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Research article

Deep injection and the potential of biochar to reduce fumigant emissions and effects on nematode control

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ABSTRACT

Reducing fumigant emissions is essential for minimizing the environmental impacts of pre-plant soil fumigation. Low permeability plastic films are effective at reducing emissions but have high initial purchase, installation, and disposal costs. The objective of this study was to evaluate if deep fumigant injection and biochar soil amendments can reduce emissions, improve fumigant distribution in soil, and provide acceptable control of plant parasitic nematodes. A pre-plant soil fumigation trial was conducted in a commercial orchard in the San Joaquin Valley, CA, USA. Treatments included two rates of Telone® C-35 (a mixture of 1,3-dichloropropene and chloropicrin) under totally impermeable film or with no surface seal, two injection depths (45 or 65 cm), and two biochar rates (20 or 40 ton ha^{-1}). Emission rates were generally low due to rain events encountered during the trial, but data clearly showed that the deep injection enhanced fumigant delivery to depths below 60 cm and resulted in significantly lower peak emission compared to the standard injection depth. Biochar applied at 40 ton ha^{-1} had the lowest emission rates during 1-month monitoring period. Although variability in nematode survival was high, tarped, deep injection, and biochar treatment showed lower survival of nematodes at various depths. Increase in fumigant persistence, especially chloropicrin, was observed in this study, likely due to the high soil moisture and low temperature. All data indicate that biochar amendments can help reduce fumigant emissions without reducing nematode control; however, additional research is needed to optimize treatments, determine the affordability of various biochar materials, and validate results under a range of field conditions.

1. Introduction

Soil fumigation continues to play a critical role in orchard replanting, primarily due to vigorous and uniform tree establishment when plant-parasitic nematodes and replanting disease is managed (Radewald et al., 1987; Browne et al., 2006; Gao et al., 2015). The phase-out of methyl bromide (MeBr), due to its contribution to the depletion of the stratosphere ozone, has resulted in wide use of other pre-plant soil fumigants in California, such as 1,3-dichloropropene (1,3-D) and chloropicrin (CP). These alternative fumigants, however, are highly regulated due to their contributions to air quality degradation after emission from the soil to the atmosphere. Federal and state regulatory agencies in the USA continue to develop and amend fumigant regulations to protect people and the environment (CDPR, 2013, 2015; USEPA, 2015), so techniques that reduce fumigant emissions from soil could determine the availability of these pest management options for growers.

Previous studies have shown that low permeability or high-barrier plastic films such as virtually impermeable film (VIF) (Qin et al., 2011; Gao et al., 2014) or totally impermeable film (TIF) (Wang and Yates, 1998) can significantly reduce emission loss, increase fumigant concentrations or residence time in soil, and improve fumigant distribution. As a result, reduced rates (1/2 rate for annual crop such as strawberry and 2/3 rate for perennials such as almonds) can be used to achieve the same efficacy as the full rate applied under standard polyethylene (PE) film or no barrier film (Fennimore and Ajwa, 2011; Gao et al., 2014, 2015). MeBr emissions were managed using relatively inexpensive PE films; however, this material is not as effective for the

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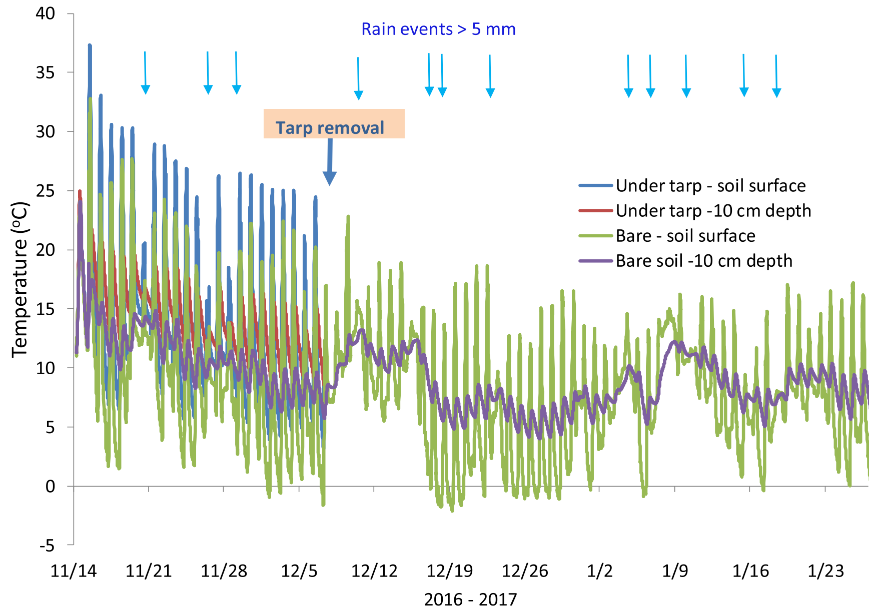

Fig. 1. Soil temperature at 10 cm in a bare plot and a TIF tarped plot during a fumigation trial conducted in fall 2016 near Hughson, CA.

alternative fumigants (Gao et al., 2011). TIF is effective in reducing emissions of 1,3-D and chloropicrin, but is 1.5–2.0 times more expensive than PE film. Recently, soil amended with biochar has shown the potential to reduce fumigant emissions (Wang et al., 2014, 2016) while also eliminating the initial purchase, installation, and disposal costs of plastic films.

