

SOIL RESPIRATION IN FOREST ECOSYSTEMS: COMBINATION OF A MULTILAYER APPROACH AND AN ISOTOPIC SIGNAL ANALYSIS

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INTRODUCTION

One of the key questions in climate change research relates to the future dynamic of soil CO₂ efflux (F_s). This efflux represents the most important CO₂ emission component of terrestrial ecosystems. However, it remains the largest source of uncertainty about carbon cycling within ecosystems because of the complexity of processes involved: multiple sources, manifold and variable driving factors (Moyes et al, 2010). Spatial and temporal variability of F_s are widely reported in the literature (Ekblad et al, 2005 ; Luo & Zhou, 2006). This variability results from variations in the intensity of biochemical and transport processes. This intensity is controlled by the climatic and edaphic conditions such as temperature, soil water content, substrate availability/quality, soil type etc. The variability is hampering spatial and temporal extrapolations required to estimate the Carbon balance at global scale. For now, most models developed to explain the observed variability are based on empirical approaches which do not identify the fundamental processes governing F_s. Therefore, such models cannot be used to describe climate change impact on F_s.

Two main processes lead to F_s: the production of CO₂ (P) in the soil and its transport from the soil to the atmosphere (Fang & Moncrieff, 1999). Both processes should be taken into account to improve the mechanistic understanding of F_s. P is often subdivided into two main components: autotrophic (root and rhizosphere) and heterotrophic (saprophytic microorganisms) respiration. These components have different responses to environmental variables. Producers and factors affecting production vary temporally and spatially both horizontally and vertically. The vertical variability of CO₂ sources is often omitted in the models while climate change is likely to differently affect the soil layers. Multilayer approach of soil respiration allows the determination of the vertical CO₂ source distribution by taking transport processes and storage into account.

Given the complexity of the processes involved, C stable isotopes (¹²C & ¹³C) are viewed as a powerful research tool in soil CO₂ efflux studies. The temporal variability of the carbon isotopic composition ($\delta^{13}\text{C}$) of F_s ($\delta^{13}\text{F}_s$) and P ($\delta^{13}\text{P}$) gives information about soil CO₂ sources partitioning (when they have different $\delta^{13}\text{C}$) and the duration of the transfer through the plant-soil-atmosphere continuum. When $\delta^{13}\text{F}_s$ can be directly measured (Marron et al, 2008), the estimation of $\delta^{13}\text{P}$ is more difficult. Indeed, it has to be obtained from $\delta^{13}\text{F}_s$ but transport processes and the vertical repartition of the sources may affect the difference between $\delta^{13}\text{F}_s$ and $\delta^{13}\text{P}$ (Goffin et al, 2011). The $\delta^{13}\text{C}$

of CO₂ respired by heterotrophic component depends on the substrates within the organic matter utilized during decomposition (Moyes et al, 2010). The $\delta^{13}\text{C}$ of CO₂ respired by autotrophic component is influenced by temporal changes in environmental conditions affecting C isotopes fractionation during photosynthesis (Kodoma et al, 2008). Because of the differences in the diffusivity of ¹²CO₂ and ¹³CO₂, discrimination between soil CO₂ respired and F_s may occur during the diffusive transport (Moyes et al, 2010).

The main objective of this study is to develop a multilayer soil model able to determine the vertical distribution of CO₂ sources and their isotopic signature validated on F_s and $\delta^{13}\text{F}_s$ data in a forest soil.

MATERIALS AND METHOD

Site Description

Measurements were carried out in a slow-growing Scots pine stand at the Hartheim forest experimental site (Southwest Germany). The mean annual temperature and precipitation are respectively 10.3°C and 642 mm. The soil is a Haplic Regosol containing 14.2 kg OC m⁻². The humus type is a mull. More details on the site are given in Maier et al (2010).

Field measurements

We measured continuously soil air CO₂ concentration ([CO₂]) by using Vaisala GMP343 CO₂ probes. The probes were inserted at 7, 25, 50 and 95 cm depth. Another probe was placed at the litter surface. Soil water content and temperature were also measured at several depths. The isotopic composition of soil [CO₂] ($\delta^{13}\text{CO}_2$) was measured using a system of porous tubes inserted at several soil depths and connected to a tunable diode laser spectrophotometer (TDLS). Four tubes of 2m length were inserted in the litter layer and at each following depth: -8 cm, -17 cm, -35 cm, -80 cm. In addition, F_s and $\delta^{13}\text{F}_s$ were continuously measured using open soil chambers on five collars, specifically designed for such application, connected to the TDLS (Marron et al, 2008).

