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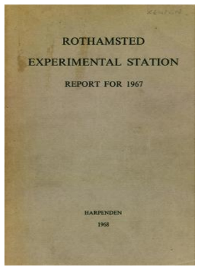

Special Reviews

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SPECIAL REVIEWS

EXPERIMENTS WITH LEY AND ARABLE FARMING SYSTEMS

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Assessing the value of leys in an arable system raises economic and management problems most of which are beyond the scope of field experiment, but one important aspect of ley farming—the degree to which leys can increase the yield of subsequent arable crops—can be evaluated only by experimental methods. Two long-term experiments, one begun at Woburn as long ago as 1937 and the other begun in 1949 at Rothamsted, were designed to answer this question; although ley farming is no longer as controversial an issue as at their inception, the experiments are contributing much to our understanding of the value of organic and inorganic residues in the soil, and to soil fertility problems in general.

The two experiments (and also the Ley Fertility experiments, started in the early 1950s on six of the National Agricultural Advisory Service's Experimental Husbandry Farms—see Harvey (1963)) are of a basically similar design, comparing the effect on the yield of arable test crops of three years of ley or three years of arable cropping. The Woburn experiment differs from the later ones in having only two test crops—the others have three.

Results of the Woburn experiment up to 1956 were discussed by Mann and Boyd (1958), and this report describes its subsequent history up to 1967. Results of the Rothamsted experiment were given in the Annual Reports for 1961 and 1964; yields from a changed cropping scheme are described later in this report.

The Woburn Ley–Arable Rotation Experiment 1956–67

In the Woburn Ley–Arable experiment there are two ley and two arable sequences whose effects are measured by test crops of sugar beet and barley (Table 1). There is one block for each year of the five-year cycle, and each block contains eight main plots, two per rotation. Half the plots (the "Continuous" series) follow the same rotation throughout the life of the experiment; the other half (the "Alternating" series) have ley and arable sequences alternately. The comparison between the continuous and alternating series takes the place of the two-fold replication found in the Rothamsted and N.A.A.S. experiments.

The main plots are split to test FYM at 15 ton/acre, applied to the same plots of the first test crop for the duration of the experiment.

Until 1956 the first test crop and the first treatment crop of the arable sequences were potatoes, and this frequent cropping with potatoes had

* The following were responsible for the experiments and for the preparation of this report, under the chairmanship of the author: G. W. Cooke, G. V. Dyke, D. S. Hooper, A. E. Johnston, J. R. Moffatt, Diana M. Parrott, G. A. Salt, D. B. Slope and C. A. Thorold. R. G. Warren, now retired, also contributed greatly to the experiments.

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already increased the population of potato cyst-nematodes when the first partial crop failure occurred in the arable treatment crop of potatoes in 1955. The first test crop was then changed to sugar beet, and the former third treatment crop of the arable (roots) sequence from sugar beet to carrots. From 1958 onwards there were serious infestations of lucerne

TABLE 1

Cropping scheme over five years, Woburn, 1956–67

Year:	1	2	3	4	5
	Treatment crops			Test crops	
Rotation					
Grazed ley	3 year grazed ley			Sugar beet	Barley
Lucerne Sainfoin	3 year lucerne* cut for hay			Sugar beet	Barley
Arable (Hay)	Potatoes	Rye	Seeds hay	Sugar beet	Barley
Arable (Roots)	Potatoes	Rye	Carrots	Sugar beet	Barley

* Replaced by sainfoin from 1964.

stem eelworm (*Ditylenchus dipsaci*) in second- and third-year lucerne; the initial introduction was probably on the seed. Attempts at control by partial soil sterilisation proved ineffective, and from 1964 onwards common sainfoin (*Onobrychus sativa*) was grown instead.

Results of test cropping

First test crop—sugar beet. In their analysis of the results up to 1955, when potatoes were the first test crop, Mann and Boyd presented evidence that potassium, and possibly other elements, such as magnesium, were being depleted; they also considered that the arable plots were seriously short of nitrogen.

To find out whether shortage of N and K was adversely affecting yields in some rotations, the sub-plots testing O *v.* FYM were split into four sub-sub-plots to test two amounts of N and of K; dressings of 0·72 cwt N/acre and 0·90 cwt K_2O/acre were compared with double these amounts. Average results for the years 1956–61 are given in full in the Appendix (Table A) and are summarised in Table 2.

TABLE 2

Mean yields of sugar beet and responses to FYM and to extra N and K fertiliser, Woburn, 1956–61

(total sugar, cwt/acre)

	Grazed ley	Lucerne	Arable (Hay)	Arable (Roots)	Mean
Mean yield	56·6	52·3	48·6	52·5	52·5
Response to:					
FYM	6·8	9·4	12·5	14·6	10·8
Extra N	−2·8	−3·0	−2·4	0·1	−2·0
Extra K	2·7	2·3	2·2	−0·4	1·7

Rates of N: 0·72 and 1·44 cwt N/acre
Rates of K: 0·90 and 1·80 cwt K_2O/acre
Rate of FYM: 15 ton/acre

Although the change of test crop gave freedom from the effects of cyst-forming nematodes, the large effects of rotation and large responses to FYM observed in the potato yields for 1950–55 were as much or more in

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evidence with sugar beet. On the "continuous arable" sequence, FYM increased yields of total sugar by 18 cwt/acre, more than 40%, whereas on the "continuous ley" sequence the increase was only 6 cwt/acre, or 10%; after lucerne results were intermediate between these extremes. The arable (hay) rotation yielded somewhat less than the other arable sequence, and responses to FYM were smaller.

Contrary to expectation, there was little or no increase in sugar yield from the extra N and K applied to the arable (roots) sequence; indeed, extra N or K (but not both) tended to decrease yields. Extra nitrogen consistently decreased the yields after lucerne and grazed ley and lucerne and arable (hay), whereas K somewhat increased them. From the quite small effects of K, it could reasonably have been concluded that the large differences in yield between the test crops of the ley and arable rotations, and between the arable plots with and without FYM, were not caused by shortage of K. However, results of soil analysis between 1958 and 1960 showed clearly that there were substantial differences in amounts of available K and that, despite the evidence from the K-test on the sugar-beet test crop, these were large enough to account for much of the observed difference in crop yield of the different rotations and of plots with and without dung. The puzzle was resolved by Warren and Johnston, who made a small experiment with sugar beet on land near by, in which they tested the effects of applying as much K as fertiliser as was applied in the FYM, and the fertiliser was either broadcast or dug-in with and without extra N (Cooke, 1961). Although their site was richer in K than the plots of the arable rotations of the Ley–Arable experiment, they found that K dug-in increased root yields by 2·7 ton/acre, whereas broadcast K gave increases of only 1·1 ton/acre, indicating that yields in the Ley–Arable experiment were bigger with FYM than with fertilisers because the FYM contained large amounts of K that had been ploughed in. In the Warren and Johnston experiment broadcast NK fertilisers checked germination and retarded growth of the seedlings, and there were probably similar effects in the Ley–Arable experiment.

It was decided to equalise the K status of the different rotations, and of plots with and without FYM, by giving large corrective dressings of K to each block as it came into the sugar-beet test crop. These dressings ranged from nil, on the ley plots receiving FYM, to 6 cwt K_2O/acre on the most deficient treatments, the lucerne and arable plots without FYM. Extra K was applied to the plots without FYM, equivalent to the total amount in the FYM; this was a rich pig dung, and from 1962 to 1966 the average amount of K applied each year was 3·6 cwt K_2O/acre. The FYM and its K-equivalent, plus one-half of the corrective K, was ploughed in for the sugar-beet crop in the preceding autumn or winter. The other half of the corrective K dressing, plus the basal dressing of 0·90 for all sugar-beet plots was applied on the plough furrow in early February. The tests of extra N and K continued, with the fertilisers applied on the seed-bed but well worked in.

The mean yields of sugar beet for the years 1962–64 are given in detail in Appendix Table B and are summarised in Table 3. Making good the K deficiency decreased the effect of FYM from more than 10 to less than 4

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cwt sugar/acre. For all rotations except lucerne, responses to K were less than in previous years. Responses to N differed between the rotations, the extra 0·72 cwt N/acre decreasing yields after ley but slightly increasing them on the arable plots. Smaller yields from the arable (hay) rotation, in which the seeds ley immediately precedes sugar beet, were thought to be associated with the small amounts of N applied to the leys and to delay in ploughing.

TABLE 3

Mean yields of sugar beet and response to FYM and to extra N and K fertiliser, Woburn, 1962–64

(total sugar, cwt/acre)

	Grazed ley	Lucerne	Arable (Hay)	Arable (Roots)	Mean
Mean yield	60·6	58·8	54·2	61·0	59·2
Response to:					
FYM	0·9	3·7	4·3	5·7	3·9
Extra N	−2·4	−1·8	1·8	0·3	−0·7
Extra K	0·9	2·3	0·7	−1·1	0·7

Rates of N: 0·72 and 1·44 cwt N/acre
Rates of K: 0·90 and 1·80 cwt K_2O/acre
Rate of FYM: 15 ton/acre

By further subdividing the plots in 1962 and again in 1963 the opportunity was taken to test the effect of magnesium (nil *v.* 500 lb/acre $MgSO_4.7H_2O$ applied on the plough furrow). There were small responses to Mg, especially with N but without FYM, and so from 1964 onwards a basal dressing equal to the amount tested was applied annually for sugar beet.

Soils derived from the Lower Greensand have the reputation of being unresponsive to P, but there was evidence from other experiments at Woburn that more P might be needed, so in 1964 a test of 1·5 cwt P_2O_5/acre, in addition to the basal dressing of 0·9 cwt P_2O_5/acre, was made on split plots, in the same manner as Mg was tested in the two previous years. Extra P had little effect except on the arable (roots) rotation, where it increased yields by 4·5 $\pm$ 2·47 cwt/acre. As it was not wished to make further tests of P, the basal dressing was then increased from 0·9 to 2·0 cwt P_2O_5/acre, half applied on the plough furrow and half in the seed-bed.

The test of only two amounts of N in the years 1962–64 could not indicate precisely the optimal N dressing after the different rotations, and from 1965 to 1967 four amounts were tested, as on the Rothamsted Ley–Arable experiment. The amounts tested differed according to rotation (Table 4). The 1962–64 results suggested that most N would be needed by sugar beet in the arable (hay) rotation, less by the arable (roots) rotation and least by the two ley rotations. Where sugar beet followed a ley, yields of total sugar increased by 4–5 cwt/acre when N was increased from 0·35 to 0·70 cwt/acre, but there was no response to larger dressings; with FYM there was little or no increase in yield with more than 0·35 cwt N/acre. As expected, sugar beet in the arable rotations needed more N; the optimum was between 1·05 and 1·40 cwt/acre according to whether or not FYM was used.

