Control of Vertical Soil Variation on Temporal Variation of Soil CO_2 Production and Emissions

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Objectives

The overall objective of our work was to elucidate and quantify C dynamics at depth and its direct influence on surface CO_2 fluxes from hourly to decadal time scales. The specific objectives that were covered in this project include: (a) development of a depth-explicit soil organic matter (SOM) model based on the CENTURY model; (b) testing whether the rate constants of CENTURY can be reconciled with vertical soil transport; (c) testing whether rates of vertical transport decrease with depth; (d) sensitivity analysis of the decrease in SOM decomposition rates with depth; (e) testing the effect of wetting and drying on GHG concentration in deep soils; (f) testing the effect of wetting and drying on fluxes of GHG from deep soils layers and out the soil system; (g) determining the effect of increased atmospheric CO_2 concentration on microbial respiration and community composition; and (h) determining the temperature sensitivity of SOM decomposition in subsoil.

Approach and Procedures

The project included field, lab and modeling components. The soil in the study site is classified as a Mollic Xerofluvent. The study location has a Mediterranean climate with MAT of 15.3°C and MAP 458.2 mm; with the majority of precipitation falling between September and May (CIMIS, 2008). The field site is flat, is not shaded during daytime, and the soil is manually kept bare during the whole year.



Figure 1: Picture of experimental site

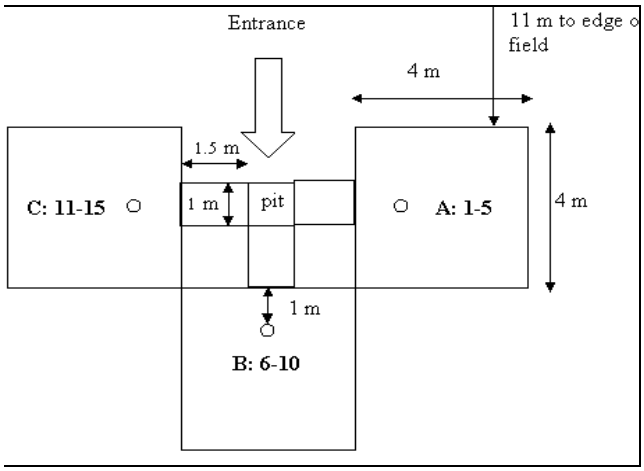

Figure 2: Top view of the field site.

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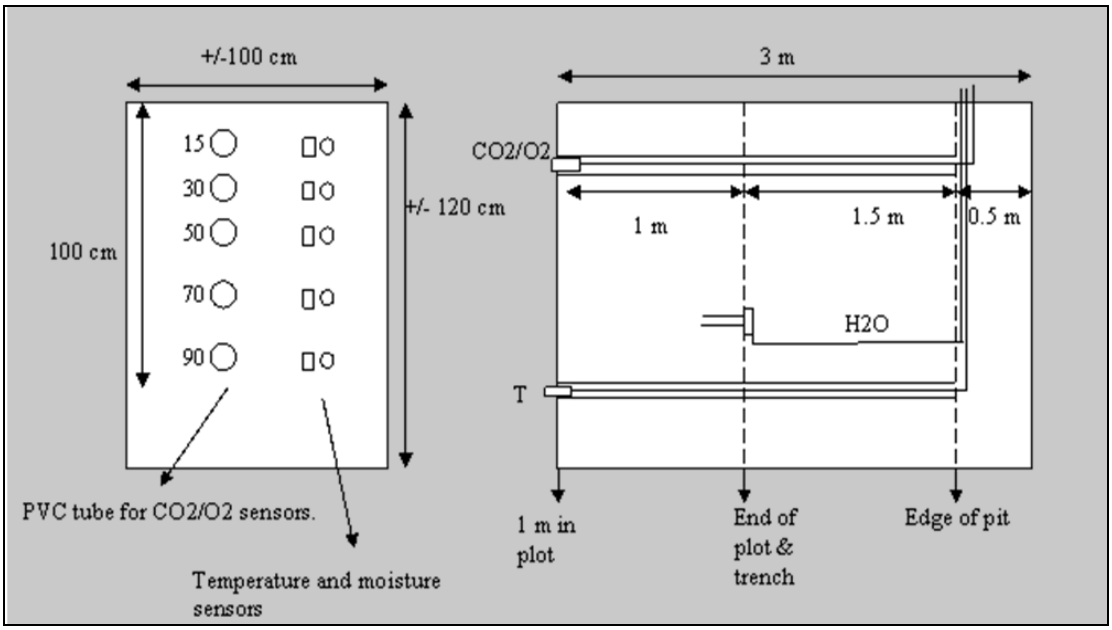

