FEATURE ARTICLE

Supplement to Journal of Nematology 22(4S):632–644. 1990.

Soil Fumigation: Principles and Application Technology[1]

H. W. Lembright[2]

Abstract: The principal soil fumigants and their order of discovery are carbon disulfide, chloropicrin, methyl bromide, 1,3-dichloropropene, ethylene dibromide, 1,2-dibromo-3-chloropropane, and methyl isothiocyanate. Biological activity of soil fumigants ranges from limited to broad spectrum. Fumigants diffuse through the continuous soil air space as gases. Physical and chemical characteristics determine diffusion rates, distribution between the soil air and moisture, and sorption onto and into the soil particles. The principal soil factors affecting the efficacy of each treatment are the size and continuity of air space, moisture, temperature, organic matter, and depth of placement. Application can be made overall with tractor injection or plow-sole, or as a row or bed treatment. Treatment for trees is best made in conjunction with tree site backhoeing.

Key words: application technology, backhoeing, chemical control, chloropicrin (Pic), fumigation depth, 1,3-dichloropropene (1,3-D), fumigant, methyl bromide (MBr), methyl isothiocyanate (MIT), nematicide, soil fumigation, ethylene dibromide (EDB), 1,2-dibromo-3-chloropropane (DBCP).

The practice of soil fumigation was initiated in 1869 with the discovery that carbon disulfide effectively controlled grape phylloxera, *Phylloxera vitifoliae* (Fitch), attacking the roots of grapes (*Vitis vinifera* L.) in France (46). Over the next century several cost effective biocidal fumigants were developed including chloropicrin (Pic), methyl bromide (MBr), 1,3-dichloropropene (1,3-D), ethylene dibromide (EDB), 1,2-dibromo-3-chloropropane (DBCP), methyl isothiocyanate (MIT), and MIT-generating compounds. Because of flammability, high application rates, and cost, carbon disulfide is seldom used today. In May 1979, DBCP was discovered in groundwater in California, which ultimately led to it being withdrawn from most of the global marketplace. A short time later EDB was banned for the same reasons. Thus increasing concern about groundwater contamination and improved capabilities for chemical detection were the primary reasons for withdrawal of two soil fumigants from the marketplace.

Soil fumigants vary considerably in their spectrum of biocidal activity. Carbon disulfide is a broad-spectrum biocide, but it requires relatively high treatment rates. Chloropicrin is the biocide with the broadest spectrum of control (21,33,39). Its cost usually restricts usage to combination formulations with MBr and 1,3-D, in which it improves the spectrum of biological activity. Although 1,3-D is used primarily as a nematicide, it can be the most cost-effective fumigant against certain specific types of fungi and weeds (5,27,28). MIT is formulated in combinations with 1,3-D, which are somewhat comparable in efficacy to mixtures of 1,3-D and Pic. MIT-generating compounds, primarily metam sodium, depend upon soil moisture for hydrolysis to produce MIT. These compounds have functioned best when applied in irrigation water (1,38).

Soil fumigants are unique soil pesticides. They are capable of diffusing and forming a distribution pattern throughout the soil profile (9,10,12–14,31,34,47,48). The magnitude of their diffusion pattern is regulated by certain physical characteristics (Table 1). Usually they are injected as liquids into the soil through tractor-drawn chisels. The liquids vaporize and begin diffusing outward from the lines of injection through the soil air space. While diffusing, the largest percentage dissolves into the films of soil moisture, and somewhat comparable quantities subsequently sorb onto the soil solids (31). The ability of fumigants

---

Received for publication 13 March 1990.

[1] This manuscript was prepared by invitation from the Society of Nematologists.

[2] Retired, formerly Research and Development, Dow Chemical USA.

TABLE 1. Physical properties of four soil fumigants.

	Vapor pressure (mm Hg at 20 C)	Solubility in water (% w/w at 20 C)	Distribution		
			Weight ratio† (W/A)	Air‡ (%)	Water‡ (%)
Methyl bromide	1,380.0	1.600	4.1	24.4	75.6
Chloropicrin	20.0	0.195	10.8	9.3	90.7
1,3-dichloropropene cis- and	18.5–25.0	0.275	17.7–24.6		
trans-isomers (avg.)	21.8		21.2	4.7	95.3
Methyl isothiocyanate	21.0	0.760	92.0	1.1	98.9

Adapted from Goring (10).

† Ratio of weights of chemical in equilibrium, in equal volumes of water (W) and air (A) at approximately the same temperature.

‡ Same ratio expressed as a percentage distribution in the soil water and air phases.

to control soil pests is determined by the concentration and time that they are present in the soil water films (9,31). Dosages delivered within the soil profile vary with time and distance from their point of application, establishing concentration gradients radiating out from the lines of injection. As with other pest control practices, the objective of soil fumigation is not pest eradication but rather pest population reduction. Reduction must be of a sufficient magnitude so that population densities are unable to rebuild to levels that would adversely affect production and quality of the crop.

Root-knot nematodes (*Meloidogyne* spp.) and some other phytoparasitic nematodes have the capability of being able to penetrate, feed, and reproduce at relatively great depths in the soil (35). This is not a common characteristic among other groups of pathogenic soil organisms. Also, the distribution and abundance of *Meloidogyne* spp. through the soil profile follow the same distribution patterns as the plant roots. Certain nematodes also reside within roots, and complete control requires root penetration by the pesticide. The qualities of root penetration and deep soil movement are unique to 1,3-D and MBr. Fortunately, these two fumigants also degrade readily within the soil profile (2,42).

Because of environmental and economic considerations, soil fumigants should be applied under optimal soil conditions so that treatment rates are the most efficient possible. To do otherwise could jeopardize their long-term usefulness and availability.

