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Sustained stimulation of soil respiration after 10 years of experimental warming

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Abstract
A number of forest and grassland studies indicated that stimulation of the soil respiration by soil warming ceases after a couple of years (Luo *et al* 2001 *Nature* **413** 622–5). Here we present results from a long-term soil warming lysimeter experiment in southern Germany showing sustained stimulation of soil respiration after 10 years. Moreover, both warmed and control treatments exhibited a similar temperature response of soil respiration, indicating that adaptation in terms of temperature sensitivity was absent. Carbon dioxide concentration measurements within the profiles are supporting these findings. The increased soil respiration occurred although vegetation productivity in the warmed treatment was not higher than in the control plots. These findings strongly contrast with current soil carbon modeling concepts, where carbon pools decay according to first-order kinetics, and thus a depletion of labile soil carbon pools leads to an apparent down-regulation of microbial respiration (Knorr *et al* 2005 *Nature* **433** 298–301). Consequently, the potential for positive climate carbon cycle feedback may be larger than represented in current models of soil carbon turnover.
Keywords: Greenhouse emissions

1. Introduction

Soil CO_2 fluxes are the second major component of the global carbon cycle (Reich and Schlesinger 1992) and play an eminent role in the context of climatic change. Soil respiration and the gas exchange between the soil and the atmosphere depend on numerous complex and nonlinear relationships, like physiological, biochemical, chemical, ecological and meteorological conditions (Kirschbaum 1995, Cox *et al* 2000). The rates of soil CO_2 efflux vary by ecosystem (Reich and Schlesinger 1992) and are the major component of whole-ecosystem respiration, which in turn explains much of the continental gradient of the net carbon balance (Schulze *et al* 1999, Valentini *et al* 2000).

In all European countries croplands are assumed to lose organic carbon (Janssens *et al* 2005). The loss may be enhanced by climate warming (Kirschbaum 1995, Cox *et al* 2000) and the emitted CO_2 may in turn reinforce climate warming. In this context the most critical issue concerns the long-term reaction of soil carbon decomposition to temperature. This involves the following questions, which could partly not be answered so far because only data from short-lived experiments were available: how temperature-sensitive is the organic carbon accumulation and decomposition in the long run? Is the organic carbon decomposition in the warmed soil still greater than in the reference soil after a long duration of soil warming? Can we reject the acclimatization hypothesis, that after a short time the

system adapts to the higher temperatures and returns to the original respiration fluxes?

2. Method

2.1. Research field

The experiment used the lysimeter facilities of the Helmholtz Zentrum München. The lysimeter station with 48 lysimeters is located just north of Munich, Germany (48°13′24N, 11°35′48E, and 490 m absolute altitude). The lysimeters, as a close-to-nature experimental set-up, are located in the middle of a 1 ha farmed area with defined crop rotation. The lysimeter vessels are made of stainless steel-cylinders (V4A) with an area of 1 m^2 and a height of 2 m. For the accurate determination of the water balance the mass of the lysimeters, the outflow and the precipitation are monitored every 10 min. The lysimeters are positioned on three high precision load cells with a resolution of 100 g. The outflow of the lysimeters is collected in weighable seepage vessels to analyze the dynamics and chemistry of the leachate. The lysimeters are equipped with tensiometers, TDR probes and temperature sensors at five depths, 30, 50, 80, 155 and 190 cm. At the same depths, suction cups and soil gas samplers were installed. Climate data are continuously recorded at a meteorological station located within the lysimeter field. The four lysimeters used in this study contained monoliths which were excavated in 1995 at Hohenwart, Germany (48°34.88N, 11°24.16E). The lysimeters were excavated at an agricultural plot, side by side at the same time. An analysis at the beginning showed that the C and N value of the soil was identical in the four lysimeters. The soil is an aric anthrosol and the soil physical parameters are given by Reth *et al* (2008).

2.2. Soil warming equipment

The simulation of a 3 K warming of the soil was performed with a heating wire placed on the soil surface. The temperature in the heated lysimeters (L14, L16) was regulated relative to the reference lysimeters (L13, L15) (figure 1). The heating experiment started in 1989 and is still running.

