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Quantification of the CO$_2$ efflux from planted soil and separation into main biogenic carbon sources

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1. **Abstract**

This study investigated the effects of roots on the soil carbon metabolism during a short-term incubation, starting five days after germination. Plant residues, using the example of $^{14}$C-labelled *Zea mays L.*, were incubated in soil of an Haplic Luvisol under controlled laboratory conditions for 22 days at 25°C. One third of all samples was cropped with wheat (*Triticum aestivum*), the second third was cropped with maize (*Zea mays L.*). The last third of the samples was maintained bare that means without plants. Each of this thirds was composed of four parts. These were the addition of three different $^{14}$C-labelled plant residues: ground roots (1.4 mg C (g soil)$^{-1}$), ground leafs, pieces of leafs (each 1.2 mg C (g soil)$^{-1}$) and the control tubes with no plant residues. The total CO$_2$ and $^{14}$CO$_2$ efflux from soil were measured regularly. Plants increased the CO$_2$ while decreasing the $^{14}$CO$_2$ efflux. The particle size of labelled litter had a temporally differentiated effect on their decomposition. Pairs of cropped and bare soils were analysed and compared according to the amounts of C sources of the total CO$_2$. It could be shown that additional carbon inputs by root exudates and additions of $^{14}$C-labelled litter resulted in priming effects. These were represented as the effect of plants on the decomposition of plant residues and the effect of plants plus plant residues on the decomposition of soil organic matter.
2. Introduction

Roots of living plants change the conditions in the rhizosphere and influence the decomposition of organic soil substances. Especially in springtime rapid changes of temperature and humidity conditions can lead to the germination of plants at simultaneously high hoards and to a good decomposability of organic material in the soil. Besides the available soil organic matter (SOM), additional C-input takes place in soils under vegetation in form of plant residues and root exudates. It is necessary to investigate the decomposition of these C sources and their interactions for estimating the conditions making soils working as source or as sink of CO$_2$. Some experiments with addition of isotopic labelled plant material or labelled SOM have shown that the decomposition of this C sources can be inhibited or stimulated by the presence of active roots.

Dormaar (1990) and Cheng & Kuzyakov (2005) explained the change of the decomposition of litter or SOM in presence of active roots more by biological than by physical factors. Reid & Gross (1982) have observed that after 22 days the $^{14}$CO$_2$ efflux decreased up to 47% compared to bare soil, if $^{14}$C-labelled barley roots in soil were decomposed in presence of maize or rygrass. Within the first 30 days, according to Martin (1986), root growth lowered the reduction of $^{14}$C-labelled soil organic matter about 28%. This observation corresponded with the studies of Billes & Bottner (1981), Sauerbeck & Gonzales (1977) and Sparling et al. (1982).

Contrary results showed a stimulation of the microbial activity and an increase of the SOM reduction caused by the influences of living roots (Cheng & Coleman, 1990). This increase in SOC-mineralisation (positive priming effect) could be determined by De Nobili et al. (2001), Hamer & Marschner (2002, 2005) and Helal & Sauerbeck (1984, 1985, 1986).

Priming effects can switch in a short space of time between positive and negative decomposition rates in comparison to the controls where no carbon was added (Kuzyakov & Bol, 2004). Depending on the plant species and the soil conditions the decomposition of SOM ranged between -70 and +330% in soils under influence of plants compared against plant unaffected soils (Cheng & Kuzyakov, 2005). Cheng & Kuzyakov (2005) summarized the currently discussed mechanisms explaining the root effects on the intensity of the decomposition of SOM with this hypothesis: drying effect, aggregate destruction, preferential substrate utilisation, microbial activation and C uptake in roots.
To evaluate the root effect respectively the effect due to the addition of organic material in the soil, it was necessary to partition the total CO$_2$ efflux. Kuzyakov (2005) delineated five biogenic main sources. These were divided in SOM-derived CO$_2$ and plant-derived CO$_2$. The total value of SOM-derived CO$_2$ originated on the one hand from the microbial decomposition of organic material in root unaffected soil called 'basal respiration'. On the other hand the total value of SOM-derived CO$_2$ descended from the increase or decrease of SOM decomposition in comparison to the 'basal respiration' in root affected soil called 'priming effect'. Plant-derived CO$_2$ enclosed root-derived CO$_2$ (root respiration and rhizomicrobial respiration) and the microbial respiration of dead plant material.

Until now, it is little known what kinds of SOC-pools were affected by priming effects, how long they acted and how the addition of various substrates interacted with themselves compared to sole addition (Hamer & Marschner, 2005).

