Soil C dynamics following the ploughing of a poorly-drained grassland

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Abstract
Perennial forage production is a predominant land use in northern temperate regions and soils under forage contain large stock of C. It is important to understand C dynamics under these systems to better assess their role in greenhouse gas budgets. Two plots, one that had received 100 m^3 /ha of liquid swine manure (LSM) annually since 1978 and an unfertilized forage field, were (i) left with vegetation intact or killed by glyphosate in the autumn, and either (ii) left as an undisturbed chemical fallow, (iii) ploughed by full inversion tillage (FIT) in the autumn, or (iv) or in the spring. Following the autumn tillage operation, we monitored CO_2 emissions from the fallow soil surface, CO_2 concentrations in the soil profile, soil temperature and water content for one year. Soil aggregation, the intra-aggregate light fraction organic matter (LFOM) and microbial biomass were also analysed. Tillage significantly decreased the quantity of water-stable aggregates and with it the content of LFOM material protected by aggregates. Yet CO_2 emissions indicated that FIT reduced soil respiration compared to chemical fallow treatments by 19 to 33%. Regression analyses suggested that reductions in CO_2 emissions were due to the placement of surface C at depth where soil temperature and oxygen availability were attenuated. Our study indicates that in this cool poorly-drained soil, respiration is largely dependant on environmental factors and not physical protection mechanisms.

Introduction
Perennial systems, whether natural grasslands, pastures or forage fields contain between 10 to 50% more C than annual production systems located on the same soil. There is therefore interest in converting current arable land to forage systems due to their potential to sequester C. However, because forage soils are C rich, land use change of current forage fields and occasional renovation of heavily-fertilized forage fields could result in significant GHG emissions. In arable lands of temperate semi-arid regions where tillage is predominantly done by chisel ploughs, which mixes the surface soil, C stocks are reduced by tillage. In these regions, the differences between C in soils of no-till and tillage production systems indicate that mixing organic material from the surface into the soil often stimulates soil respiration. Similar observations have been made with the cultivation of grasslands and forage fields (Vellinga *et al*. 2004; Grandy and Robertson 2006).

Tillage of virgin soils modifies soil structure. The conversion of grasslands to arable lands reduces the mean weight diameter (MWD) of aggregates and releases light-fraction organic material (LFOM). On the other hand no-till production systems are observed to increase aggregate size and protected particulate organic matter (POM) and LFOM. Consequently, tillage of forage soils can be expected to disrupt soil structure and mix fresh organic material and fresh microbial C into the soil surface. The principle mechanism of C loss by tillage in semi-arid temperate soils is thought to be the physical disruption of the soil structure protecting SOM.

At the same time on the cool humid soils of eastern Canada where FIT using a mouldboard plough is the dominant tillage process, tillage has not always been observed to have an impact on soil C stocks (Angers *et al*. 1997). Carbon lost from the soil surface is compensated for by accumulation of C deeper in the soil profile. Similar observations were made at other locations (Angers and Eriksen-Hamel 2008). Because FIT buries surface C deep in the soil profile, the C is likely protected by the cool conditions and the lower concentrations of oxygen in the soil profile (Angers *et al*. 1997). Furthermore, by placing the C in contact with fresh mineral surfaces, it may also be stabilized by fixation of SOM on mineral surfaces. Forage fields can sequester large stocks of C relative to annual cropping systems (Soussana *et al*. 2004). It is therefore important to understand how management actions will influence the release of C during renovation and return of these fields to annual cropping systems. The objective of this work was to quantify the response and identify the processes that alter soil respiration in either full inversion tillage using mouldboard plough or no-till seeding of two long-term forage fields (nutrient rich and nutrient poor) on cool moist soils of eastern Canada.

Materials and methods

Study site and experimental design

The study was conducted at the research farm of IRDA located near Québec City, Canada. The site was on a Le Bras series, (270 g clay/kg, 420 g silt /kg, loamy, mixed, frigid, Typic Humaquept). The mean annual temperature in Québec City is 4.2ºC and the mean annual precipitation is 1213 mm. In the fall of 2007, two long-term research plots (Angers *et al*. 2009) were divided into 24 subplots (4 treatments x 4 replicates x 2 long-term plots). The plots were left free of vegetation for one full year. One of the two long-term plots had received large doses of LSM annually since 1978 (100 m^3/ha) and the other was an unfertilized grassland (0 m^3/ha). The plots had been managed as typical forage fields since 1978. The subplots were randomly designated one of four treatments: ploughed by inversion tillage in the autumn (autumn-FIT), or in the spring (spring-FIT), chemically treated with herbicide (chemical fallow) or left as controls (grass, undisturbed). All subplots not designated as controls were chemically killed with herbicides on 10 Aug. 2007. Full inversion tillage, at a depth of 20 cm, was carried out on 4 Sept. 2007 and on 12 May 2008 using a four-share mouldboard plough.

