Using TIF Tarp and Reduced Fumigation Rates for Almond Replanting

Project No.: **13-AIR5-Gao/Doll**

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Objectives:

1) Demonstrate that the use of totally impermeable film (TIF) tarp can improve fumigant distribution in soil and increase fumigant concentration-time exposure index values for better pest control than standard polyethylene (PE) tarp in orchard replanting field fumigation.

2) Evaluate pest control efficacy (nematodes, pathogens and/or weeds) under TIF tarp and reduced fumigation rates.

3) Monitor almond tree vigor and growth from different fumigation treatments in fumigated growers' fields.

4) Determine the effective field fumigation rates under TIF tarp with regards to soil-borne pest control and almond tree performance.

Interpretive Summary:

Pre-plant soil fumigation is still one of the most effective tools to control soil-borne pests and diseases for establishing productive and healthy trees in almond replanting orchards. With the environmental constraints on fumigant use, our research has been focusing on developing fumigation methods that achieve high pest control efficiency, low emission loss, and/or use less fumigants. After a field fumigation trial was conducted from November 2012-January 2013 in Merced County, almond trees were

planted in February 2013. Tree growth has been monitored since March 2013 through May 2014 and nematode recovery was also determined in the fumigated field for about a year after fumigation. Fumigation treatments included non-fumigated control and three rates (full or maximum allowed label rate, 2/3 (66%), and 1/3 (33%)) of Telone® C35 under three surface sealing methods [bare or no tarp, standard PE tarp, and TIF). During the fumigation trial, nematode and pathogen efficacy, fumigant movement including emissions, and gaseous fumigant concentration changes under the tarp and in soil profiles were monitored. Some of the findings were reported in the previous annual report; thus will not be repeated in this report. They can be seen online at Almonds.com/ResearchDatabase by searching 12-AIR5. This report includes the major findings with pest control from fumigation, tree growth, and nematode recovery after fumigation and tree planting. Tree growth data indicate that all fumigation treatments improved tree growth significantly within the first year compared to the non-fumigated controls (tarped and non-tarped), but the differences were reduced over time based on measurements in the second year. Nematode recovery in soil after 12 months of fumigation was slow, which is shown by low population; however the data also showed random effects in all treated plots, i.e., no evident differences among treatments. Free-living nematodes (that are not harmful to trees) populations were the highest.

Another field fumigation trial was carried out in summer 2013 at USDA-ARS, Parlier, to explore the potential of carbonated fumigants (dissolving carbon dioxide into fumigant) to improve fumigant movement to deeper soils to improve efficacy and extension of TIF tarp to reduce off-edge emission loss. This idea was based on previous field data that most fumigated treatments at or above 2/3 of full rate provided 100% kill for residential nematodes in the soil above 1 m depth. However, all treatments including the full rate under TIF showed survival of nematodes in soil below 1 m depth due to less fumigant delivered to the deeper depths. As carbonation of fumigants had shown improved fumigant diffusion and efficacy in soil fumigation for annual crops, the trial was to test the potential for the improvement for perennials. High emissions from off-TIF tarp edges were determined in earlier trials from shallow injection and the trial evaluated the possibility to use extended tarp width to reduce the off-tarp edge emissions. The field data indicate that carbonation of fumigant to improve fumigant delivery to deep soil requires more field tests on carbonation condition, application method, and injection depth. An extension of 60 cm TIF tarping appeared to significantly cut down the off-tarp edge emissions although confirmation is also needed in future field tests.

Materials and Methods:

2012-2013 fumigation trial in Merced

<u>Fumigation trial and treatment.</u> A fumigation trial was conducted in a replanting almond orchard at Bluff Ranch of Braden's Farm, about 13 miles northeast of Merced from November 29, 2012 through January 12, 2013. Prior to fumigation, almond trees in this field were pulled out following harvest and the soil was prepared by the grower for fumigation. Telone® C35 (35% CP, 63% 1,3-D, and 2% other ingredients) was used in this trial. Fumigation treatments included non-fumigated control and three rates (full or

maximum allowed label rate, 2/3, and 1/3 of Telone® C35) under three surface sealing methods (bare, standard PE, and TIF) and three application rates (full or 100% rate; 66% rate, and 33% rate) of Telone® C35. Total 12 treatments with 6 replicates were applied in a randomized complete block design. During fumigation trial, three replicated blocks were monitored for efficacy on nematode and pathogens, and fumigant movement including emissions, gaseous fumigant concentration changes under the tarp and in soil profiles. Some of the findings were reported in the 2013 annual report to Almond Board and will not be repeated in this report.