Figure 3: Cross-section of the soil pit

Profile horizon	**Depth of sensor (cm)**	**Given number**	**Installed sensors**
A	15	1	CO_2, CO_2-accurate, O_2, TDR, temperature
A	30	2	CO_2, CO_2-accurate, O_2, TDR, temperature
A	50	3	CO_2, O_2, TDR, temperature
A	70	4	CO_2, O_2, TDR, temperature
A	90	5	CO_2, O_2, TDR, temperature
B	15	6	CO_2, CO_2-accurate, O_2, TDR, temperature
B	30	7	CO_2, CO_2-accurate, O_2, TDR, temperature
B	50	8	CO_2, O_2, TDR, temperature
B	70	9	CO_2, O_2, TDR, temperature (CO_2 temporarily not working)
B	90	10	CO_2, O_2, TDR, temperature
C	15	11	CO_2, CO_2-accurate,O_2, TDR, temperature
C	30	12	CO_2, CO_2-accurate, O_2, TDR, temperature
C	50	13	CO_2, O_2, TDR, temperature
C	70	14	CO_2, O_2, TDR, temperature
C	90	15	CO_2, O_2, TDR, temperature

Table 1: *Number and characteristics of locations*

At the field site, located at the student farm, in the University of California, Davis, we installed sensors for soil water content, concentration of greenhouse gases, and temperature. Three plots were used for this experiment (see figure 1-2). In each plot, a complete set of sensors (temperature, moisture, oxygen and CO_2) was installed at five depths (15, 30, 50, 70 and 90 cm; see figure 3 and Table 1) by digging a trench at the side of the plot prior to augering horizontal channels in which the sensors were installed 1 meter from the edge of the plot (Figure 3). After the installation, the trenches were backfilled, while access to the sensors was being assured by extending the sensor channels to the centrally located pit. The data acquisition and storage of the data from the pit and from the surface are carried out by a multiplexer and data logger (CRX10, Campbell Scientific). In addition, a sensor chamber for measuring surface fluxes of CO_2, N_2O, and water vapor were installed above each instrumented profile.

Parallel laboratory experiments were conducted (through collaboration with the Catholic University of Leuven, Belgium) to determine climate sensitivity of soil respiration from near surface vs. deep soil layers in order to inform model development for predicting soil CO_2 production and transport, and efflux of CO_2 from the soil surface at hourly to decadal timescales.

Results

Gas fluxes

In this study, we are able to quantify the spatial and temporal variability of soil CO_2 production. Our measurements show that there is a gradual rise of soil CO_2 concentration with depth. We found that topsoil layers showed considerable temporal variability in CO_2 concentration during the day. However deep soil layers didn't show any significant daily pattern (Figure 4).

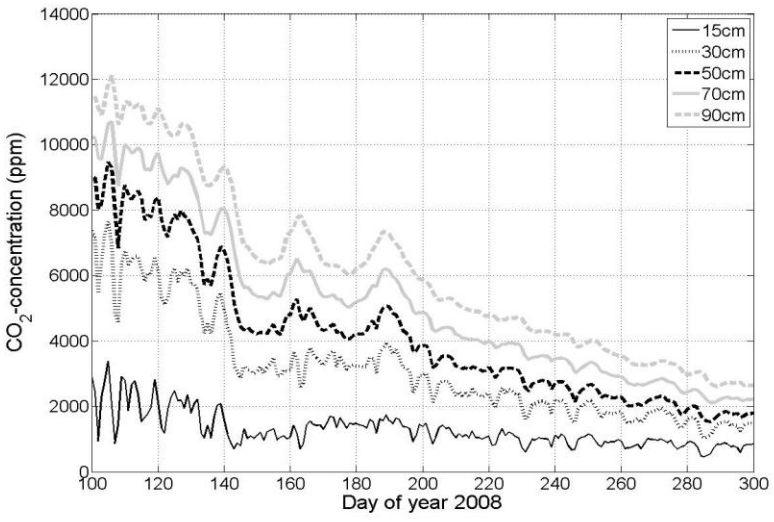

Figure 4: CO_2-concentrations at five soil depths in profile B (in ppm) over time.

During late spring and summer months, when CO_2 fluxes from the soil are near maximum, variability in soil CO_2 concentration drops significantly going from the soil surface to 90 cm, as do soil water content and temperature.

Over the measured time period, CO_2 efflux rates of up to 1.4 µmol m^{-2} s^{-1} (5.32 g CO_2 m^{-2} d^{-1}) were observed. Maximum flux-rates were usually measured in the morning (10:00) and minimums usually occurred in the end of the afternoon (18:00) (Figure 5 and 6).