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Contrary to expectation, the N requirements of sugar beet in the two arable rotations were similar, and the same amounts could well have been applied to both.

With optimal N, the best yields for the period 1965–67 were given by the lucerne/sainfoin rotation, which yielded 5 cwt/acre more than the

TABLE 4

Mean yields of sugar beet, Woburn, 1965–67
(total sugar, cwt/acre)

	cwt N/acre					
	0·35	0·70	1·05	1·40	1·75	2·10
Without FYM			(±1·37)*			
Grazed ley	61·4	66·1	65·4	65·8	—	—
Lucerne/Sainfoin	66·4	70·6	70·5	71·3	—	—
Arable (Hay)	—	—	66·9	69·6	66·2	68·0
Arable (Roots)	—	59·2	64·8	65·7	66·4	—
With FYM						
Grazed ley	65·9	64·9	66·6	63·5	—	—
Lucerne/Sainfoin	72·9	74·0	74·2	72·2	—	—
Arable (Hay)	—	—	69·3	69·1	70·0	68·9
Arable (Roots)	—	66·3	69·5	72·8	69·8	—

* For use in horizontal comparisons.

grazed-ley rotation without FYM, and 8 cwt/acre more with FYM. The large value of the organic residues to the first crop after lucerne has also been shown at Rothamsted; in addition, at Woburn the free-living nematodes *Longidorus* and *Trichodorus* were particularly numerous in plots that had been 3 years in grazed ley, and this may at least in part explain the comparatively small yields. The two arable rotations gave fairly similar yields, a few cwt/acre less than lucerne/sainfoin.

Summarising the twelve years' results, there have been large increases in mean yield from 52 cwt sugar/acre in the first 6 years to almost 70 cwt/acre in 1965–67. Large effects of FYM obtained in the first 6 years can mainly be ascribed to nutrient deficiencies made good by giving the corrective dressings of K, by dressings of Mg and by increased dressings of P. Although, given enough N for maximum yield, responses to FYM in the period 1965–67 were much less, there was still some effect of FYM not obtainable by fertilisers alone. This was small in the grazed ley and arable (hay) rotations, but considerable after lucerne (3·6 cwt sugar/acre) and after arable (roots) (5·6 cwt sugar/acre).

Second test crop—barley. The sub-plot tests of fertilisers made on the first test crop prevented similar tests on the following barley crop; however, from 1968 onwards the order of test cropping will be changed to allow a test of four amounts of N for barley.

Because of increased fertiliser dressings, better varieties and general improvements in husbandry, barley yields have much increased during the experimental period; the average was less than 20 cwt/acre in the 1940s, about 25 cwt in the early 1950s, more than 30 cwt/acre in the period 1956–61 and about 40 cwt/acre since 1962.

Throughout, the ley rotations have tended to yield a few cwt more than

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the arable rotations. The first-year residues of FYM were most effective in the early 1950s, but decreased when the fertiliser dressings were increased (Table 5).

TABLE 5

Mean yields of barley, Woburn (grain, cwt/acre)

	Grazed ley		Lucerne/ Sainfoin		Arable (Hay)		Arable (Roots)		Mean
	O	D	O	D	O	D	O	D	
1942–56	22·5	23·4	23·0	24·4	19·4	22·4	19·8	22·1	22·1
1957–61	32·1	31·8	30·7	31·9	29·2	31·5	29·7	32·6	31·2
1962–67	41·7	41·0	42·4	42·9	39·2	41·6	38·5	40·1	40·9

Standard errors:

	(i)	(ii)
1942–56	0·53	0·47
1957–61	0·98	0·50
1962–67	0·59	0·50

(i) = For use in comparisons involving different rotations
(ii) = For use in comparisons within the same rotation

O = No FYM
D = 15 ton/acre FYM to 1st test crop

Yields of the treatment crops

Arable treatment crops—potatoes. Following the crop failure in 1955, samples taken in 1956 showed that most of the blocks contained one or more plots in which the infestation with potato cyst-nematode was great enough to decrease yield. At the request of the Nematology Department, potatoes were retained as a treatment crop, but at the same time the amount of fertilisers applied to potatoes was about doubled. With these

TABLE 6

Mean yields of arable treatment crops, Woburn (1st and 2nd year)

	Previous cropping:							
	Grazed ley		Lucerne/ Sainfoin		Arable (Hay)		Arable (Roots)	
	O	D	O	D	O	D	O	D
Potatoes								
1943–56	11·2	12·6	9·8	12·1	9·4	11·3	9·4	10·9
1957–61	14·2	15·9	13·1	14·1	11·5	12·3	11·1	12·3
1962–67	12·5	14·6	10·4	12·6	6·5	7·6	6·0	7·5
Rye								
1949–56	32·7	33·3	33·0	33·3	30·3	32·3	29·6	31·4
1957–61	32·9	33·4	34·1	32·4	29·5	32·0	30·7	31·0
1962–66	36·4	35·6	36·6	35·4	32·0	33·2	35·2	34·8

Potatoes: total tubers, ton/acre
Rye: grain, cwt/acre. Crop failed 1967

O: No FYM
D: 15 ton/acre FYM to 1st test crop

larger amounts of fertiliser, yields of more than 10 ton/acre were obtained (Table 6) even on the "continuous arable" treatments, those most subject to potato cyst-nematode. However, taking potato crops every 5 years was still frequent enough to allow potato cyst-nematode populations to

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increase, especially in blocks III–V, resulting in poor yields on plots of the "continuous arable" series in 1963–65. Despite the introduction of the resistant variety Maris Piper and comparatively few potato cyst-nematodes on blocks II and I, yields from the arable plots in 1966 and 1967 were still small. There is a possibility that free-living nematodes may also be causing damage to the potato roots. In 1967 the fungus *Verticillium* was found in July infecting 38% of stems of the continuous arable (roots) series but only 6% of the alternating series, whereas *Rhizoctonia* was equally widespread in both series. To what extent interaction between fungi and free-living nematodes has contributed to these poor yields is not known, and a special investigation is planned for 1968. (See also the report of the Nematology Department (p. 152) and Plant Pathology Department (p. 132).)

Rye. Except for failure in 1967 because of poor seed-bed conditions, the second arable treatment crop, winter rye, yielded consistently well, with the average yield in any 5-year period exceeding 30 cwt/acre. The alternating series yielded slightly more than the continuous; there was little effect from FYM applied 3 years previously (Table 6).

Carrots. The two arable sequences differ only in respect of their third treatment test crop; on the change of test crop in 1956, sugar beet was replaced as the third treatment crop in the arable (roots) rotation by carrots. Partly because of failure to control motley dwarf in some years and the loss of a first sowing in 1960, mean yields (Table 7) were small in most

TABLE 7

Mean yields of arable treatment crops, Woburn (3rd year)

Seeds Hay (dry matter, cwt/acre)

	Ley		Arable	
	O	D	O	D
1945–56	58·7	66·2	52·8	58·4
1957–61	59·7	67·2	51·3	58·0
1962–67	77·7	80·9	75·4	77·8

Carrots (roots, ton/acre)

	Ley		Arable	
	O	D	O	D
1956–61*	8·3	10·2	7·0	8·6
1962–67	22·8	24·0	20·7	22·2

* Mean of 5 years; crop failed 1957.

O = No FYM
D = 15 ton/acre FYM to 1st test crop

years up to 1962, when the manuring was changed to include P and more K. After changing the variety to Autumn King in 1964, mean yields exceeding 30 ton/acre were obtained in 1965 and 1967. As for rye, differences between the alternating and continuous series and residual effects of FYM were usually small.

Seeds hay. The mixture of S.24 ryegrass, late-flowering red clover and alsike is undersown in the rye. There is usually a good first cut but little aftermath.

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Among the changes introduced in 1956, more N and K were provided for the seeds hay; in 1962 the K dressing was much increased and P fertiliser was also given. Hay yields of the "continuous" plots increased from between 50 and 60 cwt dry matter/acre in the period 1955–56 to 75–80 cwt dry matter/acre in 1962-67, and the difference between the alternating and continuous series and the residual effect of FYM, formerly substantial, is now small (Table 7).

Ley treatment crops. Despite increased fertiliser dressings, yields from the 2nd-year and 3rd-year lucerne crops were much affected by the incidence of stem eelworm (*Ditylenchus dipsaci*) from 1958 onwards (Table 8). The sainfoin, which replaced lucerne, has not been free from troubles, and the plots carrying third-year sainfoin in 1966 had to be resown in August 1965 and again in spring 1966.

TABLE 8

Mean yields of ley treatment crops, Woburn

	1st year		2nd year		3rd year	
	O	D	O	D	O	D
Lucerne/Sainfoin (cwt dry matter/acre)						
Lucerne 1944–56	14	17	52	59	60	66
Lucerne 1957–64	22	31‡	40	52	40	44*
Sainfoin 1965–67	26	27§	50	48	44	46†

Sheep days/acre	1st year	2nd year	3rd year
Grazed ley			
1944–56	1006	1871	1796
1957–61	1115	1862	1729
1962–67	1530	2160	1845

* Because of lucerne stem eelworm (*Ditylenchus dipsaci*) the plots were fallowed in 1959 and no yields were taken in 1960.
† In 1965 and 1966 the crop was resown in spring.
‡ 1957–63.
§ 1964–67.

The grass/clover ley is grazed rotationally by one or two teams of sheep; there are usually four to eight sheep per team. The plots are topped after grazing, but the amounts uneaten are usually small. The sheep days per acre averaged 1561 for 1944–61 and 1845 for 1962–67, equivalent to about 21 and 25 cwt starch equivalent per acre (reckoning $1\frac{1}{3}$ lb starch equivalent per sheep day) (Table 8).

The Rothamsted Ley–Arable Rotation Experiment

Like the Woburn experiment, the Rothamsted Ley–Arable experiment consists of four contrasted rotations whose effects are measured by the yield of arable test crops common to all rotations. The 6-year cycle has three "treatment" crops—ley or arable, followed by three test crops (Table 9). Of the four rotations compared, three have a ley sequence and the other a sequence of arable crops.

The experiment is on two fields—Fosters, an old arable field, and

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Highfield, formerly in permanent grass. On both fields there are plots of permanent grass sown down when the experiment began in 1949–51 and, on Highfield, plots of the original permanent grass sward. The two fields are almost a mile apart, but on a similar soil (Batcombe Series).

