Tracing dung-derived carbon in temperate grassland using $^{13}$C natural abundance measurements

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Abstract

To understand the role of dung-derived carbon in the carbon cycle of grazed temperate grasslands, we need a procedure to trace dung-derived C. The natural $^{13}$C tracer technique of applying C$_4$ dung to a C$_3$ grass pasture allowed us to successfully quantify the fate of cattle dung in the soil environment. Dung was collected from beef steers fed on either maize (C$_4$) or perennial ryegrass (C$_3$). The C$_4$ dung ($\delta^{13}$C = -15.4‰) or C$_3$ dung ($\delta^{13}$C = -25.7‰) was applied in circular patches to a temperate (C$_3$) grassland, with a bulk soil $\delta^{13}$C value of -27.9‰. Triplicate samples were taken from 1–5, 5–10 and 10–20 cm depth in the soil, and from zero tension lysimeters (installed at 30 cm depth) at time intervals of 150 days following dung application. The soil and lysimeter solution samples (<0.7 mm-filtered) were analysed for $\delta^{13}$C and total C. Dung C was readily detectable in the upper 5 cm of the soil profile, but not below that depth. After 150 days, only 16.6% of the applied dung-C was accounted for, with 12.6% of dung C being recovered in the soil (1–5 cm depth) and 4.0% in leachate waters collected in lysimeters (installed at 30 cm depth). Apparently, only a minor proportion of dung C is retained in the grassland ecosystem.

1. Introduction

Soils maintained under long-term grassland management can accumulate more than 50 t organic C ha$^{-1}$ (Jenkinson, 1988). There is thus a considerable potential for leaching of soluble C from grasslands in the regions of high rainfall, especially when grazing animals return an average of 1.5 t ha$^{-1}$ a$^{-1}$ excreta to the soil at conventional stocking rates (Whitehead, 1986). Assuming a grazing intensity of 700 cow days ha$^{-1}$ a$^{-1}$, an average of 6.4% of the grazed area is commonly covered by dung patches which provide a C input equivalent to ca. 22.5 t C ha$^{-1}$. Dung amendments can thus constitute an important source of C in temperate grassland ecosystems (Jarvis et al., 1996). A number of studies have documented the effects of dung patches on nutrient release (Underhay and Dickinson, 1978; Dickinson and Craig, 1990; Kerley and Jarvis, 1996) or the floristic composition of adjacent plant communities (Castle and MacDaid, 1972). Some investigations have also considered the role of earthworms and dung insects on the disappearance of excretal returns (Holter, 1979; Hendriksen, 1991a, 1991b; Gittings et al., 1994). However, the release and fate of carbon from cattle dung patches has, until now, received limited attention.

Losses of soluble organic C have been observed during the early phases of dung decay (Underhay and Dickinson, 1978; Dickinson et al., 1981). It is possible that this labile and biologically accessible C pool is responsible for enhanced soil microbial activity. Paul and Beauchamps (1989) found strong relationships between water soluble organic C concentrations and mineralization and denitrification capacities in a variety of soil types. Also, Zak et al. (1990) reported a positive correlation between the size of the soil mi-
crobial biomass (SMB) and water soluble organic C pools. However, although laboratory experiments have shown that SMB increases after dung applications (Bardgett et al., 1998), field studies have not produced the same marked increase in SMB pool size (Lovell and Jarvis, 1996). It is clear that a better understanding of the nature of the relationship between excretal C inputs and soil C dynamics requires more detailed information about the origin and fate of dissolved organic carbon (DOC) in the soil after dung applications.

