Effect of temperature, organic amendment rate and moisture content on the degradation of 1,3-dichloropropene in soil†

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Abstract: 1,3-Dichloropropene (1,3-D), which consists of two isomers, (Z)- and (E)-1,3-D, is considered to be a viable alternative to methyl bromide, but atmospheric emission of 1,3-D is often associated with deterioration of air quality. To minimize environmental impacts of 1,3-D, emission control strategies are in need of investigation. One approach to reduce 1,3-D emissions is to accelerate its degradation by incorporating organic amendments into the soil surface. In this study, we investigated the ability of four organic amendments to enhance the rate of degradation of (Z)- and (E)-1,3-D in a sandy loam soil. Degradation of (Z)- and (E)-1,3-D was well described by first-order kinetics, and rates of degradation for the two isomers were similar. Composted steer manure (SM) was the most reactive of the organic amendments tested. The half-life of both the (Z)- and (E)-isomers in unamended soil at 20 °C was 6.3 days; those in 5% SM-amended soil were 1.8 and 1.9 days, respectively. At 40 °C, the half-life of both isomers in 5% SM-amended soil was 0.5 day. Activation energy values for amended soil at 2, 5 and 10% SM were 56.5, 53.4 and 64.5kJ mol−1, respectively. At 20 °C, the contribution of degradation from biological mechanisms was largest in soil amended with SM, but chemical mechanisms still accounted for more than 58% of the (Z)- and (E)-1,3-D degradation. The effect of temperature and amendment rate upon degradation should be considered when describing the fate and transport of 1,3-D isomers in soil. Use of organic soil amendments appears to be a promising method to enhance fumigant degradation and reduce volatile emissions. 

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Keywords: biodegradation; 1,3-dichloropropene; enhanced degradation; fumigant pesticide; isomers; organic amendments

1 INTRODUCTION

1,3-Dichloropropene (1,3-D) is a soil fumigant widely used in agriculture to control plant-parasitic nematodes and fungi. Commercial formulations of 1,3-D are registered under the trademark names ‘Telone II’ (Dow Chemical Co) and ‘D-D’ (Shell Oil Co); both contain approximately equal ratios of (Z)-1,3-D (cis-isomer) and (E)-1,3-D (trans-isomer). 1,3-Dichloropropene, formulated with chloropicrin, is considered to be an important alternative pesticide to methyl bromide, which is scheduled to be phased out of production by 2005 in the USA because of its link to stratospheric ozone depletion. The (Z) and (E) isomers are clear liquids with vapor pressures of 23.0 and 34.2mm Hg (3.06 and 4.54kPa) at 25°C, respectively.1 At these vapor pressures a significant fraction of the applied material can be expected to be released to the atmosphere. It has been reported that 20–50% of the applied 1,3-D could be lost to atmospheric volatilization.2,3 The emission of 1,3-D to the atmosphere is known to contribute to air pollution and human health problems.4 In 1990, a 4-year suspension of the use of Telone II was initiated after high ambient air concentrations of 1,3-D were detected in fumigation areas of California. 1,3-Dichloropropene is a B2 carcinogen and has been classified as a toxic air substance by the US Environmental Protection Agency (USEPA).

The degradation of (Z)- and (E)-1,3-D in soil is a combination of biological and chemical mechanisms.5–7 Both (Z)- and (E)-1,3-D are initially hydrolyzed to the corresponding 3-chloroallyl alcohol, which is mainly attributed to chemical mechanisms.8–10 The isomers of chloroallyl alcohol are then oxidized to (Z)- and (E)-3-chloroacrylic acid, which are degraded to succinic acid, propionic acid and acetic acid. The aliphatic carboxylic acids are finally mineralized to carbon dioxide and water. Several bacterial strains capable of degrading both isomers of 1,3-D, 3-chloroallyl alcohol and 3-chloroacrylic acid, have been

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isolated. In soils from The Netherlands, degradation rates for the two isomers were found to be similar. The rate of (Z)- and (E)-1,3-D degradation increased with increasing temperature, and the half-lives of the two isomers ranged from a few days to a few weeks. In soils previously treated with 1,3-D, enhanced degradation of both isomers has been reported and degradation of (E)-1,3-D was found to be greater than that of (Z)-1,3-D.

