Carbon budget study using CO₂ flux measurements from a no till system in central Ohio

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Received 11 March 1999; received in revised form 12 August 1999; accepted 25 November 1999

Abstract

Enhancing carbon sequestration in soil is an important means to reduce net emissions of carbon dioxide (CO₂) to the atmosphere. The soil organic carbon (SOC) pool is the net result of carbon (C) input in the form of crop residue and biomass, and output including CO₂ flux and other losses. The objectives of this study were to: (1) determine the influence of known additions of crop residue in a no till system on CO₂ flux measured with the static chamber alkali-absorption method, and (2) calculate the C budget from the CO₂ flux and C added in crop residue. The experiment was started on a Crosby silt loam (Stagnic Luvisol) in 1989. Annually 0, 2, 4, 8 and 16 Mg ha⁻¹ wheat straw (Triticum aestivum L.) was applied. Noon soil temperature and daily CO₂ flux were determined in 1997. Residue application rate had a significant impact on soil temperature as measured at noon, especially early in the growing season. Noon soil temperature was up to 14°C higher under unmulched compared with that of mulched treatments. Measured CO₂ flux ranged from 0.4 to 4.2 g C m⁻² per day. Differences in CO₂ flux between crop residue treatments were not significant on most sampling dates, probably due to the presence of undecomposed residue in the soil which did not contribute to the CO₂ flux, and to variability in sampling. Average daily soil temperature at 5 cm depth determined on a nearby weather station explained 60% of the variation in CO₂ flux from bare plots. The C budget calculated from CO₂ flux measurements indicated a net depletion of SOC in all treatments. However, measured SOC contents indicated an increase of SOC over time in some treatments. It is likely that the annual CO₂ flux measured with the static chamber alkali-absorption method is overestimated due to omission of CO₂ measurements when soil water content is high, and perhaps other, as yet unknown factors. A comparison of the static chamber technique and improved dynamic chamber techniques and micrometeorological methods is recommended. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Carbon dioxide; Greenhouse effect; Mulching; Soil respiration; Static chambers; No till

1. Introduction

Carbon (C) sequestration in soils is gaining increasing acceptance as a means to reduce net carbon dioxide (CO₂) emissions to the atmosphere. Usually, the soil organic carbon (SOC) sequestered is measured directly by dry or wet combustion. The C sequestered in the soil can also be calculated if the C input from crop residue and other sources is known and the amount of C released as CO₂ is measured. The net C sequestration equals the C input (e.g. crop residue) minus the C output (C released as CO₂), assuming that losses due to erosion and leaching are negligible. Information on temporal changes in CO₂ flux during...
the year could indicate which management practices would minimize CO₂ evolution. To be able to use this approach, a suitable method to measure CO₂ flux is needed. Five techniques can be distinguished (De Jong et al., 1979): (1) the soil CO₂ profile method, in which CO₂ concentration in soil air is measured at different depths; (2) the dynamic chamber method, in which the CO₂ concentration of air flowing in and out of a soil chamber is compared; (3) a micrometeorological method above a canopy; (4) a micrometeorological method within a canopy; (5) the static chamber method using the alkali-absorption method. De Jong et al. (1979) reported that the alkali-absorption and the micrometeorological method measuring CO₂ concentrations above a canopy gave the best results. The principal difficulty with the soil CO₂ profile method is the estimation of the CO₂ diffusion coefficient, which is virtually impossible to assess in wet soils. The dynamic chamber method can give low or high values, depending on an increase or decrease in air pressure in the chamber. Kanemasu et al. (1974), for example, observed a 40% difference in measurements using the dynamic chamber method due to pressure differences in chambers. Reicosky et al. (1997) reported 10-fold increases in CO₂ flux under large dynamic chambers compared with that under small dynamic chambers due to pressure differences created by fans. Review of the literature, therefore, indicates that the micrometeorological method measuring CO₂ concentrations above a canopy and the static chamber techniques are currently among the best available methods to measure CO₂ flux. Micrometeorological methods, however, are costly and can only be used if plot size is large. Static chambers are suitable for small plots and can be used with different analytical techniques. For example, Raich et al. (1990) did not find systematic differences between gas chromatography and soda-lime technique in static chambers. If daily CO₂ flux is desired, the alkali-absorption method and the soda-lime technique are most suitable.

