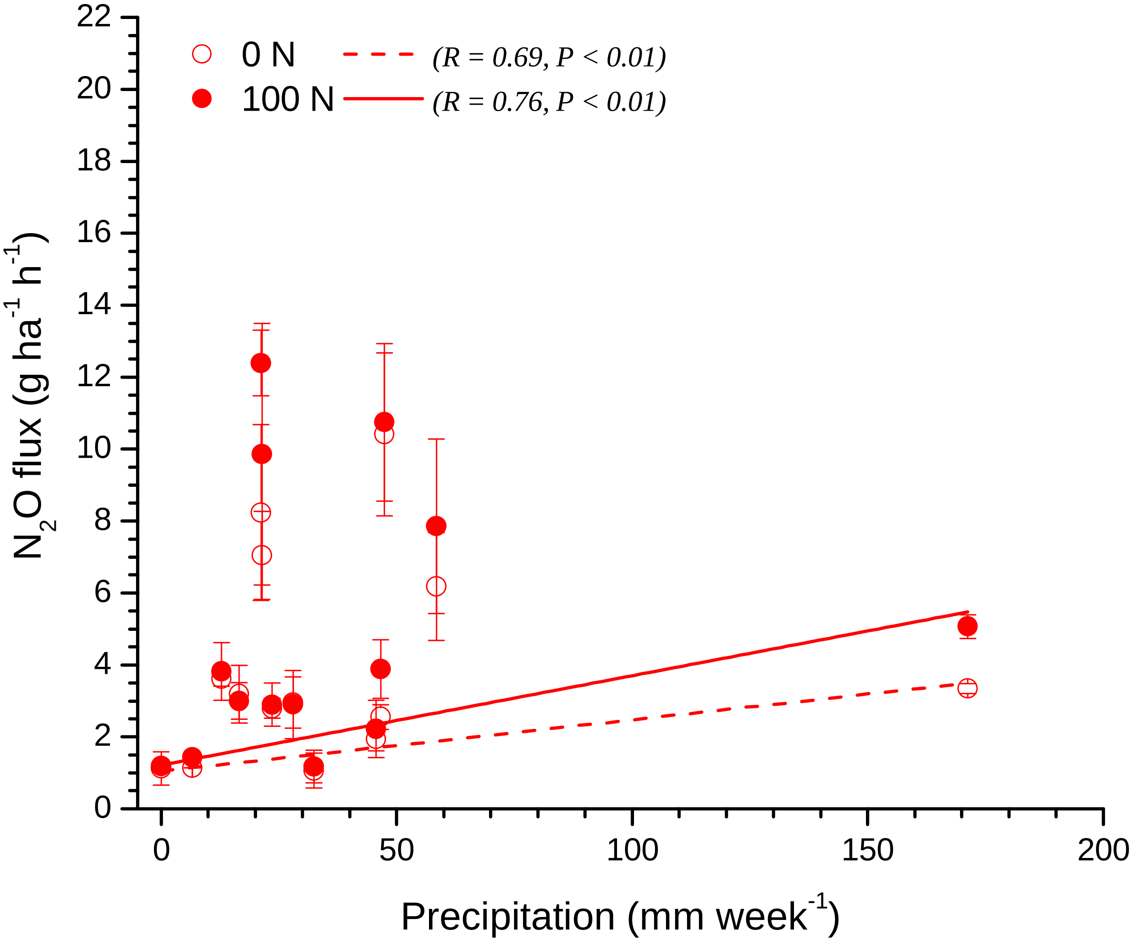

Figure 3.6: Relationships between weekly averaged hourly soil N_2O fluxes from no-till (NT) unfertilized (0 N) and fertilized (100 N) Black Chernozems and precipitation during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

