NEMATOCIDES AND NEMATICIDES - A HISTORY

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PROLOGUE

Taylor, A.L. 2003. Nematocides and nematicides - a history. Nematropica 33:225-232. The lifetime of accomplishments and contributions to Nematology by Mr. A. L. Taylor are well know by nematological, scientific and agricultural communities in general. In particular, Mr. Taylor was a pioneer in proving the benefits of the nematicides, ethylene dibromide, methyl bromide and 1,3-dichloropropene, to reduce nematode damage to crops. As part of this work, he developed application techniques such as introducing a mulch cover when applying methyl bromide, a practice still widely used today. As a result of his efforts, and those of other pioneers, nematodes were recognized as damaging pests of crop plants and the science of Nematology was greatly expanded. Mr. Taylor's contributions to nematology are chronicled in numerous publications, including book chapters on nematicides. The following contribution apparently was one of his last (written around 1978) and was only published as a Florida Department of Agriculture Internal Information Sheet. We feel it is one of his best since the publication not only gives his direct historical perspectives on the development and use of nematicides but also includes some of his personal observations. The article has received minor editing and formatting to improve clarity. Overall, however, it remains as written by Mr. Taylor some 25 years ago. We hope this article serves as another tribute to an outstanding and pioneer nematologist (J. R. Rich and L. W. Duncan).

PRÓLOGO

Taylor, A.L. 2003. Nematocidas and nematicidas - una historia. Nematropica 33:225-232. La vida de logros y contribuciones en el campo de nematología del señor A.L. Taylor es bien conocida en las comunidades de nematología, ciencia y agricultura en general. El señor Taylor fue un pionero en la comprobación del beneficio de los nematicidas bibromuro de etileno, bromuro de metilo y 1,3-dichloropropano para reducir el daño a cultivos causado por nemátodos. Como parte de su trabajo, desarrolló técnicas de aplicación como la introducción del cubierto del suelo con la aplicación de bromuro de metilo, lo cual todavía se practica hoy extensivamente. El resultado de sus esfuerzos, y de los esfuerzos de otros pioneros, fue que nemátodos fueron reconocidos como plagas dañinas para cultivos, y que la ciencia de nematología fue expandida considerablemente. Las contribuciones del señor Taylor en el área de nematología fueron relatadas en varias publicaciones, incluso en capítulos de libros sobre nematicidas. La siguiente aparentemente fue una de sus últimas contribucións (escrita en 1978) y fue solamente publicada como un informe interno del Departamento de Agricultura del Estado de Florida. Sentimos que es uno de sus mejores publicaciones, porque no solamente da sus perspectivas históricas directas sobre el desarrollo y uso de nematicidas, pero también incluye algunas observaciones personales. Este artículo recibió algunos cambios mínimos para mejorar la claridad. Sin embargo, en general, permanece como el señor Taylor lo escribió hace unos 25 años. Esperamos que este artículo sirva como otro homenaje a un destacado pionero en nematología (J.R. Rich y L.W. Duncan).

INTRODUCTION

The history of nematicides* can be divided into three parts, ancient, medieval and modern. The ancient history of nematicides is clearly associated with the early history of soil insecticides, and probably had its beginning about 1854, when Garreau recognized the insecticidal value of carbon bisulphide (also spelled disulphide and bi- or disulfide).

According to Fleming and Baker (1935) the use of carbon bisulphide (CS_2) for soil fumigation was first suggested by Thenard in 1869.** At that time, damage to French vineyards by an aphid known as the grape phylloxera (*Phylloxera vitifoliae*) was reaching alarming proportions. Indeed, the root-infesting form of this insect, introduced from America about 1860, destroyed about 1,000,000 hectares of French vineyards by 1885 (Metcalf and Flint, 1962). Research was started on the use of carbon bisulphide about 1870 and by 1877 methods and apparatus for its use had been well developed by Dr. Crolas (Newhall, 1955).

The most popular and successful application method was injection of carbon bisulphide into holes 50 centimeters apart. From these application points, fumes diffused through the soil. Later, application by spraying the undiluted liquid into the soil while plow-

*Formerly spelled nematocide and sometimes nemacide.

