What to Consider when Emission Reduction is Required from Soil Fumigation

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Summary. Emission is one of the key factors affecting fumigant use in California due to regulations. Many commodities depend on pre-plant soil fumigation to achieve profitable yield and healthy crops. The phase-out of methyl bromide as a broad-spectrum soil fumigant in pest control has placed formidable challenges in searching alternatives. Most alternatives registered today are highly regulated because of their toxic properties and their nature as volatile organic compounds (VOCs). Minimizing emissions becomes essential to maintain the practical use of fumigants. This paper reviews and summarizes findings towards field practices to minimize emissions from soil fumigation. The effectiveness on emission reduction, impact on pest control and cost are important factors to consider in determining emission reduction technique. High-value cash crops (e.g. strawberry) can afford using highly effective, but costly low permeable plastic mulches whereas crops with lower profit margins (e.g. stone fruit orchards) may need to consider lower cost methods such as water treatments and/or target-area fumigation. More stringent regulations on fumigants are likely to develop in the future. Continuous research is necessary to develop good fumigation practices in various agronomic systems to sustain agricultural production while minimizing potentially detrimental impact.

Introduction. Soil fumigation with methyl bromide (MeBr) has been used to control a variety of soil-borne pests such as nematodes, diseases, and weeds in many agricultural systems. Major industries that rely on soil fumigation include high-value cash crops (e.g., strawberry), stone fruit/ornamental and grapevine nurseries and orchards, and some vegetables (carrot, pepper, tomato). Without fumigants, productions of these crops would suffer tremendous yield losses from diseases or replant disorders. Additionally, in California, tree and grapevine field nurseries must meet the nematode-free requirements of California Department of Food and Agriculture (CDFA) Nursery Nematode Control Program. Because of its role in depleting stratospheric ozone MeBr was phased-out in the US and other developed countries as of January 2005 under the provisions of the U.S. Clean Air Act and the Montreal Protocol (an international agreement). Some limited uses of MeBr are allowed under Critical Use Exemptions (CUE) and Quarantine/Preshipment (QPS) criteria. Although limited to the few registered compounds, alternative fumigants to MeBr such as 1,3-dichloropropene (Telone or 1,3-D), chloropicrin (CP) and methyl isothiocyanate (MITC) generators (e.g., metam sodium or dazomet) have been increasingly used (CDPR, 2005; Trout, 2006). These alternative fumigants, however, are VOCs and, when released to the atmosphere, can react with nitrogen oxides under sunlight to form harmful ground level ozone, an important air pollutant. Regulations (e.g., rate limits and buffer zones) have been used to minimize emissions. Stringent regulations are developed specifically on fumigant use to reduce air emissions especially in nonattainment area such as Ventura County and San Joaquin Valley of California (CDPR, 2008; Segawa, 2008).

We have been conducting research on emission reductions from soil fumigation for over four years. Our goal is to develop agricultural practices (effective, economic, and environmentally sound methods) to minimize fumigant emissions while achieving good efficacy.

Processes and factors affecting emissions. Soil fumigants are volatile compounds. The purpose of fumigation is to achieve maximum control of soil-borne pests, which requires sufficient fumigant concentration and uniform distribution in soil. A number of processes are involved in the fate of fumigant after application to soil (Figure 1). Fumigants are subject to partitioning to soil air, water and solid (most importantly organic matter), volatilization (emission), degradation, sorption and potential leaching. Emission loss is one of the major concerns related to fumigant effects on air quality. Containment of fumigant in the soil rooting zone is necessary for minimizing emissions as well as ensuring good efficacy.

Emissions from soil fumigation are affected by soil conditions (texture, moisture and organic matter content), weather, and surface barriers as well as fumigant properties. Generally speaking, lower emission are expected from soils with fine texture, high water content, high soil organic matter (SOM) content, and low temperature compared to soils with coarse texture, dry, low SOM content and high temperature conditions. Approaches to reduce fumigant emissions include management of application methods including equipment design/injection depth, physical barrier, irrigation, amendment with chemicals or organic materials, and target area treatment.