<u>Fumigation efficacy, nematode recovery, and tree growth monitoring.</u> Soil samples down to 1.5 m (5 ft) depth at 30 cm increment were collected before and after fumigant application to determine nematode efficacy. Prior to fumigant injection, five auger samples were collected across the field. About 6 weeks after fumigation, soil samples were collected at the same depths as before fumigation from each plot of three blocks to determine residential nematode survival. Surface soils were collected after fumigation to determine pathogen populations and compared treatment differences.

About one year after fumigation, nematode recovery in the soil was determined. Soil samples from 40-50 cm (16-20 in) depth from all treated plots (i.e., 6 replicates) were collected late October 2013. The soils were extracted on December 15, 2013 for live nematode counting. Five hundred grams of soil samples were used for extractions of all possible plant parasitic nematodes using sieving and centrifugation methods (Jenkins, 1964). Live nematodes in each sample were identified and counted under a microscope (Mai and Lyon, 1975). Reported is the number of nematodes per 100 g soil.

After the fumigation trial, almond trees were planted in February 2013. All six replicated plots were monitored for almond tree growth. Tree diameters were measured three times: March 8, 2013 (initial measurement following tree planting), December 15, 2013, and March 9, 2014. Statistical analysis on all efficacy and tree growth data were performed using two way ANOVA and means separation were performed using Tukey's procedure with an alpha level of 0.05.

2013 Field Trial at USDA-ARS, Parlier

A field fumigation trial was conducted in a Hanford sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Typic Xerorthents) during May 16-June 19, 2013. The main purpose of this trial was to evaluate the potential of carbonated fumigants (dissolving carbon dioxide into fumigant) to improve fumigant movement to deeper soils and extension of TIF tarp to reduce off-edge emission loss. This trial was based on previous field data that showed even at the full rate of fumigant under TIF, there was poor nematode control in soil below 1 m depth. The low fumigant concentrations in the deeper soil suggest that there is insufficient movement of fumigant. Research has shown that carbonation of fumigants improved fumigant movement in soil fumigation for annual crops in Florida (Thomas et al., 2011) and in California, TIF improved fumigant distribution in surface soil of strawberry field (Qin et al., 2011), but no data have clearly shown the potential benefits for perennials. High emissions from off-TIF tarp edges were also a concern and the possibility to use extended tarp width to reduce the off-tarp edge emissions was tested.

Treatments tested in the field trial included non-fumigated control, full rate (48 gallons per acre or 610 kg ha^{-1}) of regular [nitrogen (N_2) pressurized] Telone® C35, full rate and 2/3 (407 kg ha^{-1}) rate of carbonated Telone® C35, in either bare soil or under PE tarp and TIF. Selected treatments were monitored for emissions and fumigant movement. The full rate with regular fumigant was applied at 113% of the target rate; the 2/3 carbonated rate was actually 87% of full rate; and the full carbonated rate was on the target. The carbonated fumigant was prepared under a pressure of 50 psi overnight following the procedure of Thomas et al. (2011). The final CO_2 dissolved in fumigants was 1.51% (w/w). In the trial, the carbonated fumigant was applied by pressurized nitrogen gas, which is different from the procedure recommended by Thomas et al. (2011) to use CO_2 as the pressurization agent. The fumigants were injected 46 cm (18 in) deep with a conventional Telone rig with shanks spaced 51 cm. The PE film or TIF was installed over the soil immediately following fumigant application. Under regular tarping conditions, the tarp edge was about 25 cm from the last shank (injection) line. We assumed that the carbonated fumigant could diffuse faster than the regular N_2 pressured fumigant, which may result in high off-tarp emissions. Thus, carbonated fumigant treatments were selected for monitoring off edge emissions. An additional 60 cm tarp extension was applied to the plots with carbonated fumigant at 2/3 rate to measure off-tarp edge emission. A full rate treatment was also monitored for off-tarp edge emissions. Emission sampling was done and flux was estimated using dynamic flow-through chamber method previous described (Gao and Wang, 2011). In addition, fumigant concentration changes or movement under the tarp and in soil was monitored to explain or support emission data using previous described methods (Gao et al., 2009).

Results and Discussion:

2012-2013 Fumigation Trial in Bluff Ranch, Merced

Nematode and pathogen control during fumigation trial. The field was infested with several plant parasitic nematodes with high populations of pin nematodes (150-660 per 100 cc soil) and low populations of ring nematodes (6-210 per 100 cc soil). Six weeks after fumigant application, Telone® C35 treatments with full and 66% rate under both PE and TIF provided 100% kill at all soil depths above 1 m. Nematode survival were detected in surface bare soil at full rate and all soil depths at 66% rate bare soil. Below 1 m soil depth, nematode survival was detected for all treatments including the TIF full rate although population was low. More survivals were found at 33% rates in soil profile compared to the higher rates. Fumigant data showed decreased concentrations at lower soil depths suggesting that the low efficacy was due to insufficient fumigant diffusion to the deeper soil. These data indicate that it is a great challenge to effectively control nematode at depth below 1 m in the orchard. Similar observation was made in an earlier field trial conducted in 2011. Detailed information about the nematode control during fumigation trial can be found in the 2013 annual report to Almond Board.