The following study could quantify, by means of the labelled-litter method, three main biogenic carbon sources for a period of 22 days under laboratory conditions. Furthermore, two priming effects were calculated that showed the influence of maize or wheat on the decomposition of litter, the influence of plants and the added litter on the decomposition of SOM. The aim of this study was to investigate the influences of maize and wheat on the decomposition of SOM and $^{14}$C-labelled plant residues commencing with the germ bud stadium of the plants.
3. Material and methods

3.1. Soil

Soil (loamy Haplic Luvisol) was sampled from the Ap horizon (0-10 cm) at the experimental field Karlshof from the University of Hohenheim. The soil contains no CaCO$_3$ and is characterized by pH 6.0, C, 1.2%, N, 0.13% and sand 4.4%, clay 23%, silt 73%. The soil was air-dried and plant residues were removed by sieving (< 2 mm). The detailed description of the soil and preparation was presented by Domanski et al. (2001).

3.2. Experimental set-up

To assess the effect of plants on the decomposition of soil organic matter the experimental set-up consisted of two factors with 12 treatments. The first factor was the influence of plants: no plant, *Zea mays* L. or *Triticum aestivum*. The presence of $^{14}$C-labelled plant material (no litter, ground roots, ground leafs or pieces of leafs) mixed in the soil, represented the second factor (labelled-litter method). From a previous experiment with repeated pulse labellings of *Zea mays* L. in $^{14}$CO$_2$ atmosphere (Werth et al., 2006) roots and leafs were taken. Roots and parts of leafs were pulverized in a ball mill (MM 200, Retsch). The other part of leafs was cut in pieces of approx. 0.5 cm$^2$. The specific activity of root residues was 1430 DPM mg$^{-1}$ C$^{-1}$ and that of leaf residues was 2480 DPM mg$^{-1}$ C$^{-1}$.

48g soil was weighted into 50 ml plastic tubes and thoroughly mixed with/without 150 mg $^{14}$C-labelled *Zea mays* L. residues per tube. Five days old seedlings (three for wheat, one for maize) were planted in the prepared tubes and were incubated for 22 days at 25°C. At the beginning the depth of moistening (with deionized water) corresponded to the depth of the roots to avoid the decomposition of the added $^{14}$C-labelled residues before the roots may have an effect on it. In the course of the experiment the soil moisture was kept constantly at 70% available field capacity. On the second day after planting small vials filled with 2 ml of 1.0 M NaOH were placed in the tubes for trapping CO$_2$. Thereafter all tubes were sealed airtight with vaseline at the plant stems.
During the whole experiment the vaseline closed the tubes without impairing the plant growth. To make sure that the complete below-ground CO\textsubscript{2} was outgassed, air was pumped through each tube for 1 h. In a closed circulation the air was pumped from the bottom to the top of the tube. At the top the air was piped into a closed CO\textsubscript{2} trapping tube filled with 3 ml 1.0 M NaOH. The exit of the trapping tube was connected with the entry of the pump.

3.3. Analyses

3.3.1. Total CO\textsubscript{2} and \textsuperscript{14}CO\textsubscript{2}

For determining the total CO\textsubscript{2} efflux, the NaOH solution was renewed periodically over a period of 22 days. The used up NaOH was quickly removed by means of a pipette and immediately refilled with new NaOH to minimize the air exchange between the tubes and the surroundings. The total CO\textsubscript{2} content trapped as sodium carbonate (Na\textsubscript{2}CO\textsubscript{3}) in NaOH was measured by titration with 0.1 M HCl against phenolphthalein after addition of 0.2 M BaCl\textsubscript{2} solution (Black, 1965). The \textsuperscript{14}C activity of \textsuperscript{14}CO\textsubscript{2} trapped in the NaOH solution was measured in 1 ml of aliquots of NaOH added 2 ml scintillation cocktail Rotiszint (1450 LSC & Luminescence Counter, Perkin Elmer) after a decay of chemiluminescence. The \textsuperscript{14}C counting efficiency was about 89\% and the \textsuperscript{14}C-activity measurement error did not exceed 3\%.

3.3.2. Microbial biomass of C and N

Soil microbial biomass of carbon and nitrogen was determined by chloroform fumigation-extraction method (Vance et al., 1987). Each soil sample was divided into two subsamples of 1 g soil (with 60\% water hold capacity). Whereas one portion was fumigated for 15 h with ethanol-free chloroform the other one remained as the control. Both the fumigated and the unfumigated soils were shaken for 1 h at 254 rev min\textsuperscript{-1} after the addition of 4 ml 0.05 M K\textsubscript{2}SO\textsubscript{4} solution. Centrifuging the K\textsubscript{2}SO\textsubscript{4} soil mixture for 15 min, the extracts were transferred using a pipette and then frozen until the analysis. Total carbon an nitrogen was measured on an Analysator multi N/C 2100, Analytikjena. The microbial biomass of C, N and \textsuperscript{14}C was calculated as the difference between fumigated and non-fumigates soil samples after correcting for extraction efficiency (K\textsubscript{C} = 0.45, K\textsubscript{N} = 0.54).
3.3.3. $^{14}$C content of the soil

The combustion of not consumed $^{14}$C-labelled plant residues remaining in the soil were determined by the solid module (Feststoffmodul HT 1300, Analtikjena). The soil was burned at a temperature of 1000°C for 15 minutes. Developing CO$_2$ was trapped in 8 ml 1.0 M NaOH. The special activity of each sample was detected by the Luminescence Counter as it was described in chapter 3.3.1.

