Short communication

Ethylene turn-over in soil, litter and sediment

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Received 24 December 1999; received in revised form 1 May 2000; accepted 26 May 2000

Abstract

Turn-over (i.e. production and consumption) of ethylene was examined in contrasting soil types to evaluate the effect of environmental changes on $\text{C}_2\text{H}_4$ dynamics. Three general responses to batch incubation with $\text{C}_2\text{H}_4$ (generally $12–16 \mu\text{l} \text{~l}^{-1}$) were observed: (i) arable soil and lake sediment required prolonged acclimation (1–4 weeks) for $\text{C}_2\text{H}_4$ consumption and showed no $\text{C}_2\text{H}_4$ production; (ii) coniferous and deciduous forest soil showed an inherent capacity for $\text{C}_2\text{H}_4$ consumption ($21–85 \text{pmol} \text{~C}_2\text{H}_4 \text{~g}^{-1} \text{~dry wt} \text{~h}^{-1}$) and a subsequent $\text{C}_2\text{H}_4$ production ($4–26 \text{pmol} \text{~C}_2\text{H}_4 \text{~g}^{-1} \text{~dry wt} \text{~h}^{-1}$), which coincided with a depletion of $\text{O}_2$ to below $\sim1\%$; (iii) coniferous litter samples showed a slight $\text{C}_2\text{H}_4$ consumption ($0–30 \text{pmol} \text{~C}_2\text{H}_4 \text{~g}^{-1} \text{~dry wt} \text{~h}^{-1}$) followed by a large $\text{C}_2\text{H}_4$ production ($32–120 \text{pmol} \text{~C}_2\text{H}_4 \text{~g}^{-1} \text{~dry wt} \text{~h}^{-1}$), again coinciding with depletion of the $\text{O}_2$ pool. The results for forest samples indicated that $\text{C}_2\text{H}_4$ was produced and consumed simultaneously under aerobic conditions, while it was only produced under sub-oxic conditions. Similar patterns of $\text{C}_2\text{H}_4$ turn-over were found in samples collected in different years and both $\text{C}_2\text{H}_4$-consuming and -producing microorganisms survived during storage at $2\,^\circ\text{C}$ for 22 months. Notably in coniferous soil, changes in $\text{C}_2\text{H}_4$ dynamics apparently could have the potential to adversely influence plant growth. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Anaerobic; Arable soil; Ethylene; Forest soil; Microorganisms

Ethylene (ethene) is a gaseous phytohormone that plays a key role in the regulation of plant physiological processes (Abeles et al., 1992). The threshold concentration for plant responses is generally less than $0.1 \mu\text{l} \text{~C}_2\text{H}_4 \text{~l}^{-1}$, which has been shown, for example, to adversely influence the growth of barley roots (Smith and Russell, 1969). Biological activity at such low concentrations distinguishes $\text{C}_2\text{H}_4$ from other air polluting hydrocarbons, which only become of activity at such low concentrations distinguishes $\text{C}_2\text{H}_4$ from other air polluting hydrocarbons. While the atmospheric $\text{C}_2\text{H}_4$ content is generally below $5 \text{nl} \text{~l}^{-1}$ (Sawada and Totsuka, 1986), $\text{C}_2\text{H}_4$ in soil may accumulate to peak amounts of $75 \mu\text{l} \text{~l}^{-1}$ under conditions favouring $\text{C}_2\text{H}_4$ production or hampering $\text{C}_2\text{H}_4$ degradation (Smith and Dowdell, 1974). Microorganisms are the major sources and sinks of $\text{C}_2\text{H}_4$ in soil, and a conceptual model may be proposed in which $\text{C}_2\text{H}_4$ is produced from precursors under both aerobic and anaerobic conditions, while the consumption of $\text{C}_2\text{H}_4$ is dependent on aerobic conditions (Hartmans et al., 1989; Zechmeister–Boltenstern and Smith, 1998). Hence, ethylene-consuming microorganisms (notably in the rhizosphere) may play an important ecological role, because they are active in keeping the soil $\text{C}_2\text{H}_4$ below a concentration that adversely influences plant growth (Hartmans et al., 1989; Otani and Ae, 1993). Yet, even small changes in the turn-over of soil $\text{C}_2\text{H}_4$ may have an effect on plant growth and development (Frankenberger and Arshad, 1995), and therefore the balance and regulation of $\text{C}_2\text{H}_4$ turn-over is of fundamental importance in soil ecosystems. Here, $\text{C}_2\text{H}_4$ turn-over in Danish soil types representing forest soil, arable soil and near-shore lake sediment was studied in response to $\text{C}_2\text{H}_4$ amendment and changes caused by $\text{O}_2$ depletion and sample storage.

