Relative effect of soil moisture on emissions and distribution of 1,3-dichloropropene and chloropicrin in soil columns

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Emissions of soil fumigants are regulated to protect air quality in California. Irrigation prior to fumigation can reduce fumigant emissions at relatively low costs; however, the optimum range of soil water content that reduces emissions without reducing efficacy is not clearly defined. The objective of this study was to determine the effects of soil water content (at 30, 45, 60, 75, 90 and 100% field capacity (FC)) on the emission and distribution of fumigants 1,3-dichloropropene (1,3-D) and chloropicrin (CP) in columns packed with a sandy loam soil. After injecting equal amounts of cis-1,3-D, trans-1,3-D, and CP, fumigant emissions and distribution in soil were monitored for 14 days. Emissions of all three compounds showed similar response to soil water content except that CP emissions were lower than both isomers of 1,3-D. The emission peak flux was highest and occurred earliest in the driest soil while it was reduced and delayed as soil water content increased. After the peak, emission flux decreased rapidly in the driest soil but more slowly in higher water content treatments. Initially, higher soil water content resulted in substantially lower cumulative emissions among the treatments, but as time progressed, the differences in cumulative emissions decreased or even disappeared. These trends were likely due to the effect of the closed-bottom short soil columns which allowed fumigants to only move upward and contribute to emission. Higher fumigant concentrations in the soil–gas phase were observed in high soil water content treatments, due to less emission loss and more fumigant retained in the soil.

1. Introduction

Pre-plant soil fumigation to control soil-borne pests is an important cultural practice for many high-value crops. The fumigants 1,3-dichloropropene (1,3-D) and chloropicrin (CP) are important alternatives to methyl bromide (MeBr) which have been phased out due to its detrimental effects on stratospheric ozone (Honaganahalli and Seiber, 1997; Ajwa et al., 2002). However, after being applied to soil, high volatility of 1,3-D and CP causes rapid emission into the air. Fumigant emissions contribute to volatile organic compounds (VOCs) in the air which react with nitrogen oxides to form ground-level ozone (Segawa, 2005). High emissions of these acutely toxic fumigants may also endanger the health of workers and by-standers. Thus peak emission flux data are used to determine adequate buffer zones and worker safety regulations, and total emission data are used to determine potential impacts of fumigant applications on a regional basis. In addition to environmental concerns, rapid emission losses of the fumigants from the soil demand high application rates for sufficient pest control. Development of feasible agricultural practices to minimize fumigant emissions is essential for addressing environmental safety and economic concerns.

Irrigation to increase soil water content prior to fumigation has been shown to effectively reduce emissions of shank-injected fumigants (Gao et al., 2008a,b). After comparing three soil water regimes, i.e. air-dry, near field capacity (FC), and near saturated in Florida sandy soil in microplots, high soil water content was found to decrease the peak flux and reduce cumulative emission losses of 1,3-D (Thomas et al., 2003). Thomas et al. (2004) in another field test also found that soil water content near FC decreased the emission of 1,3-D and CP as compared to the air-dry soil. A field trial in a sandy loam soil in California showed that the total emission loss after pre-irrigation with 25 cm of water 4 d before fumigation was 19% of applied 1,3-D and 9% of applied CP compared to 36% of applied 1,3-D and 30% of applied CP in the non-irrigated control (Gao et al., 2008b). In a column study, Gan et al. (1996) found that high soil water
content decreased the peak flux of MeBr and also delayed the occurrence of the peak. Lower MeBr emission from wet soils was also reported by Shinde et al. (2000). Increasing soil water content can reduce movement of fumigants to the soil surface and result in lower emissions, because when soil water content is high, air-filled soil porosity decreases and fumigants are known to diffuse much more slowly in the liquid phase than in the gas phase (Gan et al., 1996).