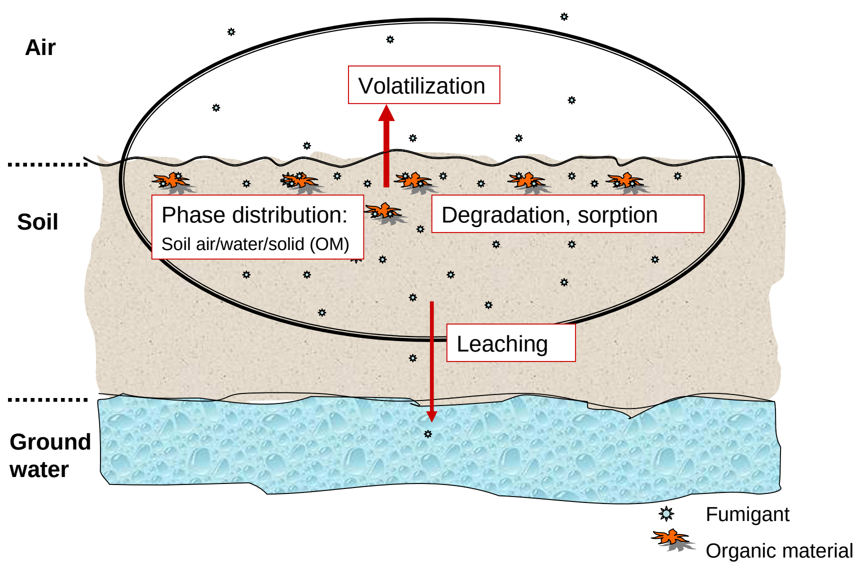

Figure 1. Illustration of processes affecting the fate of fumigants in soil.

Application method. Current fumigant applications include broadcast fumigation and chemigation. Standard broadcast fumigation refers to apply fumigants directly to a certain soil depth using conventional tractor-mounted shank-injection equipment. Chemigation refers to injecting fumigants into soil with irrigation water through sprinklers or drip-tape (drip-application). Application of fumigant to a deeper depth would lead to lower emissions than shallow depth applications. A general consensus is that emissions from drip application, especially subsurface drip application are lower than emissions from broadcast shank injections (e.g., Gao et al., 2008a; Wang et al., 2008). This is because increasing soil water content decreases air pore volume and increases the amount of fumigant partitioning in the aqueous phase. Fumigant diffusion rate in the liquid phase is much slower than through the gas phase. Substantially high soil water content would reduce fumigant distribution in soils; thus it is only possible to ensure good efficacy when fumigant is applied with water (Ajwa and Trout, 2004). However, because of the high volatility of fumigants, drip-applied fumigants near soil surface without barrier may still lead to substantial high emission losses. To date, about half of strawberry acreage especially in the west coastal areas of California has adopted drip-application technique.

Plastic film. Plastic tarp (mulch) is the most commonly used practice for containment of fumigants in soil and to control fumigant emissions. The effectiveness of tarping on emission reductions depends largely on the chemical and tarp permeability and also soil conditions. Tarping with polyethylene (PE) film including both low density or high density (LDPE or HDPE) was found ineffective to control 1,3-D emissions in relatively dry soils. However, HDPE tarp applied over a moist soil profile from irrigation substantially reduced 1,3-D emissions due to water condensation under the film (Gao and Trout, 2007). Tarped treatment with HDPE in a pre-irrigated soil in summer may also benefit overall soil pest control. Shrestha et al. (2006) observed significant reductions in weed populations due to the high temperature under the tarp (up to 47^{o}C).

Use of low permeable films such as virtually impermeable film (VIF) showed great potential to reduce emissions in earlier laboratory or small plot tests. The VIF has much lower permeability to most fumigants than PE films (Papiernik and Yates, 2001). It is a three-layered film composed of barrier polymers such as nylon sandwiched between PE polymer layers (Villahoz et al., 2008). A number of studies have shown that the VIF can retain higher fumigant concentrations than HDPE thus reducing emissions while improving efficacy especially on weed control (e.g., Noling, 2002; Hanson et al., 2008). The effectiveness of VIF on emission reductions in large field applications had been uncertain because of the easy damage to the film and permeability change from field installation. Data obtained most recently confirmed that this type of film can effectively reduce emissions (Ajwa, 2008; Qin et al., 2008b; Yates, 2008). Although the tarp permeability increased after field installation, its permeability was still substantially lower than PE films.

A new type of film, the so called total impermeable film (TIF), has been shown to have easier installation and maintaining its low permeability property in field applications (Villahoz et al., 2008; Chow, 2008). This film has permeability to fumigants 10 times lower than VIF (Ajwa, 2008). It is a multi-layer (e.g., 5 layer) film incorporated with a thin layer of ethylene vinyl alcohol copolymer (EVOH) into a standard PE based film. Field testing on this film for emission reduction has been planned. The industry has been working towards the commercial availability of this film.