Soil (0–10 cm), litter and sediment (Table 1) was collected in March 1995 and April 1997 from coniferous (mainly Picea abies) and deciduous (mainly Fagus sylvatica) forests and an oligotrophic lake (Tjele Langsø) near Research Centre Foulum, Denmark (56°29N, 9°33E). Soil and sediment (10 g) were incubated in 120 ml bottles closed by butyl stoppers. Coniferous litter samples (10 g) were similarly incubated with 8 ml of distilled water. The bottles were amended with $\text{C}_2\text{H}_4$ (final headspace concentration generally $12–16 \mu\text{l} \text{~l}^{-1}$), and the time course of $\text{C}_2\text{H}_4$ and $\text{O}_2$ turn-over was followed during incubation at $25\,^\circ\text{C}$ for up to 8 weeks. The samples from 1995 were assayed as freshly collected and after storage for 22 months at $2\,^\circ\text{C}$ in tightly sealed plastic bags. $\text{C}_2\text{H}_4$ turn-over in arable soil from Foulum (clay, 7%; silt, 10%; sand, 83%) was tested as described for forest soils, while arable soil from Lundgaard (clay, 4%; silt, 4%; sand, 90%) was tested with a 1 kg soil

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PII: S0038-0717(00)00122-X
sample incubated at 15°C with 200 µl C\textsubscript{2}H\textsubscript{4} l\textsuperscript{-1}. Further characteristics of the two arable soils were described by Hansen (1976) and Nielsen and Møberg (1985).

Gas samples (0.2–0.5 ml) for measurement of C\textsubscript{2}H\textsubscript{4} and O\textsubscript{2} were withdrawn with 1 ml gas-tight syringes and analysed on a Hewlett-Packard GC model 5840A (flame ionization detector) and a Varian 3700 GC (thermal conductivity detector), respectively (Elsgaard, 1998). Control experiments showed that O\textsubscript{2} concentrations of 50 ml\textsuperscript{-1} could be adequately quantified. Apparent rates of C\textsubscript{2}H\textsubscript{4} consumption and C\textsubscript{2}H\textsubscript{4} production were estimated from linear regression of time course data before and after O\textsubscript{2} depletion, respectively.

Water content, organic matter content (loss-on-ignition), and pH(CaCl\textsubscript{2}) were determined by standard methods (Alef and Nannipieri, 1995). With coniferous litter samples, pH(CaCl\textsubscript{2}) was measured at a ratio of 2 g litter-to-25 ml 10 mM CaCl\textsubscript{2}.

By comparison with the fresh samples (Fig. 1a–c) it was found that storage for an extended period of 22 months (2°C) caused no changes in the qualitative responses to incubation with C\textsubscript{2}H\textsubscript{4} (Fig. 1f–h). Thus, both C\textsubscript{2}H\textsubscript{4}-consuming and -producing microorganisms survived the storage period. Also, it was found that C\textsubscript{2}H\textsubscript{4} turnover in the forest samples followed a similar time course for samples collected in 1995 and 1997 (Fig. 1), although C\textsubscript{2}H\textsubscript{4} turnover generally proceeded more rapidly in samples from 1997 (Table 2). Depending on their origin, the environmental