Pathogen control in fumigation trial**.** Pathogen analysis data from soil samples collected six weeks after the fumigant injection were shown in **Table 1**. Four species of pathogens were investigated in this study: *Fusarium, Phytophthora, Pythium,* and *Verticillium*. The population of *Fusarium* and *Pythium* appear much higher than for *Verticillium* and *Phytophthora*. Although the full rate (100%) displayed lower populations than other treatments, statistical analyses indicate that the fumigation treatments do not have significant control of the pathogen populations. Large field variability and non-uniform distribution of the pests were observed. This shows that pathogen control in the perennial field is difficult with the alternative fumigants to methyl bromide. Fortunately, pathogen problem is less critical than nematodes in causing damage for almonds. If pathogens will become emerging problems for some crops, these data will help better understand of the nature of the problem in searching for solutions.

Nematode recovery after fumigation. Nematode populations in soils sampled about a year after fumigation for all 12 treatments and 6 replicates are shown in **Table 2**. The data indicate how nematode species were recovering over time after fumigation treatments. In comparison with nematode population before fumigation when pin nematodes was ≥150 per 100 cc (roughly 100 g) in all soil depths, the pin nematode population was substantially low (4 counts per 500 g soil), with similar observation for ring nematodes. Samples collected immediately after fumigant application (6 weeks after fumigant was injected to soil) indicated good control of all the nematodes in soils above 1 m depth although significant survivals were observed in soils below 1 m depth. **Table 2** data indicate that most of the parasitic nematode populations were low with relatively higher ring nematode population, but this field had uneven distribution of ring nematodes in the soils. In almost all the cases, the live nematodes were detected in only 1 or 2 plots out of 6 and most of the field plots were found without live nematodes. The group of free-living nematodes, considered non-harmful to trees, was the highest. All the data indicate that ring nematodes may be difficult to control. The 2013 report showed that ring nematodes are sporadic with highest population at soils below 1 m depth, indicating the greatest challenge to control.

Tree performances from fumigation treatment. Tree growth data monitored following planting are shown in **Table 3**. There were no significant differences in tree diameter following tree planting (measurement on March 8, 2013). After ten months (measurement on December 15, 2013), there were significant differences in tree growth between fumigated treatments and the non-fumigated control. All fumigated treatments regardless of rate and tarp, had significantly improved tree growth compared to the non-fumigated controls. Among the fumigated treatments, there were no significant differences in tree growth although there is a clear trend that trees performed better with increased fumigation rates. After 14 months (measurement on May 9, 2014), however, only the 100% rate under PE tarp or TIF showed significant improvement in tree growth than the non-fumigated control in bare soils and there were no significant difference among all other treatments. These data confirm that fumigation improves tree establishment and performance, especially in fields infested with nematodes. Whether this benefit is long term will need further continuous monitoring of the tree performance and yield .

Table 1. Pathogen control from fumigation treatments in 2012-2013 field trial in Bluff Ranch, Merced, CA.

Treatment	*Verticillium*	*Fusarium*[a]	*Pythium*	*Phytophthora*
		(CFU g^{-1} soil)		
0% No tarp	11.3	11151.5 b	2685.3	1076.6
0% PE	2.0	24945.8 ab	7517.3	160.6
0% TIF	28.0	23854.7 ab	3512.0	4.0
100% No tarp	166.0	649.9 b	677.3	386.0
100% PE	2.0	2613.0 b	2813.3	636.6
33% TIF	0.0	38841.6 a	11608.0	668.6
66% No tarp	11.3	2814.0 b	11717.3	740.0
66% PE	0.0	16274.8 ab	12473.3	973.3
66% TIF	116.6	6536.8 b	10388.0	195.3

[a] Different letters in the same column for *Fusarium* indicate significance at P<0.05. No significant differences among the treatments were determined for other three species.

Table 2. Nematode counts after one year of fumigation in Bluff Ranch, Merced, CA.

Treatment (Rate of Telone® C35 & Tarp)	Root Knot	Ring	Lesion	Stubby Root	Pin	Free-Living
			No. per 100 g soil			
100% No tarp	0	0.13	0	0	0.1	3.6
100% PE	0	0	0	0	0	12.7
100% TIF	0	7.7	0	0	0.8	10.4
66% No tarp	0	0.4	0	0	0	27.4
66% PE	0	1.1	0	0.1	0.1	8.7
66% TIF	0	0.1	0	0	0	7.2
33% No tarp	0	0.4	0	0.1	0	5.4
33% PE	0	0	0	0	0	23.6
33% TIF	0	5.3	0	0	0	9.0
0% No tarp	0	0.8	0	0.2	0	2.3
0% PE	0	3.9	16	0	0.8	2.3
0% TIF	0	6.0	0	0	0.8	3.8

Table 3. Tree diameter measurement following tree planting after fumigation treatments in Bluff Ranch, Merced, CA.

