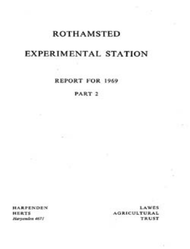
Rothamsted Experimental Station Report for 1969 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1969

PART 2

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ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1969

PART 2

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The Value of Residues from Long-period Manuring at Rothamsted and Woburn
I. Introduction

A. E. JOHNSTON

Lawes and Gilbert (1873) found that giving a crop only as much phosphorus and potassium as it took up failed to give large yields and in their experiments they always applied more P and K than the maximum taken up by the crop. Provided the excess was not leached from the soil, it remained as a residue and Lawes and Gilbert (1884) wrote, 'The recent legislative enactments giving the cultivator of the soil a claim for the manure ingredients possessing a pecuniary value which he has applied, and left in the land, add greatly to the interest of all investigations which have a bearing upon this important subject'. As Cooke (1967) recently pointed out, Lawes and Gilbert became closely involved with this important aspect of farming and the legislation whereby outgoing tenants were compensated for the residual value of improvements.

Lawes and Gilbert modified some of their experiments, and later Hall made some further changes, to measure the residual value of dressings of farmyard manure (FYM) and fertilisers. These experiments showed that, when manuring continued for many years and then ceased, soils with residues yielded better than unmanured soils and the effect of P and K residues often lasted many years. More recently, many experiments have shown that the responses of crops to a single dressing of P fertiliser have diminished rapidly after the first year, unless large amounts were applied. By the third and fourth year the effects were usually too small to measure accurately, even though as much as three-quarters of the P added as fertiliser remained in the soil. Although a crop can obtain only a little P from the residue of a single dressing applied three or four years before, the total residues from many dressings may supply much, or all, of the P needed. Similarly useful residues can accumulate from repeated dressings of K fertilisers.

In the Exhaustion Land experiment at Rothamsted, which last received P and K fertilisers in 1901, barley grown between 1949 and 1953 with adequate N, yielded twice as much on the plots given P and K last century as on those not. However, the crop recovered only an extra 4–5 lb more P and 15–20 lb more K/acre/year. This was a very small (less than 0·5%) recovery of the *total* P and K applied between 1856 and 1901, but acute deficiency of one nutrient may have been limiting the recovery of the other. Even so, such small recoveries would not justify a policy of *intentionally* building up residues in the soil unless they have merits not possessed by new annual dressings at usual amounts.

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Possible merits of residues in soil are:

1. When thoroughly incorporated in the soil, residues provide nutrients throughout the ploughed layer, the low levels of which remain moister during the summer.
2. Large fresh dressings, which may damage germinating seeds, are not needed.
3. Residues insure against the poor response to a new fertiliser dressing, which broadcast on the surface, may not have been worked in deeply.

This series of papers gives the results of experiments made to value the residues from long-period manuring at Rothamsted and Woburn. Paper II summarises the results of experiments started by Lawes and Gilbert and later by Hall. It includes the results of those that have continued to the present. Papers III, IV and V give, respectively, the forms of the experiments made between 1957 and 1962 and the results of the tests measuring the value for arable crops of the residues of many dressings of P and of K fertilisers.

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The Value of Residues from Long-period Manuring at Rothamsted and Woburn
II. A Summary of the Results of Experiments Started by Lawes and Gilbert

A. E. JOHNSTON

Lawes and Gilbert made many tests of the value of residues of fertilisers and manures accumulated in soil during the long-period of manuring in their experiments, and later, Hall made some further tests. Some of these tests still continue. The results, summarised here, were from modifications made in the following experiments:

Agdell. This 4-course rotation experiment, started in 1848, was described by Warren (1958) and more briefly on page 24.

Barnfield. Various experiments on root crops were made from 1843 to 1959 details of which were given by Warren and Johnston (1962).

Broadbalk. Details of the treatments to the winter wheat were given by Johnston and Garner (1969).

Exhaustion Land. Though mainly cereals have been grown, there was a manurial experiment with potatoes grown continuously from 1876 to 1901. The history of the site was described by Warren and Johnston (1960) and more briefly on page 23.

Hoosfield Continuous Barley. Warren and Johnston (1967) gave the details of the treatments to the barley grown on this site since 1852.

Park Grass. This experiment, started in 1856 to study the manuring of permanent meadow cut twice each year, for hay and later for aftermath, was described by Warren and Johnston (1964).

Permanent Wheat and Barley Experiments at Woburn. The design of these experiments started in 1876 by the Royal Agricultural Society was influenced by Lawes and Gilbert. The experiments have been conducted from Rothamsted since 1926 when the management of the Woburn Farm became the responsibility of the Lawes Agricultural Trust. The history of the sites is described on page 25.

The effect of residues of nitrogen fertilisers

Winter wheat: normal dressings of N. Before 1852 Lawes and Gilbert had showed that a single dressing of inorganic N to the winter wheat on Broadbalk had little residual effect on the following crop of winter wheat (Garner & Dyke, 1969). After 1852 this test, combined with one on the

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residual effects of PKNaMg, was made on plots 17 and 18 and was continued until 1967. Plot 17 received 86 lb N/acre in even years, and PKNaMg fertilisers in odd years, and plot 18 received N in odd years and PKNaMg in even years. Table 1 shows mean yields (Garner & Dyke,

TABLE 1

Effect of the residues of fertiliser N and PKNaMg on winter wheat on Broadbalk, 1852–1967

cwt/acre/year

	Plot and treatment				
	5 PKNaMg annually	17/18 PKNaMg given N residues	10 N annually	7 NPKNaMg annually	17/18 N given PKNaMg residues
Grain	8·9	8·2	12·6	17·7	16·8
Straw	14·0	13·0	20·4	33·2	29·7

1969) on these plots over the whole period 1852–1967. There was no residual effect of N. The yield on plots 17/18 with residual N was only equal to that on plot 5 given PKNaMg annually but no N. However, Table 1 also shows there was a very large residual effect of PKNaMg, because yields on plots 17/18 with N almost equalled those on plot 7, given NPKNaMg each year.

Winter wheat: large dressings of N. Winter wheat grown on plot 16 on Broadbalk during the 1860s showed another interesting residual effect. From 1852 to 1864 annual manuring on plot 16 was NPKNaMg, supplying 172 lb N/acre. The two seasons, 1863 and 1864, both favoured wheat and there was little extra gain from increasing N from 129 to 172 lb. Lawes and Gilbert (1884) stopped applying fertilisers to plot 16 in 1865 but, over the next 19 years, they recorded the yields, which are compared with those of plot 5, given PKNaMg but not N every year in Table 2.

Lawes and Gilbert thought that the very large effect of the residues in 1865, half the direct effect of the 172 lb N in 1863–64, was from ammonia remaining in the soil, for 1864 was the driest year in the then recorded history of the experiment. The 2 to 3 cwt increase in grain yield over the next three years they decided was caused by extra nitrogen released by mineralisation of the larger plant residues in the soil of plot 16 than in plot 5. After 1868, the readily mineralisable N had gone and yields were no better than those on plot 5.

Barley after turnips and swedes. After turnips and swedes had been grown on Barnfield for ten years, Lawes and Gilbert grew barley without manure in 1853, 1854 and 1855. The yields in Table 3 from Lawes and Gilbert (1857) confirmed their often repeated statement that good yields required 'available nitrogen within the soil'. Residues from the NPK given to the turnips gave a small (1·5 cwt) extra yield of grain in each of

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TABLE 2

Direct and residual effect of 172 lb fertiliser N on winter wheat on Broadbalk, 1863–83

Grain, cwt/acre/year

	Plot and treatment		
	5	16	
Year	PKNaMg annually	NPKNaMg annually including 172 lb N/acre	Effect of 172 lb N
1863	11·1	31·1	20·0
1864	9·3	28·8	19·5
	PKNaMg annually	Unmanured	Effect of N residues
1865	7·7	17·8	10·1
1866	7·2	9·5	2·3
1867	4·9	7·7	2·8
1868	9·9	12·8	2·9
Period			
1869–73	8·4	8·7	0·3
1874–78	6·9	6·7	−0·2
1879–83	7·6	6·9	−0·7

the three years. How small was emphasised in 1854 when, on part of the 'Valley' plots with the same P and K residues as the main plots, 82 lb N/acre was given, which increased yield by 17·8 cwt grain.

TABLE 3

Effect of residues from fertilisers given to roots on the yield of barley on Barnfield, 1853–55

Grain, cwt/acre/year

	Treatment to turnips 1845–52			Treatment to barley
	Unmanured	PK	NPK total N 263 lb/acre	82 lb N/acre in 1854 only
1853	10·2	10·6	11·8	—
1854	9·0	9·6	10·4	26·8
1855	9·1	9·6	10·3	12·7

Barley after potatoes. From 1902 to 1940 unmanured cereals followed the potato experiment on the Exhaustion Land. Table 4 shows the yields of cereals, which were measured on all plots only in the first three years and again from 1917 to 1922. Between 1856 and 1901 annual dressings of 86 lb N/acre were given 44 times. In 1902, yield after potatoes manured with either N or NPK was much larger than after potatoes unmanured or given only PK. However, the smaller crops on the N only than on the NPK plots left smaller residues and the effect of these disappeared in two years. On the NPK plots mineralisation of N gave small increases in yield for some years but the effect disappeared by 1919–22.

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TABLE 4

Effect of residues from fertiliser dressings on the yield of unmanured cereals on the Exhaustion Land, 1902–22

Grain, cwt/acre/year

		Treatment 1856 to 1901				
Year	Crop	Unmanured	N	P	PK	NPK
1902	Barley	16·6	29·4	16·9	12·0	31·6
1903	Barley	6·0	9·1	6·4	6·2	13·2
1904	Oats	10·8	11·2	10·9	9·9	15·3
1917	Barley	3·2	3·0	3·0	3·2	5·5
1918	Barley	4·5	6·6	6·9	7·1	9·6
1919	Barley	2·8	3·6	4·2	5·1	5·0
1921[1]	Wheat	8·1	11·6	15·7	15·2	14·4
1922	Barley	6·4	7·8	7·5	7·0	7·8

[1] The 1920 crop failed.

The effect of residues from potassium fertilisers

Residues of potassium manures were measured in four experiments.

Swedes. In the experiment with swedes on Barnfield, K was not applied between 1861 and 1870 to plots given K between 1845 and 1860. Table 5 shows mean yields for four periods for the crops given N as ammonium sulphate.

TABLE 5

Direct and residual effect of potassium fertilisers on turnips, and swedes, Barnfield, 1845–70

Roots, tons/acre/year

		Plot and treatment		
Crop	Period	4A NPKNaMg	5A NP	3A or 8A Unmanured
Turnips	1845–48	9·8	9·9	1·4
Swedes	1849–52	9·4	8·7	3·8
Swedes	1856–58[1]	6·5	5·4	1·7
		NP (KNaMg residues)	NP (no K)	Unmanured
Swedes	1861–70	5·0	4·0	1·2

[1] The crops of 1859 and 1860 failed.

At first (1845–48) there was no response to K. Later, however, because of the gradual depletion of soil K where none was given as fertiliser, there was a response and giving fresh K increased yield by 1·1 tons/acre/year between 1856 and 1858. On plot 4A the mean annual dressing of 100 lb K/acre as fertiliser between 1845 and 1860 was more than that removed in the tops and roots; the residue that accumulated in the soil during this period maintained a yield of 1·0 ton roots/acre more than on plot 5A during the next ten years, 1861–70.

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Mangolds and sugar beet. The residual effect of K fertilisers on Barnfield was confirmed between 1903 and 1959 with both mangolds and sugar beet when these crops were given N as ammonium sulphate. Strip 7, which had had K whenever it was applied to strips 4 and 6 until 1902, was manured with PNaMg only from 1903. The amount of Na and Mg was equal to that given on strip 4. Yields, of both crops (Table 6) given by K residues, from fertiliser dressings applied before 1902, were equal to those given by fresh dressings of K throughout the last 56 years of the experiment.

TABLE 6

Effect of residues from potassium fertilisers on mangolds and sugar beet on Barnfield, 1904–59

Roots, tons/acre/year

		Plot and treatment		
		6A NPK	4A NPKNaMg	7A NPNaMg (K residues)
Crop	Period			
Mangolds	1904–40	14·5	15·5	16·1
Mangolds	1941–59	11·7	12·8	12·2
Sugar beet	1946–59	6·6	7·2	7·2

Potatoes. Table 7 shows potato yields during three periods of the experiment on the Exhaustion Land; plots 9 (P only) and 10 (PKNaMg) were sited on plot 1 (PKNaMg) of the preceding wheat experiment (1856–1874).

TABLE 7

Effect of residues from potassium fertilisers on potatoes on the Exhaustion Land, 1876–1901

Tubers, tons/acre/year

	Plot and treatment		
	1 Unmanured	10 PKNaMg	9 P (K residues)
Period			
1876–81	2·3	4·1	4·0
1882–87	1·7	3·4	3·4
1888–1901	0·8	2·2	1·9

Unfortunately N was not given to these plots, but the K residues accumulated during the wheat experiment gave as good a yield of potatoes as did fresh dressings of K during the first twelve years, though yields decreased later.

Grass cut for hay. On Park Grass the early experiments on the value of residues of manurial dressings were not complicated by major changes in botanical composition, as were many of the comparisons of manurial treatment on yield. Plots 9 and 10 received the same manures (NPKNaMg) between 1856 and 1861, except that plot 10 also got sawdust, which had

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no effect on the yield of hay. Plot 10 received no more K after 1861, or sawdust after 1862. Table 8 shows the yields on these two plots and on plot 4/2 (NP).

TABLE 8

Direct and residual effect of potassium fertilisers on the yield of hay on Park Grass, 1856–75

cwt/acre/year of hay[1]

	Plot and treatment		
	9 NPKNaMg	10 NPKNaMg	4/2 NP
1856–61	56·7	55·6	43·9[2]
	NPKNaMg	NPNaMg (K residues)	NP (no K)
1862–66	48·0	47·8	36·0
1867–75	48·9	39·1	30·0
1920–59[3]	37·2	24·2	16·4

[1] Yields 1856–76 from Lawes & Gilbert, 1880. Yields 1920–59 from Warren & Johnston, 1964.
[2] 1859–61 only.
[3] Unlimed halves of each plot.

Yields with NP only (plot 4/2) decreased during each of the periods. During the first 6 years, 1856–61, there was a response to fresh K of 12 cwt hay/acre. During the next 5 years, 1862–66, the residues of K accumulated on plot 10 between 1856 and 1861, maintained as good a yield as was given by fresh dressings of K. Then, in the 9 years between 1867 and 1875, the decreasing K residues gave yields intermediate between those on plot 4/2, always without K, and on plot 9, always given K. From their analyses Lawes and Gilbert concluded that there would have been about 400 lb K remaining in the soil of plot 10 in 1862 from the 870 lb applied between 1856 and 1861. Using the uptake on plot 4/2 as a measure of the K released from the soil, they also calculated that during the next 14 years the extra crops recovered half of this residue of 400 lb K.

The large differences in yield on plots 4/2, 9 and 10 for the period 1920 to 1959 (Table 8) are probably not simply the effect of K, but reflect the interaction of manuring and differential soil acidity, which had developed on the plots, on the plant species able to tolerate each set of conditions.

The combined effect of residues from P and K fertilisers

Unfortunately no experiment made in the early period at Rothamsted tested the effects of P residues only. In some experiments Lawes and Gilbert simply stopped applying both P and K fertilisers to plots previously given them, and measured the combined effect of PK residues.

Winter wheat. The residual effects of small dressings of P and K were shown by modifying the treatments to plots 10A and 10B on Broadbalk. Both plots received PK in 1844. For the next 39 years, plot 10A had 86 lb N

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annually, whereas 10B had two more dressings of P and K (in 1848 and 1850) followed by 33 years with 86 lb N annually. Table 9 (from Lawes & Gilbert, 1884) gives yields for four 8-year periods.

TABLE 9

Effect of PK residues on winter wheat on Broadbalk, 1852–83

Grain, cwt/acre/year

Plot	10A	10B	
Treatment	PK in 1844 39 years N only	PK in 1844, 1848, & 1850 then 33 years N only	Effect of PK residues (10B minus 10A)
Period			
1852–59	11·8	14·2	2·4
1860–67	12·4	14·1	1·7
1868–75	9·8	10·4	0·6
1876–83	8·5	9·4	0·9

The residues from 60 lb P and 240 lb K produced, when N was also given, a mean annual yield increase of 2·4 and 1·7 cwt grain in the first and second 8-year periods, but after that their effects diminished rapidly.

Barley. Beginning in 1941 the barley on the Exhaustion Land was manured annually with N. Yields were taken from 1949, and averages for the first 5 years with N at 56 lb N/acre are in Table 10. Even after 50 years the residues of the P and K applied between 1856 and 1901 gave, when N was given, an extra 9 cwt grain. That these residues had such a good effect after such a long time is, no doubt, because N was not given between 1901 and 1940 and the yields of the cereals grown, and the uptakes of P and K, were small. In this experiment, though the effect as measured was that of P plus K, Warren (1956) concluded from analyses of the crops that the increase in yield was mainly from the P residues.

TABLE 10

Effect of PK residues on barley when N was given on the Exhaustion Land, 1949–53

cwt/acre/year

	Treatment (other than N) 1856–1901		
	No P no K	P[1]	PK
Grain	10·8	18·4	19·7
Straw	12·7	19·1	20·6

[1] PK, 1856–75; P, 1876–1901.

Winter wheat and barley at Woburn. In 1959 and 1960 these two crops, given basal N, were grown on every plot of the Permanent Wheat and Barley Sites at Woburn, last manured with P and K in 1926. Table 11 shows yields, as averages of all plots with appropriate treatments.

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TABLE 11

Effect of residues of PK fertilisers and FYM on wheat and barley on the Woburn Permanent Wheat and Barley Sites, 1959–60

Grain, cwt/acre/year

	Treatments applied 1877–1926		
	No P no K	PK	FYM
Winter wheat			
Wheat Site	16·9	18·8	24·8
Barley Site	24·9	24·3	28·0
Barley			
Wheat Site	19·6	24·1	24·0
Barley Site	18·3	21·5	23·8

Wheat yielded better on the Barley Site than on the Wheat Site and barley better on the Wheat Site than on the Barley Site. To what extent this reflected differences in disease or fertility between the two sites is not known. In seven of the eight comparisons, yields were increased by residues of PK accumulated between 1877 and 1926 from fertiliser or FYM.

Beans and potatoes. These two crops, grown on Agdell in 1956 and 1957 respectively, valued the combined effect of the accumulated residues of PK fertiliser given once every 4 years during the four-course rotation experiment and last applied in 1948. Table 12 gives the yields of field beans, grown without added N, and of potatoes, given basal N.

TABLE 12

Effect of residues of PK fertilisers on beans and potatoes on Agdell 1956 and 1957

	Fertiliser treatment and rotation 1848–1951					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
1956 Beans						
Grain cwt/acre	8·5	5·2	26·2	20·0	18·2	19·2
1957 Potatoes						
Total tubers tons/acre	4·4	3·0	14·4	8·6	15·5	14·1

The yields of both beans and potatoes from PK residues were as good as from many well manured crops on Rothamsted Farm. The mean increases from the combined effects of P and K were 14 cwt/acre bean grain and 8·5 tons/acre of potatoes. In five of the six comparisons, yields were smaller on plots where clover was grown in the rotation while other plots were fallowed, because P and K were removed in the clover and less was left to accumulate in the soil.

Warren (1958) showed that the two crops differed little in the amount of P they took from the starved or from the enriched soil, but the potatoes took up more K than the beans from the starved soil and much more K from the enriched soil (Table 13).

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TABLE 13

Effect of PK residues on the amount of P and K removed in the beans and potatoes grown on Agdell, 1956 and 1957

	Fertiliser treatment and rotation, 1848–1951					
	Unmanured		PK		NPK	
	Fallow	Clover	Fallow	Clover	Fallow	Clover
	Uptake of P lb/acre					
Bean grain	4	2	14	10	11	11
Potato tubers	3	2	13	7	13	12
	Extra P from residues lb/acre					
Bean grain	—	—	10	8	7	9
Potato tubers	—	—	10	5	10	10
	Uptake of K lb/acre					
Bean grain	9	5	32	22	23	23
Potato tubers	24	18	110	54	119	96
	Extra K from residues lb/acre					
Bean grain	—	—	23	17	14	18
Potato tubers	—	—	86	36	95	78

The effect of residues of FYM

FYM was the standard source of plant nutrients when Lawes and Gilbert started their experiments on the effects of the 'new' inorganic fertilisers. Yields on unmanured soil were compared with those on soils dressed with fertilisers and FYM. The dressing of FYM was 14 tons/acre, and many analyses showed this amount contained, on average, 200 lb total N. The N supplied by this dressing of FYM, when given each year in the Classical Experiments has increased the total soil N much more than where N was given as fertilisers. Lawes and Gilbert (1895) concluded that N from FYM residues gave three-quarters of the extra yield of barley between 1872 and 1891 on plots given FYM between 1852 and 1871. The conclusion that N from FYM residues gives worthwhile increases in yield for some years is supported by the results of the next three experiments below. However, FYM also supplies P and K and the effects of residues of FYM may therefore reflect any combination of N, P and K as discussed later.

Grass cut for hay. The first experiment on the value of residues of FYM was made on Park Grass. The manure, applied annually at 14 tons/acre to this permanent pasture, did not readily decompose and Lawes and Gilbert (1880) noted that the sward deteriorated with this treatment. Annual dressings of FYM were stopped in 1863 after 8 years, but yields of hay (Table 14) continued to be taken.

During the 6 years 1864–69 the residues gave yields as large as fresh dressings did during the previous 8 years. Their effect diminished during the next period, but they continued to increase yields by a small but consistent amount even between 1920 and 1959.

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TABLE 14

The direct and residual effect of farmyard manure on yields of hay in the Park Grass Experiment, 1856–1959

cwt/acre/year of hay

	Plot and treatment		
Period	3 Unmanured	2 FYM	Effect of fresh dressing
1856–63	23·8	42·9	19·1
	Unmanured	Residues of 112 tons/acre FYM	Effect of residues
1864–69	24·1	43·3	19·2
1870–75	15·1	22·5	7·4
1920–59	8·2	9·4	1·2

Potatoes. At the start of the potato experiment (1876–1901) on the Exhaustion Land, plot 2 was dressed annually with FYM for the first 6 years (1876–81), after when it was unmanured. The FYM residues on this plot gave better yields than the unmanured plot until the end of the experiment (Table 15), and during the first 6 years gave half the yield increase that fresh dressings had given between 1876–81.

