Soil Fumigation in Bareroot Tree Nurseries[1]

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Abstract.--This paper gives a general overview of fumigation in bareroot tree nurseries in the United States. Application methods, biological activity, behavior in the environment, risks, to human health, and economics are discussed. Information is presented for the more commonly used fumigants: methyl bromide, chloropicrin, dazomet, metam-sodium, and vorlex.

INTRODUCTION

Chemical fumigants have been used in forest nurseries since the early 1900's when formalin, an aqueous solution of formaldehyde gas, was recommended for control of fungal damping-off (Tillotson 1917). Other chemical fumigants were tested in forest tree nurseries in the late 1940's. Methyl bromide was initially used for weed control, but was also found to control damping-off fungi (Niner 1951), white grubs, and nematodes (Clifford 1951). Ethylene dibromide was found to be both effective and economical in controlling root rot at a southern nursery, costing less than $50 per acre ($123 per hectare) (Henry 1951). Methyl bromide fumigation was considerably more expensive at over $600 per acre ($1482 per hectare) (Clifford 1951).

In the years since those early trials, chemical fumigation of seedbeds has become an accepted pest control practice in forest tree nurseries. A survey of nursery soil fumigation practices in 1981 reported that over 90 percent of southern and western nurseries used fumigants to control a broad spectrum of nursery pests but was primarily used for weed and disease control. Around 90 percent of all soil fumigation was done with methyl bromide and methyl bromide/chloropicrin, with Telone, Vorlex, and Vapam used occasionally (Ruehle 1986). Amore recent survey of Federal nurseries in Washington and Oregon revealed that fumigants still account for 93 percent of annual pesticide use, with methyl bromide/chloropicrin and dazomet the most popular chemicals (table 1).

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Soil fumigation is an interesting topic for several different reasons. It is one of the most <u>expensive</u> cultural operations in a nursery, presently costing around $1,000 per acre ($2470 per hectare) or more. Because of this high cost, chemical fumigation can only be economically ,justified on the most valuable agricultural crops such as seed tobacco, strawberries, and ornamentals. Soil fumigation is also <u>effective</u> it works. As previously mentioned, fumigation is the most effective pest control practice used in forest nurseries today, and nursery managers consider pre-sowing fumigation to be a normal part of the cultural sequence. But soil fumigation has become <u>controversial</u> in recent years because of concern about the safety of these biocides, both at the nursery and in the surrounding area. Other concerns include disposal of fumigation tarps, possible groundwater pollution, and adverse effects on beneficial soil microorganisms. These issues have forced nursery managers to take another look at the soil fumigants that they are currently using and reevaluate other pest management options.

PHYSICAL AND CHEMICAL PROPERTIES OF COMMON NURSERY FUMIGANTS

Four chemicals have commonly been used for soil fumigation in forest nurseries in the United States and Canada in recent years (table 2).

Methyl bromide/chloropicrin (MBC) is available in two common formulations: one containing 2 percent chloropicrin (MBC-2), and another containing 33 percent chloropicrin (MBC-33). The chloropicrin in MBC-33 is an active fumigant, whereas that in MBC-2 is only added as a tracer to the methyl bromide, which has no detectable odor. MBC is available from several different manufacturers under a number of different trade names (table 2). MBC is applied as a pressurized liquid that changes into a gas when injected into the soil. This pervasive fumigant is always covered with a one or two mil [0.001 to 0.002 in. (0.025 to 0.051 mm)] thick plastic tarp, which is impermeable to the fumigant gases.

Table 1 - Average annual pesticide use in Federal forest nurseries in Oregon and Washington

Pesticide	Pounds of Active Ingredient	Percent[1] of Total
Fumigants		
MB-C	33,250	66
Dazomet	13,461	27
SUBTOTAL	46,711	93
Herbicides		
Bifenox	1,425	3
DCPA	420	1
Dicamba	25	<1
Diphenamid	585	1
Glyphosate	44	<1
Oxyfluorfen	320	1
SUBTOTAL	2,819	6
Fungicides		
Benomyl	102	<1
Captan	60	<1
Chlorothalonil	414	1
DCNA	60	<1
Metalaxyl	58	<1
SUBTOTAL	694	<1
Insecticides		
Acephate	3	<1
Carbaryl	3	<1
Chloropyrifos	50	<1
Fenvalerate	15	<1
Malathion	6	<1
SUBTOTAL	77	<1
TOTAL	50,491	100

[1] = < means less than listed value

Source: USDA Forest Service (1989)

Figure 1 - Continuous tarp fumigation consists of glued, overlapping sheets of fumigation tarp which form a solid cover.

Figure 2 - Strip fumigation consists of treating separate strips of the field, and then returning to fumigate the untreated sections.

Figure 3 - Wind can break the glue seal between adjacent strips of fumigation tarp before the exposure period is completed, requiring the area to be retreated.

Two tarping techniques have been used for covering injected fumigants. Continuous tarping is a operation in which each strip of plastic tarp is glued to the previous one, resulting in the entire field being covered with a solid sheet (fig. 1). Another alternative technique is strip fumigation where the fumigant is applied under separate sections of tarp that are covered on both sides with soil (fig. 2). After the prescribed treatment period has passed, the untreated strips of soil must be fumigated to provide complete coverage. Under either system, the tarp must remain intact during the entire fumigant exposure period. If the integrity of the fumigation tarp is broken before the end of the treatment period (fig. 3), then these areas must then be retreated.