Biochar (charcoal produced via pyrolysis of various biomass material) when applied to or incorporated into the soil has been shown to improve soil properties (Glaser et al., 2002; Lehmann and Joseph, 2009), remove or reduce the toxicity of many contaminants including pesticides (Ahmad et al., 2014; Miles et al., 2016), and suppress plant-parasitic nematodes (Huang et al., 2015; George et al., 2016; Cao et al., 2018). Biochar has also been reported to reduce fumigant emissions in lab soil column studies (Wang et al., 2014; Ashworth et al., 2017); however, no information is available on the effects of biochar on fumigant emissions under field conditions. Adsorption and degradation have been determined to be the mechanisms for fumigant dissipation by biochar (Wang et al., 2016).

Surface soils amended with biochar in which soil fumigants are injected below the amended level might simultaneously reduce emissions and increase fumigant residence time in soil due to the greater adsorption than degradation (Wang et al., 2016). Additionally, as a soil amendment, biochar has been shown to improve soil physio/chemical properties such as increased soil cation exchange capacity (CEC) (Glaser et al., 2002), improved soil hydraulic conductivity or soil water holding capacity (Guo, 2016), and improved soil fertility (Igalavithana et al., 2016). Thus in addition to reducing fumigant emission, biochar could provide a number of agricultural and environmental benefits.

A second challenge for the alternative fumigants in orchard replant situations is related to poor distribution deep in the soil profile due to relatively low vapor pressure compared to MeBr (Ajwa et al., 2010). Due to the deep rooting system of trees and vines, plant-parasitic nematodes may be present below 1.5 m or deeper in soil. In California orchard sites, soil fumigants typically are applied at 45 cm depth via straight or winged shanks. However, poor pest control efficacy has been observed below 1 m soil depth (Gao et al., 2014, 2015) due to the much lower concentrations or non-uniform distribution at those depths. Fumigant application to soil depths deeper than 45 cm could increase concentrations below 1 m depth and improve nematode control (Gao et al., 2018). The objective of this study was to evaluate if deep fumigant injection and biochar soil amendments can reduce emissions, improve fumigant distribution in soil, and provide acceptable control of plant parasitic nematodes. This research was conducted to provide additional management practices to complement those in the literature and answer the important question if biochar amendment can be an emission reduction strategy in soil fumigation.

2. Materials and methods

2.1. Fumigation trial

A fumigation trial was carried out in late fall of 2016 in an orchard located in Hughson, Stanislaus County, CA after removal of a mature almond orchard. The soil was Hanford sandy loam (Mixed, superactive, nonacid, thermic Typic Xerorthents), with 0–3% slope in the field. More information about the soil type is available at Natural Resources Conservation Service (NRCS) website (https://soilseries.sc.egov.usda.gov/OSD_Docs/H/HANFORD.html). Average daily temperature, humidity, and wind speed were 8.9 °C, 82.5%, and 1.3 $m\ s^{-1}$, respectively.

The cooperating grower removed the old orchard and prepared the site for fumigation and replanting of the orchard using standard practices for the region. After the site was prepared, several Telone® C-35 (34.7% CP, 63.4% 1,3-D, and 1.9% other ingredients) treatment combinations were applied. Properties of 1,3-D and CP, and factors or processes affecting their fate in soil can be found in Ajwa et al. (2010). Treatments included two fumigant injection depths: regular (45 cm) injection depth or a deeper (65 cm) injection depth, two application rates (100% or ~66% of current maximum rate, which is 610 $kg\ ha^{-1}$), two rates of biochar amendment (20 and 40 ton ha^{-1}) at 66% fumigant rate and injected to 65 cm depth, and two surface sealing methods (no tarp or TIF), plus a non-fumigated control. These treatments were tested in two different settings. The injection depths and rate treatments were investigated in large plots with each plot 34.0 m long and 6.4 m wide for planting 8 trees. Limited by the available amount of biochar product, testing the biochar treatment effects were carried out in small plots within the large field with each plot occupying the area of one tree (3.05 m × 3.05 m). The TIF was VaporSafe® (1-mil thickness, clear, Raven Industries, Sioux Falls, SD, USA). CoolTerra® biochar (Cool Planet, Camarillo, CA, USA), was derived 100% from coconut shell feedstock, pyrolyzed at 550 °C, and subjected to a proprietary post-production treatment to neutralize the pH and remove some residual elements. All treatment combinations were tested in a randomized

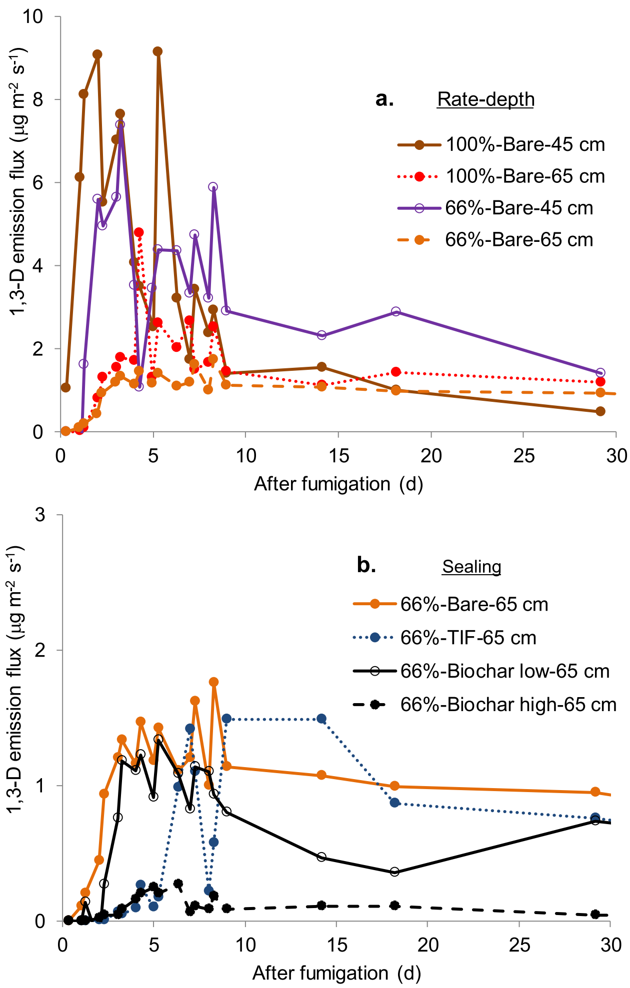

Fig. 2. Emission flux of 1,3-dichloropropene (1,3-D) from (a) regular (45 cm) or deep injection (65 cm) depths and (b) different surface sealing methods. Data after 30 days are not shown and emission became non-detectable from all treatments after 72 days of fumigant injection. Biochar low or high were applied at 20 ton ha^{-1} or 40 ton ha^{-1}, respectively. Error bars are omitted to improve readability.

complete block design with three replicates.