Adequate concentration, uniform distribution, and sufficient residence time of fumigants in soil are critical for effective pest control. Several recent studies have measured fumigant distribution in the soil–gas phase in the soil with moderate soil water content comparable to that observed in dry soil. The distribution of 1,3-D and CP in soil–air in pre-irrigated soils was similar to that observed in dry soils (Gao et al., 2008b; Thomas et al., 2003, 2004). Wang et al. (1997) also observed that MeBr distributed as uniformly in irrigated plots as in non-irrigated plots from the soil surface down to 2 m depth. However, excessive soil moisture that reduces fumigant distribution through the soil profile is undesirable because of the potential to reduce pest control (McKenny and Thomason, 1974). Fumigant diffusion was found to be negligible in near-water-saturated sandy soil (Thomas et al., 2003). For fine-textured soils, the effect of soil water content on fumigant diffusion was most striking when soils had soil water tension in excess of 50 kPa at 30 cm depth (McKenny and Thomason, 1974).

Most past studies have been based on limited treatments (e.g. air-dry soil vs. flooded soil or FC soil); there is no information to clarify the relationship between soil water content and fumigant emission and distribution in the soil. It is difficult to establish and control uniform soil water levels in field soil profiles to determine such a relationship. The optimum soil moisture condition that can prevent fumigant from rapid emissions while not reducing fumigant concentrations in soil has not been clearly defined for any soil type. Thus, we carried out a column study with six soil water content treatments. The objective was to determine the effects of soil water content on emissions and distribution of 1,3-D and CP in columns packed with a sandy loam soil.

2. Materials and methods

2.1. Soils and chemicals

A Hanford sandy loam soil (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents) was collected from the top 30 cm of a field at the USDA-ARS, San Joaquin Valley Agricultural Sciences Center, Parlier, California. The soil had a pH of 7.2 and a cation exchange capacity (CEC) of 6.8 cmol c kg⁻¹, and an organic matter content of 7.2 g kg⁻¹. The soil water content at FC is about 170 g kg⁻¹ (Skaggs et al., 2004). The soil was air-dried to a water content of 51 g kg⁻¹, sieved through a 4-mm mesh screen, and homogenized before packing in the soil columns. cis-1,3-D (purity of 98.9%) and trans-1,3-D (purity of 99%) were provided by Dow AgroSciences (Indianapolis, IN). Chloropicrin (purity of 99.9%) was provided by Niklor Chemical Co., Inc. (Mojave, CA). Ethyl acetate (pesticide grade), hexane (pesticide grade), and sodium sulfate anhydrous (Na₂SO₄, 10–60 mesh, ACS grade) were obtained from Fisher Scientific (Fair Lawn, NJ).

2.2. Soil column set-up and treatment

Soil was packed 23 cm deep to a uniform bulk density of 1.4 g cm⁻³ in closed-bottom stainless steel columns (25-cm height × 15.5-cm i.d.). Gas sampling ports were installed at 0, 10, and 20 cm below the soil surface. A Teflon-faced silicone rubber septum (3-mm thick; Supelco, Bellefonte, PA) was installed in each sampling port. The septum was replaced after each sampling. A Teflon tube was attached to the inside of each sampling port and extended to the center of the column. The experiments were conducted at laboratory temperature (22 ± 3 °C).

After packing the soil columns, water was added to the soil surface on a weight basis to achieve final water contents of 30, 45, 60, 75, 90 and 100% of FC in duplicate columns, representing treatment W30, W45, W60, W75, W90 and W100, respectively. Soil water content of 170 g kg⁻¹ was accepted as 100% FC (W100) in the tested soil and 51 g kg⁻¹ in the air-dried soil was equivalent to 30% FC (W30), thus no water was added. After water application, the columns were sealed immediately with aluminum foil and set aside for 6 weeks to allow uniform soil moisture distribution.

