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Kearney Foundation of Soil Science: Understanding and Managing Soil-Ecosystem Functions Across Spatial and Temporal Scales
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Spatial and Temporal Dynamics of Deep Soil Gaseous and Soluble Element Fluxes from New vs. Old Organic Matter

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Project Background and Objectives

Carbon dioxide fluxes from soil surfaces originate from the respiration of plant roots and microbial decomposition of organic matter (OM). The decomposition process occurring in soil ecosystem is controlled by factors that to date have not been completely elucidated mainly because of the complexity and heterogeneity of soils. The overall objective of this project was to define the factors that drive the decomposition of OM and their dynamic interactions. The heterogeneity of the soil ecosystem requires that both the spatial and temporal variability of the soil be accounted for when attempting to elucidate the interactive OM and CO_2 dynamics, especially under a changing climate. The main variables in this process are soil, climate, substrate, and decomposer microbial community. We, therefore, proposed to examine how the microbial community changes with soil depth, how temperature and moisture affect respiration and the production of CO_2 across the soil profile and if changes in temperature and CO_2 would affect interactions of quality and quantity of OM on decomposition. In general, OM goes into the dissolved or soluble state (DOM), which results in leaching of dissolved organic carbon (DOC) through the profile, sorption onto mineral surfaces that could lead to stabilization of this OM, or to further degradation by microbes. Therefore, DOM is an important contributor to CO_2 fluxes within and through the soil profile (Kalbitz et al. 2005; Guggenberger and Kaiser 2003). The concentration, chemistry, and distribution of DOM in the soil profile and how it relates to the production of CO_2 is critical to our understanding of the terrestrial carbon cycle.

The specific objectives of this project were to i) determine the how changes in temperature and moisture vertically in the soil profile and over time affect the decomposition of organic matter, ii) test the effect of elevated soil CO_2 concentrations and temperature on decomposition, iii) determine the relationship between the dynamics of DOM and CO_2 production, both from new and old sources of organic matter, along a soil profile over multiple timescales.

Approach and Procedures

The approach included both laboratory incubation experiments and field experiments. In the field, the general approach was to continuously monitor the production of CO_2 in the soil at different depths to account for both spatial (depth) and temporal (seasonal) variation. Along with CO_2 monitoring, other factors such as temperature, moisture (volumetric water content, VWC)

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and O_2 were monitored. The project was planned in two phases, first where the soil was kept bare to account only for soil heterotrophic respiration and second where the soil was planted with switchgrass to look into the contributions of new DOM into the soil. The selected field site was located at the student farm of the University of California, Davis, where we installed sensors for soil water content, temperature, O_2, and CO_2 concentration in three plots at five depths (15, 30, 50, 70 and 90 cm). In addition, three sensor chambers for measuring surface fluxes of CO_2 and water vapor were installed above each instrumented profile. Lysimeters were also installed at the same five depths to collect soil leachates for DOC and DON analyses.

Switchgrass was seeded in June 2011, which introduces new organic matter into the profile that can be identified by its C4 isotopic signature that is unique and different from the existing C3 signature at this field site. The collected soil solution leachates, at different depths and over time, are being analyzed for DOC and DON concentrations, $\delta^{13}C$ content, ^{13}C-NMR spectra and liquid ATR-FTIR to characterize the chemical composition of DOM and determine the C-functional groups. Collected gas samples from the same depths are also being analyzed for $\delta^{13}C$-CO_2, and ^{13}C-NMR to act as supportive analyses for the DOM profile. The collection of leachates, gases, and parameter monitoring will continue into 2012 at which time enough data will have been collected to allow for tracing the path and fate of the newly introduced OM.

In addition to the continuous field monitoring, laboratory experiments were conducted on soils collected from the same field site at the 15, 30, 50, 70, and 90 cm depths. Soils were fractionated into aggregate fractions and into stable vs. labile C pools. Laboratory incubation studies were conducted to determine the potential C mineralization of the soils as evolved CO_2 at 25° C. As well, homogenized topsoil (DV1 = 5-15 cm) and subsoil (DV4 = 95-105 cm) samples were incubated under a constant airflow containing either 500 ppm CO_2 (baseline CO_2), 1% CO_2 (CO2_1), 3% CO_2 (CO2_3) or 500 ppm CO_2 and 15% O_2 (O2_15) for 7 days, at either 25° C or 35° C (3 replicates per treatment). On the 3rd, 5th and 7th days of incubation, respiration rates were measured. After 7 days, one jar per treatment was removed for PLFA (only 25° C samples) and soil pH analyses. The incubation sequence was repeated with the remaining jars at their target temperatures, but all jars were subjected to the baseline CO_2 gas flow. At the end of the incubation, one replicate jar per treatment was used for determining PLFA and soil pH.

Results and Discussion

SOC in whole soil and aggregate fractions and potential C mineralization

The following horizons have been identified in the profile: A at 0-25 cm, AB at 25-35 cm, B at 35-60 cm, C1 at 60-80 cm, and C2 at 80-110 cm. As expected, greater proportions of SOC and SON was in the A horizon and generally decreased with depth (Fig. 1) which has been shown in previous research (e.g. Ajwa et al. 1998, Bruun et al. 2007). Most of the C in the whole profile was found to be associated with microaggregates (53-250 µm) and their distribution down the profile followed a similar pattern to total SOC (Fig. 2). While SOC in the macroaggregates (250-2000 µm) generally decreased with depth, there were only significant differences between the surface horizon (A) and the other depths and only small differences among other horizons (Fig. 2). When soil was chemically extracted to differentiate relative stable vs. relative labile fractions of SOC associated with the silt and clay fractions (<53 µm), greater proportions of SOC were in the labile pool (Fig. 3). However, proportions of SOC in the labile pool decreased with depth

whereas stable SOC pools increased with depth (Fig. 3). It should be noted that although differences among proportional distributions of labile C are small, absolute concentrations of labile C in the A horizon were more than double those found in the B and C horizons (data not shown). Potential C mineralization, from a four-week aerobic incubation experiment, was greatest in the A horizon with more than four times CO_2 being evolved by the end of the experiment compared to deeper horizons (Fig. 4a). In addition, greater proportions of SOC were mineralized in the surface soil compared to lower horizons (Fig. 4b). These results reflect the greater concentrations and proportions of labile C in the surface horizon compared to lower horizons.

