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SUBJECT: EFFECT OF PRE-APPLICATION SOIL MOISTURE ON EMISSIONS OF 1,3-DICHLOROPROPENE

1. Introduction

Fumigants are formulated in a way that they can move throughout the soil pore space in the gas phase. While the movement of fumigants in the soil is an essential factor in their efficacy, it also leads to unintended loss where a fraction of the fumigant is emitted out of the treated area and into the ambient air. The Department of Pesticide Regulation (DPR) has established various mitigation measures to minimize off-site emissions of fumigants by placing requirements on the application depth, soil moisture[1], water treatments, and use of plastic films (e.g., Polyethylene [PE], Totally Impermeable Film [TIF]). This document focuses specifically on the effect of pre-application soil moisture on emissions of 1,3-dichloropropene (1,3-D).

Gas phase movement (i.e., gas diffusion) of fumigant in the soil occurs through air-filled pore spaces known as the soil's *air-filled porosity*. Gas phase transport through this air-filled porosity is relatively rapid, and a large proportion of air-filled porosity can provide a conduit for a fumigant to quickly ascend through the soil profile and emit into the ambient air. The *total porosity* is the sum of *air-filled porosity* and *water-filled porosity (Eq. 1)*.

$$\textit{Total porosity} = \textit{air-filled porosity} + \textit{water-filled porosity} \qquad (1)$$

Therefore, for total porosity to remain constant, an increase in *water-filled porosity* (i.e., soil moisture) results in a reduction in *air-filled porosity*. Because transport in the aqueous phase occurs at a much slower rate than in the gas phase, this increase in soil moisture effectively restricts fumigant transport within the soil, thereby, reducing emissions into ambient air.

[1] In this document, soil moisture refers to volumetric soil water content.

While air-filled porosity is difficult to measure directly, it can be expressed as a function of bulk density (which can be used to calculate *total porosity*) and soil moisture. Several methods exist to quantitatively measure bulk density and soil moisture, but these methods are not without challenges. Measuring soil moisture and bulk density using core sampling is a time-consuming and delicate process and, as a result, not the preferred choice for measuring pre-fumigation soil moisture. Soil moisture sensors are also challenging to use due to their high sensitivity to proper installation. In all cases, the spatial heterogeneity[2] in soil properties, the effects of soil preparation on soil structure, and soil layering will introduce a considerable non-uniformity to the spatial and vertical distribution of soil bulk density and soil moisture across a field. These challenges contribute to the complexities and difficulties of developing a simple-to-follow yet comprehensive set of guidelines for determining pre-fumigation soil moisture.

Current labels for products containing 1,3-D follow the “feel and appearance” approach to determine the soil moisture content as described by Natural Resources Conservation Service (1998) for irrigation scheduling. Rather than relying on quantitative measurement of soil moisture, the “feel and appearance” method relies on a simple qualitative assessment to categorize a soil’s moisture within one of four soil moisture “bins”. These bins roughly correspond to ranges of 0-25%, 25-50%, 50-75%, and 75-100% of field capacity (FC), a widely-used and well-known term often used to indicate pre-fumigation soil moisture by fumigant applicators. Using the descriptions of soil texture, feel, and appearance, an applicator must ensure that the average soil moisture between 2” below the soil surface and the depth of application meets the description on the label[3]. For example, the depth of application in Field Fumigation Method (FFM) 1206 is 18”; as such, the label soil moisture requirements refer to average moisture for a soil layer from 2” to 18” below the surface (hereafter referred to as *top 16”*). Despite the common belief among growers and fumigant applicators that 60% -70% FC is a suitable soil moisture for fumigation (Ajwa, pers. commination), the language used in the 1,3-D label is somewhat vague. If that language is compared with the NRCS “feel and appearance” methodology, the label-required soil moisture prior to 1,3-D fumigation is more descriptive of the 25% - 50% category.