TABLE 9

Cropping scheme over six years, Rothamsted, 1962–67

	Treatment Crops (1st, 2nd and 3rd years)	Test Crops 4th year	Test Crops 5th year	Test Crops 6th year
Rotation Treatments				
Lucerne	3-year lucerne cut for hay	Wheat	Potatoes	Barley
Grass/Clover Ley	3-year grass/clover ley without N	Wheat	Potatoes	Barley
Grass Ley	3-year pure grass ley with N	Wheat	Potatoes	Barley
Arable	Ryegrass ley for hay, sugar beet, oats	Wheat	Potatoes	Barley
Other treatments				
	Permanent Grass (Original Sward)*			
	Permanent Grass (Reseeded 1949–51)			

* On Highfield only.

Initially, in addition to the lucerne there were two grass/clover leys, one grazed by sheep and receiving little N, and the other given more N was cut repeatedly at the silage stage. In 1962 the grazed ley was replaced by a different grass/clover sward (S.51 Timothy, S.215 Meadow Fescue, S.100 White Clover) grown with ample PK fertiliser but without N, and grazing was discontinued.

The other ley was changed to an all-grass ley receiving moderately large dressings of N—0·6 cwt N/acre for each cut. Pure S.37 Cocksfoot was sown in 1962 and 1963; because of severe virus infection and winter-killing of cocksfoot ley, Timothy-Meadow Fescue (without clover) was sown from 1964 onwards. Both leys are now cut by forage harvester at the early silage stage.

This report describes the results obtained with the test crops following these leys. As only one such barley crop has yet been taken, results of tests of the old-style treatment crops are also given for barley.

Yields of the test crops

***First test crop—wheat* (*1965–67*).** Four amounts of spring N were tested on wheat (see Table 10) in steps of 0·3 cwt N/acre on Highfield (0·4 cwt N/acre for the arable rotation) and of 0·4 cwt N/acre on Fosters (0·53 cwt N/acre for the arable rotation). There was also a test of autumn nitrogen—0·6 cwt N/acre on both fields.

In the previous three years, 1961–64, the mean yield of Cappelle wheat with comparable amounts of N was slightly more on Highfield than on Fosters, but in the period 1965–67 maximum yields were about 5 cwt/acre more on Fosters. The nitrogen requirements of crops grown on Highfield were, at first, much less than those on Fosters because N in the organic matter from the old turf was mineralised. Even now, more than 15 years after the original ploughing, less N is needed to achieve maximum yield, and the response to N is less.

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Previous results showed that, for wheat, the kind of rotation—ley or arable—greatly influenced both the yield without N and the response to N, but that, with optimal N, yields in all rotations were much the same. The present results are similar. With optimal N there were again quite small yield differences between the rotations (Table 10). As before, N responses differed between the rotations, and were much greater for the arable rotation, whereas on average differences between the ley rotations were only small. On Fosters, in spring 1965, wheat in the all-grass ley rotation (the ley was resown with Italian ryegrass in spring 1964) was attacked by stem-boring larvae and yields were decreased by 5–6 cwt at each rate of N; but for this, the means of this treatment in Table 10 would have been some 2 cwt greater.

TABLE 10

Wheat, Rothamsted: effect of N and rotations, 1965–67

(mean yield of grain, cwt/acre)

Cwt N/acre Autumn	Cwt N/acre Spring	Lucerne	Grass/ Clover Ley	Grass Ley	Cwt N/acre Autumn	Cwt N/acre Spring	Arable
Highfield							
—	—	45·3	46·7	46·3	—	—	34·4
—	0·30	49·5	50·8	51·5	—	0·40	51·2
—	0·60	52·1	52·1	49·5	—	0·80	53·4
—	0·90	46·7	48·7	49·2	—	1·20	51·6
0·60	—	53·3	54·8	46·2	0·60	—	46·6
0·60	0·30	43·2	55·9	48·0	0·60	0·40	52·2
0·60	0·60	46·3	44·5	49·1	0·60	0·80	49·0
0·60	0·90	36·1	44·9	44·2	0·60	1·20	47·7
Mean		46·6	49·8	48·0			48·3
Autumn	Spring				Autumn	Spring	
Fosters							
—	—	53·5	46·3	48·0	—	—	32·7
—	0·40	59·6	56·1	54·0	—	0·53	51·8
—	0·80	59·3	55·7	55·4	—	1·06	57·8
—	1·20	56·4	54·5	51·7	—	1·60	56·6
0·60	—	57·2	56·4	53·4	0·60	—	46·5
0·60	0·40	59·4	57·8	57·3	0·60	0·53	57·0
0·60	0·80	55·5	55·1	54·6	0·60	1·06	57·5
0·60	1·20	53·2	51·8	52·2	0·60	1·60	55·3
Mean		56·8	54·2	53·3			51·9

In the period 1961–64 yields were rather small, in part attributable to damage by stem-boring larvae, and responses to N by wheat after the grass/clover leys were especially large. A test of nitrogen applied in autumn was introduced because it was thought the decaying residues from the grass leys might be fixing nitrogen and that the lucerne might be enriching the subsoil with nitrogen. Autumn N much increased the yield of plots not receiving N, especially in the arable rotation, where the increase was about 12 cwt/acre on Highfield and 14 cwt/acre on Fosters; however, the increase was less than would be expected from the same amount of N applied in spring.

On Fosters, assuming that leys provide 0·50 cwt N/acre and that the efficiency of autumn N is 50% of that of spring N, the mean yields with and

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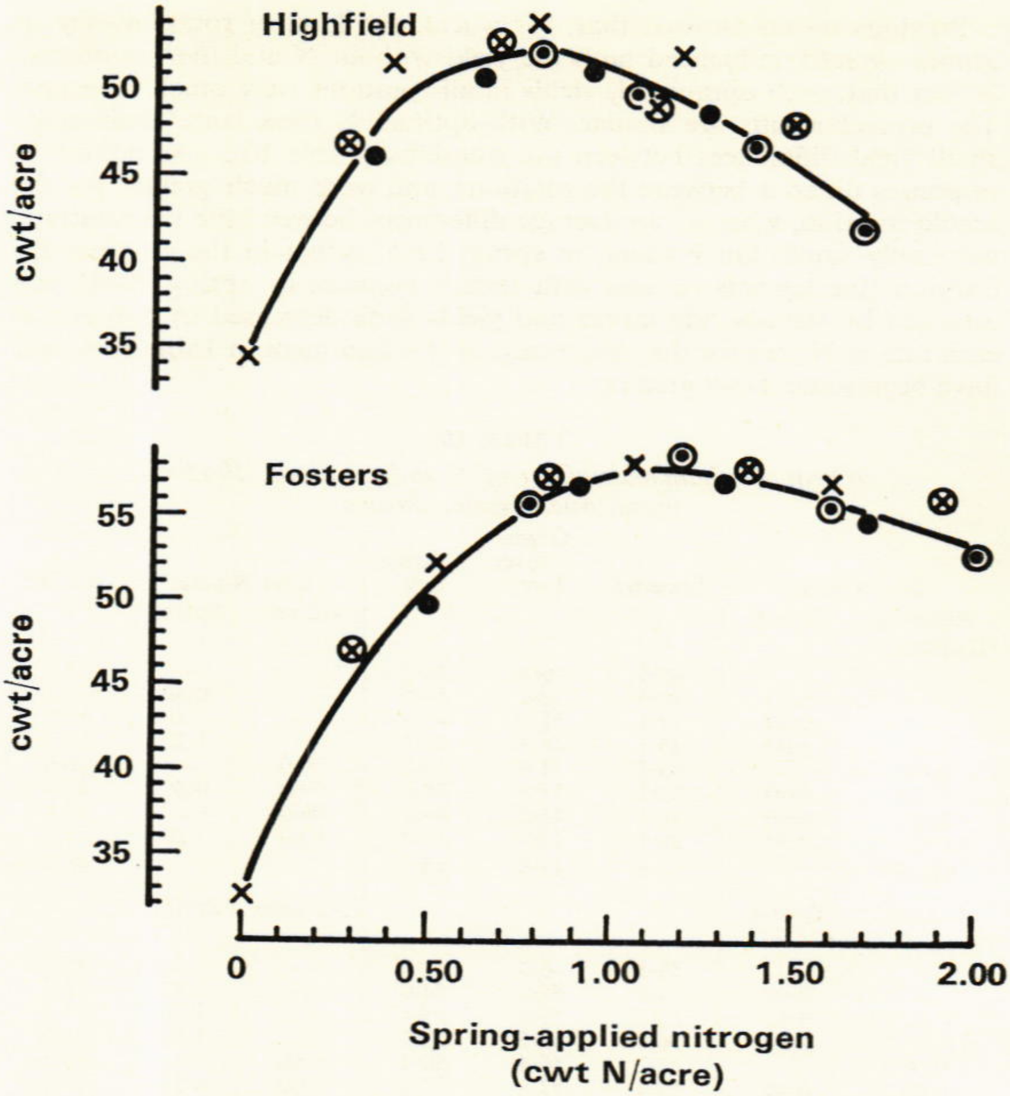

Fig. 1. Mean yields of wheat, Rothamsted 1965–67

Key to rotations: × Arable, no autumn N
⊗ Arable, with autumn N
● Ley, no autumn N
◉ Ley, with autumn N

without autumn nitrogen of the three ley rotations and of the arable rotation fall on or near a single response curve relating yield and spring N (Fig. 1). With each amount of N, lucerne yielded slightly more than the other rotations; allowing for the smaller crop from the all-grass ley rotation, the remaining variation in yield is no more than would be expected from experimental error.

On Highfield the relationship between yield and nitrogen from leys and from autumn- and spring-applied fertiliser was less simple than on Fosters,

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with unexplained differences between the yields and nitrogen responses of the different rotations; there were also large block differences and unusually large plot errors arising in part from lodging and bird damage. For Highfield, as for Fosters, the assumption that for wheat in the arable rotation autumn N was about half as efficient as spring N accounts for much of the differences between the yields with different amounts of autumn and spring N. Without N, all three leys yielded poorly on Highfield; to equate the response curve for leys without autumn N to that of the arable rotation, they must have provided less N than on Fosters, about 0·35 cwt N/acre. With autumn N, by contrast, spring N was not needed for maximum yield after leys; comparison of the mean yields after the three leys with the yields in the arable rotation, suggests that, in terms of spring-applied N, the combined effect of leys and of winter N was equal to 0·8 cwt or more spring N/acre, i.e. at least as much as on Fosters. Compared with the other leys, lucerne was relatively less effective than on Fosters, mainly because of particularly poor yields in 1965.

Second test crop—potatoes (1966–67). Potatoes yielded more than 20 tons on both fields in both years. There were only small differences in yield between the four rotations, and between FYM and equivalent fertiliser (Table 11).