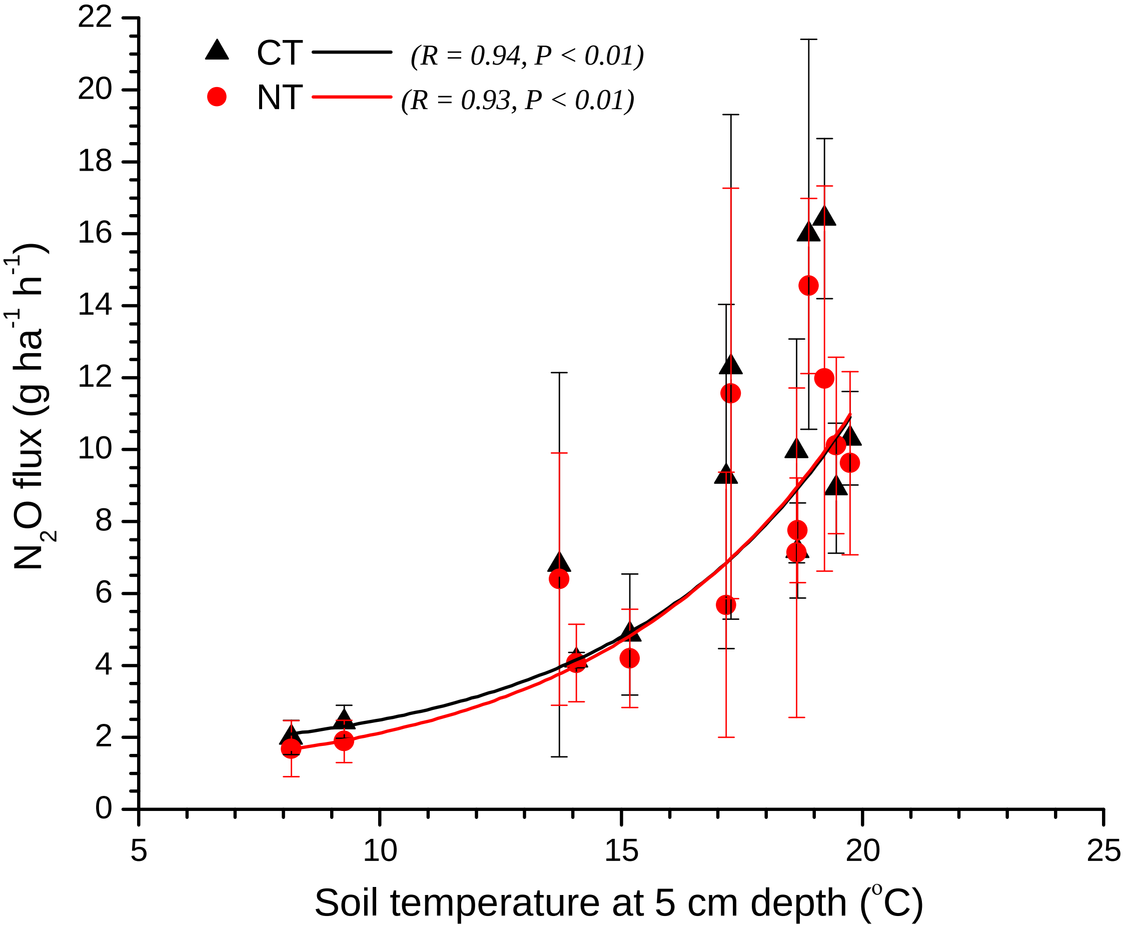

Figure 3.7: Relationships between weekly averaged hourly soil N_2O fluxes from fertilized Gray Luvisols for different tillage treatments and daily soil temperature at 5 cm depth during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

