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STUDIES ON THE CHEMICAL CONTROL OF WIREWORMS (*AGRIOTES* SPP.).

I.—THE DIRECT AND RESIDUAL EFFECTS OF BHC, DDT, D-D, AND ETHYLENE DIBROMIDE.

By C. Potter, M. J. R. Healy and F. Raw
Rothamsted Experimental Station, Harpenden, Herts.

(Plates XXIII & XXIV.)

Wireworms are important pests in Great Britain, and a considerable amount of research work has been devoted to them. Some of the more recent British work is summarised by Thomas (1949), and reviews of work in other countries are given by Lange (1947) and Ernould (1948).

Benzene hexachloride has been used to a great extent in this country to control wireworms and detailed experiments with it are described by Jameson, Thomas & Woodward (1947) and Jameson, Thomas & Tanner (1951). The latter publication describes its use when applied as a seed dressing of cereals. Golightly (1946) gave data to show that DDT could reduce wireworm attack and this was confirmed by Jameson, Thomas & Woodward (1947).

While workers abroad have found BHC effective for wireworm control on a wide range of crops, under varying experimental conditions and with a number of species of wireworm, DDT has been found to be relatively ineffective by some workers (Arnason, Fox & Glen, 1948; Pepper, Reed & Campbell, 1949; Blanka, 1950; Galakhov, 1950; Ingram & others, 1950). Other workers, however, have obtained good results with DDT (Roberts, 1947; Lane & others, 1948; Anon., 1949; Stone & Foley, 1954).

Soil fumigation for wireworm control has not been used to any extent in England, but has been found to give good results under some conditions abroad. The fumigants mainly used for this purpose are ethylene dibromide and D-D (Lange, 1945; King, Arnason & Manson, 1948; Cook, 1949; Pepper, Reed & Campbell, 1949; Stone, 1949; Stone & Foley, 1954).

In the spring of 1947 a crop of winter wheat in Little Hoos Field, Rothamsted, was severely damaged by wireworms of the genus *Agriotes*. Sampling showed that the wireworm population was about 1·25 million per acre. The following autumn, two experiments were laid down which were continued for four years. The soil was heavy clay with flints.

The experiments were designed to compare the effects of BHC, DDT, ethylene dibromide and D-D, when applied under similar conditions to control wireworms.

Since very few data were available on the after-effects of a single treatment, the experiments were continued over a period of four years to determine the effect of the various treatments on infestation of succeeding crops. Since it was known that BHC might cause taint, some experiments to determine the risk of taint by this insecticide were included.

Experiment I, 1947–51.

The treatments, applied in October 1947, were as follows:—

BHC seed dressing— seed treated at the rate of 2 oz./bushel with a dressing containing 20 per cent. technical γ isomer.

BHC combine-drilled—	3·5 per cent. wireworm dust combine-drilled with the seed at $\frac{3}{4}$ cwt./acre giving 2·9 lb./acre crude BHC $\equiv$ 5·7–6·0 oz. γ isomer per acre.
BHC broadcast—	3·5 per cent. wireworm dust broadcast immediately before sowing at 2 cwt./acre giving 7·9 lb./acre crude BHC $\equiv$ 15·2–16·0 oz. γ isomer per acre.
DDT combine-drilled—	5 per cent. DDT dust combine-drilled with the seed at 144 lb./acre giving 7·2 lb./acre technical DDT.
D-D (a liquid product consisting essentially of a number of isomeric dichloropropenes, together with 1,2-dichloropropane and other chlorinated hydrocarbons. The chief component of the mixture is 1,3-dichloropropene.)	A mixture containing D-D and tractor vapourising oil in equal volumes injected 6 in. deep 19 days before sowing at the rate of 210 lb./acre D-D.
Ethylene dibromide—	A mixture containing 20 per cent. by volume technically pure ethylene dibromide and 80 per cent. by volume tractor vapourising oil injected 6 in. deep 19 days before sowing at the rate of 45·5 lb./acre ethylene dibromide.
Controls—	No treatment.