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Type</th>
<th>Dry matter (%)</th>
<th>OM (%)\textsuperscript{a}</th>
<th>pH(CaCl\textsubscript{2})</th>
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<td>Coniferous forest soil</td>
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<td>Deciduous forest soil</td>
<td>61</td>
<td>67</td>
<td>19 (3)</td>
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<td>5</td>
<td>Tjele Langso</td>
<td>Lakeshore sediment</td>
<td>80</td>
<td>74</td>
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<td>83</td>
<td>3</td>
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<tr>
<td>7</td>
<td>Lundgaard</td>
<td>Arable soil</td>
<td>na</td>
<td>90</td>
<td>2</td>
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</tbody>
</table>

\textsuperscript{a} OM — organic matter (% of dry weight) determined as loss-on-ignition.
Table 2

Apparent consumption and production rates of C_2H_4 (pmol C_2H_4 g dry wt h^{-1}) in fresh soil, litter and sediment samples in 1995 and 1997. Samples collected in 1995 were also assayed after storage at 2°C for 22 months (1995*). Production rates were estimated from the C_2H_4 accumulation after O_2 depletion (na: not assayed).

<table>
<thead>
<tr>
<th>Type</th>
<th>No.</th>
<th>C_2H_4 consumption</th>
<th>C_2H_4 production</th>
</tr>
</thead>
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<td>11</td>
</tr>
<tr>
<td>Coniferous forest soil</td>
<td>2</td>
<td>51</td>
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<tr>
<td>Coniferous litter</td>
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<td>30</td>
<td>44</td>
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<tr>
<td>Deciduous forest soil</td>
<td>4</td>
<td>21</td>
<td>na</td>
</tr>
<tr>
<td>Lakeshore sediment</td>
<td>5</td>
<td>37</td>
<td>na</td>
</tr>
</tbody>
</table>

samples showed three general responses to incubation with C_2H_4:

(i) Samples from lake sediment (Fig. 1e and m) showed C_2H_4 consumption after a prolonged acclimation period of 2–4 weeks (defined as the time required for a 10% reduction of the initial C_2H_4 concentration). Thereafter, the C_2H_4 consumption proceeded rapidly (Table 2) and resulted in complete C_2H_4 depletion. C_2H_4 consumption in arable soil from Lundgaard and Foulum (data not shown) likewise proceeded rapidly (time courses as in Fig. 1e) after an acclimation period of 1–3 weeks. These time courses indicated that the number of ethylene-consuming microorganisms in the lake sediment and arable soil were initially low, but increased after exposure to C_2H_4 (cf. Wiggins et al., 1987). Also, the stable C_2H_4 concentration during the acclimation periods showed that C_2H_4 production was not an important process in these environments. Indeed, the absence of indigenous C_2H_4 production could be a reason for the low number of microorganisms initially adapted to C_2H_4 consumption in the sediment and arable soil. An acclimation period prior to C_2H_4 consumption has been observed for sandy arable soils, while it was not found for clayey or loamy soils (De Bont, 1976; Zechmeister–Boltenstern and Nikodem, 1999).

(ii) Forest soil samples showed an inherent capacity for C_2H_4 consumption that generally resulted in a complete depletion of the C_2H_4 pool within 2 weeks (Fig. 1). The depletion rates for the fresh coniferous soil samples ranged from 36 to 85 pmol C_2H_4 g^{-1} dry wt h^{-1}, while deciduous soil showed a depletion rate of 21–49 pmol C_2H_4 g^{-1} dry wt h^{-1} (Table 2). These depletion rates were within the range observed for Austrian lowland soils (0–231 pmol C_2H_4 g^{-1} dry wt h^{-1}), where C_2H_4 depletion was most rapid in deciduous forest soils (Zechmeister–Boltenstern and Nikodem, 1999).