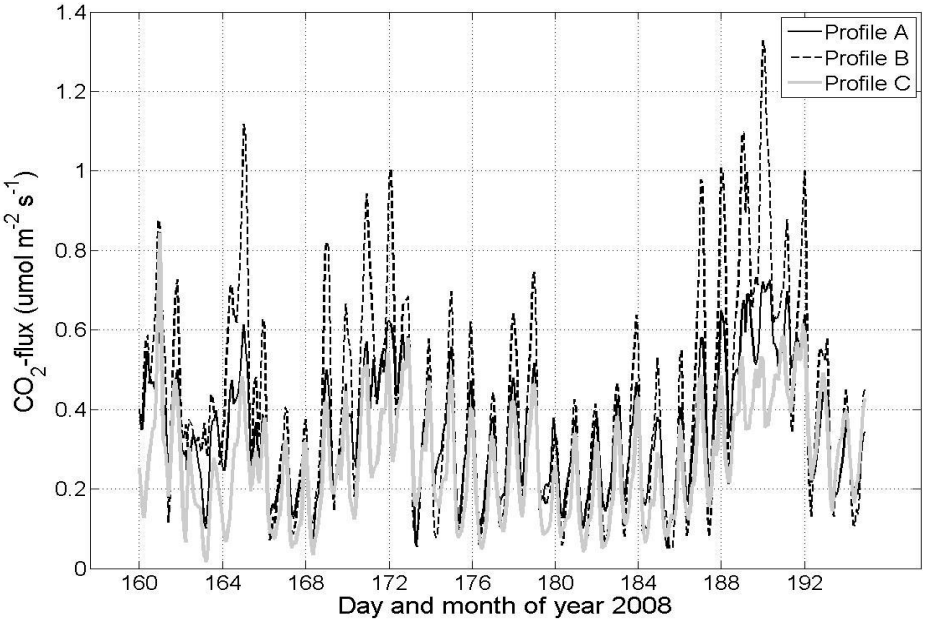

Figure 5: Measured surface flux over time, per profile

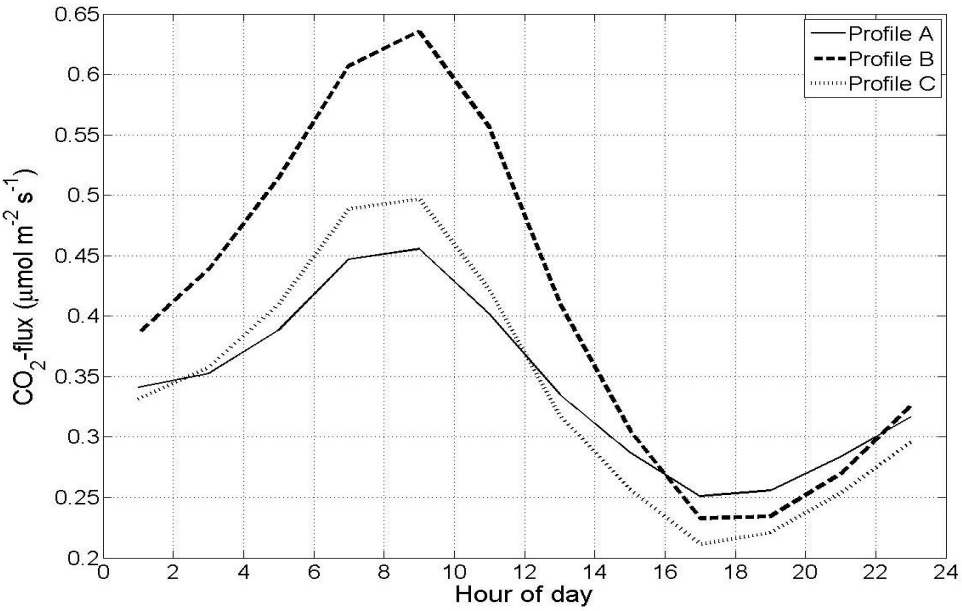

Figure 6: Averaged measured surface flux, averaged per 2 hours.

Effect of changes in soil water content and temperature on rate of CO_2 production

We quantified the effect of changing soil water content and temperature on production rates of CO_2 at the five depths. There was a positive correlation between CO_2 concentration and soil water content all depths and profiles (figures 7, 8, and 9). Our data show that relationship between CO_2 concentration and temperature appears to be mediated by changes in soil water content.