TABLE 11

Potatoes, Rothamsted: effect of rotation and of FYM v. *equivalent fertilisers, 1966–67*

(mean yield of total tubers, ton/acre)

	Lucerne	Grass/ Clover Ley	Grass Ley	Arable	Mean
Highfield					
FYM	22·8	23·4	23·6	22·0	22·9
Fertilisers	22·9	23·2	23·1	22·2	22·8
Fosters					
FYM	21·1	20·7	20·9	20·3	20·8
Fertilisers	21·7	21·7	21·1	20·7	21·3

Third test crop—barley. Since 1962 there has been a test of four amounts of N for barley, as for wheat, but the response is limited by the residual value of the N applied as fertiliser and FYM to the preceding potato crop. Table 12 gives mean yields for 1962–66, from the old-style treatment crops. The results differ little from those discussed in the Rothamsted Report for 1965. The two fields had almost the same mean yield (48 cwt/acre). Without N, Fosters, the old arable field, yielded about 2 cwt/acre less than Highfield, and about 0·5 cwt N/acre was needed to attain maximum yield, compared with about half that quantity on Highfield. With optimal N, differences in barley yield from the different rotations were small.

Only a single year's results have so far been obtained from the new-style treatment crops; these are summarised in Table 13. On Highfield, but not on Fosters, barley yields seem to have been affected by the contrast of FYM and equivalent fertilisers for potatoes; this residual effect was

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confounded with the cubic term for N to barley, and accounts for the irregular increase in the mean yields with increasing N. It might be expected to appear more strongly on Highfield because smaller amounts were tested there than on Fosters; moreover, in 1967, barley on Highfield needed much more N than in the past. Even with similar amounts of N, yields on Highfield were less than on Fosters; with optimal N, in all the rotations on Fosters yields exceeded 50 cwt/acre.

TABLE 12

Barley, Rothamsted: effect of N and rotation 1962–66

(mean yield of grain, cwt/acre)

	cwt N/acre	Lucerne	Grazed Ley	Conserved Ley	Arable	Mean
Highfield	—	46·7	48·6	44·8	44·2	46·0
	0·1	48·2	49·8	47·8	47·0	48·2
	0·2	48·6	48·9	48·6	48·4	48·6
	0·3	47·8	48·4	50·0	46·8	48·3
	Mean	47·8	48·9	47·8	46·6	47·8
Fosters	—	45·9	46·6	44·8	42·2	47·0
	0·2	49·0	49·4	47·2	—	(47·8)
	0·4	49·0	48·6	48·2	47·9	48·7
	0·6	48·8	48·2	47·7	49·2	48·0
	0·8	—	—	—	48·3	—
	Mean	48·2	48·2	47·0	(46·2)	47·9

TABLE 13

Barley, Rothamsted: effect of N and rotation 1967

(mean yield of grain, cwt/acre)

	Cwt N/acre	Lucerne	Grass/ Clover Ley	Grass Ley	Reseeded Grass	Arable	Mean
Highfield	—	36·4	41·5	39·2	51·6	33·4	40·4
	0·1	43·5	43·9	37·3	54·8	40·0	43·9
	0·2	42·8	42·5	44·6	45·8	42·9	43·8
	0·3	47·4	45·6	47·0	47·8	46·6	46·8
	Mean	42·5	43·4	42·0	50·0	40·7	43·7
Fosters	—	47·9	49·0	45·8	53·8	41·4	47·6
	0·2	51·5	52·0	52·9	55·6	—	(51·6)
	0·4	54·6	52·3	53·3	54·1	49·8	52·8
	0·6	53·1	50·0	51·6	52·3	56·5	52·9
	0·8	—	—	—	—	54·1	—
	Mean	51·8	50·8	50·9	54·0	(48·4)	51·2

Plots ploughed out from reseeded permanent grass in 1965 and put through the test cropping sequence were cropped with barley in 1967. The yields (Table 13) make an interesting contrast with those following the 3-year leys. On Fosters they yielded slightly more and on Highfield very much more than the leys; on both fields little or no N was needed for maximum yield.

Yields of the treatment crops. At Rothamsted the arable treatment crops do not, as at Woburn, give comparisons of the effects of ley and arable rotations. Average yields of the treatment crops for the years 1964–66 are given in Table 14.

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TABLE 14

Mean yields of treatment crops, Rothamsted 1964–66

	Highfield	Fosters
Leys, reseeded and permanent grass (cwt dry matter/acre/year)		
With nitrogen		
All-grass ley	75	69
Reseeded grass	91	91
Permanent grass	91	—
Without nitrogen		
Clover/grass ley	53	52
Reseeded grass	46	58
Permanent grass	45	—
Lucerne	62	61
Arable treatment crops		
One-year ley (cwt dry matter/acre)	83	80
Sugar beet (cwt total sugar/acre)	71	64
Oats (cwt grain/acre)	37	48

With 0·6 cwt N/acre for each cut, the largest yields of herbage dry matter were given by the reseeded and permanent grass, about 90 cwt/acre; this was more than from the grass ley, partly because of the smaller production in the seeding year (the leys are not undersown), but also because the leys yielded less in their 3rd year. Without N, yields of the leys and reseeded and permanent grass were between 45 and 60 cwt dry matter/acre. Lucerne yielded more than the clover/grass ley but less than the all-grass ley. The arable treatment crops yielded well, the average yield of total sugar being about the same as at Woburn.

Differences between the crops on Highfield and Fosters were fairly small; one of the largest differences, for oats in 1965, was because on Highfield bird damage led to failure of the first sowing, but there was again a large and unexplained difference in oat yields in 1967. By contrast, sugar beet yielded 10% more on Highfield. The dense grass sward of the reseeded and permanent grass plots on Highfield has prevented clover from coming in; its absence probably accounts for the smaller yields without N on these plots compared with reseeded grass without N on Fosters, where the sward has always been more open and now has some clover.

Discussion

The ley–arable rotation experiments were designed to find out whether the yield of arable crops was improved when they form part of a ley rotation instead of a purely arable one. Results of both the Rothamsted and Woburn experiments show that gains from a ley rotation are usually small or non-existent. Indeed, so much P and K is taken off cut leys that unless the loss is made good by additional dressings, soil reserves are so depleted that yields of succeeding arable crops are diminished.

Provided that the arable rotation is designed to avoid the build-up of soil-borne pests and diseases, and that adequate nutrients are applied to make good the amounts removed by cropping, the value of a ley to the subsequent arable crops can be assessed at little more than the cost of the

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extra fertiliser N required to achieve optimal yields without a ley. At Rothamsted this was about 0·5 cwt N/acre for the first crop, wheat (less on Highfield where no autumn N was applied) and about 0·2 cwt N/acre for the third crop, barley; the total might amount to no more than 1 cwt N/acre. At Woburn 1st-year effects were a little greater, 2nd- and 3rd-year effects were not measured.

The failure of leys greatly to increase the yield of the following crops implies that they must be judged on the amount and quality of their fodder production compared with that obtained from permanent grass, and on their value as alternative crops to control soil-borne pests and diseases.

Under small-plot grazing conditions, in the years up to 1962, estimated production of used starch-equivalent (SE) from both leys and permanent grass at Rothamsted was poor—about 15 cwt SE/acre/year—but little fertiliser N was used, and the contribution from clover was slight. However, since 1962 dry matter produced by the grass leys with N was still no greater than that from similarly treated permanent grass.

At Woburn the grazed leys have been more productive than the former grazed leys at Rothamsted, and since 1962 the used SE has reached 25 cwt SE/acre/annum. However, this has been achieved only by having a reserve of grassland elsewhere in the farm to fall back on in dry weather. At current prices the value of the sheep grazing is much less than the return from the arable crops, with yields of 20 tons sugar beet and carrots, 40 cwt barley, 33 cwt rye.

Although the results do not necessarily apply to all soils and farms, there is good reason to consider they apply widely. How far this is so should be known in the course of 1968, when detailed results of the six experiments on N.A.A.S. Experimental Husbandry Farms should be reported.

Future of the experiments. From 1968 the test cropping of both experiments will be changed. At Rothamsted potatoes will be the first test crop in place of wheat, and at Woburn barley will become the first test crop in place of sugar beet. The Rothamsted experiment will be discontinued in 1971, although one or more blocks will be kept for long-term soil studies. The future of the Woburn experiment has yet to be decided.

Conclusion. Including leys in an arable rotation does not greatly increase yields of the arable crops, provided that the arable cropping is designed to minimise losses from soil-borne pests and diseases and that enough fertiliser is given to make good the nutrients taken off and allowance is made for the additional N provided by the leys.

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APPENDIX

TABLE A

Mean yields of total sugar, Woburn 1956–61
(cwt sugar/acre)

	Previous cropping							
	Grazed ley		Lucerne		Arable (Hay)		Arable (Roots)	
Treatment	Cont.	Alt.	Cont.	Alt.	Cont.	Alt.	Cont.	Alt.
				(±1·70)*				
—	58·5	49·4	45·9	50·4	42·7	44·1	42·9	49·0
D	62·3	56·3	56·9	57·1	52·4	57·0	60·3	62·6
N	53·1	46·1	42·3	47·9	38·8	38·7	41·7	46·3
DN	62·6	54·3	53·5	55·0	53·5	51·7	62·1	56·6
K	61·7	52·4	47·2	51·8	42·2	46·4	40·9	46·2
DK	64·5	59·1	60·6	60·4	56·9	55·4	61·4	56·3
NK	57·2	47·7	45·5	49·7	42·0	42·7	45·3	49·5
DNK	65·1	56·2	56·2	56·0	53·6	57·0	60·3	58·6

* For use in comparisons within the same rotation and the same level of D

D = 15 tons FYM
Rates of N: 0·72 and 1·44 cwt N/acre
Rates of K: 0·90 and 1·80 cwt K_2O/acre

TABLE B

Mean yields of total sugar, Woburn 1962–64
(cwt sugar/acre)

	Previous cropping							
	Grazed ley		Lucerne		Arable (Hay)		Arable (Roots)	
Treatment	Cont.	Alt.	Cont.	Alt.	Cont.	Alt.	Cont.	Alt.
					(±2·21)*			
—	63·4	59·0	54·4	57·2	47·4	52·8	54·2	61·0
D	62·5	59·9	63·1	60·7	56·6	55·4	63·2	65·6
N	60·9	55·7	54·2	53·7	50·7	56·1	58·2	60·3
DN	62·7	57·0	59·6	59·0	56·5	56·2	67·8	61·5
K	68·5	55·8	57·8	59·8	48·4	52·7	55·3	62·9
DK	61·8	63·7	63·9	61·4	58·5	57·6	60·7	63·9
NK	60·7	56·8	57·5	61·8	52·2	56·9	55·9	57·1
DNK	60·8	60·1	60·7	57·7	55·7	55·0	64·1	63·5

* For use in comparisons within the same rotation and the same level of D

D = 15 tons FYM
Rates of N: 0·72 and 1·44 cwt N/acre
Rates of K: 0·90 and 1·80 cwt K_2O/acre