PRINCIPLES OF SOIL FUMIGATION

The principal factors affecting soil fumigant performance are soil type and texture, diffusion, dosage, air space, moisture, temperature, organic matter, and application technologies. Soil fumigation is a dynamic process influenced by various soil characteristics. That these soil characteristics also influence each other complicates the process. The objective of soil fumigation is attainment of the greatest degree of nematode reduction with the least economic input. Thus it is important to understand each of the factors that regulate fumigant diffusion and influence pest and disease control.

Soil: The soil is a matrix of inorganic and organic solids, water, and air. The pore space is made up of water and air. Field soils vary considerably in their homogeneity, resulting in varying soil profiles and, consequently, variable fumigant distribution patterns.

Diffusion: Fumigants volatilize, and diffusion through the soil air spaces occurs primarily as a gas. Diffusion is affected by the size and continuity of the air spaces. Diffusion is 10,000–30,000 times greater through soil air space than through soil water films (9,11). When fumigants are applied in irrigation water, they must be in solution, so that the water itself becomes the vehicle for pesticide distribution. The principles of water movement then regulate fumigant dispersal. The diffusion of the gaseous phases of a fumigant is not affected by gravity. Movement would be

TABLE 2. Dosage response data for various nematodes exposed to cis- and trans-isomers of 1,3-D at various temperatures.

Nematode	1,3-D isomer	Temp. (C)	LD95† (ppm day)	LD99.99† (ppm day)
Meloidogyne javanica	cis-	25	22	23
(second-stage juvenile)	cis-	15	27	28
	cis-	5	92	97
	trans-	15	36	
Meloidogyne incognita	cis-	25	21	
(second-stage juvenile)	trans-	25	35	
Heterodera schactii				
(second-stage juvenile)	cis-	25	21	24
(white cyst)	cis-	25	36	44
(white cyst)	trans-	25	75	
(brown cyst)	cis-	25	106	112
(brown cyst)	trans-	25	180	187

Adapted from McKenry and Thomason (31).

† Lethal dosages LD95 and LD99.99 expressed as concentration (ppm) × time (days).

equal in all directions if the soil air spaces and their continuity were of uniform size and distribution. This situation never occurs under field conditions. The fumigant moves from areas of high concentration to low concentration. As fumigant molecules approach recently disturbed zones or the soil surface, their movement can become less restricted. When fumigants are applied in a broadcast pattern, the outward diffusion patterns from the lines of injection produce cylinders of effectively fumigated soil. If the injection shanks are properly spaced, the cylinders of fumigated soil overlap and produce relatively uniform control in the horizontal plane. The variations in control occur in the vertical plane.

Dosage: The dosage (D) is the product of the pesticide concentration (C) and the time (T) of its presence at the target (9,31). The effective dosage is subject to many factors such as distance from injection, degradation, etc. The dosage delivered to the moisture films affects the control of most organisms. However, with larger insects that respire and live closer to the soil surface, the concentration in the air phase is more important. Entomologists first used this quantitative dosage relationship for insect control in space fumigations (3).

Some of the lethal dosages for 1,3-D against nematodes are in Table 2. The different C × T values result from the effect of temperature and from different nematode species and stages of development. The 1,3-D fumigant consists of cis- and trans-isomers. The cis-isomer is more active, but the trans-isomer has a longer half life, making both about equally active under field conditions. The actual 1,3-D dosage values listed (Table 2) and associated relative values (Table 3) provide guidelines for establishment of eventual treatment rates. If 1X is used as a base value for the most susceptible stage, i.e., the second-stage juvenile of *Meloidogyne* spp. and *Heterodera* spp., then eggs would require about 2X. Mature and aged eggs within the brown cysts of *Heterodera schactii* Schmidt would

TABLE 3. Toxicant level of 1,3-D required for 99.9% control of selected organisms at soil temperatures above 15 C.

Organism	Toxicant level†
Meloidogyne spp., second-stage juveniles	1X
All stages of *Meloidogyne* spp.	
Within 1.25-cm-d grape roots	8X
Within 1.25-cm-d fig roots	7X
Xiphinema index, all stages	1–2X
Roots of 12-month-old Thompson Seedless or Ruby Cabarnet grapes	3.3X

Adapted from McKenry et al. (32).

† Relative level of toxicant (dosage) required to kill nematodes within roots of plants.

require almost 5X, and *Meloidogyne* spp. within roots would require 7–8X. Field experience suggests that difficult-to-control stages of nematodes, such as anhydrobiotic stages of *Rotylenchulus reniformis* Linford & Oliveira, probably require 5–8X.

Soil texture: Coarse-textured soils in good tilth have the greatest pore sizes and potential for the greatest percentage of continuous soil air spaces. Fine-textured soils have relatively small pore spaces and more discontinuity among them, thus restricting diffusion and the volume of soil that can be fumigated effectively. The primary effect of reduced soil air space and continuity is the development of steep concentration gradients radiating out from the lines of application. This results in a much reduced volume of effectively fumigated soil. The coarse-textured soils have much flatter concentration gradients, resulting in far greater volumes of effectively fumigated soil. Coarse-textured soils range in particle size from coarse sand and gravel to fine sandy loam. The latter contain significant amounts of silt and clay, making them subject to soil compaction, due to equipment travel, rainfall, and irrigation. Compaction reduces pore sizes and continuity. Tillage of compacted soil can produce clods which further restrict penetration by fumigants. Clays are very fine textured and more difficult to fumigate effectively, not because they lack air space, but because the air spaces are much smaller and there is greater discontinuity. Because of origin and structure, some fine-textured soils can be well aggregated with pore spaces similar to those of the coarsest sand and gravel (7).

Soil air space: Maximizing soil air space and continuity should be a primary objective in soil preparation and timing of treatment to optimize the speed and soil volume in which the fumigant will distribute itself at effective concentrations and for adequate exposure periods. The rate of movement of a toxicant is directly proportional to the concentration of the toxicant and its diffusion coefficient (11).