Dazomet, also known as Basimid Granular [R], is a unique formulation for a fumigant because it is applied as a very fine granule that converts into a gas when it encounters water in the soil. These "micro-granules"

Table 2 - Physical and chemical properties of common soil fumigants and their application in forest nurseries

Chemical Name	Trade Name(s)	Active Ingredients/ (Breakdown products)	Formulation/Activity	Application Methods
Methyl bromide + chloropicrin	Brom-O-Gas [R] MBC-33 [R] Meta-Brom 98 [R] Namco Pathofume B [R] Pic-Brom 33 [R] Terr-O-Gas 6'7 [R]	Two formulations: 98% methyl bromide + 2% chloropicrin and 6'7% methyl bromide + 33% chloropicrin	Liquefied gas, bottled under pressure. Volatilizes at ambient pressure and temperature	Injected into the soil, and covered with plastic tarp
Dazomet	Basamid-Granular [R]	Tetrahydro-3,5-dimethyl- 2H-1,3,5-thiadiazine- 2-thione (Methyl isothiocyanate)* (Formaldehyde) (Hydrogen sulfide) (Monomethylamine)	Fine crystalline solid Volatilizes after contacting soil moisture	Incorporated into the soil, and sealed with roller and/or water
Metam-sodium	Vapam [R] Metam [R] Soil-Prep [R] Nemasol [R]	Sodium N-methyldithio- carbamate (Methyl isothiocyanate)	Liquid. Volatilizes after application to soil.	Injected into irrigation system, or into soil
Vorlex	Vorlex [R]	80% Dichloropropene/ dichloropropane 20% Methyl isothiocyanate	Liquid. Volatilizes after application to soil	Injected into soil; may or may not be tarped

* = () indicates the breakdown product and active fumigant gas

Source: modified from Thomson (1988)

are normally applied through drop-type spreaders (fig. 4), immediately incorporated into the soil (fig. 5), and physically contained with a roller or water-sealed with sprinkler irrigation. The fumigant activity results from the interaction of a mixture of different gases, the most common being methyl isothiocyanate - MITC (table 2).

Metam-sodium (Vapam [R]) is a liquid fumigant that also converts to MITC gas in the soil (table 2). It can be either injected into the irrigation system and applied through sprinklers, or directly injected into the soil. Although this fumigant can be water-sealed like dazomet, the label recommends that it can be covered with plastic tarp "for better results."

Vorlex is a liquid fumigant that volatilizes into a mixture of different fumigant gases: dichloropropane/dichloropropene, and MITC (table 2). This fumigant is soil-injected, and may or may not be covered with a plastic tarp (fig. 2).

Figure 4 - The fumigant dazomet is a fine "microgranule", which is applied with drop-type fertilizer spreaders.

Figure 5 - After application, the dazomet granules are incoporated into the soil and sealed with a roller or water seal.

BIOLOGICAL ACTIVITY OF MAJOR FUMIGANTS

Although fumigants are commonly thought to be biocides that kill all organisms, there are differences in effectiveness between the different chemicals. The common nursery fumigants are not equally effective against the four major groups of nursery pests: fungi, insects, nematodes, and weeds (table 3). The concept of a "target pest" is important when choosing a control method. Fumigation should never be used as an all-purpose pest control treatment; instead, target pests should be identified and all control options analyzed before a fumigant is used.

Fungi

All fumigants do a reasonably good ,job on the common soil pathogenic fungi, especially at the higher application rates (James 1989). The MBC-33 formulation is the only one that can control the more resistant fungal pathogens such as Cylindrocladium spp. and Macrophomina phaseolina [(Maub.) Ashby] that form resistant resting stages called sclerotia. Luckily, these persistent pathogens are not found in nurseries in cooler environments. Cordell and Wortendyke (1972) provide a good review of the older literature on the relative effectiveness of the methyl bromide formulations compared to other fumigants.

Based on many early trials, MBC-33 became the standard fumigant for forest nurseries in the United States. Dazomet, however, is becoming increasing popular as an alternative to methyl bromide fumigation in recent years. McElroy (1986) tested MBC-33, dazomet, metam-sodium, and vorlex at several Pacific Northwest nurseries and found that all gave good control of Fusarium spp. and Pythium spp., the principal soil pathogens in that area. Tanaka and others (1986) also did fumigation trials at two nurseries in this region, comparing dazomet to MBC-33 at two application rates [the standard 360 lb/ac (404 kg/ha), and a 2X rate]. They also monitored soil populations of Pythium and Fusarium and found that dazomet was nearly as effective as the standard rate of MBC-33, and that the 2X rate of MBC-33 was not ,justified. Campbell and Kelpsas (1988) report that fall fumigation with MBC-33 was more effective than dazomet or metam sodium in

Table 3 - Relative pest control effectiveness of common nursery fumigants

	Fungi	Insects	Nematodes	Weeds
MBC-33*	Yes	Yes	Yes	*Most*
MBC-2	*Most*	Yes	Yes	*Most*
Dazomet	*Most*	Yes	Yes	*Most*
Metam-Sodium	*Most*	Yes	Yes	*Most*
Vorlex	*Most*	Yes	Yes	*Most*

* Methyl bromide/chloropicrin comes in two major formulations: 67%:33'% and 98%:2%

reducing soil populations of Pythium and Fusarium through the spring sowing period. James (1989) reported that, while dazomet and MBC-33 both lower populations of pathogenic fungi, MBC-33 provides a longer period of control.

The relationship of soil pathogen population levels to seedling disease and growth is unclear, however. Tanaka and others (1986) found that MBC-33 gave better control of Fusarium root rot infections and produced significantly larger Douglas-fir [Pseudotsuga menziesii (Mirb.)Franco] seedlings than dazomet. On the contrary, Campbell and Kelpsas (1988) found that dazomet produced significantly larger ponderosa pine (Pinus ponderosa Laws.) seedlings than MBC-33; metam-sodium seedlings were also larger, although the differences were not statistically significant.

