Effect of Water Seal on Reducing 1,3-Dichloropropene Emissions from Different Soil Textures

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Soil physical conditions can affect diffusion, environmental fate, and efficacy of fumigants in soil disinfestation treatments. Water seals (applying water using sprinklers to soil following fumigation) can effectively reduce fumigant emissions from sandy loam soils. Soil column studies compared the effectiveness of water seals in reducing *cis*-1,3-dichloropropene (1,3-D) emissions from three different textured soils (loamy sand, sandy loam, and loam). Treatments included an untreated control, an initial water seal (9 mm water applied immediately before fumigant injection), and intermittent water seals (initial 9 mm water seal followed by 3 mm at 12 and 24 h). For the loamy sand, instead of the initial water seal treatment, a reduced-amount intermittent water seal (initial 3 mm water followed by 1 mm at 12 and 24 h) treatment was tested. Overall emission loss of 1,3-D from the control over 2 wk was 56% for the loamy sand, 51% for the sandy loam, and 43% for the loam. The initial water seal reduced total 1,3-D emissions to 46% in the sandy loam and 31% in the loam. The intermittent water seals reduced emission loss to 26% for the loamy sand, 41% for the sandy loam, and 21% for the loam. The reduced-amount intermittent water seal for loamy sand had little effect. Low emission loss was associated with high surface soil water content. None of the water applications reduced gaseous fumigant concentrations. Results indicate that water seal techniques may be able to effectively reduce emissions for different soil textures without reducing fumigant concentration in the soil.

An important soil fumigant, methyl bromide (MeBr), is being phased out due to deleterious effects on stratosphere ozone. Alternatives to MeBr, such as 1,3-dichloropropene (1,3-D), is increasingly used (Trout, 2006), however, most currently available alternatives are volatile organic compounds and minimizing their emissions is required to improve air quality (Segawa, 2005). Use of soil fumigants is highly regulated to minimize acute exposure risks for workers and bystanders and long-term effects on the environment.

Differences in soil physical conditions, such as texture, water content, and bulk density can affect diffusion, environmental fate, and pest control efficacy of soil fumigants. The soil texture, water content, and density affect the volume of air filled space and size and continuity of soil pores. Research has shown that changes in soil physical characteristics such as increased soil water content and higher compaction can slow the diffusion of fumigants through soil (Gan et al., 1996). Another example of slower diffusion through the soil is in finer textured soils due to high organic matter and clay content (Townshend et al., 1980; Ma et al., 2001). Fine textured soils typically have reduced fumigant diffusion because of smaller primary pores, although higher aggregate stability could result in larger secondary pores (cracks between aggregates). Finer textured soils generally hold water longer than coarser textured soils. High soil water content can reduce fumigant emission significantly (Thomas et al., 2003, 2004). Surface water seals (applying water to the soil surface) can effectively prevent rapid fumigant emissions by forming a temporarily saturated or high water content layer at the soil surface and reducing secondary (macro) porosity. Increasing soil water content reduces fumigant diffusion in soil because fumigant diffusion is much slower in the liquid phase than in the gas phase. The amount of water retained by a soil is affected by soil texture and bulk density which can vary throughout a field as well as through the soil profile. Water application to the soil surface in column studies and small plots resulted in a substantial reduction in MeBr and 1,3-D emissions (Jin and Jury, 1995; Wang et al., 1997; Thomas et al., 2003; Ashworth and Yates, 2007). Gao and Trout (2006) recently tested a water seal for reducing 1,3-D emissions and found that timing of water application as well as the use of intermittent water application were important factors. Another study

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Abbreviations: 1,3-D, 1,3-dichloropropene; SJV, San Joaquin Valley.

using sprinkler irrigation (intermittent water sealing) to reduce methyl isothiocyanate emissions found that proper timing of water applications was important for maximizing emission reductions (Sullivan et al., 2004). However, application of excessive amounts of water could impact fumigant efficacy by reducing fumigant diffusion and distribution through the soil (Thomas et al., 2003). Proper water content (near or below field capacity) may result in optimum conditions for persistence, distribution, and emission of 1,3-D in sandy soil (Thomas et al., 2004). The range of soil water content that benefits both emission reduction and fumigant efficacy has not been clearly defined and is expected to vary for different soils.