3.3.4. Calculation of contributions of three C sources to the CO$_2$ efflux

The experiment was conducted with five replicates for each treatment. For treatments without plants four replicates were appreciated as sufficient. The control tubes contained none of the two factors to measure the decomposition of SOM via derived CO$_2$ under the same conditions. The total CO$_2$ efflux was represented in mg C per pot. The reduction of $^{14}$C-labelled litter derived as $^{14}$CO$_2$ was converted into mg C per pot, too. To calculate the amounts of the carbon sources on the total CO$_2$ efflux treatments with different combinations of C sources were necessary (Fig. 1).

![Figure 1: Four different combinations of three carbon sources in the soil built the prerequisite to calculate the C sources. From each combination the total CO$_2$ efflux of all C sources together and the values of PR were measured. The index shows the number of the C sources being in the treatments.](image)

- **R**: living roots (root respiration and root exudates of maize or wheat)
- **PR**: $^{14}$C-labelled litter in form of ground roots, ground leafs or pieces of leafs
- **SOM**: soil organic matter
From each combination the total CO\(_2\) efflux which originated from all C sources together being in the soil and the \(^{14}\)CO\(_2\) from the decomposition of added \(^{14}\)C-labelled PR were measured. R and SOM had to be calculated. The amount of living roots in the combination with three C sources (R\(^3\)) was computed as the difference of the total CO\(_2\) efflux from the combination with three and from the combination of two C sources (Fig. 2). SOM was computed from the total CO\(_2\) minus the calculated (P) and the measured (PR) C sources.

![Figure 2: Calculation of the C sources from living roots (R) and from soil organic matter (SOM), which were not possible to measure.]

Because of the effect of plants on the decomposition of \(^{14}\)C-labelled plant residues, the priming effect PE 1 was calculated.

\[
PR^3 - PR^2 = PE 1
\]

To determine the effect of living plants plus plant residues on the decomposition of soil organic matter, the priming effect PE 2 was calculated.

\[
SOM^3 - SOM^1 = PE 2
\]

If PE > 0 the decomposition of the C sources (PR, SOM) were influenced positively.
4. Results

4.1. $^{14}$CO$_2$ efflux from soil due to the addition of different $^{14}$C-labelled plant residues

To evaluate the effect of plants on the decomposition of $^{14}$C-labelled plant residues (PR) the cumulative $^{14}$CO$_2$ efflux as % of 1.25 g $^{14}$C (g soil)$^{-1}$ of leafs resp. 1.4 g $^{14}$C (g soil)$^{-1}$ of roots of the initial input of labelled PR was calculated.

Over all treatments, there was the most $^{14}$CO$_2$ efflux in absence of plants (Fig. 3). In pairs of appropriate treatments without plants the $^{14}$CO$_2$ of treatments with wheat was decreased by -2% to -11% and with maize even by -15% to -28%.

Differences in the $^{14}$CO$_2$ occurred not only by the presence of plants but also by the presence of added litter. Over the duration of the experiment, about 30% of $^{14}$C input of ground roots, 30-43% of ground leafs and 40-45% of pieces of leafs were degassed (Fig. 3). That implies an increase in cumulative $^{14}$C decomposition of pieces of leafs in relation to ground leafs in treatments without plants and with wheat um +15% and with maize um +33%. The preferential decomposition of bigger plant particles corresponded with the lower total $^{14}$C content of soil with pieces of leafs measured after the completion of the experiment (Tab. 1).

However, respiratory losses showed that ground litter was decomposed directly from the beginning of the experiment. The $^{14}$CO$_2$ efflux of tubes with ground leafs had gained the 5% mark of the initial input of $^{14}$C until day 1.7, tubes with pieces of leafs one day later. After 2-4 days (no plant 4, maize 4, wheat 2 days) there was a turn to a permanent higher cumulative decomposition of bigger particle sizes.

