Dairy Farm Effluent Effects on Urine Patch Nitrous Oxide and Carbon Dioxide Emissions

Tim J. Clough* and Francis M. Kelliher

ABSTRACT

Dairy farm effluent (DFE) comprises animal feces, urine, and wash-down water collected at the milking shed. This is collected daily during the milking season and sprayed onto grazed dairy pastures. Urine patches in grazed pastures make a significant contribution to anthropogenic N2O emissions. The DFE could potentially mitigate N2O emissions by influencing the N2O to dinitrogen (N2) ratio, since it contains water-soluble carbon (WSC). Alternatively, DFE may enhance N2O emissions from urine patches. The application of DFE may also provide a substrate for the production of CO2 in pasture soils. The effects of DFE on the CO2 and N2O emissions from urine patches are unknown. Thus a laboratory experiment was performed where repeated DFE applications were made to repacked soil cores. Dairy farm effluent was applied at 0, 7, or 14 d after urine deposition. The urine was applied once on Day 0. Urine contained 15N-enriched urea. Measurements of N2O, N2, and carbon dioxide (CO2) fluxes, soil pH, and soil inorganic N concentrations were made. After 43 d the DFE had not mitigated N2O fluxes from urine patches. A small increase in the N2O flux occurred from the urine-treated soils where DFE was applied 1 wk after urine deposition. The amount of WSC applied in the DFE proved to be insignificant compared with the amount of soil C released as CO2 following urine application. The priming of soil C in urine patches has implications for the understanding of soil C processes in grazed pasture ecosystems and the budgeting of C within these ecosystems.

DUE TO ITS DUAL ROLE as a greenhouse gas (Duxbury et al., 1993) and as a precursor to ozone-depleting gases (Crutzen, 1981) there is interest in mitigating the emissions of nitrous oxide (N2O). Agricultural soils are a major source of anthropogenic N2O (Food and Agriculture Organization of the United Nations, 2001) and intensive grazing systems have relatively high emissions of N2O compared with cropping systems. For N2O mitigation strategies to be adopted they must be economical, easily applied to existing farming methods, and/or require minimal disruption to existing practices. In New Zealand, legislation prevents the direct discharge of DFE to surface waters and current farming practice consists of applying the DFE to pasture soils. Dairy farm effluent is collected at the milking shed. Animal effluent is deposited in the concrete yard area as animals wait to be milked and during milking. The yard is washed down after milking, with the wash-down water and effluent gravity-fed into tanks where pumps then empty the DFE from the tanks by spray irrigating nearby pasture. The predominant constituents of the DFE are urine and dung. Dairy farm effluent composition varies according to animal numbers, feed quality, and volume of wash-down water. Dairy farm effluent contains nitrogen (N) as urea, ammonium (NH4+), nitrate (NO3-), and organic N forms. The total N content of DFE varies but reported values range from 260 to 280 mg N L-1 (Barton and Schipper, 2001; Di and Cameron, 2004). The C content of DFE also varies with feed quality. Barton and Schipper (2001) found DFE from pasture-fed animals had a total C content of 0.2%, a dry matter content of 0.4%, and a pH of 7.9. Nitrogen application rates of DFE to pasture thus depend on its composition and the volume of irrigation. The timing of DFE application also varies with respect to the time of urine deposition and the resulting urine patches. Dairy farm effluent may be applied immediately after grazing or several days after grazing depending on the grazing rotation employed on the farm and the DFE application strategy. It is also feasible that a urine patch may receive repeat applications of DFE.

