THE IMPORTANCE OF VARIOUS FACTORS IN SOIL FUMIGATION FOR POTATOES

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INTRODUCTION

Root knot nematode has been the principle target of soil fumigation in potatoes; indeed, the use of fumigants containing 1, 3-dichloropropenes (1, 3-D) has become standard practice in many areas. These are usually applied in lines 12" apart and 8 to 10" deep 2 to 3 weeks or longer before planting and the soil surface is packed with a roller afterward. In some cases and with proper techniques of application, good results are obtained with less chemical per field acre by treating only the soil zone where the potatoes will be planted. Fisher (9) outlines some of the principles of soil fumigation and Nilsen (18) explained some of these in greater depth at the Potato Conference in 1965; observance of these factors has contributed to the success of this practice. Further field use and research indicate the need for emphasizing certain aspects for best results.

More recently, increased emphasis is being placed on controlling other soil pests from applications of soil fumigants such as fungi, bacteria, weed seeds or infestations and insects. Eradication of certain pests has been demonstrated; for example, Dallimore (4) in Idaho eradicated potato rot nematode with ethylene dibromide. The toxicity of 1, 3-D and chloropicrin to several fungi and bacteria has been reported for many years (1, 17, 19); higher rates or longer and more critical exposure periods are usually needed for control of soil fungi and bacteria than those used to control root knot nematode. Several insect pests, such as wireworms and symphylans also have been controlled economically with proper techniques (3, 16). Carter (2) and others have reported on various aspects of weed control and many who have used 1, 3-D products at 20 to 25 gpa in the field have observed a high degree of control of many weed species. The direct toxicities of different fumigants to various groups of soil organisms have been estimated by Goring (12) as shown in Table 1.

Of course, considerable differences exist in the response of specific organisms to different fumigants, and the response will vary with temperature and moisture changes.

However, the basic toxicity of the fumigants to soil pests other than nematodes is sufficient to realize additional practical benefits from their use in potato production.

TABLE 1. Relative Units of Chemical Required for Direct Control of Indicated Pests

Chemical	Nematodes	Fungi	Seeds	Soil Insects
Chloropicrin	12	25	50	10
Methyl Bromide	15	40	25	10
1, 3-D1/	8	100	75	15
EDB2/	2	200	100	5
DBCP3/	1	150	200	15

1/ 1, 3-dichloropropenes - cis and trans isomers.

2/ 1, 2-dibromoethane.

3/ 1, 2-dibromo-3-chloropropane.

In this report, the abbreviations in the table will be used for respective compounds.

Dallimore (5) and Powelson and Carter (24) reported a reduction in early dying of potatoes from soil borne diseases with 15 to 25 gallons of 1, 3-D product, but in practice, this response has been erratic. Kunkel (14) and Easton (6, 7) in Washington obtained better yields of potatoes in Verticillium wilt infected soil using combinations of 1, 3-D and chloropicrin at ratios of 15 to 30% chloropicrin than with 1, 3-D alone at higher rates. Experiences such as these suggest that a number of factors are influencing overall results. To control a wide range of soil pests and to produce maximum returns from potato crops, it is necessary to consider the relative importance of each factor and its contribution to the final results obtained with a fumigation job.

General Principles

Some factors which contribute to obtaining the best results from soil fumigation include:

1. Target pests - their nature, population density and location in soil or plant.
2. Cropping history - at least the immediate preceeding crop.
3. Soil - texture, organic matter, surface and general structure to about 24", trash, air space, temperature (level and gradient), moisture (level and gradient).

4. Chemical - dosage, handling characteristics, diffusion potential, decomposition rate or residual water solubility, and reactivity with soil constituents.
5. Application - equipment, placement (depth, spacing and 2-level outlets), sealing (devices and techniques), split application, aeration, time to planting.
6. Benefits - to subsequent crop.
7. Economics or net return.

Space and time do not permit detailed consideration of all these points and their several interactions. I hope to enlarge briefly on those aspects that seem to be most important in controlling various target pests. For the most part this discussion will be concerned with 1, 3-D and chloropicrin, since these compounds seem to be best suited for achieving general pest control in the soil at acceptable costs.