Wide variations in CO₂ flux densities are reported in the literature. These differences are partly due to the method used and partly due to actual differences in CO₂ flux caused by various factors like management, climate and soils. Buyanovsky et al. (1986) measured CO₂ flux from a winter wheat (Triticum aestivum L.) ecosystem on a Udolic Ochraqualf in Colombia, MO, and estimated a total annual C loss of 6.4 Mg ha⁻¹ per year. Hendrix et al. (1988) reported CO₂ flux in the order of 10–11 Mg C ha⁻¹ per year under different crop rotations on a Typic Rhodudult in Georgia. Alvarez et al. (1995) reported CO₂ flux of 11.6 Mg C ha⁻¹ per year on a Typic Argiudoll of the Argentinian Pampa. These three studies used the static chamber alkali-absorption method. CO₂ flux can vary considerably throughout the year and is influenced by management. Kanemasu et al. (1974) reported flux of 0.04–0.9 g C m⁻² h⁻¹ from various sources. In the study of De Jong et al. (1979) CO₂ fluxes up to 0.05 g C m⁻² h⁻¹ were reported. Reicosky and Lindstrom (1993), using static chambers and gas chromatography, measured CO₂ flux as high as 7.9 g C m⁻² h⁻¹ immediately after tillage of an Aeric Calciaquoll in Minnesota. Reicosky et al. (1997), using the same technique, measured flux densities of 11.8 g C m⁻² h⁻¹ immediately after plowing a Udic Pellustert in Texas. Dao (1998) measured peak CO₂ flux of 1.3–4.1 g C m⁻² per day (depending on tillage system) on a Paleustoll in Oklahoma using the alkali-absorption method.

In most C budget studies, the amount of C added to the soil in crop residue has to be estimated from empirical approximations. The below-ground biomass is usually the unknown factor. This experiment was, thus, conducted to minimize the below-ground addition of biomass by eliminating crop and weed growth. The objectives were to: (1) determine the influence of known additions of crop residue in a no till system on CO₂ flux measured with the static chamber alkali-absorption method, and (2) calculate the C balance from the CO₂ flux and C added in crop residue.

2. Materials and methods

2.1. Location and treatments

The experiment was located on the Waterman Farm of the Ohio State University, Columbus, OH (40°00’ N latitude and 83°01’ W longitude). Average annual temperature is 11°C and precipitation is 932 mm per year (USDA-SCS, 1980). The soil is a Crosby silt loam (fine, mixed mesic Aeric Ochraqualf in the USDA classification, and a Stagnic Luvisol in the FAO classification). All treatments were under no till. Residue management treatments were 0, 2, 4, 8 and
16 Mg ha\(^{-1}\) per year air dry wheat straw applied on plots of 2×2 m\(^2\) area, with three replications. It was observed that residue rapidly compacted after a rainstorm (very frequent around the time of residue application) and therefore no special measures were taken to keep the straw on the plots. C content of the air dry wheat straw was 0.413 g g\(^{-1}\)±0.004. The typical nutrient content of wheat straw is: 0.006 g g\(^{-1}\) N, 0.002 g g\(^{-1}\) S, 0.006 g g\(^{-1}\) K, and 0.001 g g\(^{-1}\) P (Russell, 1973). Crop residue was applied each spring. No crop was planted and therefore no fertilizer was applied. *Glyphosate* (phosphonomethyl glycie) was used to control weeds as and when needed.