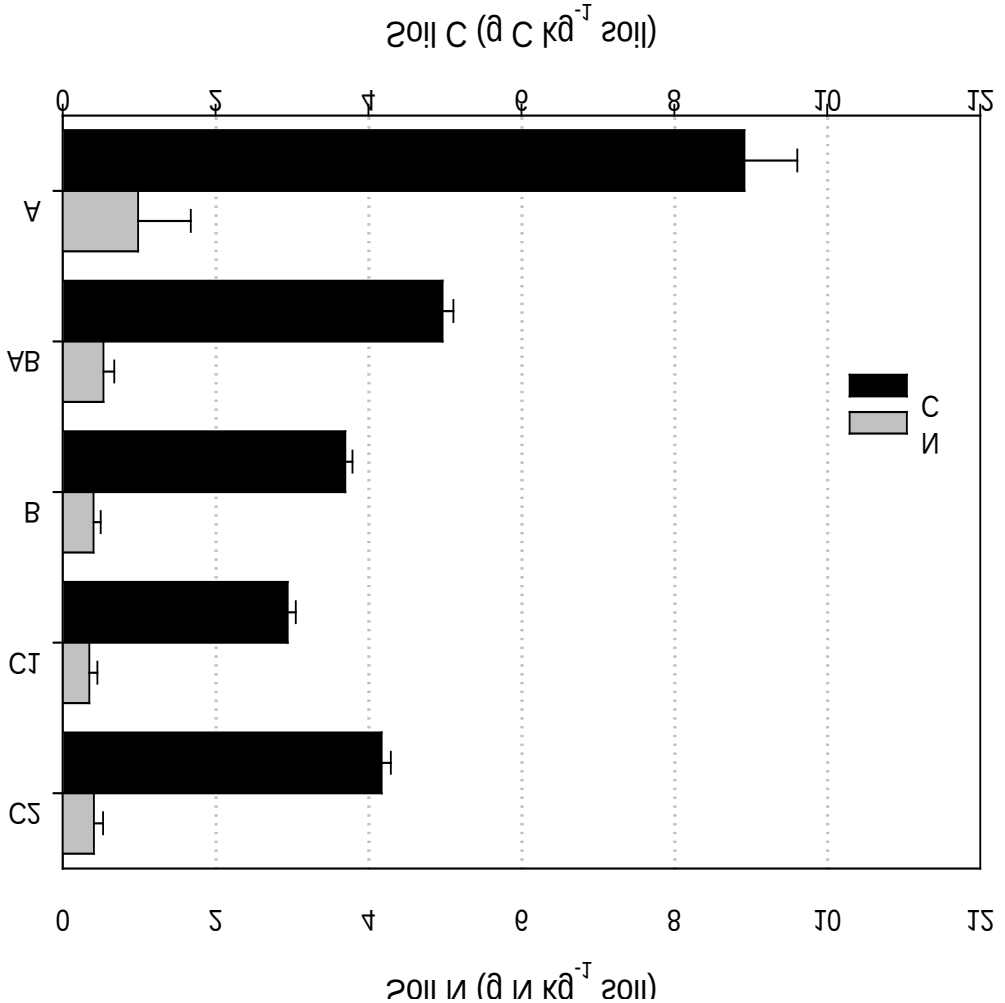


Figure 1 Soil C and N distribution across the soil profile. Error bars represent standard errors of the mean.