Insects and Nematodes

All of the fumigants do a reasonably good ,job of controlling soil insects and nematodes (table 3). Insect damage is rarely severe enough to ,justify fumigation on its own, but nematodes have been the main target pests for fumigation in forest nurseries. MBC fumigants provide excellent control of nematodes in forest nurseries (Ruehle 1975), and the MBC-2 formulation is generally recommended. Both MBC-33 and dazomet at the 350 lb/ac (393 kg/ha) rate controlled populations of the root lesion nematode (Pratylenchus penetrans Cobb), although a lesser rate of dazomet 150 lb/ac = 168 kg/ha) had less effect (McElroy 1986). Peterson and Riffle (1986) caution that, while fumigation greatly reduces the nematode populations in soil, it does not completely eradicate them.

Weeds

Weeds are sometimes the primary target pest for fumigation (Grierson 1989), but none of the fumigants control all species of weeds (table 3). MBC-33 is not as effective for controlling weeds as MBC-2 at standard application rates, but is a good herbicide at a 400 lb/ac (449 kg/ha) rate (Ruehle 1986). Methyl bromide also tends to scarify the seed coat of hard-seeded weed species such as many legumes, and actually stimulate germination immediately after fumigation. This may be beneficial in the case of fall fumigation because the recently germinated weeds are soon killed by frost. Vorlex was found to give less weed control than the other fumigants in a Pacific Northwest nursery (McElroy 1986). Since little data has been reported on which weed species are resistant to which fumigants, it would be wise to contact chemical company representatives and other nursery managers before selecting a fumigation chemical.

Microbial Reinvasion of Fumigated Soil

Because "nature abhors a vacuum", fumigated soil will eventually become recolonized by a full complement of endemic microorganisms, both beneficial and pathogenic. Even the most effective soil fumigation can be ruined if the target pest is able to rapidly reinvade the treated soil.

The most common source of reinvading microorganisms is from adjacent untreated soil, but they can also move up from soil strata underneath the fumigated layer. Reinvasion studies with the pathogenic fungus Fusarium oxysporum f. sp. melonis (Snyd. and Hans.) have shown that, although the fungus could not be isolated from fumigated soil after 6 days, by 32 days, the pathogen was isolated consistently from the outer edges of the treated area. There was also evidence that the fungus was reinvading from lower untreated soil layers because, after 10 weeks, there was a distinct population density gradient from below the fumigated layer to the soil surface (Marois and others 1983). Vaartaja (1967) studied the development of several soil microorganisms after fumigation and found that reinvasion by fungi occurred in several ways: rain splash, irrigation water, blowing dust, and soil carried on boots. Another probable source of contamination is nursery tillage equipment that carries soil from untreated to treated fields.

Rapid reinvasion with beneficial microorganisms is desirable. Many fungal species that form mycorrhizae produce air-borne spores that can blow into fumigated soils within a few months after fumigation. The fungi that form endomycorrhizae, however, are slower recolonizers because their spores are not carried by air and must be reintroduced on soil particles (Marx and others 1989). Actually, beneficial microorganisms may be the first to reestablish in fumigated soil. Fungi of the genus Trichoderma spp. and bacteria are among the earliest colonizers (Vaartaja 1967), and Trichoderma may be responsible for the positive seedling growth response often observed in fumigated soils (Ingestad and Nilsson 1964).

To slow the rate of reinvasion by soil-borne pathogens, nursery managers should reduce obvious sources of recontamination such as transported soil and surface water runoff. Nursery implements should be cleaned before being used in fumigated soil; some nurseries use portable steam cleaners to both clean and sterilize their equipment. Fumigated fields should be physically isolated by a ditch or other type of drainage system to intercept surface runoff which can carry contaminated soil particles or motile spores of water mold fungi. Because reinvasion will eventually occur, nurseries should schedule fumigation as close to the date of sowing as is practically possible. Obviously, fall-fumigated fields are more liable to recontamination than spring-fumigated ones; in many bareroot nurseries, however, fall fumigation is the only option because spring soil temperatures are too low to allow early fumigation. Reinvasion is usually slower in soils which have had pathogen populations reduced to near zero (e.g. after MBC fumigation), as compared to soils where a low residual population of pathogens remain after treatment (e.g. after dazomet fumigation).

APPLICATION CONSIDERATIONS FOR SOIL FUMIGATION

Relative Safety of Application

The primary consideration when selecting a fumigant should be worker safety. All the common fumigants are hazardous chemicals, but the MBC formulations and vorlex are "restricted use pesticides," which means that they can only be applied by specially trained, certified applicators. Because of their concerns about nursery worker safety, many nursery managers choose to contract their MBC soil fumigation. Dazomet and metam-sodium are relatively less hazardous to apply, and so most nurseries do their own fumigation with these chemicals.

Soil Properties

Soil temperature is critical to the effectiveness of all fumigants because the vapor pressure of any gas is a function of temperature. The temperature will, therefore, determine how quickly the fumigant gases pervade the soil particles and also define their persistence in the soil. In the case of the granular dazomet, temperature controls the speed of conversion of the solid particles to a gas (Neumann and others 1984). Warm soil temperatures, in the presence of moisture, also increase the metabolism of nursery pests and make them more susceptible to the fumigants (Boone 1988).