### 2.2. Temperature and SOC measurements

Continuously measured air and soil temperature data for Waterman Farm were obtained from the Ohio Agricultural Research and Development Center (OARDC, Wooster, OH). The OARDC measures air temperature in a non-aspirated shelter at 1.5 m and soil temperature 5 cm below a bare surface. Precipitation is measured with a daily recording raingauge. The soil temperature in the mulch experiment was measured on the days when CO\(_2\) flux was sampled using copper-

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**Fig. 1.** Static chamber set-up used to measure CO\(_2\) flux in this experiment.
Measurements were taken approximately every 2 weeks from April to October 1997, never less than 2 days after a rain shower. At the start of a measurement a glass jar filled with 20.0 ml of 1.0 M NaOH was placed on a perforated PVC ring in a cylinder which was then closed with a white PVC cap. The rim was filled with water to ensure sealing. The jars were left for 24 h in the closed cylinders after which they were removed, closed with a parafin-paper sealed metal lid and transported to the laboratory for analysis. Excess NaOH was titrated to pH 8.2 in the presence of excess BaCl₂ using 0.85 M HCl and phenolphtalein as indicator.

2.4. Statistical analysis and calculations

Mean soil temperature was separated by the LSD test at $p=0.05$. Annual C balance was calculated using CO₂-C flux measurements and crop residue C applied, assuming C losses due to leaching and erosion were negligible. The area under each curve was computed using the trapezoid rule: $(\text{CO}_2\text{-C flux on day } A+\text{CO}_2\text{-C flux on day } B)/2 \times (\text{number of days between } A \text{ and } B)$, assuming that on the first of February the CO₂ flux was 0 g C m⁻² per day from all treatments.

3. Results and discussion

3.1. Air and soil temperature

Average daily air and soil temperature and daily precipitation measured on Waterman Farm are presented in Fig. 2. In spring, soil temperature was lower than air temperature. In summer and autumn, air temperature was usually lower than bare soil temperature. Differences in air and soil temperature may have been due to the residual heat of the soil, soil warming by solar radiation and protection against wind. Precipitation events were evenly distributed throughout the period of analysis, except for a drier period from September to October. Total precipitation from 1 April to 10 October (the period in which CO₂ flux measurements were made) was 700 mm. Soil temperature at 5 cm depth under a bare surface could be predicted from the air temperature by the equation: soil temperature = 1.67 + 0.80 × (air temperature)¹.⁰⁶ for air temperature $≥0°C$ and soil temperature = 1.67 for air temperature $<0°C$ ($r²=0.93$). Our analysis indicates that it may be possible to use average daily air temperature to approximate soil temperature if the relationship between the two for a particular management system is known.

Fig. 2. Air and soil temperature and precipitation at Waterman Farm, Columbus, OH, 1997.
Noon soil temperature was found to be strongly influenced by crop residue rate (Table 1). Soil temperature on bare plots was usually higher at noon compared with temperature on plots receiving residue. On clear days, noon soil temperature was often above the maximum air temperature on these bare plots due to warming of the soil surface. The crop residue on the surface dampened the temperature increase. For example, on April 11 noon soil temperature under the 0 Mg ha\(^{-1}\) residue plots was 14\(^\circ\)C higher than that in other plots. The reduction of afternoon soil temperature by organic mulch due to its low apparent thermal conductivity has been reported by several other researchers (Lal, 1974; Mbagwu, 1991; Schonbeck and Evanylo, 1998; Van Donk and Tollner, 1998). Differences in soil temperature in the treatments 2–16 Mg ha\(^{-1}\) per year crop residue were negligible. In September, differences in soil temperature between the 0 Mg ha\(^{-1}\) per year residue treatment and the other crop residue treatments became smaller, although they were still significant. The decreasing soil temperature differences have been due to the increasing compaction and decomposition of the residue (and thus less insulation) and the decrease of its albedo (and therefore less reflection). Autumn soil temperature followed a consistent trend of decreasing noon soil temperature associated with increasing crop residue levels.