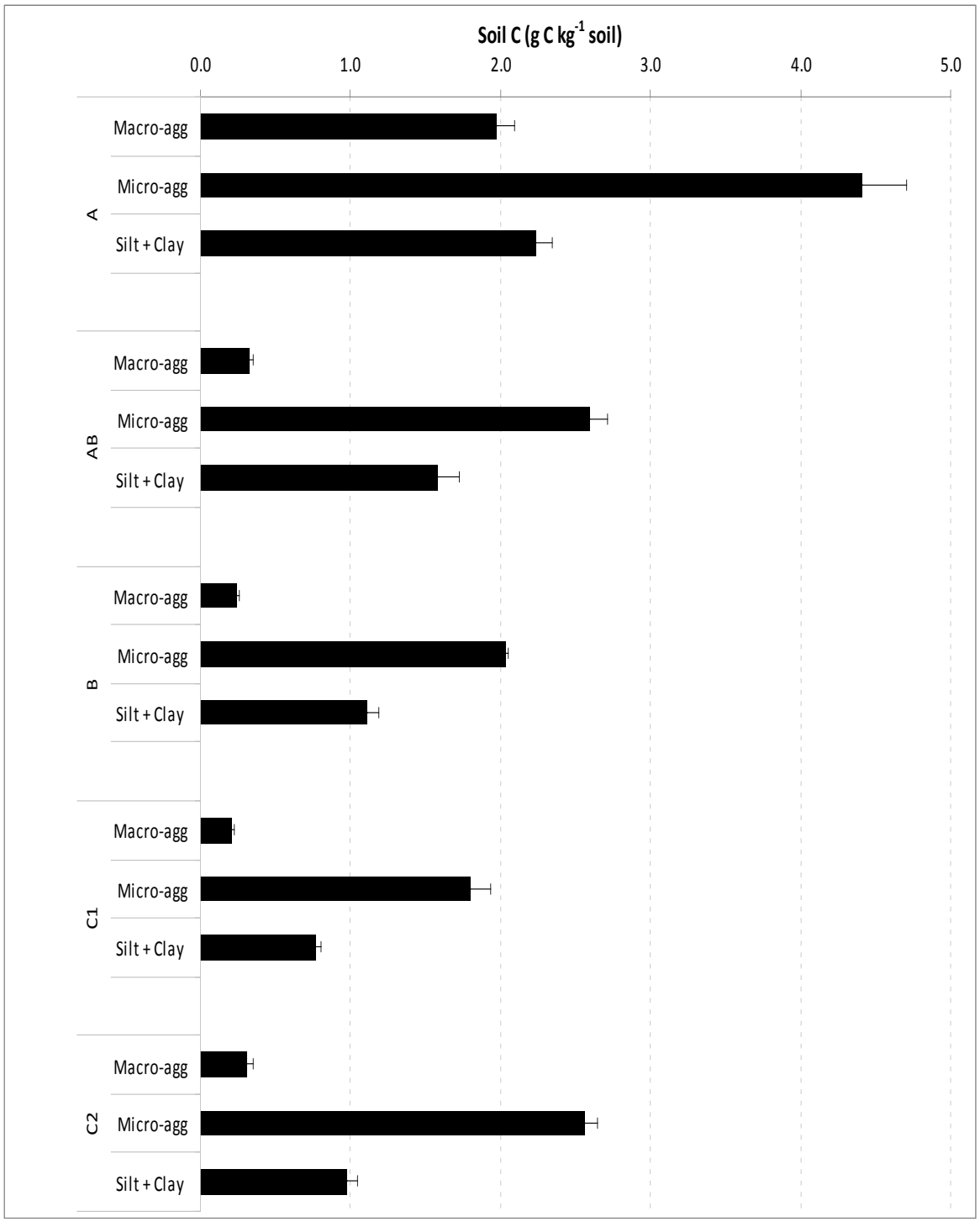


Figure 2 Soil organic C content of macroaggregates (Macro-agg), microaggregates (Micro-agg) and silt+clay fractions across the soil profile.

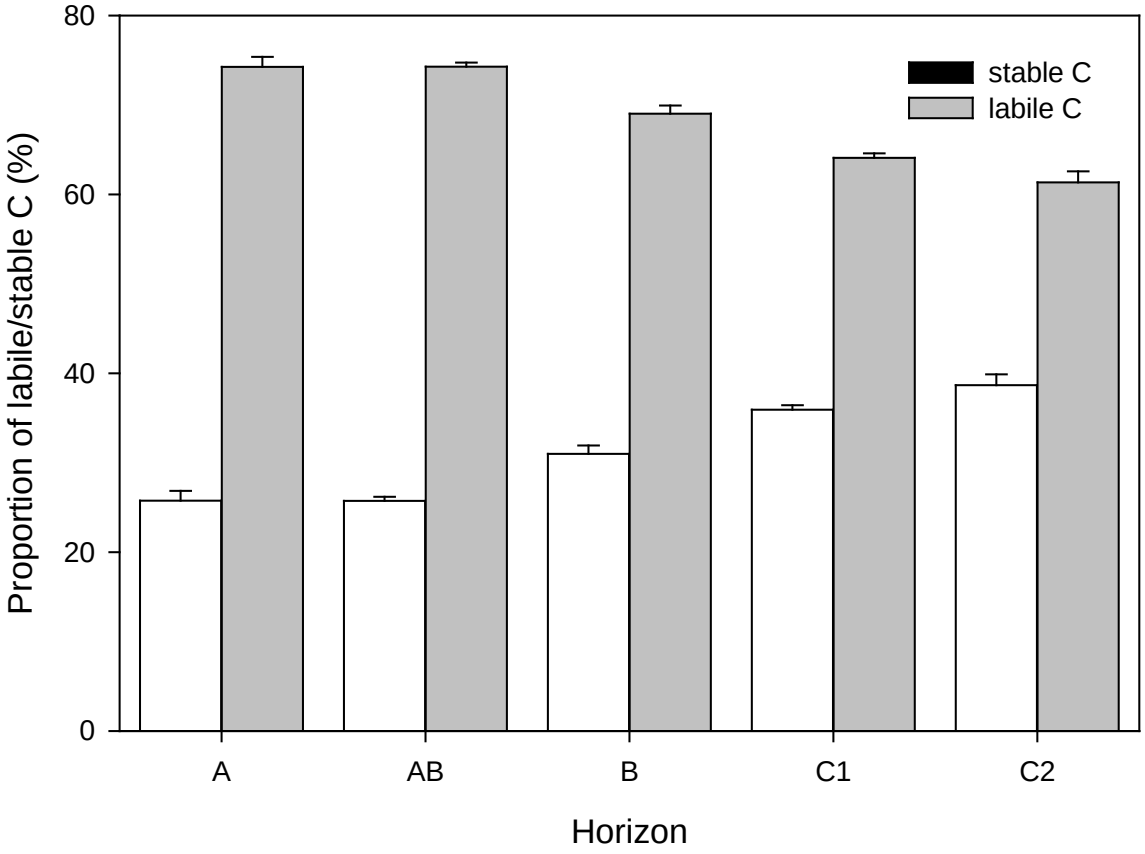
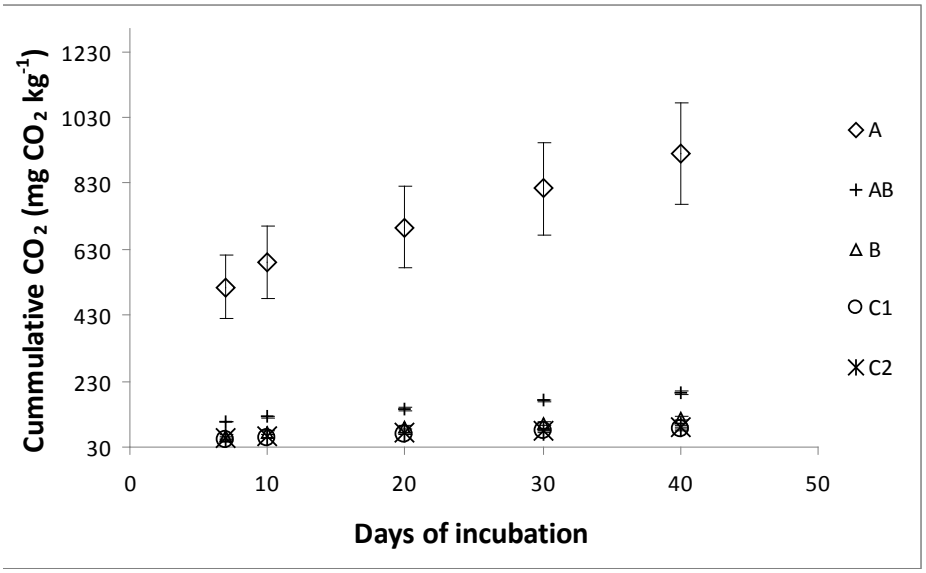