Telone® C-35 was shank-applied on 14 November 2016 using a fumigation rig, which had a spacing of 50 cm between shanks. The same rig was used to inject fumigants at both 45 cm and 65 cm depths. Fumigated areas were only 2.52 m wide along tree row center that ended up with about 40% of the orchard floor fumigated. The plastic tarp was installed following fumigant injection using another rig. Biochar was applied the day before fumigant application by spreading the materials uniformly to a 3.05 m × 3.05 m area and then incorporated into surface 0–15 cm soil to avoid the dry materials being blown away.

2.2. Field sampling for monitoring fumigant movement

Following fumigant injection and film installation, soil gas sampling probes and passive flux chambers were installed to monitor fumigant emissions and distribution in soil profile over time in selected treatments. Passive or non-vented chambers were assembled from inverted stainless steel containers similarly to those described in Gao and Trout (2007). The treatments monitored for emissions included both the regular and the deep injections with no tarp, the deep injection with TIF, and the two biochar amendment rates at the 66% fumigant rate. Fumigants in soil-gas phase were sampled using a set of stainless steel tubes (0.1-mm i.d.) inserted into the soil with the lower ends at depths of 15, 30, 45, 60, 75, and 100 cm plus an additional probe at 125 cm in a subset of plots for comparison purposes. All sampling equipment was installed in the center of a plot. Sampling for emissions were more frequent initially (twice daily), reduced to daily, and then to several times a week. Soil gas was sampled to determine gaseous fumigant concentrations in profile, but less frequently than emission sampling. The passive chamber method provides discrete emission flux estimates and is not suitable for calculating total or cumulative emission loss (Gao and Wang, 2011); thus, flux data were used to analyze the relative treatment effects on emissions. Sample collections, storage, and processing in the laboratory followed previously developed protocols (Gao et al., 2009, 2015).

2.3. Residual fumigants and nematode control

Approximately four months after fumigant application, soil samples were collected at 30 cm increments down to 1.5 m for both residual fumigant and live nematode determination. All plant parasitic nematodes in the soil samples were extracted by the sugar-flotation and centrifugation method utilizing a 25 µm sieve (Jenkins, 1964). Extracted nematodes were determined to be dead or alive and identified under the microscope at 4× magnification (Mai and Lyon, 1975).

2.4. Data analysis

Data analyses on fumigant emission flux, gaseous and residual fumigant concentration in soil, and nematode survival were conducted using SAS 9.4 (SAS Institute, 2013). A two-way analysis of variance (ANOVA) or a mixed model analysis was performed followed by mean separation using Tukey's adjustment at $P < 0.05$.

3. Result and discussion

3.1. Weather and soil conditions during field trial

Several rain events occurred before and during the fumigation trial, which affected both fumigant emissions and movement in soil profile. About 50 mm precipitation in one event occurred two weeks before the fumigation trial, which resulted in relatively high water content in the field. Fumigation treatments were not carried out until the soil water content dropped to 9.1%–11.1%. Field capacity for this soil is typically around 17%. However, following the fumigant application, a light rain event occurred within 24 h followed by a heavy rain five days later. Breaking a four-year drought pattern in the region, approximately 200 mm rain fell in the two months following fumigation (Fig. 1). Before the tarp removal (three weeks after fumigant application), plots without tarping received about 75 mm rain directly. The temperature at soil surface and 10 cm depth with or without tarp was measured (Fig. 1). Average soil temperature decreased during the first three weeks from 17.5 to 7.0 °C and ranged between 4.9 and 12.5 °C for the remaining time. Diurnal changes in temperature near soil surface were much greater than the soil temperature at 10 cm depth and higher temperature was observed under TIF than the bare plot.

3.2. Emissions

The results of 1,3-D emission flux are provided in Fig. 2. Chloropicrin emissions (data not shown) followed the same trend but with values one tenth or lower than 1,3-D. In general, all the emission fluxes from this trial were about an order of magnitude lower than in other trials conducted under warmer temperature and with little or no rainfall (Gao et al., 2009, 2015, 2018). Since the emissions from this study were relatively low, these data are best used to make relative comparisons among treatments for fumigant distribution and emission.