Since 1,3-D is a volatile and toxic compound, cost-effective methods to reduce atmospheric emissions are in need of investigation if 1,3-D is to be used as an alternative to methyl bromide. One potential method to reduce 1,3-D emissions is to accelerate its degradation in the soil surface layer, thereby minimizing 1,3-D volatilization. This has previously been accomplished by incorporating organic wastes into soil. The addition of organic amendments to soil alters biological and chemical conditions, both of which influence pesticide degradation. With regard to biological degradation, the incorporation of organic wastes into soil may promote the growth and activity of pesticide-degrading organisms, causing accelerated degradation of the target compound. Gan et al. found that the addition of a compost manure to the top 5-cm layer at 5% (w/w) reduced (Z)- and (E)-1,3-D emissions by 47 and 44%, respectively. To date, this is the only report which describes the use of organic amendments as a technique to control 1,3-D emissions from soil. The application of organic amendments should also have little or no negative impact upon pest control efficacy because enhanced degradation would be limited to the surface layer only.

Currently, no information is available concerning the combined effect of temperature and organic amendment rate on the degree of accelerated 1,3-D degradation. The primary objective of this study was to assess simultaneously the effects of temperature and application rate of an organic amendment upon 1,3-D degradation in a sandy loam soil. This information will be useful in understanding the behavior of 1,3-D in organically amended soil and determining the conditions needed for achieving optimal degradation.

2 EXPERIMENTAL METHODS

2.1 Soil, organic amendments and chemicals

The soil used in this study, Arlington sandy loam (coarse-loamy, mixed, thermic, Haplic Duriixeralf), was obtained from a field in the University of California, Riverside, Agricultural Experiment Station. Soil was removed from the plow layer (0–22 cm), passed through a 2-mm sieve without air-drying and stored at 5°C. The Arlington soil had a pH of 7.2 and contained 0.92% of organic matter. Four different organic wastes were used: composted steer manure (SM) from Hyponex Corp, Marysville, OH, USA; dewatered biosolids (BS) from the Riverside municipal sewage treatment plant, CA, USA; composted chicken manure (CKM) and composted forest products (FP) from Kellogg Supply Inc, Carson, CA, USA. The moisture contents of the SM, BS, CKM and FP were 50, 38, 36 and 122% (w/w), respectively. Each of the amendments was stored at room temperature and passed through a 2-mm sieve prior to soil incorporation. The 1,3-D standard [48% (Z) and 49% (E)] was purchased from Chem Service (West Chester, PA, USA).

2.2 Effect of amendment on degradation

This experiment was conducted to determine the effect of various organic amendments (ie SM, BS, CKM and FP) on the degradation of (Z)- and (E)-1,3-D in Arlington soil. To determine which amendment had a significant impact on the degradation of 1,3-D, each amendment was incorporated into the soil at 5% (w/w) for comparative purposes. The amended soils were prepared by thoroughly mixing both amendment and soil in one-gallon plastic bags and adjusting the moisture of the mixture to 10% (w/w) with deionized water. A soil moisture content of 10% represents 50% of the soil’s maximum water holding capacity (WHCmax). The soil mixtures were then passed through a 2-mm sieve and 10g (dry wt) quantities were added to 21-ml headspace vials. Each vial was then spiked with 200µl of an aqueous solution of 1,3-D (2.5μg litre⁻¹), which was equivalent to a soil concentration of 50mg kg⁻¹ (dry weight basis). Under field conditions, a 1,3-D soil concentration of 50mg kg⁻¹ is environmentally relevant, assuming even soil distribution, when applied at a typical rate of 250kg ha⁻¹. The treated samples were immediately capped with Teflon-faced butyl rubber septa to prevent the 1,3-D isomers from diffusing out of the vial. The vials were then incubated at 20°C in the dark, and at specific time intervals triplicate samples were removed and stored at −20°C until analyzed by gas chromatography.

2.3 Effect of temperature and amendment rate on degradation

To determine the combined effect of temperature and amendment rate on the degree of (Z)- and (E)-1,3-D degradation, soil was amended with 2, 5 and 10% (w/w) of SM and incubated at 20, 30 or 40°C. All soil mixtures were prepared as previously described and adjusted to a final moisture content of 10% (w/w) with deionized water. To distinguish between microbial and chemical degradation, a separate set of SM-amended soils were sterilized by autoclaving twice (1.0h at 121°C each time), with a 24-h interval between the first and second autoclaving. The contribution from biodegradation was calculated from the difference in the values of the degradation rate constant, k, between non-sterile and sterile samples divided by the non-sterile k value. The sterilized soil treatment was only conducted at an incubation temperature of 20°C. All soil vials were spiked with 200µl of the 1,3-D stock solution, immediately capped with septa and incubated in the dark. At specific time
intervals triplicate samples were removed and frozen at 
−20°C.