Because of cutting the aboveground biomass of the plants on day 14 a strong reduction of the $^{14}$CO$_2$ efflux occurred. The decomposition of $^{14}$C labelled PR correlated by treatments without plants with 0.94, by maize with 0.96 and by wheat with 0.95 with a logarithmic curve.
Figure 3: Cumulative $^{14}$CO$_2$ efflux originated from the decomposition of $^{14}$C-labelled Zea mays L. litter. The x-axis represents time in days after planting. The $^{14}$CO$_2$ efflux is shown as % of $^{14}$C input. The values represent means ± standard deviation (no plant n=4, with plant n=5).
4. Results

4.2. Contributions of the carbon sources to the total CO$_2$ efflux from soil

The CO$_2$ efflux consisted of decomposed exudates of living roots and root respiration, $^{14}$C-labelled litter and SOM. The mean of the cumulative CO$_2$ of every treatment was denoted in mg C per tube.

The influence of plants was shown by the comparison of the CO$_2$ progression between plants and no plants in each case of the same litter addition (Fig. 4). All treatments without plants had the lowest CO$_2$ efflux. In relation to treatments without plants treatments with maize and no addition of litter had the highest CO$_2$ efflux with an increase of the cumulative CO$_2$ of +170% to +240% (Fig. 4, diagram 1). The same constellation but with the addition of PR led to an increase of +50% to +120% (Fig. 4, diagram 2-4).

The raise of the CO$_2$ efflux due to the addition of PR was determined by the comparison of the cumulative CO$_2$ of the controls (without litter) against the appropriate treatments with litter. The increase of the cumulative CO$_2$ by adding ground leafs was higher than by adding ground roots. Independently, the decomposition of PR was influenced by the changed soil conditions caused by the presence of plants. Without the presence of plants the reduction of root litter increased the cumulative CO$_2$ by 75%, litter of leafs by 120%. Whereas in the presence of plants the CO$_2$ of roots raised 0% to 14% only and with leafs 14% to 35% in comparison with the appropriate controls without PR.

The value of the basal respiration was measured as SOM-derived CO$_2$ in the treatment without litter and without any plants. At the end of the experiment it amounted 23 mg C per tube of 48 mg soil. In the treatments without litter the basal respiration amounted $\frac{1}{4}$ of the cumulative CO$_2$ in tubes with maize, $\frac{1}{5}$ in tubes with wheat. The other part of the CO$_2$ of about $\frac{3}{4}$ respectively $\frac{2}{3}$ originated from the root-derived CO$_2$.

In summary it can be said that maize as representative of plants and leafs especially pieces of leafs as representative of litter had the strongest effects on the decomposition of the C sources. But regarding the ratio of the decomposed PR to all C sources wheat had more positive effects on the reduction of added litter than maize.
Figure 4: Cumulative CO$_2$ efflux originated from the decomposition of all C sources being in the soil. The x-axis represents time in days after planting. The CO$_2$ efflux is shown in mg C per tube. The values represent means ± standard deviation (no plant n=4, with plant n=5).
4.3. **Partition of three main biogenic carbon sources from total CO$_2$ efflux**

The three main biogenic carbon sources were calculated as described in chapter 3.3.4. The absolute values of the CO$_2$ efflux were presented as rate in mg C and as 100% per day and tube (Fig. 5.1, 5.2).

The CO$_2$ efflux rates displayed the same progression in all six variants. On day four the rate of CO$_2$ of treatments with maize reached its maximum at 10-12 mg C per day and tube. At 7-9 mg C per day and tube the maximum of the CO$_2$ rate of treatments with wheat was obviously lower. After the series of measurements the CO$_2$ efflux of treatments of maize and wheat gained in a constant decomposition rate of 0.5-1.5 mg C d$^{-1}$.

The first measurement of the CO$_2$ after 1.7 days, including the $^{14}$CO$_2$ efflux, showed the different amounts of the C sources of the total CO$_2$ caused by the different particle sizes of the added litter. The CO$_2$ of all treatments with ground material (roots and leafs) were tri- sected equally in the C sources: living roots, $^{14}$C from the decomposition of litter and SOM. The CO$_2$ efflux of treatments with pieces of leafs was divided in half of living roots and about $\frac{1}{4}$ PR and $\frac{1}{4}$ SOM.

There were differences in the amounts of the C sources caused of the influences of maize and wheat, too. The amount of living root-derived CO$_2$ from treatments with maize was constantly high with a percentage of 30-60% of the total CO$_2$ efflux per day. Whereas the amounts of root-derived CO$_2$ under the influences of wheat showed a strong volatile progression (10-70% of the CO$_2$ per day). The amount from outgassed $^{14}$CO$_2$ of the total CO$_2$ per day, from the decomposition of $^{14}$C litter, of treatments with wheat and with root litter was 30-45% (max. 62%), with ground leafs were 25-35% (max. 45%) and with pieces of leafs were 20-35% (max. 57%). On the contrary, treatments with maize showed an amount of $^{14}$CO$_2$ of the total CO$_2$ per day on an average of 20-30%. The decomposition of SOM in all treatments was in a range of 25-37% of the total CO$_2$ per day.
Figure 5.1: The amounts of the three main biogenic carbon sources as 100% of the total CO$_2$ efflux under planted soil (Zea maize L.) per day. The x-axis at the bottom represents time in days after planting and the simultaneous addition of $^{14}$C-labelled litter. Error bars show the standard deviation (n=5). The x-axis on top shows the mean of the total CO$_2$ rates in mg C per day and per tube ± standard deviation (n=5). Thereby the amount of each C source is related to a value in mg C per day and tube.
4. Results