Figure 3 Proportions of labile versus stable soil organic C in silt and clay fractions across the soil profile. Error bars represent standard errors of the mean.



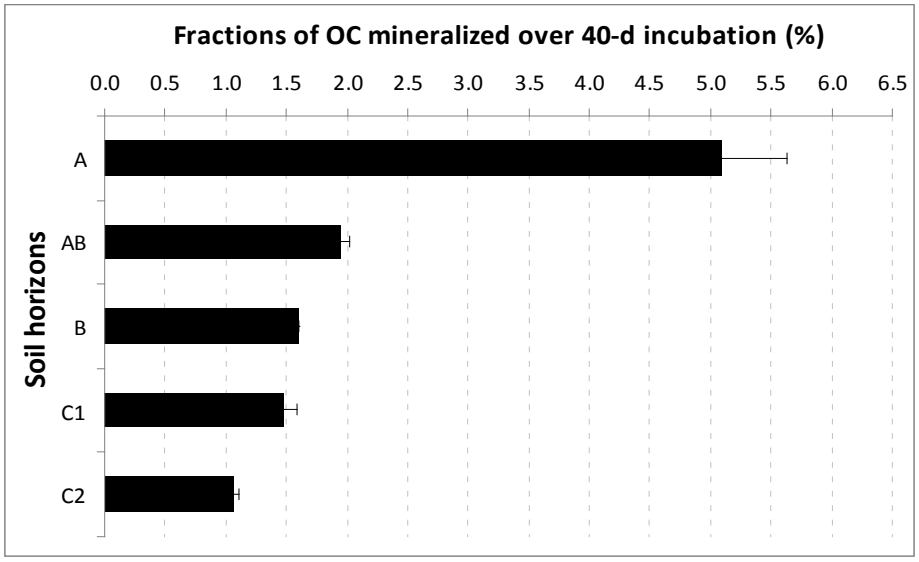


Figure 4 a) Cumulative C mineralization and b) proportions of C mineralized over a four-week aerobic incubation. Error bars represent standard errors of the mean.

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 can be 100-fold higher in subsoils than at the soil surface (data provided in later section), 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 not received much attention (Santruckova and Simek, 1997). In the topsoil, increasing CO_2 concentrations decreased soil respiration by 30-

40%, and this effect remained after decreasing the CO_2 level back to the baseline concentration (Fig. 5). In the subsoil, however, the effect of increasing CO_2 concentrations was not significant (Fig. 6) suggesting that the microbial community at depth is either distinct from the surface community or responds to increased CO_2 differently. Decreasing the oxygen level to 15% led to a decrease in soil respiration in all treatments except the subsoil 35° C treatment, but the effect disappeared after the oxygen level was reverted back to 21%. Increasing temperature did not affect the response of soil respiration to changing CO2 or O_2 concentrations, except for a small positive interaction between increased CO_2 and temperature in the topsoil.

The amount of total PLFA was higher in the topsoil compared to the subsoil and the community structure was also affected by soil depth. Figure 7 shows the principal component analysis of the PLFA analysis for the first two principal components. In the topsoil under high levels of CO_2 the microbial community shifted towards an abundance of actinomycetes and fungi and lower abundance of gram-positive bacteria. An additional shift was observed in other biomarkers (actinomycete, gram-negative, and gram-positive) with a further increase in CO_2 from 1% to 3% CO_2. In the subsoil, a similar shift in microbial community structure as in the topsoil was observed but there was no added shift when increasing CO_2 from 1% to 3%. Furthermore, the shift in the microbial community caused by the increased CO_2 did not revert back to the ambient structure during the recovery phase whereas that of the subsoil did. In summary, 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.

In situ gas concentrations and fluxes and temperature sensitivity of decomposition

Temperature in the top soil layer, to a depth of 15 cm (A horizon), was higher than that at 90 cm depth, a pattern which was observed from April till the end of September at which time the temperature at 90 cm (C2 horizon) became the highest (Fig. 8). Temperature in the A horizon dropped to about 5.5^{o} C in mid-December whereas the lowest temperature in the C2 horizon was about 12.0^{o} C. Similarly, the fluctuations in moisture content in the C2 horizon were less severe than in the topsoil; C2 moisture content was highest, at about 30% in winter and was never below 18% compared to a low of 8.5% in the topsoil.