In this memorandum, we first define FC and describe the approach used to estimate it using the HYDRUS computer model (Šimůnek , et al., 2008), a process-based soil model that simulates the movement and transport of water, solute, heat, and gas in the soil. We then use HYDRUS to evaluate the range of pre-fumigation soil moisture measurements collected by DPR staff at 16 locations throughout California, estimate FC for each of those soils, and compare those moisture measurements relative to their FC and label requirements. Lastly, we use HYDRUS to explore the effects of soil moisture on total fumigant emissions to better understand how pre-application soil moisture can be used as a mitigation tool.

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[2] Variation of soil properties in both horizontal and vertical direction.

[3] Note: Labels for combination 1,3-D + chloropicrin products (e.g., Pic-Clor) differ in their soil moisture requirements and specify 50-75% of ‘available water capacity’ in the top 9” of soil, regardless of injection depth.

2. Materials and methods

2.1. Field capacity determination

Field Capacity is defined as “the content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible” (Soil Science Society of America, 1997). The challenges and uncertainties involved in determining “negligible free drainage” led to a 2- to 3-day timeframe being used as the criteria to determine FC. However, Romano and Santini (2002) provide a detailed review of FC and show that the time-frame for “negligible free drainage” could be 10 days or longer. Ratliff et al. (1983) observed that the time-frame for negligible drainage was about 2 to 12 days and in rare cases with restrictive soil layers up to 20 days. In this memorandum we used 7-day drainage as a mid-point between 2 and 12 days as the criteria to determine FC. It should be noted here that it is a common practice for grower to till the soil and breakdown any restrictive layer prior to the fumigation.

The HYDRUS modeling domain was similar to that described for FFM 1206 by Brown (2018). Soil characteristics including soil moisture are those measured by DPR staff for 16 fields throughout the state prior to fumigation (referred to as the 16 soil profiles hereafter). It should be noted that there is no value for “wet soil” in the definition of FC and in this study the “wet” soil profile was assumed to be a fully saturated soil profile. The HYDRUS model was used to simulate the soil moisture at FC for the 16 soil profiles. For this purpose, the soil profile was saturated and allowed to drain for 21 days without evaporation. Figure 1 shows the rate of leaching over 21 days for the 16 soil profiles (gray lines). It shows that the average (black line) rate of leaching was considerably decreased during the first 48 hours and reached to about 10% and 5% of its maximum value on day 7 and day 14.

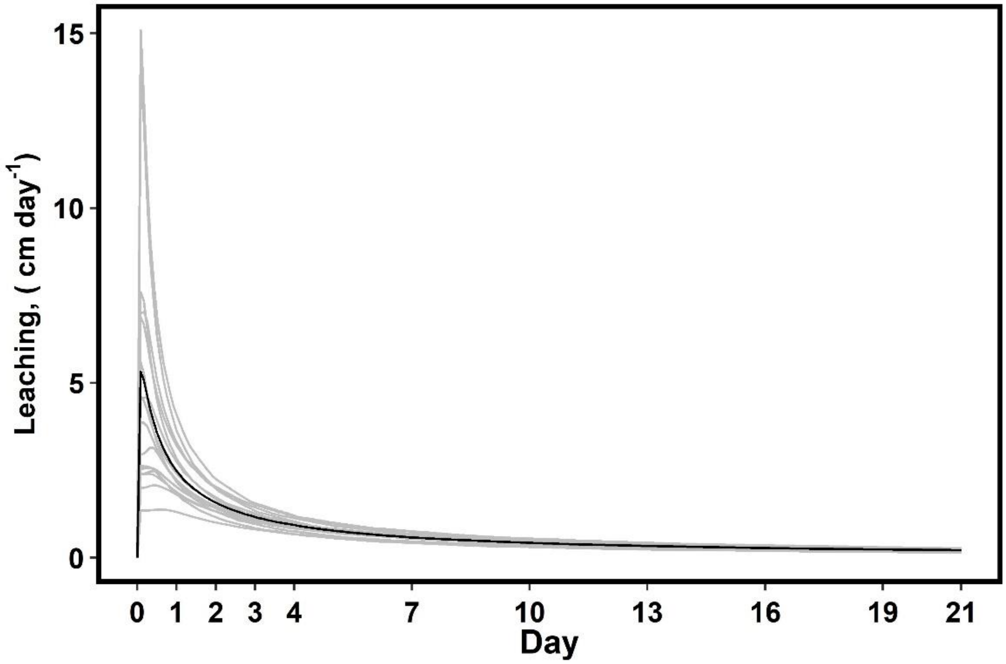

Figure 1. The rate of leaching over 21 days for the 16 soil sites.