Methods.

Recognised practice was followed for the solid insecticides which were applied by broadcasting, combine-drilling and seed dressing.

The soil fumigants were applied by means of a special injector loaned by courtesy of the Shell Company. This machine consists of a reservoir, a motor and six injector tubes, each tube attached behind a special tine of the cultivator type. The rate of flow of the fumigant and hence the rate of application for a given tractor speed can be adjusted. The whole machine is mounted on pneumatic tyres and is tractor-drawn. Some details of this machine are given by Grainger (1951) under the heading " An American Prototype Injector ". In these experiments, the tines were set 9 in. apart and set to deliver the fumigant at 6 in. depth. The tines drilled a furrow and volatile liquids dribbled through the tubes into the furrows. Immediately after each fumigant had been applied to the test plots, they were rolled to consolidate the surface.

There seems to be no evidence that the conditions at the time of treatment affect the action of the solid insecticides, but a number of workers (Newhall, 1946; King, Arnason & Manson, 1948; Cook, 1949; McClellan, Christie & Horn, 1949; Stone, 1949) have shown that temperature and soil conditions may greatly affect the action of the fumigants. Records of the prevailing conditions on the day of application were therefore taken. The weather was dull and cloudy with a S.W. wind, $15\frac{2}{3}$ ft./sec. at two metres high and 14 ft./sec. one metre high at the beginning of fumigant application and $14\frac{1}{3}$ ft./sec. at two metres and $11\frac{3}{5}$ ft./sec. at one metre at the end of the experiment. The air temperature at the surface of the soil was 16·5°C.; the soil temperature 6 in. deep was 12·5°C. The ground was clay with flints that had been harrowed down to seed-bed consistency.

At the time the experiments were started there was very little information on which materials were most economical when applied at their effective dosage rates. Dosage rates were chosen which, judged from the literature, would prove effective.

The experiment was laid out as three randomised blocks of nine plots (one for each treatment and three controls), each plot being 14 × 90 ft. (0·0289 acre). The experiment was continued for four years without further application of the treatments except that in the final year, 1951, the plots which had originally received BHC seed dressing were used for another experiment. The wheat variety was Bersee in 1948 and 1949, Squareheads Master (13/4) in 1950, and Nord Desprez in 1951, sown at 3 bushels/acre.

Effect of treatments on yield.

The direct effect of each treatment was assessed by the yield of grain and straw at harvest in 1948 and the residual effect by the yield in 1949, 1950 and 1951. These results are given in Table I.

TABLE I.

The direct and residual effects of a single treatment with different insecticides on yield of grain and straw.

	Yield of grain (cwt. per acre)								
	Controls	BHC			DDT	D-D	Ethylene dibromide	Standard errors	
		Seed dressing	Combine-drilled	Broad-cast				Controls	Others
1948	8·9	24·0*	24·8*	30·6*	20·7*	28·3*	32·1*	0·87	1·51
1949	28·4	24·2	37·3*	39·6*	36·4*	31·8*	34·1*	0·77	1·33
1950	15·5	11·7	15·0	16·1	18·0	16·9	18·8*	0·72	1·25
1951	14·7	—	16·5	17·2	20·3*	15·6	15·5	0·84	1·18
	Yield of straw (cwt. per acre)								
1948	22·8	54·6*	54·2*	65·9*	46·0*	64·1*	71·6*	2·12	3·68
1949	33·5	28·5	42·2*	46·1*	41·5	35·8	37·4*	0·89	1·54
1950	25·0	20·9	23·0	25·8	27·1	27·0	27·8	1·09	1·88
1951	16·3	—	18·0	18·9*	20·1*	17·8	17·8	0·72	1·02

* Values which significantly exceed the controls ($P < 0{\cdot}05$).