2.4 Effect of moisture content on degradation
To determine the effect of soil moisture content on the 
degradation of 1,3-D, Arlington sandy loam was 
adjusted to 25, 50, and 75% of the soil’s maximum water 
holding capacity (WHCmax). The value of the latter was 0.2 kg kg−1, 
giving soil-water potentials at 25, 50, and 75% of the WHCmax of 
5600, 1200 and 260 kPa, respectively. After adjusting the soil moisture 
content, 10 g (dry wt) of soil was weighed into 21 ml glass headspace vials which were each spiked with 
200 µl of the 1,3-D stock solution. The treated vials were immediately capped with aluminum seals and 
Teflon-faced butyl rubber septa (Supelco, Bellefonte, 
PA) and then incubated at 20°C in the dark under 
static conditions. Triplicate samples were removed at 
specific time intervals and frozen at −20°C until 
analyzed.

2.5 Sample extraction and analysis
To extract the (Z)- and (E)-1,3-D residues from the 
soil samples, vials were uncapped while still frozen, 
and ethyl acetate (10 ml) and anhydrous sodium 
sulfate (10 g) were added to each vial, followed by 
immediate recapping. Once the soils had thawed, the 
vials were shaken for 1 h on a horizontal shaker (200 
oscillations min−1), vortexed for 30 s and then allowed 
to stand until all suspended particulate matter had 
settled. After settling, a 1 ml aliquot of the soil extract 
was transferred to a GC vial. The soil extract was 
analyzed for (Z)- and (E)-1,3-D on a Hewlett-Packard 
5890 gas chromatograph equipped with a RTX-624 
capillary column (30 m, 0.25 mm × 1.4 µm, Restek 
Corp, Bellefonte, PA, USA) and connected to a 
micro-electron capture detector (µECD). The operating 
conditions were as follows: carrier gas, helium, 
1.2 ml min−1; inlet temperature, 230°C; detector 
temperature, 280°C; column temperature, isothermal 
at 110°C for 7 min. The average extraction efficiency of 
1,3-D residues was 83%. All data was subject to 
first-order fitting to obtain a degradation rate constant 
k (day−1) and error bars represent the standard error of the 
data.

3 RESULTS AND DISCUSSION
3.1 Effect of amendment on degradation
Figure 1 shows the disappearance of 1,3-D, as the sum of 
both isomers, from soil amended with 5% (w/w) BS, 
FC, CKM or SM. The reactions are well described by 
first-order kinetics (r2 > 0.96). The incorporation 
of CKM and SM into Arlington soil was found to 
substantially increase the degradation of 1,3-D. 
Degradation was 2.3 and 3.3 times faster in CKM- 
and SM-amended soil, respectively, than in un-
amended soil. In contrast, amending soil with FC 
only enhanced the rate of degradation 1.2 times, while 
1,3-D degradation was slightly inhibited in BS-
amended soil. Apparently, FC and BS contain low 
population numbers of microbial species capable of 
degrading or contributing to the degradation of 1,3-D. 
In addition, it is also evident that these organic wastes 
did not contribute to the chemical degradation of 
1,3-D.

First-order rate coefficients k (day−1) and corre-

csponding half-lives for the (Z)- and (E)-isomers are 
given in Table 1. Overall, the data show that both (Z)- 
and (E)-isomers have similar kinetic behavior, which 
supports results obtained by other workers.16–18,24,25 
Ou and co-workers5,7,19 found that the degradation 
rates of both 1,3-D isomers were similar in soils not 
previously treated with 1,3-D. To our knowledge, the 
soil used in this study, Arlington sandy loam, had 
never been previously treated with 1,3-D. In un-
amended soil, the rates of degradation for both isomers 
were identical, with a half-life of 6.3 days. However, 
degradation of the (Z)-isomer was slightly greater than 
that of the (E)-isomer in all treated soils except CKM-
amended soil. The half-lives of (Z)- and (E)-1,3-D in