3.2. \(\text{CO}_2\) flux

The \(\text{CO}_2\) flux was the highest from the 16 Mg ha\(^{-1}\) per year crop residue treatment in 7 out of 13 sampling dates, and lowest from the 0 Mg ha\(^{-1}\) per year treatment in 8 out of 13 sampling dates (Table 2). Differences in soil temperature between the 0 Mg ha\(^{-1}\) per year residue treatment and the other crop residue treatments became smaller, although they were still significant. The decreasing soil temperature differences have been due to the increasing compaction and decomposition of the residue (and thus less insulation) and the decrease of its albedo (and therefore less reflection). Autumn soil temperature followed a consistent trend of decreasing noon soil temperature associated with increasing crop residue levels.

### Table 1
Residue application rate effects on noon soil temperature (\(^\circ\)C) for selected dates in 1997

<table>
<thead>
<tr>
<th>Date</th>
<th>Air temperature</th>
<th>Noon soil temperature at 5 cm depth under different residue rates (Mg ha(^{-1}) per year)</th>
<th>LSD(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
<td>0</td>
</tr>
<tr>
<td>April 11</td>
<td>10.1</td>
<td>16.6</td>
<td>21.3</td>
</tr>
<tr>
<td>April 18</td>
<td>8.1</td>
<td>14.3</td>
<td>16.8</td>
</tr>
<tr>
<td>April 19</td>
<td>9.3</td>
<td>16.4</td>
<td>20.5</td>
</tr>
<tr>
<td>July 4</td>
<td>13.7</td>
<td>19.3</td>
<td>24.3</td>
</tr>
<tr>
<td>September 15</td>
<td>21.6</td>
<td>28.2</td>
<td>23.6</td>
</tr>
<tr>
<td>September 16</td>
<td>22.0</td>
<td>29.1</td>
<td>24.3</td>
</tr>
</tbody>
</table>

\(^{a}\) Least significant difference (\(p=0.05\)).

### Table 2
Residue application rate effect on average \(\text{CO}_2\) flux (g C m\(^{-2}\) per day ± standard deviation) in 1997

<table>
<thead>
<tr>
<th>Day</th>
<th>Residue application rate (Mg ha(^{-1}) per year)</th>
<th>LSD(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>April 11</td>
<td>0.50±0.09</td>
<td>1.20±0.45</td>
</tr>
<tr>
<td>April 18</td>
<td>0.45±0.05</td>
<td>1.18±0.28</td>
</tr>
<tr>
<td>April 30</td>
<td>0.81±0.41</td>
<td>1.47±0.43</td>
</tr>
<tr>
<td>May 22</td>
<td>1.00±0.42</td>
<td>2.04±0.73</td>
</tr>
<tr>
<td>June 6</td>
<td>1.88±1.09</td>
<td>3.25±2.52</td>
</tr>
<tr>
<td>June 17</td>
<td>0.79±0.46</td>
<td>3.23±2.07</td>
</tr>
<tr>
<td>June 20</td>
<td>1.84±0.43</td>
<td>3.74±2.29</td>
</tr>
<tr>
<td>July 4</td>
<td>2.94±1.00</td>
<td>4.17±3.33</td>
</tr>
<tr>
<td>July 16</td>
<td>2.65±0.85</td>
<td>2.87±1.32</td>
</tr>
<tr>
<td>July 30</td>
<td>1.99±0.92</td>
<td>3.33±1.64</td>
</tr>
<tr>
<td>August 25</td>
<td>3.43±1.40</td>
<td>3.73±1.02</td>
</tr>
<tr>
<td>September 15</td>
<td>1.57±0.56</td>
<td>1.96±0.86</td>
</tr>
<tr>
<td>October 1</td>
<td>0.78±0.71</td>
<td>0.81±0.58</td>
</tr>
</tbody>
</table>

