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ScienceDirect
Agriculture, Ecosystems and Environment 123 (2008) 63–68
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

# Soil organic matter mineralization and residue decomposition of spring wheat grown under elevated $CO_2$ atmosphere

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Received 16 February 2007; received in revised form 4 April 2007; accepted 16 April 2007
Available online 30 May 2007

**Abstract**

The influence of elevated atmospheric $CO_2$ concentrations ($[CO_2]$) on the decomposition of spring wheat (*Triticum aestivum* L. cv. Triso) residues remaining in the soil after harvest was simulated in a microcosm incubation experiment in the lab. Undisturbed soil cores with and without visible wheat residues were taken in the third year after establishment from a Mini-free-air carbon dioxide enrichment (FACE) system, in which we used $^{13}C$-depleted $CO_2$ to determine the contribution of plant-derived carbon to overall carbon mineralization. The Mini-FACE system is located on a Gleyic Cambisol near Hohenheim (Baden-Württemberg, Germany). Carbon dioxide production and leaching of nitrogen and inorganic and organic carbon were measured during 191 days of incubation. Rates of $CO_2$ production were generally highest in all treatments during the first two weeks of the incubation and this was followed by a steady decrease until day 58. After this day mineralization rates declined only weakly until the end of the incubation. Cumulative carbon mineralization was similar in the two treatments without visible wheat residues, but significantly lower in the elevated (−19.0%) versus ambient $[CO_2]$ treatment with visible plant residues (significant $[CO_2] \times$ residue interaction; $F_{1,13} = 7.17$; $P = 0.019$). This result demonstrated reduced decomposition of wheat residues grown under elevated $[CO_2]$. The contribution of plant-derived carbon to soil respiration was highest in the beginning, followed by a steady decrease until the end of the incubation. Irrespective of incubation time, the amount of mineralized, plant-derived carbon was higher in the treatment with visible wheat residues. Leaching of inorganic carbon (DIC) tended to be affected by $[CO_2]$ ($F_{6,8} = 4.50$; $P = 0.057$), with more DIC leached in the elevated $[CO_2]$ treatment without (+47.2%) and with visible plant residues (+29.5%) than in the respective ambient $CO_2$ treatments. The amount of carbon potentially sequestered as DIC in the wheat cropping system was small compared to the effects of elevated $[CO_2]$ on the amounts and decomposition of plant residues. Increased input of plant residues and reduced decomposition of plant-derived carbon are discussed as possible mechanisms for enhanced carbon sequestration under elevated atmospheric $CO_2$ concentration.


*Keywords:* Soil respiration; Litter decomposition; FACE; Agroecosystems

## 1. Introduction

Soil organic matter losses due to intensive management of agroecosystems substantially contribute to elevating atmospheric $CO_2$ concentrations ($[CO_2]$) (IPCC, 2001). Increasing levels of $[CO_2]$ in the atmosphere enhance net primary production, thereby increasing the input of new plant-derived carbon into the soil of grassland ecosystems

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doi:10.1016/j.agee.2007.04.001

(Hungate et al., 1997; van Kessel et al., 2000). This may positively influence C sequestration in soils. However, this increased carbon input into grassland soils can be counteracted by enhanced decomposition of old soil organic matter (priming effect), thus limiting the potential of grasslands to sequester carbon under increasing atmospheric $CO_2$ concentrations (Xie et al., 2005; Niklaus and Falloon, 2006). Depending on the type and quality of litter, the decomposability of residues from plants grown under elevated $CO_2$ concentration can be either reduced (Torbert et al., 2000; Ross et al., 2002), enhanced (Ross et al., 2002) or remain unaffected (Gorissen and Cotrufo, 2000) compared with litter produced under ambient [$CO_2$]. Decomposition of root material was also reported to be differentially affected by elevated atmospheric [$CO_2$], depending on N availability in the soil (Pendall et al., 2004).

