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Sampling soil-derived CO₂ for analysis of isotopic composition: a comparison of different techniques

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A new system for soil respiration measurement [P. Rochette, L.B. Flanagan, E.G. Gregorich. Separating soil respiration into plant and soil components using analyses of the natural abundance of carbon-13. Soil Sci. Soc. Am. J., 63, 1207–1213 (1999).] was modified in order to collect soil-derived CO₂ for stable isotope analysis. The aim of this study was to assess the suitability of this modified soil respiration system to determine the isotopic composition (δ¹³C) of soil CO₂ efflux and to measure, at the same time, the soil CO₂ efflux rate, with the further advantage of collecting only one air sample. A comparison between different methods of air collection from the soil was carried out in a laboratory experiment. Our system, as well as the other dynamic chamber approach tested, appeared to sample the soil CO₂, which is enriched with respect to the soil CO₂ efflux, probably because of a mass dependent fractionation during diffusion and because of the atmospheric contribution in the upper soil layer. On the contrary, the static accumulation of CO₂ into the chamber headspace allows sampling of δ¹³C-CO₂ of soil CO₂ efflux.

Keywords: Carbon-13; Carbon dioxide; Respiration; Sampling; Soil

1. Introduction

Carbon isotopes are widely used to understand carbon dynamics in soils as well as to disentangle the soil respiration into root and microbial contributions [1–6]. Flux-based measurements allow to quantify the behaviour and shifts in the components of below-ground C balance as well as to put boundaries on the environmental conditions responsible for the observed changes. Isotope-based measurements permit to identify the contribution of the sources (e.g., autotrophic vs. heterotrophic) of the C-fluxes linking plant and microbial function to the
observed fluxes. Accurate measurements of root and soil organic matter respiration are essential in ecological studies of terrestrial carbon budgets, from the ecosystem to the global scale, because the annual flux of CO2 from soils to the atmosphere is 10 times higher than that derived from fossil fuel combustion [7], and it is susceptible to increase in response to climatic changes [8].

Previous studies [9–11] defined the ‘soil-respired CO2’ as the CO2 coming off the soil, thus reflecting the $\delta^{13}$C-CO2 coming from the decomposition of the organic substrates, which represent the CO2 of the source. In contrast, the ‘soil CO2’, which indicates the CO2 that fills the soil pore air space, is enriched in $^{13}$CO2 by a theoretical minimum of 4.4 ‰, with respect to the respired $\delta^{13}$C-CO2 [12], because of the isotopic fractionation derived from a mass dependent diffusion effect at the steady state. Furthermore, in the upper layers of the soil profile, there is a further enrichment because of the atmospheric contribution, which depends on the efflux rate and the soil porosity. Amundson et al. [11] suggested a theoretical model to describe the vertical soil profile of CO2 isotopic composition ($\delta^{13}$C-CO2), taking into account all of these issues.

There is no unique method to measure the $\delta^{13}$C-CO2 of the soil efflux [13–15], although the Keeling plot model is one of the most frequently used. However, as it requires a large number of samples for each measurement, it is not suitable for sampling the variability in space and time in the field. The aim of this study was to obtain a method for the measurement of $\delta^{13}$C-CO2 of soil efflux, employing equipment that is reliable and portable in the field, and that allows simultaneous determination of CO2 soil efflux and of its isotopic composition, with a very limited number of air samples to analyse. For this purpose, the constant concentration (CC) system, previously described by Subke et al. [16], was implemented for collection of soil-derived CO2 (figure 1). We hypothesized that the soil CO2 efflux sampling, by the modified CC system, does not affect the soil CO2 profile and thus captures the ‘soil-respired CO2’. A comparison between different sampling setups was performed to assess this hypothesis. At the same time, all the inputs to simulate the $\delta^{13}$C-CO2 of the soil vertical profile were measured.

2. Materials and methods

2.1 Experimental setup

A large gardening pot (40 cm at base, 50 cm at the top) was filled to a depth of 35 cm with well-mixed mineral soil and fresh gardening compost. A collar (12 cm high and 25 cm OD) was
positioned inside the pot with about 6 cm insertion depth and connected to a soil respiration chamber, on which the tube pathway was changed according to the different setups used for soil CO2 sampling (discussed subsequently). The air mixing into the chamber headspace is ensured by a ring-shaped air inlet and the pump flow (adjustable in a range of about 200–800 ml min\(^{-1}\)). All the sampling procedures were replicated randomly at least three times and were performed as follows.