Nitrous oxide emissions can be promoted by DFE application to pastures. Barton and Schipper (2001) found DFE irrigation to be a source of N2O due to increases in soil N, water content, and available C when DFE was applied to peat and mineral soils. However, the study of Barton and Schipper (2001) did not examine the potential relationship between N2O and dinitrogen (N2) fluxes or the possible effect of repeated applications of DFE. The deposition of bovine urine N onto pasture soils also stimulates N2O emissions. The availability of water-soluble carbon (WSC) can influence denitrification rates and/or the ratio of N2O to N2 (Burford and Bremner, 1975; Firestone, 1982). Priming effects are short-term changes in the turnover of soil organic matter where large amounts of C, N, and other nutrients may be released or immobilized in a very short time (Kuzmakov et al., 2000). Urine addition to soils can result in increases in CO2 fluxes, over and above the amounts of C applied, with the release of native soil C indicative of a priming effect (Clough et al., 2003). The interaction of DFE and urine patches, with respect to N2O emissions, has not been reported on. It is possible that DFE application to urine patches (i) increases N2O emissions from urine patches due to the addition of extra N substrate and nutrients or (ii) alters the ratio of N2O to N2 due to the addition of C and irrigation water creating conditions conducive to the further reduction of N2O. The objectives of this study were to assess the effects of DFE on urine patch N2O, N2, and CO2 emissions.

MATERIALS AND METHODS

Soil and Treatments

A Temuka silt loam soil [Fluvaquentic Endoaquept; Soil Survey Staff (1998)] was collected from a 2-m2 area of a dairy

Abbreviations: DFE, dairy farm effluent; WFPS, water-filled pore space; WSC, water-soluble carbon.
Table 1. Timing of dairy farm effluent (DFE) treatment applications and total rates of inorganic N and water-soluble carbon (WSC) applied in the DFE treatments. The control and urine treatments did not receive DFE.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Day</th>
<th>Inorganic N</th>
<th>WSC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>DFE</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>UDFE0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>UDFE1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>UDFE2</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

† Urine was applied on Day 0 in all of the DFE treatments. DFE applications, indicated by the symbol ✓, commenced on Days 0, 7, and 14 for treatments UDFE0, UDFE1, and UDFE2, respectively.

Table 2. Mean composition of dairy farm effluent (DFE) at each application. Twenty-five milliliters of DFE was applied per core at each application.

<table>
<thead>
<tr>
<th>Application time</th>
<th>pH</th>
<th>NH₄⁻N</th>
<th>NO₂⁻N</th>
<th>NO₃⁻N</th>
<th>Water-soluble carbon (WSC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>µg mL⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>1 (fresh)</td>
<td>8.1 (0)†</td>
<td>8 (0)</td>
<td>2 (0)</td>
<td>0.1 (0)</td>
<td>466 (4)</td>
</tr>
<tr>
<td>7</td>
<td>7.8 (0)</td>
<td>15 (0)</td>
<td>1 (0)</td>
<td>0.2 (0)</td>
<td>444 (5)</td>
</tr>
<tr>
<td>14</td>
<td>8.7 (0)</td>
<td>6 (0)</td>
<td>0</td>
<td>0</td>
<td>151 (8)</td>
</tr>
<tr>
<td>21</td>
<td>8.1 (0)</td>
<td>64 (1)</td>
<td>0</td>
<td>0</td>
<td>454 (16)</td>
</tr>
<tr>
<td>28</td>
<td>8.0 (0)</td>
<td>7 (0)</td>
<td>0</td>
<td>0</td>
<td>400 (8)</td>
</tr>
</tbody>
</table>

† Numbers in parentheses are standard deviations of the means, n = 5.
RESULTS

Nitrous Oxide and Dinitrogen Gas Production

The application of DFE alone did not significantly increase the production rate of \( \text{N}_2 \) above that of the control (Fig. 1a). However, \( \text{N}_2 \) production increased in all the urine-based treatments following treatment application. The maximum \( \text{N}_2 \) production rate occurred on Day 2 at 26 ng g soil\(^{-1}\) \( \text{day}^{-1} \) in the UDFE0 treatment (Fig. 1a). Mean production rates of \( \text{N}_2 \) after urine application were rarely significantly higher than those of the control treatment, due to the data’s large variability. When the urine-based treatments were compared with one another, \( \text{N}_2 \) production rates from the UDFE0 treatment were significantly higher than the urine-only treatment on Day 2, and those from the UDFE1 treatment were higher than the urine-only treatment on Days 1, 7, and 9 (\( p < 0.01 \)). When integrated over the entire study period the amount of \( \text{N}_2 \) produced in the UDFE1 treatment (391 ± 176 [SD] ng \( \text{N}_2 \)-N g soil\(^{-1} \)) was significantly higher (\( p < 0.05 \)) than in the control (54 ± 96 [SD] ng \( \text{N}_2 \)-N g soil\(^{-1} \)) but not the urine-only treatment (185 ± 154 [SD] ng \( \text{N}_2 \)-N g soil\(^{-1} \)). The atom % \( ^{15}\text{N} \) enrichments of the \( \text{N}_2 \) produced were less than the level of \( ^{15}\text{N} \) enrichment in the urine urea N applied, ≤9 atom % \( ^{15}\text{N} \) (Table 3), with no statistically significant differences among treatments (\( p ≥ 0.08 \)).