Figure 5.2: The amounts of the three main biogenic carbon sources as 100% of the total CO₂ efflux under planted soil (Tritikum aestivum) per day. The x-axis at the bottom represents time in days after planting and the simultaneous addition of ^14C-labelled litter. Error bars show the standard deviation (n=5). The x-axis on top shows the mean of the total CO₂ rates in mg C per day and per tube ± standard deviation (n=5). Thereby the amount of each C source is related to a value in mg C per day and tube.
4.4. Priming effect 1 and 2

A priming effect (PE) is a short-term change in the turnover intensity of SOM (Kuzyakov, 2002). The increasing or decreasing decomposition of SOM compared with the SOM decomposition in root-free soil belongs to the priming effects (Kuzyakov et al., 2000; Parnas, 1976). Every kind of organic carbon especially easy available carbon added to soil may produce priming effects. This study investigated the changes of the decomposition of added $^{14}$C plant residues (PR) due to the influence of plants called PE 1 and the changes of the decomposition of soil organic matter (SOM) due to the influences of plants plus PR called PE 2. The priming effects (PE 1, PE 2) were calculated as described in chapter 3.3.4.

The priming effect 1 ranges from +90% to -65% of the decomposition rate of PR$^3$ per day in comparison to PR$^2$ (Fig. 6). In treatments with wheat there were similar periodically fluctuations of all variants of litter substrates. On average the influence of wheat decreased the decomposition rate of plant residues by -2% per day in comparison with appropriate controls without plants. Treatments with maize showed two phases of changes in the decomposition rate of PR$^3$. In the first phase the changes of the decomposition rate of PR$^3$ in comparison with PR$^2$ ranged from +10% to -35%. The first phase ended on day 8 with the maximum decrease of the decomposition rate. Within one day the maximum of the decrease of the decomposition rate changed to the maximum of the increase. This high supporting effect of the reduction of PR reached in a change of +20% of the $^{14}$CO$_2$ efflux rate at the end of the experiment. In treatments with maize the addition of root litter resulted in the lowest fluctuations, the addition of litter of leafs in the highest.

The progression of the priming effect 2, due the presence of plants plus the addition of litter, was characterized by a strong increase in the SOM mineralisation rate of treatments with litter of leafs in the middle of the experiment. The maximum of the supporting effect of the SOM mineralisation rate was around day 8 with a peak of +212% in comparison to the appropriate controls without plants. In treatments with root litter this strong increase in the decomposition rate missed.
4. Results

Figure 6: Priming effect 1: Percentage changes in mean ± standard deviation (n=5) of the decomposition rate of $^{14}$C-labelled plant resides (PR) due to the influences of living plants (maize, wheat) in % of $^{14}$CO$_2$-derived PR compared to the appropriate controls without living plants.

Priming effect 2: Percentage changes in mean ± standard deviation (n=5) of the decomposition rate of soil organic matter (SOM) due to the influences of living plants plus PR in % of SOM-derived CO$_2$ efflux compared to the appropriate controls without plants and without PR.

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**Priming effect 1 in treatments with Maize**

- Days: 1.7, 3.6, 4.6, 5.6, 6.6, 7.6, 8.7, 9.6, 10.6, 12.9, 14.6, 16.6, 21.7

**Priming effect 1 in treatments with Wheat**

- Days: 1.7, 3.6, 4.6, 5.6, 6.6, 7.6, 8.7, 9.6, 10.6, 12.9, 14.6, 16.6, 21.7

**Priming effect 2 in treatments with Maize**

- Days: 1.7, 3.6, 4.6, 5.6, 6.6, 7.6, 8.7, 9.6, 10.6, 12.9, 14.6, 16.6, 21.7

**Priming effect 2 in treatments with Wheat**

- Days: 1.7, 3.6, 4.6, 5.6, 6.6, 7.6, 8.7, 9.6, 10.6, 12.9, 14.6, 16.6, 21.7
4. Results