Soil moisture: Soil moisture content usually has the greatest impact on altering the size of the soil air spaces and their continuity. The eventual biological activity against certain target organisms (such as weed seeds) is also affected by the soil moisture content or, more precisely, the relative humidity (RH) of the soil atmosphere. A soil atmosphere with 100% RH appears optimum for maximum biological activity (39). This generally occurs at about the wilting point of the soil (−15 bars soil moisture tension). Increasing soil moisture tension above this point cannot increase RH. Increasing soil moisture above the wilting point decreases the percentage of fumigant in the soil air, which reduces its ability to diffuse and thus reduces the volume of soil that is fumigated effectively. It should be remembered that both soil moisture and soil air share the same pore spaces. Increasing one decreases the other. The fine-textured soils are more difficult to fumigate. They should be in reasonably good tilth and with soil moisture levels approaching the wilting point when fumigated. Soils holding more moisture than the wilting point result in the dilution of the fumigant concentration within the soil moisture. These two factors further reduce the dosage and the volume of effectively fumigated soil. Thus, soils holding more moisture than the wilting point can limit fumigant distribution, especially among fine textured soils.

TABLE 4. Effect of soil air space, moisture, and type in the control of the sugar beet nematode, *Heterodera schachtii* with 1,3-D as determined by yield of sugar beets. Fumigant applications made at wilting point (WP) or field capacity (FC).

1,3-D application rate (liters/ha)	Sugar beet yield (t/ha)			
	Silt loam†		Sandy loam‡	
	WP	FC	WP	FC
0	35.2	35.4	20.2	20.2
93.5	62.3**	34.7	51.1**	39.5**
140.3	63.2**	40.6	58.5**	48.6**

Adapted from Warren (43) and G. O. Turner (pers. comm.).

** denote significant differences from 0 rate at $P = 0.01$.

† Silt loam at WP contains 33% air space and 23% soil moisture; at FC, it contains 19% air space and 34% soil moisture.

‡ Silt loam at WP contains 41% air space and 7% soil moisture; at FC, it contains 31% air space and 10% soil moisture.

TABLE 5. Suggested broadcast application rates of 1,3-dichloropropene and methyl bromide for five soil types to provide lethal dosages to soil pests at depths of 75 and 150 cm.

	Suggested application rate (liters/ha)											
	Sand		Loamy sand		Sandy loam		Loam		Clay loam		Clay	
Moisture tension†	75 cm	150 cm	75 cm	150 cm	75 cm	150 cm	75 cm	150 cm	75 cm	150 cm	75 cm	150 cm
					1,3-dichloropropene							
WP (−15 bars)	47–94	374	47–94	374	70–117	374	94–140	468	140–187	561	234–281	748
Intermediate	47–94	374			94–140	374	117–164	468	187–234	561		
Near FC (−0.6 bars)	47–94	374	70–117	374	117–164	374	140–187	561	234–281	655		
					Methyl bromide							
WP (−15 bars)	224	448	224	448	280	448	280	448	392	673	560	897
Intermediate	224	448			280	560	336	560	392	673	560	897
Near FC (−0.6 bars)	224	448	280	448	336	672	392	673	448	785	560	897

Adapted from McKenry (29).

† WP (−15 bars) = wilting point (−15 bars moisture tension); near FC (−0.6 bars) = near field capacity (−0.6 bars moisture tension).

The results of the interaction of soil moisture, air space, and texture are summarized (Table 4). In two different soils, a silt loam and a sandy loam, the same 1,3-D treatments were made at two moisture regimes, wilting point and field capacity. The treatments were effective in the finer textured soil near the wilting point with a 33% air space but ineffective when near field capacity with a low air space (19%). In the coarser textured soil, fumigation was successful when near the wilting point or field capacity; however, the soil near the wilting point with greater air space gave the best results. The improved sugar beet yields reflect the degree of sugar beet nematode control. These and other experiences suggest that air space approaching 30% or greater is probably desirable for effective fumigation to occur. Diffusion studies with MBr (20) indicate similar results when soil air space exceeds 30%.

Using gas chromatography to monitor fumigant diffusion, McKenry (31), suggested a series of application rates for both 1,3-D and MBr (Table 5). The rates suggested are based on minimum lethal dosages required by the interaction of soil moisture with soil texture. Up to a twofold increase in treatment rate is suggested when soil moisture tension increases from −15 to −0.6 bars with the same soil texture. This corresponds to increasing soil moisture from wilting point to near field capacity. Rate increases up to eightfold are suggested when soil textures change from sand to clay. In addition, when a twofold increase in depth of control is needed (e.g., 150 cm vs. 75 cm), a fourfold increase in treatment rate was suggested. This is important for preplant fumigation of perennials which require a greater depth of control than annuals.

Soil temperature: Temperature has three major effects on fumigation efficacy. Increasing soil temperatures reduce water solubility of the fumigant, thus increasing its percentage in the air space and improving diffusion rates. Increasing soil temperatures also increase the biological activity against target organisms and the rate of fumigant degradation. However, soil fumigants vary considerably in their rates of degradation. For example, EDB degrades more slowly than 1,3-D. The increased degradation rate of 1,3-D has a greater impact than the increased biological activity against target organisms (29). Chemical reaction rates double for every 10-C increase in temperature (26). Since EDB degrades very slowly, it is able to maintain its effectiveness at high soil temperatures; however, chemicals that degrade slowly are potential groundwater pollutants.

Low soil temperatures increase the water solubility of each fumigant, thus reducing its air concentration and potential for effective diffusion. Low temperatures also decrease biological activity against target organisms, and the combination of the two factors tends to reduce the volume of effectively fumigated soil. All nematicides dependent upon gas diffusion are less effective at low soil temperatures, but some more so than others, suggesting different optimum soil temperatures for each fumigant. Temperatures near 20 C are probably best for 1,3-D (31).

