Movement and Persistence of 1,2-dibromo-3-chloropropane in a Soil with a Plow-pan[1]

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Abstract: Movement and persistence of 1,2-dibromo-3-chloropropane (DBCP) in a Coastal Plain soil containing a sandy plow-pan were enhanced in each of 2 years by subsoiling, increased depth of application, and increased rate of application. DBCP was extracted from the soil with hexane and analyzed by gas chromatography. Subsoiling at a 35-cm depth gave the greatest increase in lateral movement and downward penetration of DBCP in 1975 (a wet year), but had less effect in 1976 (a dry year). An increased application rate (10 kg/ha vs. 13.5) improved coverage moderately in 1975 by increasing lateral movement, but had little effect in 1976. Increased application depth (18 vs. 35 cm) improved coverage in both years though more in 1976. Deep placement extended DBCP retention time. Rainfall in 1975 probably decreased the number and size of air-filled pores, slowing loss of DBCP to the atmosphere. Because of reduced porosity, the plow-pan was impervious to the passage of DBCP unless disrupted by subsoiling. *Key Words:* subsoiling, soil porosity, soil fumigation, control.

Effective fumigation of soils depends on maintaining toxicant at concentrations sufficient to incapacitate or kill target organisms. Thus, fumigant movement must be in directions which do not facilitate losses from the target zone. Some of the factors which influence the movement, persistence, and availability of fumigants are soil organic-matter content, soil temperature, soil moisture content, and soil porosity, all of which have been extensively reviewed by several authors (1, 4, 5, 12, 19).

The porosity of the soil surface over a fumigant injection line can be economically decreased only by bedding or by using a heavy drag, because irrigation is not practical. Since fumigants move through soil most quickly in the vapor phase (5), sealing the soil surface after fumigation inhibits upward fumigant movement to the atmosphere by decreasing the number and continuity of air-filled pores. Increases in soil moisture (i.e., rain) may give the same results, by filling soil pores with water and restricting fumigant movement in the soil more to the liquid phase (4).

Some U. S. Coastal Plain soils have multiple soil horizons consisting of a loamy sand topsoil (20–25 cm) and a sandy clay subsoil. In addition, a highly compressed, sandy plow-pan layer (5–8 cm) is often present between or within topsoil and subsoil. An illustration of this three-layer soil has been published (9). Such a soil profile may affect the movement of fumigants by inhibiting downward penetration and lateral movement through the soil.

A plow-pan layer contributes to cotton stunt (2, 9, 16), a syndrome involving an interaction of nematodes and restricted root penetration to greater, moister depths (9, 18). Subsoiling at a 35-cm depth shatters the pan under the planting row, allowing roots to reach the subsurface. Fumigant nematicides are often injected during subsoiling and the soil is immediately bedded afterward both to prepare a moist seedbed and to seal the fumigant injection line. The fates of nematodes and nematicides after subsoiling are unclear. Some nematodes can increase in clay soils (13, 15), and the effects of subsoiling and placement depth have not been studied in soils with a plow-pan. O'Bannon and Tomerlin (14), however, reported that fumigant injection at a 20-cm depth in an artificial structureless soil gave better distribution than injection at 10 cm.

This study compares the relative importance of subsoiling, rate of application of DBCP, and depth of application on the movement and persistence of DBCP in a Coastal Plain layered soil.

MATERIALS AND METHODS

Plots were established on a Marlboro loamy sand (Typic Paleudult) at the Southeast Branch Experiment Station, Midville, Georgia, on April 28, 1975, and April 8, 1976. The treatments for each year were adjacent. The soil consisted of three

layers: a 20–25-cm loamy sand topsoil, a 5–8-cm sand-textured plow-pan layer, and a sandy clay subsurface (Table 1).

Treatments each year were: (A) 10 kg DBCP (a.i.)/ha, injected at 18 cm, not subsoiled; (B) 10 kg DBCP/ha injected at 18 cm, subsoiled; (C) 10 kg DBCP/ha injected at 35 cm, subsoiled; (D) 13.5 kg DBCP/ha injected at 35 cm, subsoiled. Subsoiling to a 35-cm depth was done with a standard tractor-drawn 4-row subsoiler and bedder. In 1975, the DBCP for both application depths was applied by attaching plastic tubing of the proper length to the shank of the subsoiler. In 1976, DBCP at the 18-cm depth was applied by attaching fumigant lines to ammonium knives attached adjacent to the subsoiling chisels. Nemagon (DBCP) 12.1C from a 19-liter drum was dispensed by a Reddick gravity-flow applicator and rates were adjusted by varying orifice sizes in the Reddick valves. In 1975, beds were leveled immediately after DBCP applications, and in 1976 they were left for four weeks. All samples were taken from leveled sections of beds. Treatments were applied in 30-m strips on land not previously subsoiled.