**Their reference was not direct, but to Bourcart, 1913 and 1925.

ing was tried but found to be often ineffective. Carbon bisulphide is slightly soluble in water; at 20°C one liter of water can absorb 1.79 grams of CS_2. This makes application in irrigation water possible and this method seems to have been used with some success (Newhall, 1955).

With the introduction in about 1900 of phylloxera-resistant rootstocks from grapes native to the eastern United States, the use of carbon bisulphide in vineyards was abandoned as no longer needed. But in the meantime, the idea that soil pests could be controlled by injection of volatile chemicals in the soil had been well established, and as detailed by Fleming and Baker (1935), a great deal of research had been done on control of other soil insects. This work has continued, and CS_2 is still available for use to control soil insects.

ANCIENT HISTORY

The sugarbeet nematode, *Heterodera schachtii*, was first reported as the cause of a serious disease of sugarbeets by Schacht (1859). Kuhn reported experiments with carbon bisulphide for its control in 1871.*** The experiments were evidently not very successful, but sufficiently encouraging to prompt further work by Bessey against root-knot nematodes in the United States during the first two decades of century. These experiments were reported in various U.S. Department of Agriculture publications, but there are few reports of commercial use of carbon bisulphide for nematode control.

MEDIEVAL HISTORY

World War I started in 1914 and ended in 1919. We might date the end of the era of ancient history of nematicides as falling somewhere during this period. One of the developments of the war was the use of poisonous gases as weapons to disable enemy soldiers without necessarily killing them. The first to be used was chlorine. Another was chloropicrin (CCl_3NO_2). Chloropicrin fumes in the air in low concentration cause irrigation of the eyes, with profuse flow of tears, so it was called "tear gas." Higher concentrations cause lung irritation, nausea and vomiting. Exposure is seldom fatal because the victim leaves the contaminated area as rapidly as possible or is forced to use a gas mask. At the end of the war in 1918, large stocks of chloropicrin were on hand as military surplus. Chloropicrin was tested among other chemicals in England by Mathews (1920) for control of fungi, nematodes and wireworms, and for its beneficial effect on soil bacteria. Chloropicrin was outstanding in several respects. Yield of tomatoes in pots was increased from 857 grams to 1,480 grams. It was classed among the "most effective" chemicals for control of nematodes and wireworms, and most "beneficial to bacterial activity". It also "had a remarkable effect on root action, producing the great mass of fibrous roots which has hitherto only been obtainable in a steamed soil. Many attempts have previously been made to reproduce this effect of steaming, but until this season without success." The medieval era of nematicides starts with this paper.

In 1927 and 1928, Johnson and Godfrey (1932) started field work with chloropicrin in pineapple fields in Hawaii. They concluded that:

1) Plots treated with chloropicrin consistently had the highest percentages of plants free of root knot nematodes.

2) There was good negative correlation between infection by root-knot nematodes and amounts of chloropicrin applied.

3) Weight of pineapples produced on treated plots was as much as 57.0% more than weight from control plots.

4) The value of the additional pineapples from treated plots was considerably more than the cost of the chloropicrin and its application.

Further field experiments with chloropicrin reported by Godfrey in 1935 confirmed these results, with pineapple yield increases in chloropicrin-treated plots of 31.4% and 51.2% more than the controls. Carbon bisulphide was also included in this experiment, with yield increase of 31.3% for the best treatment. The current market value of the increased yield of pineapples from plots treated with chloropicrin was \$208.70 per acre (\$515.49 per hectare). Subtracting

***This statement is according to Thorne (1961, p. 28), but no reference was given unless Kuhn (1881) was intended. This paper does report experiments with carbon bisulphide.

the cost of the chloropicrin treatment, $125.00 per acre ($308.75 per hectare), the profit was $83.70 per acre ($206.74 per hectare). This was only actual weight increase of the plant crop (first crop after planting) without regard to the higher grade of the fruit because of increased average weight, or the prospects for an increased ratoon crop (second crop after planting) because of the superior condition of the plants.

Shortly thereafter, application of chloropicrin before planting pineapples became a widely used practice in Hawaii and continued as long as World War I surplus chloropicrin remained available (Thorne, 1961).