After depletion of the O_2 pool to amounts below ~1%, a subsequent C_2H_4 increase was noted, particularly in the coniferous soil (Fig. 1f–k and Table 2). These results were in accordance with the concept that C_2H_4 is consumed and produced simultaneously at high O_2 concentrations, while only production occurs at low O_2 concentrations. Thus, under aerobic conditions, C_2H_4 depletion in the forest soil samples represented the difference between a larger gross rate of C_2H_4 consumption and a concurrent rate of C_2H_4 production. The C_2H_4 production rates in the forest soils (4–26 pmol C_2H_4 g^{-1} dry wt h^{-1}) were similar to the rates reported for deciduous and coniferous soils (3–13 pmol C_2H_4 g^{-1} dry wt h^{-1}) by Smith (1978) and within the range of 0–184 pmol C_2H_4 g^{-1} dry wt h^{-1} reported for coniferous soils (Lindberg et al., 1979).

(iii) Coniferous litter samples showed a slight decrease in the C_2H_4 pool followed by a large increase to a maximal content of 100 µmol C_2H_4 l^{-1} during incubation for 4 weeks (Fig. 1c, h and k and Table 2). The C_2H_4 dynamics in the litter samples were associated with a rapid depletion of the O_2 pool (Fig. 1h and k). The maximal rate of C_2H_4 production in the litter samples was 120 pmol C_2H_4 g^{-1} dry wt h^{-1}, which was lower than the maximal rates (647 pmol C_2H_4 g^{-1} dry wt h^{-1}) reported by Lindberg et al. (1979).

Yet, the excessive C_2H_4 production in coniferous soil and litter identified these as major sources of C_2H_4 production. This has also been observed for Austrian spruce forest soil (Rigler et al., 1997). Thus, in the absence of efficient C_2H_4 consumption, the amounts of C_2H_4 in such environments, may possibly accumulate to concentrations that cause plant injury.

As indicated here, the C_2H_4 status in soil represents the outcome of microbial processes leading to production and consumption of C_2H_4. Based on the C_2H_4 turn-over under anaerobic conditions (where C_2H_4 consumption is absent), the extent of C_2H_4 production can be tentatively evaluated (Hartmans et al., 1989). Presently, the range of such C_2H_4 production rates is 0–120 pmol C_2H_4 g^{-1} dry wt h^{-1} (Table 2). However, using an acetylene inhibition technique to differentiate between production and consumption of C_2H_4 in soil (Zechmeister–Boltenstern and Smith, 1998), it was found that C_2H_4 accumulation under anaerobic conditions resulted from both inhibition of C_2H_4 degradation and stimulation of C_2H_4 production (Zechmeister–Boltenstern and Nikodem, 1999). Thus, C_2H_4 production rates estimated under anaerobic conditions are likely to exceed the production rate that occurs under aerobic conditions. Therefore, the present data on C_2H_4 production were interpreted mainly on a qualitative basis. It was clear, however, that
notably the coniferous soil was a favourable environment for \( \text{C}_2\text{H}_4 \) production.

In conclusion, we have demonstrated a contrasting, but consistent, \( \text{C}_2\text{H}_4 \) turnover in different environments. Forest soil samples, which had the highest organic matter content (Table 1) showed the highest rates of both consumption and production of soil \( \text{C}_2\text{H}_4 \). Also, \( \text{C}_2\text{H}_4 \) turnover in these environments clearly demonstrated the role of low O\(_2\) concentrations for the accumulation of soil \( \text{C}_2\text{H}_4 \). In natural ecosystems such redox conditions typically may be imposed by flooding, soil compaction or (at least on a small scale) by stimulated microbial respiration due to, e.g. application of sewage sludge as a fertilizer to arable soil. Thus, with respect to changes in land use and management practice in agriculture and forestry, the possible implication of changes in the dynamics of \( \text{C}_2\text{H}_4 \) turnover should be considered (Tosh et al., 1994; Zechmeister-Boltenstern and Nikodem, 1999). Although it is difficult to extrapolate from the present data to field conditions, it appears that notably in coniferous forest soil, \( \text{C}_2\text{H}_4 \) production could have the potential to adversely influence plant growth.

Acknowledgements

I thank Gitte Hastrup Andersen for skilful assistance in the laboratory.

References