Arable cropping systems are important for Baden-Württemberg (southwestern Germany): in 2003, about 74.4% of the arable land area was occupied by cereals, of which wheat was the dominant crop with 24.7% of the total area (Statistisches Landesamt Baden-Württemberg and Stuttgart, 2006). In managed arable wheat cropping systems without organic fertilization, organic matter inputs are low and restricted to the roots and wheat stubble that remain on the field after harvest. Most of the plant residue material is decomposed by microorganisms within the following year. By decomposing residues in winter, microorganisms remobilize nutrients, which is very important for providing available nutrients during the next cropping period (Swift et al., 1979). In this case, changes in the amount and decomposability of plant residues under rising levels of [$CO_2$], are crucial for the future SOC balances of agroecosystems.

In a microcosm incubation experiment in the lab, we determined the effects of elevated $CO_2$ concentrations on the decomposition of spring wheat residues remaining in the soil after harvest in late summer. The soil and wheat residues for the present experiment were taken from a Mini-free-air carbon dioxide enrichment (FACE) system. The use of $^{13}C$-depleted $CO_2$ enabled us to quantify the contribution of plant-derived carbon to overall carbon mineralization. Rates of $CO_2$ production from undisturbed soil cores including the wheat residues were measured in a microcosm system. This method allowed us to simultaneously determine organic matter losses through leaching.

## 2. Material and methods

### 2.1. Field site

The field experiment was performed in a Mini-FACE system located on an arable field near Hohenheim (Baden-Württemberg, Germany) (Erbs and Fangmeier, 2006). The soil is a Gleyic Cambisol (9% sand, 69% silt, 22% clay; pH 6.8; $C_{org}$ 15.5 g $kg^{-1}$ soil dry mass in the top 10 cm of the soil). Three treatments were established on the field in spring 2002; plots with elevated atmospheric [$CO_2$] (~540 ppm $CO_2$) were compared with ambient plots (380 ppm $CO_2$) and control plots (ambient $CO_2$ level, but without frames). Each treatment was replicated five times. Spring wheat (*Triticum aestivum* L. cv. Triso), sown in combination with several weeds typical of arable systems, was annually grown on the plots during spring and summer since 2002. Fumigation of FACE plots with $^{13}C$-depleted $CO_2$ ($\delta^{13}CO_2$–C ~ −20‰) since 2002 resulted in autumn 2004 in significantly lower $\delta^{13}C$ values of −38.28 and −39.73‰ for wheat stems and roots, respectively, compared to −27.01 and −27.15‰ for wheat stems and roots grown in the ambient [$CO_2$] plots ($\delta^{13}CO_2$–C ~ −8‰) (M. Erbs, personal communication). The soil was tilled in spring before wheat sowing and inorganic NPK fertilizers (N: 140, P: 30 and K: 60 kg $ha^{-1}$ $y^{-1}$) were applied three times during crop growth. Except for the wheat stubble and root residues, which remained in the soil after harvest, no organic fertilizers were applied to the plots.

### 2.2. Experimental design

For the incubation experiment, two undisturbed soil cores were taken with perspex tubes (length 150 mm, Ø 45 mm) from the upper 10 cm of each ambient and elevated [$CO_2$] plot immediately after wheat harvesting in August 2004. This yielded a total of 20 soil cores. One soil core was taken between the wheat rows (without visible residues), the other one included a single wheat stubble in the centre of the soil core (with visible plant residues on the soil surface). For the incubation, tubes containing the soil cores were fixed airtight on ceramic plates. This allowed the drainage of soil materials under semi-natural conditions by lowering the atmospheric pressure in a box below the ceramic plates. Water leached from each of the soil cores was sampled separately in vessels placed underneath the microcosms in the box. The microcosms were closed at the top by a lid which had a small vessel attached to the underside. This vessel was filled with NaOH to absorb $CO_2$ evolved from the soil.

Microcosms were incubated at 15 °C for the first 55 days and subsequently at 10 °C until the experiment ended on Day 191. This temperature regime simulated that during decomposition processes in late summer and autumn. The microcosms were watered weekly with 10 ml distilled $H_2O$. Leaching water was collected at regular intervals, and pooled samples of seven weeks were analysed for dissolved inorganic carbon (DIC) and organic carbon (DOC) and total nitrogen ($N_t$) on a Dimatoc 100 TOC/TN-analyser (Dimatec, Essen, Germany).