Our aim was to investigate the rate and magnitude of C release from cattle dung patches into a temperate grassland soil using the natural $^{13}$C tracer technique. We hypothesised that the soluble dung carbon would be rapidly leached into the upper layers of the soil, and that the natural abundance $^{13}$C tracer technique would enable us to make quantitative determinations of the amounts of dung derived C into the soil and resulting leachates. The natural abundance $^{13}$C tracer technique exploits the natural isotopic difference between C$_3$ and C$_4$ vegetation, and has been used to quantify C origin and turnover after C$_3$/C$_4$ vegetation changes in bulk soil samples (Boutton et al., 1998), particle size fractions (Balesdent and Mariotti, 1996), and soil aggregates (Puget et al., 1995). This approach should therefore provide a quantitative means with which to assess the fate of C$_4$ fed livestock excreta ($^{\delta^{13}C} \sim -13\%$) in pasture ecosystems that are dominated by C$_3$ ($^{\delta^{13}C} \sim -27\%$) vegetation. We hypothesised that soluble dung derived carbon would be (rapidly) leached into the upper layers of the soil, and that the natural abundance $^{13}$C tracer technique would allow determination of the location and quantity of dung derived C in the soil and leachates.

2. Materials and methods

2.1. Field site

The experiment was conducted between 28 October, 1997 and 30 March, 1998. Experimental plots were established on long-term pastures situated at the Institute of Grassland and Environmental Research (IGER), North Wyke, Devon, southwest England (50°45′N and 4°53′W; National Grid Reference SX 650995). The site has a mean annual temperature of 10.5°C and a mean annual precipitation of 1035 mm. The soil type is classified as a clayey non-calcareous pelosol (Avery, 1980), corresponding to a Gleyic Cambisol, (FAO, 1997). Plots had been maintained under grass pasture for at least 10 years prior to the initiation of the experiment and had not been grazed or fertilised with N since 1995. Daily precipitation was recorded at 2 m height at a weather station adjacent to the experimental plots.

2.2. Dung application and sampling regime

Dung was collected from two beef steers fed on either maize (Zea mays L., a C$_4$ plant with a $^{\delta^{13}C}$ value of ca. −13‰) or silage made from perennial ryegrass (Lolium perenne L., a C$_3$ plant with a $^{\delta^{13}C}$ value of ca. −26‰). The resulting maize-derived (C$_4$) dung had a $^{\delta^{13}C}$ value of −15.4‰ ± 1.1, whereas the dung derived from ryegrass (C$_3$) had a $^{\delta^{13}C}$ value of −25.7‰ ± 0.4. The water contents of freshly collected dung were 82 and 85% dry weight for C$_3$ dung and C$_4$ dung, respectively. After collection, the dung was frozen at −20°C until required. The experimental setup comprised three main plots (3 m × 6 m). Within each main plot, there were three dung treatments. The three treatments consisted of the following controls: with no dung; C$_3$ — with Lolium perenne (L.) derived dung; and C$_4$ — with Zea mays (L.) derived dung.

Prior to application, the dung was thawed and homogenised. Aliquots of 1.5 kg dung were formed into circular patches of 450 cm$^2$ on top of a plastic wire mesh (7 mm) pegged out on the soil surface. The mesh enabled the movement of the experimental dung patches to allow for subsequent soil sampling (Lovell and Jarvis, 1996) without impeding the free movement of organic matter and soil fauna into and out of the excreta. Dung applications to the plots were made on 28 October 1997.

In addition, leachates were collected from zero tension lysimeters. These lysimeters had been installed in all the treatment plots in the summer of 1996. Intact soil blocks (including vegetation) of an area of 17 × 17 cm and 30 cm depth were taken. The soil in the exposed pit was then removed up to 60 cm depth. The lysimeter consisted of two stacked plastic containers (both 30 cm deep). The intact soil blocks were inserted in the upper container. Any water percolating down was collected in the lower container through six small holes in the bottom of the upper container. The holes were covered with mesh to avoid the loss of soil particles. The leachates were collected into glass sample bottles by suction using a vacuum pump.