Each 30-m strip was divided into 10-m sections, each of which was sampled at three places on each date. Values are the averages of the three samplings per treatment. Rows within treatments were spaced 95 cm apart, and only the outer side of the outer rows was sampled. Outside rows between treatments were about 4 m apart to prevent overlap of diffusing fumigant. The plot was fallowed for the duration of the experiment.

Soil-core sampling for determination of DBCP concentrations was standardized by using a board that held five vertical guide tubes 7.5 cm apart. Plots were sampled by placing a marked point on the board over the injection line and removing soil cores with a soil-sampling tube 90 cm long and 2 cm in diameter (Fig. 1).

The sampling and DBCP extraction procedures were as follows. Glass jars of 125-ml capacity with aluminum-lined screw caps were partially filled with 25 ml pesticide-grade hexane + 25 ml water. All jars were transported to the experiment site after the liquids were added. After a 50-cm soil core was taken with the sampler, the core was subdivided successively into sections comprising the depths of 5–10, 15–20, 25–30, 35–40, and 45–50 cm. Twenty-five samples were taken from each of three areas
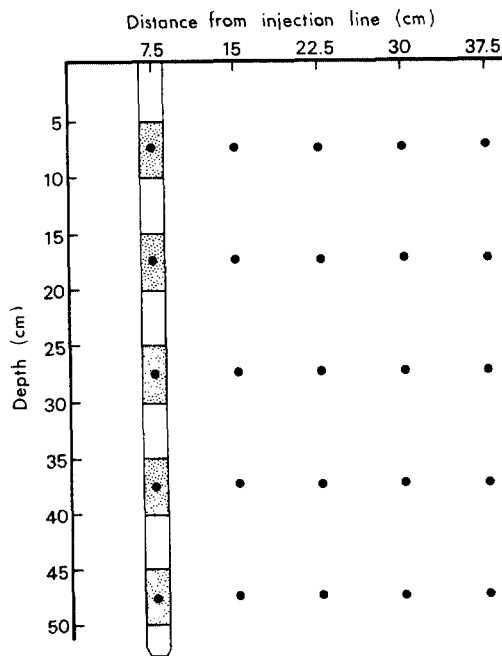

FIG. 1. Scheme of sampling to obtain soil cores for DBCP extraction. Solid circles represent centers of sampled cores; shaded areas indicate size of cores.

TABLE 1. Characteristics of soil horizons from experimental plots at the Southeast Branch Experiment Station, Midville, Georgia.

Layer	Sand[a] (%)	Silt[a] (%)	Clay[a] (%)	Bulk density[b]	Particle density[b]	Porosity (%)
Topsoil	86.2	10.8	3.0	1.56	2.65	41.1
Plow-pan	85.0	10.0	5.0	1.79	2.59	30.9
Subsoil	46.3	11.8	41.9	1.62	2.73	40.7

[a]Bouyoucos hydrometer method.
[b]Bulk density and particle density expressed in g/cm³.

in each treatment (Fig. 1), and the 5-cm soil cores were placed in the hexane + water in the jars. In 1975, sampling was performed 8, 16, 29, 50, and 72 days after treatment; in 1976, samples were taken 8, 16, 29, 50, and 77 days after treatment. Spots sampled in each area were at least 80 cm from any other previously sampled areas, to minimize distortion of diffusion patterns in undisturbed portions.

After sampling was completed on each date, the jars were transported to the laboratory and placed in a freezer to separate the water and soil components from the hexane (14). After the water was frozen, the hexane was decanted into test tubes with Teflon-lined screw caps. A small amount of anhydrous sodium sulfate was added to each tube to absorb any remaining water. Extracting soil cores containing a known amount of DBCP with the above procedure indicated that the shaking of the jars during transport back from the field plots (2.5 hr) was sufficient to extract 75–80% of the soil DBCP; therefore, additional shaking was not performed.

Concentrations of DBCP were determined by gas-chromatography analysis with techniques of Johnson and Lear (11). The analyses were made on either a Tracor MT-220 or one of two Tracor 550 gas chromatographs equipped with electron-capture detectors and utilizing glass columns packed with 3% OV-1 on Anakrom ABS (100–200-mesh) or with 1.5% OV-17 and 1.95% OV-210 on Anakrom ABS (80–100-mesh).