TABLE 15

The direct and residual effect of farmyard manure on yields of potatoes on the Exhaustion Land, 1876–1901

Tubers, tons/acre/year

	Plot and treatment		
Period	1 Unmanured	2 FYM each year	Effect of fresh dressing
1876–81	2·3	5·2	2·9
	Unmanured	Residues of 84 tons FYM	Effect of residues
1882–87	1·7	3·0	1·3
1888–1901	0·8	1·5	0·7

Barley. Effects of residues of FYM given to the potatoes on the Exhaustion Land were measured in the following cereal, and are compared in Table 16 with the effects of residues of PK fertilisers. The FYM residues increased yields greatly during the first 3 years but it is not possible to show when the effects declined because the fertiliser plots were used for an experiment on legumes between 1905 and 1911. However by 1917 the FYM plots were yielding no better than the PK plots. The yields, between 1902 and 1904, given by the NPK residues, discussed previously, and FYM residues are compared in Table 17.

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TABLE 16

Comparison of the effects of the residues of farmyard manure and PK fertilisers on yields of cereals on the Exhaustion Land, 1902–22

Grain, cwt/acre/year

Treatment 1856–1901	1902 Barley	1903 Barley	1904 Oats	1917 Barley	1918 Barley	1919 Barley	1921 Wheat	1922 Barley
PK	12·0	6·2	9·9	3·2	7·1	5·1	15·2	7·0
FYM[1]	34·2	22·6	26·8	3·5	7·9	5·4	14·1	9·6
FYM[2]	34·9	21·6	29·6	4·7	7·7	6·0	15·7	9·7

[1] FYM + P, 1876–82; FYM, 1883–1901.
[2] FYM + NP, 1876–81; FYM + P, 1882; FYM, 1883–1901.

TABLE 17

Comparison of the effects of the residues of farmyard manure and NPK fertilisers on the yields of cereals on the Exhaustion Land, 1902–04

Grain, cwt/acre/year

		Treatment 1856–1901			Effect of residues of	
		PK	NPK	FYM	NPK	FYM
1902	Barley	12·0	31·6	34·6	19·6	22·6
1903	Barley	6·2	13·2	22·1	7·0	15·9
1904	Oats	9·9	15·3	28·2	5·4	18·3

In 1902 the FYM residues only gave 3 cwt more grain than the NPK residues but in both 1903 and 1904 they gave much more because extra nitrogen from the FYM was mineralised.

The effect of P and K in FYM residues

Barley. In the three experiments described in the preceding section most of the effect of the FYM residues was from nitrogen. On the Exhaustion Land, barley yields with FYM residues were larger than with PK residues between 1902 and 1904 but not between 1917 and 1922. After 1940, nitrogen fertiliser was applied to all plots and yields between 1949 and 1953 with FYM residues were only very slightly larger than with the residues of PK fertilisers (Table 18).

TABLE 18

Comparison of the effects of old residues of farmyard manure and PK fertilisers on barley given nitrogen of the Exhaustion Land, 1949–53

cwt/acre/year
Treatment
56 lb N/acre 1949–53

	PK 1856–1901	FYM 1876–1901
Grain	19·7	20·5
Straw	20·6	22·4

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The P and K of the FYM residues must have been as 'available' as that of the fertiliser residues. Yields in Table 19 show that, as the experiment has continued, the FYM residues have given better yields than the PK residues.

TABLE 19

Comparison of the effects of old residues of farmyard manure and PK fertilisers on barley given nitrogen on the Exhaustion Land, 1949–68

Grain, cwt/acre/year

Period	N each year plus: no P no K	N each year plus: Residues of FYM given 1876–1901	N each year plus: Residues of P and K fertilisers 1856–1901	FYM minus PK residues
1949–53	10·8	20·5	19·7	0·8
1954–55	14·3	27·6	25·4	2·2
1961–62	15·4	24·6	21·4	3·2
1964–65	12·4	32·8	28·3	4·5
1966–68[1]	11·1	32·4	26·4	6·0

[1] Not 1967 when the site was fallowed.

The N and PK effects of FYM residues were also shown in the Hoosfield Continuous Barley Experiment. Plot 7 recieved the standard dressing of FYM (14 tons/acre) for the first 20 years of the experiment, then the plot was halved, and one-half (plot 7/1) remained unmanured from 1872 to 1967. Table 20 gives yields for each decade; between 1917 and 1966 mainly Plumage Archer was grown.

TABLE 20

Effect of residues of farmyard manure on barley on the Hoosfield Continuous Barley Experiment, 1872–1961

Grain, cwt/acre/year

Plot treatment	1872 –81	1882 –91	1892 –1901	1902 –11	1912 –21[1]	1922 –31	1932 –41[2]	1942 –51[3]	1952 –61[4]
1/0 unmanured	6·8	6·2	5·3	5·2	6·5	3·7	6·9	9·3	7·4
7/1 FYM residues	17·4	13·0	10·6	9·7	11·0	7·0	13·4	15·1	11·7
Increase due to FYM residues	10·6	6·8	5·3	4·5	4·5	3·3	6·5	5·8	4·3

[1] Omitting 1912. [2] Omitting 1933. [3] Omitting 1943. [4] Omitting 1953.

Warren (1956) showed that extra P and K was responsible for some of this extra yield with old FYM residues but that the limiting factor was the slow release of N from the organic matter. He calculated that between 1872 and 1956 the average amount of N that was mineralised produced an extra 3 cwt grain and 4 cwt straw each year containing about 6 lb N.

When Plumage Archer and Maris Badger were grown side by side on each plot between 1964 and 1966, yields of Maris Badger were not in-

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creased by the small amounts of extra N available on plot 7/1 (Warren & Johnston, 1967):

Barley, Hoosfield, 1964–66

Grain, cwt/acre/year

	Unmanured	FYM residues	Effect of residues
Plumage Archer	8·2	13·3	5·1
Maris Badger	8·3	8·6	0·3

This emphasises that the value of residues for new varieties of crop must be examined, for the larger yields these make possible are attained only with large amounts of nutrients.

In 1968 the Hoosfield experiment was modified and four amounts of N (0, 43, 86, 129 lb N/acre as 'Nitro-Chalk') were tested with Maris Badger. With the larger amounts of N yields on plot 7/1 were as good as those on the old plot 4/A, which received N as ammonium sulphate and PKNaMg annually since 1852, suggesting that Maris Badger's poor performance on residues alone in 1964–66 was solely because of the small supply of N:

Barley, Hoosfield, 1968

Grain, cwt/acre

		N lb/acre in 1968[1]			
Plot	Treatment	0	43	86	129
4/A	PK annually since 1852	16·1	31·3	37·3	34·2
7/1	Unmanured since 1872 (280 tons FYM 1852–71)	10·5	28·6	39·1	36·8

[1] Plot 7/1 got 57, 115 and 172 lb N instead of 43, 86 and 129 lb N.

Without fresh N in 1968, the yield on the PK plot exceeded that on the plot with very old FYM residues, probably because of the extra N mineralised from the larger root and stubble residues ploughed in on this plot. Now that N is being given, it will be interesting to see how long the P and K residues from the FYM applied 100 years ago continue to give good yields.

The effect of residues of rape cake

Lawes and Gilbert used rape cake to supply both organic matter and nutrients, mainly N, and compared its effects with those of FYM and inorganic fertilisers. It was applied at 2000 lb/acre to winter wheat and root crops and 1000 lb/acre to barley; the larger amount on average supplied 100 lb N, 20 lb P and 20 lb K. The unmanured barley taken on Barnfield in 1853–55 measured the effect of the residues of rape cake applied from 1845 to 1852 (Table 21). The rape cake residues increased yield more than did the residues of inorganic NPK fertilisers (Table 3).

During the war of 1914–18 rape cake was unobtainable and after the existing stocks were exhausted in 1916 none was applied again until 1921. Table 22 shows the yields, for three 4-year periods, with fresh dressings and residues, on Broadbalk, Hoosfield and Barnfield.

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TABLE 21

Effect of residues of rape cake on barley on Barnfield, 1853–55

Grain, cwt/acre/year

	Treatment to turnips 1845–52		
	Unmanured	PK + rape cake total N 568 lb	NPK + rape cake total N 831 lb
1853	10·2	14·7	14·9
1854	9·0	12·4	11·9
1855	9·1	11·6	11·4

TABLE 22

The direct and residual effects of rape cake on cereals and roots at Rothamsted, 1913–24

	1913–16			1917–20			1921–24		
	None	With fresh dressing of rape cake	Effect of fresh dressing	None	With residues of rape cake	Effect of residues	None	With fresh dressing of rape cake	Effect of fresh dressing
Hoosfield barley Grain, cwt/acre	7·7	20·2	12·5	4·4	6·0	1·6	3·8	11·8	8·0
Broadbalk wheat Grain, cwt/acre	5·8	10·5	4·7	5·1	7·2	2·1	3·2	6·4	3·2
Barnfield mangolds Roots, tons/acre	2·2	6·4	4·4	2·8	7·5	4·7	2·8	6·0	3·2
Tops, tons/acre	0·9	2·8	1·9	0·7	1·9	1·2	1·2	2·4	1·2

The yield of barley was much increased by fresh dressings of rape cake but the residues gave little increase in grain yield. For winter wheat, the residues gave about half the increase given by the fresh dressings and, for mangolds, both tops and roots, the residues gave yields equal to those given by fresh dressings. These results emphasise that the residues of any particular fertiliser may have a quite different effect on different crops, probably depending on the rate and time N is released, and possibly on the root system of the crop. Barley, with a short growing season, was probably unable to use N mineralised after early summer but, provided this later-mineralised N was not leached from the soil, winter wheat could use it. The long growing season of the mangolds helped them to use all the N mineralised during the growing season.

Summary

These experiments showed that soils containing residues of previous manures gave better yields than soils without such residues. The size of the effect differed with different nutrients and different crops, and even with different varieties of one crop.

A single dressing of 86 lb N/acre applied to winter wheat grown annually has no residual effect. However, large dressings of ammonium salts can leave enough residue in the soil, especially after a very dry year, to benefit a succeeding crop, when this is autumn-sown. There is an important

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indirect effect of fertiliser N when used for many years with other nutrients, the larger crops it produces means more stubble and roots are left in the soil, the extra N mineralised from these residues increases yields of future crops. This effect, though small compared with that of fresh N, usually lasted for up to three years with cereals.

The N from residues of recently applied FYM often increased yields for several years; also residues of old FYM release enough N to give small but consistent increases in yield.

Because the N effect of old residues of FYM are always much smaller than the effects of new fertiliser N dressings, the experiments made between 1957 and 1962 tested only the P and K residues from FYM.

None of the experiments made before 1957 showed the effects of P residues only. On the Rothamsted soil the effects of K residues were sometimes large, giving yields for several years as large as those given by fresh dressings. The results of these experiments do not show whether the same yield can be obtained by applying fresh dressings of P and K to starved and to enriched soils.

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The Value of Residues from Long-period Manuring at Rothamsted and Woburn
III. The Experiments Made from 1957 to 1962, the Soils and Histories of the Sites on which they were Made

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The aim of the new experiments

The value of residues can be measured in two ways:

1. By comparing yields from soil enriched with residues with those from starved soil.
2. By comparing the responses to a series of new fertiliser dressings on plots of both starved and enriched soil.

Only the first of these ways was used to demonstrate the combined effect of the PK residues on the Exhaustion Land after basal N was given in 1941, and then only for barley (Warren, 1956). We wished to extend these results by obtaining information on:

1. Other crops.
2. The separate effects of the P and K residues.
3. The value of the residues in terms of new fertiliser dressings.

Therefore experiments were made with more than one crop grown each year, and with basal N and K where P was tested and basal N and P where K was tested. Each experiment tested a series of increasing amounts of new P and K. The valuation of residues in terms of newly applied fertiliser depends on how this fresh fertiliser is applied and on the growing conditions in the year of the experiment, so we decided: (1) to do each experiment for two years and average the results from the two seasons; (2) to apply all new fertiliser to the seedbed, except for potatoes (for details see later). This is acceptable current farming practice, though, from the results of many experiments, Cooke (1956, 1957) showed that placing fertiliser near the seed was a more efficient way of using new fertiliser, which could be particularly true on impoverished soils. In the later years, tests were made of methods of applying fertilisers.

The work was done on three sites, two at Rothamsted (a part of the Exhaustion Land experiment site in 1957–58, and on the Agdell Rotation experiment site in 1959–62), and one at Woburn (part of the Permanent Wheat and Barley Sites) in 1960–62.

History of the experimental sites

The preceding cropping and the amounts of fertiliser applied to the sites of the experiments are known. All the crops were not analysed, so the amounts of each nutrient removed, and the amounts that should have remained as a

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residue, are unknown. However, a subsequent section gives the amounts of readily soluble P and K in the soils of each plot.

The Exhaustion Land Experiment. This site, as the name implies, has been used for much work on NPK residues in soil. Its history was described by Warren & Johnston (1960). Lawes and Gilbert started the first experiment in 1852 to test effects of cultivation treatments on winter wheat; it ended in 1855. From 1856 to 1874 there was a manurial experiment with winter wheat testing 4 treatments on 4 plots: unmanured; N only (as ammonium salts); PKNaMg only (P as superphosphate, K, Na, Mg each as the sulphate); and NPKNaMg. The last wheat crop was taken in 1874, the site was fallowed in 1875, and in 1876 a manurial experiment started in which potatoes were grown each year. The plots for potatoes were superimposed on those of the wheat experiment; the PKNaMg treatments were continued, and a new treatment with FYM and a comparison of sodium nitrate and ammonium salts were introduced. Hall stopped the potato experiment in 1901. From 1902 to 1940 the site was cropped mainly with cereals, usually barley, without manures and usually without recording yields. Beginning in 1941 each cereal crop received a uniform dressing of 56 lb N/acre and from 1949 onwards yields on each plot were taken to measure the combined effects of the PK residues in the presence of new N each year for one crop, barley.

Between 1856 and 1901, annual fertiliser dressings (amounts per acre) when applied were:

N	1856–1901	86 lb N as ammonium salts or sodium nitrate	
P	1856–1901	30 lb P as superphosphate, except 1897–1901 when basic slag was used	
K	1856–58	120 lb K	as potassium sulphate
	1859–74	80 lb K	
	1876–1901	120 lb K	
Na	1856–58	28 lb Na	as sodium sulphate
	1859–1901	14 lb Na	
Mg	1856–1901	10 lb Mg as magnesium sulphate	
FYM	1876–1901	14 tons	

Table 1 shows the total P and K applied during this period, yields are discussed in Paper II.

TABLE 1

Total amounts of P and K applied on the Exhaustion Land, 1856–1901

lb element/acre

	Plot									
	1	2	3	4	5	6	7	8	9	10
P as superphosphate	0	0	210	210	0	0	1260	1260	1260	1260
P in FYM	0	210	910	910	0	0	0	0	0	0
K as potassium sulphate	0	0	0	0	0	0	4520	4520	1400	4520
K in FYM	0	800	3500	3500	0	0	0	0	0	0

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The Agdell Rotation Experiment. Warren (1958) described this experiment, started by Lawes and Gilbert in 1848, which compared two 4-course cropping systems: (1) Roots, barley, undersown with clover (replaced by spring beans when the clover failed), and winter wheat; (2) Roots, barley, fallow and winter wheat. Only one, but the same, phase of each rotation was present each year. The manurial treatments were: unmanured; P (changed to PKNaMg in 1884), and NPKNaMg (N as mixture of ammonium salts and rape cake, the rape cake also provided some P and K). The manures were applied only once every four years to the swedes or turnips. In addition to the manurial treatments tested on the two rotations, Lawes and Gilbert included a test of management when roots were grown. On half plots the roots were either all carted off or were fed on by sheep; when the weather was unsuitable for feeding, the roots and tops were sliced and spread over the land and ploughed in. This treatment, which returned the nutrients taken up by the root crop on one half of each plot, was stopped in 1900, after when all produce was removed from the whole plot. The experiment continued for 26 courses until 1951, when soil acidity on the NPK plots was harming the crops, especially the swedes, which were first ruined by clubroot on these plots but soon also on the others. The acid areas were heavily chalked in spring 1954 and given a light dressing in 1959. From 1952 to 1957 the site was uniformly cropped as follows: 1952, bare fallow; 1953 barley without N; 1954 barley with N; 1955 spring wheat with N; 1956 beans; 1957 potatoes with N. Thus the crops from 1954 to 1957 measured the combined effects of the residues of P and K. Cereal yields were small but potatoes and beans yielded well. Yields are given in Paper II (page 14).

Between 1848 and 1951 fertiliser dressings were at the following rates/acre in the year in which they were applied:

N	1848–1951	43 lb N as ammonium salts plus 100 lb total N in rape cake	
P	1848–51	15 lb P	as superphosphate
	1852–55	21 lb P	as superphosphate
	1856–95	30 lb P	as superphosphate
	1896–1903	47 lb P as basic slag	
	1904–51	38 lb P as superphosphate	
K	1848–51	45 lb K as pearl ash	
	1852–95	120 lb K	as potassium sulphate
	1896–1951	200 lb K	as potassium sulphate
Na	1852–55	14 lb Na	as sodium sulphate
	1856–95	28 lb Na	as sodium sulphate
	1896–1951	14 lb Na	as sodium sulphate
Mg	1852–95	10 lb Mg	as magnesium sulphate
	1896–1951	20 lb Mg	as magnesium sulphate

Table 2 shows the total P and K applied between 1848 and 1951.

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TABLE 2

Total amounts of P and K applied on Agdell Field, 1848–1951

lb element/acre

	P			K		
Plots	Super-phosphate	Rape cake	Total	Potassium sulphate	Rape cake	Total
1 and 2	890	490	1380	4160	490	4650
3 and 4	890	0	890	3280	0	3280
5 and 6	0	0	0	0	0	0

Woburn Permanent Wheat and Barley Experiments. The Classical Experiments at Woburn on the continuous growing of cereals started with sowing winter wheat in autumn 1876 and barley in spring 1877. The plots were laid out as at Rothamsted for the barley experiment on Hoosfield, strip treatments with and without PKNaMg, crossed at right angles by strips with and without N. Separate plots also tested FYM. Initially the amounts of nutrients tested each year were the same as those used on cereals at Rothamsted, 43 and 86 lb N as ammonium salts or sodium nitrate, 30 lb P as superphosphate and 80 lb K, 14 lb Na, 10 lb Mg, all three as sulphates. FYM was tested at two amounts which varied between 4 to 6 and 8 to 12 tons/acre. Plots receiving the larger amount of N were fertilised only in alternate years from 1883, to measure the effects of N residues. Major manurial changes were made for crops harvested in 1907, both amounts of N were halved, superphosphate was given at 3 cwt/acre (25 lb P), potassium at only 0·5 cwt potassium sulphate/acre (22 lb K), sodium and magnesium were omitted and the larger amount of FYM was tested on one half plot. The remaining FYM plots tested NP, NK and rape cake. At the start of the experiment the soil was slightly acid and the ammonium sulphate increased the acidity considerably, so some tests of liming were made. Because of decreasing yields and increasing weediness of the plots, the experiment was stopped in 1926 and no more FYM and P and K were applied, except as described below. From 1927 to 1940 the plots continued to grow winter wheat or spring barley, testing, in 2 cycles each of 7 years, the effect of two years fallow on the succeeding 5 unmanured cereal crops. In 1931–32 some plots on the Barley Site were manured, plots 8 and 9 received a total of 82 lb N, 50 lb P, 132 lb K; 10a received 61 lb N, 50 lb P; 11a received 61 lb N, 132 lb K. From 1941 to 1957 three amounts of N fertilisers were tested but the plots had to be fallowed in 5 of these years. Between 1955 and 1957 individual plots received various amounts of ground chalk to bring the soils on all plots to pH 6. Having brought the surface soils to somewhere near their original soil reaction, an experiment began in 1959, with winter wheat and spring barley grown side by side on every plot, to compare the yields of each crop when grown on the Wheat and the Barley Sites. The experiment continued in 1960 and in 1961 spring wheat was grown. N was given to both wheat and barley so the value of the PK residues could be measured, the yields are discussed in Paper II (page 13).

Table 3 shows the total P and K applied between 1876 and 1959 on the plots used for the microplot experiment.

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TABLE 3

Total amounts of P and K applied on the Woburn Permanent Wheat and Barley Experiments, 1876–1959

lb element/acre

	Plots				
	7	8	9	11a	11b
Wheat Site					
P as superphosphate	0	1400	1400	0	0
P in FYM	0	0	0	750	1090
K as potassium sulphate	0	2840	2840	880	0
K in FYM	0	0	0	3000	4400
Barley Site					
P as superphosphate	0	1450	1450	0	0
P in FYM	0	0	0	750	1090
K as potassium sulphate	0	2970	2970	1010	0
K in FYM	0	0	0	3000	4400

The soils

The soils at Rothamsted are mainly derived from 'Clay-with-flints', which overlies chalk at various depths, and they have been classified by the Soil Survey of England and Wales. The Exhaustion Land site on Hoosfield is on the Batcombe series (undifferentiated), on a level plateau where the 'Clay-with-flints' is thick and the soil has a flinty loam or silt loam surface. Agdell field is on the shallow or eroded phase of the Batcombe series and has a shallow flinty clay loam surface. It is one of the most difficult fields to work on Rothamsted Farm. As the other old arable fields including Hoosfield, it was given large, but unevenly distributed dressings of chalk in the early part of the last century when the practice was to dig out the underlying chalk and spread it on the arable land (Young, 1813; Russell, 1916). Part of the east side of Agdell runs into one of the resulting dell holes.

The soil in Stackyard Field at Woburn is a sandy loam of the Cottenham series developed in drift over Lower Greensand. It was slightly acid and never received the heavy dressings of chalk that were a feature of earlier treatment of Rothamsted arable fields.