Treatment (Rate & Tarp)	Tree diameter[a] (mm)		
	3/8/2013	12/15/2013	5/9/2014
100% No Tarp	11.4	46.3 a	57.6 a
100% PE	10.6	46.2 a	57.1 a
100% TIF	10.8	45.6 a	56.2 ab
66% No Tarp	11.2	44.1 ab	55.5 ab
66% PE	11.0	45.5 a	53.8 ab
66% TIF	11.6	45.7 a	54.9 ab
33% No Tarp	11.1	43.2 abc	55.0 ab
33% PE	11.1	43.8 ab	55.4 ab
33% TIF	11.4	43.1 abc	53.7 ab
0% No Tarp	10.8	37.6 d	47.7 b
0% PE	11.0	39.3 bcd	50.0 ab
0% TIF	10.4	38.2 dc	48.9 ab

[a] Different letters in the same column indicate significance at $P<0.05$.

2013 Summer Field Trial in USDA-ARS, Parlier

<u>Effect of tarp extension on off-tarp edge fumigant emissions.</u> The off-tarp edge fumigant emission flux in the TIF tarped plot fumigated with carbonated fumigant at full and 2/3 rates are plotted in **Figure 1**. No measurement was made on the tarp because several trials have shown extremely low emissions from TIF tarped areas (e.g., Gao et al., 2013). In the summer 2013 trial, the full rate plots were tarped with regular width, i.e., the buried tarp edge was 25 cm off the last injection line. The 2/3 rate plots were tarped with additional 60 cm tarp width. Much higher 1,3-D emission flux along the tarp edges was measured from the full rate with regular tarp width than the 2/3 rate with extension of tarp width. Chloropicrin (CP) emissions were generally an order of magnitude lower than 1,3-D, and also the differences in CP emission flux between the full rate and the 2/3 rate were much smaller than 1,3-D, which implies possible differences in CO_2 ability to enhance fumigant diffusion between the two compounds. From the full rate with the regular tarp width, the peak value 3.98 $\mu g\ m^{-2}\ s^{-1}$ for 1,3-D occurred at 3.4 d after fumigant application and for CP was 0.05 $\mu g\ m^{-2}\ s^{-1}$. Estimated total emission loss from the edge was 2.17% of applied 1,3-D and 0.03% of applied CP to the plot over the 15 d monitoring period. For the 2/3 rate with additional 60 cm tarp extension, the peak flux was 0.60 $\mu g\ m^{-2}\ s^{-1}$ for 1,3-D occurred at 4.6 d and 0.03 $\mu g\ m^{-2}\ s^{-1}$ for CP. The estimated total emission loss was 0.44% and 0.02% of total applied 1,3-D and CP, respectively. Generally speaking, emissions from the 2/3 rates were much lower due to two possible reasons, extension of the tarp and the reduced rates. How each factor contributed to emission reductions needs to be further quantified in field.