Prior to fumigant injection, the aluminum foil on the top of the soil column was replaced with a flow-through gas-sampling chamber which was sealed to the column with sealant-coated aluminum tape to avoid gas leakage. A fumigant solution (250 mL) containing 111 mg (equivalent to 58 kg ha⁻¹) each of cis-1,3-D, trans-1,3-D, and CP was injected into the column-center at the 10-cm depth using a custom made long needle syringe. The relatively low fumigant application rate was due to the shallow, closed-bottom column. It was determined later that an even smaller amount of fumigants should be used in order to minimize the closed-bottom effect (for information on cumulative emissions (see discussions) because fumigants in the column can only move upward, which led to higher cumulative emission losses compared to field conditions. This can be significant when too much fumigant is injected.

2.3. Fumigant sampling and analysis

After injection of the fumigant solution (time zero), a continuous air flow at 110 ± 10 mL min⁻¹ through each sampling chamber was established by applying a vacuum to the discharge port, and monitored with a flow meter. Fumigant emission and concentration in the soil–gas phase was sampled for 14 days following fumigant injections. Emission from the soil surface was measured by collecting air samples with ORBO 613, XAD 480/40 mg (Supelco) tubes connected to the outlet of the flow-through chamber. During the daytime, sampling tubes were collected more frequently than later time, i.e., every 1 h for the first 4 d, every 2 h for the following 6 d, and every 4 h for the last 4 d of the experiment. During the overnight hours, several ORBO tubes were connected in series to be used for trapping all fumigants emitted.

The ORBO tubes were stored at −80 °C until extraction. To extract fumigants, each tube was broken and all materials were transferred into a 10-mL clear headspace vial. Five mL of hexane was added and the vial was shaken for 1 h. After settling, approximately 1 mL supernatant in the vial was transferred to a 2-mL amber gas chromatography (GC) vial for analysis. Fumigants in the extracts were analyzed using a GC-μECD [Agilent Technology 6890N Network GC system with a micro electron capture detector (μECD); Agilent Technologies, Palo Alto, CA]. A DB-VRX capillary column (30-m length × 0.25-mm i.d. × 1.4-μm film thickness, Agilent Technologies, Palo Alto, CA) was used for separation of fumigants. The GC carrier gas (He) flow rate, inlet temperature, and detector temperature were set at 2.0 mL min⁻¹, 140 °C, and 300 °C, respectively. The oven temperature program was as follows: initially 65 °C, increasing at 2.5 °C min⁻¹ to 85 °C. Using this method, retention time was 5.2, 5.9, and 6.6 min for cis-1,3-D, trans-1,3-D, and CP, respectively. The detection limit (three times the standard deviation of the background noise level) was 0.01, 0.01, and 0.001 mg L⁻¹ for cis-1,3-D, trans-1,3-D, and CP, respectively, when an injection volume of 1 μL solution was used.

The fumigants in the soil–gas phase were sampled by withdrawing 0.5-mL of soil gas from the sampling ports with a gas-tight...
syringe at 3, 6, and 12 h, and 1, 2, 3, 5, 7, 9, 12, and 14 d after fumigant injection. The gas samples were injected into 20-mL clear headspace vials and the vials were crimp-sealed very quickly with aluminum caps and Teflon-faced butyl-rubber septum (Supelco). This sampling technique was quantitative and reproducible (Gan et al., 1997). To avoid moisture effects on fumigant stability, 0.2 g of anhydrous sodium sulfate was added to each vial before sample injection. Samples were stored in an ultra low temperature freezer (−80°C) and analyzed within 3 d, a stable period of time for all fumigants under laboratory conditions (Guo et al., 2004b). The analysis was performed using the GC-μECD equipped with an automated headspace sampler (Agilent Technologies G1888 Network Headspace Sampler) system. The DB-VRX capillary column was used. Conditions for the headspace autosampler were followed as in Gao and Trout (2006).