Laboratory measurements

Several undisturbed soil cores were taken in each soil horizon to determine soil physical parameters such as porosity, pF curves and gas diffusivity. More specifically, we determined soil horizon specific relationships between relative diffusivity (D_s/D_0 , the ratio of soil diffusivity D_s to air diffusivity D_0) and soil water content (θ) employing a one-chamber method and a tracer gas. More details are given in Maier et al (2010).

Modeling CO₂ production and isotopic signature profiles

We used flux-gradient approach to determine the CO₂ production profiles. Since diffusion is the most important transport process in soils, the gradient method used to quantify gas fluxes was based on Fick's first law. Given the horizontal homogeneity of soil physical parameters, we treated the soil as a structure consisting of distinct of 5 cm thick layers ($\Delta z=5\text{cm}$). In order to compute their vertical profile, we first interpolated at each time step (30 min) [CO₂] and soil water content (θ) measurements using a cubic function. We expressed then the Fick's first law in a discrete formalism:

$$F_z = -D_s \frac{[CO_2]_{z+\Delta z/2} - [CO_2]_{z-\Delta z/2}}{\Delta z} \quad (\text{Equation 1})$$

Where, F represents the CO_2 flux ($\mu\text{mol } CO_2 \text{ m}^{-2}\text{s}^{-1}$), D_s is the CO_2 diffusion coefficient (m^2s^{-1}), $[CO_2]$ is the CO_2 concentration ($\mu\text{mol } CO_2 \text{ m}^{-3}$), z represents the depth (m), Δz represents the layer thickness (m).

D_s was derived at each depth from (i) $D_s/D_0(\theta)$ horizon specific relationships obtained from laboratory measurements and (ii) the θ profile.

The simulated surface CO_2 efflux (F_{ss}) was calculated as the flux through the litter layer.

Finally, the CO_2 production (P , [$\mu\text{mol } CO_2 \text{ m}^{-3}\text{s}^{-1}$]) profile was calculated using the discretized mass balance equation in each layer:

$$P_i = \frac{\Delta[CO_2]_i}{\Delta t} + \frac{F_{out} - F_{in}}{\Delta z} \quad (\text{Equation 2})$$

Where, $\Delta[CO_2]/\Delta t$ is the temporal variation of $[CO_2]$ in the layer, F_{out} is the flux out through the upper boundary, F_{in} is the flux in through the lower boundary, i is an index representing the layer (-).

To determine the isotopic composition of each production term ($\delta^{13}P$), we used the same methodology as for CO_2 including the $\delta^{13}CO_2$ profile measured in situ with the ratio $D_s(^{12}CO_2)/D_s(^{13}CO_2)$ set to 1.0044 (Cerling et al, 1991).

$$\delta^{13}X_i = \left(\frac{^{13}X_i / ^{12}X_i}{R_{std}} - 1 \right) * 1000 \quad (\text{Equation 3})$$

Where, $\delta^{13}X$ is the isotopic composition of X term (‰), ^{13}X and ^{12}X are the $^{13}CO_2$ and $^{12}CO_2$ component in the X term respectively; R_{std} is the standard $[^{13}CO_2]/[^{12}CO_2]$ ratio. X can be replaced by CO_2 , F and P respectively for the isotopic composition of soil $[CO_2]$, flux and production.

RESULTS AND DISCUSSION

The results presented in this study cover a period from August 27 to September 14, 2010.

Simulated surface CO_2 flux and its isotopic signature

F_{ss} follows closely the mean temporal evolution of the 5 collar measurements (figure 1). Inter day and intra day variabilities are well reproduced by the model. Moreover, F_{ss} lies always within the confidence interval of this mean. However, during rain events, simulation results diverge from the measurements. Two assumptions can explain such a pattern. First, diffusive transport could not constitute the only process at work; other transport mechanisms should be taken into account, for example the transport in the liquid phase. Furthermore, rain events often occurred at the same time as highly turbulent events provoking turbulence-induced transport that should be introduced in the model to correctly simulate these situations. The second assumption is related to the chamber design chosen for the flux measurements. Indeed, rain infiltration in soils is known to activate the microbial activity and consequently to increase F_s . However, soil chambers used to measure F_s were always closed, preventing rain infiltration and hiding this effect while the CO_2 probes used for modelling were not protected from rain and took it into account.