In general, the CO_2 flux responded positively to rain events, specifically in the fall (Nov. 2008) after a period of dry weather when the temperature was still favourable above 15° C, and in spring (June 2009 and April 2010 & 2011) as the temperatures started increasing following the winter (Fig. 8). There were also increases in surface flux in December 2009 & 2010 that could have been driven by the flux coming through the subsurface soil layers where temperature was still favourable. The magnitudes of the surface fluxes ranged from about 0.0 to 1.9 μmol CO_2 m^{-2} s^{-1} and are comparable with surface fluxes measured in other Mediterranean ecosystems (Almagro et al., 2009, Fierer et al., 2005a). The pattern of seasonal variations of the net surface flux is also comparable to studies in Mediterranean and temperate ecosystems (Almagro et al., 2009, Elberling & Ladegaard-Pedersen, 2005, Fierer et al., 2003, Rey et al., 2002) in the sense that they positively respond to an increase in temperature in spring and a moisture increase in early autumn and negatively respond to a drop in temperature in winter.

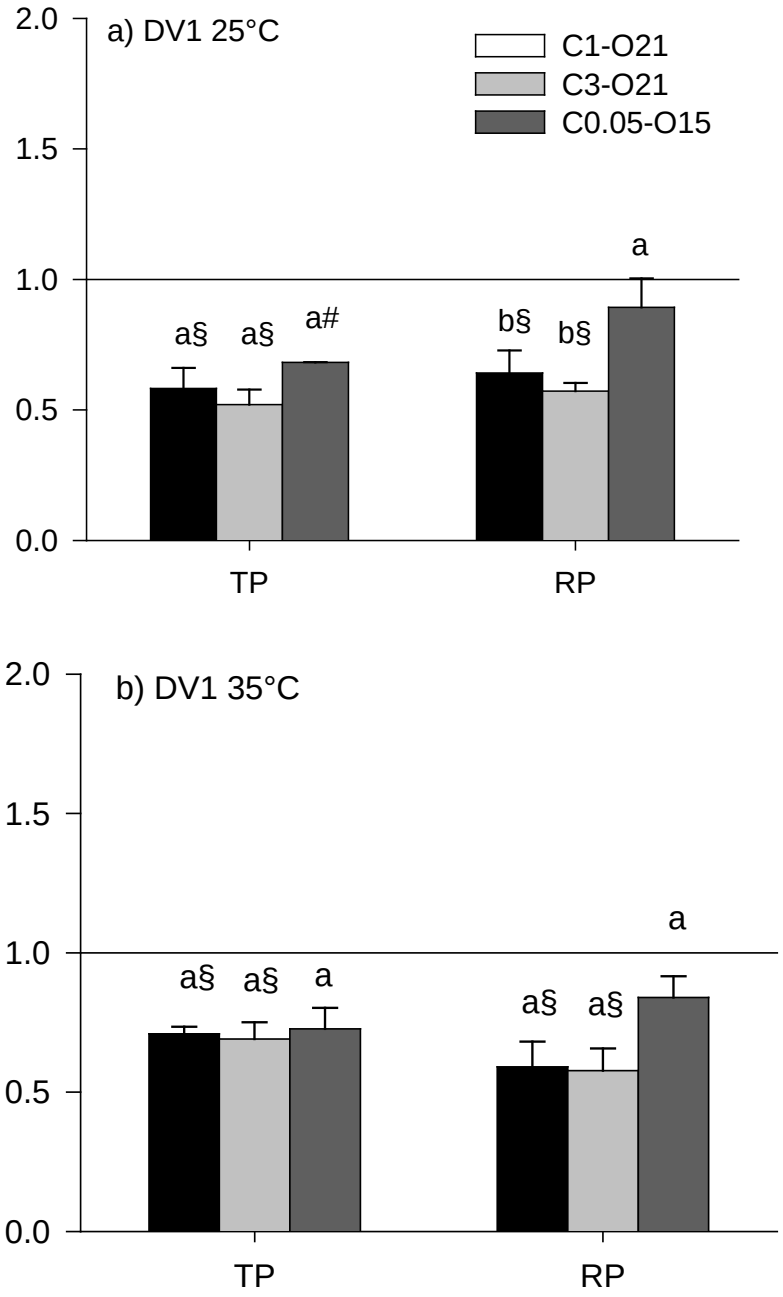


Figure 5 Respiration rates of topsoil relative to Ambient treatment for different headspace atmospheric conditions during treatment phase (TP) and recovery phase (RP) of incubation at 25°C or 35°C. Error bars denote standard deviations of the mean. Different letters indicate significant differences (P<0.05) between headspace treatments within a soil layer, incubation phase and temperature. '#' denotes significant differences between incubation phases within a soil, temperature and headspace treatment. '*' denotes significant differences between temperatures within a soil, headspace treatment and incubation phase. '§' denotes significant differences between soil layers within a headspace treatment, incubation phase and temperature. Headspace treatments whose significance letters are shown below the reference line showed a relative respiration rate significantly lower than 1 (P<0.05).