DISCUSSION

Lethal Dose

Soil fumigants by nature depend upon diffusion as a gas to become adequately distributed through the desired soil volume. The fumigants must contact the pest with a lethal dose which is concentration X time, where concentration is above the "no effect" level and time is more than a "flash" exposure. In addition to providing the proper chemical rates and diffusion conditions in the soil, these materials must be retained for times adequate to produce this "lethal dose." Infestations of fungi, bacteria and weed seeds at or near the soil surface are sources of some pest problems and this is the zone of the soil where control with fumigants in uncovered soil is most difficult. Special attention to the nature of the chemical, soil conditions and application procedures will be required for good results. Generally, this involves reducing the rate of escape of the fumigants through the soil surface, which, in turn, enhances the degree of control deeper in the soil or enlarge the soil volume affected.

Fumigant Properties

Some properties of the common soil fumigants are presented in Table 2.

TABLE 2. Some Physical Properties of Common Soil Fumigants

Chemical Name	Vapor Pressure mm Hg at 20° C	Water Solubility ppm	Water/Air Ratio*	Chemical Stability
Methyl Bromide	1380	16,000	4	---
Chloropicrin	20	1,950	11	Several days
1,3-dichloro-propene	18.5-25	2,750	18-25	Several days to weeks
1,2-dibromo-3-chloropropane	0.58	1,230	164	Several weeks to months.
1,2-dibromoethane	7.7	4,270	39	Several weeks.

*Relative weights of compounds at saturation of both phases with maximum solubility in water and gas at equilibrium over the water.

Movement of gases through soils is affected by the diffusion tendency of the fumigant; this is controlled by vapor pressure, water solubility and water/air solubility ratios. Lower temperature increases water solubility and simultaneously decreases vapor pressure of these fumigants which reduces the diffusion potential. Even with these relatively low water solubilities, the water/air ratios indicate that 80 to 97% of the fumigant is in solution at saturation.

With higher moisture, more fumigant can be dissolved in the water phase. Soil moisture helps to provide reactive surfaces on organic matter (12), but the relative importance of this hard to assess. Reactivity of the toxicant with organic matter is generally irreversible (23); in soils with 1 to 2% organic matter, changes in this factor probably affect results very little.

Although soil fumigants are adsorbed on to dry clays, water will eventually replace them on the clays. As soil moisture increases slightly above the wilting point, very small amounts of material will be retained by the clays (10). At somewhat higher soil moistures, less fumigant is available for diffusion; which is probably due to solution in the moisture films and reaction with organic matter. In soils with a color of moisture, the sorption of fumigants by the mineral fraction is of little importance.

The rate at which fumigants break down in soil may affect distribution or degree of control in any soil zone. Decomposition occurs faster at higher temperatures. This is probably of importance with 1, 3-D and chloropicrin within the 35° to 85° F temperature ranges most likely encountered in the soil. Even at the lower temperatures, these materials decompose in a few weeks.

Diffusion

The extent and amount of fumigant distribution in the soil depends greatly on the continuity and size of air spaces. The pore space in soil is that part not occupied by solid particles. The air space is that part not occupied by liquid and solid phases. As the soil particles decrease in size, the pore spaces become smaller and more tortuous. Also, as the moisture increases, the air space decreases and may become increasingly discontinuous. If these occur simultaneously as with higher moisture in fine textured soil, sufficient "dead ends" and closed passages may develop so that the fumigant may not reach many of the soil organisms in sufficient concentration to be lethal. The importance of soil moisture in sugar beet nematode control with 1, 3-D is demonstrated in Table 3, which compares yields of sugar beets from "wet" and "semi-dry" areas treated with 1, 3-D (20).

TABLE 3. Effect of Soil Moisture on Control of Sugar Beet Nematode With 1, 3-D as Reflected by Yields of Sugar Beets

GPA (1, 3-D)	Yields - Tons/A			
	Semi-Dry*	Wet	Semi-Dry	Wet
0	15.7	15.8	9.0	9.0
10	27.8	15.2	22.8	17.6
15	28.2	18.1	26.1	21.7
Soil Type	Clay Loam		Sandy Loam	
Soil Moisture	23	34	7	10 %

* About 1/3 Field Capacity. From Warren (20).