Although some soil fumigants are reported to be effective at colder temperatures, the lower temperature limit for all fumigants should be 50°F (10°C) at a soil depth of 6 inches (15 cm). Because soil temperatures take too long to warm in the spring, most northern nurseries fall fumigate while soils are still warm. Dazomet should not be applied if soil temperatures are too warm, however; Thomson (1988) recommends an upper limit of 90°F (32°C). Soil temperatures can also affect the fumigation technique; tarping is recommended for vorlex if the temperature exceeds 75°F (24°C)(Thomson 1988).

Fumigation effectiveness is also a function of soil moisture content, which should usually be in the range of 50 to 75 percent of field capacity (Boone 1988). Moist soil promotes good tilth which leads to good fumigant penetration. Again, soil moisture stimulates nursery pests to their most susceptible state (germinating weed seeds, fungi in the mycelial state, and emerging nematodes). For the granular dazomet, a soil moisture content of 60 to 70 percent is necessary for rapid conversion to a gas (Neumann and others 1984). The soil seal that is recommended for dazomet, and possibly other similar fumigants, should be maintained by periodic light irrigations for 3 to 5 days after application (Thomsom 1988). Soil can also be too wet for effective fumigation, however. Overly wet soil can form large clods when tilled and also has a high percentage of pores filled with water, both of which restrict fumigant penetration.

The physical condition of a soil is also important for effective fumigation. Soil should be tilled to a moderate-sized crumb structure if possible to generate a large proportion of macropores to carry the fumigant gases. The high surface-to-volume ratio of large clods inhibits fumigant penetration, whereas the numerous small particles that are produced in a overworked soil create micropores that slow movement of fumigant gases.

Soil organic matter content should also be considered. Undecomposed organic matter may inactivate the fumigants (Boone 1988). In the case of dazomet, the effective gases may be bound by the organic matter itself or by the ammonia created as the organic matter breaks down (BASF 1984). Green manure or cover crops should be turned under and organic amendments applied long enough before fumigation to allow complete breakdown. Organic matter may also delay dissipation of the fumigant gases; it is recommended that crops not be sown until at least 30 days after fumigating high organic soils with metam-sodium (Thomson 1988).

Exposure and Aeration Periods

The mandatory waiting period between fumigation and sowing the seedling crop consists of two different intervals: the exposure period, in which the fumigant gas is active, and the aeration period, when the gas is allowed to dissipate from the treated area. The aeration period is normally followed by a germination test (table 4). This consists of sowing seeds from a rapidly germinating species, such as radish or lettuce, in a small sample of soil from the fumigated area. A non-fumigated control soil sample should also be taken at the same time for comparison. Both soil samples should be placed in lidded glass ,jars and watered. At the end of about 5 days, the seedlings should have emerged and be developing normally (fig. 6); poor germination or distorted growth means that some fumigant fumes still persist in the soil.

The recommended number of days for the two fumigation waiting periods depends on soil temperature and weather conditions, but the total period can range from 8 to 50 days for MBC or dazomet (table 4). Dazomet typically requires a longer period under normal nursery fumigation conditions, however; because MBC is immediately converted into a gas, it becomes active more rapidly than the granular dazomet. At a typical soil temperature of 50°F (10°C), the exposure period for dazomet will take 12 days, compared to 3 days for MBC. Wet weather can cause problems with fumigant dissipation, particularly with the granular dazomet. McElroy (1986) reported that 1 inch (2.5 cm) of rain after dazomet fumigation moved the fumigant deeper into the soil; this delayed the escape of the fumigant, resulting in phytotoxicity to the crop seedlings. Similar consequences have been observed with the chloropicrin component of MBC (McElroy, personal communication).

Table 4 - The effect of soil temperature on fumigation waiting periods

	Methyl Bromide/ Chloropicrin	Dazomet
Fumigant Applied and Soil Sealed		
Exposure Period (Gas Activity)	1 to 3 days	4 to 25 days
Tarp Removed or Soil Seal Broken		
Aeration Period (Gas Escapes)	2 to 14 days	2 to 20 days
Test For Residual Fumes		
Germination Testing	5 days	5 days
Sow Crop		
Total Waiting Period	8 to 22 days	11 to 50 days

Source: BASF (1984)

Figure 6 - At the end of the aeration period, a germination test should be performed on the fumigated soil to make certain that it is safe to plant the crop.

ECONOMICS OF SOIL FUMIGATION IN FOREST TREE NURSERIES

Because fumigation is such an expensive cultural practice, it is necessary for nursery managers to provide economic ,justification. In a successful nursery operation, economic realities mandate that the costs of fumigation be offset by the benefits of the practice.

Fumigation Costs

The cost of fumigation can be prohibitive in smaller nursery operations, where cash flow problems make it difficult to come up with the money for fumigation so early in the crop cycle. Fumigation is also less expensive for larger nurseries because many fumigation contractors have the same set-up charge regardless of the amount of acres to be treated. Nurseries in remote locations are also at an economic disadvantage because contractors must reflect travel costs in their fees. One way to save money on fumigation contracts is to coordinate the timing of fumigation with other nurseries in the general area so that the contractor can visit each operation on an efficient travel circuit.

Soil fumigation costs can vary between chemicals. Campbell and Kelpsas (1988) reported that the per-unit chemical cost of applying MBC-33 was similar to dazomet, while the metam-sodium chemical costs were less. The 1989 soil fumigation costs for the 10 USDA Forest Service nurseries averaged around $1,200/ac ($2,964/ha) for MBC contracts, and around $1,000/ac ($2,4T0/ha) for nursery-applied dazomet (table 5). These figures reflect chemical and application costs, as well as the cost of tarp removal in the case of MBC.

Table 5 - Statistics on soil fumigation costs for USDA-Forest Service nurseries in 1989.