4.5. Dispersion-overview of $^{14}$C in the compartments

At the end of the experiment (22 d) 94% on average of the added $^{14}$C-labelled plant residues were found in the compartments soil (41-67%), including the not decomposed PR, $^{14}$CO$_2$ (28-49 %), soil air (0-0.1 %) and microbial biomass (2-3 %) (Tab. 1). The highest $^{14}$CO$_2$ efflux in treatments with pieces of leafs agreed with the lowest $^{14}$C content of the soil in this treatments. There was only a small lessening of the content of $^{14}$C incorporation into microbial biomass from treatments without plants to treatments with plants which originated from a higher C pool in treatments with plants in form of the release of root exudates. The same fact applied to the C : N ratio of the microbial biomass of treatments with plants in comparison to treatments without plants that was higher by a factor of about 2.5. Without plants there were the smallest $^{14}$CO$_2$ : CO$_2$ ratios because of the absence of the additional C sources of root exudates and the additional CO$_2$ release due to the root respiration. The $^{14}$CO$_2$ : CO$_2$ ratio of wheat was lower than that of maize. Neither leafs or roots nor their size (ground or pieces) did have any influence on the $^{14}$CO$_2$ : CO$_2$ ratio.

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<th>$^{14}$C litter</th>
<th>$^{14}$CO$_2$:CO$_2$</th>
<th>Soil</th>
<th>$^{14}$CO$_2$</th>
<th>MB</th>
<th>Average Sum</th>
<th>C:N of MB</th>
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<td>49</td>
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</table>

Table 1: Overview of the dispersion of $^{14}$C in all possible compartments after the addition of $^{14}$C-labelled litter in form of ground roots and leafs and pieces of leafs after an incubation time of 22 days. Presentation of the C : N ratio after the ending of the experiment and of the cumulative $^{14}$CO$_2$ : CO$_2$ ratio.
5. Discussion

5.1. Effects of the particle size on the decomposition of $^{14}$C-labelled plant residues

The decomposition of $^{14}$C-labelled pieces of leafs was higher by $\frac{1}{6}$ to $\frac{1}{3}$ than the cumulative $^{14}$CO$_2$ efflux of ground leafs after a period of 22 days. The minor cumulative decomposition of ground material suggested a greater stability and protection of ground $^{14}$C substrate at the soil aggregates. Besides, Ladd et al. (1995) described a better protection of the microbial biomass by the formation of an intimate contact to the soil matrix, especially to microaggregates or colloids < 50µm (Rutherford & Juma, 1992). Therefore, grinding minimized the turnover of microbial biomass and thus it lowered the substrate-derived CO$_2$ (Sørensen et al., 1996).

The largest effect of the particle sizes of the added litter could mainly be recognized within the first days (Stickler & Frederick, 1959). There was an enhanced early decomposition of ground litter which was shown in higher $^{14}$CO$_2$ efflux of ground leafs than of pieces of leafs partly up to day 4. Similar results have been worked out by Sims & Frederick (1970) and Nyhan (1975). Assumedly, the formation of an intimate contact between both the microbial biomass and the ground material to the soil matrix needed some days. The turn to a permanent higher cumulative decomposition of pieces of leafs started only 2-4 days after the beginning of the incubation. Within the first days the effect of the particle size on the decomposition of PR corresponded to the studies of Sims & Frederick (1970) and Nyhan (1975) who used the example of corn and grass residues.

Although there was a preferential decomposition of bigger PR, the $^{14}$C incorporation into the microbial biomass was equally about 3% of the initial $^{14}$C input in all treatments at the end of the experiment (Tab. 1). One explanation might be a change in the microbial activity or a change in the microbial turnover rather than an increase of microbial biomass, but this was undocumented. Also Kuzyakov et al. (2007) only found a little effect of the total microbial biomass by the addition of glucose, malate or glutamate. The study showed a 5-6% higher $^{14}$C incorporation into microbial biomass at the end of the 32-day-experiment in comparison to this study with the addition of litter and an incubation time of 22 days.
5. Discussion

Contrary results were presented by Sørensen et al. (1996) who found a 50% higher $^{14}$C microbial biomass in soil with not ground PR than to soil with ground PR residues after 42 days.

However, the results were hardly comparable attributable to different test conditions and different substrate additions that may have led to differences in the $^{14}$C incorporation into the microbial biomass.

5.2. Effects of plants on the total CO$_2$ efflux

The total CO$_2$ efflux from planted soil was higher than from unplanted soil (Fig. 4) because of the root respiration and the C input by root exudates. The addition of PR led to a higher increase of the CO$_2$ efflux especially this to tubes without plants rather than this to tubes with plants. The competition of plants and microorganism for anorganic nitrogen may have be decreased the increase of the $^{14}$C mineralisation of PR (Pansu et al., 1998).

Of course, the cumulative CO$_2$ was the highest if both C sources (plants and PR) were added. When only one C source (plant or PR) was added, the greatest increase of the CO$_2$ efflux was not measured in treatments with litter by addition of 1.25 g $^{14}$C (g soil)$^{-1}$ of leafs resp. of 1.4 g $^{14}$C (g soil)$^{-1}$ of roots but in treatments with plants, compared to the CO$_2$ of bare soil.