RESULTS

Movement of DBCP in a soil with a hardpan

Subsoiling vs. no subsoiling (Treatments A vs. B): In 1975, subsoiling accounted for the greatest differences between treatments (Figs. 2–5: A, B), when isoconcentration lines of 0.1 μg/DBCP/g oven-dried (OD) soil were drawn. This concentration was selected to show DBCP movement because 0.1 μg DBCP/g OD soil, when maintained for 7 weeks, is an effective dose for control of *Meloidogyne javanica* (8). In 1975, the greatest penetration below 30 cm occurred with the subsoiled treatment (B), whereas the unsubsoiled treatment (A) had little penetration below 30 cm, although the concentration laterally was comparable for both treatments during the first 16 days
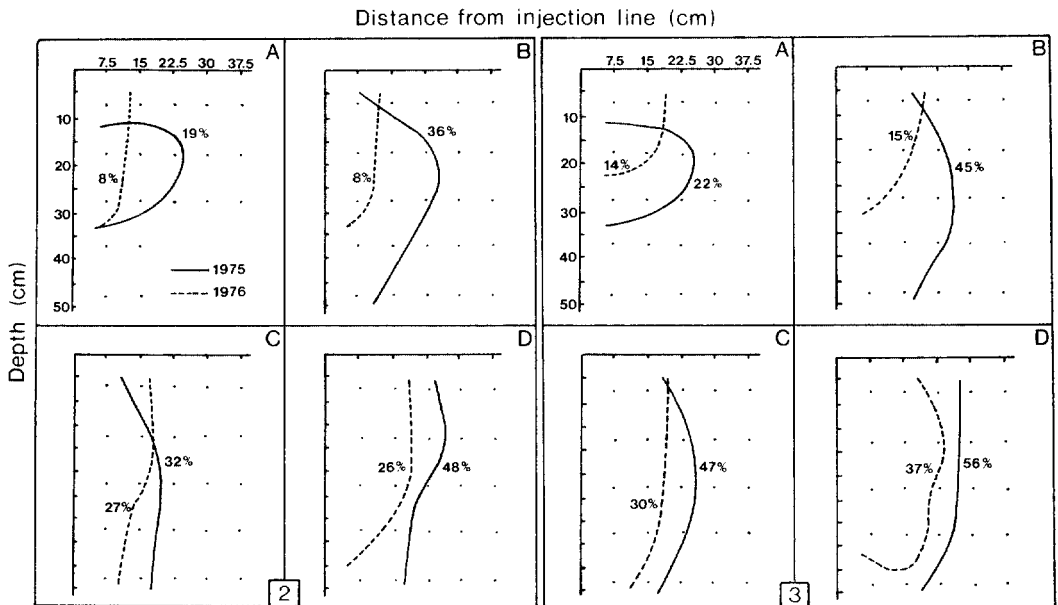
FIGS. 2-3. Isoconcentration contour lines (0.1 μg DBCP/g OD soil) 8 and 16 days after treatment. Percentages indicate percent of sampled soil plane infiltrated by at least 0.1 μg DBCP/g OD soil. A) 10 kg DBCP/ha applied 18 cm deep, not subsoiled; B) 10 kg DBCP/ha 18 cm deep, subsoiled; C) 10 kg DBCP/ha 35 cm deep, subsoiled; D) 13.5 kg DBCP/ha 35 cm deep, subsoiled.

after application (Figs. 2, 3). At 29, 50, and 72 days after treatments, treatment A showed greater reduction in lateral expansion of 0.1 μg DBCP/g OD soil than treatment B. Treatment A at 29 days covered only about one-third the area of treatment B (Fig. 3).

Subsoiling in 1976 failed to improve coverage substantially over that in unsubsoiled plots; there was little downward penetration or lateral movement (Figs. 2–5, A, B). Isoconcentration profiles were similar for most sample dates, and the areas covered were nearly equal in size. After 29 days, the subsoiled treatment B covered 16% of the sampled soil plane, while the unsubsoiled treatment A covered 13%. Patterns of diffusion for both treatments in 1976 apparently were mostly upward toward the soil surface and into the atmosphere, since expansion of fumigated areas was greatest at the 5–10-cm level (Figs. 2–4: A, B).