Soil organic matter: It is believed that in moist soils the principal mode of sorption of fumigants is on the soil organic matter (10,11), first by adsorption followed by absorption. On inorganic soil particles, sorption is restricted to adsorption. The amount of 1,3-D sorbed on soil particles in soils of low organic content is comparable to that dissolved in the soil water phase (31). Also, as the organic matter content increases, both adsorption and absorption increase and the amount of fumigant available to diffuse into the soil air phase is reduced. Recommended 1,3-D application rates are usually doubled for use in organic soils. In situations where nematode problems require exceptionally high soil fumigation efficacy, such as white potatoes grown in highly organic soils with high population densities of *Meloidogyne chitwoodi* Golden et al., doubling the rate may be insufficient to obtain acceptable economic control (4,45). As soils dry below the wilting point, sorption onto the clay particles and organic matter can be substantial (10,31). Sorption onto organic matter is a slower process than diffusion, and any practice that enables the fumigant to diffuse faster should reduce the amount of the fumigant excessively sorbed near the lines of application. Thus, fumigation of organic soils is recommended when the soil is in good tilth and near the wilting point.

APPLICATION TECHNOLOGIES

Most commercial field applications of soil fumigants are made with tractors equipped with fumigant storage, a metering system to regulate delivery rates, chisels to deliver the fumigant into the soil, and associated equipment to complete the injection rig. There are many systems that can be used very successfully; the choice is usually based on individual preferences and regional needs.

Depth of application and chisel spacing: For overall (broadcast) applications of soil fumigants, the chisels normally are spaced ca. 30–45 cm apart. Depth of application is often shallower than advisable. It has been estimated that a 30.5-cm-deep application

TABLE 6. Differences in peach trunk cross section resulting from preplant fumigation with 1,3-D of a nematode-infested† sandy loam soil comparing deep and conventional depth of application.

1,3-D rate (liters/ha)	Injection depth (cm)	Trunk cross section (cm^2)			
		Year 1	Year 2	Year 3	Year 4
468	25	6.25	33.1	55.7	104.6
468	45	9.30***	60.6***	116.3***	172.3***
935	25	9.57***	51.8***	97.2***	159.8***

Adapted from Lembright (24).

*** Significant difference ($P = 0.001$) from the 468 liters/ha rate injected 25 cm deep.

† Nematodes present: *Pratylenchus vulnus*, *Criconemella xenoplax*, and *Meloidogyne* spp.

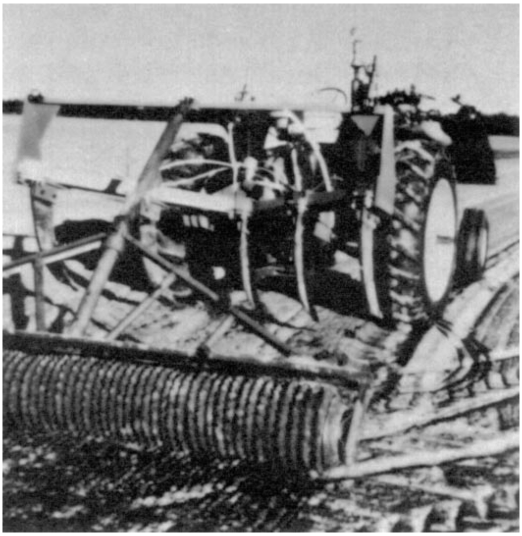

FIG. 1. Fumigation applicator with a five-chisel V-frame subsoiler unit and a toothed, loose-ring roller for sealing the soil surface.

of 1,3-D in a warm, moist sandy loam soil could result in a 5–10% loss into the atmosphere (31). Injections 45 cm deep or deeper would be expected to reduce volatilization from the surface to a neglible level and can greatly increase the depth and volume of effectively fumigated soil in deep coarse-textured soils. In finer textured soils, the deeper placement must be accompanied by higher treatment rates.

The diffusion patterns of fumigants suggest that the chisels can be 2–3 times as far apart as the injection depth. In commercial practice the 2× relationship is usually followed. With wider chisel spacing, deeper injection is possible using the same tractor horsepower.

Deep placement with overall fumigation: As indicated, deep placement of fumigants in deep coarse-textured soils is usually efficaceous. The application equipment often includes 5–7 forward-swept chisels mounted on a V-frame tool bar, with the shanks no more than 50–55 cm apart horizontally (Fig. 1). The subsoiler chisel points fracture both vertically and horizontally about 50–55 cm. In principle, the forward-swept chisel allows the shank part of the chisel to move into fractured soil, reducing the drag relative to that of a straight vertical shank. Also the lead chisel point fractures the soil horizontally for the following pair, and they in turn for the next pair, resulting in considerable reduction in drag and horsepower requirements.

In shallow sands and sandy loams, injection into the dense moist subsoil can reduce effectiveness. Application to the subsoil is effective if the soil is not too wet at that depth. Saturated soil can function as a barrier and a fumigant sponge. The most appropriate step would be to deep rip and mix the surface and subsoil before fumigation.

Surface sealing: The chisel traces (slits or chimneys) in the soil following a chisel injection of a fumigant can allow the fumigant to escape into the atmosphere rapidly, unless they are sealed or covered with adequate soil. Also, as fumigants diffuse upward and approach the loose soil surface (upper 15 cm), they can escape into the atmosphere rapidly without establishing lethal dosages. Surface sealing improves the fumigation if the proper tools are used. Many sealing devices are used, but one of the most effective is the "toothed loose-ring roller" (Fig. 1). The loose-ring configuration allows a relatively uniform but shallow surface seal. The toothed aspect of the device incorporates the "sheep's foot" principle used by engineers for compacting roadways and fills.

Naturally occurring water seals, resulting from light rains and subsequent still humid air, are capable of maintaining a wet surface layer in the upper 2–5 cm of soil during the first few days following application and can improve results. However, under otherwise dry and windy conditions, the application of irrigation water to the surface is likely to prove impractical because the surface requires repeated sprinkling to maintain a thin moist layer. Flood irrigation or high rainfall following fumigation results in the establishment of a water barrier to upward diffusion, resulting in an unsatisfactory fumigation near the surface.