\(^{a}\) Least significant difference (\(p=0.05\)).
between treatments were mostly non-significant, however. The CO₂ flux increased at the same time as did air and bare-soil temperature in spring (Fig. 2). The evolution of CO₂ flux over the year in this experiment is comparable with other studies (Buyanovsky et al., 1986; Hendrix et al., 1988; Alvarez et al., 1995; Fortin et al., 1996) and indicates a relationship between soil temperature and CO₂ flux. Analysis of the relationship between CO₂ flux from bare plots and the average daily soil temperature measured at 5 cm depth at the weather station of Waterman Farm gave a correlation coefficient ($r^2$) of 0.60 (CO₂ flux = $-0.22 + 0.02 \times$ (soil temperature)$^{1.49}$). If simulated soil temperature (Section 3.1) was used instead of measured soil temperature, the best regression equation was $\hat{y} = -0.42 + 0.11 \times$ (simulated soil temperature) ($r^2 = 0.45$). The correlation coefficients can probably be improved if soil water content is also taken into account because other authors have reported soil temperature combined with soil water content to be reasonable predictors of CO₂ flux (Franzenluebbers et al. 1994, 1995a). However, due to insufficient precision of soil water content measurements with gypsum blocks no relationship could be established between soil water content and CO₂ flux. No significant relationship was observed between noon soil temperature on the sampling dates and CO₂ flux.

The high spring soil temperature in the 0 Mg ha$^{-1}$ per year treatment may have had little effect on CO₂ flux due to a lack of substrate in the surface soil (low SOC levels) and a drier soil surface than in the other treatments. However, the CO₂ flux for the 0 Mg ha$^{-1}$ per year treatment was high from the end of June to the end of August, and comparable to the flux from plots receiving crop residue. This may mean that mineralization of SOC from deeper soil layers contributed to the CO₂ flux.

After mid-May CO₂ emission from the plots receiving 16 Mg ha$^{-1}$ per year residue was the highest, and remained among the highest until July. In early October the CO₂ flux densities from the 0, 2, 4, and 8 Mg ha$^{-1}$ per year residue plots were similar, while that of the plots receiving 16 Mg ha$^{-1}$ per year was higher. The reason may be the thick residue layer on the plots receiving 16 Mg ha$^{-1}$ per year which resulted in higher night temperature and higher humidity. The effect of the other residue rates (<16 Mg ha$^{-1}$ per year) on soil temperature had already declined by autumn due to compaction and destruction of the thinner straw layer by soil fauna. Soil temperature measurements in the early morning in autumn (not shown) confirmed that soil temperature was 1–3°C higher under the 16 Mg ha$^{-1}$ per year plots compared with the other treatments.

The lack of a significant difference of the CO₂ flux between the 0 Mg ha$^{-1}$ per year treatment and the other treatments is remarkable. Considering limited differences in SOC contents between treatments (Table 3) one would expect much higher CO₂ losses from treatments receiving much crop residue compared with those receiving little or no crop residue. A possible explanation of this may be the presence of undecomposed crop residue lying on the soil surface and perhaps incorporated into the soil by faunal activity which was not determined as SOC.

The high variability in the measured CO₂ flux may be attributed to variability in soil properties between replications within treatments. That being the case, the CO₂ flux measured from individual chambers would be systematically different, because the chambers were not moved during the year. Results for each chamber are presented in Fig. 3 with a third degree polynomial function relating day in the year to CO₂ flux fitted through the measurements. The third degree polynomial function relating day in the year to CO₂ flux fitted through the measurements.