2.2 CC system

The CC method gives reliable respiration rate measurements at the steady state by keeping the concentration within the chamber headspace at ambient CO2 level [16]. A soil CO2 efflux measurement is obtained by regulating the pump speed \(P_2\) and thus the air volume flow across the CO2 absorber, so that the CO2 concentration inside the chamber remains constant at ambient levels. At this equilibrium state, the amount of CO2 entering the chamber from the soil is balanced by the amount of CO2 absorbed by sodalime, and the soil CO2 efflux rate \((\mu\text{mol m}^{-2}\text{s}^{-1})\) can be calculated as \(F_s C_i A^{-1}\), where \(F_s\) is the mass flow \((\text{mol s}^{-1})\) across sodalime, \(C_i\) the CO2 concentration \((\mu\text{mol mol}^{-1})\) and \(A\) the chamber area \((\text{m}^2)\).

A CC system, previously described by Subke et al. [16], was modified for collection of soil-derived CO2 into a 2 l flask, which was placed before the CO2 and H2O scrubbers (figure 1a), to subsequently measure the \(\delta^{13}\text{C-CO2}\) off-line, by collecting only one flask. The 2 l flasks were Pyrex® made and sealed with two Rotaflo® stopcocks (Bibby Sterilin, UK) certified for a vacuum level of \(10^{-6}\ \text{mbar}\) and a vacuum leakage rate in the order of \(10^{-9}\ \text{mbar l s}^{-1}\) at 20°C.

Depending on the soil CO2 efflux rate, the system volume (including every part of the sampling path) and the ambient CO2 concentration, a simple mixing model can be used to calculate for how long the internal volume of air needs flushing through the system to substitute 99% of the atmospheric CO2 with soil-derived CO2 in the close system. During this experiment, the soil efflux ranged between 1.91 and 2.98 \(\mu\text{mol m}^{-2}\text{s}^{-1}\), thus the time required to substitute the initial air in the overall system volume ranged between 50 and 60 min (table 1), whereas the air residence time into the chamber headspace ranged between 6 and 8 min.

2.3 Static accumulation system

This setup is very simple, requiring only one connection between the chamber headspace and a flask, which needs to be previously evacuated to high vacuum (figure 1c). In a closed static mode (MB 1), a 2 l vacuum flask was collected after 40 min of CO2 accumulation in the chamber headspace. At the same time, a second 2 l vacuum flask was collected for the

<table>
<thead>
<tr>
<th>Method</th>
<th>CC</th>
<th>MB 1</th>
<th>MB 2</th>
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<tbody>
<tr>
<td>Soil boundary layer†</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Steady state‡</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Air recirculation</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sampling interval</td>
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<td>40 min</td>
<td>5–15 min</td>
</tr>
<tr>
<td>([\Delta\text{CO2}](\mu\text{mol mol}^{-1}))</td>
<td>0</td>
<td>&gt;500</td>
<td>&gt;100</td>
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<tr>
<td>Flask conditioning</td>
<td>Ambient air</td>
<td>Evacuated</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Number of air samples</td>
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<td>2</td>
<td>2</td>
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</table>

†The soil boundary layer implies a dynamic behaviour within the chamber headspace.
‡The steady state implies a constant CO2 concentration and a constant flow through the chamber headspace during the sampling interval.
measurement of the $\delta^{13}$C-CO$_2$ of ambient air. The mass balance approach is referred to the atmospheric background, with the second flask sampling air just outside the chamber. It is worth noting that this is not a Keeling plot type model [14], but a simple two-end member mass balance. In other words, the second collected flask has an isotopic composition ($\delta^{13}$C$_2$) because of the initial $\delta^{13}$C-CO$_2$ plus the soil-derived CO$_2$ ($\delta^{13}$C$_{in}$), and the latter can be calculated as follows:

$$\delta^{13}$C$_{in} = \frac{\delta^{13}$C$_2$[CO$_2$]$_2 - \delta^{13}$C$_1$[CO$_2$]$_1}{[CO$_2$]$_2 - [CO$_2$]$_1$$}$$ (1)

2.4 **Close dynamic system**

In a close dynamic system (MB 2, figure 1b), the soil-derived CO$_2$ was circulated from the chamber through two nitrogen preconditioned 2 l flasks, in parallel, and the IRGA [14, 15] with a residence time in the chamber headspace of about 5 min. Following are the operational steps: (1) connect the MB 2 system to the chamber; (2) open the stopcocks to both N$_2$ conditioned flasks; (3) place the chamber onto the collar and immediately begin air circulation from the chamber through both flasks and IRGA; (3) wait for a period of time to allow circulation to evenly mix the CO$_2$-free air from the two flasks with the chamber air; (4) once the air is evenly mixed by observing the damping of CO$_2$ fluctuations on the Licor, close off the stopcocks to flask 1 to take the first sample at about ambient CO$_2$ concentration; (5) wait for a period of time to allow an additional amount of CO$_2$ to accumulate in the sampling volume (table 1); and (6) close off the stopcocks to flask 2 to take the second sample.