Upon completion of the experiment (14 d after fumigant injection), soil samples from each column were taken at 0–5, 5–10, 10–15, and 15–23-cm depth intervals, and soil water content and residual fumigant in soil solid/liquid phases were determined. To extract residual fumigant in soil solid/liquid phase, an equivalent dry weight of 8 g of soil was added to a 20-mL clear vial that contained Na2SO4 (amount depended on soil water content at a 7:1 ratio of Na2SO4 to water), and then added 8 mL of ethyl acetate to the vial. The vial was crimp-sealed with aluminum caps and a Teflon-faced butyl-rubber septum and incubated at 80°C in a water bath overnight (approximately 18 h); the supernatant was settled and a portion was transferred into a 2-mL amber GC vial for fumigant analysis using the GC-μECD as described above. The fumigant degradation was calculated by subtracting cumulative emission, fumigant in soil–gas phase at the end of experiment, and the residual fumigant in soil solid/liquid phases from total amount of fumigant applied.

2.4. Statistical analysis

Statistical analysis of the data was conducted using ANOVA procedures (Proc GLM; SAS 9.1). Treatment means were separated using Fisher’s protected LSD procedures. To describe the time-series cumulative emission data, a regression analysis was performed using a three-parameter sigmoidal model (Hill equation; Sigma Plot version 10.0): \( Y = \frac{a X^b}{c + X^b} \), where \( Y \) is the fumigant cumulative emission (% of applied), \( X \) is the time (h), \( a \) is the predicted maximum emission loss, \( b \) is Hill or sigmoidicity coefficient, and, \( c \) is the time when the emission equals half of the predicted maximum emission loss (h).

3. Results and discussion

3.1. Soil water content

Soil water distribution at the end of the experiment was fairly uniform throughout the columns in all treatments (Fig. 1). The

![Fig. 1. Soil water content at the end of soil column experiment. Error bars are standard deviation of duplicate samples.](image1)

![Fig. 2. Effect of soil water content on emission flux of cis-1,3-D, trans-1,3-D, and CP. Error bars are not shown for visual clarity. The averaged relative standard deviation is in a range of 4.4–11.4% for cis-1,3-D, 3.7–9.2% for trans-1,3-D, and 5.8–16.7% for CP among all the treatments.](image2)
average soil water content in the columns within treatments ranged from 45 ± 6 g kg⁻¹ for W30 to 163 ± 2 g kg⁻¹ for W100, which were close to the target soil water contents based on FC of this soil (170 g kg⁻¹).

3.2. Emission flux

The emission flux of 1,3-D and CP increased initially following fumigant injection and then decreased across all the treatments (Fig. 2). After fumigant injection, peak emission was 80.8 µg m⁻² s⁻¹ for cis-1,3-D occurring at 3 h, 73.5 µg m⁻² s⁻¹ for trans-1,3-D at 5 h, and 69.1 µg m⁻² s⁻¹ for CP at 4 h in W30 (Table 1). Increased soil water content resulted in decreased peak emission flux and delayed occurrence of the peak. For example, the peak emission flux in W100 (FC) was reduced by 78–84% and delayed by 11–20 h compared to W30 (Table 1). In general, the emission flux of cis-1,3-D was higher than that of trans-1,3-D and CP (Table 1). The peak flux of each compound and soil water content can be described in a linear equation with negative slope: $Y = -0.49X + 94.5$ for cis-1,3-D ($R^2 = 0.94$); $Y = -0.46X + 80.6$ for trans-1,3-D ($R^2 = 0.84$); and $Y = -0.43X + 76.4$ for CP ($R^2 = 0.86$), where $Y$ is peak flux in µg m⁻² s⁻¹ and X is soil water content (g kg⁻¹). Thomas et al. (2004) also reported that higher water content delayed volatilization of 1,3-D isomers and CP in sandy soil in a microplot experiment. Two field trials by Gao et al. (2008a,b) showed that pre-irrigation, which produced a moist soil profile with relatively higher water content near the surface than subsurface before shank fumigation, reduced peak emission rate of 1,3-D and CP compared to the non-irrigated treatments. Gan et al. (1996) also reported a column study in which increasing soil water content decreased and delayed the peak flux of MeBr due to increased retardation and tortuosity factors in fumigant gas-phase transport. Our findings indicate that increasing soil water content to FC have significant impact on reducing peak emissions, and thus can reduce the risk of fumigant exposure for workers and bystanders. Therefore, soil water content should be an important factor to be considered when determining adequate buffer zones and worker safety regulations.