### 2.3. Measurement of $CO_2$ and $^{13}CO_2$

The $CO_2$ evolved in the microcosms was absorbed in 1.5 ml 1 M NaOH. For $CO_2$ determinations, the microcosms were closed with rubber stoppers and incubated for one to

five days, depending on the amount of $CO_2$ produced during incubation. Trapped $CO_2$ was measured titrimetrically with 0.1 M HCl after precipitation of carbonate with saturated $BaCl_2$ solution. Openings in the lid ensured free gas exchange between $CO_2$ determinations. Values of DOC and $N_t$ in leachates and carbon mineralized as $CO_2$ are given per microcosm.

A modified method according to Cheng and Johnson (1998) was used to determine $^{13}C$ in the $CO_2$ produced. Samples for $^{13}CO_2$–C determination were taken seven times during the incubation. The NaOH solution was quickly removed from the vessels in the microcosms and transferred into 50 ml centrifuge vessels containing 1.5 ml saturated $BaCl_2$ solution. Vessels were immediately filled up to 50 ml with distilled water and tightly closed to minimize trapping of $CO_2$ from the air. Vessels were shaken by hand and centrifuged for 10 min at 2500 rpm. After centrifugation the supernatant was discarded; the trapped $CO_2$ remained as a solid pellet in the form of $BaCO_3$ at the bottom of the vessel. The washing procedure was replicated five times until the supernatant had a neutral pH (pH 6.8–7.0), thereby avoiding further trapping $CO_2$ from the air. Subsequently, samples were dried at 65 °C for 48 h and weighed (0.3–0.5 mg) into tin capsules for analysis with an elemental analyser (EA, Euro EA 3000, EuroVector, Milan, Italy) coupled with an isotope ratio mass spectrometer (IRMS, DeltaXP Plus, Thermo Finnigan, Waltham, USA).

The proportion of residue derived C (%residue C) in $CO_2$–C was calculated by using $\delta^{13}C$ values of $CO_2$ and the following equation:

$$\%\text{residue C} = \frac{(\delta_{\text{sample}} - \delta_{\text{soil}})}{(\delta_{\text{residue}} - \delta_{\text{soil}})} \times 100,$$

where $\delta_{\text{sample}}$ stands for the $\delta^{13}CO_2$–C of the sample; $\delta_{\text{soil}}$ for the $\delta^{13}C$ of the elevated [$CO_2$] SOC and $\delta_{\text{residue}}$ for the elevated [$CO_2$] residue C.

### 2.4. Statistical analysis

Data on $CO_2$ production rates per day were analyzed by repeated measures two-way factorial ANOVA with the factors "$CO_2$" (ambient and elevated [$CO_2$]) and "residue" (without and with wheat stubble). Data on cumulative $CO_2$ production and total amounts of DIC, DOC and $N_t$ in leachates were analyzed by two-way factorial ANOVA. Some microcosms were excluded from the data set and from further analysis because either the ceramic plates or the vacuum in the boxes below the plates malfunctioned. Prior to analysis, data were checked for homogeneity of variance (Levene test) and log-transformed if required. Tukey's HSD was used for comparison of means. A statistical probability $P < 0.05$ was considered as significant. The STATISTICA 6.0 software package was used for statistical analyses (Statsoft, Tulsa, USA).