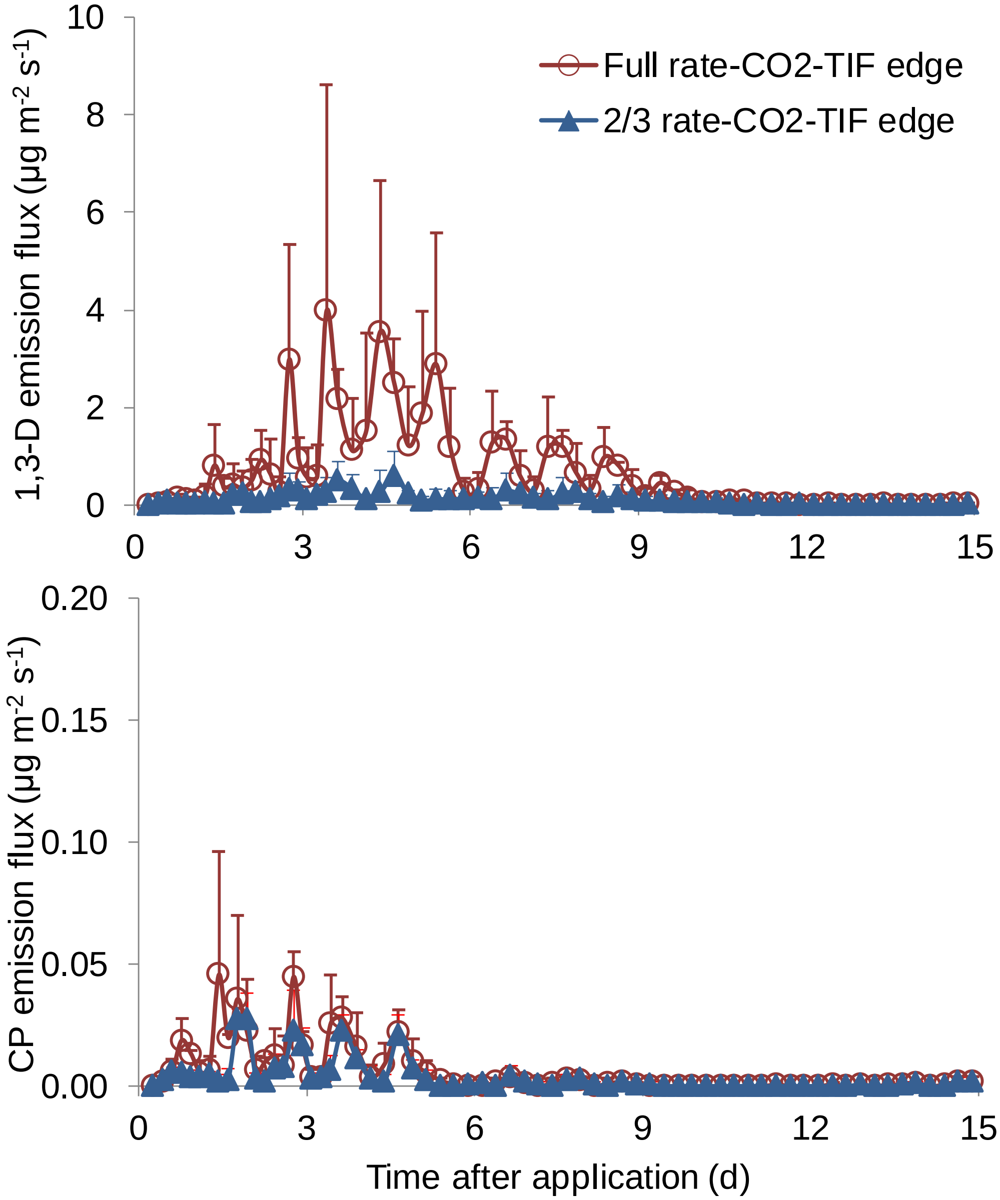

Figure 1. Emission flux of 1,3-dichloropropene (1,3-D) and chloropicrin (CP) immediately off the TIF tarp edge with full and 2/3 rates of carbonated Telone® C35. The full rate treated plots were tarped with regular width (buried edge was 25 cm from the last injection line) and the 2/3 rate plots were tarped with additional 60 cm width. Plotted are averages of three replicates.

Although the off-tarp edge emissions of 1,3-D were high at the full rate with regular tarping width, the flux values were much lower than when Pic-Clor 60 (about 40% 1,3-D and 60% CP) was applied to a shallower depth (30 cm) at 660 kg ha^{-1} (Gao et al., 2013). The peak flux measured in the earlier study was up to 440 μg m^{-2} s^{-1} for 1,3-D immediately off the tarp edge. However, the peak flux decreased significantly with distance and peak flux was reduced to 0.5 μg m^{-2} s^{-1} at 2 m from the tarp edge. All the data suggest that the deeper injection (46 cm deep) in soil fumigation to some extent may have reduced the off-tarp edge emissions (see 2013 annual report to Almond Board for measurements made in the Merced field trial) compared to injection at 30 cm depth. The extension of 60 cm tarp ensures further emission reductions along the tarp edges.

Fumigant concentration under tarp. Figure 2 shows fumigant concentration changes over time under plastic tarp (above soil surface). Under the same application rate and method, TIF retained much higher concentrations than standard PE film with similar peak time observed in two days. Under the PE, the peak value was 2.2, and 1.0 μg cm^{-3} for 1,3-D, and CP, respectively at the full-rate of regular (N_2 pressurized) fumigant. Similar 1,3-D concentrations were observed when the fumigant was carbonated except much lower CP concentrations (peak value of 0.5 μg cm^{-3}). Averaging over the whole monitoring period, 1,3-D concentration was similar between the regular and the carbonated fumigants but CP concentration from the carbonated was about a third of that from the regular fumigant. When the application rate was reduced to 2/3 rate, the fumigant concentration under PE did not reduce proportionally in comparison with the full rate carbonated fumigant applied under PE. This can be caused by high emissions through the PE film.