FIG. 2. Fumigant injection and bedding with a "ripper-hipper."

Polyethylene tarping is not essential when using 1,3-D because of the nature of the pest control objectives. MBr, a broader spectrum biocide, usually requires a tarp because surface weed and weed seed control is an objective. Also, other targeted MBr-susceptible organisms can have a high survival rate in the upper 15 cm of soil that is not tarped. However, there are MBr uses with deep placement where tarps may not be essential. An example would be a replant treatment for perennials when root-knot nematode control is needed, because root-knot nematodes, even if poorly treated, do not survive well in surface soil. Chloropicrin is usually tarped to avoid eye irritation caused by low concentrations that otherwise escape into the atmosphere. This need for tarping may be eliminated with deeper application and (or) lower rates. MIT normally does not require a tarp.

Row or bed treatment: With proper application, a row or bed treatment can be one of the most cost-effective methods for nematode control for annual crops, since the objective is strip fumigation rather than overall application. The grower saves money because not all of the field surface is treated, yet crop responses are equal or superior to those receiving broadcast treatments. One of the most common practices is to inject and list a bed over the injection chisel trace (Fig. 2). The bed may be shaped and firmed at the same time. With or without bed shaping, additional surface sealing is unnecessary.

When row or bed treatment is used and the fumigant is injected and listed up over the injection lines, the value of surface sealing will be more dependent upon the ability of an organism to survive in the drier surface soil. Because root-knot nematodes are poor survivors in dry surface soil, surface sealing may be of little value; however, pests that survive and maintain themselves in dry surface soils could require some method of surface sealing.

For row or bed treatments on deep sands or sandy loams, a single chisel is usually at least equal in performance to two chisels when the same rate of fumigant per hectare is used. Also a single chisel will allow deeper injection with the same amount of tractor horsepower, producing better results.

Plow sole application: Another method of overall fumigation is to apply the fumigant in streams into the plow furrows immediately before the soil from each moldboard covers the furrow. This is followed by a shallow disc-harrowing to provide a seal. Although the application depth is often restricted to 25–30 cm, results are generally very good (6,22). This is probably because there are no chisel traces for fumigant escape, and the soil, although moist, is usually loose and has an acceptable surface seal.

Precision tillage and deep placement: In this modification of bed treatment, the injection depth is usually 45–55 cm below the original soil surface, with an additional 15–20 cm of listed soil on top of the chisel trace. This is a common practice on sandy loams that can become compacted to the 45–55-cm depth. The technique was developed as the most cost-effective means of opening a slot through the compaction zone below the normal tillage depth. With the chisel trace in the center and below the top of the bed, a deep-rooted plant such as cotton can develop a root system both in the bed and below the compaction zone, dramatically expanding the zone of root foraging. If the compacted soil is reasonably dry when deep tilling occurs, the subsoiler chisel can fracture the zone and produce a wider tilled slot. By using a forward-swept subsoiler chisel, the drag on the shank is reduced. This allows deeper injection with the same tractor horsepower. As well as creating compaction problems, sandy loams are ideal soils for root-knot nematodes. Introducing the fumigant at the bottom of the subsoiler chisel results in a very effective deep placement fumigation. Seven experiments in California cotton-producing counties showed the dramatic improvement from the combination of precision deep tillage and deep fumigation with 42–56 liters 1,3-D/ha. Average increases in cotton production were 16% for precision tillage alone, 24% for conventional bed fumigation without precision tillage, 43% with precision tillage plus conventional depth of fumigation, and 52% for precision tillage and deep placement (25,40,41). Overall deep placement and bedding precision tillage with deep placement have proven valuable on most crops, including shallow-rooted crops (25).

Tree replant treatment: Success with deep placement stimulated extensive studies on replanting problems with tree crops. In the first comparative studies on a sandy loam soil (24), deep placement (45 cm) of 468 liters 1,3-D/ha during the first year of growth increased trunk cross section by 49% over the same rate injected 25 cm deep (Table 6). A comparable increase in trunk growth was obtained with 935 liters/ha applied 25 cm deep. During the following 4 years, deep placement resulted in even greater improvement in trunk growth.

Research on tree replant sites addressed some of the same problems associated with precision tillage and deep placement (24,30,36,37). However, in addition to occasional soil compaction problems, restricted root growth occurred also from other types of soil stratification. This was apparent in the alluvial soils of the Sacramento and San Joaquin valleys of California. Subsoiling, as used in precision tillage and deep placement, was successful only when soil compaction was the primary problem. When soil stratification resulted from differences in soil texture, roots did not grow through the stratified soil interfaces. The maintenance of a saturated, oxygen-depleted interface zone prevented root elongation. Also common in this area are soils with true hardpans, which physically restrict root penetration. These same soils were also ideal for "replant" nematode problems. The solution proved to be using a backhoe to dig tree site holes approximately 150 × 150 × 150 cm (Fig. 3). After digging, a small bulldozer blade was used to refill the hole. The net effect was to disrupt all types of soil stratification, allowing good root development into a