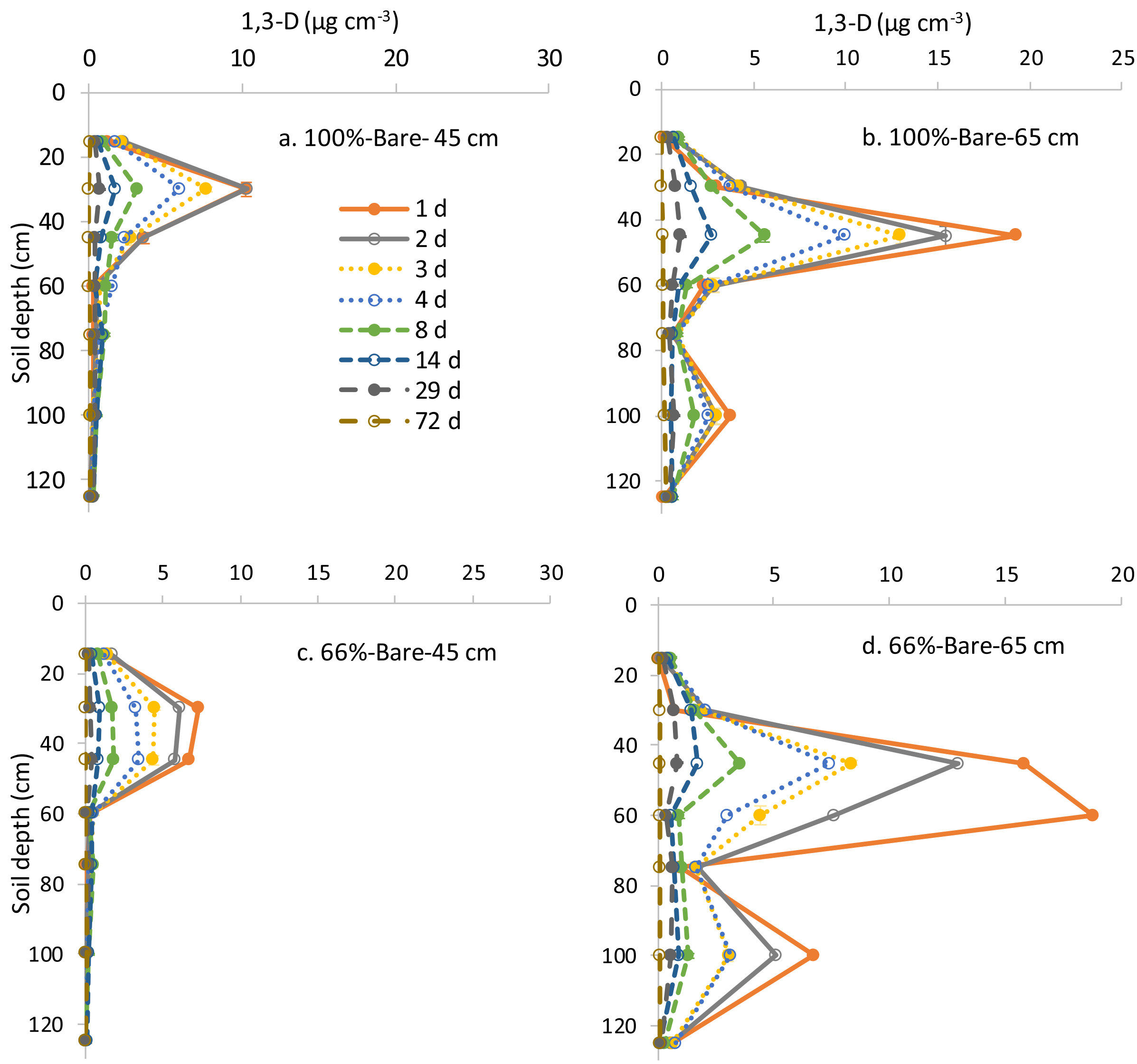

Fig. 3. 1,3-dichloropropene (1,3-D) concentrations in soil-gas phase affected by application rate and injection depth following Telone® C-35 application. Plotted are averages of three replicates. Error bars are omitted to improve readability.

Between the two injection depths, the deeper injection (65 cm depth) resulted in significantly lower flux values than those from the regular injection (45 cm depth) especially during the first 4–5 days (Fig. 2a). TIF resulted in much lower emission rates compared to the bare soil treatment and the low biochar rate during the first five days, but emission rates increased significantly thereafter even before tarp removal (Fig. 2b). The TIF permeability may have been affected by humidity or soil moisture as other research has shown that increased humidity could increase the permeability of the film by 2–3 orders of magnitude (Papiernik et al., 2010; Qian et al., 2011). The high biochar application rate (40 ton ha^{-1}), however, reduced emissions consistently during the one month monitoring period following fumigant injection. The last emission sampling was conducted two months after application at which time only trace 1,3-D emissions ($< 0.2\,\mu g\,m^{-2}\,s^{-1}$) and no CP emissions were measured.

The generally low emission fluxes in this trial were believed to be caused by the relatively high soil water content. In two field trials conducted previously 1,3-D emission peak flux was measured up to 120 or $44\,\mu g\,m^{-2}\,s^{-1}$ from PE tarped plots in a sandy loam or a sandy soil respectively, or $16\,\mu g\,m^{-2}\,s^{-1}$ from the bare sandy soil (Gao et al., 2018). Soil temperature was similar in all these trials and the only difference in this current trial was the much higher soil moisture due to winter precipitation that resulted in emission flux below $10\,\mu g\,m^{-2}\,s^{-1}$. In another fumigation trial conducted earlier (October) without rain, 1,3-D peak emission flux of 22 or $80\,\mu g\,m^{-2}\,s^{-1}$ were measured from bare or PE tarped plots, respectively (Gao et al., 2015). Data from all trials indicate that rain events before or shortly after fumigation resulted in reduced emission, which had an effect similar to "water seal". Water seal, which was investigated in earlier studies, refers to water application following fumigant injection to maintain high surface soil water content to reduce emissions (Gao et al., 2008, 2009). Although high moisture conditions are beneficial from an emissions reduction standpoint, excessive soil moisture can restrict fumigant movement in soils and could reduce nematode control.