TIF retained fumigant concentrations often twice or higher than PE. The peak fumigant concentrations were 4.8, and 1.8 μg cm^{-3} for 1,3-D, and CP, respectively at the full rate of regular fumigants under TIF. At the full rate of carbonated fumigants, the concentration of 1,3-D was even higher (peak 5.7 μg cm^{-3}) but the CP concentration dropped to 1.0 μg cm^{-3}. The average 1,3-D concentration over the monitoring period was similar regardless carbonation while CP from carbonated fumigants appeared to be half of the regular fumigant applied. When the application rate was reduced to 2/3 rate, the 1,3-D concentration was reduced in proportion or more (~50% for 1,3-D and 20% for CP of those at the full rate). Dissipation including degradation is the major contribution factor to the fumigant concentration decrease because of the effectiveness of TIF to retain fumigants.

Fumigant distribution in soil profile. There were no significant differences in fumigant concentrations in soil profile between the carbonated and regular fumigants applied at the full rate under TIF (**Figure 3**). Similar fumigant distribution patterns were observed in all the tested plots with the highest concentration occurred near the injection depths (46 cm). The maximum concentration was 30 μg cm^{-3} for 1,3-D occurred at 5 h and 18 μg cm^{-3} for CP occurred at 10 h after application at the full rate regular fumigant (**Figure 3a,c**). The carbonated fumigants did not show significant improvement on fumigant distribution, at least initially, although by Day 3 or later, there appeared to be a more uniform distribution of 1,3-D, but with lower CP concentrations in the carbonated fumigant plots compared to the regular fumigants. It should be noted that carbonation procedure in this trial did not meet the recommended conditions by Thomas et al. (2011). During application of carbonated fumigants, it is recommended to use carbon dioxide to pressurize the cylinder to deliver fumigants to soil. Due to equipment limitations, regular nitrogen gas was used to apply the fumigants. Thus, determining whether or how carbonation can improve fumigant distribution in soil profile for perennial crops relies on further investigations.