H. von Liebig, the son of Baron Liebig with whom Lawes and Gilbert argued so bitterly about the source of N for plants, was the first person to analyse Rothamsted soil for P and K. He extracted P soluble in dilute nitric acid, and K soluble in dilute acetic acid, from the soil from five plots on Broadbalk, and found that, after twenty-five years, there was more soluble P and K in the manured than in the unmanured soil (von Liebig, 1872). Dyer examined the soils from the Hoosfield Continuous Barley experiment (Dyer, 1894) and those from Broadbalk (Dyer, 1901, 1902). Using 1% citric acid and constant boiling HCl, he confirmed that manured soils had more soluble P and K than the unmanured soils. Subsequently many attempts made to estimate 'available' P and K in agricultural soils used soils from the Classical Experiments for reference. Because manuring of these Rothamsted soils has continued for so long, there are large differences in soluble P and K between those with and without residues and almost any

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method of analysis will distinguish between them. The usefulness and limitations of some of the methods for P when used for Rothamsted and Woburn soils were discussed by Warren and Johnston (1965). The methods

TABLE 4

Analyses of soil from plots used for microplot experiments at Rothamsted and Woburn, 1957–62

Site and plot	Total P %	Total K %	P soluble in 0·5 *M*-$NaHCO_3$ ppm	P soluble in 0·01 *M*-$CaCl_2$ g mol/l $\times 10^{-6}$	K soluble in 1 *N*-ammonium acetate ppm
Rothamsted					
Exhaustion Land					
1	0·044	1·31	3	0·30	83
3	0·064	1·40	15	1·24	112
5	0·046	1·39	4	0·24	76
7	0·064	1·41	12	0·66	111
9	0·065	1·37	14	0·98	83
Agdell					
1	0·074	1·21	15	0·24	160
2	0·075	1·16	12	0·17	180
3	0·071	1·15	16	0·37	184
4	0·065	1·14	8	0·25	141
5	0·054	1·04	4	0·09	104
6	0·053	1·04	4	0·11	102
Woburn					
7 Wheat Site	0·079	0·69	22	0·65	57
7 Barley Site	0·058	0·82	14	0·32	65
8 Wheat Site	0·096	0·68	56	2·34	67
8 Barley Site	0·080	0·80	37	1·51	93
9 Wheat Site	0·086	0·70	42	2·07	83
9 Barley Site	0·079	0·85	36	1·67	93
11a Wheat Site	0·070	0·73	19	0·74	77
11a Barley Site	0·068	0·81	28	0·89	102
11b Wheat Site	0·075	0·70	25	0·74	96
11b Barley Site	0·076	0·83	22	0·89	101

All total P and K analyses were done on 0–6 in. samples: readily soluble P and K analyses on the Exhaustion Land Soils were on 0–6 in. samples: for Agdell and Woburn soils the samples were 0–9 in. depth. Total P by perchloric acid digestion; total K by hydrofluoric acid digestion.

at present considered most suitable for soluble P and K were used to characterise the soils where these experiments were made, and Table 4 shows the results, together with those for total P and K for samples taken between 1950 and 1955.

The form of the experiments

Design. The design of the experiments, plot sizes and numbers had to be varied to fit the existing plot layout, allowing suitable headlands between the various crops for the necessary cultivations. This imposed considerable restrictions and all the experiments were made using microplots, which

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meant that after the initial seedbed preparation many operations, including harvesting of all crops, were done by hand. From year to year and site to site, some changes were made but all plots of each crop received basal N at optimum rate for the crop, all plots testing P received basal K, and all plots testing K received basal P. These basal dressings were at least the largest amount tested for each crop in any year. P was tested at a unit amount of 12·5 lb P/acre, i.e. P1, P2, P4 were 12·5, 25, 50 lb P/acre. K was tested at a unit amount of 14 lb K/acre, i.e. K2, K4, K8 were 28, 56, 112 lb K/acre.

The Exhaustion Land 1957–58. Plan 1 (p. 32) shows the Exhaustion Land site and the plots (1, 3, 5, 7 and 9) used for the microplot experiment. The east half of the site was divided into 12 blocks each extending across the five plots. Only alternate blocks were cropped in 1957, those that were fallowed were cropped in 1958, so there was no cumulative effect in 1958 of fertiliser applied in 1957. Each year the six cropped blocks carried one of the six crops, barley, spring wheat, potatoes, swedes, kale or sugar beet. The old plots were paired so that No. 1 (unmanured), and No. 7 (NPK), tested new K with and without K residues, and No. 5 (N), and No. 9 (P), tested new P with and without P residues. Each block contained 20 microplots (each 0·0032 acre), four per plot to test four amounts of P or K applied as new fertiliser. In 1957 each microplot was made almost square because each group of four was arranged so that two were on the north and two on the south side of each large plot. The new treatments were assigned at random. There was a constant difference in yield between pairs of plots on the north and south sides of each old plot, probably related to a soil difference. In 1958 the four microplots of each group were arranged so that each one spanned the full width of the old plot, which had the added advantage that all microplots had the same number and positions of tractor wheelings. Individual tests with each crop were not replicated in either year. Table 5 shows the basal and test fertilisers, and diagram 1 (p. 33) the arrangement of the microplots in 1957 and 1958 on the eastern 6 cropping blocks.

TABLE 5

Basal and test fertilisers, Exhaustion Land, 1957–58

lb element/acre

Crop	N basal	P test			K test		
Barley	56	12·5	25	50	14	28	56
Spring wheat	67	12·5	25	50	14	28	56
Swedes (1957)	67	12·5	25	50	14	28	56
(1958)	45						
Potatoes	112	12·5	25	50	28	56	112
Kale	201[1]	12·5	25	50	28	56	112
Sugar beet	112	12·5	25	50	28	56	112

For all crops basal P for K test was 50 lb P.
For barley, spring wheat, swedes, basal K for P test was 56 lb K.
For potatoes, kale, sugar beet, basal K for P test was 112 lb K.
N as ammonium sulphate;[1] P as powdered superphosphate; K as potassium sulphate.
[1] Applied as 67 lb N to seedbed and then 2 top dressings each of 67 lb N as 'Nitro-Chalk'.

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For all crops except potatoes, the fertilisers were broadcast by hand and harrowed in just before drilling the seed. The potato land was set up in ridges 27 in. apart and the fertilisers applied along the bottoms of the furrows and half way up the sides of the ridges, before the potatoes were hand-planted 15 in. apart and the ridges split back to cover the sets. Varieties used were: barley, Plumage Archer; spring wheat, Koga II; swedes, Wilhelmsburger; potato, Majestic; kale, Thousand Headed; sugar beet, Klein E.

Agdell 1959–62. Plan 2 (p. 34) shows the Agdell site and the division, made in 1958, of the six plots in the rotation experiment into grass and arable halves. The grass was sown in 1958, and the arable was fallowed before the microplot experiment was made during 1959–62. Because of the size of the site and to allow some replication, we decided to test only the value of the P residues for three crops on Agdell. In each year the amounts of new P were the same for all three test crops, barley, potatoes, sugar beet. Because the experiment was to be continued for several years and all crops were to be grown each year, the microplots had to be used more than once. Plan 2 also shows how each arable half plot was divided into three blocks, one for each crop, giving 18 blocks on the site. The blocks were separated by paths to prevent lateral movement of soil during ploughing and cultivating. The sequence of crops was barley, potatoes, sugar beet. In 1959, each block was divided into four sub-blocks each of three microplots, so that there were 4 replicates of each of the three treatments P0, P1, P4. Each microplot was 0·0034 acre. The response curves derived from the 1959 yields suggested that maximum yield had not been reached and 75 lb P/acre (P6) was tested in 1960. This was done by halving each microplot, that with treatment P0 in 1959 tested P0 and P1 in 1960, P1 in 1959 tested P4 and P6 (the residual effect of P1 was assumed to be very small), and P4 in 1959 tested the residues of this dressing, P4r, and the residue plus the largest amount of new P, P4r + P6. An unexpected feature of the 1960 results was how well the P4r treatment yielded. This treatment had P4 broadcast on the seedbed in spring 1959, it was ploughed-in in autumn 1959 and cropped without new P in 1960. This suggested that ploughing new fertiliser into this difficult soil could be more efficient than broadcasting it on the seedbed. We decided to test methods of incorporating new fertiliser in 1961–62, but the experiment had to be made on the blocks used in 1959–60. Those blocks on the old rotation plots 1, 3, 5 were used in 1961 and those on the old plots 2, 4, 6, were used in 1962 after being fallowed in 1961. Each block was divided lengthways and the new microplots were made this width; the length was that of the sub-block used in 1959–60, so that there were now eight microplots (each 0·0050 acre) per block each with the same amount of residues from the 1959–60 test treatments. On these eight microplots tests were made of: (a) no new P (in duplicate), (b) 37·5 and 75 lb P ploughed in, (c) 37·5 and 75 lb P to the seedbed and (d) 75 and 150 lb P half of each dressing being ploughed in and the other half broadcast on the seedbed. Diagram 2 (p. 35) shows the sequential arrangement of the microplots on one block.

The 1959–60 results showed that, on this impoverished soil, the amounts

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of the basal fertiliser dressings, which were considered optimum in general practice, may be too little because the soil is so poor and the fertiliser could not be incorporated throughout the ploughed layer. Basal K dressings were therefore increased during the course of the experiment and we tried to incorporate them thoroughly into the soil by dividing the dressings, ploughing some in, applying some over the rough ploughed land and some to the seedbed. Table 6 shows the basal and test fertilisers.

TABLE 6

Basal and test fertilisers, Agdell, 1959–62

lb element/acre

Crop		N basal	K basal	P test		
Barley	1959	56	56	12·5	50	—
	1960	67	56	12·5	50	75
	1961–62	67	84	37·5	75	150
Potatoes	1959	112	112	12·5	50	—
	1960	134	112	12·5	50	75
	1961–62	134	224	37·5	75	150
Sugar beet	1959	112	112	12·5	50	—
	1960	134	112	12·5	50	75
	1961–62	112	279	37·5	75	150

N, 1959 ammonium sulphate; 1960–62 as compound 16-0-16 (16% N 16% K_2O).
P, 1959–60 powdered superphosphate; 1961–62 granular superphosphate.
K, 1959 potassium sulphate; 1960–62 as compound 16-0-16, to seedbed, 1961–62 autumn and spring extra basal K as potassium sulphate.
Ploughed in test and basal fertilisers were applied for 1961 on 5 December 1960 and for 1962 on 12 October 1961.

In 1959 and 1960 all the fertilisers for barley and sugar beet were applied by hand and harrowed in just before drilling the seed. For potatoes the land was set up in ridges and the fertilisers applied along the bottoms of the furrows and half way up the sides of the ridges. After the potatoes were hand-planted 15 in. apart in the rows, the ridges were split back to cover the sets. In 1961 and 1962 when ploughing in P was tested and some basal K was ploughed in the fertilisers to be ploughed in were applied the previous autumn. For each crop the seedbed dressings were given in the spring as in 1959–60 except that the N and K for barley were given as a compound containing 16% N and 16% K_2O and this was broadcast from the combine seed drill as the seed was drilled (for experimental details see Widdowson *et al.* (1964)). Varieties used were barley, Proctor; potato, Majestic (chitted seed); sugar beet, Klein E.

Woburn Permanent Wheat and Barley Sites 1960–62. The microplot experiment was made on plots 7, 8, 9, 11a, 11b, on both sites. Plan 3 (p. 36) shows the positions of the plots in the field; for the microplot experiment all the plots 11a and 11b were considered as one 'plot' making seven plots in all.

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The seven plots were divided into 4 blocks and cropped as follows from 1960 to 1962:

Block	Year	Wheat Site (Plot 7, 8, 9)	Barley Site (Plot 11, 9, 8, 7)
I	1960	winter wheat without P or K	winter wheat without P or K
	1961	winter wheat without P or K	winter wheat without P or K
	1962	oats without P or K	oats without P or K
II	1960	winter wheat without P or K	winter wheat without P or K
	1961	fallow	sugar beet microplots
	1962	sugar beet microplots	fallow
III	1960	barley microplots	barley microplots
	1961	fallow	potato microplots
	1962	potato microplots	fallow
IV	1960	potato microplots	potato microplots
	1961	fallow	barley microplots
	1962	barley microplots	fallow

Thus block I continued the cropping as on the remainder of the Classical Sites and blocks II, III and IV were used for the microplot experiments. Each block has 112 microplots (each 0·00257 acre except those on plot 11 which were larger), sixteen per plot, of which eight tested P and eight K, so that both P and K were tested on each old plot. In 1960 of the eight microplots in each testing unit, four received no new test fertiliser so that fresh dressings could be tested in subsequent years, two tested the smaller and two the larger amount of new P or K.

The 1960 results, together with the experience gained on Agdell, suggested the need to compare ploughed-in fertiliser with seedbed dressings, and this comparison was made in 1961–62. For the barley and potato tests, the eight microplots on each testing unit were used as follows: of the four that were unmanured in 1960, two were not given new fertiliser, the other two tested the lesser amount of P or K either ploughed in or broadcast on the seedbed. The two microplots, which tested the lesser amount of P or K in 1960, in 1961–62 tested the largest amount, either ploughed in or to the seedbed, and the two microplots with the largest amount in 1960 were unmanured in 1961–62 to test the residual effects of the dressing. For barley, potatoes and sugar beet, new P was tested at 12·5 and 50 lb P/acre (P1 and P4). New K was tested at 14 and 54 lb K/acre for barley in all three years. For potatoes the amounts were 28 and 112 lb K/acre in 1960 and these were increased to 42 and 168 lb K/acre in 1961–62. Because sugar beet in both 1961 and 1962 were grown on new ground, three amounts of new K, 84, 168 and 336 lb K/acre could be tested. Table 7 (p. 38) shows the basal and test fertilisers, and diagram 3 (p. 37) the arrangement of the microplots on one crop block on part of the Barley Site in 1960 and the subsequent use of the microplots in 1961.

continued on page 38

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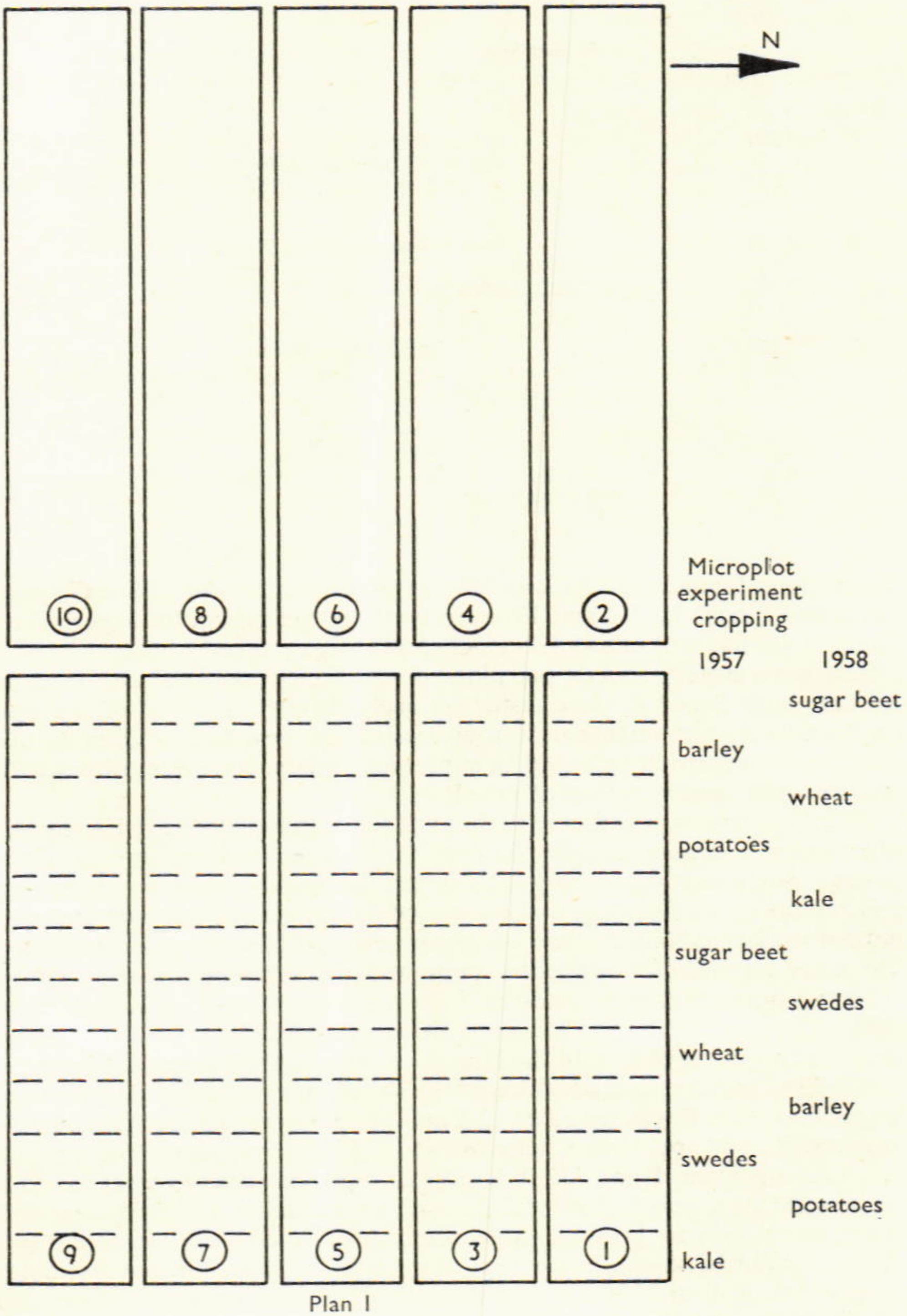

PLAN 1. The Exhaustion Land showing the twelve blocks on plots 1, 3, 5, 7 and 9 during 1957–58 and the crops grown on each block each year.

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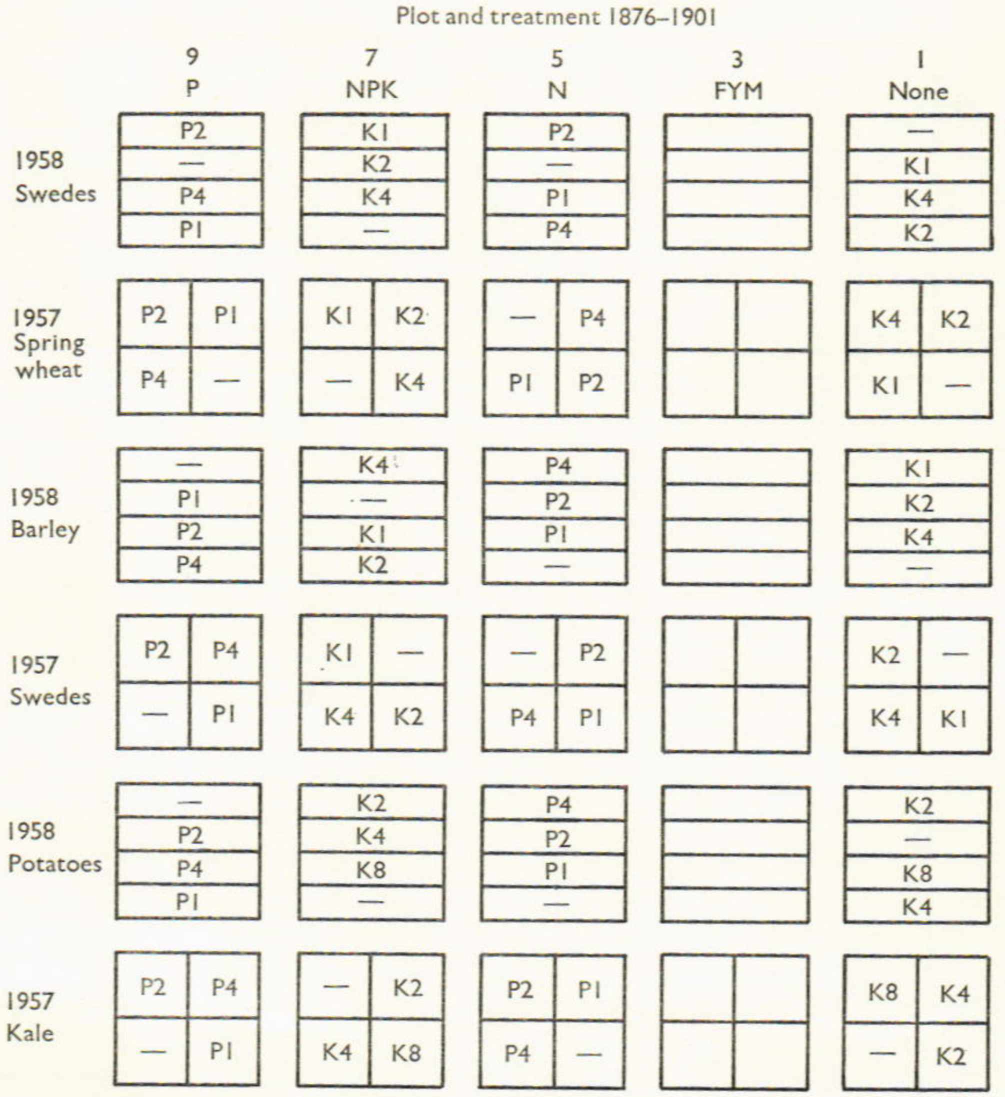

Diagram 1.

DIAGRAM 1. The Exhaustion Land, 1957–58, showing the cropping and the arrangement of the microplots and P and K treatments on six of the twelve blocks.
(P1, P2, P4: 12·5, 25, 50 lb fresh P/acre; K1, K2, K4, K8: 14, 28, 56, 112 lb fresh K/acre.)

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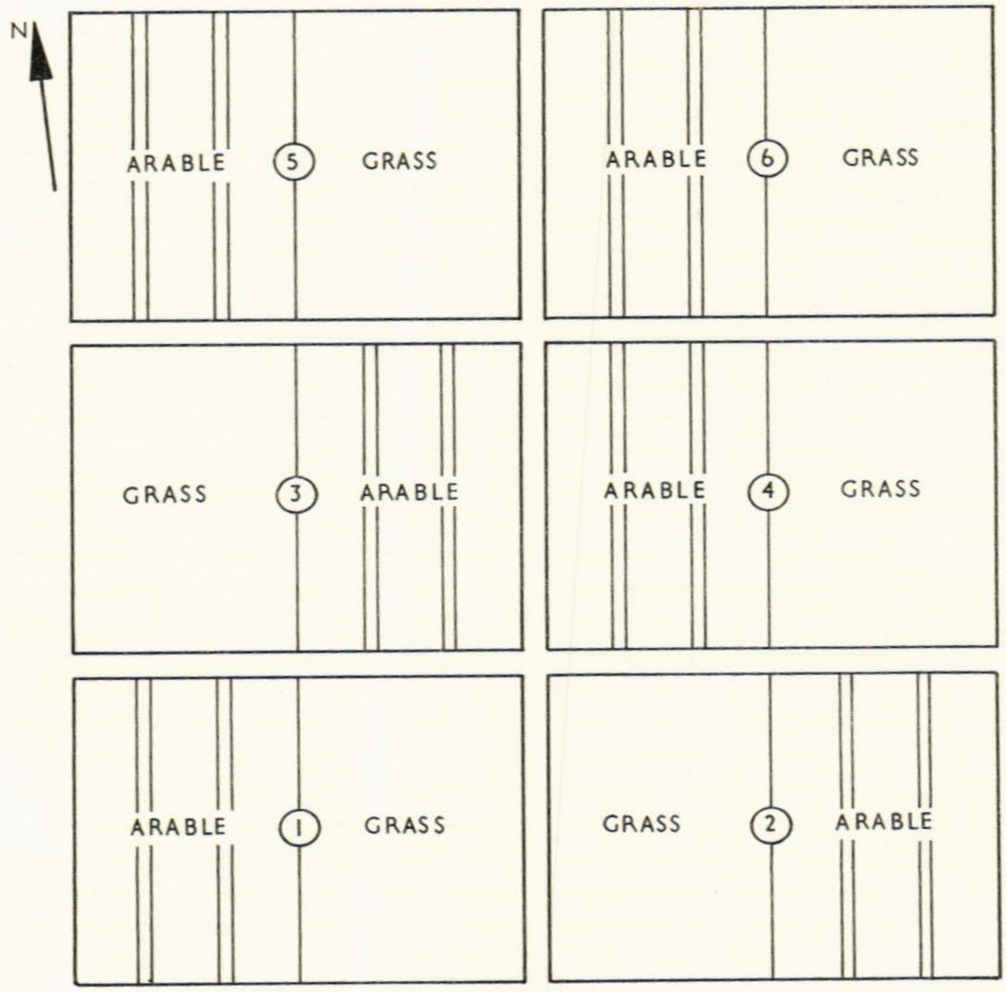

Plan 2

PLAN 2. Agdell showing the halving of the six rotation plots into grass and arable made in 1958, and the division of each arable half into three blocks for the microplot experiment from 1959 to 1962.