The dung patches were numbered within each row and selected at random for sampling at 7, 14, 28, 42, 70 and 150 days after dung application. Soil samples were collected from below each treatment with a spade in order to obtain undisturbed soil blocks from 0–5, 5–10, and 10–20 cm depth intervals. The top 1 cm of the surface soil was not analysed due to a superficial incorporation of dung material into the underlying soil, making precise identification of the dung–soil boundary impossible. All soil samples were oven dried...
at 30°C and ground to a fine powder with a pestle–mortar prior to analysis. Leachates were collected of the following periods: 0–13, 13–21, 21–26, 26–29, 29–36, 36–47, 47–74, 74–89, and 136–150 days after dung application, filtered through 0.7 µm glass fibre filters (GF/F, Whatman International, Maidstone, England) and freeze dried prior to analyses.

2.3. Analyses

The total C and N contents of the dried, ground soil were determined by combustion using a C/N/H/S Analyser (Elementar Analysesysteme GmbH, Hanau, Germany). The triplicate δ13C‰ values of the surface soil samples (1–5 cm) were obtained by continuous flow-isotope ratio mass spectrometry (CF-IRMS), using an automated nitrogen/carbon analysis-mass spectrometry (ANCA-MS) system (Europa 20/20, Crewe, UK). Ground wheat flour was used as the working standard. The triplicate δ13C‰ values of the soils from 5–10 and 10–20 cm depths, and the freeze-dried leachates were determined using a Finnigan MAT Delta S isotope ratio mass spectrometer (Finnigan MAT, Bremen, Germany) coupled with a Carlo Erba EA-1108 elemental analyser (Fisons Instruments, Milan, Italy). The isotope ratios of the samples were compared with the isotope ratio of a reference gas, CO2 (99.995%, Linde), which had been calibrated against two reference substances. These were: sucrose and ANU, supplied by the International Atom Energy Agency (Vienna, Austria) and NBS 19 CaCO3, supplied by the National Bureau of Standards (Gaithersburg, United States). The dissolved organic carbon (DOC) was determined on filtered (0.7 µm GF/F) and freeze-dried leachate samples with a Total Organic Carbon Analyser (Skalar Analytical, Breda, Netherlands).

2.4. 13C incorporation and C flux calculations

The overall C concentration of the C3 and C4 amended leachates and soils did not significantly differ during the experiment. The calculation of dung-derived C incorporation was, therefore, done according to the following simple expression:

\[ D = \frac{(\delta_{3S} - \delta_{3S})}{(\delta_{d} - \delta_{d})} \times 100 \]  

(1)

where \( D \) is the percentage of dung-derived C (%), \( \delta_{3S} \) and \( \delta_{3S} \) are the leachate or soil (δ13C) isotope values amended with C4 or C3 dung at the sampling time \( t \) and \( \delta_{d} \) and \( \delta_{d} \) are the (δ13C) isotope values of the original C4 and C3 dung prior to application. The difference in δ13C between the original C3 and C4 dung was 10.3%. With the assumption that C3 and C4 dung materials undergo the same transformation and transport processes, the equation gives a correct estimation of dung-derived C.

The water content of the dung was 84%, and therefore, 1.5 kg dung contained 240 g dung dry matter. The C content of the dung dry matter was 40%, and straw amounted to 12% of the applied dung C. The amount of dung C in each pat was therefore (240 × (40–12)) = 67.2 g dung C. This amount of dung was applied to 450 cm² and was equivalent to 1.49 kg dung C m⁻².

The percentage of total applied dung C (\( P \)) incorporated in the 1–5 cm surface soil was calculated as follows:

\[ P = \frac{BCDV}{T}, \]

(2)

where \( B \) is the bulk density (g cm⁻³), \( C \) is the soil C content in the C4 dung amended plots at sampling date \( t \) (mg C g dry soil⁻¹), \( D \) is the percentage of dung-derived C (%), \( V \) is the volume of the soil sample in the 1–5 cm depth interval beneath the patch area of 450 cm² (1800 cm³) and \( T \) is the total dung C in each pat (67,200 mg). The total C of the topsoil (1–5 cm) was 1757 ± 57 g C m⁻², which is based on measurements obtained from the three replicate control plots on six sampling dates.