2.2. Estimation of total emission

The HYDRUS model was used to estimate the total emission of 1,3-D fumigant, for all 16 soil profiles. The modeling domain was similar to FFM 1206 described by Brown (2018). The soil moisture profile at FC for each of the 16 soil profiles was multiplied by 0.2, 0.4, 0.5, and 0.7 to define pre-fumigation soil moistures of 20%, 40%, 50%, and 70% FC for HYDRUS modeling. The HYDRUS model simulated the emission of 1,3-D fumigant for 21 days. Total emissions under each pre-fumigation soil moisture scenario were taken as the cumulative emissions at the end of the 21-day modeling period.

3. Results and discussion

3.1. Soil moisture

Figure 2 shows the moisture profiles at FC as estimated by HYDRUS (blue solid line) and that of measured by DPR staff prior to fumigation (red dashed line), while Figure 3 shows the percentage of FC for the top 16” soil layer for each of the 16 soil profiles. The soil moisture profile prior to fumigation varies between soil profiles, especially if they are compared relative to their associated FC. For example, “din1” is the driest profile with soil moisture of less than 20% FC. On the other hand, “LH2” has the wettest soil profile with soil moisture of about 80% FC.

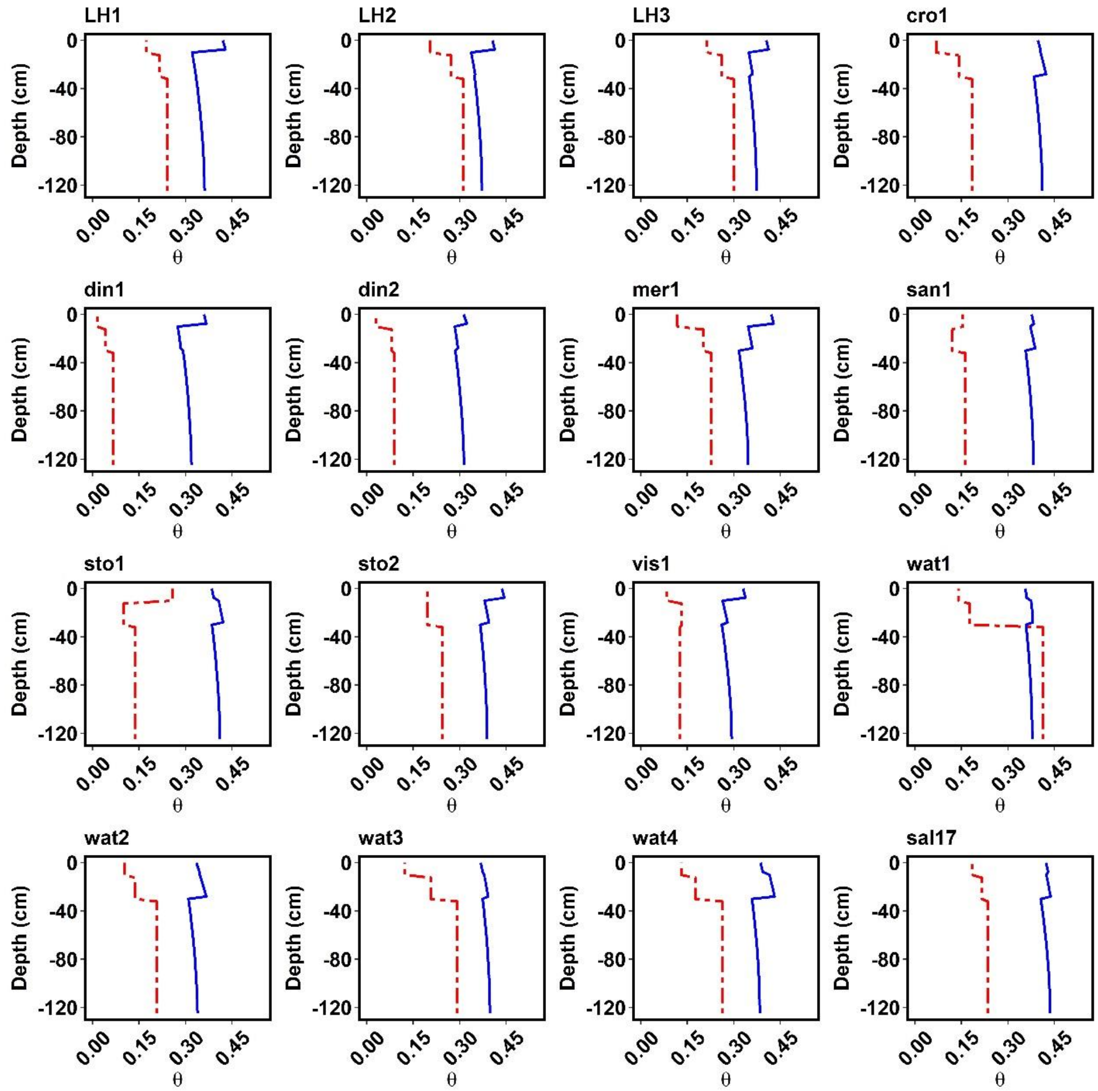

Figure 2. The moisture profiles at FC (blue solid line) and measured prior to fumigation (red dashed line) for the 16 soil profiles. The vertical axes show the depth of soil profile and the horizontal axes show the soil moisture (volumetric water content).

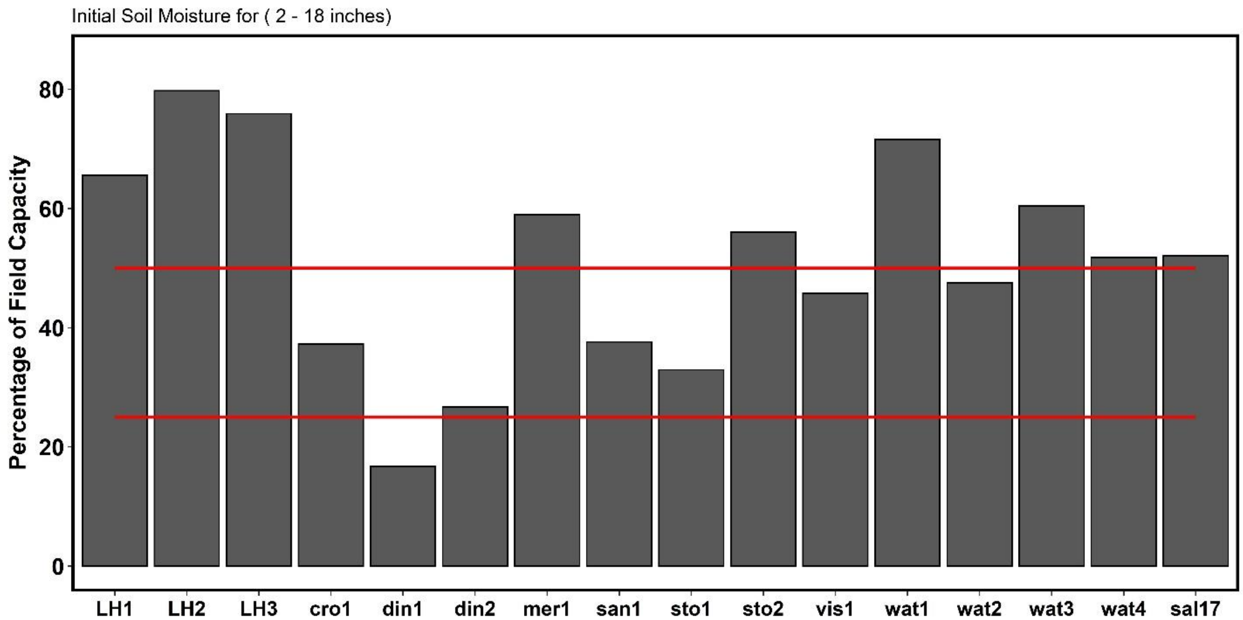

Figure 3. The percentage of field capacity for the top 16” soil layer for each of the 16 soil profiles. The horizontal red lines show the 25% and 50% FC.