Except during rain events, the simulated isotopic composition of F_{ss} ($\delta^{13}F_{ss}$) has the same order of magnitude and a similar pattern as the measurements but with larger amplitudes of variation (figure 1). In this case, the simulations were not always included within confidence interval of measurement average. Anyway, inter day and intra day variabilities were fairly well reproduced by the model. Measurements were however slightly lagged compared to simulation outputs.

During dry days, $\delta^{13}F_{ss}$ followed the same general trend as F_{ss} , increasing together with F_{ss} and vice versa. As a result, the larger ^{13}C enrichment was observed at the end of the afternoon, when F_{ss} was the highest. This was observed for both simulated and measured fluxes. One explanation could be a larger daily fluctuation of soil CO_2 sources which are enriched in ^{13}C .

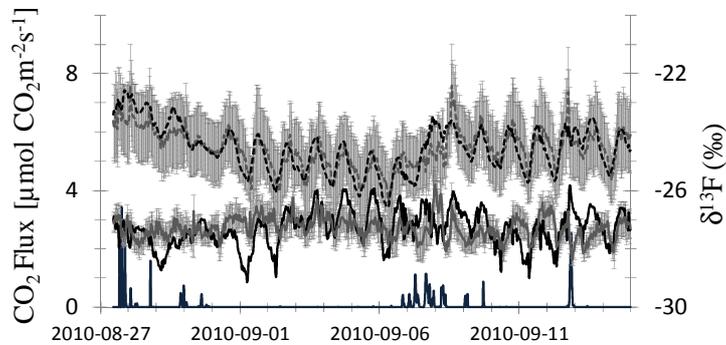


Figure 1: **left axis:** the dotted grey line represents the measurement average over the 5 collars; dotted black line represents the F_{ss} . The dark blue vertical lines represent the rain events [mm]. **Right axis:** the solid grey line represents the $\delta^{13}F_s$ average of chamber measurements; Solid black line represents $\delta^{13}F_{ss}$. The grey bars represent the confidence interval of measurement average over 5 collars.

Simulated CO_2 source distribution and their isotopic signature

According to the simulations, 89% of total CO_2 produced during the study period came from the top 25 cm depth, 27% of which coming from the litter layer. This distribution is consistent with the fine root counting and the carbon organic content profile measured in Hartheim.

Furthermore, top soil CO_2 production terms presented a larger amplitude variation and phase shift in comparison with deeper CO_2 sources. For example, as represented during dry days at figure 2, the CO_2 production terms simulated in layers between 5 and 10 cm depth presented a larger amplitude variation than those simulated between 20 and 25 cm depth. During dry days, we can relate such results to temperature measurements. Actually, the amplitude variation and the phase of production terms presented the same general behavior as the temperature measured in each layer.

The long term average of $\delta^{13}P$ calculated on the soil profile is -27.4‰ . This is consistent with values reported in the literature. In comparison, the long term averages of measured and simulated $\delta^{13}F_s$ are respectively -27.28 and -27.31‰ . It means that $\delta^{13}P$ and $\delta^{13}F_s$ were nearly the same over period of few days, showing that the steady state assumption (flux=production) is

valid with relatively long time integration. Further analyses are currently on progress.

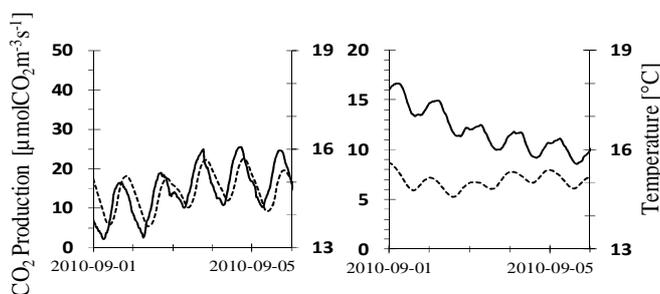


Figure 2 : *Left Graph*: Solid line represents CO₂ production in the layer between 5-10 cm depth and dotted line the temperature measured in that layer. *Right Graph*: Solid line represents CO₂ production in the layer between 20-25 cm depth and dotted line the temperature measured in that layer.

CONCLUSIONS

The simulations of surface CO₂ flux and its isotopic signature are globally consistent with the chamber measurements, especially during dry days. However, the $\delta^{13}\text{C}_{\text{ss}}$ presents larger amplitude of variation than the chamber measurements. The dynamic and the distribution of production terms can be related respectively to climatic and soil variables. The isotopic composition of production calculated on the soil profile is consistent with values reported in the literature.

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