3.3. *Fumigant distribution in the soil profile*

Distribution of 1,3-D in soil-gas phase over time is provided in Figs. 3 and 4. Chloropicrin followed almost the same distribution pattern as 1,3-D except at lower concentrations. As an example, Fig. 5 compares CP concentration changes between the two injection depths (45 cm vs. 65 cm). For both 1,3-D and CP, the highest soil-gas

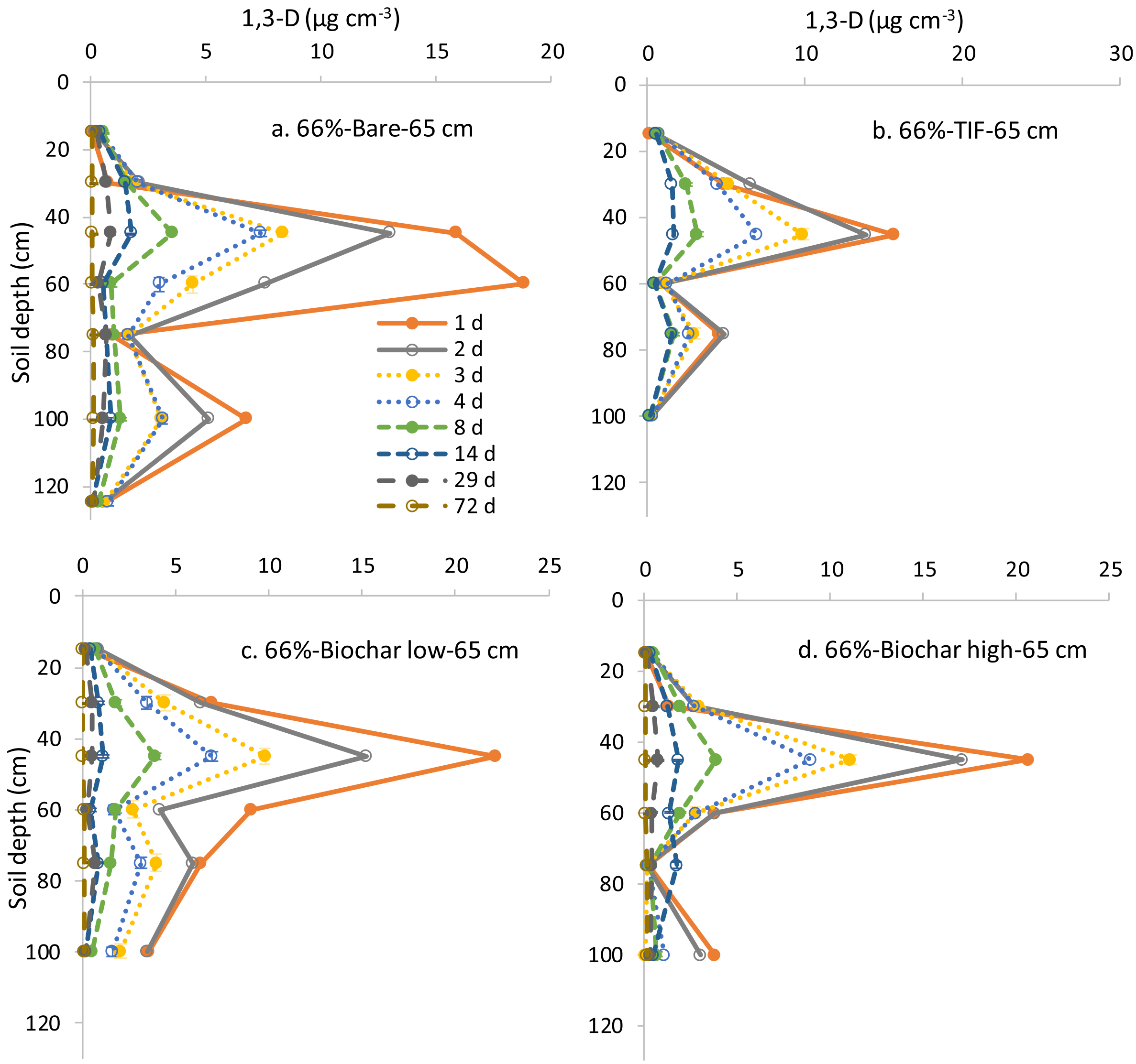

Fig. 4. 1,3-dichloropropene (1,3-D) concentrations in the soil-gas phase as affected by surface sealing method following application of Telone® C-35. Plotted are averages of three replicates. Error bars are omitted to improve readability.

concentration was observed at 30–45 cm soil depth in plots treated with the 45 cm injection depth, but at 45–60 cm from the deep injection (Fig. 3). The deep injection also resulted in significantly higher fumigant concentrations at the 100 cm depth compared to the 45 cm injection treatment. The extremely low concentration at 75 cm from all monitored plots was likely due to the presence of a hard pan layer in the orchard. Although not measured directly, the hard layer was noticed when the soil-gas probes were installed after fumigant injection. The soil-gas data also indicate that the deep injection did enhance fumigant diffusion into the deeper depths, which is also supported by the data from deep injection with various surface sealing methods (Fig. 4). The fumigant concentrations at 120 cm were generally low overall but were still much higher from the deep injection than the regular injection (Figs. 3–5).