The leaching flux of organic C was calculated as follows:

\[ F = CV/At, \]

(3)

where \( F \) is the leaching flux (mg C d⁻¹ m⁻²), \( C \) is the DOC concentration (mg C l⁻¹), \( V \) is the collected leachate volume (l), \( A \) is the lysimeter area (0.0289 m²), and \( t \) is the time interval from the previous sampling (days). The sum of \( F \) values reveals the amount of cumulatively leached C within the experimental period.

2.5. Statistics

For statistical comparisons of leachates and topsoil δ13C values, we conducted a multivariate analysis of variance in a 3 × 9 and 3 × 6 repeated measures design, respectively, followed by post-hoc separation of means with the procedure of Least Significant Difference (LSD) or contrast analysis. Time was treated as repeated (dependent) measures between the groups. Additional soil depths for the δ13C values were included as three additional factors within the group. We used the software package STATISTICA 5.1 of Windows (STATSOFT, 1995). The error bars in the tables for dung-derived C represent errors calculated with the rule of error multiplication according to Gauss (Hartung, 1989).
Table 1
δ13C, dung-derived C, incorporated dung pat C and dung-C amount in the topsoil (1–5 cm)

<table>
<thead>
<tr>
<th>Days</th>
<th>Control</th>
<th>C3 dung plot</th>
<th>C4 dung plot</th>
<th>Dung derived C in the soil</th>
<th>Incorporated dung pat C in the soil</th>
<th>Dung C in the soil a</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>δ13C (%)</td>
<td>% native soil C</td>
<td>% applied dung C</td>
<td>(g C m⁻²)</td>
<td>% native soil C</td>
<td>% applied dung C</td>
</tr>
<tr>
<td>7</td>
<td>−28.36 ± 0.13</td>
<td>2.3 ± 0.1</td>
<td>2.7 ± 0.1</td>
<td>49 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>−28.70 ± 0.06</td>
<td>3.8 ± 0.2</td>
<td>4.2 ± 0.2</td>
<td>63 ± 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>−28.58 ± 0.09</td>
<td>6.9 ± 0.1</td>
<td>8.3 ± 0.1</td>
<td>124 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>−29.08 ± 0.07</td>
<td>9.4 ± 0.4</td>
<td>11.1 ± 0.5</td>
<td>166 ± 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>−28.53 ± 0.04</td>
<td>3.7 ± 0.1</td>
<td>4.4 ± 0.1</td>
<td>66 ± 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>−28.52 ± 0.26</td>
<td>11.0 ± 0.5</td>
<td>12.6 ± 0.6</td>
<td>188 ± 9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a The total C of the 1–5 cm topsoil was 1757 ± 57 g C m⁻².

Table 2
Amount of leached C and composition of the leachates at different days after dung application