High value cropping systems in California contribute to the state being among the highest fumigant using states in the United States. Sandy loam soils are commonly found in orchards, vineyards, and nurseries along the east side of San Joaquin Valley (SJV), CA. Finer-textured soils (e.g., loam or clay loam) and coarser-textured soils (e.g., loamy sand) are also common in some areas in the SJV. Better understanding of how to effectively apply fumigants and minimize emissions in various soils is important for agricultural producers and for minimizing environmental risks. Most research on water seals has been conducted on sandy loam soil, but little information is available for finer or coarser textured soil. The objective of this study was to determine the effectiveness of water seals on reducing 1,3-D emissions from three soils of different textures (loamy sand, sandy loam, and loam) in column tests. The hypothesis of this research was that, with the same amount of water applied, water seals may be more effective for reducing fumigant emissions in fine-textured soils compared to coarse-textured soils.

Materials and Methods

Soils and Chemicals

Three different textured soils: Atwater loamy sand, Hanford sandy loam, and Madera loam were used in this study and their selected soil properties are shown in Table 1. The Atwater loamy sand (coarse-loamy, mixed, active, thermic Typic Haploxeralfs) was obtained from a cultivated field in Atwater, CA (Merced County). The Atwater series soils are distributed along the east side of the SJV, comprising 36,000 ha in Fresno, Merced, and Madera Counties, and are mainly used for production of truck crops, tree fruits, nuts, grain, and alfalfa (USDA-NRCS, 2004). These soils occur on gently undulating to rolling dunes formed from granitic alluvium that are stratified and lack uniform particle size distribution. The Hanford sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents) was obtained from the USDA-ARS San Joaquin Valley Agricultural Sciences Center near Parlier, CA. Hanford series soils are widely distributed in the SJV and in the valleys of central and southern California and typically are used for growing a wide range of fruits, vegetables, and general farm crops (USDA-NRCS, 2004). The Madera loam (fine, smectite, thermic Abruptic Durixeralfs) was obtained from Bright's Nursery in Le Grand, CA. The Madera soil series is used mainly for irrigated cropland and is distributed in the eastern side of the Sacramento and SJV of California in gently sloping alluvium mainly from granitic rock or mixed sources (USDA-NRCS, 2004).

All soils were collected from the surface to 30 cm depth and air dried. Soils were passed through a 4-mm sieve and mixed before being packed into columns. The water content for the Atwater loamy sand, Hanford sandy loam, and Madera loam soils were 12, 50, and 50 g kg^{-1}, respectively. Ethyl acetate (pesticide grade), hexane (pesticide grade), and sodium sulfate anhydrous (Na_2SO_4, 10–60 mesh, ACS grade) were obtained from Fisher Scientific (Fair Lawn, NJ). *Cis*-1,3-dichloropropene (purity of 98.9%) was provided by Dow AgroSciences (Indianapolis, IN).

Soil Column Experiment

Soil columns were used to test treatment effects on emissions and the fate of 1,3-D after applying to soil. Column studies often involve repacking soil to a target density rather than undisturbed soil as in the field. Pore size distribution is often uniform in the packed soil columns from the preparation (sieving and mixing) of soil materials. Soil columns with a specific dimension limit fumigant transport because of the restricted side movement and downward movement. While soil column studies allow for better control of the study conditions; the disadvantage is that the results may not be directly applicable to field conditions. For example, fumigant injection to the columns resulted in a point source compared to the channeled source from shank injection in the field. As a result, emission peak time may vary significantly in laboratory column studies from field fumigation. As a less time consuming and more cost-effective approach, laboratory soil column tests are more appropriate for comparisons of relative differences or effects of treatments on fumigant emissions and behavior in soil.

The column design and study methods are similar to previously reported (Gao and Trout, 2006). Based on measurements from the field, the soil columns were packed to a bulk density of 1.6 g cm^{-3} for the loamy sand and 1.4 g cm^{-3} for the sandy loam and the loam soils. The columns had soil-gas sampling ports at the soil surface and in 10-cm increments to 60 cm depth below the soil surface. A Teflon-faced silicone rubber septum (3-mm thick; Supelco, Bellefonte, PA) was installed in each sampling port and was replaced after each sampling. A Teflon tube attached to the inside of each sampling port extended to the center of the column. A flow-through gas sampling chamber was placed on the top of the soil column for trapping and measuring emissions and sealed with sealant-coated aluminum tape to avoid gas leakage.

One hundred microliters of liquid *cis*-1,3-D (122 mg) (equivalent to an application rate of 65 kg ha^{-1}) was injected into the column center at the 30-cm depth through a custom made long needle syringe. *Cis*-1,3-D was chosen because of the similar chemical behavior between the two isomers (*cis*- and *trans*-1,3-D). Previous research indicates that *cis*-1,3-D diffuses slightly faster than *trans*-1,3-D through soil (Yates et al., 2002; Thomas et al., 2003). Soil surface treatments were:

1. Control--no surface water application.
2. Initial water seal--Spraying 9 mm of tap water onto soil surface just before fumigant injection.