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SUBSTITUTES FOR ORGANOCHLORINE INSECTICIDES TO CONTROL SOIL INSECTS THAT ATTACK CEREALS

D. C. GRIFFITHS

The important cereal pests, wireworms, wheat-bulb fly, leatherjackets and frit fly, can be controlled by organochlorine insecticides, but these insecticides have some disadvantages in practice. For example, the chlorinated cyclodienes aldrin and dieldrin are toxic to birds [123] and, in the United Kingdom, were voluntarily withdrawn from use as seed-dressings on spring-sown cereals in December 1961. Organochlorine insecticides are stable compounds, and when applied to soil they persist for many years [124]. Their residues can harm some beneficial insects in amounts too small to affect pests [125], but some pests that have been exposed to organochlorine insecticides for long periods have developed resistance. Resistance to organochlorine insecticides has not yet occurred in soil pests of cereals in the United Kingdom (U.K.), but has occurred in species of wireworms that attack potatoes and sugar beet in the United States of America (U.S.A.) [15, 126, 127, 128]. The increasing use of organochlorines led to small amounts of them occurring in the body fat of people not occupationally exposed to organochlorines, and in some birds and their eggs. Such effects were reviewed in 1964 by the Advisory Committee on Poisonous Substances Used in Agriculture and Food Storage. Their report [129] placed no restriction on the use of BHC, but recommended that uses of DDT should be reviewed after 3 years and that immediate restrictions be placed on the more toxic compounds, aldrin and dieldrin. There has been much work to find replacements among compounds that are more easily metabolised in the soil, in plants and animals, and without unwanted long-term effects. The results of the search, mainly among organophosphorus and carbamate insecticides, are summarised and discussed here.

The same materials have been tested under different names or numbers by various authors, but in this article references to the same compound are put together under the name adopted by the British Standards Institution (Recommended Common Names for Pesticides [130] and supplements), or by the Entomological Society of America [131]. Where no name exists, the manufacturer's code number is given. To aid identification, recently adopted names are listed also by the previously used name or code number. The lists of synonyms given by Warry [132] and Kenaga [133] are useful for reference.

Wireworms (Elateridae)

Wireworms are larvae of certain Elaterid beetles, mainly *Agriotes* spp. in the U.K. They inhabit old grassland and damage susceptible crops, for example, cereals and root crops, in the first few seasons after ploughing the old grass. Seed-dressings of γ-BHC are used extensively in the U.K. to

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protect cereals from attack, but there is little evidence that such dressings applied at the recommended rates to autumn-sown cereals kill many wireworms or protect subsequent crops from attack [134, 135]. The use of aldrinated fertiliser was discontinued as a result of the 1964 M.A.F.F. Report [129], which recommended also that aldrin and dieldrin soil treatments against wireworms should be used only on potato crops for the next 3 years, when this use should be reviewed again.

Most tests in the laboratory have been made with *Agriotes* spp. in the U.K. and *Conoderus falli* Lane and *Melanotus communis* (Gyll.) in the U.S.A. However, non-organochlorine insecticides have been tried against several other species of wireworms in the field, and Table 1 lists more than a hundred such compounds tested against several types of wireworms on various crops.

Compounds that worked well in laboratory tests in different parts of the world include the organophosphorus insecticides B 29952, B 30237, B 30468, B 30911, "Dursban", fenitrothion, fenthion, Hercules 3004, Murphy P1973 and P2188, and the carbamate Hercules 5727. In most laboratory tests [1, 2, 3, 4, 5, 6, 15, 21, 42] wireworms have been confined in containers with soil that has been mixed with the insecticide. The insecticide is more thoroughly mixed with the soil than it would be in the field, and it cannot leach from the containers. The soils are not subjected to weathering, the watering regime differs from conditions in the field, and confined, wet soils may become acid. Therefore, materials that do well in the laboratory may not necessarily perform well in field conditions.

Materials with some field effectiveness. Parathion is the most extensively tested organophosphorus insecticide, and only tests that compared it with other organophosphates have been included here. It was effective or moderately effective in field use against more than 10 species of wireworms on various crops in different parts of the world, but in the U.K. parathion has been less effective than aldrin when applied in a similar way. Other organophosphorus compounds reported to be effective in the field are Bayer 38156 and Stauffer N2790 ("Dyfonate"), two related insecticides; the former has been tested against species of *Agriotes* in the U.K. and species of *Conoderus* in the U.S.A., and the latter against these and other types of wireworms. Diazinon and fensulfothion were moderately effective against species of *Conoderus*, *Limonius* and other wireworms in the U.S.A. and Canada, but were not very effective against *Agriotes* in the U.K. Methidathion (GS 13005) was twice reported effective against wireworms in the U.S.A., but did not work well against *Dalopius pallidus* and *Agriotes mancus* in Canada. Phorate has been tested extensively abroad and, like parathion, is one of the best organophosphorus compounds tried against wireworms in potatoes in the U.K. Thionazin is very toxic to wireworms in laboratory tests, but field results vary. Trichloronate (B 37289) gave some good results against wireworms in the U.S.A. and Canada: it had some effectiveness against *Agriotes* spp. in the U.K., but less than aldrin in the quantities tested.

Methods of applying insecticides. Common methods of applying insecticide are to spread granules or to spray the soil, and then harrow or disc the

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TABLE 1

Possible substitutes for organochlorine insecticides tested against wireworms

(Numbers following the ; refer to papers in the list of references)

American Cyanamid
AC 12008; 18
18706 *see:* ethoate methyl
43064; 5, 6, 42
47031; 42
Allied Chemicals
GC 3561; 2
3562; 1
3583; 2
3661; 1
4072 *see:* chlorofenvinphos
6506; 36
aminocarb; 10
Aphidan; 5
arprocarb; 2, 27, 34, 36
azinphos ethyl; 5, 18, 34
azinphos methyl; 1, 6, 18, 29, 42

Bayer 22408; 2
22684; 2
23453; 1
24498; 2
25141 *see:* fensulfothion
25198; 2
29952; 2
30237; 2
30468; 2
30554; 2
30911; 2
34042; 2
34098; 2
37289 *see:* trichloronate
37344 *see:* methiocarb
38156; 3, 6, 7, 10, 28, 29, 30, 32, 54, 137
39007 *see:* arprocarb
44646 *see:* aminocarb
Baygon *see:* arprocarb
Bidrin; 1, 5, 6
Birlane *see:* chlorofenvinphos
Bomyl; 1, 6
Boots RD 14526; 4
14639; 4
14838; 4, 137
14977; 4
14984; 4
14991; 4
15038; 4
18242; 4
bromophos; 4, 137

a carbamate; 5
carbaryl; 1, 3, 6, 10, 154
carbophenothion; 1, 3, 6, 55
chlorfenvinphos; 2, 5, 6, 10, 29, 36, 45, 54
Chlorthion; 1
Ciodrin; 2, 10
Cidial; 31

Delnav *see:* dioxathion
demeton; 6, 19, 21, 22, 33, 56
diazinon; 1, 4, 6, 8, 9, 10, 16, 26, 29, 30, 31, 32, 34, 35, 36, 38, 39, 40, 41, 42, 44, 45, 46, 54, 154
dichlofenthion; 1, 4, 9, 10
dichlorvos; 1, 3, 10
dimethoate; 3, 6, 58
dioxathion; 1, 6
disulfoton; 1, 3, 6, 8, 13, 28, 32, 34, 36, 38, 41, 42, 48, 54, 56, 57, 154
Du Pont 691; 2

Dursban; 5
Dyfonate *see:* Stauffer N 2790

EPN; 19, 24, 33, 37, 43
ethion; 1, 4, 6
ethoate methyl; 1, 5
Ethyl Guthion *see:* azinphos ethyl

fenchlorphos; 29, 54
fenitrothion; 2, 4, 7, 53, 154
fensulfothion; 2, 5, 6, 8, 10, 34, 36, 42, 45
fenthion; 2, 3
fentin acetate; 4
Fitios *see:* ethoate methyl
Folithion *see:* fenitrothion

Geigy GS 12968 *see:* lythidathion
13005 *see:* methidathion
30493; 2
30494; 2
Guthion *see:* azinphos methyl

Hercules 3004; 1
3895; 2
5727; 2, 11, 34

Imidan; 2
Isolan; 3

lythidathion; 45

malathion; 1, 6, 10
mecarbam; 5, 29, 54
methidathion; 32, 34, 45
methiocarb; 2
mevinphos; 1, 6
Monsanto CP 7769; 1
9533; 2
10502; 1
10516; 1
10561; 2
10878; 2
11549; 2
11903; 2
12432; 2
Murphy P 1973; 5
2188; 5

naled; 1, 6
Niagara 9203; 34
9205; 6
10242; 34, 36, 44
NC 1721; 4, 31
1531; 31
2107; 31
2108; 31

parathion; 1, 5, 6, 8, 9, 10, 14, 15, 16, 17, 19, 20, 21, 22, 23, 24, 25, 28, 32, 33, 34, 36, 37, 38, 40, 41, 42, 46, 48, 52, 53, 54, 59, 154
parathion methyl; 1, 33
phorate; 1, 3, 6, 8, 9, 12, 16, 18, 28, 32, 36, 38, 41, 42, 47, 48, 49, 51, 54, 154
Phosdrin *see:* mevinphos
phosphamidon; 1
Plant Protection R 30569; 38
Pyrazothion; 2

Ronnel *see:* fenchlorphos

Shell 8530; 6, 32

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TABLE 1 (*Continued*)

Shell SD 4092; 1
4239; 1
4457; 2
5532; 2
5539; 2
9098; 42
Stauffer N2790; 4, 6, 7, 8, 32, 34, 38, 39, 42, 44, 45, 46, 50, 53, 54, 55
3055; 6
5092; 6
R1448; 2
1505; 2
Sumithion *see:* fenitrothion

Temik *see:* UC 21149

Thiocron; 36
thionazin; 1, 3, 6, 7, 9, 10, 11, 12, 16, 28, 29, 30, 34, 36, 41, 44, 47, 54
trichloronate; 7, 8, 13, 32, 38, 44, 45
trichlorphon; 1, 6, 154
Trithion *see:* carbophenothion

UC 8305; 1, 6, 41
10854 *see:* Hercules 5727
21149; 36, 42

Vapam; 59
VC 13 *see:* dichlofenthion
Zectran; 10
Zinophos *see:* thionazin

insecticides in before planting the crop. With organochlorine insecticides many workers favoured applying the insecticide early so that they had time to take effect before a crop was planted. With the shorter-lived organophosphates and carbamates early applications have given variable results. In the U.S.A. Day *et al.* [9] and Cuthbert *et al.* [17] protected potatoes against *Conoderus falli* by applying insecticides to the previous cover crop, but in Quebec, Lafrance [45] found re-invasion of potatoes by second-year larvae of *Dalopius* and *Agriotes* in plots treated with diazinon the previous year. A very late application of diazinon in July protected sweet potatoes from species of *Conoderus* in tests by Brett *et al.* [39].