In the year of application all the treatments resulted in a marked increase in yield of grain and straw. BHC broadcast and the soil fumigants gave the best results followed by BHC seed dressing and BHC combine-drilled. DDT was the least effective, though even here the yield of both grain and straw was more than twice that of the control plots.

In the following year when wireworm damage, as judged by the yield of the control plots, was much less, the BHC seed dressing showed no residual effect. BHC combine-drilled, BHC broadcast and DDT showed a substantial residual effect. The soil fumigants, especially D-D, were somewhat less effective.

In subsequent years residual effects were less marked, though ethylene dibromide showed a significant effect in 1950 and BHC broadcast and DDT in 1951.

Effect on plant growth.

In the spring of 1948 and 1949, estimates of plant height and density were made. Four one-yard lengths of drill were chosen at random in each plot, and the number of plants and the heights of three plants in each yard were recorded. The results are given in Table II.

TABLE II.

Effect of treatments in the year of application and the year following application on plant density and height of wheat plants.

Date	Controls	BHC Seed dressing	BHC Combine-drilled	BHC Broad-cast	DDT	D-D	Ethylene dibromide	Standard errors controls	Standard errors others
Plant numbers (thousands per acre)									
1.iii.48	1170	1327*	1095	1322*	1247	1317*	1357*	34	59
13.iv.48	465	1021*	804*	1250*	801*	1197*	1678*	56	98
10.v.49	1240	1068	1477	1744*	1545*	1489*	1390	61	105
Plant height (in in.)									
1.iii.48	3·10	3·01	2·98	2·99	3·14	3·07	3·07	0·06	0·10
13.iv.48	4·56	5·35*	4·83	5·51*	5·04	5·92*	5·93*	0·13	0·22
10.v.49	11·2	10·9	12·4*	12·6*	12·4*	11·4	11·7	0·26	0·44

* Values which significantly exceed those of the controls ($P < 0{\cdot}05$).

These results agree with those in Table I. By mid-April 1948, when wireworm damage had severely thinned the control plots, all the treated plots carried a much denser stand of wheat accompanied by better growth on plots treated with BHC seed dressing, BHC broadcast, D-D and ethylene dibromide (see Pl. XXIII, figs. 1–4, & XXIV, fig. 1).

In 1949 there was a residual effect on the plots previously treated with BHC combine-drilled, BHC broadcast, DDT and D-D.

TABLE III.

Effect of treatments in 1948 on the wireworm population assessed in 1950.

Total wireworm counts,* September 1950.

Year-group	Controls	BHC Seed dressing	BHC Combine-drilled	BHC Broad-cast	DDT	D-D	Ethylene dibromide	Total
1st ..	25	3	11	0	4	18	6	67
2nd ..	63	21	3	3	3	16	8	117
3rd ..	24	17	7	1	4	14	4	71
4th ..	11	6	3	0	1	1	2	24
Total ..	123	47	24	4	12	49	20	279
% in top 6 in.	74	77	75	50	75	84	60	

* Controls, 9 plots; others, 3 plots.

Effect on the wireworm population.

The plots were sampled for wireworms in September 1950. Four random soil samples each 4 in. diameter and 12 in. deep were taken from each plot, divided into an upper and lower half and the wireworms extracted by a standard flotation method. The length of each wireworm when fully extended was measured and on the basis of the size distribution of all the wireworms they were divided into four groups corresponding approximately to year groups, *i.e.*, to larvae hatched in the four years 1947–50. The results are summarised in Table III.

The counts were transformed to square roots for analysis, first including all larvae and then excluding first-year larvae, *i.e.*, those which hatched in 1950. The results are given in Table IV.

TABLE IV.

Analysis of the effect of insecticide treatments on the wireworm population.

Mean numbers of wireworms per plot (square root transformation)

	Controls	BHC			DDT	D-D	Ethylene dibromide	Standard errors	
		Seed dressing	Combine-drilled	Broad-cast				controls	others
All larvae	3·70	3·87	2·83	1·33*	2·03*	4·10	2·60*	0·25	0·43
Less 1st-year larvae	3·30	3·73	2·20*	1·33*	1·63*	3·23	2·20*	0·25	0·43

* Values significantly less than those of the controls ($P < 0·05$).