Table 1. Selected properties of Atwater loamy sand, Hanford sandy loam, and Madera loam.

Soil properties	Atwater loamy sand	Hanford sandy loam	Madera loam
Bulk density, g cm^{-3}	1.6	1.4	1.4
Sand, g kg^{-1}	880	548	404
Silt, g kg^{-1}	50	396	344
Clay, g kg^{-1}	70	56	252
Water content at 33 kPa suction, g kg^{-1}	54	170	230
Organic matter content, g kg^{-1}	7.2	7.4	11.2
Cation exchange capacity, $cmol_c$ kg^{-1}	3.3	6.8	20

3. Intermittent water seals--Same as treatment 2 followed by two sprayed water applications of 3 mm at 12 h and 24 h after 1,3-D application.

Treatment 2 was not tested in the loamy sand soil and instead, a reduced-amount intermittent water seal treatment (i.e., initial water 3 mm + 1 mm at 12 and 24 h) was tested. The 3-mm water application was calculated to bring the 5-cm surface soil layer to field capacity in the loamy sand as was intended with the 9-mm water seal treatment in the sandy loam. For the loam soil, 9 mm of water would bring a 4-cm surface soil to field capacity, that is, 1 cm less than in the sandy loam soil. To apply water after the fumigant injection, the top chambers were removed from the columns. Thus chambers from other treatments were opened at the same time to avoid biasing the emission measurements. The emission rate during the period when the top chamber was removed was estimated based on the volume of the chamber, open time, and fumigant concentration before and after the open period. A total of three sets of column tests (maximum of six columns in each test) were conducted for all three soils. The data for the sandy loam was previously reported by Gao and Trout (2006) and was used for comparing with other two soils in this study. All treatments were run in duplicate except the reduced-amount intermittent water seal treatment used in the loamy sand. The column experiment was conducted at 22 ± 3°C and sampling and monitoring occurred for 2 wk after fumigant injection.

Fumigant Sampling and Analysis

After column assembly and injection of 1,3-D, a continuous flow rate of 110 ± 10 mL min^{-1} through the top chamber was maintained by vacuum and monitored with a flow meter. One flow meter was used for each column. The flow meters were connected using Tygon (Saint-Gobain Performance Plastics, Akron, OH) tubing and all were connected in parallel to the vacuum system. Fumigant emission from the soil surface was measured by collecting the air samples from the flow-through air-chamber with ORBO 613, XAD-4 80/40mg (Supelco) tubes connected to the outlet of the chambers. The XAD tubes can adsorb 1,3-D efficiently with >90% recovery (Gao et al., 2006). The tubes were replaced every 1 h for the first 3 d during the day or specified time (0800 h to 0300 h first day, 0800 h to 2200 h the second day and 0800 h to 1800 h the third day) and every 2 to 4 h (0800–1800 h) for the remainder of the study. For the unspecified time period or overnight, a chain of 2 to 6 ORBO tubes was connected to ensure trapping of all emissions. The 1,3-D in ORBO tubes were extracted and analyzed using the methods described in Gao and Trout (2006). The 1,3-D in the soil-gas phase was sampled by withdrawing a 0.5-mL volume of soil gas from each of the sampling ports with a gas-tight syringe at 3, 6, 12, 24, and 48 h, and 3, 5, 8, 11, and 14 d after fumigant injection. The gas samples were injected into 20-mL clear headspace vials and analyzed within 72 h, a stable period of time for 1,3-D under laboratory conditions (Guo et al., 2004). The analysis was performed using a GC-μECD and an automated headspace sampler (Agilent Technologies G1888 Network Headspace Sampler) system (Gao and Trout, 2006). Upon completion of the experiment, soil samples from each column were taken at 10-cm intervals, and soil water content and residual 1,3-D in the soil were determined. Soils were extracted at 1:1 solvent/soil ratio (8 mL ethyl acetate: 8 g oven dry equivalent) as presented in Guo et al. (2003). Soil extracts were analyzed on the GC-μECD using ethyl acetate as the standard and sample solvent.