	Fumigation Costs Per Acre	
	Contract Application	Nursery Application
Methyl bromide/chloropicrin		
Number of nurseries	5	1
Average	$ 1,137	$ 902
Range	$942 to $1280	N/A[1]
Dazomet		
Number of nurseries	0	4
Average	N/A	$1,032
Range	N/A	$938 to $1173

[1] N/A = Not applicable

Benefits from Fumigation

The benefit side of the economic scale can be subjective, and figures are often outdated because the comparisons were only done when fumigation was first implemented. One easy way to determine fumigation benefits is to leave one or more small "check" or untreated areas in the seedbed so that seedling yield information can be compared to fumigated areas. Growth information, such as seedling height, caliper, biomass, and root growth, should be collected at intervals during the growing season because the benefits are sometimes only visible at one time during the rotation. The true test of fumigation benefits, however, is to harvest seedlings from each area and have them graded; this will generate actual "shippable seedling" data that can be converted back into dollars and compared to fumigation costs.

BEHAVIOR OF FUMIGANTS IN THE ENVIRONMENT

Because fumigants are highly toxic pesticides, there is widespread concern that they or their breakdown products may contaminate the water, air, or soil in the nursery or in adjacent areas. The physical properties of fumigants determine how readily they move or persist in the environment after application; environmental factors, such as soil characteristics and amount of rainfall, also influence contamination potential and persistence. Several physical characteristics for MBC and dazomet determine their pollution potential in the environment (table 6).

Water Quality

Both surface and groundwater can become contaminated with pesticides from surface water runoff or leaching through the soil profile. The likelihood that a particular fumigant will contaminate water is dependent on a number of factors, including soil characteristics, pesticide characteristics, the local climate, amount of precipitation and/or irrigation, number of applications of the pesticide, rate at which the pesticide is applied, surface and groundwater hydrology of the site, drainage system at the site, and cultivation practices used at the site to increase infiltration (USDA Forest Service 1989).

The most significant factors affecting water pollution by pesticides are solubility in water and leaching potential (table 6). Pesticides must first dissolve in the soil water before they can leach downward. The situation concerning the solubility of fumigants in water is confusing because the solubility of a gas in water is usually measured under greater atmospheric pressure than that normally encountered in nursery soil (Chemical Fate Testing Guidelines 1983). Even though MBC is given a "moderate" solubility rating in water (table 6), it is estimated that only about 0.1 % of the applied MBC would ever leach from the nursery soil (USDA Forest Service 1989). Even though dazomet has a "high" water solubility rating, the leaching potential for its principal active ingredient (MITC) is negligible due to its rapid degradation in the soil and its high volatility (table 6). In fact, no groundwater contamination by methyl bromide, metam sodium, or MITC has yet been detected in the United States (Parsons and Witt 1988), although traces of MBC were identified in groundwater in Holland (Rattink 1984).

Table 6 - Effect of physical properties of methyl bromide/chloropicrin (MBC)and dazomet on water, soil, and air pollution

Pollution Site	MBC	Dazomet
Water		
Solubility in water[1]	Moderate	High
Leaching potential	Low	Negligible
Soil		
Persistence in soil[2]	Low	Low
Decomposition mode	Biological and chemical	Chemical
Air		
Volatility[3]	High	High

[1] Solubility is rated as High (> 100 ppm), Moderate (1-100 ppm), and Low (< 1 ppm).

[2] Persistence is rated in half-lives: High (> 180 days), Moderate (30-180 days), and Low (< 30 days).

[3] Volatility is rated in vapor pressure units: High (> 1.00 mm Hg), Moderate (0.001 - 1.00 mm Hg), and Low (< 0.001 mm Hg).

Source: USDA-Forest Service (1989)

Groundwater contamination by 1,2-dichloropropane and 1,3-dichloropropene, two components of the fumigant vorlex, has been detected in a number of states (Parsons and Witt 1988). However, it has not been determined that these occurrences were due to vorlex contamination because these two chemicals are found in other fumigants, such as D-D, and are also used for other non-agricultural purposes.

Surface water run-off can occur when rainfall or irrigation exceed the infiltration capacity and water flows over the soil surface or when water moves laterally through the soil profile into a surface water source such as a stream or drainage ditch. Surface water can become polluted either directly with soluble pesticides or when non-soluble pesticides are adsorbed onto soil particles and carried along with surface water flow. The surface water run-off potential for MBC is considered negligible (USDA Forest Service 1989); the situation for dazomet, vorlex, or metam-sodium is unclear but should not be significant.

Soil Quality

Two physical characteristics of fumigants that affect the soil pollution potential are persistence in soil and the type and rate of decomposition.

The soil persistence of MBC is rated low (table 6) because MBC is rapidly broken down by both biological and chemical means (USDA Forest Service 1989). MBC and inorganic bromide residues are absorbed by plants and animals; MBC is metabolized and the inorganic residues are relatively non-persistent. There is very little information about the environmental fate of chloropicrin, including its persistence in the soil (USDA Forest Service 1986).

Following incorporation, dazomet is also relatively non-persistent in soil (table 6). This fumigant chemically breaks down into many different products, all of which are lost from the soil within a few days through further degradation and volatilization, which are dependent on soil moisture and temperature. Soil type and pH also influence the effectiveness of the fumigant and its rate of breakdown. Soils with high clay or organic matter content can bind MITC, thus reducing its effective concentration (BASF 1984) and intermediate pH values (around 6.5) maximize degradation. (USDA Forest Service 198T). There is little information on metam-sodium, but, since MITC is the primary breakdown product, its behavior in soil should be similar to that of dazomet.