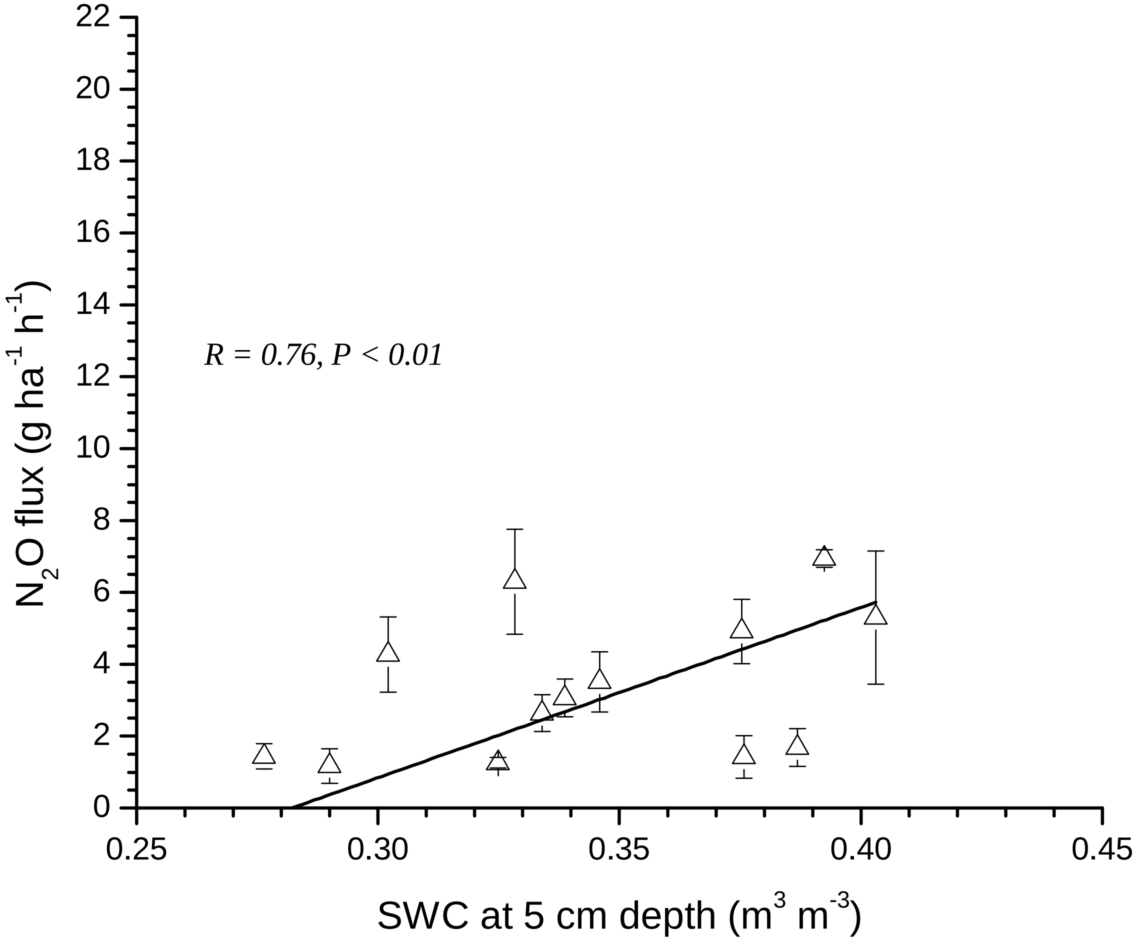

Figure 3.8: Relationships between weekly averaged hourly soil N_2O fluxes from tilled (CT) unfertilized (0 N) Gray Luvisols and weekly averaged daily soil water content at 5 cm depth during 2010. Each dot represents an average of four replicates and bars represent ± standard errors

Chapter 4

4 Synthesis

One of our two major objectives in the beginning of the study was to quantify CO_2 emissions after tillage reversal on long term no till Black Chernozems and Gray Luvisols, two major Western Canadian soils. The principal aim for that was to test the underlying idea of the Assurance Factor in the existing carbon offset quantification protocol of Government of Alberta for tillage management system to account for the average risks of tillage reversal on greenhouse gas emissions (Alberta Environment 2009). This Assurance Factor assumes that the rates of loss of soil carbon in the form of CO_2 emissions after tillage reversal are equal to those of carbon sequestration under long term no till management. We showed a gross growing season estimation of CO_2 emissions after tillage reversal on long term no till Chernozems and Luvisols and compared those emission rates with historical carbon sequestration rates on the same soils after the adoption of long term no till (Chapter 2). The rates of growing season carbon losses in the form of CO_2 emissions after tillage reversal were consistently higher than the annual rates of historical carbon sequestration under long term no till management for both the soil types. Absence of decrease in the rate of emission for two consecutive tillage events on Chernozems also indicated that the trend of CO_2 emission rates being higher than the sequestration rates was not a transient effect. However, the difference in time scale between our study (2 years) and the historical storage change study (27 years) makes it reasonable to speculate such large CO_2 emissions after tillage reversal might gradually decrease over time. A long term (10 years or so) flux study would be interesting to further test this hypothesis. Our findings also indicated that CO_2 emission after tillage reversal to sequestration under long term no till ratio can substantially be affected by other agricultural practices like nitrogen fertilization etc. and soil types. For Black Chernozems we found a higher emission to sequestration ratio for 100 N applications compared to unfertilized control plots. The opposite trend was true for our findings on Gray Luvisols. Comparison between the two unfertilized soils revealed that Gray Luvisols with relatively lower indigenous fertility than Black Chernozems had higher CO_2 emission to sequestration ratio. Besides, wetter Black Chernozems emitted higher CO_2 after tillage reversal than drier weather condition. Our findings, therefore, explored the need for accounting the effects of N fertilizer application, soil types and soil physical environment i.e., soil moisture and temperature while quantifying the average risks of tillage reversal for weed controls, crop failure etc. on CO_2 emissions. We also, hereby, have provided an initial framework of accounting for those factors along with tillage in quantifying carbon offset due to tillage management.