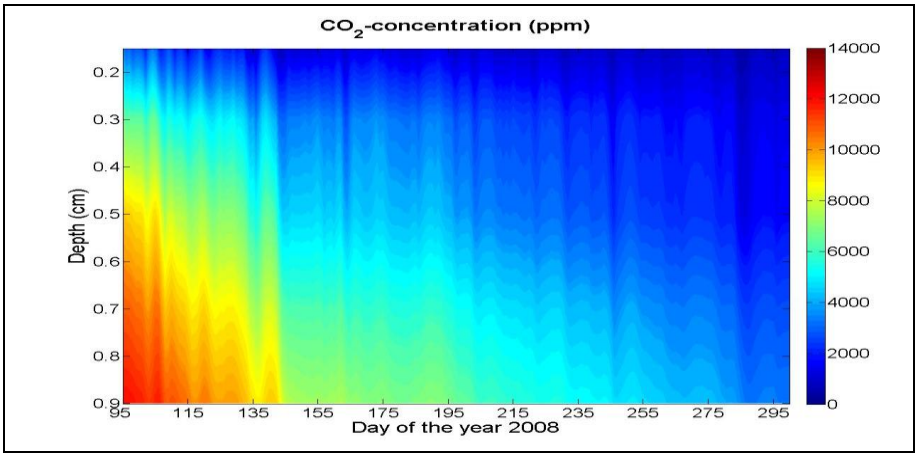

Figure 7: CO_2 in time and depth, interpolated

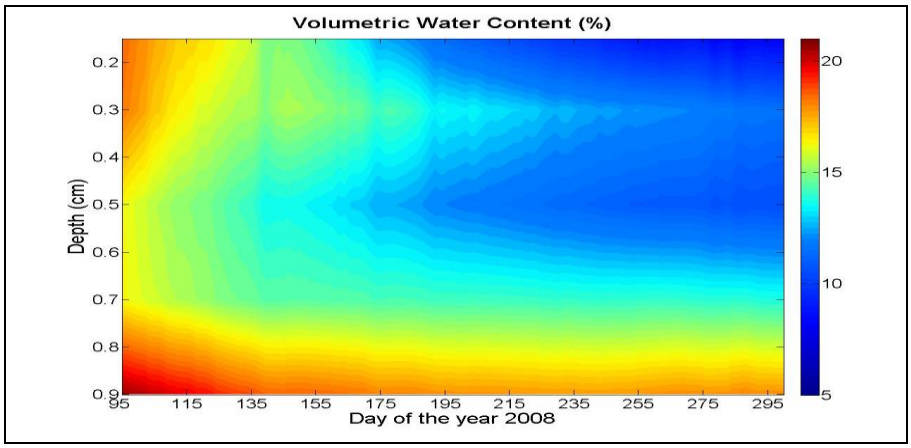

Figure 8: VWC in time and depth, interpolated

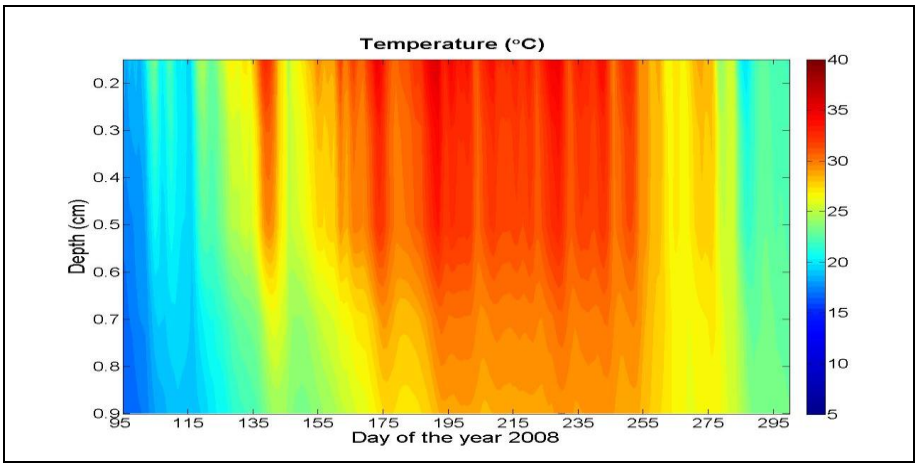

Figure 9: Temperature in time and depth, interpolated

Our preliminary results show that very small changes in soil water content and temperature in deep soil layers lead to very significant changes in deep soil CO_2 concentration (Figure 10).

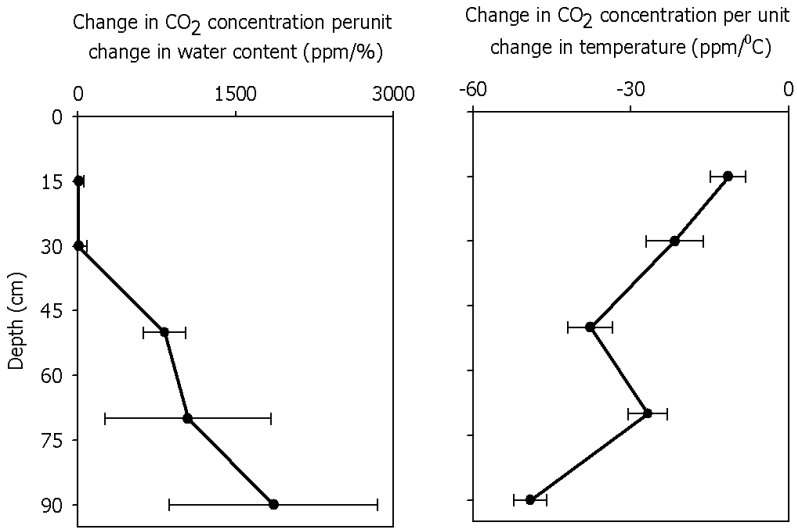

Figure 10: Change in soil CO_2 concentration/production per unit change in volumetric water content and temperature during spring and early summer months 2008 at five soil depths, n=3 for error bars.