After the emission flux peak, fumigant emissions decreased most rapidly in W30 and the rate of decrease was slowed as soil water content increased (Fig. 2). The fumigant dissipated faster in drier soil conditions than soils with higher soil water content. At the end of the experiment, emission rates were <0.01 µg m⁻² s⁻¹ for all three compounds in W30, compared to 0.40, 0.63, 0.01 µg m⁻² s⁻¹ for cis-1,3-D, trans-1,3-D, and CP, respectively in W100.

3.3. Cumulative emissions loss

The cumulative emission for 1,3-D isomers and CP increased rapidly and plateaued in the driest soil in about 2 days (Fig. 3). As

![Fig. 3. Measured cumulative emission and fitted curves using a 3-parameter sigmoidal regression model (Hill equation) of cis-1,3-D, trans-1,3-D, and CP for 14 days after fumigant injection as affected by soil water content in 23 cm soil columns filled with sandy loam soil. Symbols are the mean value of duplicate samples. Error bars are not shown for visual clarity. The averaged relative standard deviation is in a range of 0.8–8.1% for cis-1,3-D, 0.3–7.9% for trans-1,3-D, and 1.8–13.7% for CP among all the treatments.](image)

### Table 2

<table>
<thead>
<tr>
<th>Treatment</th>
<th>cis-1,3-D</th>
<th>trans-1,3-D</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$c$</td>
</tr>
<tr>
<td>W30</td>
<td>81.2 a</td>
<td>1.62 a</td>
<td>10.7 a</td>
</tr>
<tr>
<td>W45</td>
<td>80.9 a</td>
<td>1.50 b</td>
<td>22.6 b</td>
</tr>
<tr>
<td>W60</td>
<td>83.3 b</td>
<td>1.42 c</td>
<td>29.8 c</td>
</tr>
<tr>
<td>W75</td>
<td>85.8 c</td>
<td>1.38 c</td>
<td>40.4 d</td>
</tr>
<tr>
<td>W90</td>
<td>83.9 b</td>
<td>1.39 c</td>
<td>49.2 e</td>
</tr>
<tr>
<td>W100</td>
<td>78.4 d</td>
<td>1.37 c</td>
<td>63.9 f</td>
</tr>
</tbody>
</table>

Parameters: $a$, predicted maximum emission loss (% of applied); $b$, Hill or sigmoidicity coefficient; $c$, time when emission reached half of total emission loss (h). In general, the coefficient of determination ($r^2$) was greater than 0.99. Values with same letter in the same column are not statistically different ($P < 0.05$).
soil water content increased, the cumulative emission increased more slowly but continued to increase for longer time (Fig. 3). As a result, much larger differences in cumulative emission loss between water treatments were observed at earlier times than later.

Table 2 lists the sigmoidal model (Hill equation) fitting parameters for the time-series cumulative emission data. The predicted maximum emission loss \((a)\) for any compound was lowest in W100 \((P < 0.05)\). The parameter \((c)\) is used for describing the treatment effect on predicted cumulative emission loss, which increased steadily as the soil water content increased. In the driest soil (W30), half of the predicted maximum emission loss of cis-1,3-D, trans-1,3-D and CP occurred in 10.7, 16.0, and 7.9 h, respectively, while it took 63.9, 83.8, and 41.7 h to reach the same level of relative emission loss in W100 (Table 2). These results suggest that the high soil water content in the soil columns prolonged fumigant emission as more fumigant was retained in the wetter soil. Regression analysis also showed positive linear relationships between the parameter \((c)\) and soil water content. The slope of the linear regression was 4.20, 5.50, and 0.37 for cis-1,3-D, trans-1,3-D and CP, respectively, indicating that increasing soil water content would prolong the emission of the 1,3-D isomers more than of CP.