### Table 3
Calculation of annual C budget (1997)

<table>
<thead>
<tr>
<th>Annual residue application rate (Mg ha$^{-1}$ per year)</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Total CO₂–C flux (Mg C ha$^{-1}$ per year)</td>
<td>3.84</td>
<td>5.64</td>
<td>4.51</td>
<td>5.34</td>
<td>6.63</td>
</tr>
<tr>
<td>(B) Total crop residue-C added (Mg C ha$^{-1}$ per year)</td>
<td>0.00</td>
<td>0.83</td>
<td>1.65</td>
<td>3.30</td>
<td>6.61</td>
</tr>
<tr>
<td>(B)−(A) (Mg C ha$^{-1}$ per year)</td>
<td>−3.84</td>
<td>−4.81</td>
<td>−2.86</td>
<td>−2.04</td>
<td>−0.02</td>
</tr>
<tr>
<td>SOC contents (0–10 cm) (Mg C ha$^{-1}$)</td>
<td>10.1</td>
<td>11.5</td>
<td>10.7</td>
<td>11.2</td>
<td>14.0</td>
</tr>
</tbody>
</table>
polynomial function gave a reasonable fit, explaining from 56 to 93% of the variation in CO₂ flux during the year for each individual chamber. The fact that most often the regression curves do not cross indicates that at least some variability in the measurements was due to spatial variation in soil properties between replications of the same treatment. Exceptions to this are the 8 and 16 Mg ha⁻¹ per year treatments. Replicate 3 of the 8 Mg ha⁻¹ per year treatment had higher CO₂ flux than replicate 2 until July, when this trend was...
reversed. Replicate 2 of the 16 Mg ha\(^{-1}\) per year treatment had higher CO\(_2\) flux than the other two replicates until July, after which the CO\(_2\) flux from the other two replicates was higher. There are also some exceptionally high flux measurements in most treatments at some time, for example, in June for replicate 2 of the 2 Mg ha\(^{-1}\) per year as well as the 16 Mg ha\(^{-1}\) per year treatment. These peaks may indicate bursts of microbiological activity which apparently do not take place at the same moment for all treatments or replicates. The absence of consistently higher or lower CO\(_2\) flux measurements from certain replicates over others indicates that CO\(_2\) flux is also highly variable temporally. This may be due to variability over time in factors like porosity, drainage, SOC content, or earthworm and microbial population.

### 3.3. C budget calculation

Although comparison of relative CO\(_2\) flux measurements using the static chamber technique are valid, there is uncertainty about the accuracy of the absolute CO\(_2\) flux measured with this method (Anderson, 1982). The magnitude of the calculated annual CO\(_2\) flux (Table 3) is comparable to reports in the literature (Buyanovsky et al., 1986; Hendrix et al., 1988; Alvarez et al., 1995). Total C lost as CO\(_2\) followed the order: 16>2>4>8>0 Mg ha\(^{-1}\) per year. The higher CO\(_2\) flux from the 16 Mg ha\(^{-1}\) per year residue treatment is due partly to higher CO\(_2\) flux during the year and partly because on the last sampling date CO\(_2\) flux was higher than that of the other treatments. The higher soil humidity under the 16 Mg ha\(^{-1}\) per year treatment in autumn may have led to higher flux but it is unlikely that this continued to be important after October with the onset of rains in the autumn. However, no measurements were made to confirm this.