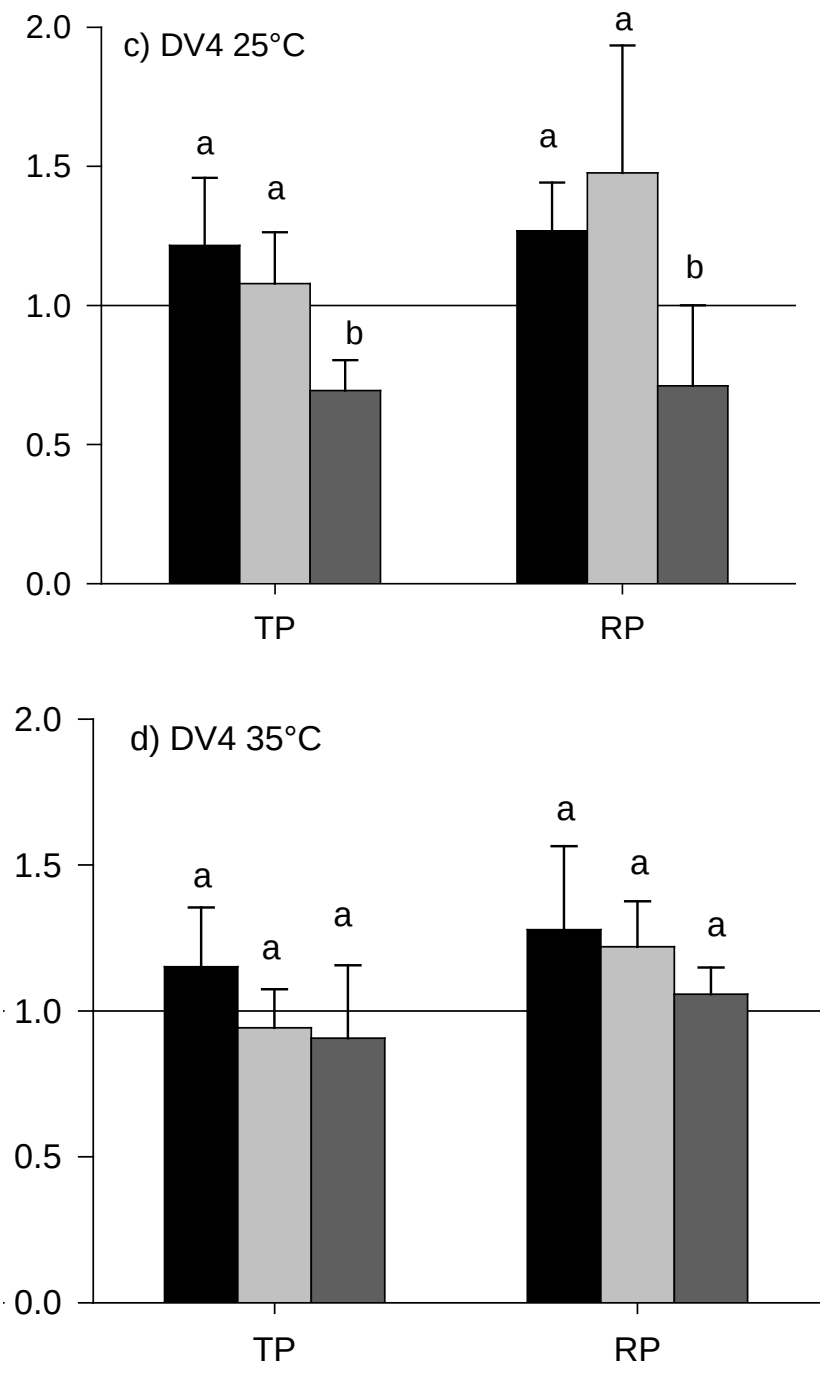


Figure 6 Respiration rates of subsoil relative to Ambient treatment for different headspace atmospheric conditions during treatment phase (TP) and recovery phase (RP) of incubation at 25°C or 35°C. Error bars denote standard deviations of the mean. Different letters indicate significant differences (P<0.05) between headspace treatments within a soil layer, incubation phase and temperature. Headspace treatments whose significance letters are shown below the reference line showed a relative respiration rate significantly lower than 1 (P<0.05).