Several workers have applied granular organophosphates in a concentrated band to the planting furrow [9, 12, 14, 48, 49, 52, 54]. With one exception [9], granules placed in the furrow have protected potatoes better against wireworms than when broadcast. Similarly, insecticides applied in the drill row of corn crops [19, 32] have given good results.

Tobacco plants have been protected from wireworm attack in the U.S.A. and Russia by adding organophosphorus insecticides to the transplanting water used to moisten the soil around the plants [10, 33, 47, 59]. Baits have been used to estimate wireworm populations [136], and a bait of diazinon on corn grits was effective against *Conoderus* and *Melanotus* [40]; the value of such insecticidal baits merits more study.

The organophosphorus insecticides AC 12008 [18], azinphos ethyl [18], azinphos methyl [18], Bayer 38156 [7], demeton [22, 56], diazinon [26], disulfoton [56], ethion [4], parathion [21, 22, 23, 25], Stauffer N2790 [55] and trichloronate [7, 13] have all been tried as seed-dressings, but results have usually been inconclusive or less good than with standard γ-BHC seed-dressings. γ-BHC rapidly stops wireworms from feeding, a property not shared by many other insecticides, for whereas wireworms did not bite nutrient-soaked paper discs treated with γ-BHC they readily bit similar discs treated with some other insecticides [137].

Wheat-bulb fly (*Leptohylemyia coarctata* Fall.)

Adult female wheat-bulb flies lay eggs during July and August in bare soil, either of fallow fields or under crops lifted early or that do not cover the soil completely during the egg-laying period. Eggs hatch the following year in late January to early March, and the larvae burrow into and destroy

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the shoots of winter wheat, barley and rye, and some grasses. Oats are not susceptible, and spring cereals usually escape attack because they are sown after the eggs have hatched. The pest can be controlled by applying insecticides to the soil, to the seed or to the growing crop in spring. Treating soil requires several pounds of insecticide per acre and is more likely to harm other soil fauna than are seed-dressings, which use only 2–3 oz insecticide/acre. Although seed-dressings are slightly less efficient than soil treatments in killing wheat-bulb fly larvae or in protecting plants from attack, they cost less and are easier for the farmer to use because he can buy his seed already dressed. Seed-dressings of γ-BHC, aldrin and dieldrin have therefore been extensively used for several years, but, because of the hazard to birds, seed treated with aldrin or dieldrin should not be sown later than 31 December, and their use in the U.K. is to be reviewed again shortly. Spraying with organophosphorus insecticides in spring is usually practised only when other measures of control were ineffective or omitted, and recent experiments have mainly studied how to time the sprays correctly.

Tables 2a and 2b list the non-organochlorine insecticides that have been tested against wheat-bulb fly as seed-dressings, granules or spring sprays; they include some arsenical and fluorine compounds which Bardner [61] compared with organophosphorus and carbamate insecticides in early tests.

Seed-dressings. Candidate insecticides are tested by applying them to seeds, sowing the seeds during autumn either in boxes to which wheat-bulb fly eggs are introduced [61] or in infested field soils [60] and examining the plants for damage next spring. These methods do not show whether a material that fails to protect plants does so because it lacks persistence or lacks toxicity to wheat-bulb fly larvae.

Of the 65 non-organochlorine materials tried as seed-dressings, 49 were ineffective and 12 were moderately effective, i.e. they gave better plant stands than untreated seeds but did not equal the organochlorines, or were less consistent than the organochlorines on a range of soil types. These moderately effective materials were the organophosphorus insecticides "Aspon", azinphos ethyl, AC 43064, B 38156, bromophos, diazinon, dichlofenthion, dioxathion, parathion, Stauffer N2790, trichloronate and VC 3-759. Of the remaining four insecticides, chlorfenvinphos and ethion have now been tested extensively in field trials with very good results: carbophenothion has also worked well, and "Dursban", so far tested only in single-row trials, was sufficiently promising to be included in larger trials for 1967/8.

Granules. Materials tested as granules are the organophosphorus insecticides AC 43064, AC 47470, chlorfenvinphos, B 38156, diazinon, dichlofenthion, disulfoton, mecarbam, menazon, parathion, phorate, Plant Protection R 30472, R 30569, Stauffer N2790, thionazin and trichloronate.

Where comparisons can be made, materials effective as seed-dressings are effective also as granules: because more insecticide is used, granules of

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TABLE 2

Possible substitutes for organochlorines tested against wheat-bulb fly
(a) as soil treatments or seed-dressings, (b) as sprays

(Numbers following the ; refer to papers in the list of references)

(*a*)

Allied Chemicals GC 4072 *see:* chlorfenvinphos
American Cyanamid AC 43064; 60, 66
American Cyanamid AC 47031; 60
American Cyanamid AC 47470; 66
Aphidan; 80, 85
Aspon; 80
azinphos ethyl; 60

barium silicofluoride; 61
Bayer 37289 *see:* trichloronate
Bayer 38156; 4, 65, 66, 75, 76, 77
Bidrin; 60
Birlane *see:* chlorfenvinphos
Boots RD 14639; 4
Boots RD 14838; 4
Boots RD 14984; 4
Boots RD 15721; 60
bromophos; 60, 68

calcium arsenate; 61
a carbamate; 80
carbaryl; 63
carbophenothion; 55, 60, 63, 82
chlorfenvinphos; 65, 66, 69, 72, 82, 84
Chlorthion; 61
coumaphos; 80

Dazomet; 4
Delnav *see:* dioxathion
demeton; 61
demeton methyl; 61
diazinon; 61, 64, 65, 66, 69, 71
dichlofenthion; 4, 64, 65, 66, 69
dimethoate; 63, 64, 71
dioxathion; 80
disulfoton; 60, 63, 66, 74
Dursban; 80
Dyfonate *see:* Stauffer N2790

ethion; 60, 65, 66, 69, 79, 80, 81, 82, 83, 87
ethoate methyl; 80, 85
Ethyl Guthion *see:* azinphos ethyl

fenchlorphos; 69, 77
fenitrothion; 4
fenthion; 76
Fentin acetate; 60
Fitios *see:* ethoate methyl
fluoroacetanilide; 61
Folithion *see:* fenitrothion

Geigy GS 12968 *see:* lythidathion
Geigy GS 13005 *see:* methidathion

lead arsenate; 61
lythidathion; 71

malathion; 61
mecarbam; 4, 66
menazon; 65
methidathion; 60, 71
mevinphos; 63
Murphy P 1973; 80

Paraoxon; 61
parathion; 61, 64, 66
phorate; 61, 63, 66
Phosdrin *see:* mevinphos
Plant Protection R 30472; 60, 66
Plant Protection R 30569; 60, 66
Pyrolan; 61

Ronnel *see:* fenchlorphos

Shell SD 8211; 60
Shell SD 8447; 60
sodium fluoroacetate; 61
Stauffer N2790; 55, 60, 65, 66, 68, 69
Sumithion *see:* fenitrothion

thionazin; 4, 66
Tributyltin oxide; 60
trichloronate; 4, 13, 65, 66, 67, 69, 74, 75, 76, 77
trichlorphon; 61
Trithion *see:* carbophenothion

vamidothion; 60
VC 13 *see:* dichlofenthion
VC 3-759; 60
VC 3-670; 60
VC 3-764; 60
VC 3-768; 60
VC 9-85; 60

Zectran; 4
zinc fluoroacetate; 61
Zinophos *see:* thionazin

(*b*)

American Cyanamid AC 43064; 66
azinphos methyl; 67, 86

Bayer 38156; 74
Bidrin; 66, 74

demeton; 62
demeton methyl; 78
diazinon; 87
dimethoate; 4, 66, 67, 70, 74, 78, 86, 87

ethion; 86
endothion; 87
ethoate methyl; 85

fenthion; 78
formothion; 66, 73, 86

menazon; 74
mevinphos; 78, 87

parathion; 62, 78
phosalone; 86
phorate; 62

thionazin; 66, 70
trichlorphon; 62, 66, 78
trichloronate; 70, 74

vamidothion; 86

some compounds (e.g. phorate and disulfoton) have been active against wheat-bulb fly where seed-dressings have not. As already explained, however, granules cost more than seed-dressings and are less selective in their action. Some good results have been obtained in experiments with granules spread over the crop during spring [13, 67, 74, 75, 85], and this method, like spring sprays, might be useful when earlier measures have not been taken or have failed.

Sprays. The effectiveness of spring sprays depends on when they are applied in relation to the stage of development of both the plant and the larvae [66, 70, 78]. Spraying with dimethoate increased yields most when the larvae were young and the plants had unattacked side buds that could replace the damaged central shoots [70]. Early sowing is itself a considerable safeguard, for early sown crops usually have enough unattacked shoots to withstand moderate infestations of wheat-bulb fly larvae. A disadvantage of sprays is that it is often too wet for a ground sprayer to be used early enough to give the best results. Non-organochlorine insecticides tested as sprays are listed in Table 2b, but no materials have any special advantage over dimethoate or formothion, the ones commercially used.

Leatherjackets (*Tipula* spp.)

Leatherjackets are larvae of crane flies, of which *Tipula paludosa* Meig. is the most common species damaging cereals in the U.K. Adult flies lay eggs in grassland during summer and autumn, the eggs hatch in about 10 days, and the larvae feed just below the soil surface on the roots and underground stems of grass throughout the winter and the following spring. When the grass is ploughed the larvae feed on the newly planted crop,

TABLE 3

Possible substitutes for organochlorine insecticides tested against leatherjackets as sprays, granules or baits

(Numbers following the ; refer to papers in the list of references)

azinphos methyl; 92

Bayer 37289 *see:* trichloronate
Birlane *see:* chlorfenvinphos

carbaryl; 88, 92, 94, 95
Carbamate A; 92
Carbamate B; 92
chlorfenvinphos; 91, 94
Chlorthion; 92

demeton methyl; 88
diazinon; 88, 92, 94
dichlorvos; 92
dimethoate; 88, 92
Dipterex *see:* trichlorphon

fenitrothion; 91, 93, 94
fenthion; 92
Folithion *see:* fenitrothion

GC 4072 *see:* chlorfenvinphos
GS 12968 *see:* lythidathion
Guthion *see:* azinphos methyl

lythidathion; 91

malathion; 88, 91, 95
mecarbam; 88
mevinphos; 92

naled; 95

an organophosphorus compound; 92

parathion; 89, 90, 91, 92, 94
phorate; 94
Phosdrin *see:* mevinphos
phosphamidon; 88, 92

Sumithion *see:* fenitrothion

trichloronate; 94
trichlorphon; 88, 91, 92
thionazin; 91

Zinophos *see:* thionazin

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whether cereals, root crops or vegetables. In warm, damp weather leatherjackets can feed on the surface, cutting off the plants at ground level. Chemical control is by baits of Paris Green (copper aceto-arsenite), or by sprays or baits of the organochlorine insecticides γ-BHC or DDT. However, some varieties of barley are sensitive to DDT, and BHC can taint subsequent root crops. Some work has therefore been done on control with non-organochlorine compounds. Table 3 lists the insecticides tested. Baits containing the organophosphorus compounds fenitrothion, parathion and thionazin worked well in tests by Golightly [91], and an unnamed carbamate (A) in tests by Lange [92]. Sprays used with some success include fenthion, fenitrothion, an unnamed organophosphate, thionazin, chlorfenvinphos and parathion. The last three materials also worked as granules, as did trichloronate and phorate. Fenitrothion as a spring spray has lived up to its earlier promise in recent field trials in England [93], but in Scotland was effective only at 2 lb a.i./acre, whereas parathion was very effective at 3 oz a.i./acre [94].