In summary we found that, the CO_2-concentration along the soil profile, averaged over the three profiles can be well described by a quadratic curve (Figure 11).

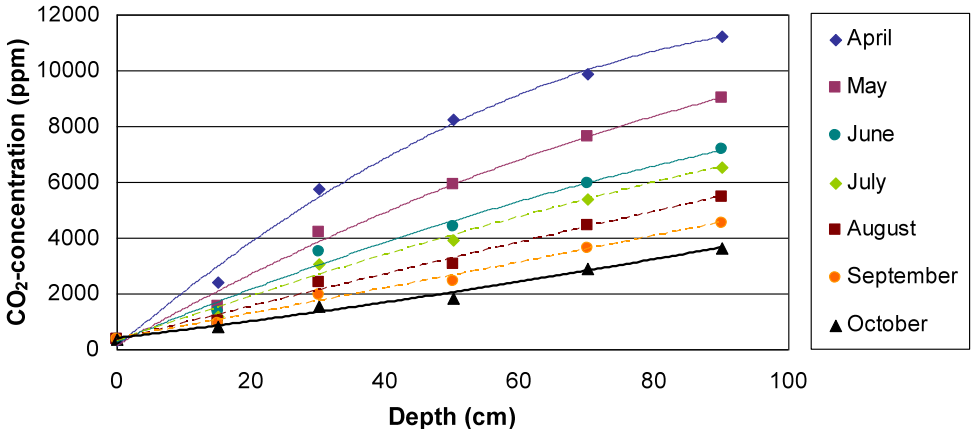

Figure 11: CO_2- concentrations over depth together with a quadratic fit

Different response of soil microbial respiration rate and community composition to high CO_2 concentration in topsoil compared to subsoil

Although the concentration of CO_2 in subsoils can be 100-fold higher than at the soil surface (see field monitoring data), the effects of such a high CO_2 concentration on microbial community structure and function are largely unknown. In food processing, the use of CO_2 to suppress microbial activity is well known, but the effects of high CO_2 concentrations (i.e. more than 1% CO_2) on soil microbial activity have hardly been investigated (Santruckova & Simek 1997). Accurate subsoil SOM models, however, require the inclusion of all relevant process drivers. Therefore, we designed a laboratory set-up that allows measuring soil respiration at varying CO_2 concentrations, and combined this with measurements of phospholipid fatty acid (PLFA) biomarkers to assess the effect of CO_2 concentration on microbial community structure. Homogenised topsoil and subsoil (1 m deep) samples from the soil profile at the monitoring site were pre-incubated at 20°C for two weeks under ambient atmospheric conditions, after which they were exposed to a constant airflow containing either 500 ppm CO_2 (Low CO_2) or 3% CO_2 (High CO_2) for 5 days. Every day, respiration rates were measured by closing the incubation jars for several hours and measuring the CO_2 concentration increase. Care was taken to avoid an excessive increase in CO_2 concentration. At the end of the incubation, PLFA content was determined, as well as the distribution of individual PLFA biomarkers.

Under “Low CO_2” conditions, soil respiration rate in the topsoil was 60 times higher than in the subsoil, but for ”High CO_2”, this difference was reduced to a factor of 6 (Fig. 1). This was mainly caused by a sharp drop in topsoil respiration rate, while subsoil respiration rate did not decrease significantly with increasing CO_2 concentration. Total PLFA content in the topsoil decreased from 2.9 mg PLFA-C kg^{-1} soil for “Low CO_2” to 0.5 PLFA-C kg^{-1} soil for “High CO_2”, while subsoil PLFA content remained constant with increasing CO_2 (0.4 mg PLFA-C kg^{-1} soil).

Analysis of the distribution of individual biomarkers with Cluster Analysis revealed that microbial community structure changed with increasing CO_2 only in the topsoil. Furthermore, topsoil microbial biomarker distribution seemed to change towards the pattern observed in the subsoil (Fig. 2). Our results suggest that subsoil microbial community structure and function are better adapted to high levels of CO_2, and that topsoil microbial community structure can be altered by changing CO_2 concentrations.