Results and Discussion

Soil Water Content

Soil water content in soil columns was determined at the end of experiment, 2 wk after water applications (Fig. 1). Water distribution was relatively uniform throughout the columns for the control with minor loss at the surface and averages of 1.8% (v/v, 32% FC) for the loamy sand, 7.3% (v/v, 31% FC) for the sandy loam, and 7.2% (v/v, 22% FC) for the loam. Water application treatments increased soil water content in the surface layers (e.g., 0–20 cm for the loamy sand and loam soils and 0–30 cm for sandy loamy). The sandy loam soil had more downward movement of water applied, which might be associated with its lower bulk density than the loamy sand soil. Corresponding to the amount of water applied, the high intermittent water seal treatment (9 mm + 3 mm at 12 h + 3 mm at 24 h) resulted in the highest soil water content for each soil, followed by the single water application and the reduced-amount intermittent water application treatments.

In the columns, the surface (0–10 cm) soil always retained the highest soil water content from the water applications. Even for the loamy sand soil, the surface soil in the high intermittent water treatment had a water content of 12.7% (v/v), which was greater than FC (8.6%, v/v). The surface soil water content for the loamy sand soil was reduced to 6.4% (v/v) in the low amount intermittent water application treatment. For the sandy loam and loam soils, the surface soils had a water content of 55 and 58% of their FC values, respectively in the intermittent water seal treatment. The loamy sand surface soil had a similar soil water content as the sandy loam soil which was attributed to its higher bulk density (1.6 vs. 1.4 g cm^{-3} for the other two soils). As a result, the air volume in the loamy sand surface soil was 27% (data not shown) compared to 34% for the sandy loam and 29% for the loam soil for the intermittent water treatment.

Emission Flux

The emission flux of 1,3-D from the column treatments is shown for the loamy sand, sandy loam, and clay loam soils in Fig. 2. Peak emission flux decreases as soil texture becomes finer. For the control treatment, the peak 1,3-D emission from the loamy sand

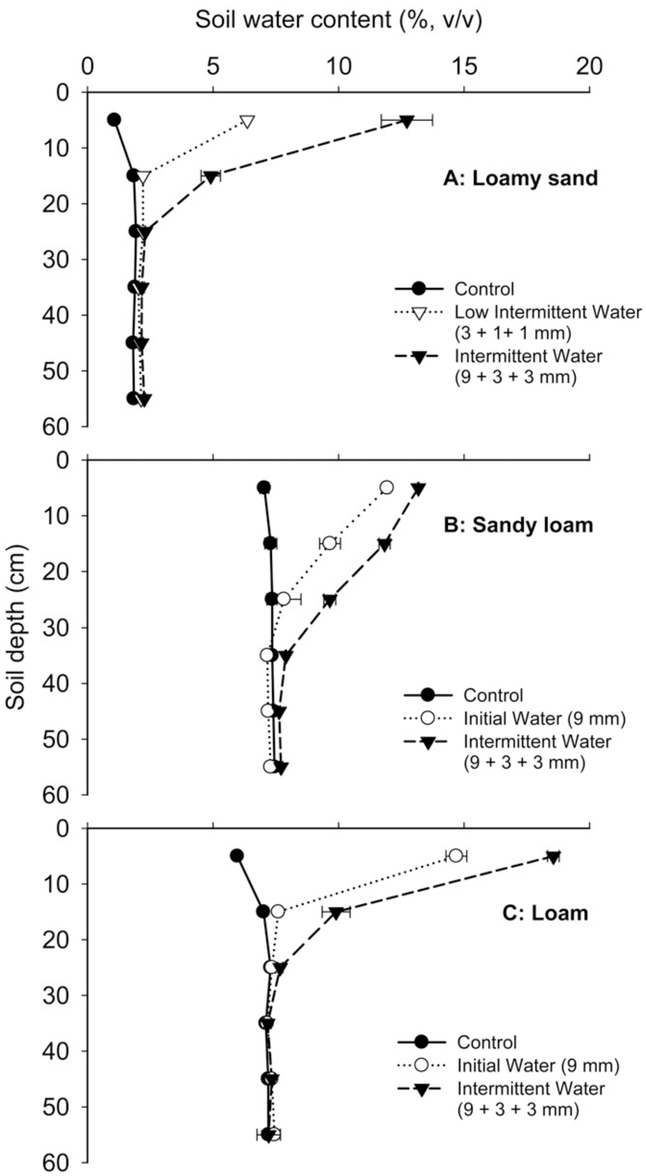

Fig. 1. Distribution of soil water content (%, v/v) with depth determined at the end of the soil column experiment: (A) loamy sand, (B) sandy loam, and (C) loam. Error bars are the standard deviation of duplicate samples.