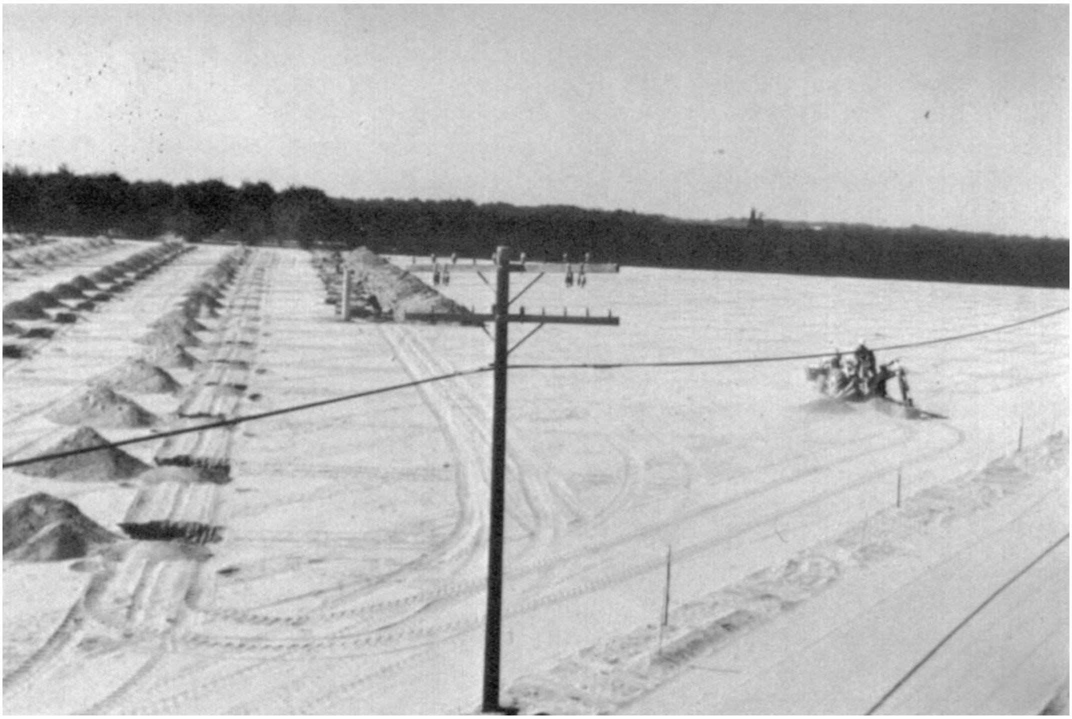

FIG. 3. Backhoeing a stratified sandy loam. Soil variation is apparent between mounds of soil.

planting hole at least 150 × 150 × 150 cm in size. Both 1,3-D and MBr could be injected at a single point in the center of the site, 100–150 cm deep, while refilling the holes. Results were spectacular (36); in some trials peach trees at the end of the first growing season were 300–360 cm tall, whereas those in the untreated plots were 75–200 cm tall. In an almond replant experiment, the backhoeing was combined with MBr at 0.45 or 0.91 kg per tree site injected into the bottom of the backhoe hole being refilled. The treatments increased tree trunk cross-sectional area by 57–99% the first year and by 113–156% the second year (Table 7). In a similar study with peaches, MBr at 0.45 kg, 1,3-D at 0.95 liters, and 1,3-D plus Pic at 0.95 liters per tree site were compared, using a 6-m × 6-m tree spacing. These produced respective increases in trunk cross-sectional areas

TABLE 7. Effect of subsoiling, backhoeing, and backhoeing plus methyl bromide site fumigation on trunk growth of almond replants.

Physical soil treatment	Methyl bromide application rate (kg)	Trunk cross section (cm²)	
		Year 1	Year 2
Subsoiled	0	6.0	24.9
Backhoed	0	6.9	32.5
Subsoiled	0.45 (untarped)	9.0	51.0***
Backhoed	0.45 (untarped)	9.5	55.1***
Subsoiled	0.45 (tarped)	8.4	46.0**
Backhoed	0.45 (tarped)	10.5	53.0***
Subsoiled	0.91 (untarped)	8.0	37.9**
Backhoed	0.91 (untarped)	12.0	63.8***

Adapted from Ross and Meyer (36).
, * Significant difference from 0 rate at $P = 0.01$ and $P = 0.001$, respectively.

TABLE 8. Effect of subsoiling, backhoeing, and backhoeing plus site soil fumigation on peach replants.

Physical soil treatment	Fumigant treatment and rate per tree site	Trunk cross section (cm²)	
		Year 1	Year 2
Subsoiled	None	7.0	26.7
Backhoed	None	7.2	24.1
Backhoed	1,3-D (0.95 liters)	16.5	61.9
Backhoed	1,3-D + Pic (0.95 liters)	11.7	68.3
Backhoed	MBr (0.45 kg)	17.4	73.5

Adapted from Ross and Myer (36).