In 1935, I was appointed Junior Nematologist by the Bureau of Plant Industry, U.S. Department of Agriculture and assigned to the Coastal Plain Experiment Station at Tifton, Georgia. My principal assignment was investigation of the possibilities of soil nematicides. Being entirely unaware of the details of the French work with carbon bisulphide in the late 1800's, I spent some time reinventing the hand applicator (Taylor, 1939) apparatus for delivering a continuous stream of nematicide into a furrow and a plow applicator. I also confirmed the work of Dr. Godfrey and his colleagues, reporting good results with 200 to 400 pounds of chloropicrin per acre (224 to 448 kilograms per hectare). Equally good results were obtained with 500 to 1000 lbs. of carbon bisulphide per acre (560 to 1120 kg / ha) applied by injection into the sandy loam soil at Tifton. When carbon bisulphide was applied as a water emulsion in furrows, about five times as much was required (Taylor 1943, 1949).

Between 1937 and 1941, the Innis Speiden Company of Niagara Falls, New York, (later renamed Larvacide Products Co.) was actively promoting the use of chloropicrin as a soil nematicide and insecticide in addition to its use as a fumigant for grain in storage. Their principal nematicide customers were owners of greenhouses, nurseries and seedbeds for large-scale vegetable production. So far as I am aware, this was the first commercial promotion of nematicides.

In 1940, Christie and Cobb reported an experiment with the insecticide methyl bromide for control of chrysanthemum foliar nematode on planting material. Methyl bromide is a liquid if kept in closed containers, but becomes a gas at about 4^{o}C at atmospheric pressure. They concluded that control was impractical because of phytotoxicity and because only recently hatched larvae were killed. Hawkins (1939) used methyl bromide for control of white-fringed beetle (*Graphognathus leucoloma*) in potting soil. This suggested trials as a soil nematicide by Taylor and McBeth (1940). After partially successful preliminary experiments, satisfactory results were obtained in field plots by releasing methyl bromide as a gas in tile lines buried under soil covered with gas impervious glue-coated paper. These authors (1941a) had better results by simply covering the soil with a gas impervious paper supported about 8 centimeters above the soil surface, and releasing the methyl bromide between the cover and the soil surface. This method is still widely used, but plastic covers have long since replaced paper. In the course of this work, apparent control of soil fungi and bacteria were noted.

Taylor and McBeth (1941b) reported an experiment with "spot" treatment of soil as a means of saving nematicide and the labor of applying it in fields where crops planted in widely spaced hills are to be grown. They referred to previous experiments which indicated that root-knot nematode larvae move through the soil at an average rate of less than one centimeter per day in the sandy loam soil of southern Georgia. If planted in a nematode-free area of soil, a plant would not be heavily attacked in its early stages of growth when comparatively few nematodes can damage it severely. The method was successful for watermelon production. Later, the logical extension of the method to "row" treatment was made (Taylor, 1949). Row treatments can be made with power applicators and have probably been used more than any other method.

MODERN HISTORY

The end of the medieval era of nematicide history and the beginning of the modern era was marked by the publication in 1943 of a paper by Dr. Walter Carter of the Pineapple Research Institute, Honolulu, Hawaii. This was a report of field experiments with a mixture of 1,3-dichloropropene and 1,2-dichloropropane. The material, called "D-D mixture" by Carter, was reported to be less expressive and easier to handle than chloropicrin. The D-D mixture produced comparable results so far as control of nematodes and insects, and gave favorable plant growth responses. A second more detailed paper by Carter (1945) supported these conclusions with excellent data.

In 1944, ethylene dibromide (EDB) was being tested as a soil nematicide by the Dow Chemical Company at Seal Beach, California (Thorne and Jensen, 1947), and apparently at about the same time by Christie

(1945) at the USDA Plant Industry Station at Beltsville, Maryland. Dr. Christie's small-scale test indicated that EDB was as effective as the D-D mixture for control of root-knot nematodes. So far as I am aware, the results of the tests at Seal Beach were never published. In 1947, Thorne and Jensen published the first paper on field experiments with EDB for control of the sugarbeet nematode, *Heterodera schachtii*.