The mechanisms for that high soil water content (near FC) reduces 1,3-D and CP emission are likely due to the slower diffusion

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total emission</th>
<th>Residual fumigant</th>
<th>Degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>W30</td>
<td>80 a</td>
<td>74 a</td>
<td>0</td>
</tr>
<tr>
<td>W45</td>
<td>78 a</td>
<td>74 a</td>
<td>39 a</td>
</tr>
<tr>
<td>W60</td>
<td>79 a</td>
<td>73 a</td>
<td>38 a</td>
</tr>
<tr>
<td>W75</td>
<td>80 a</td>
<td>72 ab</td>
<td>38 ab</td>
</tr>
<tr>
<td>W90</td>
<td>78 ab</td>
<td>67 bc</td>
<td>36 ab</td>
</tr>
<tr>
<td>W100</td>
<td>71 b</td>
<td>59 c</td>
<td>32 b</td>
</tr>
</tbody>
</table>

Values in the table are the percentage of the applied fumigant amount; Values with same letter in the same column are not statistically different according to LSD, \((P < 0.05)\). Total emission was a measured value. Residual fumigant included both gas-phase and solid/liquid phase. Degradation was calculated by the difference between the amount applied and the measured emission and residual values.
rate through the moist soil and increased degradation. For example, Jury et al. (1983) reported that generally fumigant diffusion through the soil liquid phase is 10–100 times slower than through the gas phase. Some researchers suggest that high water content accelerates the degradation (increased hydrolysis) of MeBr (Shinde et al., 2000) and 1,3-D (Guo et al., 2004a). Guo et al. (2004a) explained that the increased hydrolysis was because of more 1,3-D in the water phase. However, another study reported that 1,3-D degradation was not affected by soil moisture (Dungan et al., 2001).

Total emission losses from our column study (Table 3) were much higher than usually reported in field studies. The high emission in this study was likely due to the relatively shallow closed-bottom columns as compared to field applications which have no restrictive lower boundary. The fumigants injected into the columns can only escape upward (emission); whereas in a field, gases can move upward, downward, and laterally in the soil profile. As a consequence, the closed-bottom columns likely led to higher total emission loss compared to field conditions. The emission data from this experiment provided comparative or relative fumigant emission information from soil water treatments. It is expected that the combination of environmental and biological factors in the field could accelerate the fumigant degradation and may result in larger differences in fumigant emissions between the moist soils and dry soil than what was observed in these soil columns.

### 3.4. Fumigants in soil–gas phase

Similar distribution patterns over time were observed for cis-1,3-D, trans-1,3-D, and CP in soil–gas phase; therefore, only cis-1,3-D data are shown and discussed in Fig. 4. The highest cis-1,3-D concentration was measured at the first sampling time (3 h) near the injection depth (10 cm) in all the treatments, and the fumigant concentration in soil gas at the depths of 0 and 20 cm were very low at that time. The lowest peak fumigant concentration in the driest soil is due to the rapid emission loss. The fumigant concentrations were relatively uniform throughout the whole soil column by 6 h in W30, W45 and W60, 12 h in W75 and W90, and 24 h in W100 indicating that high water content reduced the diffusion rate. After uniform distribution was reached, the fumigant concentration in soil–gas phase gradually decreased to very low levels in all treatments.