Following urine application, the production rate of \( ^{15}\text{N} \)-labeled \( \text{N}_2 \) increased from Day 1 to peak on Day 2 (343 ng g soil\(^{-1}\) \( \text{day}^{-1} \)) with no significant differences among \( ^{15}\text{N} \)-labeled treatments at this time (Fig. 1b).

However, the production rate of \( \text{N}_2 \) did vary with treatments on Days 7 and 9, when the rate of \( \text{N}_2 \) production in the UDFE1 treatment was higher than that in the urine-only treatment (\( p < 0.04 \)). When integrated over the entire study period the amount of \( \text{N}_2 \) produced in the UDFE1 treatment (4789 ± 1166 [SD] ng \( \text{N}_2 \)-N g soil\(^{-1} \)) was again significantly higher (\( p < 0.05 \)) than in the urine-only treatment (3132 ± 397 [SD] ng \( \text{N}_2 \)-N g soil\(^{-1} \)). The enrichment of the \( \text{N}_2 \) gas in the headspace treatment reached a maximum of 0.385 atom % \( ^{15}\text{N} \) on Day 2 in the UDFE2 treatment (Table 3).

The ratio of \( \text{N}_2\text{O}–^{15}\text{N} \) to (\( \text{N}_2\text{O}–^{15}\text{N} + \text{N}_2–^{15}\text{N} \)) did not differ significantly among the urine-based treatments (\( p ≥ 0.07 \)) on any given sampling occasion. However, the overall mean ratio did vary significantly with sampling time (\( p < 0.01 \)). It was at a maximum between Days 3 to 6 [0.21 (SD = 0.07) to 0.32 (SD = 0.09)] and <0.15 outside this period with a minimum of value of 0.06 (SD = 0.02).

Inorganic Nitrogen Concentrations and Nitrification Rates

The soil \( \text{NH}_4^+–\text{N} \) concentrations increased immediately (\( p < 0.01 \)) following urine and UDFE0 treatment applications, peaking on Day 7 at 345 µg \( \text{NH}_4^+–\text{N} \) g soil\(^{-1} \)
in the urine-only treatment (Fig. 2a). Concentrations of soil NO$_3$–N were elevated in the urine and UDFE0 treatments after 7 d, reaching 0.68 μg NO$_3$–N g soil$^{-1}$ at this time, but the high variability of the data meant that these concentrations were not different from the control and DFE treatments (Fig. 2b). From Day 14 onward soil NO$_3$–N concentrations remained at <0.14 μg NO$_3$–N g soil$^{-1}$ but with higher concentrations in the urine treatment than the control on Days 14 and 28 ($p < 0.05$). Soil NO$_3$–N concentrations increased above those in the control treatment following the addition of urine in both the soil and UDFE0 treatments ($p < 0.001$) peaking at 597 μg NO$_3$–N g soil$^{-1}$ (Fig. 2c). The DFE-amended soils and controls did not differ with respect to soil NO$_3$–N concentrations (Fig. 2c).

The net rates of change in soil inorganic N concentrations were significantly higher ($p < 0.01$) for the urine and UDFE0 treatments than in the nonurine treatments, up until Day 14. After this time there was no difference among treatments in the net rates of change in the soil NH$_4$–N and NO$_3$–N concentrations. Rates of change in soil NH$_4$–N concentrations were negative by Days 7 to 14, peaking at −31 μg NH$_4$–N g soil$^{-1}$ d$^{-1}$. The maximum net rate of nitrification (i.e., the increase in the soil NO$_3$–N concentrations), 43 μg NO$_3$–N g soil$^{-1}$ d$^{-1}$, also occurred between 7 and 14 d in the UDFE0 treatment. The net rate of change in soil NO$_3$–N concentrations had become negative by Day 28.