## 3. Results

### 3.1. Carbon mineralization

Rates of $CO_2$ production were generally highest in all treatments at the beginning of the incubation (between 1.34 and 3.75 mg $CO_2$–C $d^{-1}$), and this was immediately followed by a steady and strong decrease to rates of 0.60–1.34 mg $CO_2$–C $d^{-1}$ after 55 days (Fig. 1). This strong decline occurred during the period of incubation when temperature was constant at 15 °C. After adjustment to 10 °C at day 55, $CO_2$ production rates declined further, reaching rates of 0.46–1.15 mg $CO_2$–C $d^{-1}$ at day 58. Thereafter, mineralization rates only weakly declined to between 0.36 and 0.67 mg $CO_2$–C $d^{-1}$ at the end of the incubation period of 191 days. Carbon mineralization rates were significantly affected by incubation time (repeated measures ANOVA; $F_{31,402} = 108.8$; $P < 0.001$). During the whole experiment, $CO_2$ production was higher in the ambient treatment than in the elevated treatment for microcosms with plant residues; in microcosms without wheat stubble; however, $CO_2$ efflux did not differ between the ambient and elevated treatment. Cumulative carbon mineralization was therefore similar in the two treatments without wheat stubble, but significantly lower in the elevated (−19.0%) versus ambient [$CO_2$] treatment with visible plant residues (significant [$CO_2$] × residue interaction; $F_{1,13} = 7.17$; $P = 0.019$) (Fig. 2).

The depleted $^{13}C$ signal of the wheat residues grown under elevated [$CO_2$] was detectable in the respired $CO_2$ throughout the incubation. At any date, the $\delta^{13}CO_2$–C signature was in between the $^{13}C$ signature of the soil organic carbon from the elevated [$CO_2$] plots (−26.62‰) and that of the elevated [$CO_2$] wheat residues. However, the contribution of plant-derived carbon to soil respiration was highest in the beginning, and this was followed by a steady decrease until the incubation ended (Fig. 3).

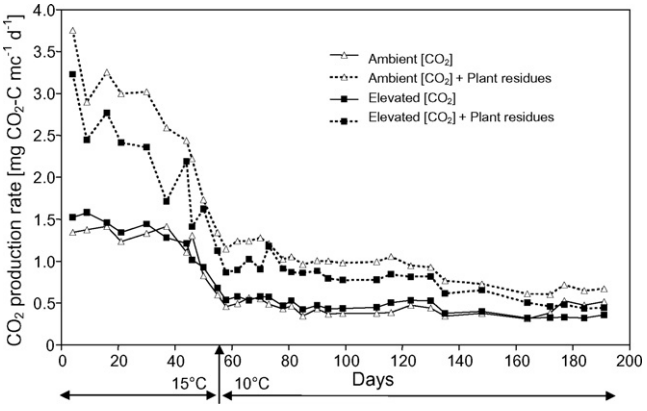


Fig. 1. Rates of daily $CO_2$–C production per microcosm (mc) during the 191-day incubation period. Incubation temperature was changed from 15 to 10 °C at Day 55, indicated by an arrow. Data points represent means of three to five replicates per treatment.

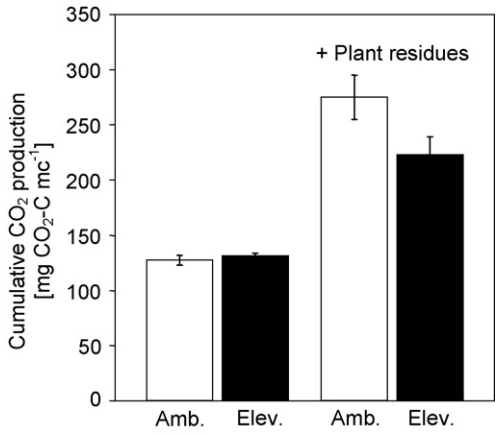


Fig. 2. Cumulative $CO_2$ production per microcosm (mc) of soil cores from the ambient (Amb.) and the elevated (Elev.) [$CO_2$] treatment without and with wheat stubble (+ plant residues) after 191 days of incubation. Means of three to five replicates per treatment with standard error.