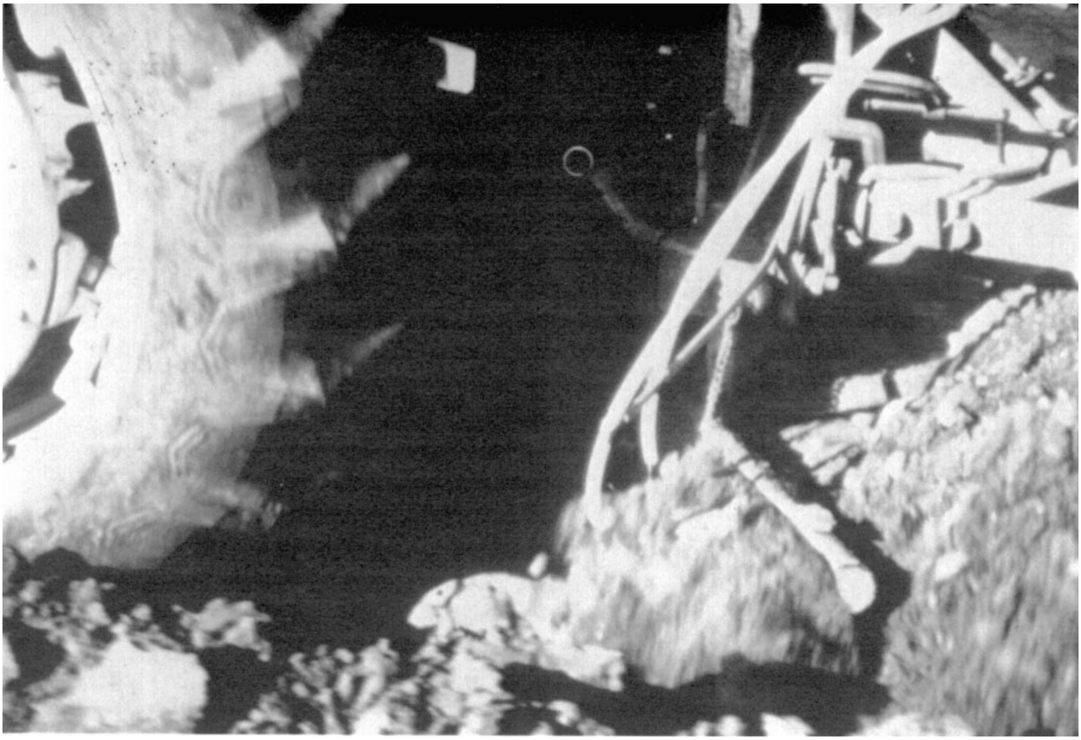

FIG. 4. Final treatment of a split application of 1,3-D with a plow applicator and using a Warren scraper.

of 148, 135, and 66% the first year and 175, 132, and 155% the second year (Table 8).

Methods of handling infested surface soils for improved fumigation: Split applications of high rates of fumigant are used when "near eradication" of nemátodes is the objective. Usually the first application is a conventional but rather deep injection followed by plowing before a second injection. Plowing is used to turn under the poorly fumigated surface soil, which is treated with additional fumigant in the second injection. The better the plow inverts the soil, the better are the results.

A second method initially injects a major portion of the fumigant, followed by a plowsole application. A scraper ahead of each plowshare deposits the poorly fumigated 5–10 cm of surface soil into the plow furrow and introduces additional fumigant on it just before covering (6). This method was evaluated by the USDA for use in the potato-cyst nematode eradication program on Long Island in New York (22). Warren (44) improved this practice with an improved scraper (Fig. 4). This method results in good weed control.

Special bed shaping, bed fumigation: About 4 or more days after fumigation, a bed shaper that plows off the surface soil of the bed can be used to reshape the bed and deposit surface soil to the side of the bed. This practice has been observed to improve control of nematodes such as *Heterodera schactii,* since eggs in cysts can survive in the drying bed surface. Depending upon rates of 1,3-D used, this same practice can give weed control down the center of the bed or even over the entire bed.

Water applications of nematicides: Development of application technology and use of nematicides in irrigation water was initiated about 1955. From 1955 to 1979, DBCP was used as a postplant treatment for the control of nematode root disease complexes of grapes, citrus, peaches, almonds, bananas, and other fruit crops in areas highly dependent upon irrigation (15–17,19,23,49). Applications were made using flood, furrow, and sprinkler irrigation. Application of DBCP through drip irrigation was in the exploratory stages (8) when the product was banned. Subsequent drip irrigation studies involved the nonfumigant organophosphate and carbamate nematicides and 1,3-D. It should be recognized that DBCP and 1,3-D applied in irrigation water no longer function as fumigants but rather as nematicides in solution.

There are four principal factors regulating the distribution of water-applied nematicides through the soil profile (8,15–17,19,49). They are amount of water applied, speed of water delivery, infiltration rate of water into the soil, and concentration of the nematicide in the applied water. Under optimum conditions, the initial distribution of lethal dosages through the soil profile is to about one-half the depth of the wetted soil. However, with the more residual nematicides, subsequent water may distribute them deeper, if they can be desorbed in adequate concentrations from the soil organic matter. A more likely explanation of deeper control with time may be their nematistatic activity, which interrupts the normal life cycle of the nematode and stops or slows reproduction (18).

LITERATURE CITED

1. Adams, P. B. 1986. Soil fumigation by chemigation with metham sodium. Pp. 270–272 *in* K. D. Hickey, ed. Methods for evaluating pesticides for control of plant pathogens. St. Paul, MN: American Phytopathology Society.

2. Anonymous. 1986. Data submitted to the Environmental Protection Agency in response to "special data call in" for groundwater data for methyl bromide. Methyl Bromide Industry Panel, Environmental Protection Agency, Washington, DC.

3. Busvine, J. R. 1957. A critical review of the techniques of testing insecticides. Commonwealth Institute of Entomology, London.

4. Carlson, H. L., H. Ferris, and B. B. Westerdahl. 1987. Columbia root-knot nematode, biology and control. Research progress report, University of California, Davis.

5. Carter, G. E. 1967. Soil fumigation also controls quackgrass. Down to Earth 23:16–18.

6. Dallimore, C. E. 1955. Methods of increasing efficacy of soil fumigation in experimental fields. Plant Disease Reporter 39:511–515.

7. Eckert, P. C. 1964. Physical properties of low humic latasols. University of Hawaii, Honolulu (Unpubl.).

8. Garvey, P. M., and J. L. Chesness. 1977. Nematicide distribution under a drip emitter. American Society of Agricultural Engineers paper 77-2016.

9. Goring, C. A. I. 1962. Theory and principles of soil fumigation. Advances in Pest Control Research 5:47–84.

10. Goring, C. A. I. 1967. Physical aspects of soil in relation to the action of soil fungicides. Annual Review of Phytopathology 5:285–318.

11. Hartley, G. S. 1964. Herbicide behavior in the soil. I. Physical factors and action through the soil. Pp. 111–161 *in* L. J. Andus, ed. The physiology and biochemistry of herbicides. New York: Academic Press.

12. Hemwall, J. B. 1959. A mathematical theory of soil fumigation. Soil Science 88:184–190.

13. Hemwäll, J. B. 1962. Theoretical consideration of soil fumigation. Phytopathology 52:1108–1115.

14. Hemwall, J. B. 1960. Theoretical considerations of several factors influencing the effectivity of soil fumigants under field conditions. Soil Science 90: 157–168.

15. Hodges, L. R., and B. Lear. 1973. Effect of time of irrigation on the distribution of 1,2-dibromo-3-chloropropane in soil after shallow injection. Pesticide Science 4:795–799.