Soil gas measurements, soil sampling and analyses

Soil surface fluxes of CO_2 were measured using non-flow-through non-steady state chambers (Rochette and Bertrand 2008). A soil profile was dug and instrumented within 1 metre of the chamber. Soil air samplers were inserted horizontally at depths of 5, 15, 25 and 45 cm to measure the concentrations of CO_2 and O_2. Soil samples were taken on 29 Sept. 2007 and 22 July 2008 at depths of 0-5, 5-10, 10-20 and 20-30 cm. Water-stable aggregates (1-6 mm), intra and inter LFOM (NaI at a specific gravity of 1.7), microbial biomass C and bulk density were measured.

Results and discussion

Soil respiration

Respiration rates in the fall of 2007 were consistent with other soils of eastern Canada and cooler humid regions with fresh organic material integrated into soils ranging from 0.10 to 0.3 mg CO_2 m^{-2}/s (e.g. Rochette and Angers 1999) (detailed data not shown). The seasonal respiration pattern was typical of cool humid temperate climates with long periods of low CO_2 emissions in the spring due to the cool moist soils, followed by sharp increases in respiration associated with soil warming events (Rochette and Angers 1999). In the summer of 2008, CO_2 fluxes were lower than the norm for this region, likely due to the cool wet summer and the lack of fresh organic material input.

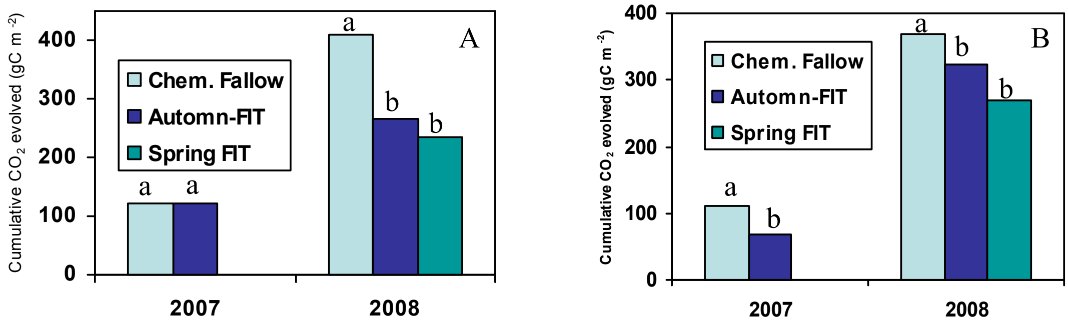

Figure 1. Cumulative CO_2-C emissions from unfertilized (A) and fertilized (B) long-term grasslands subjected to autumn or spring full-inversion tillage (FIT), and compared to a chemical fallow.

After one year, total respiration, as represented by CO_2 emissions, decreased in the order of chemical fallow fertilized>chemical fallow unfertilized>autumn-FIT fertilized > autumn-FIT unfertilized > spring-FIT fertilized > spring-FIT unfertilized (Figure 1). Soil respiration was reduced by 27% by A-FIT and 33% by S-FIT on unfertilized soils and 19% by A-FIT and 21% by S-FIT on fertilized soils (unfertilized ($p=0.07$) and fertilized ($p<0.001$), respectively). Total emissions from the spring-FIT treatments on both unfertilized and fertilized sites were equivalent to the autumn-FIT treatments during the summer of 2008. These results are surprising, as it is often taken for granted that the ploughing of grassland will have a stimulatory effect on respiration (Vellinga *et al*. 2004; La Scala Jr *et al*. 2009).

Physical effects of tillage on the soil profile
Tillage resulted in a disruption of aggregate structure. On the fertilized site, compared to chemical fallow subplots, tillage reduced the percentage of soil in water stable aggregates by 13 and 20% in soils of the autumn-FIT subplots in autumn 2007 and summer 2008 respectively, and spring-FIT reduced stable aggregates by 7% (data not shown). On the unfertilized site, the quantity of stable aggregates in soil of the autumn-FIT treatments also tended to be lower by 7% (p=0.09) and 6% (p=0.16) in autumn 2007 and summer 2008, respectively, and the spring-FIT unfertilized tended to be lower by 6% (p=0.14) than the chemical fallow.