The yield increases were greatest in the finer textures soil with low moisture. It is significant that, even in sandy soils, higher moisture levels limit diffusion as indicated by the higher yields in drier soil.

The solubility of fumigants in the soil moisture is necessary to control the pests since they exist in the water phase or are covered by water films. 1, 3-D, chloropicrin and EDB are relatively low in solubility, so ample vapor remains in the gaseous phase to allow adequate diffusion through the soil volume. The organisms to be controlled are "conditioned" or made more susceptible with higher soil moisture. Seeds must be imbibed and other organisms also may be more susceptible. The relationships of pest condition to moisture varies with each organism to some extent. The pest organisms are generally adequately "conditioned" when the soil moisture is in the range of 1/4 to 3/4 of field capacity. This range appears to be a good moisture level to provide air space for good diffusion. In finer soils, the moisture should be nearer the "1/4" end of the range.

Speed of diffusion as a part of the time x concentration factor can affect the kill of pests. The optimum dosage for control varies tremendously for different organisms but research has shown that better pest control is obtained in uncovered soil near the surface at slower rates. This is demonstrated in Figure 1 by comparing kills of nematodes at different levels in the soil above and below the injection points with 1, 3-D (faster diffusion) and DBCP (slower diffusion); the soil was not covered and conditions simulated those encountered in the field.

FIGURE 1. Nematode Control Patterns with Fumigants having Slower (DBCP) Vs. Faster (1, 3-D) Diffusion Potentials

% Control

DBCP

81	100	100	100	90
100	100	100	98	100
98	100	100	100	100
100	100	100	100	100
34	88	100	68	76
10	18	28	24	0
14	0	10	14	58
34	14	0	0	0

1, 3-D

58	68	58	82	48
100	100	100	100	100
100	100	100	100	100
100	100	100	100	100
100	100	100	100	100
100	100	100	86	96
48	68	68	48	38
24	14	34	68	28

Injection Point (x, between the second and third rows of each grid)

Soil Depth 24"

12"

From Goring & Youngson (12)

This control pattern indicates that as compared to 1, 3-D DBCP gives a lethal dose to the surface over the injection point whereas 1, 3-D does not because DBCP moves more slowly past the organisms at the shallow level. 1, 3-D moved rapidly through this portion of the soil and lethal concentrations were not developed. The improved control with depth below the point of injection of 1, 3-D is the result of faster diffusion with a boundary to limit escape in that direction. It is also evident from that data that diffusion can be too rapid for good pest control.

Temperature

The vertical temperature gradient in the soil can influence diffusion. If the top 2-3" of soil is warmer than at deeper levels the tendency of diffusion will be greatest upward and out of the soil. If, however, the soil is colder above, as occurs in late fall, escape from the soil would be retarded.

The effect of temperature on organism response varies with the compound and the pest. The nematicidal activity of 1, 3-D appears to be equal over a range of 35° to 85° F. Its activity on weed seeds and fungi seems to decrease somewhat at temperatures below about 50° F (10). The nematocidal action of chloropicrin is also slightly less below 55° F (10, 22), but EDB loses nearly all its toxicity below 55° F (10). Easton (7) found little effect of soil temperature in the range of 39° to 65° F on control of Verticillium wilt with 1, 3-D-chloropicrin mixtures.

As discussed above, the rate of chemical breakdown and diffusion potential are reduced at lower temperatures. With adequate continuous air space, better pest control is likely to result with 1, 3-D and chloropicrin in the range of temperatures from about 40° to 60° F. Of course, good results will be obtained at higher temperatures but application time may be adjusted to take advantage of improved chemical efficiency.

Sealing and Compacted Layers

Most crop soils have more air space in the top few inches of soil or above the line of injection than below this level. Breaking up compacted layers at depths to 20 or 24" deep and increasing air space at these depths is likely to increase the depth of pest control and may improve control at shallow levels also because of longer exposure. Packing the soil after treatment serves to reduce the air space in the top 2-3" and reduce the rate of diffusion through this layer. This not only tends to delay the loss of fumigant from deeper levels but should enhance control of pests within these shallow layers, again because of longer exposures. Good "sealing" very soon after treatment is essential to give optimum pest control. The soil surface must be free of trash and clods and in loose friable condition. A light rain, such as 1/4-1/2", helps considerably to further retard loss of fumigant.