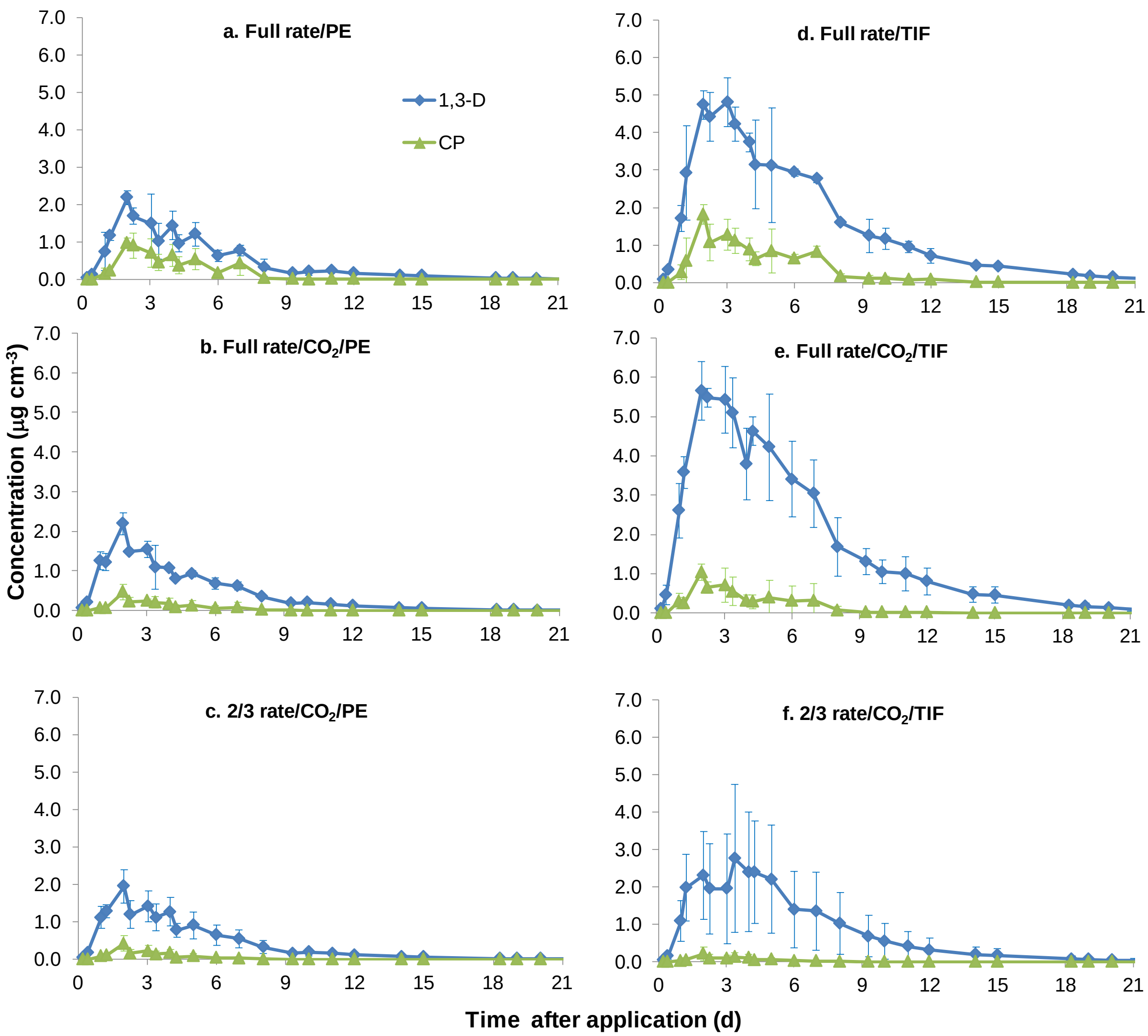

Figure 2. 1,3-Dichloropropene (1,3-D) and chloropicrin (CP) concentrations in air under tarp (above soil surface) after fumigant application. Plotted are averages of three replicates.

Figure 4 shows 1,3-D concentrations in soil profile at various locations: center of the plot and near the edge of a fumigated plot at the full rate with regular TIF tarping width or at the 2/3 rate with an extension of 60 cm tarp width. Chloropicrin concentration changes were similar to 1,3-D except with lower values (data not shown). At the edge of the full rate plots, the fumigant concentration showed the maximum 1.4 and 0.6 $\mu g\ cm^{-3}$ for 1,3-D and CP, respectively 3 d after application. The average concentration at the edge was <10% of that at the center (refer to **Figure 3b,d**). At the 2/3 rate of carbonated fumigant, the maximum concentrations were 14.8 and 10.5 μg cm^{-3} for 1,3-C and CP respectively, which is in proportion to that at the full rate (**Figure 4**). At 25 cm from the last injection line under the tarp, the highest concentrations were measured about 24 h after fumigant application with a value of 5.0 and 2.9 μg cm^{-3} for 1,3-D and CP, respectively (**Figure 4d**). Note these values were higher than that from the full rate with regular tarp width 25 cm (**Figure 4b**). With additional 60 cm tarp extension, the highest fumigant concentration was reduced to only 0.6 and 0.2 μg cm^{-3} for 1,3-D and CP, respectively. The much lower fumigant concentration at the extended tarp edge than the regular tarped edge can explain the much lower off-tarp edge emission measured (**Figure 1**).

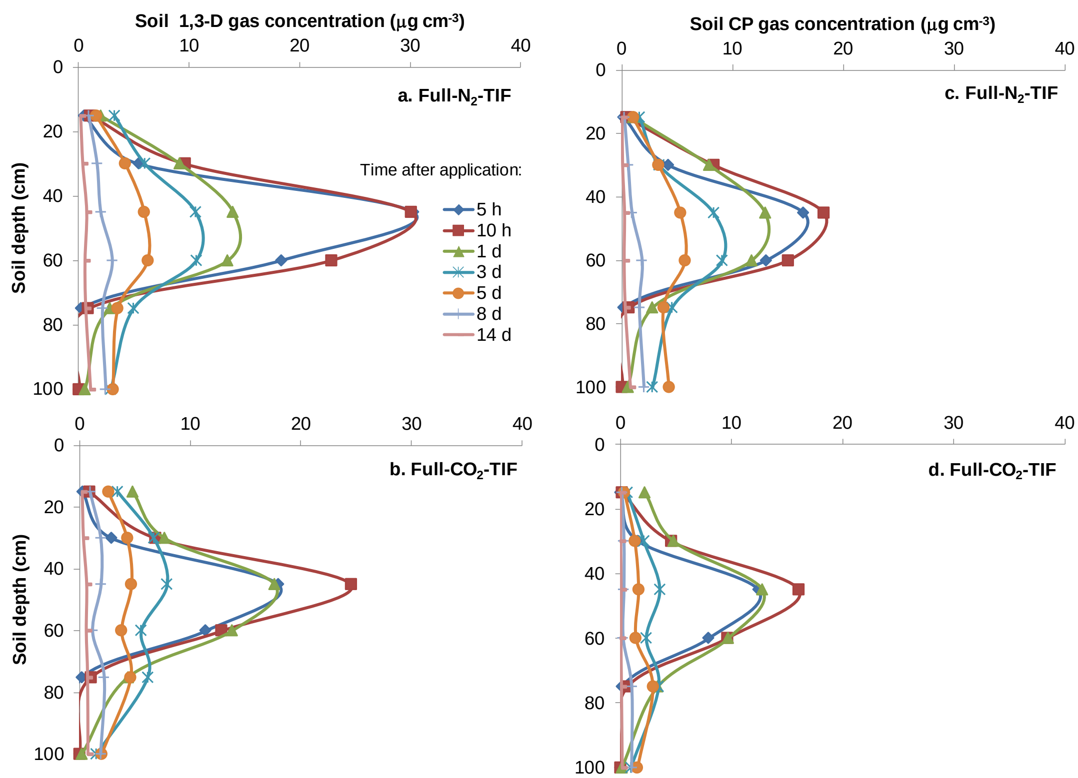

Figure 3. 1,3-Dichloropropene concentrations (a and b) and chloropicrin (c and d) in soil-gas phase from full rate of regular and carbonated Telone® C35. The full rate of regular fumigant was applied 13% over its target rate and after taking this into consideration, there appear no differences in initial soil fumigant concentrations between the carbonated and regular fumigants applied. Plotted are averages of three replicates. Error bars are omitted for readability.