A possible assumption for the higher increase of CO$_2$ in treatments with plants instead of treatments with litter could be a higher C input by plants rather than by the added litter. Besides, it was assumed that the labile C of the exudates simplify the mineralisation of native soil organic matter (Kuzyakov, 2002) and thus stimulated the microbial activity (Cheng & Coleman, 1990; Clarholm, 1985b; Haider et al., 1987; Kuzyakov et al., 2000).

But Kuzyakov et al.(2007) also reported from a minor effect of the root exudate components on the decomposition of $^{14}$C-labelled plant residues. On the one hand the decomposition depended on temperature and substrate, but on the other hand a constant exudate addition may have decreased the need to mineralise litter (Kuzyakov et al., 2007) and may also have decreased the need to mineralise SOM.

Whether plants deposited exudates continuously or not, may have depended on the plant species. In this experiment all variants with maize had a higher total CO$_2$ efflux but a lower $^{14}$CO$_2$ efflux as the appropriate variants with wheat. This implied a higher $^{14}$CO$_2$:CO$_2$ ratio
of maize (Tab. 1). A possible evidence for an intermittent release of exudates by wheat gave the marked varying amounts of the root-derived CO$_2$ (10-75% of the CO$_2$ per day) during the whole experimental time (Fig. 5.1, 5.2), whereas treatments with maize showed lower variations of the root-derived CO$_2$ (30-60% of the CO$_2$ per day).

5.3. **Priming effects due to additional organic carbon**

5.3.1. **Influences of plants on the decomposition of $^{14}$C-labelled plant residues**

In agreement with the results of Billes & Bottner (1981) and Reid & Gross (1982) there was a higher cumulative $^{14}$CO$_2$ efflux in absence of plants. The negative effect of plants was manifested in a lower cumulative $^{14}$CO$_2$ efflux which was decreased about -15% to -28% for maize and -4% to -10% for wheat in relation to the treatments without plants at the end of the experiment. This values raised as a result of daily ups and downs of the priming effect 1 of +90% to -65% trough the changes of the PR$_3$-CO$_2$ efflux in relation to the PR$_2$-CO$_2$ per day. Reid & Gross (1982) explained the suppressed decomposition of labelled materials under vegetation with the following arguments, whereby probably point (1) and (4) did not apply for this experiment.

1) Competition between the roots and soil microbes for labelled materials;

2) Increasing predation of microbes around roots that otherwise might have utilized labelled substrate;

3) Utilisation by a significant portion of the soil microbes released from the roots in preference to the labelled organic materials;

4) Production of materials by roots and/or rhizosphere microbes which inhibited the activities of microbes attempting to use labelled substrate.

The point of criticism of Sparling et al. (1982) that the lower $^{14}$C decomposition was caused by the $^{14}$C uptake by roots and so the decomposition was more apparent than real could not be excluded due to a total $^{14}$C retrieval rate on an average of 94%. On the other hand it could not conduce to a satisfying explanation. As well Dormaar (1990) assumed that the decrease of the $^{14}$C decomposition is not real because of the $^{14}$C incorporation in the rhizosphere population. This expectation was not applicable for this experiment for the
reason that there were no differences in the $^{14}$C incorporation between the compared treatments with and without plants (Tab. 1).

Positive priming effects appeared in all treatments with wheat by fluctuations around zero. In treatments with maize positive PE occurred mainly in treatments with additional pieces of leaves after day eight. Cheng & Coleman (1990) also found a stimulating effect on the mineralisation of $^{14}$C-labelled rye straw. They explained it by a higher microbial activity. Living roots stimulated the biodegradation of litter, so that a faster breaking down by enzymes induced a higher C-mineralisation (Billes & Bottner, 1981).

5.3.2. Influences of plants plus plant residues on the decomposition of soil organic matter

If all positive and negative priming effects of each treatment were summarised over the whole experimental period and were related to the appropriate cumulative total CO$_2$ efflux, no differences appeared as result between maize and wheat respectively between the variants with ground or not ground plant material. Decisively for the change of the decomposition of SOM in this experiment was the addition of labelled litter of roots or leaves (Fig. 6). The addition of leaves changed the SOM decomposition in relation to the controls without PR and without plants by $+212\%$ to $-40\%$ per day. It was not depending on the particle size. On the contrary, roots affected the fluctuation of the SOM decomposition by $+25\%$ to $-61\%$ per day. Thereby, the changes of SOM decomposition were situated in the range of $-70\%$ to $+330\%$ determined by Cheng & Kuzyakov (2005) as possible changes of the SOM decomposition under the influence of plants in relation to plant unaffected soils.