Placement

Placement of the fumigant lines can affect the distribution of pest control. Generally greater volumes of soil are treated with deeper injections of fumigants (23), however, control in the shallow layers may be correspondingly decreased. Injection at 2 depths may be a feasible solution, as shown in Table 4 (20). Distributing the fumigant through deeper levels also resulted in improved nematode control as reflected in the yields.

Table 4. Effect of Placement on Control of Root Knot Nematode with EDB as Reflected in Yields of Sugar Beets

Lbs. EDB/A	Injection Depth	Yield Tons/A
60	8"	25.2
60	8" + 20"	30.4
0	--	13.8

Broadcast application in sandy loam soil.

From Warren (20).

For several years, injection as deep as 20-24" has been tried experimentally (20) but due to the depth at which chisels were pulled as well as the shapes of the chisels, considerable horsepower was required to pull these tools. The newer more powerful tractors plus better design of shape of chisel makes deep injection more practical today. Lembright et al. (15) reported improved results with deep injection of 1, 3-D on cotton, sweet potatoes and melons. The chisel depth increases below 10-12", the spacing can increase to 24-30" at 20-22" deep. More testing will be required to determine the best use of this technique, but it seems that optimum results would be obtained by placement of the toxicant at 2 levels with the shallow chisels halfway between the deep outlets, as indicated in Table 4, above. It is probable also that simply subsoiling to depths of 22 to 24" before application will permit adequate diffusion with fumigant placement at 12 to 15" deep to control pests in the top 20-24" of soil.

Recently there has been interest in controlling patches of perennial weeds, such as Canada thistle, with 1, 3-D. In making applications for such weed control, care must be taken to provide conditions for diffusion to depths of 3 to 4' to kill roots; also, provision for kill of seeds occurring at shallow levels should be made. This practice is not recommended, but is believed to be practical with the proper procedures and chemical rates.

Control of Pests Near the Soil Surface

Control of certain pests to the soil surface is possible by a repeat application procedure. With 1, 3-D or chloropicrin, 2/3 of the total rate needed could be applied and sealed. After about 7 to 10 days, the field would be plowed 8 to 10" deep using a scraper ahead of each plow to push all of the top soil under the turned furrow. The remainder of the fumigant is applied to the bottom of the furrow during plowing or injected afterward. Resealing at this time is very important.

Row Treatments

Application of fumigants along the line where the crop will be planted is called "row treatment." Sometimes one chisel is placed directly under the row or two chisels per row may be used. Usually the flow rates per chisel are the same in row application as for overall application where chisels are placed 12" apart; this results in using less chemical per field acre. If, however, the amount of fumigant used for complete coverage is concentrated in the 1 or 2 chisels per row, somewhat better pest control may be obtained in the volume of soil where the main part of the root system will be located.

Potato roots, later in the season, occupy the space between the rows and pests in this zone will usually take a toll at that time. Critical comparisons of row vs. overall treatments where the output per chisel is the same usually indicate that the added chemical is worth the difference.

Chemicals and Rates

The chemical and rate of application will depend greatly on the pests to be controlled. For root knot nematodes, a broadcast application of an 80% 1, 3-D product at 15 to 20 gallons per acre is adequate. Although 1, 3-D has some fungicidal activity, a combination of chloropicrin at 2.5 to 5 gallons and 20 to 30 gallons 1, 3-D product per acre is much more effective for control of Verticillium and other fungi. Combination products of these materials are available commercially.

Reductions in weed populations have been apparent with many treatments of 1, 3-D at rates of 25 to 40 gpa. With proper conditions and procedures, this could become an important added benefit from soil fumigation, however, more research is needed in this area.

Both 1, 3-D and EDB will control symphylans, wireworms and other soil insects. Since these insects move down in the soil as temperature decreases the time of application should be made when they are most likely to be in the fumigated zone.

Crop Rotations

A previous crop may influence pest control with soil fumigants in at least 3 ways. Certain crops encourage propagation of certain organisms because they are attractive hosts or because cultural practices favor this relationship. The previous crop also may leave residues that tend to discourage the target pests of potatoes. The pest organism may be harbored in undecomposed plant residues from the previous crop. These three factors as affected by crop rotations are all important considerations when planning a fumigation program.