### Soil Surface pH and Soil Moisture

Despite the high pH of the DFE applied, there was no significant difference in the soil surface pH of the control and DFE treatments (Fig. 3a). Where urine was a treatment constituent, the soil surface pH increased rapidly to be >8.0 following urine application. This was significantly higher than the control and DFE treatments from Day 2 to 10. From Day 11 to 18, there was no significant difference in the soil surface pH among treatments. After this time the soil surface pH in the urine treatments declined to be less than the DFE and control treatments with the UDFE0, UDFE1, and UDFE2 treatments having soil surface pH values that lay between the values of the urine and control treatments (Fig. 3a). Soil moisture contents at Days 7, 14, 21, 28, and 43, were 76, 78, 78, 76, and 74% WFPS respectively, all with a standard error of the mean of 2%.

### Soil Carbon Dioxide Production Rates and Water-Soluble Carbon

Before treatment applications, the soil CO$_2$ production rates averaged 150 mg CO$_2$ kg soil$^{-1}$ d$^{-1}$ and did not differ significantly among treatments. When urine was a treatment constituent the CO$_2$ production rate increased ($p < 0.01$) immediately after urine application, with higher CO$_2$ production rates than in either the control or DFE treatments until Day 5 (Fig. 3b). The maximum CO$_2$ production rate was 1046 mg CO$_2$ kg soil$^{-1}$ d$^{-1}$ on Day 2 in the urine-only treatment compared with the control (Fig. 3b). No significant or consistent treatment differences in CO$_2$ production occurred after DFE application on Day 7. Following DFE applications on Day 14, the production rates of CO$_2$ were higher from the control and the DFE treatment than any of the urine-based treatments ($p < 0.05$). After Day 23, CO$_2$ production rates were still higher from both the control and DFE treatments, while the rate in the urine-only treatment was the lowest ($p < 0.05$). The CO$_2$ production rates for the DFE and urine treatments were of an interim in value compared with the other treatments (Fig. 3b). When integrated over 10 d the urine-treated soils (range 3638–3764 mg CO$_2$ kg soil$^{-1}$) produced more CO$_2$ ($p < 0.01$) than the control or DFE-treated soil (range 1602–1765 mg CO$_2$ kg soil$^{-1}$). However, when integrated over 39 d the difference among treatments became insignificant with the control soil producing 4401 ± 712 mg CO$_2$ kg soil$^{-1}$ and the highest-yielding urine-treated soil 5042 ± 1215 mg CO$_2$ kg soil$^{-1}$; errors are standard deviations. Correlation of soil pH versus CO$_2$ production rate ($y$) for Days 1 to 43 ($y = −0.18 + 0.06x$)
and Days 10 to 43 ($y = -0.8 + 0.18x$) were also significant ($p < 0.001$) with $r^2$ values accounting for 60.3 and 22.5% of the variance, respectively.

The application of DFE alone did not significantly change the CO$_2$ production rate compared with the control treatment. However, there was a significant effect of urine application (Table 4) on CO$_2$ production rate. In the urine-based treatments, 61 to 68% of the total CO$_2$ flux for the 39-d measurement period occurred in the first 10 d. For the control and DFE treatments the corresponding range was 34 to 37% (Table 4). Assuming all the C substrates added in the urine evolved as CO$_2$ (i.e., 2526 mg CO$_2$ kg$^{-1}$ soil), the treatment effect excess attributable to increased soil microbial activity was 1112 mg CO$_2$ kg soil$^{-1}$. Dividing the excess CO$_2$ produced by the CO$_2$ produced in the control treatment produced a synthetic urine priming effect of 0.69.