Frit fly (*Oscinella frit* (*L*))

Oscinella frit has three generations a year in most parts of the British Isles. Damage to cereals is most serious in spring oats and in maize. Adult flies lay eggs on and at the bases of young plants, and the larvae that emerge bore into the young shoots and destroy the growing points. Young plants are killed, and slightly older plants produce many weak tillers. A second generation of larvae, which arises from eggs laid in summer, damages oat grains. The third generation of larvae overwinters in grasses, but if the grass is ploughed the larvae may damage a following cereal crop (autumn-sown wheat, barley or rye).

Chemical control of frit fly on late-sown oats is by two DDT sprays, one just before or at the time frit flies lay their eggs on young plants, the second about a fortnight later. Several organophosphorus sprays have been tried (Table 4a), and parathion and dimethoate were promising on late-sown oats [98] and on maize [116], even when applied as single "late" sprays, i.e. about a fortnight after egg laying, when symptoms of attack were conspicuous. The late sprays have the advantage that they avoid treating crops that will not be attacked, but correct timing is important [110]. The beneficial effects of sprays, especially of non-persistent materials, against the first generation of frit fly may be offset by second-generation frit invading the crop and attacking the grain, as Jepson [100] found with parathion sprays.

Table 4b lists non-organochlorine insecticides tested as soil or seed treatments against frit fly. Trials of granules by Walker [96] showed that phorate was more effective than thionazin in protecting silage maize, and worked better applied in the furrow than broadcast. Jepson and Mathias [104] also obtained good results with phorate used in this way to protect sweet corn. However, in other trials Walker [102] found that the relative control given by broadcasting granules over young plants or by applying granules to the furrow at sowing depended on the time of attack; his studies with radioactive phorate showed that broadcasting phorate gave

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an intense concentration of up to 17 ppm phorate equivalent in the plants after 1–3 weeks, whereas placing it in the furrow produced less activity for 9 weeks. A disadvantage of placing phorate in the furrow is that it sometimes damages young plants [103, 138].

TABLE 4

Possible substitutes for organochlorines tested against frit fly

(a) *sprayed on to plant*, (b) *applied to seed or soil*

(Numbers following the ; refer to papers in the list of references)

(*a*)	(*b*)
azinphos methyl; 116	demeton; 56
demeton; 113, 118	dimethoate; 98, 122
demeton methyl; 97, 109	disulfoton; 56, 57, 103, 115, 119
diazinon; 116	ethion; 107
dimefox; 111	methyl parathion (+parathion); 117
dimethoate; 98, 116	OMPA *see:* schradan
Dipterex *see:* trichlorphon	parathion; 98, 112, 115, 117
DNOC; 118	Pestox III *see:* schradan
Ethyl Guthion *see:* azinphos methyl	phorate; 96, 97, 102, 103, 104, 105, 107 115, 121
methyl parathion (+parathion); 117	schradan; 101, 108, 111, 117
OMPA *see:* schradan	thionazin; 96
parathion; 97, 98, 100, 106, 110, 112, 113, 116, 117, 118, 120	Zinophos *see:* thionazin
Pestox III *see:* schradan	
schradan; 111	
thionazin; 114	
trichlorphon; 97	
Zinophos *see:* thionazin	

Seed-dressings of demeton, disulfoton, parathion, phorate and schradan have been reported to have some effect, but seed-dressings have limitations because some frit fly eggs are laid on the plant, and larvae from these may enter the plants above soil level [99]. Organophosphorus insecticides that are active as seed-dressings against wheat-bulb fly are therefore less likely to work against frit fly because they owe much of their success to action in the soil. To control frit fly adequately the advantage would seem to lie with moderately persistent, very systemic materials.

The present status of the pests and the insecticides

The pests. Progress in control of wireworms with non-organochlorine insecticides has been disappointing considering the many materials tested. In the U.K., soil treatments with aldrin are still superior to soil treatments with other types of insecticide, and no non-organochlorine insecticide of acceptable mammalian toxicity rivals γ-BHC as a seed-dressing. In the U.S.A. the organophosphorus insecticides diazinon, parathion and phorate are recommended against species of wireworms that are resistant to organochlorines, but, before resistance developed, organophosphorus compounds like parathion did not compare favourably with organochlorine insecticides [20, 21, 24]. Therefore in the U.K., where wireworms

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have not developed resistance to organochlorines, it is not surprising that aldrin still gives the best results. However, some organophosphorus compounds are quite effective when put in the furrow and may be profitable in protecting potatoes, but are too costly to use for cereals.

Of the cereal pests discussed, the search for substitutes to replace the persistent organochlorine insecticides has probably met most success with wheat-bulb fly. Chlorfenvinphos and ethion seed-dressings have been adequately tested and are very effective against this pest. Liquid seed-dressings of chlorfenvinphos and powder seed-dressings of ethion are now available commercially. Carbophenothion and "Dursban" have also given promising results as seed-dressings in experiments. Granules of chlorfenvinphos, N2790 and trichloronate are effective, but insecticides are more difficult to apply in this form, and the cost would probably be justified only when growing special varieties for seed. Correctly timed spring sprays of parathion, dimethoate and formothion have given reasonable results in experiments, and the last two, being less toxic than parathion to mammals, are used commercially.

Against leatherjackets, several organophosphorus compounds are effective as baits, but these are difficult to prepare and to apply evenly. Of the sprays, fenitrothion is less toxic to mammals than the other organophosphorus insecticides tried, but it is not marketed in the U.K. for agricultural use. Granular formulations are more suitable than sprays with the more toxic materials.

Experiments on chemical control of frit fly have decreased with the decline in the acreage of oats in the U.K. Of the non-organochlorine sprays, parathion has given good results, but is very toxic to mammals. The less toxic organophosphate dimethoate gave promising results in experiments [98, 116], but requires further testing. Should the acreage of oats increase again to the point where frit fly is troublesome, suitable organophosphorus insecticides might provide acceptable alternatives to DDT. For treating soil or seed, the need for systemic insecticides has already been explained. With insecticides that are very toxic to mammals, granular formulations with a small percentage of active ingredient are preferable to seed-dressings because they are less hazardous to handle, but oats can be sown early to reach a non-susceptible stage of growth by the time frit fly lay their eggs, and the use of expensive granular treatments is probably not justified: with sweet corn the optimal sowing date is in May, and phorate granules are recommended for this crop.

The insecticides. Sprays can be applied to the aerial parts of plants to kill shoot-boring stages of wheat-bulb fly and frit fly, but the four pests discussed in this paper spend part of their lives in soil, and their control often involves putting insecticide in soil to kill insects directly, or to be taken up by the plants, and so to kill insects living in the shoots. Placing insecticides in soil brings special problems. Not only must the insecticide be toxic to the pest but it must resist leaching enough to remain in the root zone, it must not be lost by volatilisation, or degraded chemically or microbially before it has done its job, and it must not be so strongly adsorbed by soil that it is inactive biologically.

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Except for two references [111, 139], there is no information about the toxicity of non-organochlorine insecticides as stomach, contact or fumigant poisons to larvae of wheat-bulb fly, frit fly, leatherjackets or wireworms. Most testing has been done in soil, and when an insecticide fails, it is not known whether this is because it is not toxic to the insect or because it lacks some other property mentioned above. The importance of microbial decomposition, leaching and volatilisation of soil insecticides was discussed by Edwards [124], but most work so far has been done on organochlorine insecticides, and few organophosphorus materials have been studied in detail. Adsorption of insecticides in soil is of key importance, because it affects the extent of leaching and decomposition, and the concentrations available for killing insects by contact or fumigant action. For example, Harris and Mazurek [143] showed that, of 10 insecticides deposited on a metal surface, all except DDT volatilised and killed crickets held on a screen ¼ in. above the treated surface. In contrast, when the insects were held above the same insecticides incorporated in a moist sandy loam, aldrin, heptachlor, chlordane, trichlorphon and mevinphos were still moderately volatile, but diazinon, parathion and dieldrin were only slightly volatile, and DDT and Zectran were not volatile and killed no insects in 24 hours. This loss of fumigant activity was attributed to adsorption of insecticide in soil, and the processes of adsorption are discussed below. The fate in soil of few non-organochlorine insecticides has been studied in detail, but enough materials have now been tested against soil pests of cereals to try to discuss why some insecticides work better than others.

Adsorption. Several authors have shown [125, 140, 141, 142, 149] that insecticides in soil are more active in moist than in dry conditions. To explain why dieldrin-treated mud blocks were more toxic to mosquitoes at high than at low humidities, Barlow and Hadaway [140] suggested that water was adsorbed preferentially on the active sites of soil particles, so displacing insecticide and resulting in increased mobility of insecticide molecules. Harris [143, 144, 145, 146, 147, 148] developed the idea that the initial activity of an insecticide in a mineral soil depends upon the degree to which it is adsorbed on the active sites of soil particles and how well it can compete with water for these sites. By measuring in a Potter spray tower the contact activity of a range of insecticides to crickets and flies, and comparing these values with their activity in moist and dry soil, he concluded that some insecticides, e.g. the organochlorines isobenzan, HRS 1671, aldrin and lindane, and the organophosphorus compounds phorate, UC 8305 and trichloronate, were not strongly adsorbed by dry soil and did not compete with water for active sites on the soil particles, and so would be expected to give consistently good initial control of soil insects in mineral soils. In contrast, other organophosphorus insecticides like Bomyl and azinphos methyl, although toxic to the test insects in spray-tower tests, worked poorly in soil, because they were strongly adsorbed, even in moist soil. Another group, including the organophosphates thionazin, diazinon, dichlofenthion, SD 9098 and GS 12968, were strongly adsorbed by dry mineral soil, but competed so little with water for active sites on the soil particles that they were very toxic in moist mineral soil, and so would be

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expected to give inconsistent results in the field. A fourth class of materials, including the organophosphates fenitrothion, methyl parathion, GS 13002 and the carbamates Niagara 10242 and UC 21149 ("Temik"), were moderately to strongly adsorbed by dry soil but only moderately competitive with water for the active sites, and in Harris's view would be expected to give consistent results in mineral soils provided they were used at greater concentrations than their contact-toxicity figures would suggest.