Depth of DBCP application (Treatments B vs. C): The depths of application (18 or 35 cm) in 1975 had little effect on the percentage of the soil profile covered by a 0.1 μg DBCP/g OD soil concentration. Lateral movement and downward penetration followed a similar pattern throughout the

sampling period (Figs. 2–5: B, C). In 1976, however, DBCP placed at 18 cm (Figs. 2–4: B) moved little downward or laterally, whereas placement at 35-cm (Figs. 2–4: C) gave greater downward penetration and somewhat greater lateral movement. In general, deep placement gave 2–3× as much coverage as shallow placement.

Rate of DBCP application (Treatments C vs. D): Increasing the application rate of DBCP (10 vs. 13.5 kg (a.i.)/ha) improved coverage consistently in 1975 (Figs. 2–4: C, D), but differences were most pronounced 50 days after treatment applications (Fig. 5: C, D), where the greater concentration of the higher rate maintained large infiltrated areas. In 1976, increasing the rate of application resulted in little improvement in coverage.

Soil temperature and moisture: Soil environmental factors were generally quite different between the two years. Maximum soil temperature at a 10-cm depth was usually higher in 1975 than in 1976. Soil moisture content during the first 16 days after DBCP application was higher in 1975 than in 1976, because of more rainfall during the first five months of 1975. The yearly difference is more pronounced when daily
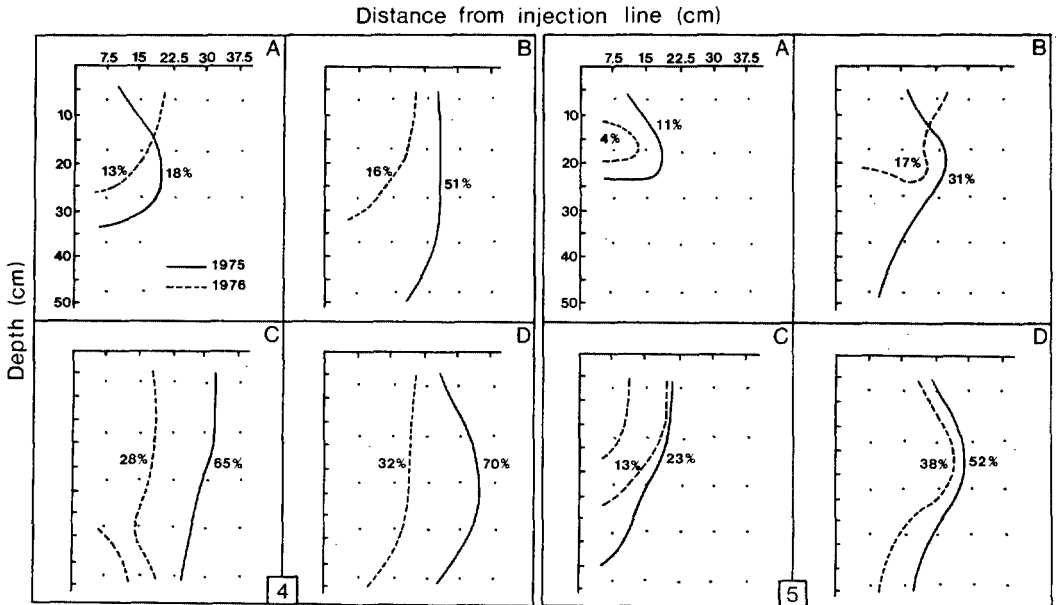
FIGS. 4-5. Isoconcentration contour lines (0.1 μg DBCP/g OD soil) 29 and 50 days after treatment. Percentages indicate percent of sampled soil plane infiltrated by at least 0.1 μg DBCP/g OD soil. A) 10 kg DBCP/ha applied 18 cm deep, not subsoiled; B) 10 kg DBCP/ha 18 cm deep, subsoiled; C) 10 kg DBCP/ha 35 cm deep, subsoiled; D) 13.5 kg DBCP/ha 35 cm deep, subsoiled.

rainfall is examined for the first 19 days after DBCP application (Fig. 6). Frequent rainfall occurred in the first 19 days after treatment and totaled about 4 cm; in the comparable period in 1976, no rain occurred until the 17th day.