2.3. CO_2 measurements

Stainless steel cylinders (127 mm in diameter, 80 mm in height) with caps were used to measure the CO_2 emissions. The cylinders were placed between the cropping rows and pushed down 20 cm into the soil. If present, weed or other plants were removed from the interior. For the measurement the cylinders were closed with the caps and the gas concentrations in the chamber and in the soil started to equilibrate. After 20 min the gas in the chamber was sampled, sucking the air into an evacuated 100 ml glass flask. The CO_2 efflux F was calculated with the increase of the CO_2 concentration from C_0 at the start of the sampling period to C_t after the sampling time dt (20 min):

$$F = A(C_t - C_0)/\mathrm{d}t. \tag{1}$$

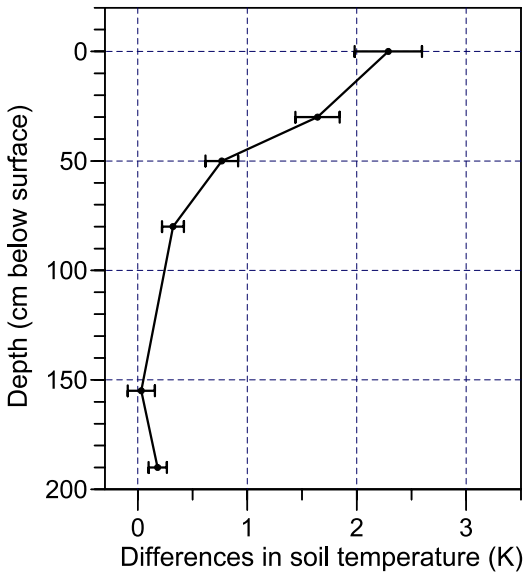

Figure 1. Profile of the soil temperature difference between the heated and unheated lysimeters; temperature data are from the year 2007. Temperature sensors are at the depths of 3, 30, 50, 80, 155 and 190 cm.

The constant A was determined experimentally. The increase of the soil temperature during the collection of the gas sample was less than 1 K. Each of the four lysimeters was equipped with five gas collection chambers. Altogether 102 measurements at each of the 20 chambers were performed.

For the soil air CO_2 concentration measurements the soil gas was slowly sucked into evacuated gas vessels (100 ml) via thin stainless steel tubes (lengths 350 mm, inner diameter 2 mm, with a dead volume 1 ml), which were covered at the sample orifice with a Gore-Tex® membrane. Altogether 86 gas probes were inserted into the four monoliths at 30, 50, 80, 155 and 190 cm depths. The gas vessels were slowly filled within 150 h to avoid a major disturbance of the soil atmosphere. In 2007, samples were taken weekly. All gas samples were analyzed using an automated probing gas chromatographic system (GC 14A, Shimadzu, Duisburg, Germany) with a ^{63}Ni electron capture detector (ECD) (Ruser *et al* 2001).

2.4. Modeling

For illustrative purposes the ICBM-Model by Andrén and Kätterer (1997) has been applied to the site. This model (equations (2)) assumes two organic carbon fractions (C_Y: young, i.e. labile, C_O: old, i.e. stable) which are decomposed by first-order kinetics and where the fraction h of the outflow from $C_Y(rk_1C_Y)$ is transformed into C_O (i.e. h represents humification) while the old fraction is entirely decomposed into $CO_2(rk_2C_O)$. Litter input i enters the system through the labile carbon pool (C_Y):

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}C_Y(t) &= i - r \cdot k_1 \cdot C_Y(t) \\ \frac{\mathrm{d}}{\mathrm{d}t}C_O(t) &= r \cdot h \cdot k_1 \cdot C_Y(t) - r \cdot k_2 \cdot C_O(t). \end{aligned} \tag{2}$$