Reduced diffusion rate of fumigant in moist soil may reduce pest control efficacy where fumigant injection points are widely spaced or deep soil treatment is required. However, our study showed that the measured fumigant concentrations in the moist soils throughout soil depths were consistently higher than those in the dry soil, which may be because fumigants were retained more and emitted slowly in moist soils. A positive linear relationship for fumigants between soil–gas phase and soil–water phase and between soil–water phase and solid phase had been reported (e.g., Kim et al., 2003). Thomas et al. (2004) also reported higher 1,3-D and CP concentrations in soil–gas phase at FC as compared to dry soil during the fumigation period (except the initial few hours following fumigant injection) in a microplot. Field measurements from California trials showed that fumigant concentration (1,3-D and CP) in pre-irrigated soil was similar to that in dry soil (control) (Gao et al., 2008a). Gao et al. (2008b) also observed that effective nematode control was obtained by 1,3-D and CP in both pre-irrigated and non-irrigated soils.

### 3.5. Residual fumigants in soils

Upon completion of the experiment (14 d), fumigant residual concentrations in the gas-phase were less than 0.07 mg L⁻¹ for cis-1,3-D and trans-1,3-D while CP was found at only trace levels (Fig. 5A). Concentrations of residual fumigants in soil solid/liquid phases were generally similar throughout the column in each treatment (data not shown). Across the soil profile, concentrations of residual fumigants in soil solid/liquid phases were 0.02 mg kg⁻¹ of cis-1,3-D, 0.06 mg kg⁻¹ of trans-1,3-D, and 0.002 mg kg⁻¹ of CP for W30 (Fig. 5B). The amount of residual fumigants increased with the soil water content and was the highest in the W100 treatment (0.12 mg kg⁻¹ of cis-1,3-D, 0.32 mg kg⁻¹ of trans-1,3-D, and 0.01 mg kg⁻¹ of CP). These results suggest that high soil water content increased fumigant retention in soil. However, the values of residual fumigant in solid/liquid phases generally were less than 2% of the applied amount in our experiment. Thomas et al. (2004) also reported that residual 1,3-D and CP were higher in soils near FC than in dry soil. The high residual fumigants in moist soil may be a concern for causing phytotoxicity in the subsequently planted crop.

### 3.6. Fate of fumigants

At the end of the experiment, a mass balance was conducted to obtain the amount of fumigant degraded in the soil based on total applied, measured emission loss, and residual fumigants in soil–gas phase and solid/liquid phase. Greatest fumigant degradation (28%, 39%, and 68% for cis-1,3-D, trans-1,3-D, and CP respectively) occurred in W100 (Table 3). As more soil pore space was occupied by water in 100% FC soil in this study, fumigant diffusion through...
the soil was much slower. As a consequence, more fumigant was retained in the soil for longer time which likely led to the higher degradation. A similar trend for MeBr degradation was reported by Gan et al. (1996).

The longer residence time of fumigant in moist soil is beneficial for pest control. However, unless degraded, it may lead to an extended period of emission losses which could contribute to a high total emission loss, i.e., not beneficial for VOC emission reductions. Higher fumigant concentrations may also prolong the waiting time between fumigation and planting. The ideal scenario is to retain the fumigant in the soil long enough to achieve efficacy, but degrade the fumigant before it can leave the soil surface. All these should be further investigated under field conditions.

4. Conclusions

This column study showed that increasing soil water content up to FC reduced and delayed peak fumigant emission flux. This would reduce the acute exposure risks to workers and by-standers. However, the cumulative emission loss of each fumigant by the end of the experiment was only slightly reduced at soil water contents up to FC. These results were partially due to the effect of closed-bottom columns used in the test. The driest soils had the greatest fumigant emission immediately following injection, while the soils with the highest soil water content had relatively higher emissions later. These results indicate that maintaining a relatively high soil moisture level at or below FC for fumigation can be important to control fumigant emissions. Increasing soil water content up to FC level in the studied soil increased fumigant concentrations in soil–gas phase, which suggested that pest control might also be improved. However, increasing soil water content could reduce the fumigant diffusion rate; thus delaying the time to achieve uniform distribution throughout soil profile. Further research, particularly under field conditions, will be necessary to confirm the findings and identify the optimum soil moisture condition for soil fumigation.

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