![Figure 1. Disappearance of 1,3-dichloropropene, as the sum of (Z)- and (E)-isomers, from Arlington sandy loam, unamended and amended with various organic wastes and incubated at 20°C.](image)

<table>
<thead>
<tr>
<th>Matrix</th>
<th>k (day−1) (± SD)</th>
<th>t1/2 (days)</th>
<th>r²</th>
<th>k (day−1) (± SD)</th>
<th>t1/2 (days)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unamended soil</td>
<td>0.11 (+0.01)</td>
<td>6.3</td>
<td>0.96</td>
<td>0.11 (+0.01)</td>
<td>6.3</td>
<td>0.97</td>
</tr>
<tr>
<td>BS soil (5%)</td>
<td>0.11 (+0.01)</td>
<td>6.3</td>
<td>0.99</td>
<td>0.09 (+0.00)</td>
<td>7.7</td>
<td>0.99</td>
</tr>
<tr>
<td>FC soil (5%)</td>
<td>0.14 (+0.01)</td>
<td>5.0</td>
<td>0.99</td>
<td>0.12 (+0.01)</td>
<td>5.8</td>
<td>0.99</td>
</tr>
<tr>
<td>CKM soil (5%)</td>
<td>0.23 (+0.01)</td>
<td>3.0</td>
<td>1.00</td>
<td>0.27 (+0.01)</td>
<td>2.6</td>
<td>0.98</td>
</tr>
<tr>
<td>SM soil (5%)</td>
<td>0.39 (+0.03)</td>
<td>1.8</td>
<td>0.99</td>
<td>0.36 (+0.02)</td>
<td>1.9</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 1. First-order degradation rate 
constants (k), half-life (t1/2) values, and 
correlation coefficients of fitting (r²) for 
Arlington sandy loam amended with 
various organic amendments at 20°C

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SM-amended soil were 1.8 and 1.9 days, respectively. Since SM was found to substantially increase the rate of (Z)- and (E)-1,3-D degradation over that of the other amendments tested, it was selected for continued use in our degradation studies.

3.2 Effect of temperature and manure application rate on degradation

The degradation of 1,3-D-isomers in Arlington soil was accelerated as both temperature and SM application rate increased (Fig 2). The differences in the rates of degradation of the (Z)- and (E)-isomers were found to be similar in unamended soil and SM-amended soil at all temperatures tested. In unamended soil, the first-order degradation rate constants at 20, 30 and 40 °C were 0.11, 0.21 and 0.47 day⁻¹, respectively, for (Z)-1,3-D, and 0.11, 0.24 and 0.57 day⁻¹, respectively, for (E)-1,3-D. The corresponding half-life values were 6.3, 3.3 and 1.5 days for (Z)-1,3-D and 6.3, 2.9 and 1.2 days for (E)-1,3-D (Table 2). As the temperature increased from 20 to 40 °C, degradation of (Z)-1,3-D and (E)-1,3-D in unamended soil increased 4.3 and 5.2 times, respectively. The degradation rates for both isomers changed by a factor of about 2 for each 10 °C change in temperature. Under typical fumigant and soil conditions, more 1,3-D degradation can be expected to occur in the soil surface than in the subsurface layers, since surface layers are generally subject to larger temperature fluctuations.

Figure 2 shows that k increases with temperature at all rates of SM application for both (E)-1,3-D and (Z)-1,3-D. It is interesting that, at 20 and 30 °C, the value of k did not differ substantially between SM rates of 5 and 10% for either isomer. This suggests that degradation of 1,3-D at these temperatures is insensitive to the application rate of SM. However at 40 °C, the degradation rates of the (Z)- and (E)-isomers at 10% SM were 36 and 33% greater, respectively, than at 5% SM. Over the temperature range of 20 to 30 °C, it appears that optimum degradation of 1,3-D in SM-amended soil lies approximately at the 5% application rate. Although the application of 10% SM substantially increased the degradation of the 1,3-D isomers at 40 °C, the addition of 5% SM represents a more feasible field application rate. The incorporation of 5% SM into the top 5-cm soil layer (assuming an average bulk density of 1.3 g cm⁻³) would require approximately 36 tonneha⁻¹ (dry wt) of amendment.