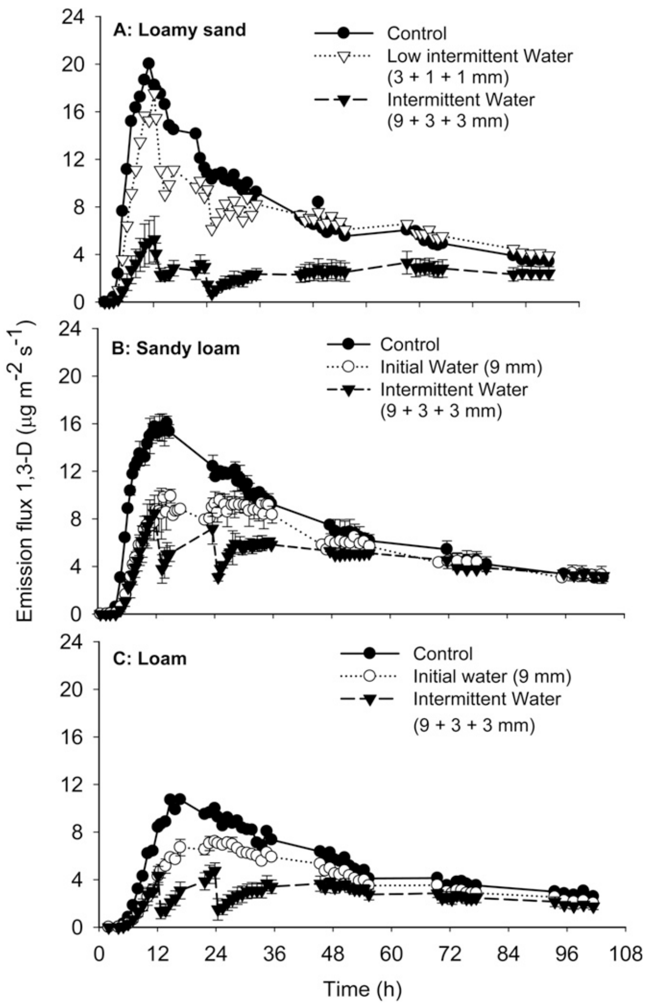

Fig. 2. Comparison of 1,3-D emissions from different soil surface treatments: (A) loamy sand, (B) sandy loam, and (C) loam. Error bars are the standard deviation of duplicate samples.

was 20 μg m^{-2} s^{-1} occurring 11 h after injection, 16 μg m^{-2} s^{-1} at 15 h after injection from the sandy loam, and 11 μg m^{-2} s^{-1} at about 15 h after injection from the loam (Fig. 2). The difference in emission flux for the three soils are likely due to differences in soil texture reflected in the clay content, and to differences in organic matter and soil water content (Fig. 1, Table 1). Both soil water content and organic matter are important factors affecting fumigant degradation and transport. Increasing the soil water content retards soil gas diffusion which can result in reduced emissions from the soil surface. Greater bulk density of the loamy sand compared to the other two soils did not over-ride the effect of its presumably larger primary open pore space between soil particles and its lower soil water content. The loam soil had higher clay and organic matter content which may sorb 1,3-D, thus suppressing the amount of 1,3-D that diffused through the soil and decreasing emission flux.

The peak flux was reduced by about 35% by the initial water seal treatment for both the sandy loam (Fig. 2B) and loam soils (Fig. 2C) as compared to the control. The addition of the initial water seal resulted in delayed peak emission with peak fluxes at 15 h for sandy loam and at 24 h for the loam. Additional 3 mm water applications at 12 and 24 h further suppressed peak 1,3-D emissions by about 55% compared to control for the sandy loam and loam, and about 75% for the loamy sand soils. After the final water application at 24 h, 1,3-D emission rates were stabilized and then gradually decreased with time for all three soils. The reduced-amount intermittent water seal (3 mm at 0 h, and 1 mm at 12 and 24 h) in loamy sand had little influence on emission reductions. Water applied to the loamy sand soil was expected to infiltrate quickly due to large particle size (sands) with larger pores compared to the finer-textures soils with which had more small particle (clays, silts). Thus, it is commonly thought that forming an effective barrier to fumigants with water seals might be difficult in sandy soils. This appeared to be the case for the low amount of intermittent water treatment (3 +1 + 1 mm water). For the high amount of intermittent water treatment (9 + 3 + 3 mm water), however, water applied to the loamy sand soil did not

Table 2. Reduction in 1,3-D cumulative emissions for different treatments and soils expressed as percent reduction.