After 43 d, WSC was dominated by organic C. Inorganic WSC was below detection limits. Water-soluble organic carbon (WSOC) in the DFEU0 and DFEU1 treatments averaged 0.18 µg WSOC g soil$^{-1}$. This concentration was higher ($p < 0.01$) than that of the control, DFE, or urine-based treatments (average 0.07 µg WSOC g soil$^{-1}$). Assuming an average WSOC content of 330 µg mL$^{-1}$ in the DFE applied, then three 25-mL

Table 4. Cumulative CO$_2$ flux.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Days 0 to 10</th>
<th>Days 0 to 39</th>
<th>Days 0 to 10 as % of Days 0 to 39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1602</td>
<td>4740</td>
<td>34</td>
</tr>
<tr>
<td>DFE</td>
<td>1765</td>
<td>4822</td>
<td>37</td>
</tr>
<tr>
<td>Urine</td>
<td>3638</td>
<td>5375</td>
<td>61</td>
</tr>
<tr>
<td>UDFE0</td>
<td>3721</td>
<td>5796</td>
<td>68</td>
</tr>
<tr>
<td>UDFE1</td>
<td>3764</td>
<td>6133</td>
<td>61</td>
</tr>
<tr>
<td>UDFE2</td>
<td>3681</td>
<td>5650</td>
<td>66</td>
</tr>
<tr>
<td>LSD</td>
<td>723</td>
<td>1201</td>
<td>5</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† DFE, dairy farm effluent; UDFE, urine + dairy farm effluent applied on Days 6, 7, and 14 for treatments UDFE0, UDFE1, and UDFE2, respectively.
DFE applications amounted to 80 μg WSOC g soil\(^{-1}\), well in excess of the WSOC recovered.

**DISCUSSION**

**Nitrogenous Gas Production**

Apart from the UDFE0 and UDFE1 treatments the addition of DFE to the urine patch did not affect the N\(_2\)O production rate. Likewise the daily N\(_2\) production rate was only affected in the UDFE1 treatment, while the ratio of N\(_2\)O–15N to (N\(_2\)O–15N + N\(_2\)–15N) was not affected. The magnitude and the duration of N\(_2\)O production from the urine-treated soils were consistent with previous work, where comparable soils have received the same rate of urine and had similar pH (Clough et al., 2001, 2004). It was hypothesized that the addition of WSC in the DFE applications, would enhance heterotrophic microbial processes such as denitrification, since WSC has been shown to be well correlated with denitrification (Burford and Bremner, 1975). The addition of extra C was also expected to influence the ratio of the N\(_2\)O to N\(_2\) (Firestone, 1982).

The increases in N\(_2\)O production in the UDFE0 and UDFE1 treatments on Days 2 and 7, respectively, were short lived and relatively small in comparison with the total N\(_2\)O flux at these times. When integrated over the entire study period the UDFE1 treatment produced more N\(_2\)O than the control and had there been increased replication it is possible that a treatment effect may have been seen between the UDFE1 and urine-only treatment. Likewise the UDFE1 treatment produced more N\(_2\) than the urine-only treatment. Since the fresh DFE composition was very similar across all application times it is likely that this increase in denitrification in the UDFE1 treatment was due to conditions in the urine-affected soil 1 wk post-urine application. These conditions could have included the relative concentrations of inorganic N in the soil. The gateway through which N\(_2\)O must be formed is NO\(_2\)–N and it was at Day 7 that soil NO\(_2\)–N concentrations were at their highest. Master et al. (2003) showed the significance of soil NO\(_2\)–N concentrations while measuring N\(_2\)O production from effluent-treated soils. The small increase in N\(_2\) production in the UDFE1 treatment was most likely a result of the increased N\(_2\)O production and its further reduction to N\(_2\). The lack of significant differences in the ratio of N\(_2\)O–15N to (N\(_2\)O–15N + N\(_2\)–15N) may have been due to added C sources being unavailable to the denitrifiers, the C released as a result of urine addition nullifying any potential affect of the added C, or inorganic N levels determining the ratio of N\(_2\)O–15N to (N\(_2\)O–15N + N\(_2\)–15N) (Firestone et al., 1979).