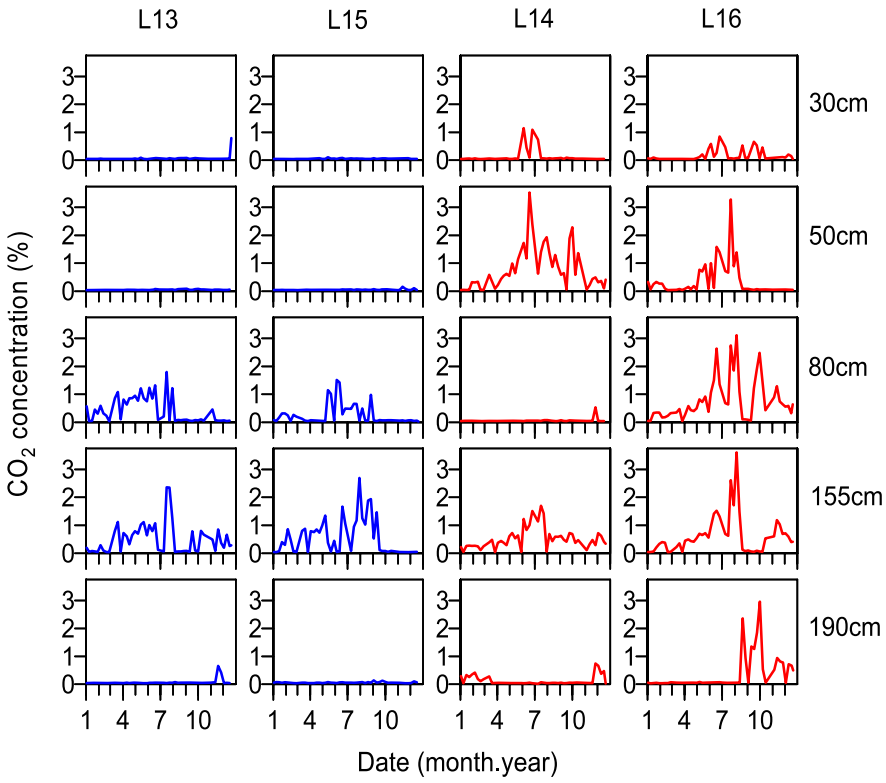

Figure 2. Time series of the CO_2 concentrations in the soil air of both the reference lysimeters (L13, L15) and the warmed lysimeters (L14, L16) at the indicated depths measured in 2007. Shown are the maximal CO_2 concentrations for each depth and each measurement session. Note that the CO_2 concentrations are given in %; they are never below the atmospheric concentration.

In the model k_1 and k_2 are standardized decomposition rates which are modified through the scalar r. This model has been successfully calibrated and applied for a range of agricultural sites (Kätterer *et al* 1998). For that reason and since the response characteristic does not depend on the absolute magnitude of the soil carbon pool, it has been applied to the site without further calibration. The temperature response of the decomposition, however, was modified to reflect the response of respiration to temperature with three alternative assumptions: (i) only the old pool decomposition is sensitive to temperature, i.e. all temperature response comes from this pool, (ii) both pools are equally sensitive to temperature (standard assumption) or (iii) only the young pool decomposition is sensitive to temperature, i.e. all temperature response comes from this pool. Assumptions (i) and (iii) are extremes and hence bracket the theoretically possible response of such a simple first-order kinetics model.

3. Results

The CO_2 concentrations in the soil air of the four lysimeters at the five depths are shown in figure 2. In the reference lysimeters an elevated amount of CO_2 was only found at depths between 80 and 155 cm whereas in the warmer soil elevated CO_2 concentrations were found at all depths (apart from the probe located in lysimeter 14 at a depth of 80 cm). The most striking CO_2 increase was registered in the upper half of the heated soil monolith.

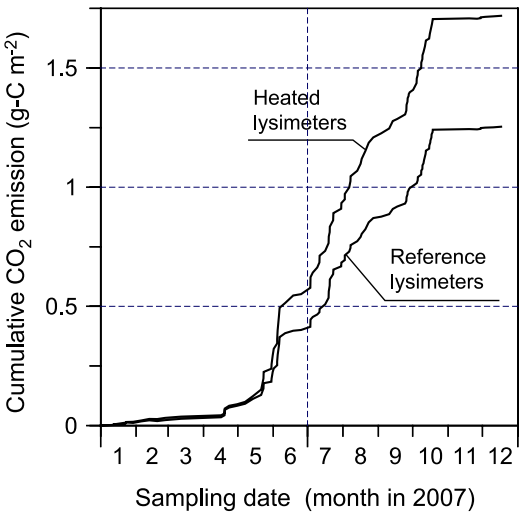

Figure 3. Cumulative CO_2 emissions from the lysimeters measured at 102 sampling sessions. The total emissions during the sampling periods (about 34 h) from the heated lysimeters are 38% higher than from the reference lysimeters.