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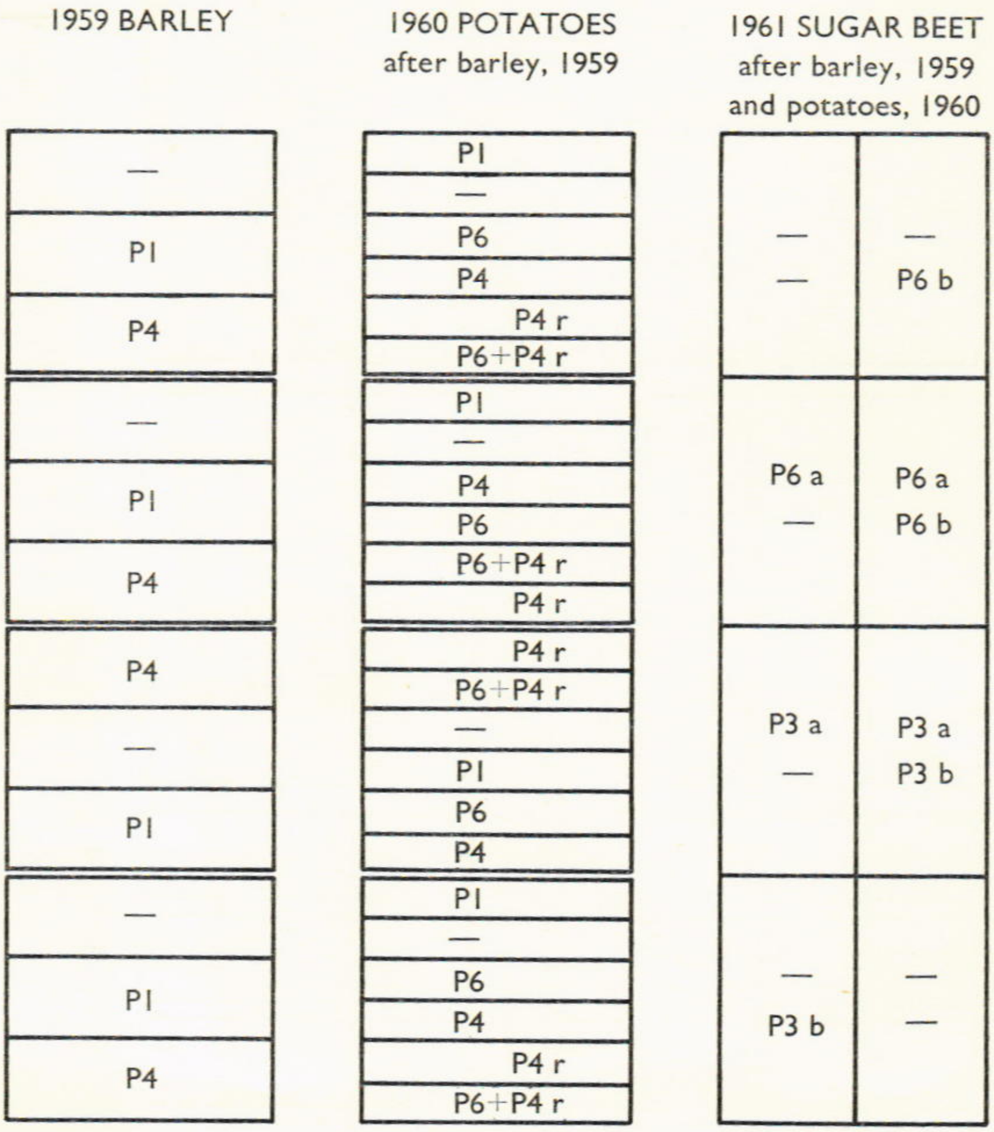

Diagram 2.

DIAGRAM 2. Agdell, 1959–61, showing the cropping and the arrangement of the P treatments on one crop strip in three successive years.
(P1, P3, P4, P6: 12·5, 37·5, 50, 75 lb fresh P/acre. 1960, P4r, residue of 50 lb P/acre applied in 1959. 1961, a, P dressing ploughed in; b, P dressing broadcast on the seedbed.)

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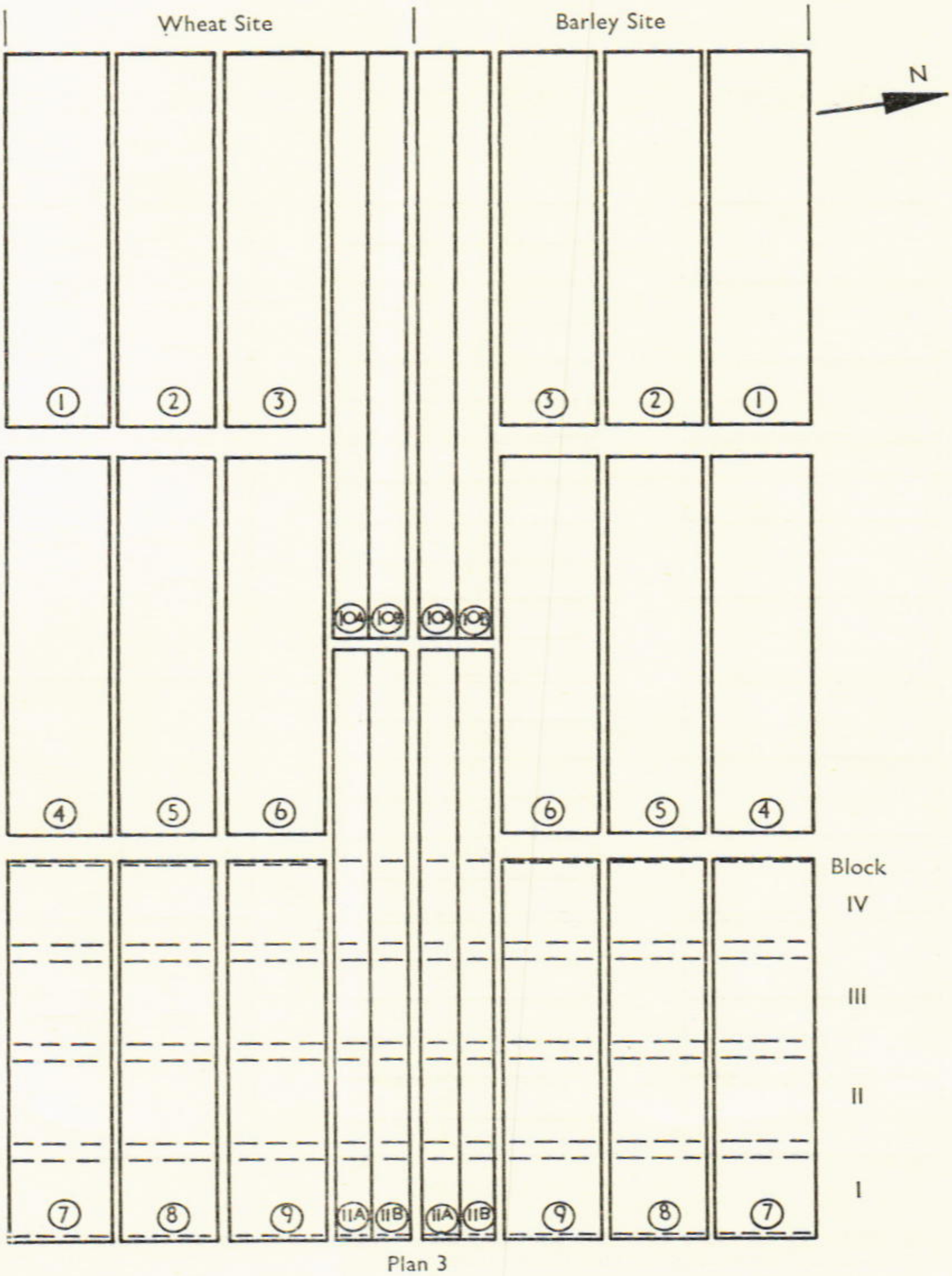

PLAN 3. Woburn Permanent Wheat and Barley Sites showing the four blocks on plots 7, 8, 9 and 11 during 1960–62.

DIAGRAM 3 (opposite). Woburn, 1960–61, showing the cropping, the P and K treatments and the arrangement of the microplots on each plot, on a part of one block, in two successive years.
(P1, P4: 12·5, 50 lb fresh P/acre; K1, K2, K4, K8: 14, 28, 56, 112 lb fresh K/acre; 1961, r, residue of the dressing applied in 1960; a, new dressing ploughed in; b, new dressing broadcast on the seedbed.)

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Plot and treatment 1877–1926	1960 Potatoes				1961 Barley after potatoes 1960			
	—	P4	—	P1	P1 b	P4 r	—	P4 b
7 None	P1	—	P4	—	P4 a	—	P4 r	P1 a
	—	K8	K2	—	K1 b	K8 r	K4 b	—
	K2	—	—	K8	K4 a	—	K1 a	K8 r
	P1	—	P4	—	P4 a	P1 a	P4 r	—
8 NPK	P4	—	P1	—	P4 r	—	P4 b	P1 b
	K8	—	K2	—	K8 r	—	K4 b	K1 b
	K2	—	—	K8	K4 a	—	K1 a	K8 r
	—	K2	—	K8	K1 b	K4 b	—	K8 r
9 NPK	—	K8	K2	—	—	K8 r	K4 a	K1 a
	P1	—	P4	—	P4 a	P1 a	P4 r	—
	P4	—	P1	—	P4 r	P1 b	P4 b	—
11B FYM	—	P4	P1	—	P1 b	P4 r	P4 b	—
11A NK	P1	—	—	P4	P4 a	—	P1 a	P4 r
11B FYM	—	K2	—	K8	K1 a	K4 a	—	K8 r
11A NK	K8	—	K2	—	K8 r	K1 b	K4 b	—

Diagram 3.

(see opposite page)

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TABLE 7

Basal and test fertilisers, Woburn Permanent Wheat and Barley Sites, 1960–62

lb element/acre

Crop		N basal	P test		K test		
Barley	1960–62	67	12·5	50	14	56	—
Potatoes	1960	134	12·5	50	28	112	—
	1961–62	134	12·5	50	42	168	—
Sugar beet	1961–62	112	12·5	50	84	168	336

N as 'Nitro-Chalk'.
P as granular superphosphate.
K as potassium sulphate.
Basal P for all crops for the K test was 50 lb P/acre.
Basal K for the P test varied for each crop, barley 56 lb; potatoes 112 lb in 1960; 168 lb in 1961–62; sugar beet 336 lb.
In 1960 basal P and K was applied to seedbed; in 1961–62 it was ploughed in. Ploughed in test and basal fertilisers were applied in 1961 on 24 January and in 1962 on 26 January.

In 1960 all the fertilisers were broadcast by hand on the seedbed, immediately before drilling the barley and machine planting the potatoes except that the N for the barley was broadcast from the combine drill as on Agdell. In 1961 and 1962 when ploughed in and seedbed dressings were tested all the ploughed in test fertilisers and the basal P and K were ploughed-in in January each year. The seedbed dressings and the nitrogen were applied by hand, just before drilling the barley and sugar beet and machine planting the potatoes, except that the N for the barley was applied as in 1959. Varieties: barley, 1960–61 Plumage Archer, 1962 Proctor; potato, Majestic (chitted seed); sugar beet, Klein E.

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The Value of Residues from Long-period Manuring at Rothamsted and Woburn
IV. The Value to Arable Crops of Residues Accumulated from Superphosphate

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The histories of the sites of these experiments, the form of the experiments and the crops grown, are described in paper III (page 22).

Yields

Cereals

Effect of seedbed dressings. Appendix Table 1 shows the yields of barley and spring wheat on the Exhaustion Land in 1957–58, of barley on Agdell in 1959–60 and at Woburn in 1960–62. On all but one site in one year the cereals responded to new P up to the maximum tested on starved soils without P residues; the exception was on the Wheat Site at Woburn in 1962 when, without new P fertiliser, this soil gave an anomalously large yield. On each site the response to new P was always greater in the wetter (total March–June rainfall) of the two years.

Table 1 shows that, at Rothamsted, yields of barley grain on starved soils without new P were small, 12 to 16 cwt/acre, and 50 lb/acre of new P increased them by 11 to 12 cwt/acre. The experiments were made with Plumage Archer, which in the Classical Barley Experiment on Hoosfield in 1964–66 gave similar yields to Maris Badger on poor soils but smaller ones with full NPK manuring. Table 1 also shows that the responses to new P

TABLE 1

Effect of a new dressing of 50 lb P/acre on the yields of barley grown on soils with and without P residues at Rothamsted and Woburn, 1957–62

Grain, cwt/acre

	Rothamsted		Woburn	
	Exhaustion Land mean 1957 & 1958	Agdell mean 1959 & 1960	Wheat Site mean 1960 & 1962	Barley Site mean 1960 & 1961
Starved soil				
Without new P	16·2	12·3	24·6	17·2
With new P	27·8	23·0	25·2	20·4
Response to new P[1]	11·6	10·7	0·6	3·2
Enriched soil				
Without new P	24·8	27·2	29·2	24·1
With new P	27·7	30·9	30·2	27·4
Response to new P[1]	2·9	3·7	1·0	3·3

[1] New P at 50 lb P/acre applied broadcast to the seedbed.

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were much smaller, only 3 to 4 cwt/acre, on Rothamsted soils containing residues of previous P manuring than on soils without residues. At Woburn, barley yielded more on the soils without residues, 17 to 25 cwt/acre, than at Rothamsted, and the responses to new P (1 to 3 cwt) were smaller.

Table 2 shows the yields on starved and enriched soils without new P; residues increased yields of barley grain by 9 to 15 cwt/acre at Rothamsted and 5 to 7 cwt at Woburn.

TABLE 2

Effect of P residues in the soil on the yields of cereals given no new P at Rothamsted and Woburn, 1957–62

Grain, cwt/acre

	Rothamsted			Woburn	
	Exhaustion Land mean 1957 & 1958		Agdell mean 1959 & 1960	Wheat Site mean 1960 & 1962	Barley Site mean 1960 & 1961
	Barley	Spring wheat	Barley	Barley	Barley
Soil given no new P and with					
No residues	16·2	19·0	12·3	24·6	17·2
P residues	24·8	22·4	27·2	29·2	24·1
Increase due to P residues in the soil	8·6	3·4	14·9	4·6	6·9

Some of the soils with residues behaved atypically. Because it is not yet possible to explain the low yields or lack of response to new fertiliser, the yields are given only in the Appendix Tables. On Agdell plots 1 and 2 and on both plots 8, but especially on the Wheat Site at Woburn, yields of cereals were smaller than on the other enriched soils and there was no response to new P. All these plots became very acid before 1920 and liming just before the microplot experiments were made did not restore their productivity. Warren and Johnston (1962) discussed the poor yields of barley in 1961 on plot 1 on Agdell when, on microplots not given a fresh dressing of P, the young plants became very yellow; similar young barley plants on Rothamsted Farm were diagnosed deficient in N and/or K. Though these yellow plants on Agdell contained less N and K than green plants they also contained very much less P than the green plants on microplots given a fresh dressing of P; the poor physical condition of the soil after the very wet winter slowed the growth of roots of the yellowed plants and prevented them from getting enough P from the residues. Thus, on a poor seedbed, barley may need a fresh dressing of phosphate when the soil contains only a moderate amount of soluble P. At Woburn there were no obvious differences in the condition of the seedbeds on the various plots and each year barley made good early growth. In 1962, sugar beet on plot 8 on the Wheat Site showed signs of magnesium deficiency, as did cereals in 1967 in a new experiment on this site. In a test of Mg in 1968, Bolton (1969) showed that giving Mg increased % Mg in wheat plants in May, but it increased grain yield too little to explain the small barley yields on plot 8.

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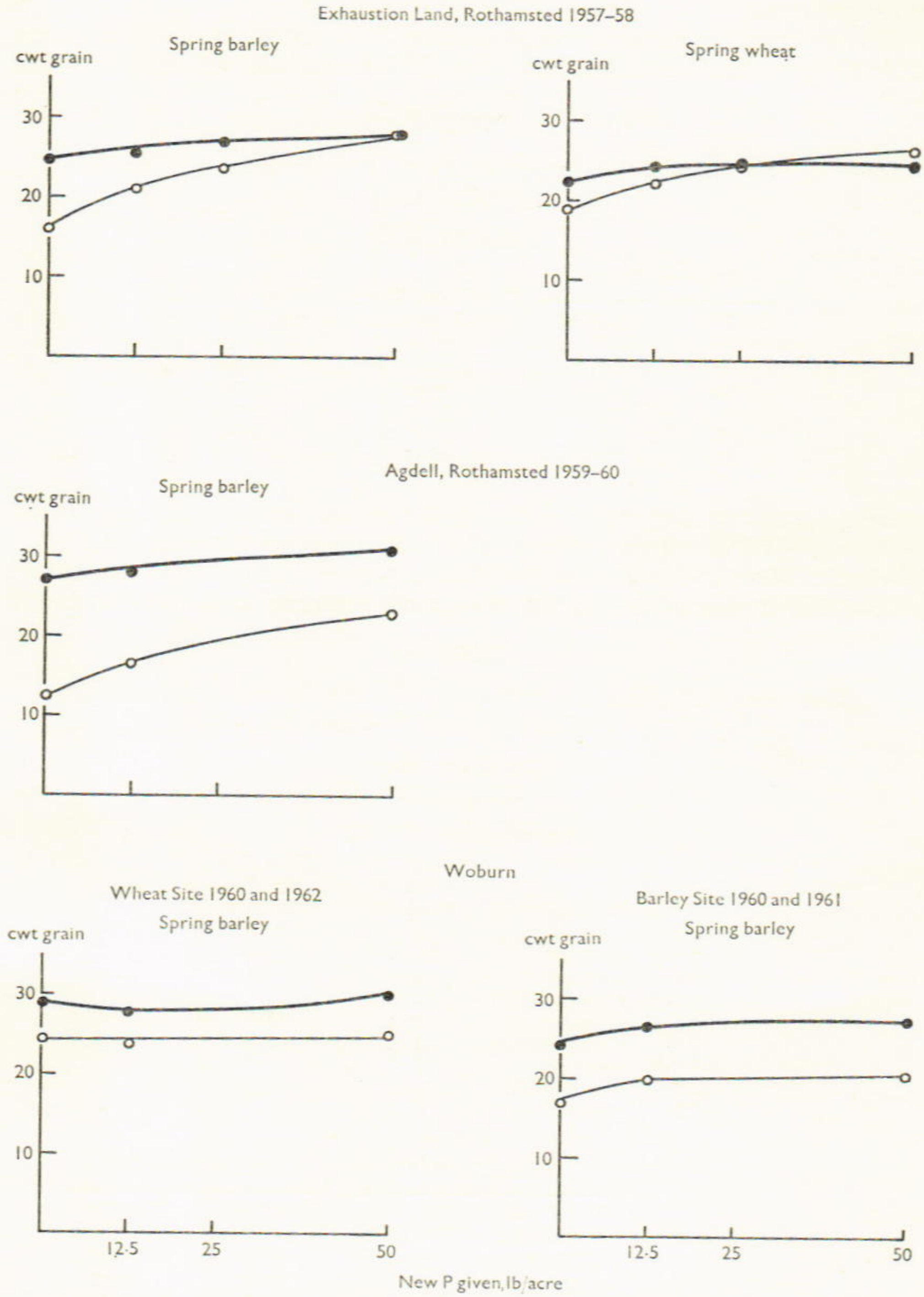

FIG. 1. Effect of P residues and new P on the average yield per acre of cereal grain, Rothamsted and Woburn, 1957–62.

(With ● and without ○ P residues.)

However the small yields of potatoes on the Wheat Site at Woburn may have been caused by Mg deficiency, though the leaves of the plants showed no symptoms.

Fig. 1 shows the response curves to new P on both starved and enriched soils. Only on the Exhaustion Land can the P residues be valued in terms of

TABLE 3

Effect of new broadcast dressings of P and a new residue of P on barley, Agdell, 1960

Grain, cwt/acre

P given lb/acre In 1959	P given lb/acre In 1960	Plots 3 and 4 with old P residues	Plots 5 and 6 no P residues
0	0	23·0	10·5
0	12·5	23·4	12·6
0	50·0	26·8	16·7
0	75·0	27·0	19·0
50	0	24·6	16·8
50	75·0	26·6	21·0

a fresh broadcast dressing of P having the same effect on yield, for barley this was 30 lb P, for spring wheat 12 lb P. On the other three sites yields on the enriched soils without new P were larger than on starved soils with new P.

In the first year of the Agdell experiment enriched soils without new P

TABLE 4

Effect of new P, ploughed in or broadcast on the seedbed, on barley yields at Rothamsted and Woburn, 1961–62

Grain, cwt/acre

Rothamsted

Agdell, mean 1961–62

P given lb/acre		Plots 3, 4 with P residues	Plots 5, 6 no P residues
0		31·1	22·0
37·5	seedbed	34·2	27·4
75	seedbed	34·0	23·6
37·5	ploughed in	33·8	25·0
75	ploughed in	29·6	29·0
37·5 +37·5	ploughed in seedbed	31·6	27·8
75 +75	ploughed in seedbed	33·2	32·4

Woburn

P given lb/acre		Wheat Site 1962 Plot 9 with P residues	Wheat Site 1962 Plot 7 no P residues	Barley Site 1961 Plot 9 with P residues	Barley Site 1961 Plot 7 no P residues
0		31·6	29·1	25·3	17·9
12·5	seedbed	29·1	27·5	26·6	20·6
50	seedbed	32·1	27·2	27·9	21·3
0		31·7	26·3	25·3	22·2
12·5	ploughed in	31·5	26·0	25·7	23·7
50	ploughed in	29·9	32·3	24·9	25·5

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gave such larger yields than starved soils with new P, that the experiment was modified in 1960 to test 75 lb of new P/acre and the residues of the 50 lb P/acre applied in 1959. Even with 75 lb P/acre, yields did not equal those on enriched soil without new P (Table 3); on the starved soil in 1960 the residue of the 50 lb P/acre applied in 1959 yielded as well as the same dressing newly applied and this residue also enhanced the effect of the new 75 lb/acre P.