Soil type	Treatment	Cumulative emissions	Percent emission reductions†	
			48 h	2 wk
		% of applied		
Atwater loamy sand	Control	56	—	—
	Low intermittent water seals (3 mm + 1 mm at 12 and 24h)	52	22	9
	Intermittent water seals (9 mm + 3 mm at 12 and 24h)	26	78	53
Hanford sandy loam	Control	51	—	—
	Water seal (9 mm)	46	25	9
	Intermittent water seals (9 mm + 3 mm at 12 and 24h)	41	49	19
Madera loam	Control	43	—	—
	Water seal (9 mm)	31	28	27
	Intermittent water seals (9 mm + 3 mm at 12 and 24h)	21	59	50

† Percent reduction in 1,3-D emissions was determined using the cumulative emission flux measured at 48 h and 2 wk and is expressed relative to the control treatment.

demonstrate significant downward movement in soil columns as most of the water was retained in the 0- to 20-cm soil layer (Fig. 1). Significantly lower emission rates were observed in the high-amount intermittent water seal treatment. The high surface soil water content and low air-filled porosity likely contributed to the significantly lower emissions. All surface treatments had similar emission rates beyond 108 h in this study and decreased to 0.0 to 0.3 μg m^{-2} s^{-1} by 2 wk after fumigant injection (data not shown).

Cumulative Emissions Loss

Table 2 shows the total emission losses of 1,3-D and comparisons of treatments in emission reductions. Within a treatment, emission losses usually were higher in the coarse textured soil compared to fine textured soil. An exception was for the loamy sand with higher amount of water seals which had similar emission reductions (53% reductions for 2-wk measurement) as the loam soil due to the high surface soil water content and low porosity as discussed above. Compared to the control, the intermittent water seal treatment reduced cumulative emission loss by about 50% in the loam soil and 20% in the sandy loam soil. The higher porosity in the sandy loam soil (34%) compared to the other soils (27–29%) explains the reduced effect of intermittent water treatments on 1,3-D emission reductions in the sandy loam. These results indicate that, although water seals are more effective in the finer textured soil, with sufficient amounts of water intermittent water seals can also reduce emissions in coarser-textured soil. Comparing cumulative emission losses as percent of the control, emission reductions for the first 2 d following water applications were greater than the whole 2-wk monitoring period (Table 2). Similar results were also observed in a field test (Gao et al., 2008) indicating that water seals can be important in protecting workers and bystanders from acute exposure following fumigant injection.

Soil-Gas Phase and Residual 1,3-D in Soils

The distribution of 1,3-D in the soil-gas phase over time is shown in Fig. 3. The greatest concentration of 1,3-D at the first sampling time (3 h) was near the injection depth (30 cm). The