Starting in 1946, experimental and commercial use of nematicides increased rapidly. Both the Shell Chemical Corporation and the Dow Chemical Company decided to market nematicides. Both companies began vigorous campaigns of advertising, demonstration and research to find other and perhaps better nematicides. DD and EDB were inexpensive enough so that their use was potentially profitable for the farmer on crops of moderate to high value. Both were already in extensive use by the Hawaiian pineapple industry.

As an employee of the Shell Chemical Corporation from 1946 to 1949, I was assigned to market-development in the southeastern United States, concentrating on tobacco in the Carolinas, Georgia and Florida. My experience there was similar to that of numerous colleagues in other parts of the United States and in foreign countries.

The market for nematicides developed slowly because an enormous amount of educational work was necessary. Many farmers had never heard of nematodes and had certainly never seen any. Some were familiar with root-knot nematodes galls, but did not know what caused them and did not associate their presence with reduced growth and yield. There was little data to show that nematodes could cause significant reductions of crop yields. To sell nematicides, farmers had to be persuaded to believe that:

1) There are little worms called nematodes which attack crop plants. Nematodes, too small to recognize without a microscope, exist in enormous numbers in farm fields.

2) Nematodes damage roots and are a primary cause of reduced plant growth and crop yields.

3) Nematodes can be controlled by application of nematicides.

4) Control results in increased crop yields.

5) With crops of moderate to high value per acre, the selling price of the yield increases is 4 or 5 times the cost of the nematicide and its application.

6) Nematicides are therefore a good investment.

An educational program was needed because the farmers had been cultivating the same land for many years and were satisfied that they were getting as good yields as possible, certainly average for the neighborhood. The old way of farming was working very well; why should they change? We were asking them to invest money in chemicals and equipment to control pests they had never seen in all the years they had been working the soil. The application methods were unlike any they had ever used before, and the results were unknown.

Eventually a marketing technique based on field demonstrations was developed. With the generous help of Extension Service personnel, arrangements would be made to cooperate with leading farmers in a community. Equipment and chemical was furnished to fumigate areas in fields where tobacco was to be planted. The rest was done by the farmers, who planted, fertilized and cultivated the whole field as usual. Early in the growing season, results began to be visible. Tobacco plants in the treated area were larger and more uniform than those in the adjacent untreated part of the field. The improvement continued all through the season. At any time, it was possible to dig roots for comparison of stunted, knotted or rotted roots from untreated soil with extensive, healthy roots from treated soil. The growth difference was plainly visible in the field and far more convincing than any amount of talking and advertising. The next step was to convince the farmer that use of nematicides was profitable, that the selling price of the increased yield was at least 4 or 5 times as much as the expenditure for the nematicide and its application.

Field demonstrations were slow to produce results because only one could be conducted each season. A series was needed to provide convincing evidence that nematicides would produce dependable results if properly used. The usual sequence of events in a neighborhood was at least two years of demonstrations followed by two or more years of independent trials by the farmers. Then the more prosperous and progressive farmers were ready to adopt nematicides as a regular practice. In the meantime, neighboring farmers were watching developments over the fence, and were being shown results by the County Agent or other Extension Service Personnel. The time from the first demonstrations in most communities to widespread use of nematicides was about eight years. Looking back, it is easy to see why so much time was needed. Everything was new and unfamiliar, and learning required time and experience.

About 95% of tobacco growers in North Carolina now start the season by planting seedbeds in soil treated with methyl bromide, then about 85% transplant into fields treated with nematicide, usually by row treatments. Analysis of field demonstration experiments (Todd, 1976, 1977) conducted by the North Carolina Extension Service indicates that the best treatments increase yields of a root-knot-susceptible tobacco variety by an average of about 35%, as compared with the untreated control plots. This is only one example of the way nematicides have increased farming efficiency, not only in the United States, but in much of the rest of the world. It is also an example of the results of intensive Extension Service effort backed by research.

All the activity and publicity associated with the development of nematicides had a highly important effect on Nematology and on the number of Nematologists. In 1945, there were few Nematologists employed by the U.S. Department of Agriculture at Beltsville and the four USDA field stations. There was one professional nematologist in California, a few at Rothamsted, and a few more elsewhere in the world, probably less than 20 devoting even part-time to research in any phase of Nematology.