In general the overall lack of any enhanced N\(_2\)O production or consumption following DFE application to the urine-treated soils may be a consequence of the added DFE substrates (C and N) being of an insignificant amount when compared with those either supplied in the urine or those substrates released from the soil due to urine addition as discussed below.

Alternatively the general lack of any enhanced N\(_2\)O production or consumption in the DFE plus urine treatments could have been due to the microbial population being influenced by soil chemical factors within the urine patch. It has recently been noted that different denitrifying species in the soil can be promoted or inhibited by the type of treatment applied to the soil. For example Wolsing and Prieme (2004) found that soils treated with mineral fertilizer or cattle manure produced different communities of denitrifying bacteria. Denitrifier community structure can influence N\(_2\)O fluxes (Cavigelli and Robertson, 2000; Munch, 1989). In our study, soil pH changes over time in the urine-based treatments may have influenced denitrifier function or community composition.

Previous work, at similar soil temperatures to this study, found N\(_2\)O fluxes increased when a mineral soil was treated with DFE (Barton and Schipper, 2001). However, the N\(_2\)O fluxes were only higher in the DFE-treated soils for 3 h in the autumn and 48 h in the spring (Barton and Schipper, 2001). Due to our moderate sampling regime any significant N\(_2\)O production would not have been detected in the 3 h following DFE application. The lack of significant DFE-induced N\(_2\)O production in our study, when compared with Barton and Schipper’s (2001) results, may also be a consequence of the higher inorganic N concentrations in their DFE application, the presence of pasture and thus root mucilage increasing denitrifier activity (Mounier et al., 2004), the differences in soil depth, soil moisture effects, and soil drainage. It would be worthwhile repeating aspects of our study in conjunction with soil wetting and drying cycles and in the presence of pasture species to determine if, over the long term, DFE applications make any difference to urine-induced N\(_2\)O production. Dairy farm effluent, under the conditions of this study, was not a suitable management tool for mitigating N\(_2\)O emissions.

The atom % 15N enrichment of the N\(_2\)O produced also indicates that N other than the 15N-labeled urea N was contributing to the N\(_2\)O flux. That is, the atom % 15N enrichment of the N\(_2\)O produced was less than the level of 15N enrichment applied, particularly on Days 1 and 2. The hydrolysis of urea raises the soil pH and solubilizes soil organic matter that can, in turn, lead to significant deamination (Sen and Chalk, 1993). Such an unlabeled source of N could have provided further N substrate for the N\(_2\)O production mechanisms. Alternatively other natural abundance N, such as the glycine N applied in the urine, could have contributed to the substrates utilized by the N\(_2\)O producing mechanisms and contributed to a reduced N\(_2\)O–15N enrichment.

**Soil Carbon and Priming**

Measured fluxes of CO\(_2\) from synthetic urine and urea granules (Lockyer, 1984; Lovell and Jarvis, 1996; Tenuta and Beauchamp, 2000) have been accredited to the chemical reactions involved in urea hydrolysis and the ensuing hydrolysis of the carbonate ions to form CO\(_2\) (Sherlock and Goh, 1983). Allowing for such chemical reactions, there was still a release of CO\(_2\) from the soil equivalent to 303 mg C kg soil\(^{-1}\) over 10 d as a result of urine
application. This priming effect has been noted before in urine-treated soils (Clough et al., 2003) and the concept of priming has been reviewed by Kuzyakov et al. (2000). Insoluble organic forms of C, such as feces, were also applied in the DFE and some of this insoluble C may also have been mineralized and become available to microorganisms. It should also be noted that not all of the applied WSC in the DFE would have been readily available to the soil microorganisms (Lundquist et al., 1999). Overall the amount of C applied in the DFE was insignificant in comparison with the C released during soil priming. The priming effect of urine on CO₂ flux lasted 5 d and was possibly driven by the solubilization of soil organic matter, due to the high soil pH at this time. Another factor enhancing the priming of soil C could have been the high inorganic N concentrations in the soil resulting from urine application. Previous work has shown both positive and sporadic relationships between the amount of available mineral N and the amount of C mineralized (Chantigny et al., 1999; Liljestroth et al., 1990; Merckx et al., 1987). If priming of soil C increases the release of CO₂ for 5 d every grazing, and grazing occurs approximately every 3 wk in intensively managed pastures, then priming is a very significant feature of microbial activity in the soil urine patch. Carbon is also returned to pastures due to photoassimilation of C and has been reported to equal 1320 kg C ha⁻¹ yr⁻¹ under a temperate high-fertility dairy pasture (Sagar and Hedley, 2001). Thus the priming effect observed here does not necessarily represent a net loss of C from the urine patch. In fact other studies in grazed grasslands have found grasslands to be both a source and a sink for CO₂ (Leahy et al., 2004; Xu and Baldocchi, 2004). Further work needs to establish the direction of the net flux and the relative magnitudes of the mechanisms responsible (i.e., chemically induced CO₂ fluxes from urine patches and the release of CO₂ via soil respiration).