It can be seen that, three years after application, the plots treated with BHC broadcast, DDT and ethylene dibromide had a distinctly lower wireworm population than the control plots. These three treatments had a marked residual effect on yield of grain and straw in 1949 and on either grain or straw in 1950 or 1951. If the first-year larvae are excluded, the plots treated with BHC combine-drilled also have a lower population than the control plots and this treatment also had a marked residual effect on yield in 1949. The populations of the plots treated with BHC seed dressing and D-D were very similar to that of the controls. D-D had shown a residual effect on yield of grain in 1949 though this effect was the least of those produced.

It can be seen from Table III that none of the treatments had any marked effect on the vertical distribution of the wireworms.

Experiment II, 1947–51.

The second series of treatments, applied in October 1947, were as follows:—

BHC seed dressing— (S)	Seed treated at the rate of 2 oz./bushel with a dressing containing 20 per cent. technical γ isomer.
BHC combine-drilled— (D_1, D_2, D_3)	3·5 per cent. wireworm dust combine-drilled with the seed at $\frac{1}{4}$, $\frac{1}{2}$ and 1 cwt./acre giving 0·98, 1·96 and 3·92 lb./acre crude BHC $\equiv$ 1·9–2·0 oz., 3·8–4·0 oz. and 7·6–8·0 oz. of γ isomer per acre.
Controls (O)—	No treatment.

The experiment was laid out in three replicates, each consisting of three incomplete blocks of three plots. The plot size was 14 × 90 ft. as in Experiment I. After harvest in 1948 one replicate was set aside for the experiment on tainting described below. In the remaining two replicates half the control plots and half the BHC seed-treatment plots were sown with seed treated with the BHC seed dressing. All the remaining plots were sown with untreated seed. Subsequently untreated seed was used throughout. In the fourth year some of the plots which had received the BHC seed dressing were used for another experiment. Wheat varieties and seed rates were as in Experiment I.

Effect of treatments on yield.

The yields of grain and straw are given in Table V.

TABLE V.

Direct and residual effects of different BHC treatments on the yield of grain and straw.

1947 treatments ..	0†	0	S	S	D1	D2	D3	Standard errors		
1948 treatments ..	0	S	0	S	0	0	0	1	2	3
				Grain (cwt. per acre)						
1948	13·4		26·5*		28·4*	27·5*	27·1*	0·76	1·42	1·12
1949	27·1	28·6	23·8	25·3	32·5*	35·6*	36·3*	1·07	1·37	1·23
1950	11·4	11·5	8·1	7·6	13·3	15·7	17·2*	1·47	1·88	1·69
1951	19·8	—	—	—	19·5	19·9	20·6	—	0·58	0·66
				Straw (cwt. per acre)						
1948	32·8		56·2*		60·2*	60·4*	58·0*	1·63	2·65	2·23
1949	30·1	32·6	28·4	30·7	36·6*	38·2*	40·5*	1·28	1·64	1·47
1950	18·7	19·8	14·7	13·0	20·0	22·8	24·6	2·26	2·89	2·59
1951	20·6	—	—	—	19·7	19·9	20·2	—	0·67	0·76

* Values significantly greater than the controls ($P < 0.05$).

Standard errors 1 for comparisons O v. S v. (mean of D's)
2 ,, ,, D_1 v. D_2 v. D_3
3 ,, ,, O, S v. D_1, D_2 or D_3.

† See text for explanation of treatment symbols.

In the year of application all the treatments were effective to a similar extent. In the two subsequent years BHC combine-drilled showed a residual effect but the BHC seed dressing did not, the yields from the seed-dressed plots being less than the controls, as in Experiment I. The BHC seed dressing applied in 1948 had no detectable effect in contrast with the results from both experiments in the previous year. This may have been due to the less severe wireworm attack.