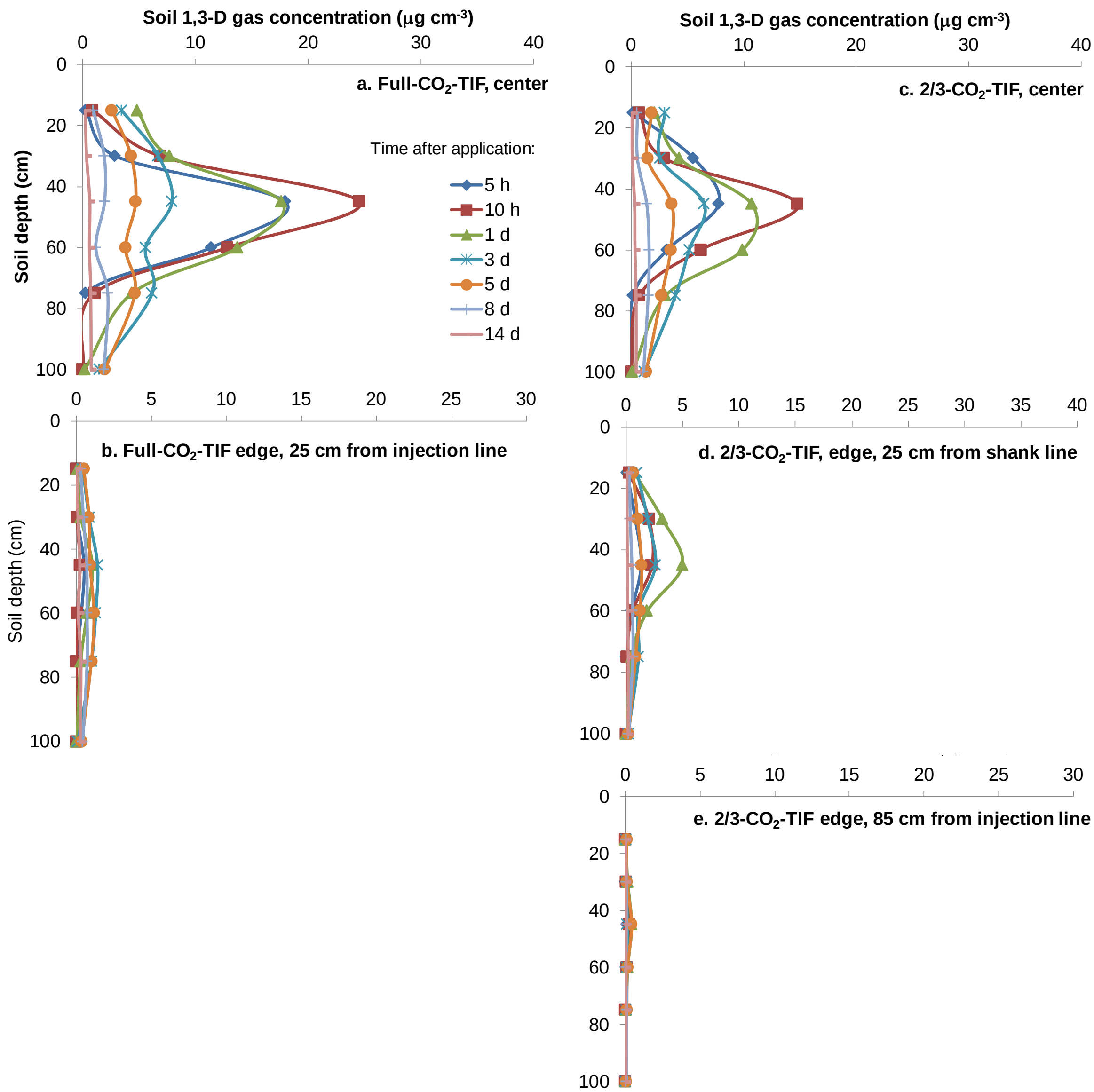

Figure 4. 1,3-Dichloropropene concentrations in soil-gas phase in various locations: center of the plots, 25 cm from the last shank line (regular tarp edge) and extension of 60 cm tarping edge from the 2/3 rate carbonated Telone® C35. Plotted are averages of three replicates. Error bars are omitted for readability.

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Research Effort Recent Publications:

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