In the autumn of 2007, on the unfertilized site, aggregate disruption caused by tillage resulted in a decrease of 23% and 19% in the intra-aggregate light fraction organic material (iLFOM) relative to control and chemical fallow treatments. A similar trend was observed on the fertilized site where average quantities of iLFOM in samples taken from the spring-FIT plots decreased by between 25 and 35% relative to the undisturbed chemical fallow and control sites. These results are typical of the physical impact of tillage on soils. The occlusion of LFOM is a primary means of physically protecting SOM and the destabilization of aggregates is thought to be the primary mechanism for the reduction in SOM when soils are converted to arable land. Reductions in soil aggregation and associated POM or LFOM following cultivation of native prairie have been related to increased soil respiration (e.g. Grandy and Robertson 2006). Our results on poorly-drained soils confirm the negative impact of cultivation on aggregation and occluded SOM, but differ from other studies where a concurrent increase in soil respiration is observed.

Environmental factors: soil temperature and water content influencing respiration
The destabilization of soil structure and release of aggregate-occluded LFOM in combination with the reductions in microbial biomass (data not shown) that we observed in FIT subplots would also suggest that an increase in easily available C for decomposers should result in accelerated decomposition and respiration. However, losses of C-CO_2 were much lower on FIT plots. Regression analysis indicated that, overall, emissions from chemical fallow subplots were strongly related to the temperature of the soil at 5 cm depth (R^2=0.63**), while emissions from autumn-FIT treatments are correlated with temperature (partial R^2=0.42**) at depth (40 cm). Furthermore, the slope of the temperature-CO_2 emission relationship is very similar in the two treatments. In real terms this result simply means that the peaks in CO_2 emissions under the FIT soils tended to be attenuated in the same way that temperature is attenuated with depth. The slope of the temperature-CO_2 emission relationship in spring-FIT subplots is much lower than that of autumn-FIT and chemical fallow treatments, but this likely due to the aging of the fresh residues as the spring tillage plots were killed with herbicide at the same time as the autumn-FIT and spring-FIT plots. Respiration generally responds in an exponential manner to increases in soil temperature, however in field studies such as these, it is difficult to separate non-linearity associated with the aging of soil residues from non-linearity associated with increased soil temperature. Average temperature during the snow-free season was only one degree warmer at the soil surface (5cm) of chemical fallow treatments, compared 25 cm depth. However in mid summer, there were differences of up to 10^{o}C between 5cm and 15cm and throughout the spring, peak temperatures were on average 5^{o}C greater close to the soil surface than at 15 cm (data not shown). The inversion of the soil profile with FIT places the majority of carbon at roughly 15-20 cm. Due to the exponential response of respiration to temperature differences, it is likely these peak temperatures that result in greater overall respiration.

However a negative effect related to the amount of oxygen in the soil profile (R^2=0.08**) was also observed in FIT plots in the fall. Emissions from spring-FIT were strongly influenced by the amount of oxygen in the soil profile (partial R^2=0.31**), and temperature was only a secondary factor in explaining emissions (partial R^2=0.24**). Temperature and soil water content are understood to be the controlling factors on soil respiration. What is often neglected however is that the relationship between soil water content and soil respiration is a quadratic relationship (Linn and Doran 1984) and emissions tend to decrease as soils approach saturation? Due to the very moist fall of 2007 and summer of 2008, soils were often close to saturation in our case. This point is emphasized by the strong relationship observed between O_2 quantities in the soil profile and emissions in the spring-FIT treatment.

Conclusions
In poorly-drained soils under long-term perennial forages, we observed reductions in soil respiration with full inversion tillage relative to a chemical fallow treatment. The physical placement by FIT of residues and

C deeper in the soil profile where they are exposed to cooler temperatures and when soils are moist, reduced oxygen can reduce soil respiration. Tillage did physically disrupt soil aggregates and appeared to reduce the protection of light fraction organic material. Many studies make the assumption that the physical disruption of soils results in an eventual depletion in C stocks. Our study indicates that in this cool and poorly-drained soil, respiration is largely dependant on environmental factors and not physical protection mechanisms. In the context of climate change it will be important to understand how different soils may react to management practices in order to provide reasonable estimates of C loss under different land use and land management strategies. Carbon loss due to tillage must be estimated and modeled taking into account the complex interactions between the vertical distribution of environmental factors such as soil temperature and water content, and impact of different tillage procedures on physical and physico-chemical protection mechanisms.

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