16. Hodges, L. R., and B. Lear. 1973. Distribution and persistence of 1,2-dibromo-3-chloropropane in soil after application by injection and in irrigation water. Nematologica 19:146–158.

17. Hodges, L. R., and B. Lear. 1974. Persistence and movement of DBCP in three types of soil. Soil Science 118:127–130.

18. Hough, A., and I. J. Thomason. 1975. Effects of aldicarb on the behavior of *Heterodera schachtii* and *Meloidogyne javanica*. Journal of Nematology 7:221–229.

19. Johnson, D. E., and B. Lear. 1968. Evaluating the movement of 1,2-dibromo-3-chloropropane through soil. Soil Science 105:31–35.

20. Kolbezen, M. J., D. E. Munnecke, W. D. Wilbur, L. H. Stolzy, F. J. Abu-El-Haj, and T. E. Szuskiewicz. 1974. Factors that affect deep penetration of field soils by methyl bromide. Hilgardia 42:465–492.

21. Kreutzer, W. A. 1965. The reinfestation of treated soil. Ecology of soil-borne plant pathogens. Berkeley: University of California Press.

22. Lear, B., W. F. Mai, J. Feldmess, and F. J. Spruyt. 1952. Soil fumigation experiments on Long Island, New York, to control golden nematode of potatoes. Phytopathology 42:193–196.

23. Lembright, H. W. 1965. Use of Fumazone nematicide in the production of fruit and nut crops in western areas. Down to Earth 21:3–7.

24. Lembright, H. W. 1976. Solutions to problems associated with the replanting of peaches. Down to Earth 37:12–21.

25. Lembright, H. W., M. J. Healy, and M. G. Norris. 1968. Improved soil fumigant utilization through deep placement. Down to Earth 4:10–12.

26. Lucas, H. J. 1935. Organic chemistry. New York: American Book Company.

27. Lyda, S. D., G. D. Robinson, and H. W. Lembright. 1967. Soil fumigation control of phymatotrichum root rot in Nevada. Plant Disease Reporter 51:331–333.

28. Martin, F. N., and E. D. Whitney. 1990. In-bed fumigation for control of rhizomania of sugar beet. Plant Disease 74:31–35.

29. McKenry, M. V. 1978. Selection of preplant fumigation. California Agriculture 32:15–16.

30. McKenry, M. V., and C. O. Hesse. 1978. Preplant fumigations of planting sites. California Agriculture 32:14–15.

31. McKenry, M. V., and I. J. Thomason. 1974. 1,3-dichloropropene and 1,2-dibromoethane compounds: I. Movement and fate as affected by various conditions in various soils. II. Organism–dosage-response studies in the laboratory with several nematode species. Hilgardia 42:392–438.

32. McKenry, M. V., I. J. Thomason, D. E. Johnson, R. Neja, and F. Swanson. 1978. Preplant fumigation with 1,3-D nematicides. California Agriculture 32:12–13.

33. Munnecke, E. E., J. L. Bricker, and M. J. Kolbezen. 1978. Comparative toxicity of gaseous methyl bromide to ten soilborne phytopathogenic fungi. Phytopathology 68:1210–1216.

34. Munnecke, D. E., and S. D. Van Gundy. 1979. Movement of fumigants in soil, dosage responses, and differential effects. Annual Review of Phytopathology 17:405–429.

35. Raski, D. J., and B. Lear. 1962. Influence of rotation and fumigation on root-knot nematode populations on grape replants. Nematologica 8:143–151.

36. Ross, N. W., and J. L. Meyer. 1972. No more poor orchards . . . backhoeing and fumigating for orchards. Down to Earth 28:1–4.

37. Ross, N. W., and J. L. Meyer. 1975. Orchard preplant land preparation new and replant. California Agriculture 29:12–14.

38. Santo, G. S., and M. Qualls. 1984. Control of *Meloidogyne* spp. on Russet Burbank potato by applying metham sodium through center pivot irrigation systems. Journal of Nematology 16:159–161.

39. Stark, F. L., Jr. 1948. Investigations of chloropicrin as a soil fumigant. New York (Cornell) Agriculture Experiment Station. Memoirs 278:1–61.

40. Stockton, J. R., L. M. Carter and G. Paxman. 1964. Precision tillage for cotton. California Agriculture 18:8–10.

41. Stromberg, L. K. 1965. 1964 cotton trials Fresno, California. Cooperative report, USDA and University of California, Fresno.

42. Van Dijk, H. 1980. Dissipation rates in soil of 1,2-dichloropropane and 1,3- and 2,3-dichloropropenes. Pesticide Science 11:625–632.

43. Warren, L. E. 1958. Do nematodes reduce your sugar beet crop? Spreckles Bulletin 22:14–15.

44. Warren, L. E. 1971. A shallow scraper to aid Telone nematicide in control of weeds and diseases in the top few inches of the soil. Down to Earth 27: 8–11.

45. Westerdahl, B. B., H. C. Carlson, and J. D. Radewald. 1988. Fumigant dispersal in a silty clay loam soil containing 10–12 percent stable organic matter. Journal of Nematology 20:664 (Abstr.).

46. Wilhelm, S. 1966. Chemical treatments and inoculum potential of soil. Annual Review of Phytopathology 4:53–77.

47. Youngson, C. R., R. G. Baker, and C. A. I. Goring. 1962. Diffusion and pest control by methyl bromide and chloropicrin applied to covered soil. Journal of Agricultural and Food Chemistry 10:21–25.

48. Youngson, C. R., and C. A. I. Goring. 1962. Diffusion and nematode control by 1,2-dibromoethane, 1,3-dichloropropene and 1,2-dichloropropane in soil. Soil Science 93:306–316.

49. Youngson, C. R., C. A. I. Goring, and R. L. Noveroske. 1967. Laboratory and greenhouse studies on the application of Fumazone in water to soil for control of nematodes. Down to Earth 23:27–32.