Persistence of DBCP in a Marlboro loamy sand Coastal Plain soil

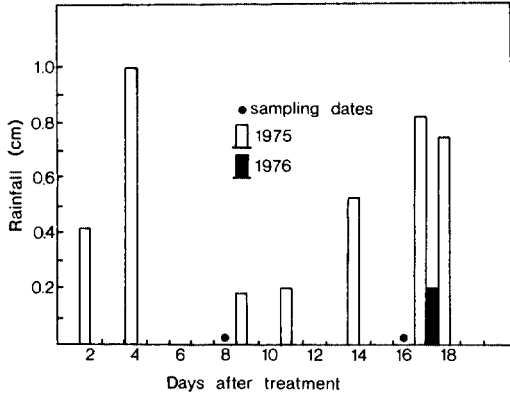When concentrations at each of the sampling points were plotted against time

FIG. 6. Rainfall per day at the Southeast Branch Experiment Station, Midville, Georgia, during the first 19 days after treatment applications.

and interpolated, DBCP accumulation at most sampled areas reached a maximum one to two weeks after DBCP application. The preponderance of exposure to DBCP was greatest in the first 4 weeks after application, regardless of the way it was applied. The effectiveness of a fumigant depends not only on its rate and direction of movement but also on its accumulation and persistence at any particular point in the soil. This persistence is generally quantified by determination of dose as a cumulative concentration for a given time (17, 21), or $\sum_{t=1}^{n}$ [DBCP], where t = initial day, n = number of days, and [DBCP] = concentration of DBCP in μg/g OD soil. Thus, by plotting concentrations over time and interpolating the points, doses can be calculated by determining the area under each curve. The critical value for control of larvae of root-knot nematodes, *Meloidogyne* spp., has been determined as 4–6 μg-days/g OD soil (8, 21). Dose determinations are given in Table 2.

As in determinations of the percentage of the soil plane covered (Figs. 2–5), available doses for the first 28 days varied considerably between years and with changes

TABLE 2. Doses (μg-days/g oven-dried soil) of DBCP in sampled areas during the first 28 days after application of treatments.[a]

Depth, distance (cm)[c]	Treatment[b]							
	A		B		C		D	
	1975	1976	1975	1976	1975	1976	1975	1976
5-10, 7.5	18	39	23	33	21	60	42	66
15-20, 7.5	29	28	122	24	88	28	123	42
25-30, 7.5	32	2	73	5	67	21	139	25
35-40, 7.5	0	0	46	0	48	7	103	7
45-50, 7.5	0	0	10	0	11	2	13	1
5-10, 15.0	12	5	22	12	20	7	28	12
15-20, 15.0	12	3	41	5	38	9	99	12
25-30, 15.0	14	0	75	1	68	4	147	13
35-40, 15.0	0	0	18	0	22	2	37	5
45-50, 15.0	0	0	5	0	13	0	15	1
5-10, 22.5	0	0	3	0	2	0	11	0
15-20, 22.5	6	0	12	0	9	0	16	1
25-30, 22.5	0	0	14	0	15	0	11	0
35-40, 22.5	0	0	2	0	10	0	7	0
45-50, 22.5	0	0	0	0	0	0	1	0

[a]Values of zero indicate no detection by GLC instruments.
[b]A = 10 kg DBCP/ha applied 18 cm deep, not subsoiled; B = 10 kg DBCP/ha applied 18 cm deep, subsoiled; C = 10 kg DBCP/ha applied 35 cm deep, subsoiled; D = 13.5 kg DBCP/ha applied 35 cm deep, subsoiled.
[c]Sample depths and distances from injection line.

in application methods (Table 3). Subsoiling greatly improved DBCP persistence at lower depths in 1975, but had little effect in 1976. Increasing the depth of application improved persistence much more in 1976 than in 1975, while application rate increases in both years enhanced persistence.

After the doses were calculated, the information was plotted on the soil plane to determine the zones of effective doses, and the resultant areas were converted to percentages (Table 3). The results are similar to those shown by examination of concentrations: subsoiling was the major factor in attaining a larger zone of control (≥ 5 μg-days/g soil) in 1975, whereas in 1976 deeper DBCP placement gave the greatest increase.

DISCUSSION

Subsoiling plus deep placement resulted in the best coverage in both years, but the effect was more pronounced in 1976 than in 1975. Either application technique or soil moisture conditions may account for the difference. Some of the DBCP placed at 18 cm in the subsoiling line in 1975 (Treatment C) may have trickled below that level, accounting for relatively little difference between application depths. On the other hand, personal observation suggests that the act of subsoiling may create substantial air pockets in soil. Thus, liquids applied slightly to the side of the subsoiler may still trickle into subsoiling spaces.