Figure 3 shows the cumulative CO_2 efflux from the heated and the reference lysimeters. The soil warming enhanced the efflux considerably. Within the 102 measurement sessions in 2007 the reference lysimeters emitted 1.26 g-C m^2 within 34 h altogether, whereas the warmed soils emitted 1.74 g-C m^2, an increase of 38%. The cumulative CO_2 efflux from the

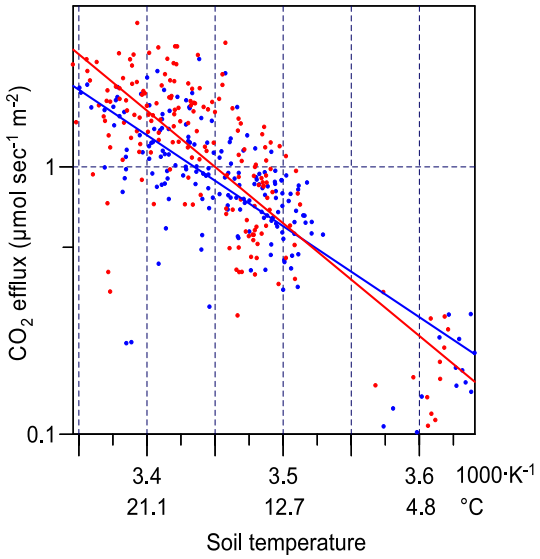

Figure 4. CO_2 emissions from ambient temperature lysimeters (L13, L15, blue symbols) and from the heated lysimeters (L14, L16, red symbols), data from 1.1.2007 to 1.1.2008. Further, the corresponding regression lines ($r^2 = 0.59$ and $r^2 = 0.63$, respectively). The activation energy in the heated lysimeters tends to be greater than in the reference lysimeters ($E_A = 81 \pm 8$ kJ mol^{-1} and $E_A = 65 \pm 7$ kJ mol^{-1}, respectively).

two warmed lysimeters differ by 16%, whereas the reference lysimeters differ by 3% in the cumulative effluxes.

The temperature dependence of the soil organic carbon decomposition obeys the Arrhenius equation (3) as shown in many studies (Lloyd and Taylor 1994, Reth *et al* 2005):

$$k(T) = A \exp(-E_A/RT) \tag{3}$$

where k is the reaction rate, A is the maximum reaction rate, E_A is the activation energy (J mol^{-1}), R is the gas constant (8.314 J K^{-1} mol^{-1}) and T is the soil temperature in kelvin. The fit of the experimental data, the measured effluxes and the corresponding soil temperatures at 30 cm depth to this equation provides information on the activation energy and the maximum of the emission rate F_{max} (figure 4). Interestingly the activation energy of the organic matter in the warmed lysimeters tends to be higher than the activation energy in the reference lysimeters: $E_A = 81 \pm 8$ kJ mol^{-1} and $E_A = 65 \pm 7$ kJ mol^{-1}, respectively. This may indicate the more advanced degradation of the soil organic material in the warmer soils; the material became more recalcitrant in the warmed environment (Agren and Wetterstedt 2007).

Applying the fitted values of the activation energies E_A and of the maximal emission rates F_{max}, the Arrhenius equation in the form

$$F(T) = F_{max} \exp(-E_A/RT) \tag{4}$$

provides estimates of CO_2 emissions F at a given soil temperature T. Using the whole-year soil temperature record at the lysimeter station the total emission in 2007 is estimated to be 240 g-C m^{-2} a^{-1} and 320 g-C m^{-2} a^{-1} from the reference and heated soil, respectively. These values are lower than the estimates inferred from intermittent measured CO_2 emissions of 325 g-C m^{-2} a^{-1} and 448 g-C m^{-2} a^{-1}, respectively, but the ratio of 1.33 is similar.

Compared to the CO_2 emissions into the atmosphere, the carbon losses to the groundwater are three orders of magnitude smaller, 440 mg-C m^2 a^{-1} and 299 mg-C m^2 a^{-1} from the reference and the heated lysimeter, respectively. Note that the reference lysimeters export 68% more DOC than the heated ones, which can be considered as a consequence of the relative low activation energies for soil carbon decomposition in the not heated lysimeters.

4. Discussion

We also tested the dependence of the decomposition rate on the water content, but the soil water content was fairly constant throughout 2007 and always high enough not to limit the decomposition rate, both in the reference and in the warmed soils, although the soil warming did alter the water balance. Evapotranspiration from the warmed soil was 44% higher than from the reference lysimeters, but the soil water content was nearly unaffected, a consequence of the high water retaining capacity of the experimental soil.

The CO_2 effluxes into the atmosphere are temperature-dependent and follow more or less the Arrhenius equation which explains up to 63% of the variance. The temperature dependence was determined in many studies (Reich and Schlesinger 1992, Lloyd and Taylor 1994, Kätterer *et al* 1998, Epron *et al* 1999). However, the fact that respiration in the warmed soil was still 38% higher than in the reference soil after 10 years of warming strongly contradicts current understanding of soil carbon dynamics which predicts a relatively rapid decline of warming effects due to depletion of labile substrate (figure 5(A)).