Persistence of 1,3-dichloropropene (1,3-D, a component of vorlex) in the soil is considerably higher; the half-life of 1,3-D is 14 to 180 days, depending on environmental conditions. 1,3-D disappears through degradation (biological and non-biological hydrolysis), dispersion through the soil, volatilization into the air, and irreversible binding to soil particles. Temperature and soil moisture influence the rate of these processes (USDA Forest Service 1987).

Air Quality

Since fumigants are gases or volatilize after application, there is potential for drift into adjacent areas (table 6). The labels on all four fumigants direct the applicator to seal the soil surface in some fashion (water seal, rolling, or plastic seal) after application. If properly

Table 7 - Toxicity of common nursery fumigants in relation to other chemicals

Toxicity Category	Pesticide Label Signal Words	Pesticides and Other Chemicals	Acute Toxicity [1] Oral LD_{50}	Acute Toxicity [1] Other
I-Severe	Danger-Poison		0-50 mg/kg	
		Chloropicrin	38	Dermal = 100 mg/kg Inhalation = 0.178 to 150 mg/l
		Nicotine	50	
II-Moderate	Warning		50-500 mg/kg	
		DDT	100	
		Caffeine	200	
		Methyl bromide	214	Inhalation = 4.5 mg/l
		Dazomet	363	Dermal = 200 to 10,400 mg/kg Inhalation = 302 to 60,000 mg/l
		Vorlex	538	Dermal = 470 to 961 mg/kg Inhalation = 11 mg/13
III-Slight	Caution		500-5,000 mg/kg	
		Metam-sodium	820	
		Aspirin	1,700	
		Table Salt	3,750	
		Glyphosate	4,320	
IV-Very	Slight Caution		5,000-50,000 mg/kg	
		Oxyfluorfen	5,000	
		Captan	9,000	
		Ethyl alcohol	13,700	

[1] Oral and dermal ratings are measured in lethal doses (LD50), and inhalation ratings in lethal concentrations (LC50) - the amount of pesticide per unit of body weight that is required to kill 50% of the test animals. These values are only examples of some study results - published values may vary considerably.

Sources: USDA Forest Service (1989); USDA Forest Service (1987); Bohmont (1983); Great Lakes Chemical Company (1989); Thomson (1988) applied, damaging aerial concentrations of a fumigant should occur rarely, due to the restrictive seal, rapid degradation of the fumigant, and the large volume of air into which it can disperse if it escapes through the seal. However, if the seal is poor or weather conditions prevent rapid dispersion (for example, an inversion layer), toxic fumigant concentrations may build up and injure adjacent plants, animals, or people. Myers (1989) reports that, following MBC fumigation at a forest nursery, an air inversion caused a local accumulation of MBC gases; they had apparently escaped through the tarp and caused minor health effects to residents living near the nursery. Forest nursery managers have reported fumigant damage to adjacent seedlings for both MBC and dazomet. White pines seem to be particularly susceptible to dazomet fumes (Scholtes 1989), whereas Douglas-fir is sensitive to MBC (Myers 1989).

EFFECTS OF FUMIGANTS ON HUMAN HEALTH

All pesticides are poisons, and fumigants are among the most acutely toxic pesticides used in bareroot forest nurseries. It should be remembered, however, that the actual hazard of any chemical is a function of both toxicity and exposure. If fumigants are applied by trained, certified applicators and according to label instructions, the potential health hazards can be

Table 8 - Potential health hazards of common nursery fumigants

Fumigant	Known Health Hazards
Methyl bromide	Exposure Symptoms - Although it has no odor, methyl bromide causes severe chemical skin burns, swelling of bronchial membranes, and kidney damage. Small amounts will cause nausea and vomiting, and may lead to mental confusion, double vision, tremors, lack of coordination, and slurred speech. Continued exposure leads to coma and death.
	Cancer - Variable information.
	Reproductive/Developmental - Organ weight variation in offspring of rats; fetal and maternal toxicity.
Chloropicrin	Exposure Sumptoms - Chloropicrin has an obnoxious odor and was used as a chemical warfare agent in World War I. It is extremely irritating--causing tearing, swelling of bronchial membranes, gasping, and vomiting. Severe exposure may result in irregular heartbeat and asthma.
	Cancer - Insufficient information.
	Reproductive/Developmental - No information.
Dazomet	Exposure Symptoms - Dazomet is irritating to skin and eyes.
	Cancer - None observed in animal studies.
	Reproductive/Developmental - No information on dazomet, but methyl isothiocyanate causes maternal toxicity and fetal death in animals.
Vorlex	Exposure Symptoms - Highly irritating to eyes, skin, and lungs.
	Cancer - Methyl isothiocyanate is not carcinogenic in animals, but 1,3-dichloropropene appears to be.
	Reproductive/Developmental - No information on vorlex, but xylene, one of the ingredients, causes birth defects in animals.

Sources: USDA Forest Service (1989); USDA Forest Service (1987); Bohmont (1984); Thomson (1988); Great Lakes Chemical Company (1989).

reduced to acceptable levels.

All chemicals, including pesticides, can be ranked according to the dose of the chemical required to kill half of a population of test animals; this dose is known as the LD_{50} (table 7). Although oral exposures are most frequently used to determine LD_{50}, other types of chemical exposure are more relevant for fumigants. With all fumigants, there is a risk of inhalation exposure due to their gaseous nature at the time of application or shortly after. Because dazomet is applied as a fine granule, inhalation of granules could be significant as well. There is a dermal exposure hazard with both MBC if skin comes into contact with the pressurized liquid, and dazomet if granules contact the skin.

The common nursery fumigants vary considerably in their toxicity, ranging from the severe to the slight category (table 7).