Our second objective of quantifying potentials of N_2O emission reduction or risks of N_2O emissions after tillage reversal was far more complex and less studied than the first one. Our findings showed significant strong positive correlations between N_2O emissions and CO_2 emissions on hourly bases for both fertilized and unfertilized Black Chernozems ($R \sim 0.85$, $P<0.001$) and Gray Luvisols ($R \sim 0.75$, $P<0.001$) (Figures 4.1 and 4.2) that is in consistent with other’s findings (Nyakatawa et al. 2011). These results gave us the first hint of need for accounting average risks of additional N_2O emissions after tillage reversal along with those of CO_2 emissions. Further analyses of growing season estimates made a vivid picture of additional N_2O emissions triggered by tillage reversal on long term no till Chernozems and Luvisols that can range from 25 to 80% of additional equivalent CO_2 emissions after tillage reversal on the same soils depending upon soil type and the amount of nitrogen application (Table 4.1). Generally nutrient poor Gray Luvisols had higher risks of N_2O emissions after tillage reversal than organic matter rich Black Chernozems (Table 4.1) regardless of nitrogen fertilizer application. Nitrogen fertilizer application increased the risks of N_2O emissions after tillage reversal (Table 4.1). Regardless of tillage, our study indicated substantial losses of applied mineral N in the forms of N_2O emissions from both the soils that are in excess of the IPCC N_2O loss coefficient of 1.25% applied to western Canada (Johnston 2005) (Table 4.2). Luvisols with relatively low water permeability due to the presence of denser subsoil lost almost 4.5 times more mineral N applied than well drained Chernozems (Table 4.2).

In terms of quantifying average risks of greenhouse gas emissions while formulating offset protocols, our study came up with the following recommendations:

1) The ratio of the rates of CO_2 emission after tillage reversal to the rates of carbon sequestration should be scientifically examined for major soil types under different fertilizer management for adequately longer term to account for sufficient weather anomalies with a combination of field studies during the growing season and subsequent modeling studies for

estimating the emissions during winter and spring thawing to derive annual scenarios.

2) Annual rates of N_2O emissions should also be enumerated as of CO_2 emissions above and the average risks of N_2O emissions, which can be substantial as per our findings, should also be accounted for along with those of CO_2.

In the bigger picture, agricultural sector has a relatively lower share .i.e., 15% of global anthropogenic greenhouse gas emissions (FAO 2008). However, from our study we learned that agriculture has a greater potential of reducing greenhouse gas emissions through facilitating sequestration of atmospheric CO_2 into soil organic matter and reducing N_2O emissions by reducing rates of mineralization stimulated by soil disturbances through the adoption of conservation agriculture like long term no-till. The total greenhouse gas potentials and the rates of sequestrations, however, are dependent on several other agricultural practices like nitrogen and residue management as well as soil physicochemical properties such as soil organic matter, soil moisture and temperature. The permanence of greenhouse gas sink also depends upon the long term nature of the management practice since our study showed that the sequestered greenhouse gases due to the adoption of long term no till is reversible. Soils with generally lower inherent soil organic matter has a higher C sink potential than soils with higher soil organic matter but this sink in such soil is subjected to higher risks of reversal.

4.1 Literature cited

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Table 4.1: Growing season estimates of soil CO_2 and N_2O emissions (CT - NT) during 2010 from Black Chernozems and Gray Luvisols stimulated by tillage reversal

Soil type	N-fertilizer treatment	Net CO_2 emission after tillage reversal (t CO_2 ha^{-1} growing season $^{-1}$)	Net N_2O emission after tillage reversal (kg N_2O ha^{-1} growing season $^{-1}$)	CO_2 equivalent net N_2O emission after tillage reversal (t CO_2E ha^{-1} growing season $^{-1}$)*
Chernozem	0 N	2.221	1.792	0.556 (25)
	100 N	2.433	2.514	0.779 (32)
Luvisol	0 N	2.453	2.658	0.824 (34)
	100 N	1.067	2.757	0.855 (80)

***** *assuming 1 mole of N_2O ≈ 310 moles of CO_2; values in parentheses represent the percentage of CO_2 emissions after tillage reversal*