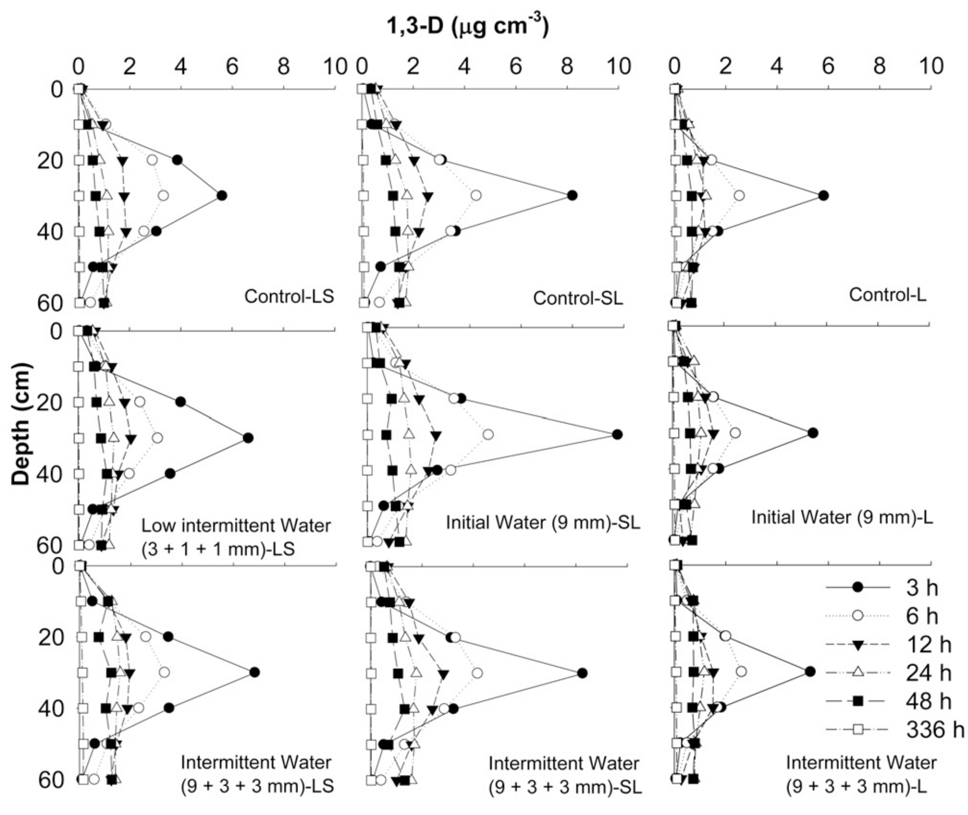

Fig. 3. Soil gas phase distribution of 1,3-D under different surface treatments. LS = loamy sand, SL = sandy loam, L = loam.

fumigant redistributed quickly in the columns and a relatively uniform 1,3-D distribution in the columns of <2 μg cm^{-3} was established within 24 h. Differences in fumigant concentration in the soil-gas phase were greater between the soils than between treatments within a soil. The loam soil had about 10 to 20% lower fumigant concentrations compared to the other two soils. The relatively higher clay and organic matter content in the loam soil may have contributed to faster fumigant degradation. Upon completion of the experiment (2 wk), the soil gas-phase concentrations were 0.1 to 0.2 μg cm^{-3} for loamy sand and loam and 0 to 0.01 μg cm^{-3} for sandy loam.

Water seal treatments did not reduce fumigant concentrations in the soil-gas phase in these three soils. Similar results were observed in other cases (e.g., Gao and Trout, 2006; Gao et al., 2008; Thomas et al., 2003, 2004) when emission was reduced from increasing soil water content, fumigant concentration in the soil air was not affected. Upon water application, soil water content increases mostly in surface layers. This high surface soil water content can retain fumigant in the soil profile and reduce fumigant diffusion or transport from soil to surface air resulting in reduced emissions. Although the water applications did not affect fumigant distribution or significantly reduce its concentrations in any of the soils, past studies have indicated that too much water can reduce fumigant efficacy (McKenry and Thomason, 1974). Thus, the amount of water used in surface seals must balance emission reductions against efficacy reduction.

Residual 1,3-D in the soil (solid) and liquid phases was measured at the end of the experiment (Fig. 4). Although residual 1,3-D was low in all soils, concentration tended to be highest in the fine texture soil, likely because of higher residence time in soils and also increased binding to clay and organic matter particles (Gan et al., 1994; Kim et al., 2003; Xu et al., 2003).

Fate of 1,3-D

The degradation of 1,3-D in soil columns was calculated by subtracting cumulative emissions, fumigant in soil gas after 14 d, and residual fumigant in solid/liquid phase from the total amount (122 mg per column) of 1,3-D initially applied (Table 3). Because residual amounts were small, calculated degradation was inversely related to the cumulative emissions from each treatment. Over 2 wk, 42 to 75% of the 1,3-D applied was degraded in the three soils. Higher volume water applications led to longer retention time in the soil and resulted in greater fumigant degradation which was also observed in previous column studies (Gao and Trout, 2006). Increasing soil water content alone did not appear to affect the degradation rate of 1,3-D in batch incubation experiment (Dungan et al., 2001). The higher degradation rate in the column experiments were due to the high surface soil water content that reduced emissions and retained fumigants in soil profile. Fumigant degradation was generally greater in fine textured soil compared to coarse textured soil except the higher water seal in the sandy loam soil which also had relatively high degradation. The fate of 1,3-D in soils appear to be affected by a combination of factors including soil texture and bulk density, soil water content, and organic matter content.