Irrigation. With proper management**,** water treatment can be used to minimize emissions. This includes post-fumigation water seal (applying water with sprinklers following fumigation) and pre-irrigation (irrigation prior to fumigant application). The latter is simply to achieve adequate soil moisture if soil is dry but to a level that will not inhibit fumigant distribution in soil profile. Water seal reduces fumigant emissions by forming a high water content layer at the soil surface to serve as a diffusion barrier. Some earlier studies showed that high water content in surface soil provided a more effective barrier to 1,3-D movement than HDPE tarp (e.g. Gan et al., 1998). Intermittent water seals following fumigation have been recognized for effective emission reductions such as on MITC (Sullivan et al., 2004) and 1,3-D or chloropicrin (Gao and Trout, 2007). The effect is more profound on reducing emission peak flux (up to 80% reduction) following fumigant application (Gao et al., 2008b). When irrigation stops, however, emission flux tends to increase depending on fumigant concentrations in soil and, as a result, cumulative or total emission losses may not be reduced as substantially as the peak flux. Reducing the peak flux is important, however, because in addition to reducing the potential exposure risk to workers and bystanders during fumigation, buffer zone distance requirements are based on the peak flux. Although water seals were not found to reduce fumigant concentration and distribution in the soil profile, the high water content in the surface (0-15 cm) soil can decrease pest control at the soil surface (Hanson et al., 2008), thus, sequential treatment for the surface soil may be necessary.

Chemical amendment. Soil amendments with chemicals (e.g., ammonium or potassium thiosulfate (ATS or KTS), thiourea, or polysulfides) are extremely effective for reducing emissions. These chemicals can react with fumigants such as MeBr, 1,3-D, CP and methyl iodide to form non-volatile compounds by dehalogenation (Wang et al., 2000). Application of KTS with water to soil surface showed better control on weeds (Hanson et al., 2007). The practicality of using these chemicals as a field practice to reduce fumigant emissions is inconclusive at this time. Two field trials involving spraying KTS to soil surface following fumigation revealed that this chemical can reduce emissions of 1,3-D and CP significantly (Gao et al., 2008c). However, strong reactions between KTS and the fumigant in soil occurred resulting in a red-brownish soil and a very unpleasant smell that lasted for over a month in the vicinity. This was not observed in a strawberry field trial when KTS was applied to furrows of raised-beds (Qin et al., 2008ab). However, little fumigant emissions occurred from the furrows. Zheng et al. (2007) indicated that the smell may have been derived from further degradation of byproducts of thiosulfate and the fumigants.

Organic amendment. Soil amendment with organic materials such as composted manure has shown effectiveness in degrading fumigants and also reducing emissions in laboratory studies. Because of the strong incorporation of fumigants into organic matter (Xu et al., 2003), soil in high SOM content was reported to give lower emissions (Ashworth and Yates, 2007). However, there is insufficient field data at this time to conclude that organic amendments can effectively reduce fumigant emissions. Yates et al. (2008) reported that a field with incorporation of organic matter in previous year had much lower emissions than a field without the amendment but with water seals. In a field trial, manure incorporation at the rates of 12.4 and 24.8 Mg/ha (~5-10 tons/ac) did not reduce fumigant emissions (Gao et al., 2008c). Much higher manure application rates may be needed to achieve emission reduction from soil fumigation. Higher manure application rates, however, may not be economically feasible for some commodities because of the associated costs. This option may limit to those fields with access to free or low cost organic materials.

Target-area treatment. Fumigation to target areas such as tree rows or tree sites may be applicable for some orchards where pre-plant disease is the major concerns in preventing establishment of healthy crops. Shank application of fumigants in row-strip (shank-strip) or drip-application of fumigant in tree site (drip-spot) have been proposed and tested in field for efficacy of alternative fumigants (Browne et al., 2008). These target area treatment reduces emissions by reducing total treatment acreage to less than 50% (shank-strip) or 10% (drip-spot) of total field area.

Cost. Using low permeable plastic tarps appears the most promising technique in reducing emissions as well as achieving good efficacy. Costs of using HDPE tarp is about $2200/ha including: materials (tarp and glue: $1300/ha), application ($650/ha), and removal and disposal ($250/ha (Gao and Trout, 2006). Low permeability films (e.g., VIF or TIF) are expected to cost 1.5-2 times of PE films. In addition to the high cost, there are concerns on release of fumigants upon removal of the tarp or when planting holes are cut that increase the potential exposure risk to workers. Thus, longer waiting period of time between fumigation and tarp removal may be necessary to allow fumigant degradation in soils. If applicable, injection of thiosulfate under the tarp prior to tarp removal can effectively reduce this risk (Qin et al., 2007) although no field tests have been conducted. Commodities with low profit margin (e.g., stone fruit orchards and annual vegetables) may not be able to afford the costly plastic materials. Water seals, deep injection, drip application or incorporation of high rates of organic materials are the options in these crops. Using water costs much less than HDPE tarp and also offer some environmental benefits because no material disposal is required. The overall cost of using water at present is substantially lower than using plastic tarp. The cost for a 25-mm water application by sprinklers is in the range of $100–800/ha, depending on whether grower owns or rents the sprinkler system (Gao and Trout, 2006). Commercially available composted manure costs are in the range of $15-30/ton. Costs of higher rates than 25 ton/ha may not be feasible for these commodities.

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