Hence no (apparent) acclimation or down-regulation of soil respiration was observed. The contradictory model result, which is consistent with previous studies (Knorr *et al* 2005, Luo *et al* 2001), is only partly contingent on the assumption of how different soil carbon pools respond to temperature, a widely discussed topic (Knorr *et al* 2005, Reichstein *et al* 2005b, 2005a, Fang *et al* 2005) (figure 5(B)). If the short-term temperature response is fully assigned to the young pool with higher turnover (variant (iii) in figure 5(B)), the theoretical treatment effect would even be smaller, because more substrate would be depleted. At the other extreme, if the short-term temperature response is completely assigned to the old pool (i), the theoretical treatment effect would be larger, since less substrate would be depleted within 10 years—but still significantly lower than in the experiment. One could argue that if the response would come from very old pools which could be modeled with multiple-pool models, the experimental effect could be mimicked. However, since pools with slow turnover contribute little to soil efflux, it is evident that in this case a >30% stimulation of total soil respiration would have to be caused by an enormous (unrealistic) stimulation of the old pool decomposition. In fact, already for the two-pool model employed here, an overall stimulation of the soil respiration of 35% by a warming of 3 °C (which corresponds to an overall

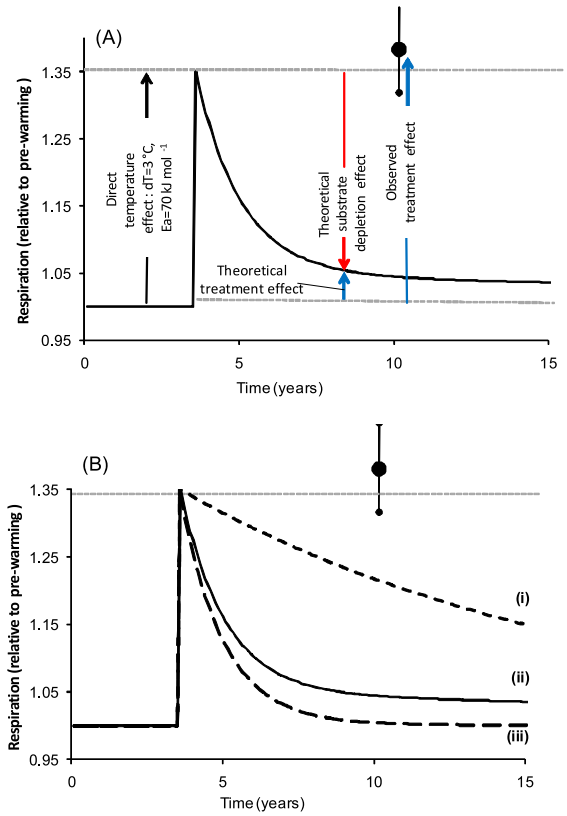

Figure 5. (A) Theoretical treatment effect on heterotrophic soil respiration using a two-pool model (Andrén and Kätterer 1997, Knorr *et al* 2005). The two-pool model predicts a decline of the warming effect due to substrate depletion (apparent acclimation). The theoretical treatment effect is much smaller than the observations which show a sustained warming effect. (B) Sensitivity analysis of the dependence of the theoretical substrate depletion effect on the temperature sensitivity of the old versus young pool: (i) the whole direct temperature effect is assumed to come from the old pool (young carbon decomposition independent of temperature), (ii) old and young C pool share a common temperature sensitivity ($E_A = 70$ kJ mol^{-1}), (iii) the whole direct temperature effect is assumed to come from the young pool only (old carbon decomposition independent of temperature).

activation energy approx. 70 kJ mol^{-1}) can only be achieved by a 270% stimulation of the respiration from the old pool if the young pool was insensitive to temperature. This simple calculation shows that the theoretical apparent acclimation cannot be avoided with the classical first-order kinetic model.

One might rather speculate that in the warming treatment additional processes were triggered which mobilize carbon and are not described in current models. The enhanced concentration in the warmed treatment might, for example, change microbial growth and activity, leading to enhanced soil organic matter decomposition (Fontaine *et al* 2007). These results highlight the complexity of soil processes involved in a response to climate change and call for a major refinement of current modeling approaches.

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