Effect on plant growth.

In the spring of 1948, estimates of plant density and height were made as in Experiment I. The results are given in Table VI.

These results agree with those in Table V. By mid-April, all the treated plots had a much denser stand of wheat than the controls, accompanied by better growth on the plots whether treated with BHC as a seed dressing or combine-drilled (see Pl. XXIV, figs. 2–4).

The effect of the treatments on the wireworm population was not investigated.

TABLE VI.

Effect of different BHC treatments on plant density and height of wheat plants.

Date	0†	S	D_1	D_2	D_3	Standard errors		
						1	2	3
Plant numbers (thousands per acre)								
1.iii.48	1125	1332*	1235	1220	1123	28	59	44
13.iv.48 ..	650	1220*	1021*	1135*	921*	56	89	76
Plant height (in in.)								
1.iii.48 ..	3·11	3·24	3·16	3·29	3·07	0·05	0·10	0·08
13.iv.48 ..	4·72	5·46*	5·62*	5·64*	5·16	0·14	0·20	0·18

* Values that significantly exceed those of the controls.

Standard errors 1 for comparisons O v. S v. (mean of D's)
2 ,, ,, D_1 v. D_2 v. D_3
3 ,, ,, O, S v. D_1, D_2 or D_3.

† See text for explanation of treatment symbols.

Tainting by BHC.

In the season 1948–49 one replicate of Experiment II was cropped with lettuces, red beet, carrots and potatoes to investigate possible tainting by the BHC treatments applied in the previous year. The test crops were sown in rows across the plots and sampled at random for tasting. Seven judges, selected from a group of volunteers after preliminary tests with aqueous dilutions of BHC were asked to award marks out of 10 for general flavour. The lettuces were tasted raw, the other vegetables were peeled or scraped and boiled. Because of

TABLE VII.

Average scores in tainting trials.
(angular transformation—90° = excellent flavour)

	0†	S	D_1	D_2	D_3	Standard errors	
						1	2
Lettuces	52	52	64	38	50	4·5	7·7
Beetroot	41	55	54	23*	34	3·6	6·2
Carrots	48	50	48	49	27*	3·4	5·9
Potatoes	71	64	55*	57*	53*	3·1	4·4

* Values significantly below the controls ($P < 0{\cdot}05$).

Standard errors 1 for comparisons O v. S
2 ,, ,, O, S v. D_1, D_2 or D_3.

† See text for explanation of treatment symbols.

drought in the growing season, the lettuces, beetroot and carrots had a strong natural flavour in all the plots and the potatoes proved the most sensitive test crop. The scores were transformed to degrees for analysis. The results are given in Table VII.

These tests show that BHC, combine-drilled at the rate of 1·96 lb./acre and above, tainted beetroot, carrots and potatoes. Potatoes were tainted when BHC was combine-drilled at the rate of 0·98 lb./acre. When applied as a seed dressing, BHC appears to cause no noticeable taint.

Discussion and Conclusions.

All the treatments were effective in controlling wireworms in the year of application. At the dosage level applied, good residual effects were shown by BHC broadcast, and DDT combine-drilled followed by ethylene dibromide and BHC combine-drilled. The residual effect of D-D was less marked and the BHC seed dressing showed no beneficial residual effect. While the direct effect of all the treatments may be due to a repellent or toxic action, it seems clear from the results of the wireworm sampling that the residual effects are closely associated with the effect of the treatments on the wireworm population.