3.2. Effects of soil moisture on total emissions

Figure 4 shows the emission ratio (% of initial mass of applied 1,3-D emitted) of the 16 soil profiles versus their measured soil moisture (% of FC). The graph shows a clear trend in which the emission ratio decreases as the soil moisture increases. The driest soil, “din1”, produced the highest emission ratio of 56% and the soil with highest moisture, “LH2”, resulted in the lowest emission ratio of 17%. The lower the soil moisture, the higher the air-filled porosity and as a result higher flux of 1,3-D from soil (through air-filled porosity) to the ambient air.

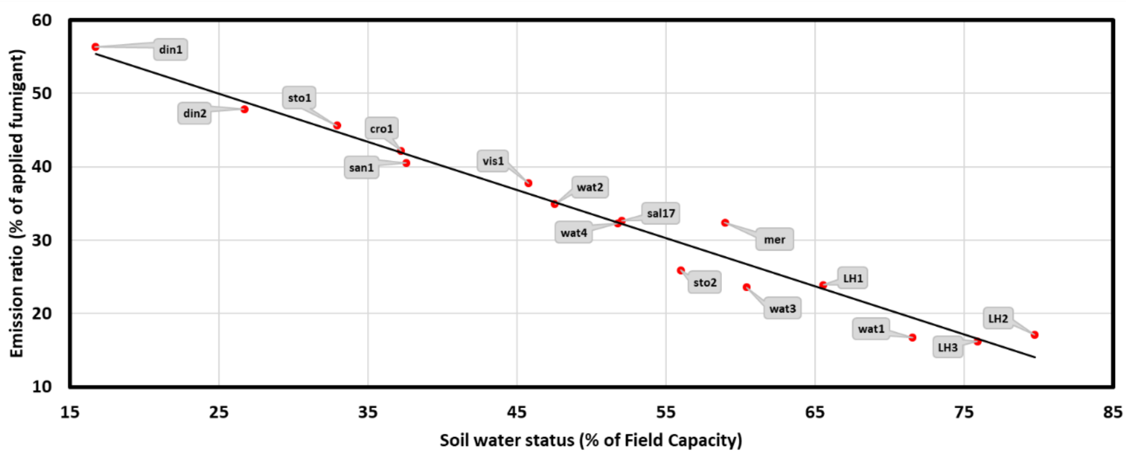

Figure 4. The emission ratio (% of applied 1,3D) of the 16 sites versus their measured soil moisture (expressed as % of Field Capacity).

It should be noted that soil moisture is one of the several factors, such as soil layering and total porosity of each layer, affecting the simulated emission ratio in Figure 4. Therefore, additional HYDRUS simulations were conducted to evaluate the sole effect of soil moisture on emission ratio. Figure 5 shows the effect of soil moisture on the 1,3-D emission ratio. The black triangles represents the average of all 16 soil profiles while the individual soil profiles are shown by red circles. The relationship between soil moisture and emission ratio follows the same trend as in Fig. 4. Results presented in both Figures 4 and 5 show that an increase in soil moisture from 20% to 70% FC has the potential to reduce the average emission ratio by third. However, as is shown by the scatter around the average emission ratio at each level of FC, it should be noted that the soil moisture is one of several factors affecting the emission ratio. Therefore, the emission ratio from site “A” with higher soil moisture could be higher than the emission ratio from site “B” with lower soil moisture.