Table 4.2: Growing season estimates of loss of N fertilizer applied through N_2O emissions (100 N- 0N) during 2010 from Black Chernozems and Gray Luvisols

Soil type	Tillage	Net N_2O emission stimulated by N fertilizer application (kg N_2O ha^{-1} growing season $^{-1}$)	Net loss of fertilizer N applied through N_2O emission (kg N ha^{-1} growing season $^{-1}$ or % of total N fertilizer applied)
Chernozem	CT	3.083	1.962
	NT	2.361	1.502
Luvisol	CT	13.884	8.835
	NT	13.785	8.772

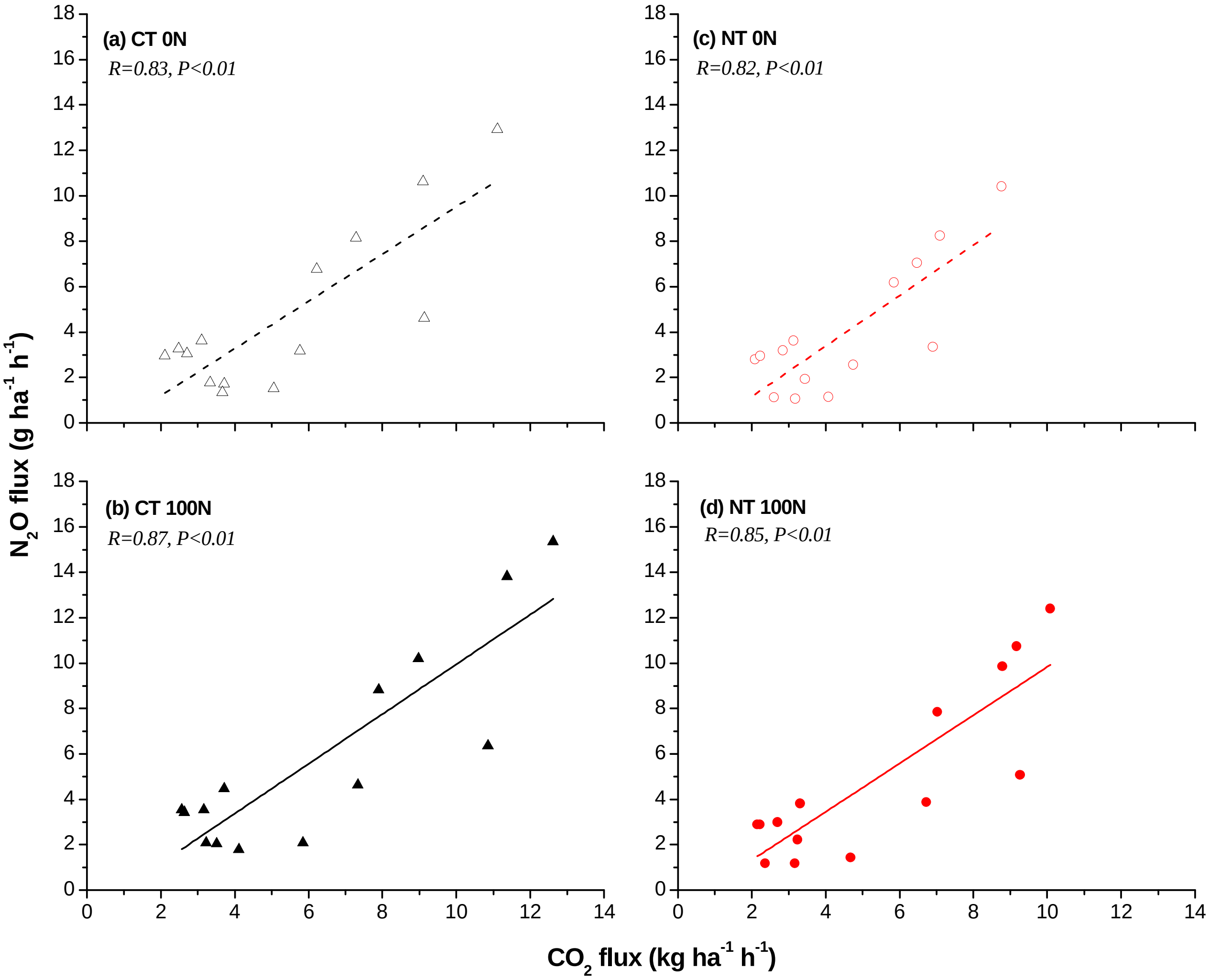

Figure 4.1:Relationships between soil N_2O and CO_2 fluxes for different tillage treatments and nitrogen applications over Black Chernozems during 2010. Each dot represents an average of four replicates.