The next historic event was the discovery of the nematicidal value of DBCP (1,2-dibromo-3-chloropropane). McBeth and Bergson (1955) were the first to publish results in which the chemical formula was given. McBeth was in charge of the Shell Chemical Corporation nematicide screening program. In a previous paper (McBeth, 1954), DBCP was discussed under its experimental number, OS 1897. DBCP is another fumigant, but it has also been extensively used as an emulsion in irrigation water. DBCP, unlike DD and EDB, is not highly toxic to many crop plants and can be applied at planting or after planting. It has been extensively used for control of the citrus nematode (*Tylenchulus semipenetrans*) and for control of other nematodes on living trees and grapevines.

As experience with nematicides accumulated, it became evident that there were other effects in addition to killing nematodes. Insects in the soil at the time of application were killed. There were occasional reports of weed control with DD, but it evidently was not a dependable weed killer. Methyl bromide applied under a plastic cover killed weed seeds in soil, eliminating expensive hand weeding of vegetable seedbeds. Control of bacteria and fungi in soil was good with methyl bromide, and occasionally good with DD or EDB.

Vapam (sodium N-methyl dithiocarbomate dihydrate), introduced by the Stauffer Chemical Company in 1956, was effective for control of nematodes, weed seeds and soil fungi. Vapam was not a volatile liquid but decomposed in the soil to form a penetrating gas, and thus acted as a fumigant.

The next nematicide to be placed on the market in 1957 was a "nonfumigant" called "V-C 13 Nemacide" by the Virginia-Carolina Corporation of Richmond, Virginia. Its active ingredient was 0-2, 4-dichlorophenyl 0,0-diethyl phosphoro-thioate, the first of a series of organophosphate nematicides. These are commonly called "nonfumigant" nematicides and sometimes "contact" nematicides.

Since 1960, numerous new nematicides have been tested, and some placed on the market. The principal difficulty has not been in finding chemicals which control nematodes under ideal conditions, but in finding chemicals which will control nematodes dependably when used by farmers under a wide variety of farm conditions.

The nematicides listed in Table 1 became available on world markets, and application methods for use on a wide variety of annual and perennial crops have been developed by cooperation between Experiment Stations, Extension Service personnel and industry. The list is short, but use of one or more of the chemicals named will solve most nematode problems. The expense of nematicide application has also decreased. Nematicides are now regularly used by growers of many crops once considered to be outside the profitable range.

The important advances have been in simplification of application methods and in reduction of application rates. Granular formulations of non-fumigant nematicides may be distributed over the soil surface or liquid formulations sprayed on the soil surface. Both methods are more effective if followed by mixing with the upper layer of the soil, but this is not considered essential by many manufacturers and users. Several of the non-fumigant nematicides have systemic action. They are taken up by the plant and nematodes feeding on the plant are controlled.

Development of the nematicide market and farmer profit: As the use of nematicides developed in the

Table 1. Nematicides commonly found in world markets.

Common Name	Commercial Name	Manufacturer	*Mode of Action
Aldicarb	TEMIK	Union Carbide	Nonfumigant
Carbofuran	FURADAN	Niagra Chemical	Nonfumigant
Chloropicrin	CHLOR-O-PIC	Great Lakes	Fumigant
1,3-D	TELONE	Dow Chemical	Fumigant
DD Mixture	D-D, VIDDEN - D	Shell Chemical	Fumigant
EDB	DOWFUME W-85	Dow Chemical	Fumigant
Ethoprop	MOCAP	Mobil Chemical	Nonfumigant
Fenamiphos	NEMACUR	Chemagro (Mobay)	Nonfumigant
Fensulfothion	DASANIT	Chemagro (Mobay)	Nonfumigant
MBr	DOWFUME MC-2	Dow Chemical	Fumigant
Oxamyl	VYDATE	Dupont de Nemours	Nonfumigant

Editors note: Most manufacturers have merged and thus changed names since writing of the article by Mr. Taylor. The production of DBCP (dibromochloropropane) manufactured under at least two names, NEMAGON (Shell Chemical Co.) and FUMAZONE (Dow Chemical Co.), was discontinued in 1977.

modern era, commercial production and sales increased to about $70,000,000 per year in the United States in 1978. Nematicide markets in foreign countries have been developed concurrently with the U.S. market. There has been a corresponding increase in number of nematologists, and a parallel process of farmer education in many other countries.