Comparison of ploughed-in and seedbed dressings for barley. Because there was this large effect of the ploughed-in residue of a single dressing of P fertiliser, ploughed in and seedbed dressings of P fertilisers were compared on Agdell and at Woburn in 1961 and 1962. Table 4 shows that on Agdell there was a maximum yield of 33 to 34 cwt grain on the enriched soil and this was only approached (32 cwt grain) on the starved soil with a combined dressing of 75 lb P ploughed in plus 75 lb P to the seedbed. At Woburn on the Wheat Site, maximum yield of 31 to 32 cwt grain on the enriched soil was only equalled on the starved soil by ploughing in 50 lb P (the largest amount tested); on the Barley Site, 26 to 28 cwt of grain was obtained with residues and again this was only equalled on soils without residues by ploughing in 50 lb of fresh P.

Potatoes

Effect of seedbed dressings. Often when FYM was given to potatoes the soil was drawn into ridges and the manure was put in the furrows before setting the potatoes. The ridges were then split back to make new ridges over the potato sets. Cooke (1949) showed that, when potatoes were planted this way, fertilisers could be applied by various techniques that allow some degree of fertiliser placement. In our experiments, the fertiliser was put in the *bottoms* of the furrows before planting (Cooke, 1949, Method C), this was done on the Exhaustion Land and Agdell where the potatoes were set by hand, but at Woburn the potatoes had to be machine planted and so the fertilisers were applied on the flat seedbed immediately before planting, which distributed the fertiliser through the ridge as in Method A. Appendix Table 2 shows the yields on the Exhaustion Land in 1957–58, on Agdell in 1959–60, and at Woburn in 1960–62.

Potatoes on all sites and in all years on soils with and without P residues responded to new P up to the largest amount tested. Table 5 shows that at Rothamsted where the yields on starved soils were small (5 tons/acre) the responses to 50 lb new P/acre were between 5 and 8 tons. The enriched soils on Agdell produced 12 tons/acre but those on the Exhaustion Land only 8 tons/acre. On these enriched soils responses to new P were smaller than on the starved soils. At Woburn yields on the starved soils (14 tons/acre) were larger than at Rothamsted but the responses to new P on both starved and enriched soils were small (about 1 ton/acre).

Table 6 shows the yields with and without P residues when new P was not given and the large yields with the residues. Fig. 2 gives the response curves to new P.

On the Exhaustion Land the residues could be valued in terms of a new dressing of P; for the potatoes this was no more than 5 lb P/acre. On the

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TABLE 5

Effect of a new dressing of 50 lb P/acre on the yield of potatoes grown on soils with and without P residues at Rothamsted and Woburn, 1957–62

Tubers, tons/acre

	Rothamsted		Woburn	
	Exhaustion Land mean 1957 & 1958	Agdell mean 1959 & 1960	Wheat Site mean 1960 & 1962	Barley Site mean 1960 & 1961
Starved soil				
Without new P	5·1	4·8	13·8	14·1
With new P	13·0	10·1	14·6	15·8
Response to new P[1]	7·9	5·3	0·8	1·7
Enriched soil				
Without new P	8·4	11·9	16·7	15·8
With new P	13·0	15·2	18·0	16·6
Response to new P[1]	4·6	3·3	1·3	0·8

[1] New P at 50 lb P/acre given along the bottoms of the furrows before hand planting on the Exhaustion Land and Agdell, on the flat seedbed before machine planting at Woburn.

TABLE 6

Effect of P residues in the soil on the yields of potatoes given no new P at Rothamsted and Woburn, 1957–62

Tubers, tons/acre

	Rothamsted		Woburn	
	Exhaustion Land mean 1957 & 1958	Agdell mean 1959 & 1960	Wheat Site mean 1960 & 1962	Barley Site mean 1960 & 1961
Soil given no new P and with				
No residues	5·1	4·8	13·8	14·1
P residues	8·4	11·9	16·7	15·8
Increase due to P residues in the soil	3·3	7·1	2·9	1·7

TABLE 7

Effect of new broadcast dressings of P and a new residue of P on potatoes, Agdell, 1960

Tubers, tons/acre

P given lb/acre			
In 1959	In 1960	Plots 3 and 4 with old P residues	Plots 5 and 6 no P residues
0	0	16·0	6·1
0	12·5	17·4	8·7
0	50	20·1	12·6
0	75	20·2	13·6
50	0	17·3	10·0
50	75	20·1	14·6

other three sites yields on enriched soils without new P were more than on starved soils with new P, except at Woburn where the residues on the Barley Site could be valued at 50 lb new P/acre.

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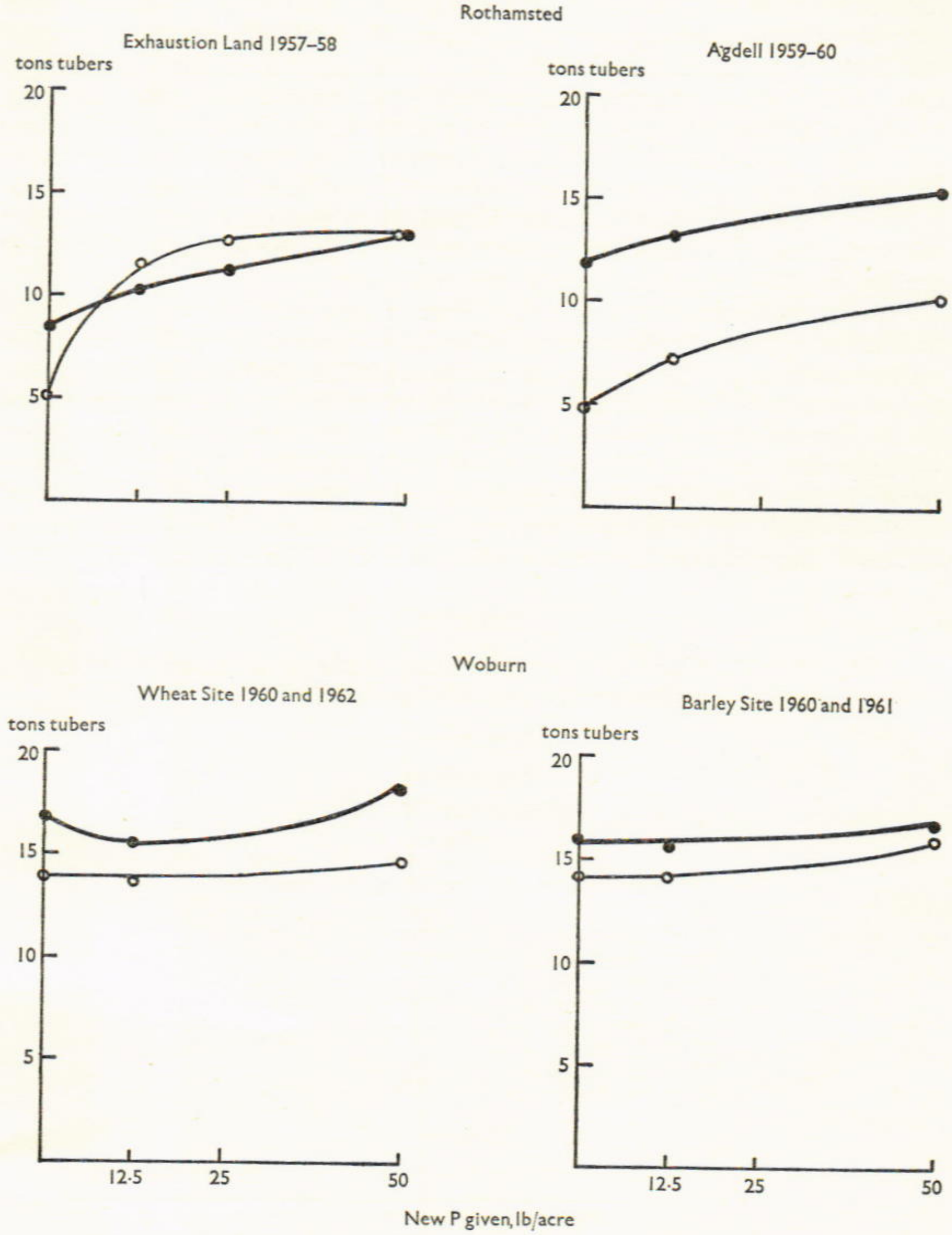

FIG. 2. Effect of P residues and new P on the average yield per acre of potato tubers, Rothamsted and Woburn, 1957–62.

(With ● and without ○ P residues.)

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When the Agdell experiment was modified in 1960, P was tested at 75 lb P/acre for potatoes. As Table 7 shows, on the enriched soils this did not further increase the yield, and on the starved soil, though 1 ton/acre more potatoes was obtained by increasing P from 50 lb to 75 lb, the yield was still less than on enriched soil without a new dressing of P. Table 7 also shows that, in 1960, on the starved soil the residues of the previous year's dressing of 50 lb P gave an extra 4 tons/acre of potatoes; even more interesting was that these one-year-old residues, together with the new dressing of 75 lb P/acre, gave more potatoes that would have been suggested by extrapolating the response curve to new dressings in that year. In 1960 on soils with residues potatoes gave a small response to the residue of 50 lb P applied in 1959 only when new P was not given.

Further evidence that single dressings of new fertiliser can have large residual effects on very impoverished soils but inconsistent effects on richer soils came from the yields of potatoes on Agdell. In 1961–62 on the starved soil without new P the yield of 7·8 tons/acre (Table 8) was 3 tons more than on the same plots in 1959–60 (Table 5). On the enriched soils of plots 3 and 4, the yields were the same in 1959–60 and 1961–62 (12·2 and 11·9 tons respectively). The 1961–62 microplots were superimposed on those of 1959–60 which had received some fertiliser P and the residue of this dressing increased the yield on the starved soil but not on the enriched soil.

TABLE 8

Effect of new P, ploughed in or broadcast on the seedbed, on potatoes at Rothamsted and Woburn, 1961–62

Tubers, tons/acre

Rothamsted

Agdell, mean 1961–62

P given lb/acre		Plots 3, 4 with P residues	Plots 5, 6 no P residues
0		12·2	7·8
37·5	seedbed	11·9	9·2
75	seedbed	15·8	9·9
37·5	ploughed in	12·6	9·4
75	ploughed in	11·9	10·2
37·5 +37·5	ploughed in seedbed	14·7	10·2
75 +75	ploughed in seedbed	13·2	10·3

Woburn

P given lb/acre		Wheat Site 1962 Plot 9 with P residues	Wheat Site 1962 Plot 7 no P residues	Barley Site 1961 Plot 9 with P residues	Barley Site 1961 Plot 7 no P residues
0		14·8	12·5	13·7	10·9
12·5	seedbed	13·2	11·9	12·5	11·3
50	seedbed	16·4	12·8	14·1	12·7
0		15·3	11·0	12·3	11·6
12·5	ploughed in	13·4	13·3	15·3	12·5
50	ploughed in	14·5	15·2	14·1	13·0

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Comparison of ploughed-in and seedbed dressings. Ploughed-in and seedbed-dressings of fertilisers for potatoes were compared on Agdell and at Woburn (Table 8), but neither method of application was consistently superior. On the starved soil on Agdell, even a new dressing of 150 lb P/acre did not give the same yield as the enriched soil without new P, but at Woburn ploughing in 50 lb P/acre on the starved soil gave the same yield as the enriched soil without new P. However, on both sites a new dressing of P on the enriched soil gave a larger yield than the same amount of new P on the starved soil, except when the new P was ploughed in on the Wheat Site at Woburn.

Sugar beet

Effect of seedbed dressings. Sugar beet, which were grown on the Exhaustion Land and Agdell in the same years as the other crops, were grown at Woburn only in one year on each site. Appendix Table 3 gives the yields on the Exhaustion Land, 1957–58; on Agdell 1959–60; at Woburn 1961–62. Table 9 shows that, on the starved soils at Rothamsted, sugar

TABLE 9

Effect of a new dressing of 50 lb P/acre on the yield of sugar from beet grown on soils with and without P residues at Rothamsted and Woburn, 1957–62

Sugar, cwt/acre

	Rothamsted		Woburn	
	Exhaustion Land mean 1957 & 1958 plots 5 & 9	Agdell mean 1959 & 1960 plots 3, 4, 5, 6	Wheat Site 1962 plots 7 & 9	Barley Site 1961 plots 7 & 9
Starved soil				
Without new P	30·6	26·9	50·2	32·1
With new P	45·6	38·2	47·4	34·6
Response to new P[1]	15·0	11·3	−2·8	2·5
Enriched soil				
Without new P	45·2	46·0	51·0	43·0
With new P	47·8	47·8	54·3	43·6
Response to new P[1]	2·6	1·8	3·3	0·6

[1] New P at 50 lb/acre broadcast on the seedbed.

yields were increased from 31 to 46 cwt/acre on the Exhaustion Land and from 27 to 38 cwt on Agdell by a dressing of 50 lb P/acre. However, much of this increase was given by a new dressing of 25 lb P/acre. On the enriched soils, the response to new P was only 2–4 cwt sugar/acre. At Woburn the sugar-beet experiment was the most disappointing in the series. Beet was grown only for one year on each site, whereas for the other crops on each site there are averages of two results. Responses to new P were small and variable, but did not exceed 3·0 cwt sugar/acre on either the starved or enriched soils.

Table 10 shows the yields at Rothamsted without any new P, and the large increases in yield from the residues of P on the enriched soils. At Woburn, on the Barley Site, yield on starved soil (30 cwt/acre) was similar to

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that on the starved soils at Rothamsted and the residues in the enriched soil gave an extra 11 cwt sugar. On the Wheat Site in 1962, yields on both soils were much larger (50 cwt/acre) and the P residues gave no extra yield.

TABLE 10

Effect of P residues in the soil on the yield of sugar when no new P was given at Rothamsted and Woburn, 1957–62

Sugar, cwt/acre

	Rothamsted		Woburn	
	Exhaustion Land mean 1957 & 1958 plots 5, 9	Agdell mean 1959 & 1960 plots 3, 4, 5, 6	Wheat Site 1962 plots 7 & 9	Barley Site 1961 plots 7 & 9
Soil given no new P and with				
No residues	30·6	26·9	50·2	32·1
P residues	45·2	46·0	51·0	43·0
Increase due to P residues in the soil	14·6	19·1	0·8	10·9

Fig. 3 gives the response curves of sugar beet to new P on both starved and enriched soils at Rothamsted. The residues on the Exhaustion Land were equivalent to a new dressing of about 25 lb P/acre. On Agdell, taking the mean of the two years, the residues were worth much more than any new dressing of P tested, largely because of the large yield given by the residues in the first year, 1959. Table 11 shows that, in the second year,

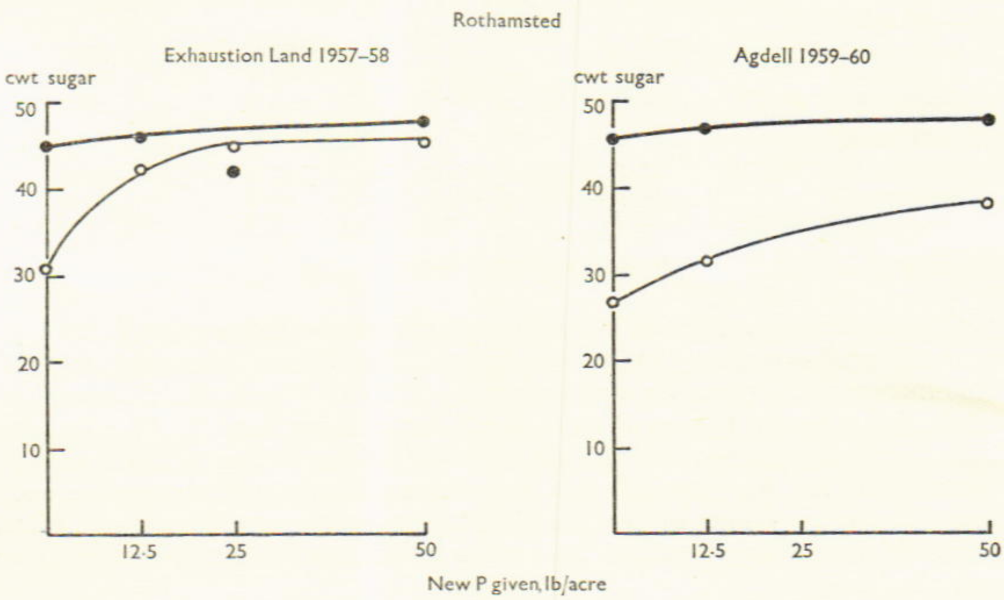

FIG. 3. Effect of P residues and new P on the average yield per acre of sugar, Rothamsted, 1957–60.

(With ● and without ○ P residues.)

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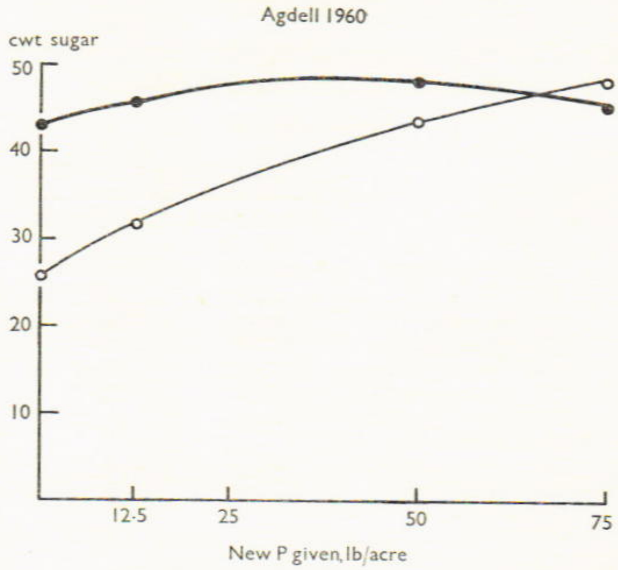

FIG. 3a. Effect of P residues and new P on the yield per acre of sugar, Agdell, 1960. (With ● and without ○ P residues.)

TABLE 11

Effect of new broadcast dressings of P and a new residue of P on sugar yields, Agdell, 1960

Sugar, cwt/acre

P given lb/acre In 1959	P given lb/acre In 1960	Plots 3 and 4 with old P residues	Plots 5 and 6 no P residues
0	0	43·1	25·7
0	12·5	45·8	31·8
0	50	48·2	43·6
0	75	45·2	48·2
50	0	43·8	42·7
50	75	49·7	46·6

1960, when more new P was applied to the seedbed than in 1959, yields on starved and enriched soils were the same with 75 lb P/acre. From the response curves in Fig. 3a, the residue was valued at 50 lb new P.

Comparison of ploughed-in and seedbed dressings. The soils of Agdell are difficult to cultivate and often form a cloddy structure not easily penetrated by roots. The comparison of ploughed-in and seedbed dressings of fertilisers in 1961–62 showed that these soils yield more reliably when they contain residues. Table 12 shows that, for each treatment, the yield on the enriched soil was 8 to 13 cwt sugar/acre more than on the starved soils. The yields in Table 12 also indicate that the deep-rooting sugar beet responded more to ploughed in than to seedbed dressings of P. At Woburn, where the same comparison was made in the same years, yields varied too much to differentiate between ploughed in and seedbed dressings of P.

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TABLE 12

Effect of new P, ploughed in or broadcast on the seedbed, on sugar yields at Rothamsted, 1961–62

Sugar, cwt/acre

P given lb/acre		Agdell, mean 1961–62: Plots 3 and 4 with P residues	Plots 5 and 6 no P residues
0		64·5	54·7
37·5	seedbed	63·8	55·5
75	seedbed	67·6	60·2
37·5	ploughed in	75·2	64·4
75	ploughed in	71·8	58·3
37·5 +37·5	ploughed in seedbed	74·8	61·8
75 +75	ploughed in seedbed	78·4	65·4

Swedes and kale

Effect of seedbed dressings. These two crops were only grown in two years, 1957–58, and on one site, the Exhaustion Land. Appendix Table 4 shows yields of both crops were larger in 1958, the wetter of the years.

On the starved soil, swedes responded well (5·6 tons/acre) to the smallest amount of new P added (12·5 lb P/acre) and gave further increases of 1·9 and 1·8 tons from the next two amounts of P given. Kale behaved differently; it responded well (4·4 tons) to the smallest amount of P but only little more to further P. Table 13 shows that P residues increased yield of both crops greatly, by 7·0 tons of swede roots and 4·4 tons of kale. On these enriched soils, the response to new P was much smaller than on the starved soils.

TABLE 13

Effect of P residues in the soil on the yield of swedes and kale when no new P was given at Rothamsted on the Exhaustion Land, 1957–58

Tons/acre

	Swedes: Tops	Swedes: Roots	Kale
Soil given no new P and with			
No residues	1·8	8·5	14·8
P residues	2·9	15·5	19·2
Increase due to P residues in the soil	1·1	7·0	4·4

Fig. 4 shows that, with the largest amount of new P tested, the yield of swedes was the same on both starved and enriched soils but the largest amount of new P on the enriched soil gave 1·3 tons more kale than any other treatment. The response curves (Fig. 4) valued the residues as worth 20 lb broadcast new P for swedes and 15 lb P for kale.