The appearance of positive or negative priming effects in the SOM decomposition depended on the nutrients budget and on the C : N ratio of the organic material (Kuzyakov, 2000). On the addition of equal weight of roots and leaves, roots had an adverse C : N ratio. In case of a nitrogen limitation this could lead to a decreased decomposition of SOM (Merckx et al., 1987; Van Veen et al., 1989). A decreased decomposition of SOM occurred especially in treatments with roots.

In spite of preferential carbon mineralisation of exudates or plant materials (Sparling et al., 1982; Billes et al., 1988), the SOM decomposition can be enhanced by a co-metabolic process (Kuzyakov et al., 2000). Humble molecular organic acids from roots resulted in a
5. Discussion

chemical disturbance of the organic soil substance (Jones, 1998). This disturbance increased the microbial degradation of SOM, if enough quantities, above all rhizodepositions, have enhanced the microbial activity (Kuzyakov et al., 2000).

Despite constant laboratory conditions the soil conditions changed within the experimental period. The soil conditions changed on the one hand by the reduction of the organic carbon especially the easy available C sources in the soil due to the decomposition. On the other hand it changed by a modification of the soil by plants due to the formation of a rhizosphere which induced positive or negative priming effects.

6. Conclusion

This study is one of the few that focused on the influence of plants during their first growing period at simultaneously available plant residues and SOM. The influences of the C sources among themselves on their microbial decomposition depended on their decomposability and their availability. The reduction of plant residues were affected by the influence of the plant species (maize had more negative effects on the $^{14}$C decomposition as wheat) and of the material and particle size of the added plant residues (pieces, leafs more positive effects on the decomposition than ground particles, roots) over the whole experimental period. Changes between positive and negative priming effects 1 and 2 of the degradation of plant residues and SOM fluctuated within a few days maximum between +210% to -65% in comparison to the appropriate treatments per day. The decomposition of SOM was influenced mainly by the material of the plant residues (by leafs positive, by roots not/negative) whereas the plant species scarcely played a role. Conspicuously maize always had a higher total CO$_2$ efflux and a lower $^{14}$CO$_2$ efflux from the decomposition of $^{14}$C-labelled plant residues than wheat. The huge fluctuating amounts of root-derived CO$_2$ at the total CO$_2$ efflux and the higher $^{14}$C decomposition in treatments with wheat resulted on the assumption that higher decomposition rates of $^{14}$C-labelled material depended especially on the plant species and their intermittent release of exudates. In following studies it is necessary to investigate which factors affecting intermittent exudate release of plants and in which way this factors promote the decomposition of organic soil material.
7. References


Food and Agriculture Organisation and Agrochemistry in Braunschweig, Sept 6-10, 1976. IAEA, Vienna, pp 159-170.


8. Appendix

8.1. Titration of CO$_2$ trapped in NaOH

CO$_2$ trapped in NaOH: \[ 2\text{NaOH} + \text{CO}_2 \rightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} \]

Addition of BaCl$_2$: \[ \text{BaCl}_2 + \text{Na}_2\text{CO}_3 \rightarrow \text{BaCO}_3 \downarrow + 2\text{NaCl} \]

Titration of the excess NaOH with HCl using phenolphthalin as an indicator:

\[ \text{NaOH} + \text{HCl} \rightarrow \text{NaCl} + \text{H}_2\text{O} \]

8.2. Calculation of the CO$_2$ content of the trap

Factor = 0.5 * 12g C/mol * V$_{\text{NaOH initial addition}}$ / V$_{\text{NaOH titrated}}$ * C$_{\text{HCl}}$

CO$_2$ in trap (mg C per tube) = Factor * (V$_{\text{HCl}}$ – V$_{\text{HCl consumed}}$)

C: molar concentrations; V: volume

8.3. Conversion of $^{14}$CO$_2$ measured in DPM into mg C

$^{14}$C (mg C per tube) = DPM$_{\text{measured}}$ / DPM$_{\text{initial addition}}$ * litter addition (mg) * % C of litter

DPM: dots per million: Unit of the $^{14}$C activity measured with the Luminescence Counter.

8.4. Standard deviation (SD)

SD of measured values (CO$_2$, $^{14}$CO$_2$, PR, SOM$^1$): \[ SD = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2} \]

SD (Gauß) of calculated values (R, SOM$^{2,3}$, PE 1, 2): \[ SD = \sqrt{\sum_{i=1}^{N} \left( \frac{\delta y}{\delta x_i} \right)^2 \Delta \bar{x}_i^2} \]
9. **Assertion under oath**

Herewith I affirm that I drew up this presented work by myself and without using others than the listed resources.

All passages which were extracted literally or analogously from published or unpublished literature were marked as suchlike. This work wasn't presented any exam authority until now.

Bayreuth, March 2nd, 2009

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