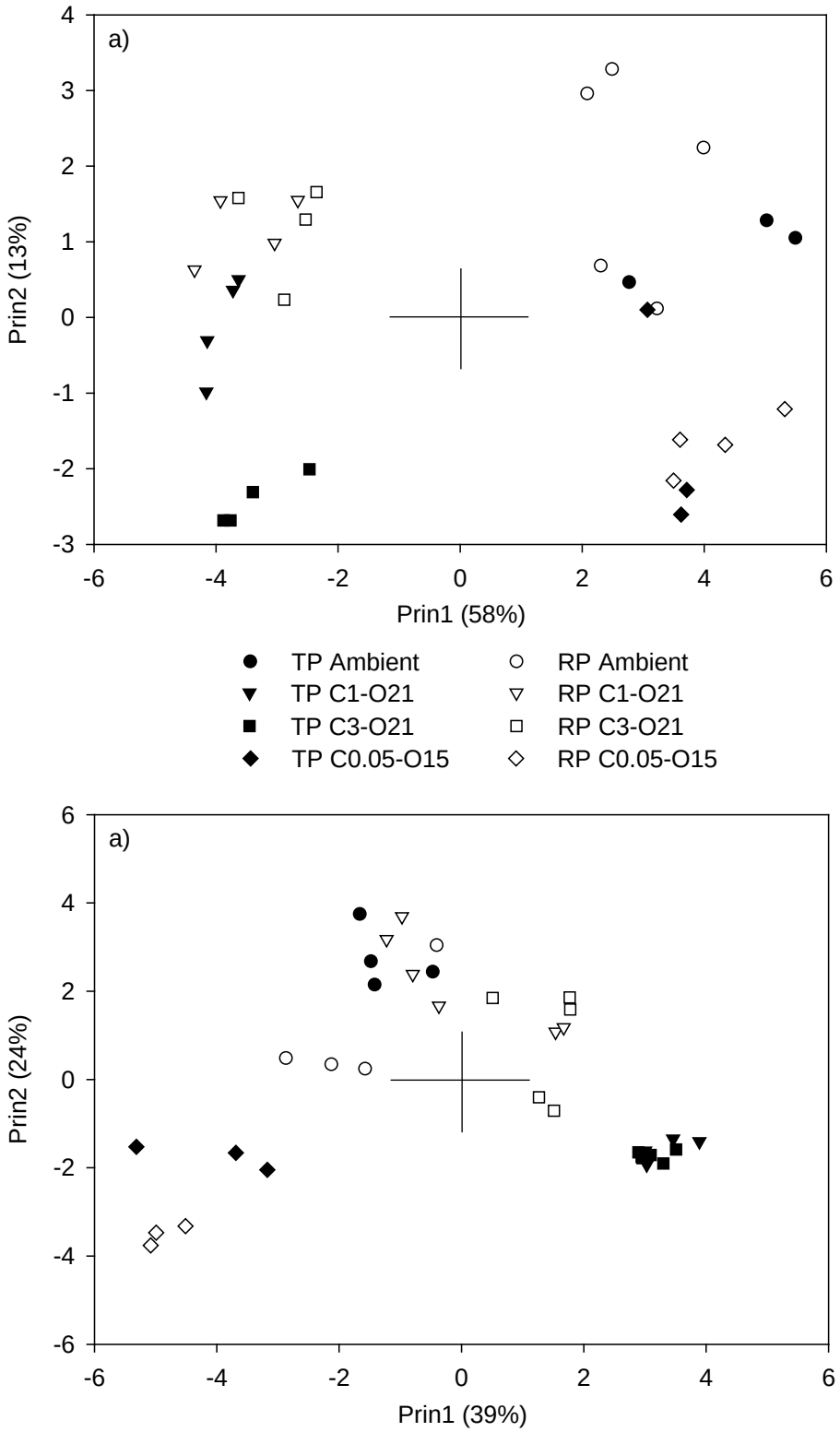


Figure 7 Principal component scores of (a) topsoil and (b) subsoil for the two first principal components obtained with PCA of PLFA analysis. TP is treatment period while the CO_2 treatments are being applied and RP is the recovery period after the CO_2 treatments.

Comparing the surface and subsurface CO_2 fluxes (Fig. 8), they are within the same range in winter but the surface flux increases more dramatically than the subsurface flux when spring starts. Throughout that year, the flux at 90 cm depth has a more or less stable rate between 0.0 and 0.6 µmol CO_2 m^{-2} s^{-1} which leads to its contribution to the surface efflux more important during winter time. In general, we observed that temperature controls surface fluxes when moisture is not a limiting factor but when surface moisture drops to about 10% during summer the control of temperature on efflux is lessened. As for the subsurface soil fluxes, they are controlled by temperature because moisture is never limiting.

The concentration of CO_2 (Fig. 9) in the topsoil layers showed considerable temporal variability during the day. However, deep soil layers did not show any significant daily pattern (Fig. 9) compared to top soil. There is a gradual increase of soil CO_2 concentration with soil depth (Fig. 9), with the highest concentration being at the 90 cm depth at an average of 0.48 µmol cm^{-3} compared to 0.14 µmol cm^{-3} at a depth of 15 cm. Increased CO_2 concentration with depth has been reported by Fierer et al. (2005) and Elberling and Ladegaard-Pedersen (2005). On a seasonal scale, we expected that CO_2 concentrations would be greatest during spring of each year when both temperature and moisture were favourable for microbial activity and that it would be somewhat lower during winter as a result of temperature limitation and during summer as a result of moisture limitation, which can be clearly seen from Fig. 9. Seasonal variation was relatively high with highest concentrations occurring around mid-November 2008 corresponding to high moisture content, and a large rainfall event (>35 mm over a few days) at this period accompanied by a relative high soil temperature (greater than 15° C), conditions that are similar to spring and favourable to microbial activity. It should be noted that this rainfall event occurred after a relative drought that had caused the lowest recorded VWC (Fig. 8) during the study period, which therefore resulted in a flush of microbial activity.