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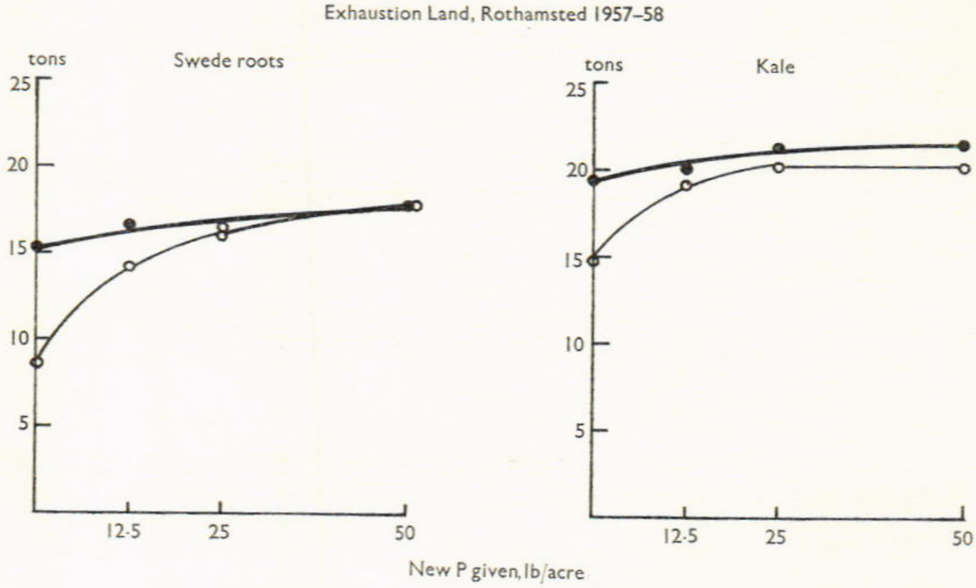

FIG. 4. Effect of P residues and new P on the average yield per acre of swede roots and kale, Rothamsted, 1957–58.

(With ● without ○ P residues.)

Discussion of the phosphorus tests

Table 14 shows the increases in yield of all crops from 50 lb P/acre applied as a broadcast dressing of superphosphate on all sites, excluding the poor yields on those Classical plots where previous treatment made the soils acid. At Rothamsted all crops on starved soil responded to new P very much more than on the enriched soils. On the Exhaustion Land, barley, spring wheat, potatoes and swedes yielded similarly on both starved and enriched soils when given a new dressing of 50 lb P/acre. Sugar beet and kale yielded rather more on soil with residues than on soil without. On the starved Agdell soils, none of the three crops, barley, potatoes and sugar beet, yielded as much when given 50 lb/acre new P as on the enriched soil without new P. At Woburn all crops, except for one test with sugar beet, responded to new P, though the responses were small, and were nearly the same on soils with and without residues. This was unexpected with potatoes, but this crop yielded very well at Woburn with all treatments.

At Rothamsted, residues did not lessen the responses to new P by potatoes as much as with other crops, and the response curves for potatoes were steeper than for other crops. This difference may mean that potatoes are less able than other crops to use phosphorus in the soil because the roots do not 'search' the soil mass so thoroughly, or it may be because the new P was placed in the furrows, under the seed tubers, whereas for the other crops it was broadcast and harrowed in about 2 in. deep.

At Woburn, potatoes without new P yielded very much more than at Rothamsted, suggesting that the roots were able to remove more nutrients from this light soil than from the heavy soil at Rothamsted. Smaller respon-

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TABLE 14

Effect of a broadcast dressing of 50 lb P/acre as superphosphate on the yields of crops grown on soils with and without P residues at Rothamsted and Woburn, 1957–62

		Rothamsted				Woburn			
		Exhaustion Land mean 1957 & 1958		Agdell mean 1959 & 1960		Wheat Site mean 1960 & 1962		Barley Site mean 1960 & 1961	
	New P given lb/acre	No residues	With P residues	No residues	With P residues	No residues	With P residues	No residues	With P residues
Barley grain, cwt	0	16·2	24·8	12·3	27·2	24·6	29·2	17·2	24·1
	50	27·8	27·7	23·0	30·9	25·2	30·2	20·4	27·4
	50 minus 0	11·6	2·9	10·7	3·7	0·6	1·0	3·2	3·3
Spring wheat grain, cwt	0	19·0	22·4	—	—	—	—	—	—
	50	26·2	24·0	—	—	—	—	—	—
	50 minus 0	7·2	1·6	—	—	—	—	—	—
Potatoes tubers, tons	0	5·1	8·4	4·8	11·9	13·8	16·7	14·1	15·8
	50	13·0	13·0	10·1	15·2	14·6	18·0	15·8	16·6
	50 minus 0	7·9	4·6	5·3	3·3	0·8	1·3	1·7	0·8
Sugar beet sugar, cwt	0	30·6	45·2	26·9	46·0	50·2	51·0	32·1	43·0
	50	45·6	47·8	38·2	47·8	47·4	54·3	34·6	43·6
	50 minus 0	15·0	2·6	11·3	1·8	−2·8	3·3	2·5	0·6
Swedes roots, tons	0	8·5	15·5	—	—	—	—	—	—
	50	17·8	17·9	—	—	—	—	—	—
	50 minus 0	9·3	2·4	—	—	—	—	—	—
Kale tons	0	14·8	19·2	—	—	—	—	—	—
	50	20·1	21·4	—	—	—	—	—	—
	50 minus 0	5·3	2·2	—	—	—	—	—	—

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ses to new P at Woburn may have been because the new P was applied on the flat before the sets were machine planted.

When valued by the difference in yield between soils with and without residues, obtained with crops given enough N and K, the residues of old P dressings have considerable value at both Rothamsted and Woburn. Table 15 summarises these increases in yield of all crops on all sites. When

TABLE 15

Effect of old residues of fertiliser P dressings at Rothamsted and Woburn, 1957–62

Yield/acre

Crop	Site	Years	No residues	With P residues	Increase due to P residues	% increase in yield due to residues
Barley grain, cwt	Exhaustion Land	1957 & 1958	16·2	24·8	8·6	53
	Agdell	1959 & 1960	12·3	27·2	14·9	121
	Woburn					
	Wheat Site	1960 & 1962	24·6	29·2	4·6	19
	Barley Site	1960 & 1961	17·2	24·1	6·9	40
Spring wheat grain, cwt	Exhaustion Land	1957 & 1958	19·0	22·4	3·4	18
Potatoes tubers, tons	Exhaustion Land	1957 & 1958	5·1	8·4	3·3	65
	Agdell	1959 & 1960	4·8	11·9	7·1	148
	Woburn					
	Wheat Site	1960 & 1962	13·8	16·7	2·9	21
	Barley Site	1960 & 1961	14·1	15·8	1·7	12
Sugar beet sugar, cwt	Exhaustion Land	1957 & 1958	30·6	45·2	14·6	48
	Agdell	1959 & 1960	26·9	46·0	19·1	71
	Woburn					
	Wheat Site	1962	50·2	51·0	0·8	2
	Barley Site	1961	32·1	43·0	10·9	34
Swedes roots, tons	Exhaustion Land	1957 & 1958	8·5	15·5	7·0	82
Kale tons	Exhaustion Land	1957 & 1958	14·8	19·2	4·4	30

the extra yield is expressed as a percentage of the yield on the corresponding starved soil, the yield increases for all crops were between 18 and 65% on the Exhaustion Land and 70 and 150% on Agdell. At Woburn they were less, 2 to 40%.

Table 16 shows the value of the P residues in terms of an equivalent dressing of new P fertiliser, estimated from response curves to new P on starved soil; this could be done only for the residues on the Exhaustion Land. The range of amounts, 5 to 30 lb, is large, so though the residues must be the same chemically, they do not have one general value, but their value depends on the crop grown.

These results show the need for experiments on different soils. In the first experiments on the Exhaustion Land, yields of four of the six crops tested were the same on starved and enriched soils when the largest amount of new P was given. Therefore, given basal N and K, there was no difference between the two soils other than the amount of available P and this difference could be removed by applying 50 lb of fresh P/acre as superphosphate. In the second experiment, made on Agdell in 1959–60, the yields on

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TABLE 16

Value of fertiliser P residues expressed as broadcast dressing of P having the same effect on yield, the Exhaustion Land, Rothamsted, 1957–58

	lb P/acre
Barley, grain	30
Potatoes, tubers	5
Sugar beet, sugar	25
Spring wheat, grain	12
Swedes, roots	20
Kale	15

enriched soils without new P were larger than on starved soils with new P. This was true even when, in the second of the years, the largest amount of new P applied broadcast was increased to 75 lb P/acre. The results on the lighter soil at Woburn in 1960–62 were similar to those on Agdell.

Yields on the starved soils on Agdell could not be increased to those on enriched soils, even by ploughing in fertiliser P, but applying new P fertiliser this way gave larger yields than applying it to the seedbed. Analysis of soil samples, taken 9 in. deep, during early summer, showed that less of the ploughed in P had remained readily soluble, but because it was deeper it increased yield more than seedbed dressings. On some soils, therefore, P residues can give better yields than fertiliser P freshly applied at the rates and in ways usually recommended.

A third important result was that often all amounts of newly applied P fertiliser tested gave larger yields on soil enriched with residues than on starved soil.

Phosphorus concentration in the crops

Tables 17, 18 and 19 give the percentages of phosphorus in the dry matter of the crops grown in these experiments.

Cereals. The phosphorus concentration in the dry matter of cereals (Table 17) was smallest for those grown on Agdell where the new P gave the largest increase in yield. At Rothamsted, though new P fertiliser gave larger yields, it did not increase the P concentration in the grain. This contrasted strikingly with the effect of the residues, which consistently increased the concentration of P in the grain. Without new P, there was 0·24 to 0·29% P in grain grown on the starved soils and from 0·27 to 0·35% P on the enriched soils. Where dressings of new P are given annually on the Hoosfield Continuous Barley plots, the soil has much larger residues than those of these microplot experiments and the barley grain contains from 0·37 to 0·41% P, supporting the view that P distributed through the cultivated soil layer is more accessible to the plant than new broadcast dressings. Residues had little effect on % P in straw, whether or not new P was given. There was little difference between seedbed dressings and ploughed in new P on the % P in the grain.

Potatoes. On the Exhaustion Land and Agdell, where both residues and new P dressings gave large increases in yields of potatoes, the residues

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TABLE 17

Effect of P residues and new P on the percentage of P in grain and straw of cereals grown at Rothamsted and Woburn, 1957–62

% P in dry matter

Rothamsted

	Exhaustion Land mean 1957 & 1958 P to seedbed				Agdell					
					Mean 1959 & 1960		Mean 1961 & 1962			
					P to seedbed		P to seedbed		P ploughed in	
	Barley		Spring wheat		Barley		Barley		Barley	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
No new P given to soil with										
No residues	0·29	0·06	0·29	0·05	0·24	0·06	0·24	0·04	0·24	0·04
P residues	0·35	0·06	0·35	0·05	0·32	0·06	0·27	0·03	0·27	0·03
Effect of P residues	0·06	0	0·06	0	0·08	0	0·03	−0·01	0·03	−0·01
New P given (50 lb P/acre)[1] to soil with										
No residues	0·31	0·05	0·31	0·04	0·25	0·06	0·22	0·02	0·24	0·02
P residues	0·35	0·06	0·35	0·05	0·32	0·05	0·25	0·03	0·28	0·03
Effect of P residues	0·04	0·01	0·04	0·01	0·07	−0·01	0·03	0·01	0·04	0·01
Effect of new P (50 lb P/acre)[1] in the										
Absence of residues	0·02	−0·01	0·02	−0·01	0·01	0	−0·02	−0·02	0	−0·02
Presence of residues	0	0	0	0	0	−0·01	−0·02	0	0·01	0

[1] 75 lb P/acre Agdell 1961–62.

Woburn

	Wheat Site 1962				Barley Site 1961			
	P to seedbed		P ploughed in		P to seedbed		P ploughed in	
	Barley		Barley		Barley		Barley	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
No new P given to soil with								
No residues	0·32	0·06	0·28	0·04	0·36	0·06	0·34	0·04
P residues	0·36	0·05	0·32	0·04	0·36	0·04	0·34	0·03
Effect of P residues	0·04	−0·01	0·04	0	0	−0·02	0	−0·01
New P given (50 lb P/acre) to soil with								
No residues	0·36	0·06	0·30	0·04	0·34	0·04	0·32	0·04
P residues	0·37	0·06	0·36	0·04	0·36	0·05	0·36	0·04
Effect of P residues	0·01	0	0·06	0	0·02	0·01	0·04	0
Effect of new P (50 lb P/acre) in the								
Absence of residues	0·04	0	0·02	0	−0·02	−0·02	−0·02	0
Presence of residues	0·01	0·01	0·04	0	0	0·01	0·02	0·01

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TABLE 18

Effect of P residues and new P on the percentage P in potatoes grown at Rothamsted and Woburn, 1957–62

% P, in dry matter

	Rothamsted				Woburn			
		Agdell						
	Exhaustion Land mean	Mean	Mean 1961 & 1962		Wheat Site 1962		Barley Site 1961	
	1957 & 1958 P in furrows	1959 & 1960 P in furrows	P to seedbed	P ploughed in	P to seedbed	P ploughed in	P to seedbed	P ploughed in
No new P given to soil with								
No residues	0·12	0·13	0·15	0·15	0·17	0·16	0·19	0·17
P residues	0·16	0·17	0·17	0·17	0·16	0·15	0·20	0·22
Effect of P residues	0·04	0·04	0·02	0·02	−0·01	−0·01	0·01	0·05
New P given (50 lb P/acre)[1] to soil with								
No residues	0·14	0·14	0·15	0·17	0·18	0·14	0·20	0·18
P residues	0·15	0·17	0·17	0·19	0·19	0·16	0·22	0·20
Effect of P residues	0·01	0·03	0·02	0·02	0·01	0·02	0·02	0·02
Effect of new P (50 lb P/acre)[1] in the								
Absence of residues	0·02	0·01	0	0·02	0·01	−0·02	0·01	0·01
Presence of residues	−0·01	0	0	0·02	0·03	0·01	0·02	−0·02

[1] 75 lb P/acre Agdell 1961–62.

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increased P concentration in tuber dry matter more than did the newly applied P (Table 18). Residues increased % P by 15 to 30%, about the same as for cereals. At Woburn, where yields without P residues were large and where both residues and newly applied P gave only small increases in yield, there was no big change in the % P in dry matter.

Swedes, sugar beet, kale. Table 19 shows only the analyses of those crops grown on the Exhaustion Land. Without new P, % P in the crops on enriched soil was 40 to 100% more than on starved soil, a much larger increase than with cereals or potatoes. New P increased % P in the crops on starved soils to the concentrations in plants grown on enriched soil without new P, a result not achieved with cereals and potatoes. New P had much smaller effects with residues than without.

TABLE 19

Effect of P residues and new P on the percentage of P in sugar beet, swedes and kale grown on the Exhaustion Land, Rothamsted, 1957–58

	Sugar beet		Swedes		
	Tops	Roots	Tops	Roots	Kale
No new P given to soil with					
No residues	0·19	0·08	0·29	0·16	0·20
P residues	0·26	0·13	0·41	0·34	0·28
Effect of P residues	0·07	0·05	0·12	0·18	0·08
New P given (50 lb P/acre) to soil with					
No residues	0·24	0·13	0·42	0·32	0·26
P residues	0·26	0·14	0·44	0·32	0·32
Effect of P residues	0·02	0·01	0·02	0	0·06
Effect of new P (50 lb P/acre) in the					
Absence of residues	0·05	0·05	0·13	0·16	0·06
Presence of residues	0	0·01	0·03	−0·02	0·04

Phosphorus content of the crops

Tables 20 to 23 show the uptakes of phosphorus by the harvested parts of the crops grown.

Cereals. Without new P, uptake of P by the whole crop from starved soils ranged from 4 to 6 lb P/acre at Rothamsted and 7 to 9 lb P at Woburn (Table 20). On enriched soils 8 to 10 lb P was taken up at Rothamsted and 9 to 11 lb P at Woburn, so the residues provided 3 to 6 lb P at Rothamsted and 1 to 2 lb P at Woburn. With new P, uptakes on the Exhaustion Land were much the same from starved and enriched soils, 9 to 11 lb P, but on Agdell and at Woburn the presence of residues increased the uptake of P because yield was increased by residues on these sites but not on the Exhaustion Land.

Potatoes. The tubers of the potato crop from the starved soil on the Exhaustion Land and on Agdell 1959–60, contained only 3 lb P/acre (Table 21). On Agdell in 1961–62 the uptake was larger, 5·6 lb P, probably

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TABLE 20

Effect of P residues and new P on the amount of P in the grain and straw of cereals grown at Rothamsted and Woburn, 1957–62

lb P/acre/year

Rothamsted

	Exhaustion Land mean 1957 & 1958 P to seedbed						Agdell								
							Mean 1959 & 1960 P to seedbed			Mean 1961 & 1962					
	Barley			Spring wheat			Barley			P to seedbed Barley			P ploughed in Barley		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
No new P given to soil with															
No residues	4·4	1·4	5·8	5·2	1·2	6·4	2·8	1·0	3·8	5·0	0·6	5·6	5·0	0·6	5·6
P residues	8·5	1·9	10·4	7·6	2·0	9·6	8·4	1·4	9·8	7·9	0·7	8·6	7·9	0·7	8·6
Effect of P residues	4·1	0·5	4·6	2·4	0·8	3·2	5·6	0·4	6·0	2·9	0·1	3·0	2·6	0·1	3·0
New P given (50 lb P/acre)[1] to soil with															
No residues	8·2	1·4	9·6	7·8	1·8	9·6	5·2	1·1	6·3	4·7	0·5	5·2	6·6	0·6	7·2
P residues	9·2	1·9	11·1	8·1	2·1	10·2	9·4	1·4	10·8	8·2	1·0	9·2	7·6	0·9	8·5
Effect of P residues	1·0	0·5	1·5	0·3	0·3	0·6	4·2	0·3	4·5	3·5	0·5	4·0	1·0	0·3	1·3
Effect of new P (50 lb P/acre)[1] in the															
Absence of residues	3·8	0	3·8	2·6	0·6	3·2	2·4	0·1	2·5	−0·3	−0·1	−0·4	1·6	0	1·6
Presence of residues	0·7	0	0·7	0·5	0·1	0·6	1·0	0	1·0	0·3	0·3	0·6	−0·3	0·2	0·1

[1] 75 lb P/acre Agdell 1961–62.

Woburn

	Wheat Site 1962						Barley Site 1961					
	P to seedbed Barley			P ploughed in Barley			P to seedbed Barley			P ploughed in Barley		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
No new P given to soil with												
No residues	7·3	1·4	8·7	7·1	0·9	8·0	5·8	1·1	6·9	7·2	0·9	8·1
P residues	9·9	1·4	11·3	8·9	1·3	10·2	8·2	1·2	9·4	8·1	1·0	9·1
Effect of P residues	2·6	0	2·6	1·8	0·4	2·2	2·4	0·1	2·5	0·9	0·1	1·0
New P given (50 lb P/acre) to soil with												
No residues	8·4	1·4	9·8	9·2	1·1	10·3	6·6	1·0	7·6	7·7	1·1	8·8
P residues	10·6	1·9	12·5	10·4	1·1	11·5	9·3	1·6	10·9	8·4	1·3	9·7
Effect of P residues	2·2	0·5	2·7	1·2	0	1·2	2·7	0·6	3·3	0·7	0·2	0·9
Effect of new P (50 lb P/acre) in the												
Absence of residues	1·1	0	1·1	2·1	0·2	2·3	0·8	−0·1	0·7	0·5	0·2	0·7
Presence of residues	0·7	0·5	1·2	1·5	−0·2	1·3	1·1	0·4	1·5	0·3	0·3	0·6

because these microplots were superimposed on those of 1959–60, some of which had received P. From the old residues intimately mixed with the soil, the potatoes extracted at least twice as much P. At Woburn the potatoes could get more than three times as much P from the starved soil as from the starved soils at Rothamsted, especially in the wet year of 1960. However, much less extra P was taken up from the residues at Woburn. With new P, uptake of P increased because yield increased.

TABLE 21

Effect of P residues and new P on the amount of P in potato tubers grown at Rothamsted and Woburn, 1957–62

lb P/acre/year

Rothamsted

	Exhaustion Land mean 1957 & 1958 P in furrows	Agdell: Mean 1959 & 1960 P in furrows	Agdell: Mean 1961 & 1962	
			P to seedbed	P ploughed in
No new P given to soil with				
No residues	2·8	3·0	5·6	5·6
P residues	6·0	9·5	9·2	9·2
Effect of P residues	3·2	6·5	3·6	3·6
New P given (50 lb P/acre)[1] to soil with				
No residues	9·0	7·2	7·0	8·0
P residues	9·6	12·5	12·7	10·3
Effect of residues	0·6	5·3	5·7	2·3
Effect of new P (50 lb P/acre)[1] in the				
Absence of residues	6·2	4·2	1·4	2·4
Presence of residues	3·6	3·0	3·5	1·1

Woburn

	Wheat Site			Barley Site		
		1962			1961	
	1960 P to seedbed	P to seedbed	P ploughed in	1960 P to seedbed	P to seedbed	P ploughed in
No new P given to soil with						
No residues	13·4	8·9	8·7	17·6	9·1	10·3
P residues	15·8	10·4	10·9	17·1	12·3	13·1
Effect of P residues	2·4	1·5	2·2	−0·5	3·2	2·8
New P given (50 lb P/acre) to soil with						
No residues	15·9	11·2	11·0	19·2	11·5	11·6
P residues	21·3	12·6	11·7	22·1	13·1	14·4
Effect of P residues	5·4	1·4	0·7	2·9	1·6	2·8
Effect of new P (50 lb P/acre) in the						
Absence of residues	2·5	2·3	2·3	1·6	2·4	1·3
Presence of residues	5·5	2·2	0·8	5·0	0·9	1·3

[1] 75 lb P/acre Agdell 1961–62.

Sugar beet. Sugar beet took up about the same total P from both the starved soils of the Exhaustion Land and of Agdell during the first period in

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TABLE 22

Effect of P residues and new P on the amount of P in sugar beet grown at Rothamsted and Woburn, 1957–62

lb P/acre/year

Rothamsted

	Exhaustion Land mean 1957 & 1958 P to seedbed			Agdell: Mean 1959 & 1960 P to seedbed			Agdell: Mean 1961 & 1962 P to seedbed			Agdell: Mean 1961 & 1962 P ploughed in		
	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total
No new P given to soil with												
No residues	6·4	3·1	9·5	5·2	1·8	7·0	8·8	6·5	15·3	8·8	6·5	15·3
P residues	9·0	8·0	17·0	9·4	5·4	14·8	13·2	11·8	25·0	13·2	11·8	25·0
Effect of P residues	2·6	4·9	7·5	4·2	3·6	7·8	4·4	5·3	9·7	4·4	5·3	9·7
New P given (50 lb P/acre)[1] to soil with												
No residues	10·8	7·8	18·6	10·3	3·5	13·8	11·2	9·8	21·0	12·6	11·2	23·8
P residues	10·0	9·1	19·1	12·9	6·6	19·5	15·9	14·0	29·9	16·2	16·1	32·3
Effect of P residues	−0·8	1·3	0·5	2·6	3·1	5·7	4·7	4·2	8·9	3·6	4·9	8·5
Effect of new P (50 lb P/acre)[1] in the												
Absence of residues	4·4	4·7	9·1	5·1	1·7	6·8	2·4	3·3	5·7	3·8	4·7	8·5
Presence of residues	1·0	1·1	2·1	3·5	1·2	4·7	2·7	2·2	4·9	3·0	4·3	7·3

[1] 75 lb P/acre Agdell 1961–62.