In this case, the mass balance is not considering the atmospheric background but just the first air sample, which has, at ambient CO$_2$ concentration, a different isotopic composition due to the dilution with the nitrogen of the initial air into the chamber headspace and to the contribution from the soil-derived CO$_2$, and the equation we used is the same as for MB 1.

2.5 **Sampling for determination of $\delta^{13}$C-CO$_2$ of soil air and of CO$_2$ source**

The soil $\delta^{13}$C-CO$_2$ was obtained by probe sampling of soil CO$_2$. The probe, inserted within the soil to a depth of about 20 cm, was connected to a nitrogen filled 2 l flask, equilibrated for a week with the soil CO$_2$ by diffusion.

The isotopic composition of the source material was determined by incubation over 2 days in 1 l glass jars [13] of soil subsamples, in five replicates. Each of the five soil subsamples was taken from the pot in the five subsequent days over which the experiment took place. An amount of 100 g of soil was collected from the pot and incubated in an air-tight jar. The air inside jars was then flushed through sodalime until it reached 0 ppm of CO$_2$, checked by an infrared gas analyser (Li-Cor 840, Li-Cor, Inc., Lincoln, Nebraska, USA). Jars were kept closed in the dark at the same temperature of the soil pot (which ranged from 22 to 23°C) for 2 days and then directly connected to a cryogenic line for the CO$_2$ purification [17]; a sodalime-filled tube was connected to the jar to keep the pressure in the jar at atmospheric level.

2.6 **Measurement of CO$_2$ concentrations and $\delta^{13}$C-CO$_2$**

The CO$_2$ concentration of the air sampled in vacuum flasks was determined barometrically by the pressure gauge in the isotope ratio mass spectrometry (IRMS) variable-volume bellow
CO₂ sampling of soil

calibrated with different amounts of cryogenically purified CO₂ from known CO₂ concentration air samples, with an uncertainty of 22 µmol mol⁻¹. For the MB 2 and CC setups, CO₂ concentrations were measured by an infrared gas analyser (Li-Cor 840, Li-Cor, Inc.).

From each flask, the CO₂ was concentrated via cryogenic purification and the δ¹³Cₚδ was determined by stable IRMS (Deltaplus, Thermofinnigan, DE), which for δ¹³Cₚδ has a precision of 0.04 ‰ (because of the uncertainty introduced by the use of solid copper for the reduction of N₂O to N₂ at 500 °C) and an accuracy of 0.09 ‰ [17]. A cylinder of CO₂ in air certificated from CSIRO Atmospheric Research (Aspendale, Australia), was cryogenized and analysed among samples for data quality control.

2.7 Soil δ¹³C-CO₂ vertical profile model

We adapted the model of Amundson et al. [11] to our study case, measuring all the input variables to assess the results obtained by the different sampling techniques. We assumed the same diffusion coefficient as for CO₂ diffusion in air, and for ¹³CO₂ diffusion coefficient, we took into account the theoretical difference of 4.4 ‰. Thus, the soil δ¹³C-CO₂ vertical profile was simulated to derive δ¹³C-CO₂ of soil CO₂ efflux and of CO₂ source, and the results were compared with those obtained by the experimental soil chamber samplings described earlier. As model input, the soil efflux rate derived from the CC measurement, the source δ¹³C-CO₂ derived from the jar incubation and the atmospheric δ¹³C-CO₂ from the MB 1 outside chamber flask collection were used (figure 2).

Figure 2. Modelled δ¹³C-CO₂ vertical profile in the pot, for the first of three replicated sampling by the CC system. Adapted from Amundson et al. [11].
3. Results and discussions