The fumigant concentration data in the soil-gas phase also indicate increased persistence, or decreased degradation in this trial, which is likely due to the combination of high soil moisture and low temperature. Although the observation applies to both 1,3-D and CP, the effects on CP appeared greater. Chloropicrin dissipation in soil has been monitored under various field conditions and it is generally accepted that CP has a much shorter half-life than 1,3-D (Ajwa et al., 2010). When moisture increased in a sandy loam soil (similar to the current study) from air-dry (5%) to near field capacity (17.5%), the half-life of CP was 2–3 days compared to the 5–11 days for 1,3-D (Qin et al., 2009). In the same study, higher soil moisture did not significantly increase degradation rate of CP, but increasing temperature did. When Telone® C-35 was applied to soil in several field tests without rain, CP dissipated from the soil-gas phase with all concentrations below detection limit (0.1 µg cm^{-3}) after 12 days (Gao et al., 2015). In another trial with some rain, CP also dissipated in 15 days in a sandy loam soil but was detected more than 21 days in a sandy soil when more rain was received (Gao et al., 2018). Although hydrolysis is one of the major pathways in 1,3-D chemical degradation and the hydrolysis rate constant increases with soil moisture content (Guo et al., 2004), chemical hydrolysis appears to play only a minor role compared to microbial degradation for both 1,3-D and CP (Dungan and Yates, 2003; Jeffers and Wolfe, 1996). In the current field trial, even one month after fumigant injection, CP concentrations in the soil gas-phase from all treatments were up to 1.2 µg cm^{-3}, which is well above the detection limit. Increasing water content at room temperature did not increase the CP degradation rate in a lab study (Qin et al., 2009), thus the increased persistence of CP in this field study must be due to the

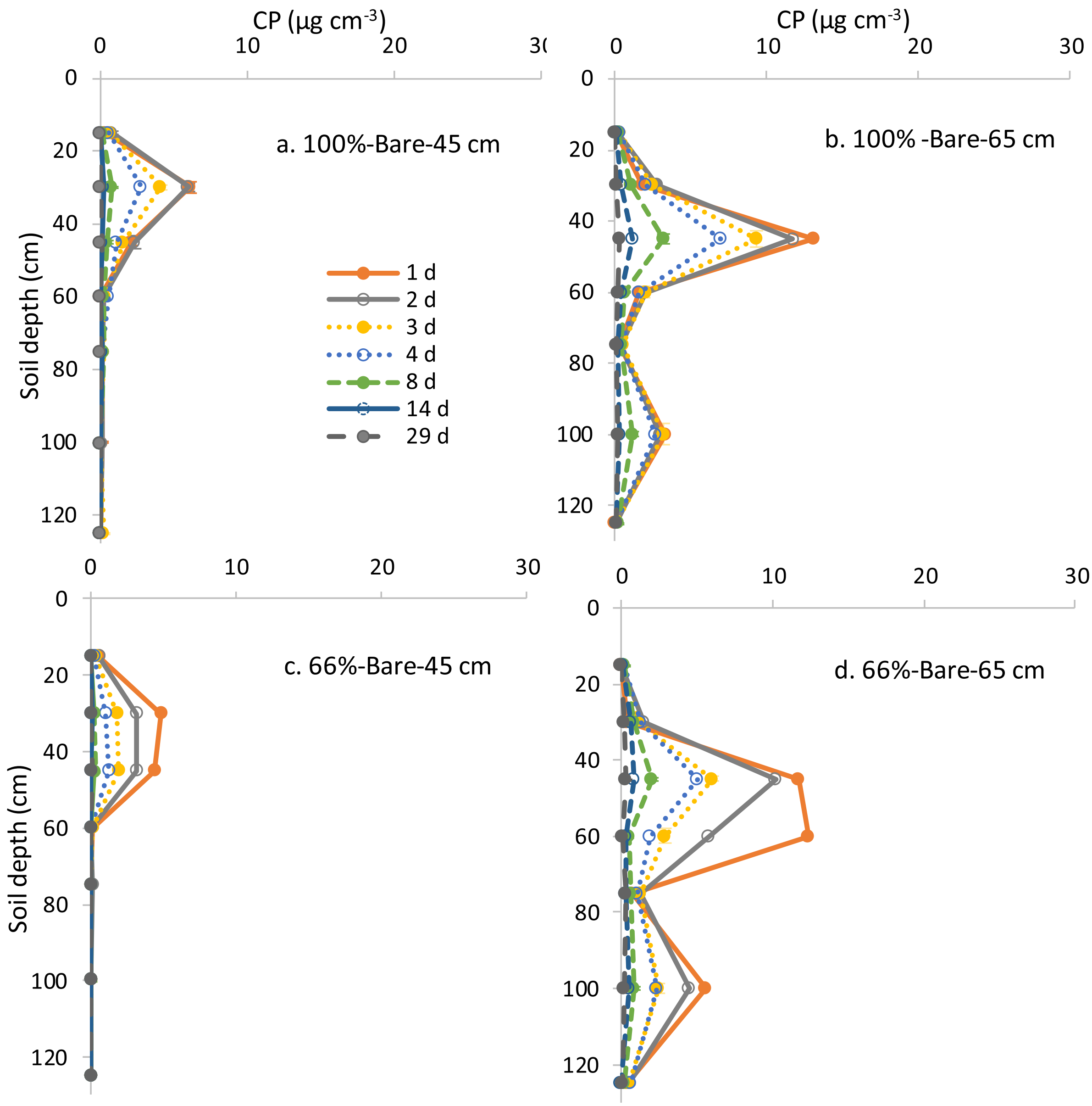

Fig. 5. Chloropicrin (CP) concentrations in the soil-gas phase as affected by application rate and injection depth following Telone® C-35 application. Plotted are averages of three replicates. Error bars are omitted to improve readability.

combination of high soil moisture and low soil temperature. The increased persistence of fumigants might also be attributed to competitive degradation between 1,3-D and CP (Zheng et al., 2003). To further examine what might affect the CP persistence, we plotted the ratio of CP to 1,3-D 14 days after fumigant injection when CP had dissipated from other trials. The application ratio of CP to 1,3-D was 0.55. The ratio was clearly impacted by the injection depth; the 65 cm injection depth significantly increased the ratio of CP to 1,3-D compared to the regular injection (Fig. 6a). Note the increased CP/1,3-D ratio at lower depth suggesting increased persistence may have also caused downward movement of CP in the profile. There was no significant difference in the ratio when fumigants were applied at the 65 cm injection depth (Fig. 6b).