<table>
<thead>
<tr>
<th>Days</th>
<th>Precipitation mm day⁻¹</th>
<th>Control</th>
<th>C3 dung plot</th>
<th>C4 dung plot</th>
<th>Dung derived C (g C m⁻² day⁻¹) in leachates beneath C4 dung</th>
<th>Soil derived C (g C m⁻² day⁻¹) in leachates beneath C4 dung</th>
<th>Dung-derived C % of leached C</th>
<th>Primed C a</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–13</td>
<td>3.0</td>
<td>0.23 ± 0.16</td>
<td>0.19 ± 0.12</td>
<td>0.24 ± 0.20</td>
<td>0.10 ± 0.08</td>
<td>1.14 ± 0.11</td>
<td>42</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>13–21</td>
<td>5.3</td>
<td>0.50 ± 0.10</td>
<td>2.04 ± 0.33</td>
<td>2.76 ± 0.30</td>
<td>1.85 ± 0.20</td>
<td>0.91 ± 0.10 b</td>
<td>67</td>
<td>15 b</td>
</tr>
<tr>
<td>21–26</td>
<td>4.2</td>
<td>0.76 ± 0.31</td>
<td>3.13 ± 0.67</td>
<td>3.10 ± 0.24</td>
<td>2.20 ± 0.17</td>
<td>0.90 ± 0.07</td>
<td>71</td>
<td>5</td>
</tr>
<tr>
<td>26–29</td>
<td>2.2</td>
<td>0.90 ± 0.59</td>
<td>2.61 ± 1.59</td>
<td>2.05 ± 0.25</td>
<td>1.13 ± 0.14</td>
<td>0.92 ± 0.11</td>
<td>55</td>
<td>1</td>
</tr>
<tr>
<td>29–36</td>
<td>3.9</td>
<td>0.47 ± 0.13</td>
<td>1.72 ± 0.61</td>
<td>1.66 ± 0.14</td>
<td>0.98 ± 0.08</td>
<td>0.68 ± 0.06</td>
<td>59</td>
<td>13</td>
</tr>
<tr>
<td>36–47</td>
<td>3.8</td>
<td>0.25 ± 0.04</td>
<td>0.74 ± 0.12</td>
<td>1.02 ± 0.02</td>
<td>0.78 ± 0.01</td>
<td>0.25 ± 0.01</td>
<td>76</td>
<td>&lt; 0</td>
</tr>
<tr>
<td>47–74</td>
<td>5.2</td>
<td>0.08 ± 0.03</td>
<td>0.45 ± 0.15</td>
<td>0.50 ± 0.19</td>
<td>0.31 ± 0.11</td>
<td>0.19 ± 0.07 b</td>
<td>62</td>
<td>22 b</td>
</tr>
<tr>
<td>74–89 b</td>
<td>3.2</td>
<td>0.09 ± 0.01</td>
<td>0.33 ± 0.10</td>
<td>0.52 ± 0.14</td>
<td>0.20 ± 0.06</td>
<td>0.31 ± 0.09 b</td>
<td>39</td>
<td>43 b</td>
</tr>
<tr>
<td>89–136</td>
<td>2.3</td>
<td>0.14</td>
<td>0.34</td>
<td>0.47</td>
<td>0.16</td>
<td>0.31</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>136–150</td>
<td>1.3</td>
<td>0.19 ± 0.07</td>
<td>0.35 ± 0.06</td>
<td>0.42 ± 0.12</td>
<td>0.11 ± 0.03</td>
<td>0.30 ± 0.08 b</td>
<td>27</td>
<td>27 b</td>
</tr>
<tr>
<td>Cumulative (0–150)</td>
<td>30.5 ± 4.6E c</td>
<td>91.8 ± 16.1 G</td>
<td>110.3 ± 12.6 G</td>
<td>59.7 ± 4.9 F</td>
<td>30.6 ± 7.5 F</td>
<td>54</td>
<td>18 b</td>
<td></td>
</tr>
<tr>
<td>%Dung pat C (0–150)</td>
<td>6.1 ± 1.1 F</td>
<td>7.4 ± 0.8 F</td>
<td>4.0 ± 0.3 E</td>
<td>3.4 ± 0.5 E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Primed C estimated for each period, by subtracting the amount of leached soil-derived C in C4 dung plots (g) with leached C at the control site, divided by total leached C in C4 dung plots.
b Indicates significant higher leaching of soil-derived C beneath the C4 plots compared to the control treatments (positive priming; P < 0.05).
c Taken as midpoint between 74–89 and 136–150 day period.
d Different capital letters (E–G) indicate significant difference at the P < 0.05 level of probability.
3. Results

3.1. Dung-derived C in the soil

The soil C concentration (1–5 cm depth) underneath dung patches did not change significantly with time or between C3 and C4 treatments (p > 0.05; data not shown). Obviously, total C analysis was not sensitive enough to trace accumulation of dung-derived OM in the mineral soil.