Table 2. Half-life (t₁/₂) values and first-order correlation coefficients of fitting (r²) for Arlington sandy loam amended with different rates of composted steer manure

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>Matrix</th>
<th>(Z)-1,3-D</th>
<th></th>
<th>(E)-1,3-D</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>t₁/₂ (days)</td>
<td>r²</td>
<td>t₁/₂ (days)</td>
<td>r²</td>
</tr>
<tr>
<td>20</td>
<td>Unamended soil</td>
<td>6.3</td>
<td>0.96</td>
<td>6.3</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>SM soil (2%)</td>
<td>2.6</td>
<td>0.99</td>
<td>3.0</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SM soil (5%)</td>
<td>1.8</td>
<td>0.99</td>
<td>1.9</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SM soil (10%)</td>
<td>1.9</td>
<td>1.00</td>
<td>2.0</td>
<td>1.00</td>
</tr>
<tr>
<td>30</td>
<td>Unamended soil</td>
<td>3.3</td>
<td>0.97</td>
<td>2.9</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>SM soil (2%)</td>
<td>1.1</td>
<td>0.99</td>
<td>1.2</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>SM soil (5%)</td>
<td>0.8</td>
<td>0.99</td>
<td>0.8</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SM soil (10%)</td>
<td>0.7</td>
<td>1.00</td>
<td>0.7</td>
<td>1.00</td>
</tr>
<tr>
<td>40</td>
<td>Unamended soil</td>
<td>1.5</td>
<td>1.00</td>
<td>1.2</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SM soil (2%)</td>
<td>0.6</td>
<td>1.00</td>
<td>0.7</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SM soil (5%)</td>
<td>0.5</td>
<td>1.00</td>
<td>0.5</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>SM soil (10%)</td>
<td>0.4</td>
<td>1.00</td>
<td>0.3</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Figure 2. First-order rate constants (k, day⁻¹) for degradation of (Z)- and (E)-1,3-dichloropropene in Arlington sandy loam incubated at different temperatures and amended with different rates of composted steer manure.
pared with unamended soil, the addition of 5% SM increased degradation of both 1,3-D isomers, on average, 3.4, 3.8 and 2.7 times at 20, 30 and 40°C, respectively. Corresponding half-lives were 1.9, 0.8 and 0.5 days. All half-life values, at each of the SM rates and temperatures tested, are given in Table 2.

The relationship between temperature and degradation of both 1,3-D isomers closely followed the Arrhenius equation \((r^2 > 0.98)\). The activation energy \((E_a)\) at different rates of application was calculated as the slope of the plot of \(\ln k\) versus \(1/T\). The \(E_a\) values for amended soil at 2, 5 and 10% SM were 56.5, 53.4 and 64.5 kJ mol\(^{-1}\), respectively. The sensitivity of the rate of a reaction to changes in temperature depends on the value of \(E_a\). Low \(E_a\) values are often associated with insensitivity to temperature. In 2, 5 and 10% SM-amended soil, the average increase in degradation per 10°C increase in temperature were 2.1, 1.9 and 2.4, respectively, for \((Z)\)-1,3-D, and 2.2, 2.1 and 2.4, respectively, for \((E)\)-1,3-D. These results agree well with the general rule that the rate of a reaction doubles with every 10°C rise in temperature.

It is evident from the above data that degradation of 1,3-D isomers in soil is enhanced by both temperature and organic amendment; by controlling each of these factors it may be possible to reduce atmospheric emissions. Not only does the use of organic amendments enhance 1,3-D degradation, but their use in conjunction with soil solarization techniques, such as tarping, could provide additional emission and pest-control benefits. Tarping is a method often used to thermally destroy soil-borne plant pathogens by increasing the temperature in the soil surface. The increased soil temperature, as previously discussed, should also be effective in accelerating fumigant degradation, especially in the soil surface. Tarping is also a method used to increase fumigant efficacy and reduce emissions, but it is not completely effective since plastic tarps are often permeable to fumigants.\(^{27,28}\) Theoretically, the use of organic amendments should increase the effectiveness of tarping, from both an emissions and pest-control standpoint. Haidar and Sidahmed\(^{29}\) reported that the use of chicken manure was effective in reducing the solarization period required to eliminate an obligate root parasitic weed. Organic amendments are also known to suppress soil-borne pathogens through the stimulation of antagonistic organisms or production of toxic volatile gases.\(^{30-33}\) Therefore, integrating fumigation with soil solarization (through tarping) and organic amendments may provide the best possible scenario to control 1,3-D emissions and in some cases increase pest-control efficacy. Ultimately this may lead to reduced pesticide usage.