MBC is the most toxic fumigant used in forest nurseries because chloropicrin ranks in the severe category and methyl bromide is in the moderate category (table 7). Chloropicrin, also known as "tear gas", is extremely irritating to eyes and skin (table 8). Concentrations as low as 2 ppm can be lethal if inhaled for as little as 1 minute, and concentrations of 0.1 ppm can be injurious over longer periods (Thomson 1988). Pure methyl bromide is relatively less toxic than chloropicrin and is rated in the moderate toxicity category (table 7). This fumigant is particularly dangerous to use because it is colorless and odorless. Chronic exposure to methyl bromide causes severe health hazards (table 8); exposure to 2,000 ppm of methyl bromide for 1 hour may be lethal (Thomson 1988).

In formulations containing a mixture of methyl bromide and chloropicrin, exposure time to excessive amounts is usually very short; this is due to the extremely irritating nature of the chloropicrin which compels the person being exposed to quickly move from the area. Information about the cancer-causing ability of MB and chloropicrin is varied. For chloropicrin, there is no information regarding carcinogenicity. For MB, some carcinogenic effects are reported (Great Lakes 1989) although very recent reports indicate no cancer effects (Sargent 1989).

Dazomet and vorlex share a common active ingredient (MITC), and rank in the moderate toxicity category (table 7). Dazomet does not break down into a gas until it contacts soil moisture; because of this, it is easier to control than an injected gas. The micro-granule formulation of dazomet can be irritating to skin and eyes (Thomson 1988). Although dazomet has not caused cancer in animal studies, other health effects have been observed (table 8).

Metam-sodium also breaks down into MITC, but is slightly less toxic than dazomet or vorlex, which places it in the slight toxicity category (table 7). Metam-sodium can be irritating to skin, eyes, and mucous membranes (Thomson 1988), but the risk of cancer from exposure to MITC is apparently low (table 8).

Quality of Fumigant Exposure Data

The quality of information on the effects of fumigants on human health is marginal or inadequate in some areas (tables 8 and 9). The published

Table 9 - Quality of nursery pesticide database for each toxicity category.

Fumigant	Systemic	Carcinogenic	Reproductive/ Developmental	Mutagenicity	Neurotoxicity	Immunotoxicity
Methyl bromide	Adequate	Sufficient: new studies could change conclusions	Marginal: variable results	Adequate	Adequate	Inadequate
Chloropicrin	Adequate	Marginal: variable results	Inadequate	Marginal: variable results	Inadequate	Inadequate
Dazomet	Sufficient: new studies could change conclusions	Adequate	Sufficient: new studies could change conclusions	Marginal: variable results	Sufficient: new studies could change conclusions	Marginal: variable results

Source: USDA Forest Service (1989).

information can be categorized by six types of toxicity: systemic, carcinogenic, reproductive and developmental, mutagenicity, neurotoxicity, and immunotoxicity (table 9). Very little work is done on humans; human data is usually derived from accidents or from operational exposure. Therefore, most tests have been done on animals, such as rats or rabbits, and much of the available information is difficult to interpret and compare because different units were used and results were variable. Table 9, however, categorizes the general state of data (adequate, sufficient, marginal, or inadequate) from available published animal studies.

Human Health Risks

When determining the danger of a particular pesticide, both the toxicity of the material, as well as the probability of exposure, are important. The nursery workers at greatest risk for exposure to fumigants are those involved in applying them: tractor drivers, shovelers, and tarp lifters (table 10). Other nursery workers, such as weeders or inventory crew, will have almost negligible risk since they are in the fields after the fumigant has long since dissipated. For the general public, including residences adjacent to the nursery, there is more potential risk of exposure to fumigants than other pesticides due to the gaseous nature of the fumigants allowing them to diffuse and be carried away from the site of application and onto neighboring property.

The probability that detrimental health effects will occur has been estimated, based on Threshold Limit Values (TLV's), for the various workers involved in fumigant application and for the general public (table 10). A TLV is the estimated maximum concentration for an 8-hour workday exposure that will not result in any adverse effects. Workers using MBC-33 are at the highest risk because their estimated doses for chloropicrin exceed the TLV. Workers applying dazomet are at a lower risk because their estimated doses are less than the TLV (table 10). Risks associated with dazomet application should be further reduced by the lag time between application and formation of toxic compounds in the soil. Gases from both MBC and dazomet can drift for some time after application and may cause workers and neighbors to experience some degree of minor irritation. Although there are not documented cases of serious injury to these people, fumigant drift under certain weather conditions have caused concern (Myers 1989).

FUTURE AVAILABILITY OF FUMIGANTS

For the past few years, nursery managers have expressed concern about the possibility that the use of some fumigants, particularly MBC, will be severely restricted or banned. This is a legitimate concern because other fumigants have been banned after they were detected in groundwater in agricultural areas. A soil fumigant (DBCP) is the most widespread pesticide contaminant of groundwater in the United States, and its use was suspended in 1979. Since then, other fumigants have also been detected in groundwater and subsequently removed from the market: D-D, a nematicide, along with EDB, a close chemical relative of MBC (Russell and others 1987). Because of this "guilt by association," groundwater is being tested across the country for MBC, but it has not been detected as of this date (Parsons and Witt 1989). It is considered unlikely that MBC would ever be detected, however, because it rapidly dissociates into inorganic bromide and a methyl-containing substance before reaching

Table 10 - Probability of health hazards for public and workers exposed to common soil fumigants

Fumigant	Public	Fumigation Applicators[1]		
		Driver	Shoveler	Tarp lifter
Methyl bromide	Low	Moderate	Moderate	High
Chloropicrin	Moderate	High	I[2]	I
Dazomet	Low	Moderate	N/A[2]	N/A

1 Average exposures per workday, based on historical data of workers not wearing protective clothing.

2 I = Insufficient information; N/A = Not applicable

Source: USDA Forest Service (1989)

groundwater supplies (Bentson and Lavey 1989).