These suggestions may help to explain the activity of trichloronate and phorate against cereal pests and the inconsistent performance of thionazin against wireworms, and diazinon against wheat-bulb fly. A difficulty is that deductions about adsorption, based on an indirect measurement such as the number of insects killed, can mislead if a change in soil conditions affects the behaviour of the insects. Further, Gerolt [150] showed that insects took up more dieldrin from glass in moist than in dry air, and he suggested that the mobility of insecticide molecules is affected by R.H. and that the effect of humidity is not restricted to specific substrates. Ebeling and Wagner [170] showed that the displacement of insecticides from a substrate by water depended on the insecticide itself and on its formulation, but took place on hydrophilic substrates and not on hydrophobic substrates. When they eliminated the effect of the substrate by suspending flour beetles above layers of insecticide 1 cm thick more insects were killed at 80% R.H. than at 20% R.H. with some formulations of diazinon, and they concluded that some explanation other than displacement of insecticide from a substrate by water was needed.

Adsorption of insecticides on the organic matter of soils is also very important. Several authors [142, 151, 152] have shown that organochlorine insecticides are relatively inactive in soils with much organic matter. Other types of insecticide are similarly affected: in tests with the organochlorines heptachlor and DDT and the organophosphorus materials dichlofenthion, diazinon and parathion in 10 types of soil, Harris [153] concluded that heptachlor, DDT and dichlofenthion were adsorbed by the clay fraction, the three organophosphorus materials by the sand or silt fraction and all five materials by the organic matter. His lists [144] showed that many insecticides, organochlorines, organophosphates and carbamates were much less active in a moist muck soil than in a moist sandy loam. He also studied how soil moisture affected the insecticidal activity of diazinon, parathion, DDT and heptachlor [148] in sandy loam (1·44% organic matter, mineral fraction = 76·6% sand : 21·06% silt : 2·34% clay), a clay soil (9·09% organic matter, mineral fraction = 17·02% sand : 31·32% silt : 51·66% clay) and a muck soil (64·6% organic matter, mineral fraction = 14·47% sand : 38·82% silt : 46·71% clay). The influence of soil moisture on insecticidal activity depended on the soil type: it was greatest in the sandy loam, but in the clay with 9·09% organic matter the insecticides also became more active as moisture content increased, whereas in the muck soil the insecticides were relatively inactive at all moisture contents. Similarly, these four insecticides, and dichlofenthion, were not very toxic to crickets in dry or moist muck soil containing 39·76% organic matter [153].

Not all insecticides are equally strongly adsorbed by organic matter.

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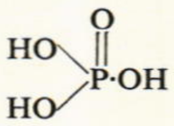
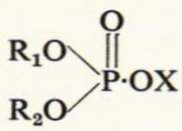
Direct chemical measurements by Graham-Bryce [155, 156] showed that phorate and disulfoton were strongly adsorbed in soils with much organic matter, but in the three soils so far studied dimethoate and menazon were much less strongly adsorbed. Possibly many organochlorines and some relatively lipophilic organophosphates like phorate are adsorbed mainly on the organic matter of soils, whereas relatively hydrophilic insecticides are adsorbed mainly on the mineral fraction. However, it is not yet certain what physical properties of insecticides or what features of their chemical structures influence adsorption on organic matter as opposed to adsorption on clay, silt and sand. Many more direct measurements of adsorption are needed, especially with series of insecticides whose substituents are varied systematically.

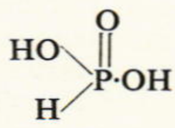
Decomposition. More persistent insecticides are required to control some cereal soil pests than others. Short-lived materials may control leatherjackets if they are applied when the insects are feeding at or near the soil surface. In contrast, insecticides applied in the autumn to protect plants against wheat-bulb fly must persist until the following spring when the larvae attack. Moderate persistence may be necessary also for insecticides used against wireworms, because insecticide and soil cannot be thoroughly mixed in the field, so control may depend partly on insects moving into zones of insecticide, and the probability of this happening increases with extended persistence of the insecticide. Moderate persistence may also be an advantage in soil insecticides used against frit fly, but systemic properties are also very important. Of the non-organochlorine insecticides so far tested, organophosphorus compounds have proved best when applied to soil against the cereal pests discussed. These compounds are esters of phosphoric acid, phosphonic acid and related acids, in which the hydrogen atoms have been replaced by other groups.



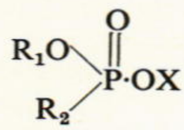
Phosphoric acid



Phosphate insecticide



Phosphonic acid



Phosphonate insecticide

R_1 and R_2 are commonly methyl (CH_3), ethyl (C_2H_5) or propyl (C_3H_7); the doubly bound O and/or the O of the OX group is replaced by S in phosphorothioates or phosphorodithioates; variations in X among organophosphorus insecticides are many.

The best results against wheat-bulb fly were obtained with carbophenothion, chlorfenvinphos, ethion, "Dursban" and the moderately effective compounds listed on p. 336. All except chlorfenvinphos have the doubly bound O and/or the O of the OX group replaced by S, and nearly all are diethyl phosphates and phosphonates (R_1 and $R_2 = C_2H_5$), whereas ineffective organophosphorus compounds tried against wheat-bulb fly included diethyl compounds, dimethyl compounds and some methyl/propyl and methyl/butyl compounds. Against wireworms several dimethyl organophosphates, like fenthion and fenitrothion, have done well in

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laboratory tests, and two dimethyl compounds methidathion [32, 34] and Niagara 9203 [34] were reported effective in the field. Most reports of field effectiveness, however, refer to diethyl phosphates and phosphonates, and it is the diethyl compounds phorate, parathion and diazinon that have gained acceptance in the U.S.A. for field use. Against frit fly the systemic phorate is the only non-organochlorine recommended. Therefore, in those situations where soil insecticides need moderate persistence to control cereal pests the most successful of the organophosphorus insecticides are mostly diethyl, S-substituted phosphates and phosphonates.

One possible reason may be hydrolysis rates. The phosphorus atom of organophosphorus insecticides has a partial positive charge, and this site is susceptible to attack by hydroxyl ions (OH^-) during alkaline hydrolysis. The size of the positive charge depends on whether the substituents of the molecule tend to draw electrons away from the phosphorus atom or to donate electrons to it. The =O atom has a greater electron-withdrawing effect than the =S atom, so series of organophosphorus insecticides containing the latter are less easily hydrolysed [157, 158, 169]. Similarly, methyl groups donate less electrons to the phosphorus atom than do ethyl groups, which in turn donate less electrons than isopropyl groups, and holding one alkyl group constant and increasing the size of the other showed that the order of ease of hydrolysis is methyl > ethyl > isopropyl [159]. Hydrolysis destroys the insecticidal activity of organophosphorus compounds and has been shown to be a path of breakdown in soil of parathion [160], Imidan [161], diazinon and thionazin [162]. The rate of hydrolysis would be expected to depend on pH and temperature, but in equivalent conditions should happen faster with dimethyl phosphates than with corresponding S-substituted diethyl compounds, and may therefore help to explain the persistence and effectiveness of the latter. Mulla's results [163, 164] support this, for in laboratory tests which compared many organophosphorus compounds and carbamates, certain of the diethyl phosphorothioates and phosphonothioates remained active longest in soil. Also, some dimethyl compounds, active against wireworms in laboratory tests where conditions are sometimes acid, have failed in the field. The variable results of thionazin in wireworm trials could also be explained in terms of relative persistence in field soils of different pH, and in one trial [7] residues of this insecticide were greater in the more acid than in the less acid areas of the same field.

In the present state of knowledge, however, there is need to be wary of taking any particular argument too far. Variations in the part X of the molecule greatly affect hydrolysis rates of organophosphates [171]. This may be why certain dimethyl compounds persist in soil, e.g. fenthion and B 37342 [167], dimethoate applied in usual amounts [165] and large amounts [166], and why some diethyl compounds are short lived. For some compounds, if leaching, microbial attack or volatilisation occur very rapidly, rates of hydrolysis may be relatively unimportant.

Volatility, solubility. Diethyl organophosphorus compounds are likely to be less volatile than their corresponding dimethyl analogues, but adsorption in soil affects the vapour toxicity of insecticides, and the stated vapour

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pressure of an insecticide is not a good indication of its fumigant activity in soil. Diethyl S-substituted organophosphates would be expected to be less polar, and so less soluble in water than corresponding dimethyl phosphates, and where diethyl and dimethyl analogues can be compared (e.g. demeton S, parathion, demeton O, carbophenothion and their methyl analogues) this is true. Most of the compounds effective against wheat-bulb fly and wireworms are very slightly soluble in water (150 μg/1 or less) but it is not clear whether slight solubility *per se* is a useful characteristic of soil insecticides, and the relationship between solubility, adsorption and leaching, for molecules of widely differing chemical structure, is far from clear.

Conclusions

At least three things may contribute to the success of an organochlorine insecticide like aldrin in the soil. It is toxic to many insect pests; it is less readily inactivated than many other insecticides by adsorption on the mineral fraction of soil; it has great persistence.

The factors that govern persistence and adsorption of insecticides in soil are not fully understood. Most work has been done with insecticides of widely differing structures, and further studies are needed on how adsorption and decomposition are affected by altering a single substituent of a molecule at a time.

Until now, the testing of soil insecticides has largely been empirical. In such tests diethyl organophosphorus compounds seem to have given better results than dimethyl organophosphates or carbamates against wheat-bulb fly, wireworms and possibly frit fly. By analogy with Harris's work this may be because these materials, like aldrin, are not strongly inactivated by the mineral fraction of soil, but there is no reason to think they would not be adsorbed by organic matter. Diethyl organophosphorus compounds are likely to be less soluble and less volatile than their dimethyl analogues: they may also be less easily hydrolysed, and so have some advantage where moderate persistence in soil is required. Although individual ones differ widely in their toxicity to mammals, diethyl organophosphorus compounds are more toxic to mammals than their corresponding dimethyl analogues [168], but if they work better than dimethyl compounds in soil this disadvantage may have to be tolerated to control certain soil-borne pests.

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