3.3 Degradation mechanisms in manure-amended soil

As mentioned previously, the degradation of 1,3-D isomers in soil is a result of biological and chemical mechanisms. Figure 3 shows the degradation rate constants of the 1,3-D isomers in sterile and non-sterile unamended and SM-amended Arlington soil. Fumigant degradation in sterile soil is generally attributed to chemical reactions, while degradation in non-sterile soil is a combination of biological and chemical reactions. Therefore, differences between rate constants of the sterile and non-sterile soil mixtures were assumed to be attributable to microbial degradation.

The rate of chemical degradation of the 1,3-D
isomers increased linearly ($r^2 > 0.98$) with respect to the rate of SM application, but this was not the case with respect to biological degradation (Fig 3). Increasing the application rate of SM to 10% had a negative impact upon the rate of biological 1,3-D degradation. In SM-amended soil, biological mechanisms accounted for 14 to 44% and 20 to 42% of the (Z)-1,3-D and (E)-1,3-D degradation, respectively (Fig 4). The greatest percentage of biological degradation occurred in the 2 and 5% SM soil mixtures, while in unamended soil, only 9% of the degradation was biologically associated. Significant differences in the biological degradation rates between the two isomers also occurred in the 2 and 10% SM soil mixtures. In 2% SM-amended soil, the rate of biological degradation of the (Z)-isomer was 1.5 times higher, while in 10% SM-amended soil, the biological degradation rate of the (E)-isomer was 1.4 times higher. In general, enhanced degradation is greater for (E)-1,3-D than for (Z)-1,3-D, but only in soils previously treated with 1,3-D.17.19 Although our soil had not previously been treated with 1,3-D, isomeric differences in the 2 and 10% SM soil mixtures may be attributed to the presence of micro-organisms capable of preferentially degrading either (Z)- or (E)-1,3-D.

Overall, chemical mechanisms were the predominant degradative process; 1,3-D can be transformed via nucleophilic substitution with soil organic matter or degraded through a hydrolytic reaction.8-10,20 However, adjusting the soil moisture content to 25, 50 and 75% of its maximum water holding capacity had no effect on the degradation rate of either (Z)- or (E)-1,3-D (Fig 5). Since this experiment was conducted at 20°C only, a similar impact from biological and/or chemical degradation mechanisms in SM-amended soil would not be expected at lower and/or higher temperatures. Gan et al20 previously deter-

 mined in unamended Arlington soil that microbial degradation of 1,3-D remained essentially unchanged over the temperature range of 20 to 40°C, but was completely inhibited above 40°C; chemical degradation consistently increased with temperature from 20 to 50°C.

4 CONCLUSIONS

Use of fumigant pesticides is an essential practice to protect many agricultural crops from parasitic nematodes. However, emission of fumigants to the atmosphere is often detrimental to the environment. As a result, cost-effective control strategies are needed, especially for those fumigants which are now being considered replacements for methyl bromide. Results from this study confirm that the use of organic wastes, such as composted steer manure, enhances degradation of (Z)- and (E)-1,3-D in soil. By enhancing 1,3-D degradation in the soil surface layer, it is likely that 1,3-D emissions can be reduced to levels that meet ambient air quality standards. This must, however, be determined on a case-by-case basis, since differing amendment quality and soil properties will affect fumigant behavior and degradation. Use of organic amendments may be particularly useful in sandy soils, where fumigant degradation is generally slow and diffusion is rapid. The application of organic amendments may not only reduce fumigant emissions, but also improve soil fertility, crop yields and microbial

Figure 4. The relative contribution of biological mechanisms to the degradation of (Z)- and (E)-dichloropropane in unamended and amended Arlington sandy loam at 20°C.

Figure 5. Degradation of (Z)- and (E)-1,3-dichloropropene at 20°C in unamended Arlington sandy loam with different soil moisture contents.
diversity and hence soil health. Ultimately, application of amendments may provide a means to dispose of agricultural/industrial organic wastes. Minimal interference with pest-control efficacy should occur, since accelerated pesticide degradation would be limited to the soil surface layer only. Field studies should be conducted to evaluate the effectiveness of integrating organic amendments with 1,3-D fumigation as a method to control emissions. Research should also be conducted to understand the interactions of soil organic amendments on the degradation of other fumigants. Additional considerations should be given to integrated pest management techniques such as soil solarization.

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