As a general rule, farmers investing in nematicides confidently expect and usually realize a minimum profit of four times their investment. For the estimated total value of the nematicide market ($70,000,000 in 1978), the increase in crop values for the United States would be $280,000,000.

For tobacco in North Carolina in 1977, growers spend an estimated $14,737,000 for chemical soil treatment and $3,438,000 for application, a total of $16,175,000. In that state alone in this one year, nematicides added at least $72,000,000 to the farm value of tobacco (Todd, 1977).

The cost of the research which developed the basic information for the industry and farmers is impossible to calculate accurately, but I doubt that as much as $1,000,000 was expended by federal or state research organizations in the United States during any one of the 35 years of the modern era of nematicide history. Profits of American farmers every year are at least eight times the total cost of research.

Indirect results of nematicide research and development: Some indirect results of nematicide research and development are also significant.

1) The importance of plant-parasitic nematodes as a major class of agricultural pests was conclusively proven. Before widespread demonstrations of increased yields following applications of nematicides, nematodes had been mostly ignored. Being practically invisible, their existence in enormous numbers in most all agricultural soils of the world was suspected only by a few pioneer scientists.

Except in the sugar beet industry, first in Germany during the ancient era, and in the United States during the medieval era, no organized effort was made to control any plant-parasitic nematode. Sugar beets were a special case. Sugar beet processors must have a steady and reliable supply of sugar beets within economic transportation distance of their expensive sugar factories. Farmers near the factories planted beets year after year on the same land. The sugar beet nematode, *Heterodera schachtii*, multiplied in the fields until yield were reduced below the cost of production for the farmers, and the sugar factory no longer had enough beets for profitable operation. The remedy was crop rotation systems developed by cooperative efforts of the farmers and the processors, and strictly followed by both to their mutual advantage (Thorne, 1961).

Similar situations have been resolved more quickly and easily by use of nematicides during the modern era. Numerous others remain and more will develop as farming continues to move toward specialization and industrialization in the more developed countries. In less developed countries, the first step in reduction of crop losses caused by nematodes is training of native nematologists who can conduct a campaign to educate farmers. An important part of the campaign is demonstration of better growth and yield following application of nematicides. Eventually, this campaign will have a highly significant effect on agricultural production in the countries where it is most needed.

2) Widespread use of nematicides has stimulated research on non-chemical methods of nematode control. Because it is simple and easy for the farmer, reduction of crop loss due to nematodes by use of nematode-resistant cultivars is often the best method of control. If the cultivar is nearly immune, the nematode population of the soil is also reduced (Oostenbrink, 1972).

In the ancient and medieval eras of nematicide history, few resistant cultivars were reported and there was little attempt to develop them by plant breeders. In the modern era, many have been reported, and there is growing interest by plant breeders in adding nematode resistance to the other desirable qualities of crop plants. Fassuliotis (1976) lists about 125 vegetable cultivars with resistance to various species of root-knot nematodes. Numerous resistant cultivars of field crops are mentioned in various chapters of "Economic Nematology" (Webster, 1972). A few rootstocks for fruit and nut crops are also available. Those resistant to *Meloidogyne* species are listed by Taylor and Sasser (1978).

Use of resistant cultivars has expanded greatly in the past 20 years. According to Todd (1977) more than half of the tobacco grown in North Carolina in 1977 were cultivars resistant to *Meloidogyne incognita*, the most common root-knot nematode in that state.

The future of nematicides: During the course of an investigation started in 1977, the Environmental Protection Agency of the United States Government cited health hazards and made stringent regulations of procedure used in manufacture, handling and application of DBCP. This nematicide which had been on the market for over 20 years is no longer manufactured in the United States. This event will certainly have a considerable influence on the future of nematicides. Perhaps it is the begging of a new era.

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