There were no differences in the δ13C values of soil organic C between C3 dung and control treatments (Table 1). The δ13C values of C in the surface soil (1–5 cm), however, were higher under C4 than under C3 or control treatments (p < 0.001; Table 1). In contrast to total C analysis, the determination of 13C natural abundance enabled detection of dung-derived C in soil. The temporal incorporation of C4 dung increased the soil δ13C value from −28.3% at day 7 to −27.6% at day 150 (Table 1). The δ13C values for the soil in the C3 dung treatment were relatively constant, therefore, the percentage of dung-derived C in the C4 soil was related to the increase in the soil δ13C values following C4 dung application (Table 1). One week after dung application, 2.3 ± 0.1% of soil C (1–5 cm depth) was dung-derived, increasing to 11.1 ± 0.5% after 150 days (Table 1). This was equivalent to 2.7 ± 0.1% and 12.6 ± 0.6% of the applied dung pat C, and amounted to 40 ± 2 and 188 ± 9 g dung C m⁻² in the 1–5 cm soil profile (Table 1). The highest flux of 5.8 g C m⁻² day⁻¹ dung-derived C into the soil occurred in the first 7 days after dung application. The overall rate of dung-C incorporation was 1.3 g C m⁻² day⁻¹ for the 150-day period. All, dung had disappeared from the soil within 42 days, therefore, the breakdown rate was greater than 35.5 g C m⁻² day⁻¹.

During the experiment, the penetration of organic matter from the dung was limited to the top 1–5 cm of the soil profile (Fig. 1). The temporal changes in the soil δ13C values at 5–10 cm depth did not reveal significant movement of C4 dung carbon to that depth (data not shown). The soil δ13C values for 10–20 cm depth were therefore measured only for the last sampling date (150 days after dung application), showing only an increase in δ13C values with increasing depth at the control site (Fig. 1).

3.2. Dung-derived C in the leachates

The application of dung led to a significant increase in the organic C flux in the leachates (P < 0.001; Table 2), but there were no significant differences in the flux rates of DOC beneath C3 and C4 dung patches (Table 2). The dung-induced C flux showed a maximum between 21 and 26 days after application (Table 2), and declined thereafter. The leaching rates were not correlated with rainfall events (Table 2).

There were no significant differences between the δ13C values of the leachates from the control and C3 dung amended plots (Fig. 2). However, the δ13C values of the leachates of the soil amended with C4 dung were significantly higher (P < 0.001) than those obtained from either the control or the C3 dung treatment (Fig. 2).

This indicated that a significant proportion of the C in the leachates was derived from the C4 dung. Thus, changes in δ13C values of the leachates beneath the C4 dung reflected temporal, variations in the proportion of dung-derived C, ranging from 27–76% (Table 2).

After 150 days, the cumulative leaching losses amounted to 30.5 ± 4.6 g C m⁻² in the control compared to 91.8 ± 16.1 and 110.3 ± 12.6 g C m⁻² below the C3 and C4 treatments, respectively (Table 2). The leachates in the C4 treatment contained 50.6 ± 7.5 g C m⁻² native soil C and 59.7 ± 4.9 g C m⁻² dung-derived C (Table 2), which constituted 4.0% of the initial C in the dung patches (Table 2). The average leaching flux
of the dung derived-C was 0.4 g C m\(^{-2}\) day\(^{-1}\) over the 150-day period.

Knowing the proportion of dung-derived C in the enabled, allowed us to distinguish the amount of dung-derived C from that of soil-derived C in the plots that were amended with C\(_4\) dung. For several sampling periods, the amount of soil-derived C that was leached from the dung-treated plots exceeded that at the control site, and the cumulative total amount of soil-derived C leached from the dung-treated plots was also significantly higher than for the control site (Table 2). Hence, the dung amendments appeared to promote DOC mobilisation from the SOM. The proportion of additionally mobilised DOC (= primed C) in the leachates was higher in the latter part of the study (Table 2).