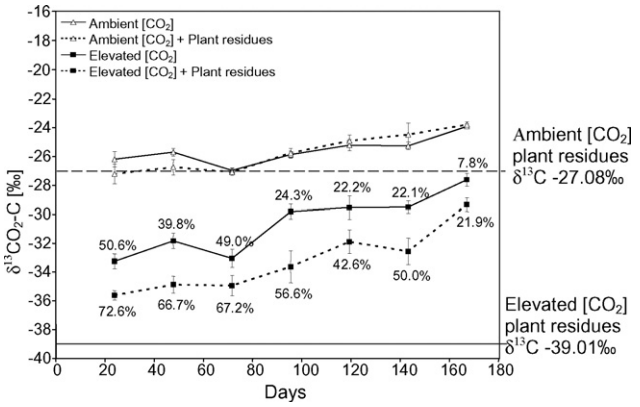


Fig. 3. Isotopic signature $\delta^{13}C$ of $CO_2$–C produced during the incubation in microcosms. Soil $\delta^{13}C$ is −25.62 and −26.62‰ for the ambient and elevated [$CO_2$] treatment, respectively. The contribution of $CO_2$–C derived from wheat residues is indicated by percentage values for the elevated [$CO_2$] treatment. Data points represent means of three and five replicates per treatment with standard error.

Irrespective of the incubation time, the amount of mineralized plant-derived carbon was higher in the treatment with visible wheat residues. Except for the smaller differences between the $\delta^{13}C$ signal of the soil organic carbon ($\delta^{13}C$: −25.61‰) and the wheat residues, the isotopic signature of the produced $CO_2$ in the ambient treatments showed the same pattern as in the elevated [$CO_2$] treatment (Fig. 3).

### 3.2. Leachate

The amounts of DIC, DOC and $N_t$ in pooled leachates were almost homogeneously distributed on the four sampling dates during the 191-day incubation (data not shown). The cumulative leached amount of total nitrogen was affected neither by [$CO_2$] nor by the presence of residues (Table 1). In the ambient [$CO_2$] treatment almost 50% of the carbon was leached in the organically bound form, and 50% as inorganic carbon. The latter component tended to be affected by [$CO_2$] ($F_{6,8} = 4.50$; $P = 0.057$ for factor [$CO_2$]), with greater amounts of DIC leached in the elevated [$CO_2$] treatment without (+47.2%) and with visible plant residues (+29.5%) than in the respective ambient $CO_2$ treatments (Table 1). Leaching of DOC was not affected by the presence of wheat residues in the microcosms.

## 4. Discussion

In treatments without visible wheat residues, the total amount of $CO_2$ produced did not differ between the elevated and the ambient [$CO_2$] treatment. Soil cores of these two treatments contained less root biomass than the treatments with visible wheat residues, and differences in decomposability might not be detectable. In contrast, total carbon mineralization was significantly lower in the elevated [$CO_2$] treatment with visible wheat residues than in the corresponding ambient treatment. Reduced decomposition of wheat straw grown under elevated $CO_2$ was reported by Frederiksen et al. (2001) for a five-month decomposition study in litterbags. Other studies investigating root decomposition in grass species also found reduced decomposition rates in the elevated [$CO_2$] treatment when nitrogen was not limiting plant growth (Gorissen, 1996; Gorissen and Cotrufo, 2000; van Groenigen et al., 2005). In arable ecosystems, nitrogen is typically supplied to the soil in the form of inorganic fertilizers to ensure sufficient plant growth and crop yield. Inorganic NPK fertilizers were also applied to the plots of the FACE experiment according to the typical farming conventions for spring wheat.

The lower total carbon mineralization we observed in the elevated [$CO_2$] treatment here is even more remarkable if the biomass of the wheat stubble, including the senescent root

Table 1
Cumulative amounts of total nitrogen ($N_t$), dissolved inorganic (DIC) and organic carbon (DOC) per soil core during 191 days of incubation in microcosms (mc) with standard errors in parentheses

| | Ambient [$CO_2$] ($n = 5$) | Ambient [$CO_2$] + plant residues ($n = 3$) | Elevated [$CO_2$] ($n = 4$) | Elevated [$CO_2$] + plant residues ($n = 3$) |
|---|---|---|---|---|
| $N_t$ (mg N $mc^{-1}$) | 2.303a (0.281) | 1.879a (0.415) | 2.373a (0.389) | 2.075a (1.013) |
| DIC (mg C $mc^{-1}$) | 1.264a (0.156) | 1.610a (0.324) | 1.861a (0.336) | 2.085a (0.081) |
| DOC (mg C $mc^{-1}$) | 1.312a (0.158) | 1.202a (0.239) | 1.284a (0.108) | 1.280a (0.096) |

Values within rows sharing the same letter were not significantly different (Tukey's HSD; $P < 0.05$).

system, is included in the calculations. This stubble and root biomass tended to be higher by 12.0 and 9.44%, respectively, in cores taken from the elevated [$CO_2$] plots in August 2004 (unpublished data). This underlines the importance of a reduced decomposability of wheat residues grown in an elevated $CO_2$ atmosphere with regard to the total carbon mineralization by the system.