3.4. Residual fumigant

Residual soil fumigants were determined approximately four months after fumigant injection (Fig. 7). Soil samples below 60 cm depth had extremely low or non-detectable fumigants indicating that most of the fumigants had dissipated. The surface soils had the highest fumigant concentrations although with large variability. Biochar amendments tended to raise fumigant concentration (1.1–2.5 mg kg^{-1}, but highly variable) and TIF covered plots showed the lowest concentration (0.1 mg kg^{-1}) that might be attributed to higher soil temperature than non-tarped treatments. There was no clear indication of how injection depth affected the fate of the fumigants after this long period of time. Biochar affects fumigant dissipation in soil by adsorption and chemical degradation. Wang et al. (2016) tested six biochar products from different feedstocks and concluded that strong adsorption (49–93%) resulted in an increased half-life of fumigants of 300–3500%. This raises a concern over potential impact of the increased persistence of fumigants in soil on crops that bears further investigation.

Generally speaking, the fumigant concentrations detected four month after fumigant injection in the current trial were much higher than those determined in previous trials with shorter monitoring

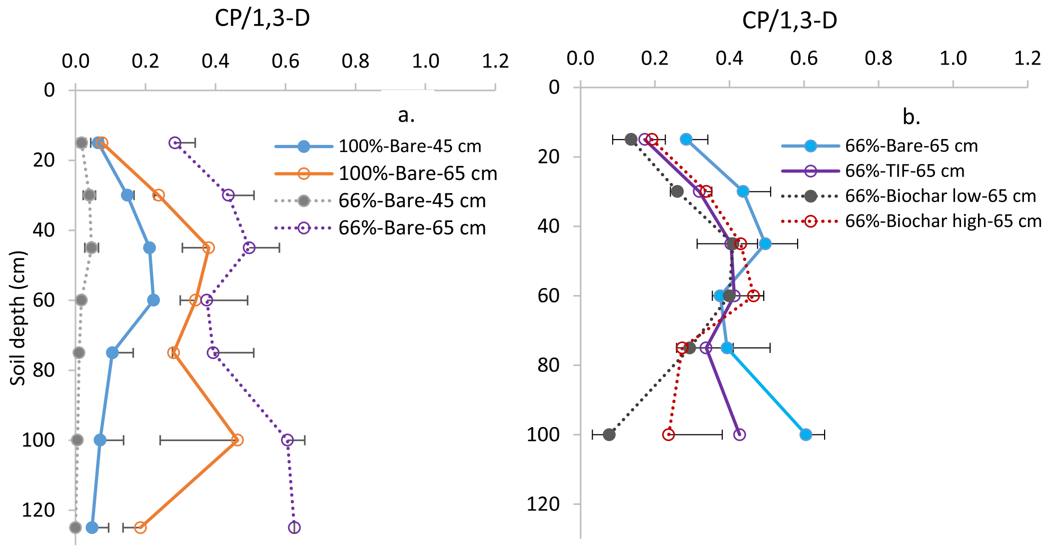

Fig. 6. Effects of injection depth and surface soil treatments on the ratio of 1,3-dichloropropene (1,3-D) to chloropicrin (CP) in soil-gas phase fourteen days after injection of Telone® C-35. Plotted are averages of three replicates. Error bars are standard error of the mean (n = 3).

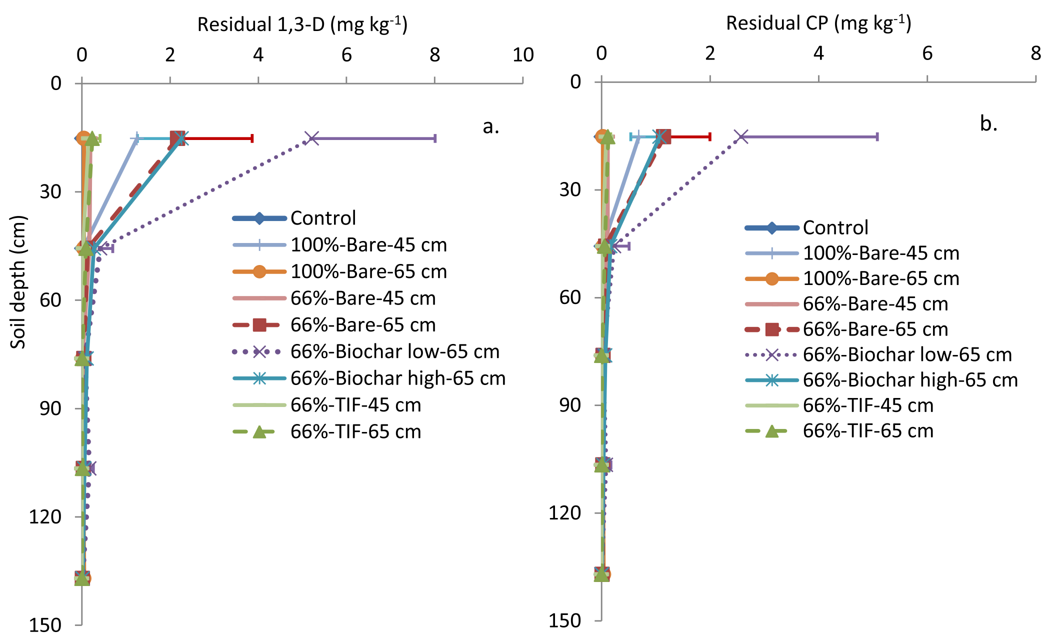

Fig. 7. Soil residual fumigant concentrations approximately four months after fumigant application. Error bars are standard error of the mean (n = 3).

periods (< 2 months) (Gao et al., 2009, 2015; 2018). Although usually undetectable by the end of monitoring periods in previous experiments, chloropicrin residues in this trial were as high as 2.6 mg kg^{-1} in the biochar treated surface soil. The average ratio of CP to 1,3-D among the treatments ranged from 0.52 to 0.70, with most of them above the application ratio of 0.55. These data partially support the observation of increased persistence of CP due to the high soil moisture and low temperature.