4. Discussion

4.1. Dung-derived C in soil

This study showed that the natural \(^{13}\)C tracer technique approach of applying C\(_4\) dung to a C\(_3\) grass pasture could be used to quantify the fate of cattle dung in the soil.

We found that 150 days after dung application only a minor proportion (12.6%) of the applied dung C was retained in the topsoil (1–5 cm) of the grassland ecosystem. However, in our study, the dung-derived C in the first 1 cm of the soil under the dung pat was not examined, and the absolute mass of dung C transferred into the soil was therefore underestimated.

The lack of temporal changes in the \(^{13}\)C values below 5 cm depth in the soil did not prove that no C\(_4\) dung carbon was translocated to such depth. The errors associated with the sampling procedure and analysis averaged 0.16% of the obtained values, i.e. equivalent to ca. 1.6% dung-derived C incorporated in the soils. Hence, our result merely indicates that the proportion of dung-derived C in the soil below 5 cm depth was less than (the ‘detection’ limit of) 1.6%.

4.2. Dung-derived C in leachates

The leaching rates did not correlate with the rainfall events. We therefore assume that our leaching rates reflected both, the period of microbial transformation of the dung material to water soluble (i.e. mobile C) forms, and changes in the relative increase in surface area of the dung exposed to rain, leading to variations in leaching losses.

The high incorporation rates of dung-derived C in the soil (1–5 cm) in the first 7 days after dung application did not correspond to that of the DOC flux which peaked at 26 days. This suggests that some time is needed for both, the microbial communities to process and alter some dung-derived C constituents, as well as for the DOC itself to saturate sorbing sites before it can pass further down the soil column.

The prominent DOC flux maximum, 21–26 days after dung application, agrees with the results from other comparable experimental studies. For example, Underhay and Dickinson (1978) interpreted increasing caloric values from the dung material from day 6 to 19 as a sign of leaching of soluble organic compounds. Dickinson et al. (1981) found that C–N ratios in applied dung pats decreased during the first 17 days, which they associated with the loss of soluble carbohydrates. Finally, Holter and Hendriksen (1988) showed that the respiratory rate of microorganisms and also the loss of dung OM, reached its maximum between 21 and 32 days after application.

The precise mechanisms by which the addition of dung C to the soil induces this additional release (‘priming’) of native C from day 21 onwards are, as yet, not fully understood. However, the input of additional labile C (derived from the dung) may promote microbial activity (Schlegel, 1992), and this microbially mobilised native C could be lost during leaching, or ‘new’ dung-derived C might compete with native SOM for sorption sites.

The steep decrease in DOC flux after day 42 was probably connected to the disappearance of the dung pats from the soil surface by that time, which limits the dung C available for leaching to only the dung-derived C previously incorporated in the soil. Holter (1979) and Gittings et al. (1994) found that dung pats took ca. 50–65 days to disappear. However, the breakdown of dung pats is an extremely variable process and a wide range of rates of breakdown have been reported (Castle and MacDaid, 1972; Dickinson and Craig, 1990; Lovell and Jarvis, 1996). The biotic influences on the dung decay were not quantified in this study.

Additional research was conducted to examine the temporal trends in dung-C incorporation in five separate particle size fractions. This study supported the hypothesis that initial input of dung during the first 42 days after application was dominated by the cumulative input of (microbially) mobilised DOC, whereas later dung-derived C inputs resulted from the build-up or translocation of particulate residues (Amelung et al., 1999).

5. Conclusions

The application of C\(_4\) dung to a C\(_3\) grass pasture allowed us to successfully trace dung-derived C in the soil environment. Dung C was readily detectable in the upper 5 cm of the soil profile, but not below that.
depth. All dung C disappeared from the surface within 42 days, but less than one-fifth of its applied amount was accounted for in soil and leachates. Thus, most C from dung pats was lost from the soil environment.

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