Woburn

	Wheat Site 1962 P to seedbed			Wheat Site 1962 P ploughed in			Barley Site 1961 P to seedbed			Barley Site 1961 P ploughed in		
	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total
No new P given to soil with												
No residues	10·2	9·2	19·4	11·3	9·8	21·1	5·9	3·7	9·6	7·2	3·8	11·0
P residues	13·2	11·8	25·0	12·0	11·3	23·3	9·9	7·8	17·7	8·1	6·7	14·8
Effect of P residues	3·0	2·6	5·6	0·7	1·5	2·2	4·0	4·1	8·1	0·9	2·9	3·8
New P given (50 lb P/acre) to soil with												
No residues	12·8	9·9	22·7	11·1	9·7	20·8	8·6	5·3	13·9	7·8	5·2	13·0
P residues	10·6	12·0	22·6	11·3	12·3	23·6	9·8	8·6	18·4	9·4	8·7	18·1
Effect of P residues	−2·2	2·1	−0·1	0·2	2·6	2·8	1·2	3·3	4·5	1·6	3·5	5·1
Effect of new P (50 lb P/acre) in the												
Absence of residues	2·6	0·7	3·3	−0·2	−0·1	−0·3	2·7	1·6	4·3	0·6	1·4	2·0
Presence of residues	−2·6	0·2	−2·4	−0·7	1·0	0·3	−0·1	0·8	0·7	1·3	2·0	3·3

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both experiments, and the extra uptake from the residues was 7·5 lb P/acre (Table 22). During the second period on Agdell, 1961–62, uptakes from the starved soils were twice as much as in 1959–60, but the extra uptake from the old residues (9·7 lb P/acre) was only a little greater, so the plants must have taken up either much more native soil P or extra P from the residues of the dressings given in 1959–60. The residues at Woburn supplied much less P (2 to 4 lb/acre) for sugar beet than the residues at Rothamsted. With new P, the crop still took up the same amount of extra P from the residues at Woburn and on Agdell as it did without new P, but not on the Exhaustion Land where, with new P, the uptake from the residues was much less.

Kale and swedes. Table 23 shows the uptakes by both crops from the Exhaustion Land in 1957–58. Kale took up much the same amount of P as sugar beet, except on the enriched soil with new P, where it took up more. With new P, the increase in yield between starved and enriched soils was small, 1 ton/acre increase in 20 tons/acre, and some of the extra uptake from the enriched soil with new P was probably 'luxury' (without a commensurate increase in yield). Swedes took up about 4 lb/acre P from starved soil without new P, about the same amount as potatoes. However, in contrast to potatoes, the swedes took up very much more P from the enriched soil, 16 lb compared to 6 lb by potato tubers.

TABLE 23

Effect of P residues and new P on the amount of P in kale and swedes grown on the Exhaustion Land, Rothamsted, 1957–58

lb P/acre/year

		Swedes		
	Kale	Tops	Roots	Total
No new P given to soil with				
No residues	9·6	1·4	3·1	4·5
P residues	19·8	3·2	12·6	15·8
Effect of P residues	10·2	1·8	9·5	11·3
New P added (50 lb P/acre) to soil with				
No residues	17·6	3·4	12·3	15·7
P residues	25·0	3·7	13·0	16·7
Effect of P residues	7·4	0·3	0·7	1·0
Effect of new P (50 lb P/acre) in the				
Absence of residues	8·0	2·0	9·2	11·2
Presence of residues	5·2	0·5	0·4	0·9

Summary of the effects of P residues and new dressings of P fertiliser on P uptake

On any one site, different crops can be compared to see how much P they take up in the presence and absence of residues. From the starved soil without new P on the Exhaustion Land, of the six crops grown, potatoes (3 lb P/acre, possibly 4 lb if tops are included) extracted least P, and kale and

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sugar beet extracted $2\frac{1}{2}$ to 3 times as much. Swedes took up only little more than potatoes, and cereals were intermediate between potatoes and kale. Although the swedes got only a small amount of P from the starved soil, they extracted as much extra P as kale from the soils with residues, swedes, 11 lb P, kale, 10 lb. Sugar beet, which were in the ground longer than swedes, were less efficient than swedes or kale at taking up P from the residues; they took up only 7·5 lb P, but this was twice as much as that taken up by cereals or potatoes. The relative ability to obtain P from starved soils was confirmed for the three crops grown on Agdell and at Woburn. On both these sites, as on the Exhaustion Land, sugar beet took up more P from the residues that did potatoes, which took up the same amount as barley. Thus on the three sites each crop behaved in the same way relative to the others. These residues, because of their age, must have been intimately mixed with the soil and, on any one site, had the same solubility. That different crops take up different amounts of P is presumably related to the ability of their roots to search the soil mass for nutrients and to the length of time they grow. However, there may also be physiological differences that affect the ability of different crops to absorb phosphorus from the soil.

When new P was applied more of this was taken up from starved soils than from enriched soils, except in three tests with potatoes, two at Woburn and one on Agdell. The apparent percentage recoveries, defined as

$$\frac{\text{extra uptake from added P}}{\text{added P}} \times 100,$$

of the freshly added P are small, and only 7 of the 54 values exceeded 10%. Only on the Exhaustion Land, when yields were the same, was the same total P removed from the starved and enriched soils when new P was given. Otherwise the greater yield on soil with residues and new P was always accompanied by the crop taking up more P.

Summary

In these experiments made to value accumulated residues from many dressings of P fertilisers, all crops gave larger yields on enriched soils than on starved soils when new P fertiliser was not given but fresh N and K were.

In the first experiment, on the Exhaustion Land at Rothamsted, four crops (barley, spring wheat, potatoes and swedes) of the six tested gave the same yield on the starved and enriched soils when new P was given and the other two crops (sugar beet and kale) gave almost the same yield. The cereals and potatoes recovered less than 0·5% and the other crops less than 1% per year of the total amount of P applied between 1856 and 1901. These results on the Exhaustion Land would not have justified a policy of deliberately building up residues in soil instead of giving new P each year when needed. However, on Agdell and at Woburn, new P failed to give as large yields of any of the three crops tested on previously starved as on enriched soils. Again the recovery of P from the residues was very small.

Larger yields were always associated with the uptake of more P. Thus, if the crop has to rely on newly applied P, this must be placed where the roots can take it up. Residues, which have been in the soil a long time, are

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intimately mixed with the soil, so the growing roots can get P from anywhere in the cultivated layer. Thus the plant is not prevented from obtaining enough P by poor mixing of a fresh dressing, or poor soil structure resisting root growth to a limited volume of soil.

P residues are probably now accumulating in many well fertilised soils, but how many soils in this country would behave as those on the Exhaustion Land and those on Agdell and at Woburn is not known. More experiments are needed to set limits, on each type of soil, to which P residues must be accumulated before different crops do not respond to new P on enriched soils.

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APPENDIX TABLE 1

Yields of cereals grown on the Exhaustion Land and Agdell at Rothamsted and on the Wheat and Barley Sites at Woburn, 1957–62

cwt/acre at 85% dry matter

Rothamsted

Exhaustion Land

Classical Experiment plot	New P dressing to seedbed lb/acre	Barley grain 1957	Barley grain 1958	Barley grain Mean	Barley grain Response	Barley straw 1957	Barley straw 1958	Barley straw Mean	Barley straw Response
5 no residues	0	20·4	12·1	16·2	—	19·7	26·6	23·2	—
	12·5	22·1	20·2	21·2	5·0	19·7	33·5	26·6	3·4
	25	22·8	24·6	23·7	7·5	22·4	37·2	29·8	6·6
	50	26·2	29·4	27·8	11·6	21·1	39·6	30·4	7·2
9 with P residues	0	25·6	24·0	24·8	—	21·1	38·4	29·8	—
	12·5	25·1	25·8	25·4	0·6	22·0	38·1	30·0	0·2
	25	26·4	27·5	27·0	2·2	25·0	39·3	32·2	2·4
	50	26·0	29·4	27·7	2·9	22·9	38·1	30·5	0·7

Classical Experiment plot	New P dressing to seedbed lb/acre	Spring wheat grain 1957	Spring wheat grain 1958	Spring wheat grain Mean	Spring wheat grain Response	Spring wheat straw 1957	Spring wheat straw 1958	Spring wheat straw Mean	Spring wheat straw Response
5 no residues	0	19·3	18·7	19·0	—	23·0	28·4	25·7	—
	12·5	20·3	24·2	22·2	3·2	26·3	41·6	34·0	8·3
	25	21·2	27·4	24·3	5·3	29·6	48·6	39·1	13·4
	50	23·2	29·1	26·2	7·2	33·0	51·2	42·1	16·4
9 with P residues	0	21·2	23·7	22·4	—	27·3	46·6	37·0	—
	12·5	24·1	24·5	24·3	1·9	32·4	42·4	37·4	0·4
	25	23·8	24·7	24·2	1·8	31·9	45·7	38·8	1·8
	50	22·6	25·5	24·0	1·6	30·8	48·1	39·4	1·4

Agdell

Classical Experiment plot	New P dressing to seedbed lb/acre	Barley grain 1959	Barley grain 1960	Barley grain Mean	Barley grain Response	Barley straw 1959	Barley straw 1960	Barley straw Mean	Barley straw Response
5 and 6 no residues	0	14·1	10·5	12·3	—	18·6	13·4	16·0	—
	12·5	20·6	12·6	16·6	4·3	21·6	14·5	18·0	2·0
	50	29·4	16·7	23·0	10·7	28·0	17·4	22·7	6·7
3 and 4 with P residues	0	31·3	23·0	27·2	—	29·8	22·8	26·3	—
	12·5	32·4	23·4	27·9	0·7	29·9	21·8	25·8	−0·5
	50	35·0	26·8	30·9	3·7	32·2	25·9	29·0	2·7
1 and 2 with P residues	0	23·8	21·8	22·8	—	19·4	25·3	22·4	—
	12·5	25·0	22·0	23·5	0·7	21·2	24·1	22·6	0·2
	50	22·6	24·6	23·6	0·8	20·6	25·7	23·2	0·8

Woburn

Wheat Site

Classical Experiment plot	New P dressing to seedbed lb/acre	Barley grain 1960	Barley grain 1962	Barley grain Mean	Barley grain Response	Barley straw 1960	Barley straw 1962	Barley straw Mean	Barley straw Response
7 no residues	0	20·0	29·1	24·6	—	24·0	26·3	25·2	—
	12·5	20·3	27·5	23·9	−0·7	24·0	24·6	24·3	−0·9
	50	23·2	27·2	25·2	0·6	26·9	25·0	26·0	0·8
8 with P residues	0	18·5	26·5	22·5	—	24·3	24·3	24·3	—
	12·5	18·5	28·3	23·4	0·9	24·9	22·0	23·4	−0·9
	50	18·1	24·9	21·5	−1·0	26·5	21·2	23·8	−0·5
9 with P residues	0	26·9	31·6	29·2	—	31·5	32·1	31·8	—
	12·5	26·3	29·1	27·8	−1·4	31·1	29·3	30·2	−1·6
	50	28·3	32·1	30·2	1·0	31·5	30·1	30·8	−1·0

Barley Site

Classical Experiment plot	New P dressing to seedbed lb/acre	Barley grain 1960	Barley grain 1961	Barley grain Mean	Barley grain Response	Barley straw 1960	Barley straw 1961	Barley straw Mean	Barley straw Response
7 no residues	0	16·6	17·9	17·2	—	19·6	20·9	20·2	—
	12·5	19·3	20·6	20·0	2·8	21·0	22·8	21·9	1·7
	50	19·6	21·3	20·4	3·2	23·3	24·1	23·7	3·5
8 with P residues	0	23·4	23·4	23·4	—	24·2	30·2	27·2	—
	12·5	24·3	26·4	25·4	2·0	24·8	30·2	27·5	0·3
	50	25·8	23·7	24·8	1·4	28·8	35·2	32·0	4·8
9 with P residues	0	22·9	25·3	24·1	—	24·0	32·5	28·2	—
	12·5	25·8	26·6	26·2	2·1	29·5	32·5	31·0	2·8
	50	26·9	27·9	27·4	3·3	32·3	36·7	34·5	6·3

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APPENDIX TABLE 2

Yields of potatoes grown on the Exhaustion Land and Agdell at Rothamsted and on the Wheat and Barley Sites at Woburn, 1957–62

Tubers, tons/acre

Classical Experiment plot	New P dressing[1] to seedbed lb/acre				
		Rothamsted Exhaustion Land			
		1957	1958	Mean	Response
5 no residues	0	5·0	5·2	5·1	—
	12·5	11·4	11·6	11·5	6·4
	25	11·8	13·6	12·7	7·6
	50	12·7	13·3	13·0	7·9
9 with P residues	0	9·3	7·4	8·4	—
	12·5	9·6	11·0	10·3	1·9
	25	11·4	11·0	11·2	2·8
	50	12·9	13·2	13·0	4·6
		Agdell			
		1959	1960	Mean	Response
5 and 6 no residues	0	3·6	6·1	4·8	—
	12·5	5·8	8·7	7·2	2·4
	50	7·6	12·6	10·1	5·3
3 and 4 with P residues	0	7·8	16·0	11·9	—
	12·5	9·0	17·4	13·2	1·3
	50	10·2	20·1	15·2	3·3
1 and 2 with P residues	0	6·8	18·7	12·8	—
	12·5	8·4	19·6	14·0	1·2
	50	10·2	22·2	16·2	3·4
		Woburn Wheat Site			
		1960	1962	Mean	Response
7 no residues	0	15·1	12·5	13·8	—
	12·5	15·3	11·9	13·6	−0·2
	50	16·3	12·8	14·6	0·8
8 with P residues	0	14·8	11·5	13·2	—
	12·5	17·0	13·4	15·2	2·0
	50	16·1	15·5	15·8	2·6
9 with P residues	0	18·6	14·8	16·7	—
	12·5	17·7	13·2	15·4	−1·3
	50	19·7	16·4	18·0	1·3
		Barley Site			
		1960	1961	Mean	Response
7 no residues	0	17·3	10·9	14·1	—
	12·5	16·7	11·3	14·0	−0·1
	50	19·0	12·7	15·8	1·7
8 with P residues	0	18·7	12·7	15·7	—
	12·5	19·4	11·8	15·6	−0·1
	50	19·8	13·4	16·6	0·9
9 with P residues	0	17·8	13·7	15·8	—
	12·5	18·6	12·5	15·6	−0·2
	50	19·2	14·1	16·6	0·8

[1] In the furrows before hand planting at Rothamsted, over the flat seedbed before machine planting at Woburn.

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APPENDIX TABLE 3

Yields of sugar from beet grown on the Exhaustion Land and Agdell at Rothamsted and the Wheat and Barley Sites at Woburn, 1957–62

Sugar, cwt/acre

Classical Experiment plot	New P dressing to seedbed lb/acre				
		Rothamsted Exhaustion Land			
		1957	1958	Mean	Response
5 no residues	0	18·3	42·8	30·6	—
	12·5	27·6	57·5	42·6	12·0
	25	28·7	61·4	45·0	14·4
	50	29·4	61·8	45·6	15·0
9 with P residues	0	29·6	60·8	45·2	—
	12·5	36·0	56·0	46·0	0·8
	25	29·0	55·5	42·2	−3·0
	50	32·5	63·1	47·8	2·6
		Agdell			
		1959	1960	Mean	Response
5 and 6 no residues	0	28·1	25·7	26·9	—
	12·5	31·8	31·8	31·8	4·9
	50	32·9	43·6	38·2	11·3
3 and 4 with P residues	0	49·0	43·1	46·0	—
	12·5	47·7	45·8	46·8	0·8
	50	47·4	48·2	47·8	1·8
1 and 2 with P residues	0	32·9	42·8	37·8	—
	12·5	34·2	44·6	39·4	1·6
	50	36·3	46·7	41·5	3·7
		Woburn			
		Wheat Site		Barley Site	
		1962	Response	1961	Response
7 no residues	0	50·2	—	32·1	—
	12·5	43·8	−6·4	34·7	2·6
	50	47·4	−2·8	34·6	2·5
8 with P residues	0	52·1	—	38·5	—
	12·5	45·2	−6·9	33·5	−5·0
	50	45·7	−6·4	31·6	−6·9
9 with P residues	0	51·0	—	43·0	—
	12·5	45·5	−5·5	34·5	−8·5
	50	54·3	3·3	43·6	0·6

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APPENDIX TABLE 4

Yields of swedes and kale grown on the Exhaustion Land at Rothamsted, 1957–58

tons/acre

Classical Experiment plot	New P dressing to seedbed lb/acre	1957	1958	Mean	Response
		Swede roots			
5 no residues	0	6·9	10·1	8·5	—
	12·5	8·4	19·8	14·1	5·6
	25	11·1	20·8	16·0	7·5
	50	12·2	23·4	17·8	9·3
9 with P residues	0	10·4	20·6	15·5	—
	12·5	11·6	21·5	16·6	1·1
	25	11·8	20·5	16·2	0·7
	50	12·2	23·6	17·9	2·4
		Swede tops			
5 no residues	0	1·0	2·5	1·8	—
	12·5	1·4	4·5	3·0	1·2
	25	1·8	4·8	3·3	1·5
	50	1·8	4·7	3·2	1·4
9 with P residues	0	1·8	4·0	2·9	—
	12·5	2·0	3·3	2·6	−0·3
	25	2·2	4·2	3·2	0·3
	50	2·0	4·1	3·0	0·1
		Kale			
5 no residues	0	13·2	16·3	14·8	—
	12·5	15·8	22·7	19·2	4·4
	25	17·4	22·8	20·1	5·3
	50	19·2	21·0	20·1	5·3
9 with P residues	0	15·2	23·1	19·2	—
	12·5	16·5	23·5	20·0	0·8
	25	17·6	24·9	21·2	2·0
	50	17·7	25·2	21·4	2·2

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The Value of Residues from Long-period Manuring at Rothamsted and Woburn

V. The Value to Arable Crops of Residues Accumulated from Potassium Fertilisers

A. E. JOHNSTON, R. G. WARREN and A. PENNY

These experiments were made on the Exhaustion Land at Rothamsted during 1957–58 and at Woburn on the Permanent Wheat and Barley Sites during 1960–62. Paper III (page 22) gives the histories of the sites and the experimental details, including amounts of K tested and basal N and P fertilisers. For the reasons given in the fourth paper (page 40), the yields of crops grown on both plots 8 at Woburn are given only in the Appendix Tables.

Yields

Cereals. Appendix Table 1 shows the yields of barley and spring wheat on the Exhaustion Land during 1957–58, and of barley at Woburn during 1960–62. New K increased grain yields by 1·4 to 2·5 cwt/acre on the starved soils but did not affect yield on the enriched soils (Table 1). There were also small increases in straw yields when new K was given.

TABLE 1

Effect of a new dressing of 56 lb K/acre on the yield of barley grown on soils with and without K residues at Rothamsted and Woburn, 1957–62

Grain, cwt/acre

	Rothamsted Exhaustion Land mean 1957 & 1958	Woburn Wheat Site mean 1960 & 1962	Woburn Barley Site mean 1960 & 1961
Starved soil			
Without new K	26·6	26·7	23·2
With new K	28·4	29·2	24·6
Response to new K[1]	1·8	2·5	1·4
Enriched soil			
Without new K	28·2	26·4	26·6
With new K	28·4	26·4	26·3
Response to new K[1]	0·2	0	−0·3

[1] New K at 56 lb K/acre applied broadcast to the seedbed.

Table 2 shows the yields on starved and enriched soils without new K. Residues slightly increased the yield of barley at Rothamsted and on the Barley Site at Woburn, but barley on the Wheat Site at Woburn and spring wheat on the Exhaustion Land yielded slightly less with than without residues.

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TABLE 2

Effect of K residues in the soil on the yields of cereals given no new K at Rothamsted and Woburn, 1957–62

Grain, cwt/acre

	Rothamsted Exhaustion Land mean 1957 & 1958		Woburn	
			Wheat Site mean 1960 & 1962	Barley Site mean 1960 & 1961
	Barley	Spring wheat	Barley	Barley
Soil given no new K and with:				
No residues	26·6	26·4	26·7	23·2
K residues	28·2	23·8	26·4	26·6
Increase due to K residues in the soil	1·6	−2·6	−0·3	3·4

The response curves to new K on both starved and enriched soils show the residues cannot be valued in terms of a new dressing of K, because the responses to new K fertiliser were too small and the yields on starved and enriched soils were too variable (Fig. 1).

Ploughed in and seedbed applications of new K fertiliser were compared in the experiments at Woburn in 1961–62. Yields (Table 3) show that the method of applying the new K had little effect.

TABLE 3

Effect of new K, ploughed in or broadcast on the seedbed, on barley yields at Woburn, 1961–62

Grain, cwt/acre

		Wheat Site 1962		Barley Site 1961	
K given lb/acre		Plot 9 with K residues	Plot 7 no K residues	Plot 9 with K residues	Plot 7 no K residues
0		28·5	28·9	28·1	25·9
14	Seedbed	—[1]	31·9	27·3	25·6
56	Seedbed	26·5	32·1	25·7	26·2
0		25·6	32·5	22·1	25·6
14	Ploughed in	29·9	34·8	25·4	27·6
56	Ploughed in	27·1	34·9	26·3	27·0

[1] No yield recorded because of extensive bird damage.

Potatoes. New K fertiliser was applied in different ways on the two sites. On the Exhaustion Land it was placed in the bottom of the furrows before the potatoes were set by hand, at Woburn it was either ploughed in or applied to the flat seedbed before the chitted seed was planted by machine. Appendix Table 2 shows the yields on the Exhaustion Land and at Woburn.