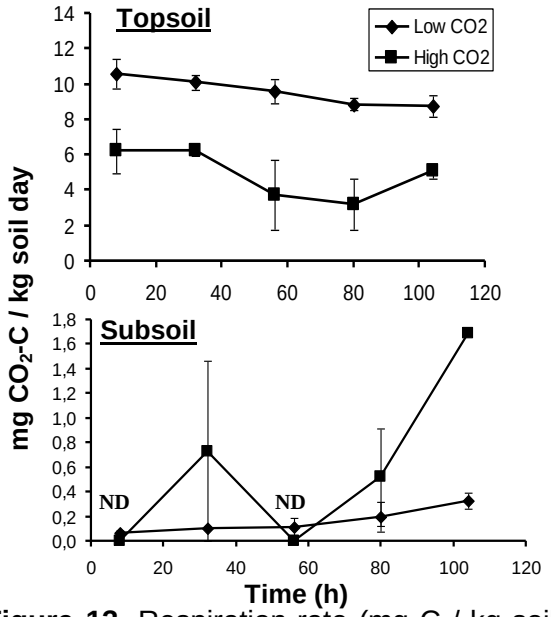

Figure 13. Respiration rate (mg C / kg soil day) for topsoil and subsoil during incubation at 500 ppm CO_2 (Low CO_2) or at 3% CO_2 (High CO_2). Error bars denote standard deviations (n=3). ND: below detection limit.

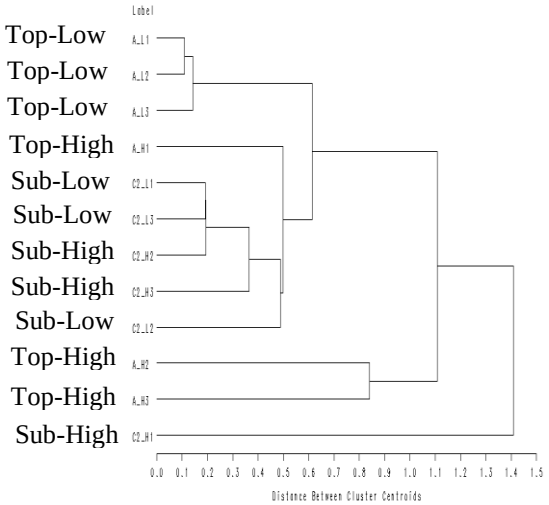

Figure 12. Cluster Analysis (SAS 9.2) for topsoil (Top) and subsoil (Sub) after incubation at 500 ppm CO_2 (Low) or at 3% CO_2 (High), based on relative abundance of individual PLFA biomarkers. Samples clustering together in Cluster Analysis have more similar PLFA fingerprints than samples further removed.

Protection of SOM determines the temperature sensitivity of SOM decomposition in the subsoil

On a global scale, 60% of the C stock in the upper meter of the soil is found below 20 cm (Jobbagy & Jackson 2000). Predicting impacts of climate change on soil C stocks therefore depends on accurate knowledge of changes in temperature sensitivity of SOM decomposition with depth. However, much remains unclear about how temperature sensitivity (Q_{10}) is affected by the driving factors that change with depth, like SOM quality, SOM protection and environmental factors (Davidson & Janssens 2006). To assess the effect of SOM quality and SOM protection on Q_{10} with depth for the soil profile at the monitoring site, we incubated soil samples taken at four depths (DV1 to DV4) under standard laboratory conditions (excluding environmental factors such as water content and oxygen level) at 25°C and at 35°C for 239 days, with respiration rates measured frequently. Q_{10} values were determined with the Q_{10}-q methodology. This approach determines temperature sensitivity of SOM fractions of decreasing lability in the same soil sample.

Cumulative respiration decreased with depth at both temperatures (Fig. 3), with top layer respiration being almost ten times higher than respiration in deeper layers. The overall effect of temperature was much larger at the surface than in the deeper layers. Q_{10}-q values for the least labile respired SOM were only higher than those for the most labile respired SOM in the top layer (Fig. 4). If Q_{10}-q values increase with decreasing SOM lability, SOM quality affects the temperature response of SOM in that sample. If Q_{10}-q values do not change, this indicates an attenuating effect of SOM protection on Q_{10} (Gillabel et al., in prep.). Therefore, these results suggest that in the top layer, SOM quality played a dominant role in determining the temperature response, whereas SOM protection attenuated the temperature response of SOM in the deeper layers.