The CC setup and the MB 2 approach measure $\delta^{13}$C-CO$_2$ values of $-18.56\%$o ($\pm 0.40\%$o) and $-18.35\%$o ($\pm 0.40\%$o), respectively, which are similar to the $\delta^{13}$C-CO$_2$ value of the ‘soil CO$_2$’ as measured by the soil probe, despite fundamentally different sampling pathways and intervals (figure 3 and table 2). In contrast, the MB 1 approach measures a $\delta^{13}$C-CO$_2$ value of $-24.25\%$o ($\pm 2.1\%$o), which is consistent with the $\delta^{13}$C-CO$_2$ value of $-23.69\%$o ($\pm 0.27\%$o) of the soil CO$_2$ source, as measured from the jar incubation, but with significantly higher uncertainty when compared with the other methods (figure 3). A large part of the uncertainty associated with this method is due to the necessity of having very precise CO$_2$ concentration measurements and a larger number of samples. However, the strong disturbance of the soil profile, due to the high concentration reached inside the chamber, does not seem to be critical for the measurement of the $\delta^{13}$C-CO$_2$ soil efflux. Judging from the results of this experiment, the accumulation in the chamber headspace appears to eliminate the mass dependent diffusion effect occurring during soil respiration due to the large amount of CO$_2$ coming from the source. Additionally, the MB 1 technique takes into account the atmospheric contribution.

The soil $\delta^{13}$C-CO$_2$ similarity obtained with the two dynamic methods (i.e., CC $-18.56 \pm 0.40\%$o SD and MB 2 $-18.35 \pm 0.40\%$o SD) supports the idea that they are not sampling the isotopic composition of the source, but rather of soil air, which carries a very similar $\delta^{13}$C-CO$_2$ signal ($-19.4 \pm 0.15\%$o SD). A possible explanation could be that the soil chamber equilibrates with the pore air at the insertion depth, thus a horizontal $^{13}$CO$_2$ flux exchange establishes because of the mixing of the atmospheric $^{13}$CO$_2$ near the soil surface [11]. For that reason, the CC and MB 2 systems result in the collection of air samples composed of a mixture of source CO$_2$ and atmospheric CO$_2$. Nevertheless, the $\delta^{13}$C-CO$_2$ efflux values can be estimated from MB 2 and CC data using the model of Amundson et al. [11], to simulate the atmospheric contribution to the soil CO$_2$ at the collar insertion depth (figure 2). Indeed, a good agreement was obtained between the mean of the modelled values ($-23.97 \pm 0.82\%$o SD) and the jar incubation mean ($-23.69 \pm 0.27\%$o SD).

![Figure 3. $\delta^{13}$C-CO$_2$ measured from air samples collected with different setups. Error bars are standard deviations.](image-url)
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<tr>
<td>[CO₂] (µmol mol⁻¹†)</td>
<td>[CO₂] (µmol mol⁻¹†)</td>
<td>δ¹³C-CO₂</td>
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<tr>
<td>480</td>
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<td>-18.6</td>
</tr>
<tr>
<td>410</td>
<td>907</td>
<td>-18.52</td>
</tr>
<tr>
<td>410</td>
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<td>-18.56</td>
</tr>
<tr>
<td>472</td>
<td>946</td>
<td>-18.387</td>
</tr>
<tr>
<td>495</td>
<td>737</td>
<td>-19.282</td>
</tr>
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† ± 1 µmol mol⁻¹ SD.
‡ ± 22 µmol mol⁻¹ SD.
4. Conclusions

This experiment indicates that the methodological approaches which proved to give the most reliable determination of soil CO$_2$ efflux rate (i.e., no disruption of soil CO$_2$ vertical gradient, air mixing within the chamber headspace [18]) are not necessarily the best methods to determine the $\delta^{13}$C-CO$_2$ of the soil efflux source. In fact, the CC appears to act as a large air-filled soil pore in equilibrium with the soil $\delta^{13}$C-CO$_2$ at the collar insertion depth, because of the replacement within the chamber of atmospheric CO$_2$ with soil-derived CO$_2$, removing the undisturbed $^{13}$CO$_2$ gradient. We interpret this result suggesting that our CC system samples soil CO$_2$ for reproducible measurements of $\delta^{13}$C-CO$_2$ (0.4‰ SD), at the collar insertion depth, and that $\delta^{13}$C-CO$_2$ of soil efflux can be derived by applying a soil diffusion model [11].

Infrared laser spectroscopy, with tuneable diode laser (TDL), has reached a level of precision and accuracy for measurements at ambient CO$_2$ concentration, which are comparable to the sampling techniques relying on IRMS [19]. TDL measurements require less than 31 of sample air and produce results within 10 min and would therefore provide a valuable improvement of these soil air sampling techniques. At present, measurements are limited by the small number of samples that can be obtained using sampling flasks and the time needed for analysis, both of which would be considerably improved if a TDL could be used on-line. Such a setup would open new investigation possibilities for isotopic composition of sources at natural abundance in a number of terrestrial ecosystems, where, at present, uncertainties due to large standard errors caused by the limited number of samples obtained prohibit the detection of significant differences between source contributions.

Acknowledgements

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References