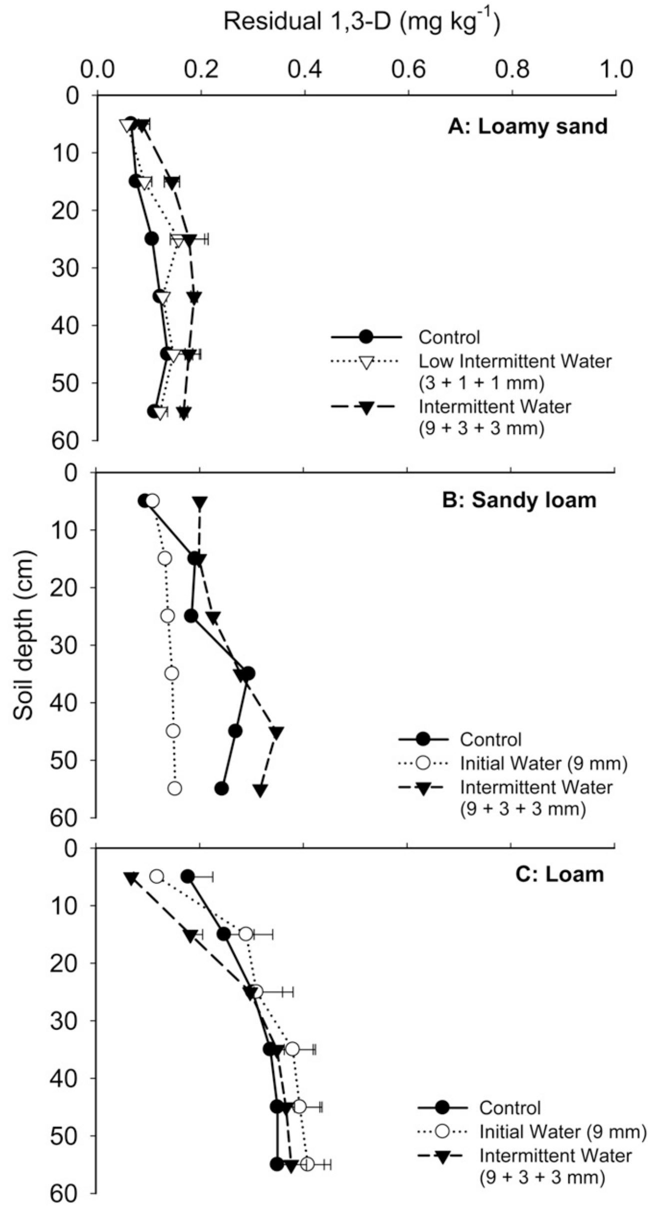

Fig. 4. Residual 1,3-D concentration with soil depth: (A) loamy sand, (B) sandy loam, (C) loam. Error bars are the standard deviation of duplicate samples.

Conclusions

Difference in soil texture and water seal applications to the soil surface greatly affected 1,3-D emissions. The highest cumulative emissions as well as earlier and higher 1,3-D peak emission fluxes were in coarse-textured loamy sand soils when no water seal was applied. Lower emissions in the fine-textured soils were likely due to higher clay, organic matter and soil water content. Fine-textured soil (e.g., loam) generally had slower diffusion and more residual 1,3-D compared to coarse texture soil (e.g., loamy sand) at similar soil water conditions. Findings from this study showed that applying a sufficient amount of water to the soil surface can effectively reduce emissions for a relatively wide range of soil textures. Regulating the amount of water applied to surface soils is essential for ensuring adequate

Table 3. Fate of 1,3-D 2 wk after injection into soil columns.

Soil type	Treatment	Cumulative emission†	Solid/liquid phase†	Gas phase†	Degraded‡
		% of applied§			
Atwater loamy sand	Control	56.4 (0)	1.6 (0)	0.12 (0)	41.9
	Low intermittent water seals (3 mm + 1 mm at 12 and 24 h)	51.5	1.8	0.1	46.6
	Intermittent water seals (9 mm + 3 mm at 12 and 24 h)	26.3 (5.9)	2.3 (0.1)	0.39 (0)	71.0
Hanford sandy loam	Control	50.6 (1.6)	3.3 (1.6)	0.08 (0.11)	46.0
	Water seal (9 mm)	46.1 (1.1)	2.6 (0.5)	0.02 (0.03)	51.2
	Intermittent water seals (9 mm + 3 mm at 12 and 24 h)	41.1 (3.8)	3.4 (1.4)	0.16 (0.14)	55.3
Madera loam	Control	42.7 (0)	4.8 (0)	0.25 (0)	52.3
	Water seal (9 mm)	31.0 (0.2)	4.3 (0.4)	0.25 (0.03)	64.5
	Intermittent water seals (9 mm + 3 mm at 12 and 24 h)	21.3 (3.6)	3.7 (0.1)	0.26 (0)	74.8

† Measured.

‡ Calculated by difference of measured values and applied amounts.

§ Values in parentheses are the standard deviation of duplicate column measurements.

fumigant efficacy while reducing fumigant emissions. While the amount of water used in the column studies may not necessarily represent the effective amount of water needed in field conditions, these results provide valuable data for future field tests of water seal practices to effectively minimize fumigant emissions in different soil types.

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