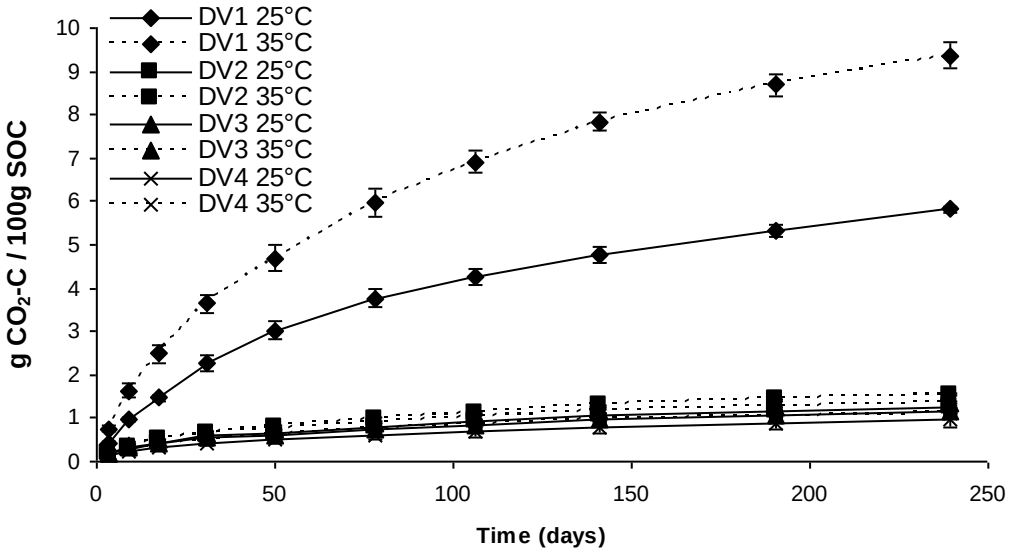

Figure 14: Cumulative respiration (g CO_2 / 100g SOC) for four layers of a soil profile incubated at 25°C (full lines) or at 35°C (dashed lines). Error bars denote standard deviations (n=3).

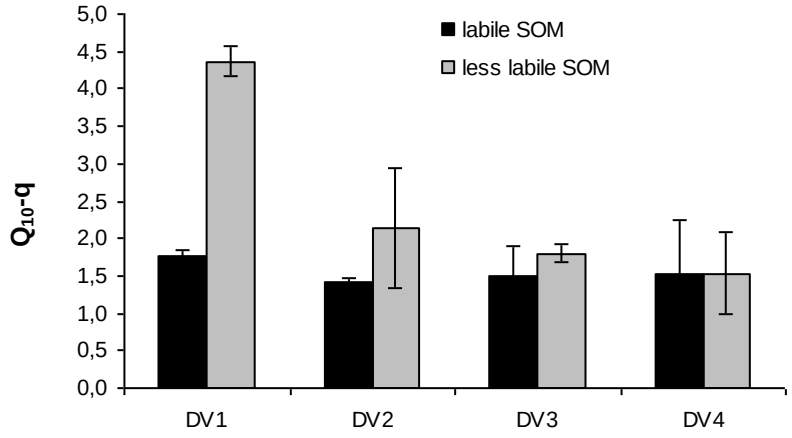

Figure 15

Modeling dynamics of deep SOM

A SOM model was written in MATLAB. The model includes a depth-dependent decrease in root C input and decomposition rate, and vertical soil movement due to pedoturbation and leaching. The calibration of this model was done based on experimental data of carbon isotopes (^{12}C, ^{13}C, and ^{14}C) from profiles in Iowa and mineral radionuclides (^{137}Cs and excess ^{210}Pb) from the U.K.

The model was able to represent well these profiles of the carbon isotopes and mineral radionuclides (Figs. 16 & 17). Nevertheless, several generally assumed concepts needed to be rejected to have a functional depth-explicit model. First, adding vertical soil transport (calibrated by the mineral isotope profiles) to the existing CENTURY model caused a complete disappearance of the passive C pool. The latter could only be resolved by assuming a decrease in transport rates with depth and a 10 times smaller rate constant for microbial decomposition than the rate constant assumed in CENTURY.

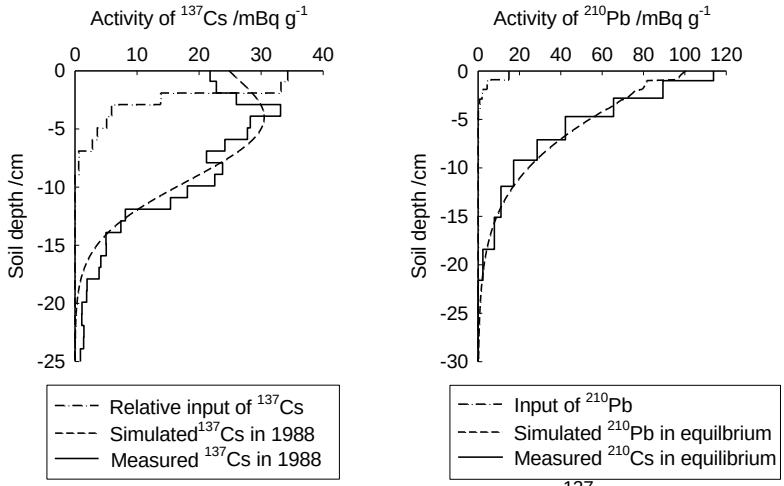

Figure 16: Input, measured, and modelled depth profiles of ^{137}Cs, and excess ^{210}Pb. Input and measured profiles are averages from data of Walling and Quine (1990, 1992) for ^{137}Cs, and He and Walling (1997) for ^{210}Pb-ex.