Timing

Applications should be timed to take advantage of soil conditions that result from partial depletion of soil moisture, favorable temperature levels and gradients in soil, length of time to planting, least interference with other operations, etc.

In the spring soil moisture is usually much higher, temperatures are rising at the surface and time to planting may be short. The desired optimum application conditions are more likely to exist in the fall so often times. Fall fumigation will result in better results than spring. Following fall fumigation, a grain cover crop could be planted to hold the soil until the field is ready for the next crop.

Economics

The grower expects maximum return for each increment of expense in producing a crop. Soil fumigation must meet the standards for this return or the money may be better invested in other phases of his operation. A realistic way to predict this return is to project a yield-chemical dosage response curve, expressed in dollars. Of course, all benefits from the fumigation which may not be directly measured by increased yields such as control of certain weeds should be included in the return. With adequate inputs, the yield or return response curve will tend to plateau at some added increment of cost. Additional profit will fail to increase beyond that level. The grower can decide how much he wants to invest up to that point. The actual utility of such a response curve lies in the ability of the grower to predict the shape and level of the response curve. Results from several experiences should provide the information to develop the curve.

SUMMARY

These generalities and individual factors must be quantified and integrated into final guidelines for practical use in crop production. The influences the different factors have and the direction in which each operates to affect pest control and subsequent improved yields are summarized below.

Summary of Factors (cf. 1, 3-D and chloropicrin)

Chemical and rate - Specific recommendations for each pest.
- Nematodes and insects - 1, 3-D at 15-25 gpa.
- Fungi and bacteria - 1, 3-D + chloropicrin (85:15 ratio) at 25-40 gpa.
- Weeds - seeds and perennials - 1, 3-D at 25-50 gpa.
- Diffusion potential of the fumigant is less at lower temperatures.
- Chemicals should be out of soil at planting time.

Soil Conditions

Previous crop residues must be incorporated and decomposed.

Soil temperature range at time of application.

	35		40		50	60		70		80		85	
Too Low		good		best			acceptable				Fair		Too High °F.

(Soil temperatures are usually lower at surface than within soil.)

Moisture and Soil Texture Relationship

Air Dry	Wilting Point				Field Capacity	Sat.
0	1	2	3	4	5	6*

|← Too dry → | ← Best → | Fair → | Too Wet →|

- |← Clay →| (1 to 3.5)
- |← Clay Loam →| (1 to 4)
- |← Loam →| (1 to 4.5)
- |← Sandy Loam →| (1 to 5)
- |← Sands →| (1 to 5.5)

*Relative soil moisture

Structure - Break up compacted layer to 24" deep. Surface should be free of clods and trash and friable.

Sealing - Good firming of surface soil; a light rain or light sprinkler irrigation improves seal.

Aeration - Wait 3 to 4 weeks to disturb, especially in fall. Check for fumigant odor in soil before planting.

Timing

Refer to above list for best conditions plus operational advantages.

Fall application is usually preferred.

Application

Equipment - Good quality, applications at adequate depth, accurate metering, good sealing device.

Depth of injection - For pest control through larger soil mass- inject deeper. As depth of injection increases, chisel spacing may be greater - 20" depth can be 24-30" apart.

Two level injection and proper sealing can improve pest control near surface as well as at deeper levels in soil.

Control of root knot and other nematodes, near soil surface is not as critical as it is for Verticillium and other diseases and for weed seeds.

For perennial deep rooted weeds, control is needed at the 3-4' depth as well as near surface in order to control the seeds.

Split application is best for shallow pest control or eradication.

Subsequent benefits - Increasing dosage and better procedure may improve return from crop after potatoes.

Economics - Relate projected return to increments of cost. When reasonable accurate predictions are possible, added costs of chemical or procedure may be justified by either increased yield or reduced total cost of production or both.

Final assessment of the relative importance of the different factors in fumigation should be done when the pests and their location in the soil are defined. Careful consideration of the factors discussed above will help to achieve the most efficient use of fumigant of potatoes.

Continued research, field experience, improvements in equipment and techniques will add even further to improving returns from soil fumigation of potatoes.

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