Another concern about the future of soil fumigants is the possible link to cancer. MBC is particularly suspect because it is considered a possible mutagen in humans (USDA Forest Service 1989), and the closely-related EDB has already been shown to be a potent carcinogen in animals (Russell and others 1987). Although further cancer testing is underway for both methyl bromide and chloropicrin, the results are inconclusive so far (USDA Forest Service 1989).

At the present time, however, none of the four currently used fumigants (MBC, dazomet, metam-sodium, or vorlex) are in any danger of losing their pesticide registration in the United States. We specifically inquired about the re-registration status of the MBC fumigants and company representatives and EPA scientists informed us that they will continue to be available to the agricultural community (Andersen 1989).

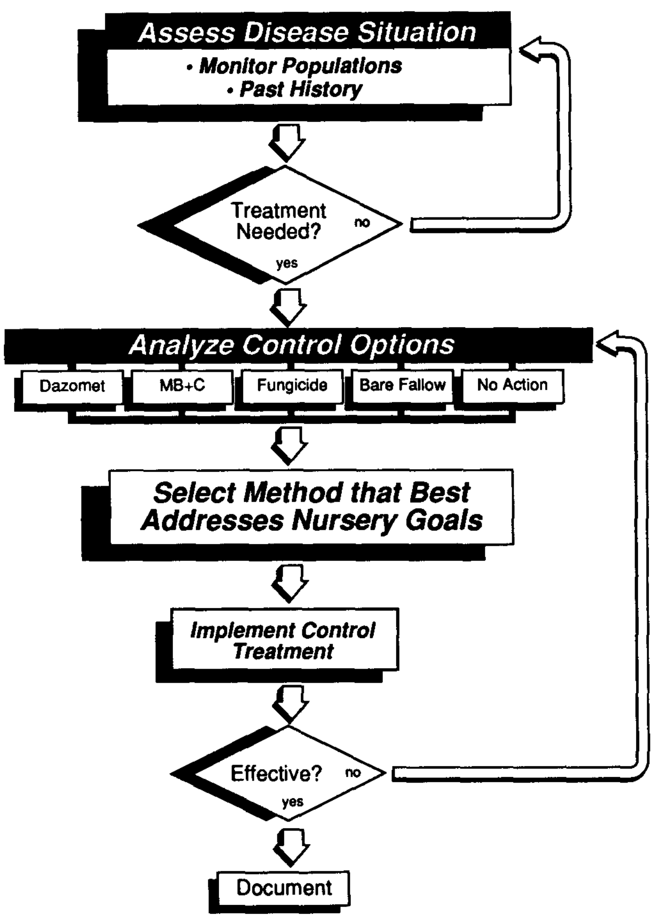

Figure 7 - A flow chart can help nursery managers think through the sequential steps in a integrated pest management (IPM) program. This example shows the sequence of events for managing a soilborne disease problem.

CONCLUSIONS AND RECOMMENDATIONS

Although fumigants are extremely toxic pesticides, they are relatively not persistent in the environment, they have immediate severe health risks, but long-term risks are not much more severe than other pesticides. If properly applied with adequate precautions, they can continue to be a major weapon in the chemical arsenal.

Fumigation and Integrated Pest Management

Soil fumigation, along with other cultural activities and pesticides, should always be viewed in the larger context of an overall nursery pest management plan. Progressive nurseries have begun to define their pest management activities in the context of Integrated Pest Management (IPM). IPM in forest nurseries can be defined as:

> "Integrated nursery pest management is the maintenance of seedling pests at tolerable levels by the planned use of a variety of preventive, suppressive, or regulatory methods (including no action) that are consistent with nursery management goals. It is implicit that the actions taken are the end-result of a decision-making process where pest populations and their impact on hosts are considered and control methods are analyzed for their effectiveness as well as their impact on economics, human health and the environment" (USDA Forest Service 1989).

Use of a fumigant, like any other pest control method, must be analyzed for the entire range of nursery effects:

* control of the target pest
* impact on seedling growth and survival
* cost of application
* effect on the environment
* hazard to worker health and public safety.

Selection of a pest control method to control a specific target pest will depend on the priorities and resources of the nursery. Pesticides are no longer applied based solely on their ability to control a pest or because they are considered to be more cost effective than other methods. Other issues, such as risk to human health, may drive the decision to use or not use a particular pest control method.

The decision-making process for managing soil-borne pests in a forest nursery can be illustrated with a flow chart which shows both the steps and the order in which they are taken (fig. 7). In this flow chart, there are several key steps:

1. Determining whether or not there is a pest problem in need of treatment

2. Deciding which pest control methods are available to reduce or prevent crop damage

3. Analyzing the benefits and drawbacks of each method

4. Selecting the best pest management method in accordance with the goals and priorities of the nursery

5. Implementing pest treatment

6. Evaluating the treatment for effectiveness

Documentation is an important yet often neglected part of an IPM program. Adequate documentation includes figures on pest population trends, type of control treatment (what was used, rates, dates of application, etc.), and treatment effectiveness, but there should also be some documentation of the analysis and rationale used for selecting the treatment to aid in future decisions.

If fumigants are analyzed and applied in a comprehensive IPM context, nursery managers can be assured that they are acting in a logical, environmentally sound manner and will continue to be able to use these effective pesticides.

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