Isotopic signatures of emitted $CO_2$–C revealed that new plant-derived carbon substantially contributed to the carbon mineralized in the elevated [$CO_2$] treatments. This is obvious in the treatment with wheat stubble, but even when no particulate residues were visible in the soil about half the respired $CO_2$–C was derived from plant material early in the incubation. This plant-derived $CO_2$–C originated from the decomposition and mineralization of exudates, root cells, fine roots and soil microorganisms that fed on plant products of the last two years. Since plant compounds differ in their isotopic signature (Hobbie and Werner, 2004), and since decomposition of different residue fractions (cellulose, lignin etc.) follows a different temporal pattern (Crow et al., 2006), the contribution of plant carbon to total respired $CO_2$–C might be slightly under- or overestimated. Because differences in the $\delta^{13}C$ signature between plant and soil carbon were small in the non-fumigated plots, the proportions of plant-derived C to the produced $CO_2$ could only be quantified for the elevated [$CO_2$] treatments.

The leaching of total nitrogen, as well as of organic carbon, was not significantly affected by residues and [$CO_2$]. Amounts of DOC and DON in soil solutions were found to be decreased by elevated [$CO_2$] and N fertilization during sward establishment of *Lolium perenne*, but differences diminished over the duration of the experiment and increasing plant age (Hill et al., 2006). In our experiment, effects of elevated [$CO_2$] on DOC and nitrogen leaching were rather negligible as the soil cores for the present experiment were taken at the end of the vegetation period. Although, the amount of inorganic carbon in the leachate was not significantly affected by the experimental factors, DIC tended to be higher in the elevated [$CO_2$] treatments. Increased DIC in soils at elevated [$CO_2$] was reported for a forest FACE experiment throughout the growing period by Karberg et al. (2005). They assumed that this is possibly followed by higher DIC inputs into the groundwater, thus entering a potential long-lived sequestration reservoir for carbon in the deep oceans. Our data indicate that, beside forest ecosystems, agroecosystem soils also experience higher DIC at elevated [$CO_2$]. The calculated amounts of carbon potentially sequestered in the form of DIC are marginal in the present experiment, compared to the reduced mineralization of plant-derived carbon during winter fallow. During the vegetation period, however, the amount of carbon entering the soil as $CO_2$ (and becoming dissolved in DIC) could be higher under elevated [$CO_2$] and become more important for carbon sequestration. In addition, increasing inputs of plant biomass under elevated [$CO_2$], and a longer retention time of the plant-derived carbon in the soil due to reduced decomposition, might also contribute to C sequestration. These may, therefore, be a possible pathway for C sequestration in other wheat-cropping systems in temperate regions of the world under a future $CO_2$ enriched atmosphere.

## 5. Conclusions

This study demonstrated that in spite of higher plant biomass, residue decomposition and carbon mineralization was reduced when wheat plants were grown under elevated [$CO_2$]. The amount of inorganic carbon in the leachate tended to be increased under elevated [$CO_2$], thus representing an additional possible mechanism for carbon sequestration in soils of arable cropping systems under future elevated $CO_2$ concentrations. However, changes in decomposition and SOC turnover in agroecosystems will also be driven primarily by changes in temperature and amounts and temporal pattern of precipitation. The interactions of these different factors on SOC dynamics of agroecosystems under climate change scenarios need to be investigated in more detail for different climate regions of the world.

## Acknowledgements

This study was funded by the federal state of Baden-Württemberg (BWPLUS, BWK 23003).

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