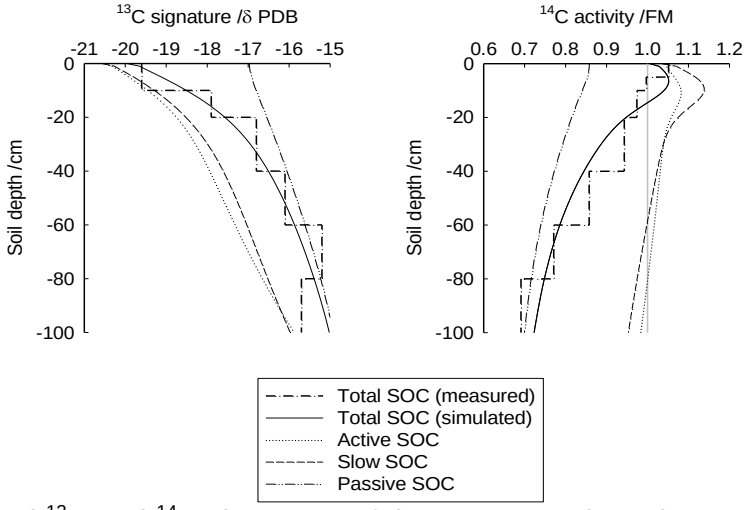

Figure 17: Simulated ^{13}C and ^{14}C signatures of three SOC pools and measured and simulated ^{13}C and ^{14}C signatures of total SOC with depth

Discussion

Rate of CO_2 efflux from the soil surface depends on CO_2 production across the whole soil profile and spatial organization of the soil matrix. Despite significant recent advances in our understanding of how different environmental factors regulate the rate of CO_2 efflux from the soil system, significant gaps remain in our understanding of variables that regulate CO_2 production and flux in deep soil layers, including how plant physiology regulates rate of C input in subsoil layers, vertical redistribution of C along the soil profile, and the effect of environmental factors (microclimate) on deep CO_2 production and its transport along the soil profile.

Some of the most important contributions of this study to advancing our understanding of SOM dynamics at depth include:

- Quantification of temporal variation of CO_2 concentration along the soil profile
- Determination of how changes in soil temperature and moisture levels control CO_2 production in deep soil layers
- Independent determination on how soil moisture and temperature conditions affect rates of soil CO_2 production during wetting and drying phases
- Ability to separate the effects of changes in microclimatic variables in the soil vs. atmospheric conditions on rates of CO_2 efflux from the soil
- Ability to relate changes in soil CO_2 production and flux along a depth profile to soil physical and chemical properties, including soil organic matter content, aggregate protection of OM and stock of labile soil organic matter.

The CENTURY model does not include any vertical transport of slow or passive SOC. Only the active C can move downward through leaching. Our modelling results suggest that the omission of vertical soil transport in CENTURY leads to an overestimated mean residence time of passive SOM. Second, the first-order decomposition rate for passive C in CENTURY could not be reconciled with the vertical transport rates of SOC. A reduction in microbial

decomposition rate of passive C of about 10 times was necessary to keep passive C at equilibrium levels. Third, no satisfactory model agreement could be found if the decomposition rate at 100 cm decreased more than 10 times that at the soil surface. As a result of the interplay between root inputs, reduced decomposition with depth and vertical transport, the relative importance of in situ SOC assimilation through root input versus carbon import from upper profile locations changes with depth. Our model simulation indicates that over the first meter of the soil profile, the importance of root input decreases with depth; while the importance of vertical C transport gradually increases. At 1 m, root input is responsible for only 25% of the C input. Hence, it is clear that vertical transport dominates soil C input at depth and that it should be included when studying and/or modelling deep SOC dynamics. However, little experimental data exists on vertical transport rates at depth, which is necessary for further advances in understanding of deep-soil C dynamics.

The addition of vertical transport within a depth explicit carbon model indicates that the conceptually defined turnover times of soil C and their response to changes in environmental factors might have been overestimated. All of the above results exemplify the important role that vertical soil transport plays in determining the turnover of SOC pools and ultimately the shape of the SOC profile.

Further findings from the current study are that the observed increases in SOM turnover along the soil profiles is accompanied by a decrease in SOC quality (for microbial consumption) and can only be simulated if there is a significant vertical transport of SOC that is accompanied by a decrease in basal decomposition rate. Preliminary findings suggest that vertical transport of DOM is likely more important for the lower quality/lability of SOC at depth than changes in soil moisture content and temperature. A new study is now setup to directly test the contribution of DOM for SOM loss and how dynamics of soil DOM and CO_2 evolve over time.

References

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