Increasing application rate did not appreciably increase the zones of DBCP coverage (Figs. 2, 3, 4). Youngson and Goring (22), Walla (20), and Hodges and

TABLE 3. Percentage of the soil profile covered by a dose of DBCP of at least 5.0 μg-days/g oven-dried soil during the first 28 days after treatment applications.

Treatment	1975	1976
A) 10 kg DBCP/ha, applied 18 cm deep, not subsoiled	23.6%	10.6%
B) 10 kg DBCP/ha, applied 18 cm deep, subsoiled	45.2%	13.5%
C) 10 kg DBCP/ha, applied 18 cm deep, subsoiled	50.5%	21.1%
D) 13.5 kg DBCP/ha, applied 35 cm deep, subsoiled	55.3%	28.8%

Lear (7) all observed that increasing the rates of DBCP application did little to enlarge the zone of effective treatment, although the resultant concentrations in the area were generally higher. With regard to increasing application depth, Gilpatrick et al. (3) and Youngson and Goring (22) reported that control was likely to be better at the level of application than at shallower depths.

The ability of DBCP to move through the plow-pan and the clay subsoil was not precisely determined, because the sampling technique was not structured to take samples exclusively from each horizon and the pan. Nevertheless, movement through sandy clay occurred readily (Figs. 2–5), since the porosity of the subsoil was about the same as that of the topsoil (Table 1). The inability of the fumigant, however, to move below the plow-pan even in 1975, suggests that this layer interfered with downward penetration. Taylor and Gardner (18) found that a plow-pan prevented the penetration of cotton roots to deeper soil, primarily as the result of a synergistic action of bulk density and moisture, producing greater soil strength (18). In this study, bulk density was much higher in the plow-pan than in the adjacent layers, and since particle densities were similar, the porosity of the plow-pan was lower. Consequently, less water was required to prevent fumigant movement. The reasoning agrees with that of Turner (19), who observed a positive correlation of low porosity with low nematode control. Youngson and Goring (22) found that lowered porosity decreased control of *Meloidogyne* spp., and Walla (21) reported that a plowsole prevented downward penetration of DBCP even with higher application rates.

Soil moisture content has been implicated in variability of fumigant effectiveness. Henry's Law demonstrates that at 20C, 163.8 times as much DBCP will be dissolved in a volume of water as in an equal volume of air (5). Thus, low soil moisture will likely allow the release of more fumigant into soil air, and quick diffusion out of the soil. Soil moisture content was influenced probably by rainfall. In 1975, rainfall occurred regularly during the first 17 days after treatment applications, while in 1976, no rain fell during the com-

parable period until the 19th day (Fig. 6). In fact, in 1976 there were several complaints from growers in Georgia that fumigation with DBCP did not provide adequate nematode control (J. L. Crawford, pers. comm.). Hodges (6), using irrigated plots, found that DBCP movement was enhanced when irrigation water was applied immediately after injection. He reasoned that addition of water prevented rapid upward movement of DBCP and further recommended that irrigation be performed within 5–10 days of fumigant application.

Since irrigation is not feasible in most areas, the combination of subsoiling followed by deep placement of fumigants, in soils with a plow-pan or similar impervious layer, should give the most effective nematode control.

Adequate soil fumigation practices depend on establishing the dose necessary to incapacitate or kill a given nematode species. When doses for certain points of the soil profile are calculated and then compared with known lethal doses for a particular nematode species, a "zone of kill" can be determined. Unfortunately, relatively little information is available on the toxicity of DBCP to most plant-parasitic nematodes. Goring (4), after exposing various nematodes to initially known quantities of DBCP for 7–14 days, found large differences in sensitivity (most to least sensitive): *Tylenchorhynchus* sp., *Meloidogyne* sp. (L2), *Belonolaimus* sp. = *Hemicycliophora* sp. = *Rotylenchulus* sp., *Hoplolaimus* sp., *Pratylenchus* sp., *Rotylenchus* sp., *Heterodera* sp. (cysts and larvae). *Meloidogyne* sp. was up to 25 times as sensitive as *Rotylenchus* sp. Clearly not all plant-parasitic nematodes can be considered as one in attempting to determine optimum rates and operations for fumigation.

Subsoiling with deep placement of the fumigant is the method most likely to achieve adequate fumigant distribution in soils with a plow-pan. The information presented herein should help in determining the best application methods. Further evaluation of zones of effectiveness in relation to other nematodes besides *Meloidogyne* spp. will also aid in refining methods of applying fumigants.

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