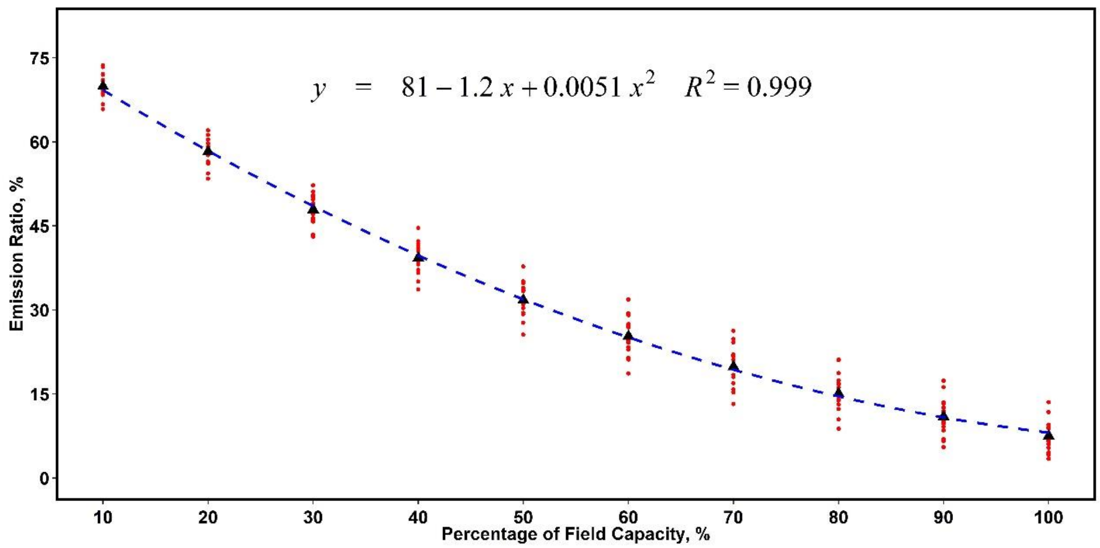

Figure 5. The effect of soil moisture on the 1,3D emission ratio. The red circles show the emission ratio of each individual site at each soil moisture. The blue line represent the average of all 16 sites.

4. Summary and Conclusion

In this memorandum, the HYDRUS-estimated FC for all 16 soil profiles were determined. The field-measured soil moisture (as percentage of FC) of all 16 soil profiles were determined and compared with the soil moisture required by labels of products containing 1,3-D. The HYDRUS-estimated 1,3-D emission ratios of these 16 soil profiles were plotted against their associated soil moisture. In the end, HYDRUS modeling was used to estimate the 1,3-D emission ratios for each site at four different soil moisture contents ranging from 10% to 100% of their FC.

Based on the results presented in this memorandum, it can be concluded that:

1- Soil moisture is one of the main factors affecting the emission of fumigants including 1,3-D. An increase in soil moisture reduces the fraction of air-filled porosity, which reduces the emission of fumigant from the soil into ambient air.

2- The language used on current 1,3-D product labels is vague and appears to allow relatively low soil moisture (25% - 50% FC). Possibly due in part to this vague label language, the range of soil moistures measured by DPR staff (within 24 hours prior to fumigation) was relatively large, varying from 17% up to 80% of FC.

3- Although soil moisture is a critical factor affecting fumigant emissions, even with soil moisture held constant emission ratios continue to show substantial variation by soil type due to a number of other factors affecting fumigant emissions. Therefore, the effect of soil moisture on emission ratio should not be quantified based on a single field or modeling experiment.

5. References

1. Brown, C. (2018). HYDRUS-simulated flux estimates of 1,3-dichloropropene maximum period-averaged flux and emission ratio for approved application methods. California Department of Pesticide Regulation, Sacramento, CA.
2. – (1998). Estimating soil moisture by feel and appearance. Natural Resources Conservation Service, United States Department of Agriculture. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_051845.pdf. (Last accessed (07/30/2019).
3. Ratliff, L.F., Ritchie, J.T., and Cassel, D.K. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci. Soc. Am. J. 47:770–775.
4. Romano, N. and Santini, A. 2002. 3.3.3 Field. In: J. H. Dane, C. G. Topp, editors, Methods of Soil Analysis: Part 4 Physical Methods, SSSA Book Ser. 5.4. SSSA, Madison, WI. p. 721-738. doi:10.2136/sssabookser5.4.c26
5. Šimůnek, J., van Genuchten, M.T., and Šejna, M., 2008. Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes.Vadose Zone Journal 7, 587–600. https://doi.org/10.2136/vzj2007.0077
6. Soil Science Society of America. 1997. Glossary of soil science terms. SSSA, Madison, WI.