3.5. Nematode control

The total populations of plant parasitic nematodes from different treatments were counted in soil sampled four months after fumigant applications (Fig. 8). On average, pin nematode (*Paratylenchus*) accounted for 70% of the total population. Other species were minor including lesion (*Pratylenchus*, < 5%), root knot (*Meloidogyne*, < 5%), stunt (*Tylenchorhynchus*, < 10%), *Tylenchidae* (< 10%), stubby-root (*Trichodorus*, < 1%), and ring (*Mesocriconema*, < 1%) nematodes. Although the non-fumigated control had the highest nematode population throughout the soil profile, nematode populations in bare soil fumigated plots were not statistically lower than the non-fumigated plots regardless of injection depth. There appears to be no clear effect on nematode populations in soil profile between the two injection depths (Fig. 8a). Biochar treatments, however, tended to have lower nematode population in surface soils than the control (Fig. 8b). The TIF clearly improved nematode control especially from the deeper injection (Fig. 8c) that was attributed to the retention of fumigant by the tarp and less impact from increased soil moisture from rain compared to bare soils.

Still unclear is whether or not biochar amendment in soil fumigation

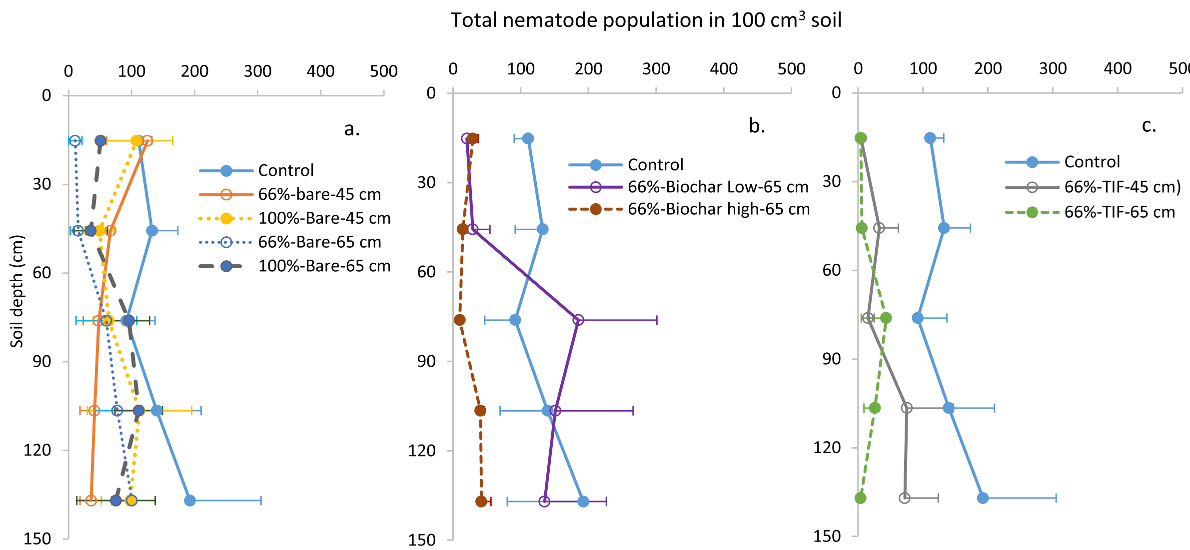

Fig. 8. Total population of plant-parasitic nematodes in soil approximately four months after application of Telone® C-35. Error bars are standard error of the mean (n = 3).

reduces nematode control. Ashworth et al. (2017) determined effective emission reduction by a rice husk-derived biochar in a chamber study and observed reduced soil-gas fumigant concentrations in the upper soil that may limit nematode control. Graber et al. (2011) raised similar concern after observed that adequate nematode control was achieved at 13 and 26 Mg ha^{-1} of cornstraw biochar and 1,3-D of 94 and 187 L ha^{-1}, respectively. However, they speculated that if the biochar absorbed the organic chemicals by one or more order of magnitude, then adequate nematode control would not be achieved. Under field conditions, however, fumigant concentrations tend to be lower in surface soil unless tarped with expensive low permeability film. Our field data at least indicate that the biochar amendment at either low or high rate did not compromise nematode control in the surface soil (Fig. 8b). The increased persistency of fumigants in soil and effects on efficacy affected by biochar need further clarification with field data.

4. Conclusion

This study investigated several aspects of pre-plant soil fumigation in a field trial that was significantly affected by late-fall rain events and cool temperatures. Effects of deep injection and biochar amendment on fumigant emission reduction and movement in soil as well as the fate of fumigants and nematode control were determined. The data showed that injection of fumigants at a 65 cm soil depth enhanced fumigant delivery to below 60 cm depth compared to the regular injection at 45 cm depth and significantly reduced emission rates immediately following injection. Biochar soil amendment showed the potential as an emission mitigation strategy. At 40 ton ha^{-1} the biochar product tested was equally or more effective than TIF in reducing emissions. However, the biochar tested in this study was derived from coconut shells, which would likely be too expensive and not likely to be adopted by growers. Further determination is needed on the relative efficacy of biochar products from local orchard feedstocks and their fumigant emission reduction potential under drier soil conditions than that from this study. Biochar amendment as an emission reduction strategy in orchard pre-planting fumigation also offers many other benefits in improving soil properties.

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