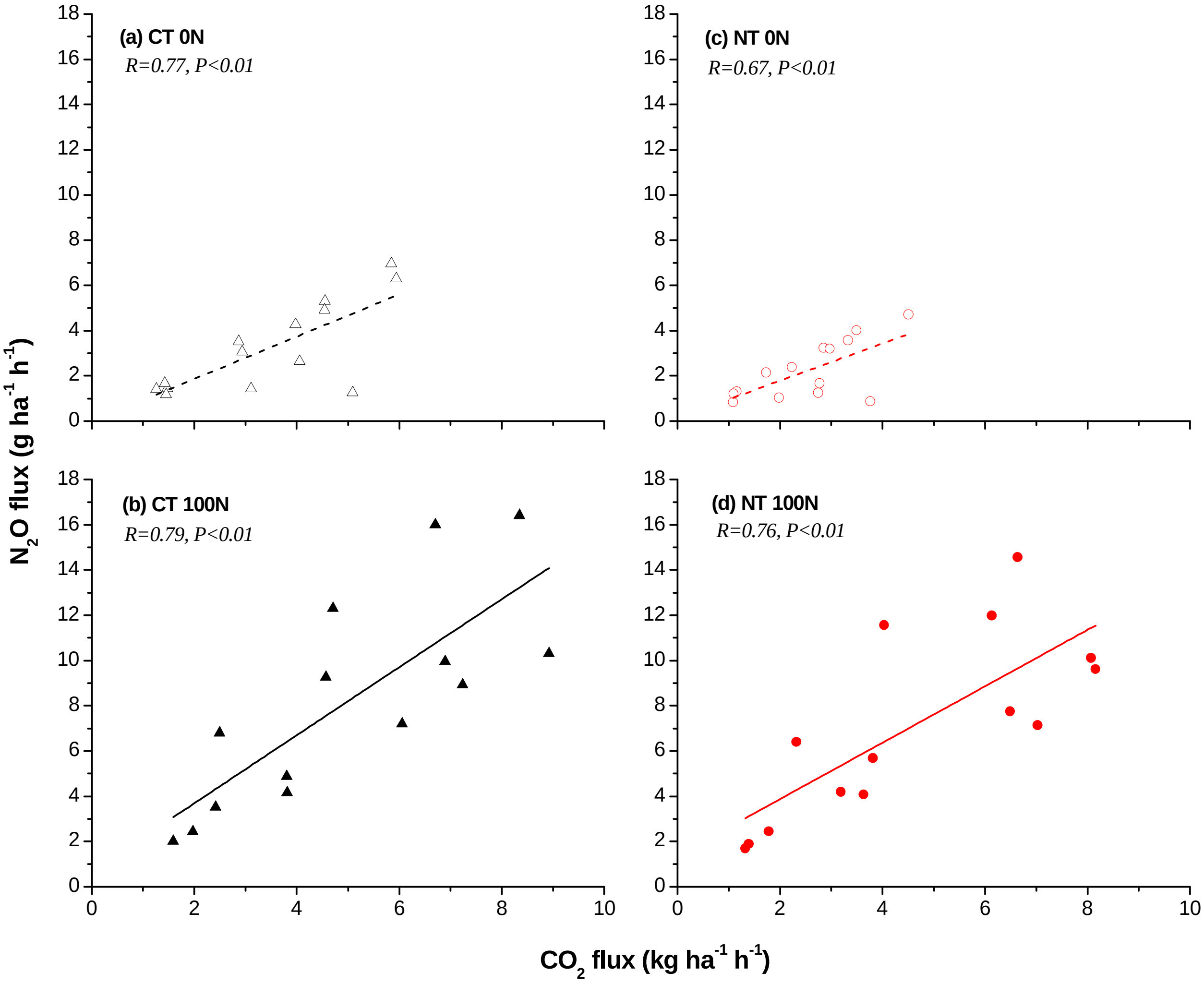

Figure 4.2: Relationships between soil N_2O and CO_2 fluxes for different tillage treatments and nitrogen applications over Gray Luvisols during 2010. Each dot represents an average of four replicates.