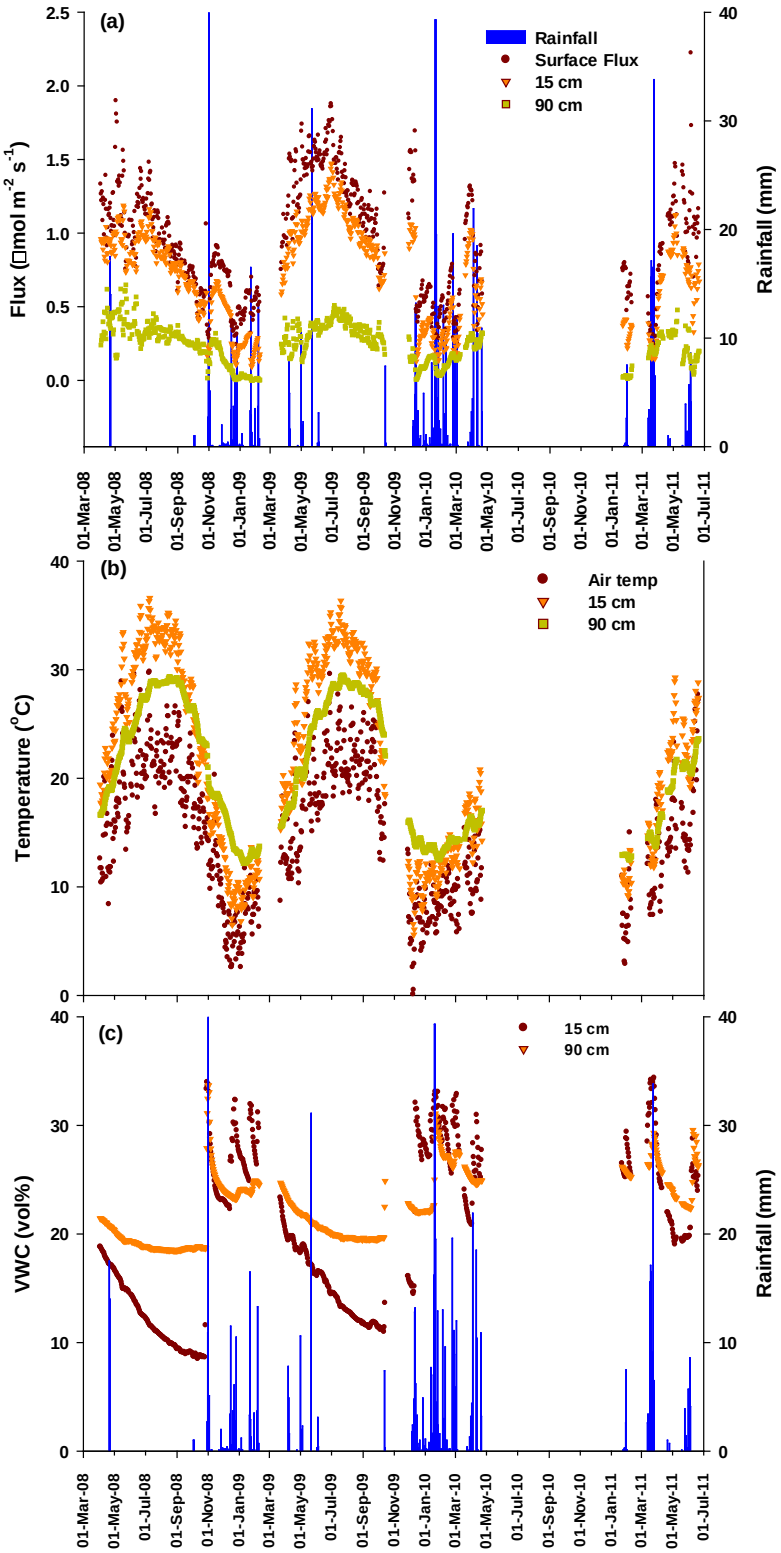


Figure 8 Average (Profile B & C) CO_2 flux (µmol m^{-2} s^{-1}) (a), soil temperature (^oC), and volumetric water content (%) and rainfall (mm) (c), in the soil profile at the surface, and at 15 and 90cm depths from April 2008 till June 2011. Note gap in data between 22-Apr-2010 and 22-Jan-2011.

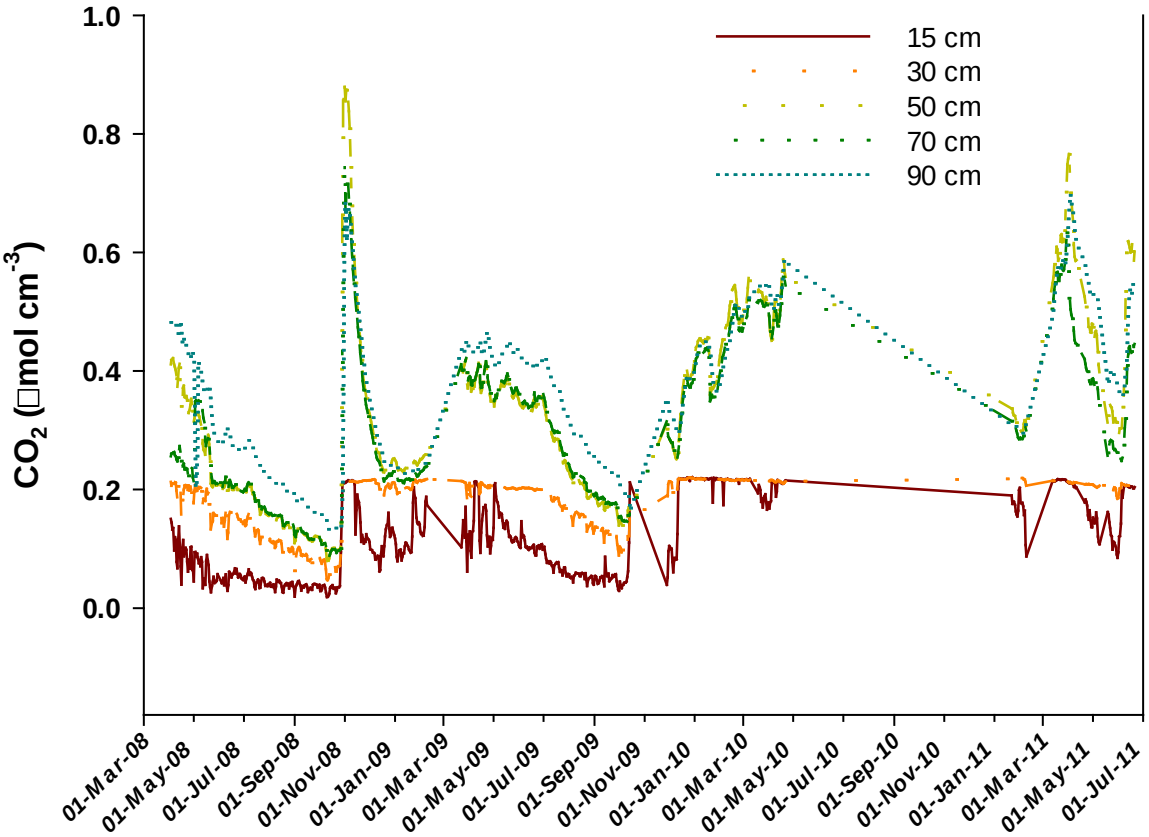


Figure 9 Average (Profile B & C) concentration (µmol cm^{-3}) of CO_2 in the soil profile at 15, 30, 50, 70, and 90cm depth from April 2008 till June 2011. Note gap in data between 22-Apr-2010 and 22-Jan-2011.

Conclusion

The deeper soil layers differ in their microbial community, temperature and moisture contents, and respiration rates. The surface soil has a much greater quantity of labile organic carbon compared to the subsoil, which agrees with the higher amounts of mineralized C from the surface. Subsoil microbial community structure and function are better adapted to high levels of CO_2, whereas topsoil microbial community structure is altered by changing CO_2 concentrations. Results from the field CO_2 monitoring experiment indicate that surface soil respiration has a higher daily and seasonal variability than that of the subsoil which is more constant throughout the year and becomes an important contributor to the surface CO_2 flux during winter time. We are now in the final phase of the field experiment where the dynamics of DOC over space and time are being examined.

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