The soil surface pH values in the urine-treated soils declined to be less than that of the control and the DFE-treated soils, after 23 d. Over the same period the CO₂ production also declined at a greater rate in the urine-treated soils, when compared with the control and DFE treatments. Assuming all chemical production of CO₂ has ceased it is reasonable to assume that this decrease in CO₂ production indicates a decrease in soil microbial activity; possibly a result of the urine treatment effect on soil pH. At the same time as CO₂ production was decreasing, nitrogenous gas production was also decreasing. This could not be due to a lack of N substrate since soil NO₃⁻-N concentrations were high and soil WFPS conditions were suitable for denitrification (Dobbie and Smith, 2001). This suggests C was becoming limiting at this time or the soil environment was not conducive to high rates of denitrification due to the lowering soil pH.

The close correlation between soil pH and CO₂ production over the first 10 d is readily explained by chemical processes. Increases in soil pH following urine application are a result of urea hydrolysis, while the decrease in soil pH that then follows is a result of hydrogen ions being produced as a consequence of the ammonia volatilization and nitrification processes (Haynes and Sherlock, 1986).

Repeating aspects of this study in the presence of pasture species, in situ, would also overcome any possible artifacts of the laboratory methodology used here. Air drying of soil has been shown to release soil organic C (Merckx et al., 2001). It is theoretically possible that C was released during air-drying of the soils, partially masking the potential effect of DFE carbon on the soil denitrifiers; although equilibration of the soil cores on the water tension tables should have nullified this. Sieving of the soil could potentially also have disrupted microorganism community environments and populations. It has been shown that soil aggregate size can affect the production of N₂O from applied effluent (Master et al., 2003). Likewise any effects pasture species had on soil bulk density and soil aeration could be considered with in situ studies.

**CONCLUSIONS**

In summary the repeated application of DFE to urine patches, commencing at 0, 7, or 14 d after urine deposition, did not mitigate the N₂O production rates from the simulated urine patch, or change the ratio of N₂O to N₂ gas fluxes. The application of DFE to urine patches 7 d after urine deposition increased the total amount of N₂O produced over the 43-d measurement period when compared with the control soil but not when compared with a urine-only treatment. The application of DFE 7 d after urine deposition also resulted in small increases in N₂ gas production. The amount of WSC applied in the DFE was insignificant compared with the C released from the soil in the urine patch. This was evident from the measured cumulative CO₂ flux, which was greater than the C inputs in the urine and DFE combined and reasons for this are suggested. Dairy farm effluent, under the conditions of this study, was not a suitable management tool for mitigating N₂O emissions. However, a field-based study in the presence of pasture plants should be done to verify this. The priming of soil C in urine patches has implications for the understanding of soil C processes in grazed pasture ecosystems and the budgeting of C within these ecosystems.

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**REFERENCES**


Chantigny, M.H., D.A. Angers, D. Prévost, R.R. Simard, and F.P. Chalifour. 1999. Dynamics of soluble organic C and C mineraliza-


Food and Agriculture Organization of the United Nations. 2001. Global estimates of gaseous emissions of NH\textsubscript{3}, NO and N\textsubscript{2}O from agricultural land. FAO, Rome.