The C budget calculations indicate that there was a net loss of C in all treatments. The losses were highest under the low crop residue application rates and decreased with increasing residue rate. Calculated C losses were very high and would have led to depletion of SOC content in the top 10 cm of the soil in a period of 3–4 years for the 0 and 2 Mg ha\(^{-1}\) per year treatments. The data on SOC contents, however, indicate that SOC contents did not decrease in the treatments receiving more than 2 Mg ha\(^{-1}\) per year of residue (Duiker and Lal, 1999). Peterson et al. (1998) reported that, under no till management in the Great Plains of the USA, each Mg ha\(^{-1}\) of residue returned to the soil increased SOC content by 1.52 g kg\(^{-1}\) indicating that at least part of the C added to the soil in residue was converted into SOC. Franzenluebbers et al. (1995a,b) employing the static-chamber alkali-absorption technique in a 9-year old experiment in south central Texas, reported mostly higher measured CO\(_2\)-C losses than C-inputs in crop residue. In both studies, however, SOC content had increased since the initiation of the experiment. The CO\(_2\) flux measurements in the experiments by Franzenluebbers et al. were made at night, when CO\(_2\) flux would be expected to be lower than during the day due to lower temperature (Grahammer et al., 1991), indicating that CO\(_2\) flux might have been higher if day time measurements were included. There are different explanations possible for the apparent overestimation of the CO\(_2\) flux employing the static chamber alkali-absorption method. First, measurement of CO\(_2\) flux on dry days may lead to an overestimation because lower flux may have occurred during periods of high soil water content. High soil water content decreases decomposition rates because anaerobic microbiological activity dominates over aerobic activity when air filled porosity decreases below 20–30% (Linn and Doran, 1984). Additionally, gas exchange with the atmosphere is more difficult. Franzenluebbers et al. (1995a) reported an increase of average CO\(_2\) flux with increase in water fillable pore space below 90%, although in individual treatments the relationship was sometimes negative. Franzenluebbers et al. (1995b) observed a mixed effect of soil water content on soil CO\(_2\) flux. Secondly, it may be suggested that high ambient temperature and humidity inside the static chambers may lead to higher decomposition rates compared with the outside of the chamber. A positive relationship between CO\(_2\) flux and soil temperature has been reported by many researchers (Franzenluebbers et al., 1995a,b; Fortin et al., 1996), although in warm, dry climates soil temperature effects are overruled by soil water content (Franzenluebbers et al., 1994). It is not evident, however, that the average soil temperature will be higher under the chamber than outside of the chamber, because soil inside the chamber is not exposed to direct sun light. Providing shade above the chambers would artificially reduce temperature further. High ambient humidity inside the chamber may not have
much effect on decomposition of SOC, because the relative humidity of the soil atmosphere approaches 100% except in extremely dry soils. There is therefore no straightforward explanation of the apparent overestimation of CO$_2$ flux with the static chamber alkali-absorption technique except for the omission of measurements on soils with a water content exceeding 80%. A comparison of the static chamber technique with improved dynamic chamber techniques that avoid high or low pressure inside the chamber (Rayment and Jarvis, 1997) and micrometeorological methods is therefore recommended to resolve some of these questions.

4. Conclusions

Residue application had a significant impact on noon soil temperature. The difference was large between unmulched and mulched treatments. Among the plots that received from 2 to 16 Mg ha$^{-1}$ per year crop residue noon soil temperature differences were negligible from spring until autumn. Measured CO$_2$ flux ranged from 0.4 to 4.2 g C m$^{-2}$ per day, comparable to fluxes reported in the literature employing the same method. Although the total calculated CO$_2$ flux from the 0 Mg ha$^{-1}$ per year treatment was lower than that from the other treatments, there was not a consistent relationship between CO$_2$ flux and the amount of mulch applied. An explanation of this phenomenon may be the presence of undecomposed mulch in the soil (larger than 0.1 mm) that was not determined in our method of SOC determination. Another possible explanation, supported by the high spatial and temporal variability in CO$_2$ flux measurements, is that peaks (and dips) in CO$_2$ flux are missed in the sampling scheme. Calculation of the annual C balance based on measured CO$_2$ flux and C added to the soil in crop residue indicated a net depletion of SOC content in all treatments except for the 16 Mg ha$^{-1}$ per year treatment. This did not correspond with measured SOC content which increased with crop residue application. The annual CO$_2$ flux calculations apparently overestimate CO$_2$ flux due to timing of measurements and perhaps other, unknown factors. These problems may be partly resolved by measuring CO$_2$ flux at shorter time intervals (especially during and after rainshowers). High humidity and temperature of the atmosphere inside the chambers are not considered valid reasons for high CO$_2$ flux because humidity and temperature of the soil are not likely to be higher under the chambers compared with that outside of the chambers. The variability of CO$_2$ measurements was high, both spatially and temporally, attributed to variations in soil properties like porosity, drainage, SOC content, microbial and earthworm populations and activity. A comparison of the static chamber alkali-absorption technique with improved dynamic chamber techniques and micrometeorological methods is recommended to resolve the question of overestimation of CO$_2$ flux with this method.

References