When applied at 0·98 lb./acre and over, BHC tainted the potatoes grown the following year and other root crops when applied at 1·96 lb./acre and over. BHC seed treatment is economical and easily applied and there is no appreciable risk of taint of subsequent crops. Seed treatment for wireworm control has been explored to a considerable extent using BHC (Arnason & Fox, 1948; Dogger & Lilly, 1949; Hensill, 1949; Lange, Carlson & Leach, 1949; Faber, 1951; Jameson, Thomas & Tanner, 1951; Fletcher, 1952; Kulash, 1953; Kulash & Monroe, 1954). In general, good protection can be obtained in the year of application and, in some instances, reduction in wireworm population is recorded, but it appears that serious damage may be caused in subsequent years if no further treatment is given; furthermore, a seed dressing has been found inadequate in some instances where there is a very heavy infestation (Kulash, 1953; Dogger & Lilly, 1949). A number of workers have found that BHC either applied broadcast or drilled in with the seed gives good protection in the year of application and the experiments recorded have indicated that the population is reduced so that subsequent crops are not likely to suffer serious damage. However, these treatments are liable to cause taint in susceptible crops. There are now a number of records of off-flavour of crops due to various insecticides applied in the soil and this may limit their use. The conditions under which tainting of BHC can occur in England have been studied by Jameson & Tanner (1951) and Jameson & Peacock (1953), and Holmes (1951) discusses the general problem of taint by BHC. The use of refined preparations containing a high content of γ isomer appears greatly to reduce the tainting properties of this insecticide but appears not to eliminate them. The nature of the soil may influence the liability to taint by BHC (Sakurai, 1952). The experiments indicate that DDT can be used successfully to control wireworms and will reduce the population to safe limits. The data tend to confirm the results of other workers that DDT is slow to take effect (Anon., 1949; Lane & others, 1948), and it may give best results in the year of application if applied some weeks or months before planting (Ernould. 1948). The speed of action of DDT may be influenced by the type of soil (Fleming, 1950).

Although the soil fumigants gave good results in the year of application and ethylene dibromide reduced the population sufficiently to give good residual effects, the necessity for special machinery for application tends to make the fumigants compare unfavourably with the solid poisons in practice. It also seems probable that their effectiveness is more dependent on the conditions of application.

Summary.

Following crop failures due to wireworm (*Agriotes* spp.) attack on Little Hoos Field, Rothamsted, two experiments were made on the use of four chemicals to prevent wireworm attack on wheat. The chemicals used were BHC, technical DDT, ethylene dibromide and D-D.

Benzene hexachloride in the form of a dust containing 3·5 per cent. crude BHC was broadcast at the rate of 7·9 lb./acre crude BHC ≡ 15·2–16·0 oz. γ isomer per acre and was combine-drilled with the seed at rates ranging from 0·98–3·92 lb./acre crude BHC ≡ 1·9–8·0 oz. γ isomer per acre. It was also applied as a seed dressing at the rate of 2 oz./bushel of a dressing containing 20 per cent. technical γ isomer of BHC. DDT was drilled with the seed at 7·2 lb./acre technical DDT and ethylene dibromide and D-D were injected into the soil as soil fumigants by means of a special machine at 45·5 lb./acre and 210 lb./acre, respectively.

All these treatments gave a marked increase in yield over the control plots in the season following treatment (1947–48). The highest yields were given by the plots treated with ethylene dibromide (32·1 cwt./acre) and BHC broadcast (30·6 cwt./acre) and the lowest by the DDT treatment (20·7 cwt./acre), the corresponding untreated plots producing only 8·9 cwt./acre.

In the following year the plots were sown without further treatment, with the exception of some plots in the second experiment which were sown with seed dressed with high γ isomer BHC and one block of nine plots which was set aside for testing for possible taint with BHC treatments.

When judged on their residual effects as indicated by crop yields, plant counts and wireworm populations, BHC broadcast and combine-drilled and the plots combine-drilled with DDT gave the best results. The two soil fumigants were not so effective and there was no evidence that the BHC seed dressing had any beneficial residual effect.

Taste tests for possible tainting effects in the 1948–49 season, using lettuces, carrots, beetroot and potatoes, indicated that BHC applied to the soil at rates of 1·96 lb./acre and upwards may taint root crops, at least in the second year after treatment. The results are discussed in the light of other work on this subject.

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