Table 4 shows that on both starved *and* enriched soils at Rothamsted and Woburn potatoes responded to new K at the largest amount tested, a striking contrast to the lack of response to K by cereals. Potatoes on the Exhaustion Land responded less to K than to P, but at Woburn the response to K was much larger than to P. On the starved soil at Rothamsted, the

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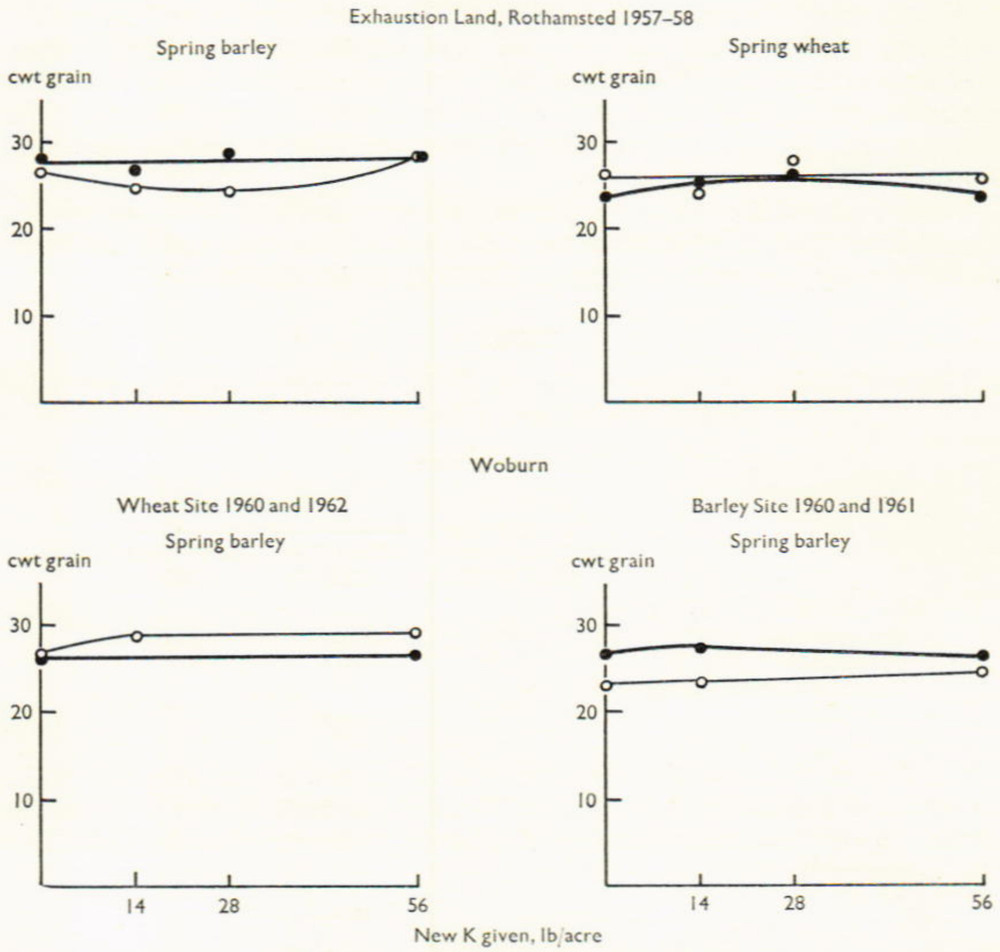

FIG. 1. Effect of K residues and new K on the average yield per acre of cereal grain, Rothamsted and Woburn, 1957–62.

(With ● and without ○ K residues.)

TABLE 4

Effect of a new dressing of 112 lb K/acre on the yield of potatoes grown on soils with and without K residues at Rothamsted and Woburn, 1957–62

Tubers, tons/acre

	Rothamsted Exhaustion Land mean 1957 & 1958	Woburn Wheat Site 1960	Woburn Barley Site 1960
Starved soil			
Without new K	6·8	11·9	14·3
With new K	12·4	17·0	18·2
Response to new K[1]	5·6	5·1	3·9
Enriched soil			
Without new K	11·0	16·3	16·4
With new K	14·6	19·3	18·2
Response to new K[1]	3·6	3·0	1·8

[1] New K at 112 lb K/acre given along the bottoms of the furrows before hand planting on the Exhaustion Land, on the flat seedbed before machine planting at Woburn.

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yield was only 6·8 tons/acre and giving 112 lb K increased it by 5·6 tons. A Woburn, yield on the starved soil was double that at Rothamsted, 11·9 tons/acre on the Wheat Site, 14·3 tons/acre on the Barley Site, but the increases in yield from 112 lb of new K were about the same as at Rothamsted, on the Wheat Site 5·1 tons and less on the Barley Site, 3·9 tons.

Table 5 shows the yields on starved and enriched soils without new K. The residues gave large increases in yield, about three-quarters of the extra yield given by the fresh dressing of 112 lb K to the starved soil.

TABLE 5

Effect of K residues in the soil on the yields of potatoes given no new K at Rothamsted and Woburn, 1957–62

Tubers, tons/acre

	Rothamsted Exhaustion Land mean 1957 & 1958	Woburn Wheat Site 1960	Woburn Barley Site 1960
Soil given no new K and with			
No residues	6·8	11·9	14·3
K residues	11·0	16·3	16·4
Increase due to K residues in the soil	4·2	4·4	2·1

Fig. 2 gives the response curves to new K on starved and enriched soils. On both the Exhaustion Land and at Woburn the residues can be valued in terms of a new broadcast dressing of K having the same effect on yield. The residues were worth:

	lb new K/acre
Exhaustion Land, Rothamsted	56
Wheat Site, Woburn	75
Barley Site, Woburn	16

Both on the Wheat Site at Woburn and on the Exhaustion Land, the response curves did not show a maximum and, with any amount of new K tested, yield on the enriched soil always exceeded that on the starved soil.

When ploughed in and seedbed dressings of fertiliser were compared at Woburn in 1961–62, the amount of new K applied was increased to see whether this would decrease the difference between the yield on soils with and without residues. Table 6 shows the yields with 42 and 168 lb K, but unfortunately one of the two plots without new K on plot 9 on the Wheat Site yielded very badly. On the starved soil on both sites, only the largest amount of new K ploughed in increased yield to equal that on the enriched soil without new K. However, giving new K to the enriched soils increased yield still further.

Sugar beet. This crop was grown on the Exhaustion Land in 1957–58, at Woburn on the Barley Site in 1961 and on the Wheat Site in 1962. Table 7 shows the yields of sugar on the Exhaustion Land with new K broadcast on the seedbed and Table 8 yields at Woburn when seedbed dressings and

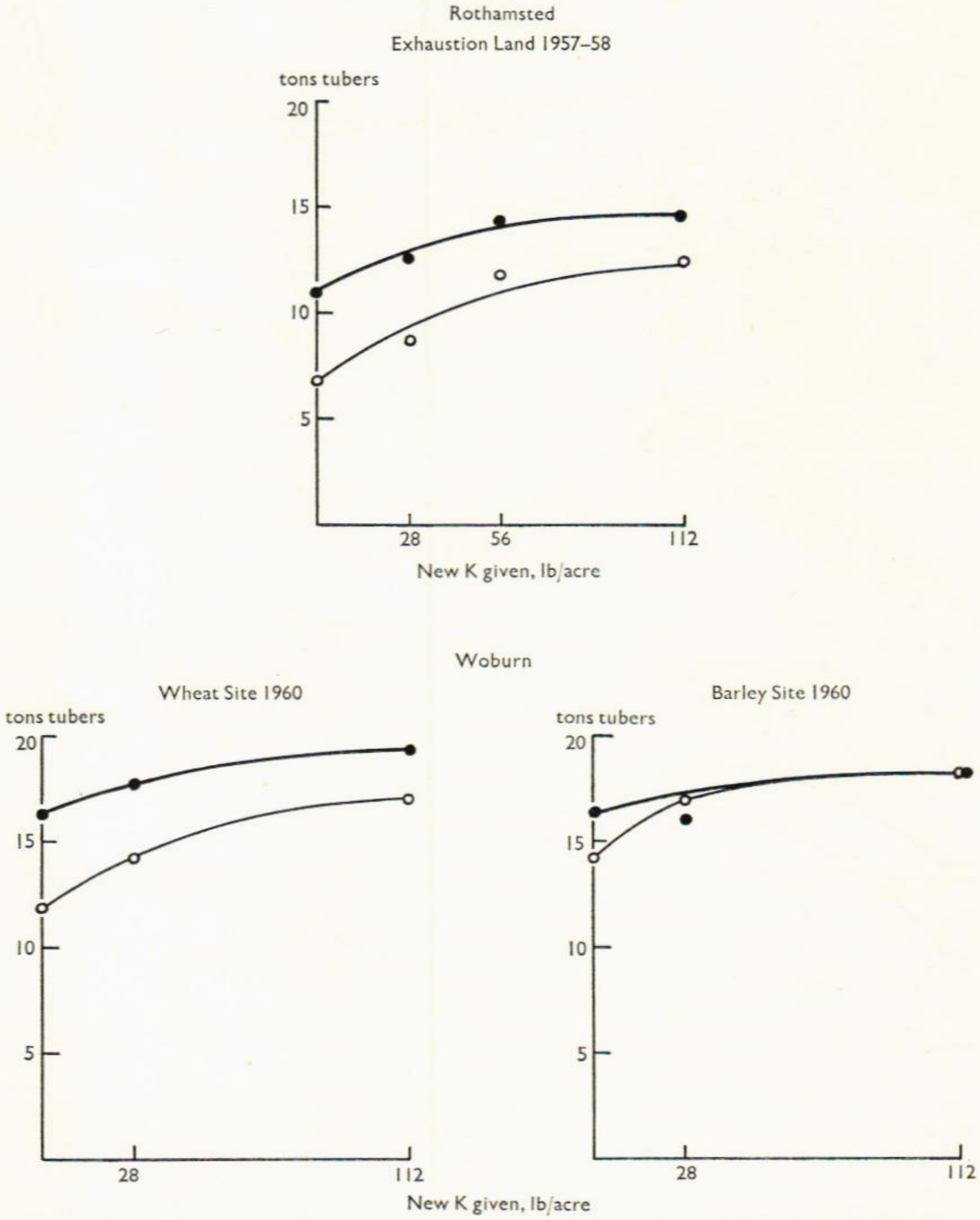

FIG. 2. Effect of K residues and new K on the average yield per acre of potato tubers, Rothamsted and Woburn, 1957–60.

(With ● and without ○ K residues.)

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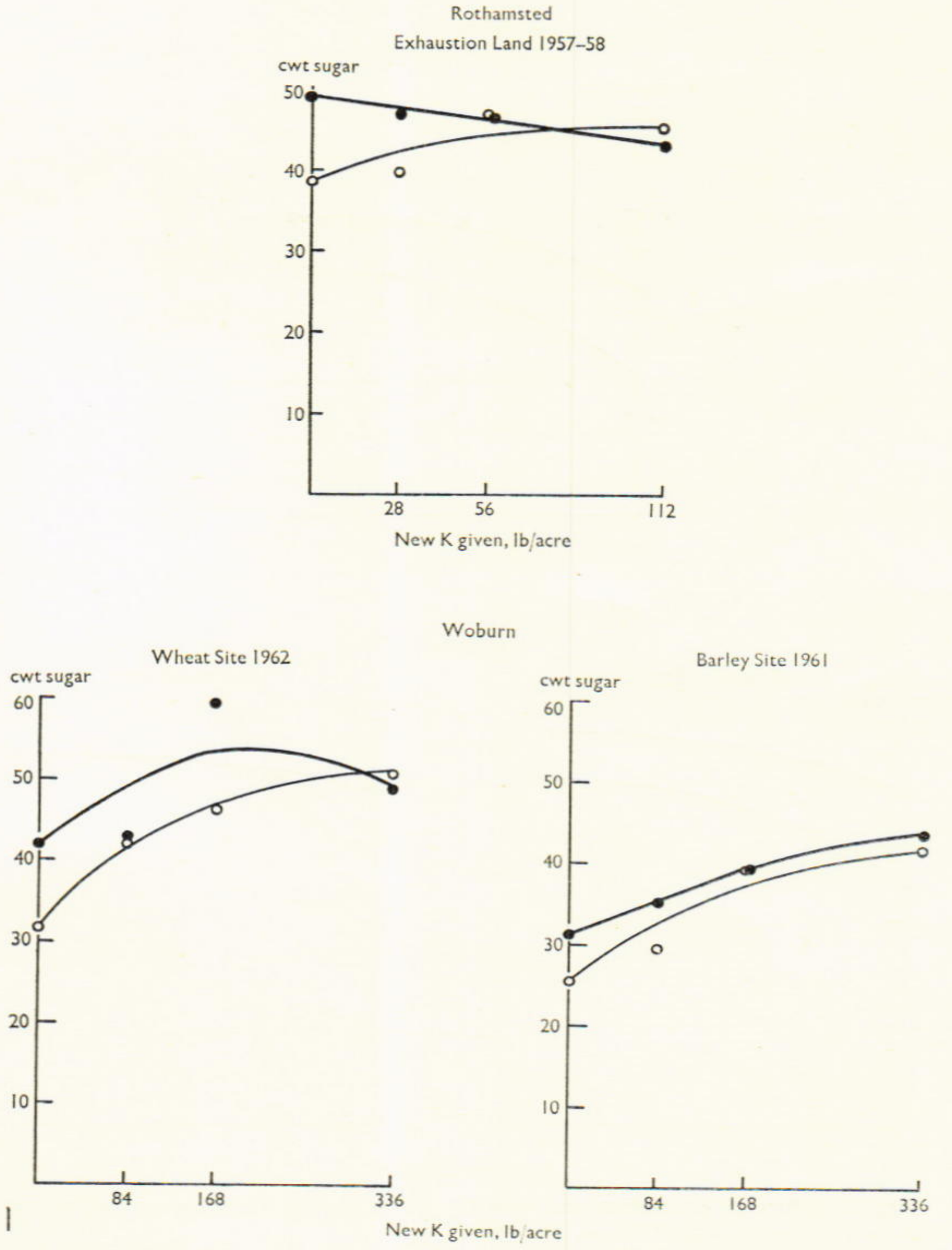

FIG. 3. Effect of K residues and new broadcast dressings of K on the average yield per acre of sugar at Rothamsted and Woburn.
(With ● and without ○ K residues.)

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TABLE 6

Effect of new K, ploughed in or broadcast on the seedbed, on potato yields at Woburn, 1961–62

Tubers, tons/acre

K given lb/acre		Wheat Site 1962 Plot 9 with K residues	Wheat Site 1962 Plot 7 no K residues	Barley Site 1961 Plot 9 with K residues	Barley Site 1961 Plot 7 no K residues
0		13·2	10·8	12·0	8·6
42	Seedbed	12·8	12·4	11·8	10·4
168	Seedbed	14·5	11·8	15·0	10·2
0		8·1	9·1	13·0	8·3
42	Ploughed in	12·3	12·4	12·5	11·1
168	Ploughed in	13·5	13·3	14·6	12·7

TABLE 7

Effect of new broadcast dressings of K on the yields of sugar from beet grown on soils with and without K residues on the Exhaustion Land, Rothamsted, 1957–58

Sugar, cwt/acre

Classical Experiment plot	K given lb/acre	1957	1958	Mean	Response
1 no K residues	0	25·9	51·8	38·8	—
	28	20·8	58·6	39·7	0·9
	56	30·7	63·2	47·0	8·2
	112	26·3	64·2	45·2	6·4
7 with K residues	0	31·2	66·7	49·0	—
	28	30·5	62·8	46·6	−2·4
	56	30·6	65·2	47·9	−1·1
	112	27·9	58·7	43·3	−5·7

TABLE 8

Effect of new K, ploughed in or broadcast on the seedbed, on sugar yields at Woburn, 1961–62

Sugar, cwt/acre

K given lb/acre	Wheat Site 1962 Plot 9 with K residues	Wheat Site 1962 Plot 7 no K residues	Barley Site 1961 Plot 9 with K residues	Barley Site 1961 Plot 7 no K residues
To seedbed				
0	42·0	31·6	31·4	25·5
84	42·5	41·9	35·2	29·7
168	59·7	46·2	39·6	39·3
336	48·8	50·8	43·7	41·8
Ploughed in				
0	45·5	38·0	29·1	18·2
84	43·2	40·9	42·0	34·1
168	50·2	43·7	36·6	33·1
336	45·3	52·5	43·6	33·0

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ploughed-in new K were tested in amounts up to 336 lb K/acre. On the Exhaustion Land beet yielded less in 1957 than in 1958, partly because of a severe attack by virus yellows. On the starved soil in 1957 the position of the microplots within the old Classical Experiment plot had a larger effect on yield than the new dressings of K. The microplots dressed with 28 and 112 lb/acre of new K, which were on the south side of the plot, gave a smaller mean yield than the other pair on the north, which had 0 and 56 lb new K. However, in 1958, yields were more consistent because the arrangement of the microplots was improved, and on the starved soil new K increased yield by 12 cwt of sugar/acre. On the enriched soil there was no response to new K.

Table 7 also shows that, without new K the effect of the residues was to increase sugar yield by 10 cwt/acre on the Exhaustion Land. At Woburn the residues increased yield by between 5 and 10 cwt/acre without new K (Table 8). The yield of sugar was the same on starved and enriched soils with new K at the largest amount tested. The residues on the Exhaustion Land could not be valued in terms of a new dressing of K (Fig. 3), but at Woburn they were worth between 75 and 85 lb of fresh K/acre.

TABLE 9

Effect of new broadcast dressings of K on the yields of swedes and kale grown on soils with and without K residues on the Exhaustion Land, Rothamsted, 1957–58

tons/acre

Classical Experiment plot	K given lb/acre	1957	1958	Mean	Response
		Swede roots			
1 no K residues	0	10·7	19·4	15·0	—
	14	11·9	21·9	16·9	1·9
	28	11·8	20·9	16·4	1·4
	56	11·5	20·6	16·0	1·0
7 with K residues	0	12·4	24·9	18·6	—
	14	12·7	25·3	19·0	0·4
	28	12·9	24·8	18·8	0·2
	56	12·9	25·0	19·0	0·4
		Swede tops			
1 no K residues	0	2·6	3·8	3·2	—
	14	2·5	4·3	3·4	0·2
	28	2·2	4·4	3·3	0·1
	56	2·4	4·1	3·2	0·0
7 with K residues	0	2·3	4·0	3·2	—
	14	2·2	4·4	3·3	0·1
	28	2·5	4·3	3·4	0·2
	56	2·2	4·2	3·2	0·0
		Kale			
1 no K residues	0	17·3	23·1	20·2	—
	28	16·5	21·1	18·8	−1·4
	56	19·8	22·6	21·2	1·0
	112	17·4	19·1	18·2	−2·0
7 with K residues	0	18·0	24·2	21·1	—
	28	18·4	23·3	20·8	−0·3
	56	18·4	23·0	20·7	−0·4
	112	20·9	24·6	22·8	1·7

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Swedes and kale. These two crops were grown only on the Exhaustion Land in 1957–58 and Table 9 gives yields of both. Swede roots responded to new K only on the starved soil, and maximum response (2 tons/acre) was to the smallest amount (14 lb/acre) of new K. However, the soil with residues yielded consistently more than the soil without, by about 3 tons/acre. The residues could not be valued in terms of a fresh dressing because the yield on starved soil with new K was less than on enriched soil without new K. The yields of swede tops were not increased by residues in the soil or by fresh K. Kale did not respond to new K on the starved soil, but on the enriched soil, the largest amount of K tested gave an extra 1·7 tons. The average yield was 2 tons/acre more with residues.

Discussion of the potassium tests

On the starved soils on the Exhaustion Land cereals without new K gave the same yield in both seasons. However, potatoes, sugar beet, kale and swedes all yielded more in 1958 than in 1957. 1958 was wetter, but less virus yellows in the sugar beet and less mildew on the swedes contributed to better yields in 1958.

Table 10 summarises the responses of the crops to the largest amount of new K applied as a seedbed dressing. At both Rothamsted and Woburn new K increased yield of barley on starved soil by 1 to 2 cwt grain but had no effect on enriched soil. Spring wheat on the Exhaustion Land did not respond to new K, on either the starved or enriched soil. In all years, and at both Rothamsted and Woburn, new K greatly increased potato yields on both starved and enriched soils. Sugar beet yields were usually increased by new K on starved and enriched soils, but not on the enriched soil of the Exhaustion Land, where the yield with new K was less than might have been expected. Swedes at Rothamsted gave small increases in yield with new K especially on starved soils, but yields of kale did not always increase with new K.

When the fertiliser K residues are valued by the difference in yield on soils with and without residues but with adequate N and P, they have considerable value at both Rothamsted and Woburn, except perhaps for cereals. Table 11 summarises the increases in yield from the presence of residues in the enriched soil.

The large crops currently being grown on many well fertilised soils take up much K, and it is not known whether K is accumulating in soils as is P. The section on K uptake shows that much K goes into the straw of cereals and the tops of sugar beet and how much K is removed from the soil depends on what happens to these parts of the crop. The accumulation of K is also related to the release of native soil K by weathering and the equilibrium between readily soluble and 'fixed' K. The rates of weathering and fixation of K differ considerably in different soils. Recent work at both Rothamsted and Woburn shows that change in the amount of K soluble in 1*N*-ammonium acetate is a good indication of the depletion or accumulation of readily soluble soil K during a cropping cycle. Current work is examining the release of K from reserves of 'fixed' K accumulated from fertiliser dressings.

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TABLE 10

Effect of a broadcast dressing of K as potassium sulphate on the yields of crops grown on soils with and without K residues at Rothamsted and Woburn, 1957–62

	Rothamsted			Woburn				
		Exhaustion Land mean 1957 & 1958			Wheat Site mean 1960 & 1962[1]		Barley Site mean 1960 & 1961[1]	
	New K given lb/acre	No K residues	With K residues	New K given lb/acre	No K residues	With K residues	No K residues	With K residues
Barley	0	26·6	28·2	0	26·7	26·4	23·2	26·6
grain, cwt	56	28·4	28·4	56	29·2	26·4	24·6	26·3
	56 minus 0	1·8	0·2	56 minus 0	2·5	0·0	1·4	−0·3
Spring wheat	0	26·4	23·8	—	—	—	—	—
grain, cwt	56	25·7	23·8	—	—	—	—	—
	56 minus 0	−0·7	0·0	—	—	—	—	—
Potatoes	0	6·8	11·0	0	11·9	16·3	14·3	16·4
tubers, tons	112	12·4	14·6	112	17·0	19·3	18·2	18·2
	112 minus 0	5·6	3·6	112 minus 0	5·1	3·0	3·9	1·8
Sugar beet	0	38·8	49·0	0	31·6	42·0	25·5	31·4
sugar, cwt	112	45·2	43·3	336	50·8	48·8	41·8	43·7
	112 minus 0	6·4	−5·7	336 minus 0	19·2	6·8	16·3	12·3
Swedes	0	15·0	18·6	—	—	—	—	—
roots, tons	56	16·0	19·0	—	—	—	—	—
	56 minus 0	1·0	0·4	—	—	—	—	—
Kale	0	20·2	21·1	—	—	—	—	—
tons	112	18·2	22·8	—	—	—	—	—
	112 minus 0	−2·0	1·7	—	—	—	—	—

[1] No sugar beet at Woburn in 1960.

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TABLE 11

Effect of old residues of fertiliser K dressings at Rothamsted and Woburn, 1957–62

Yields/acre

Crop	Site	Years	No K residues	With K residues	Increase due to K residues
Barley grain, cwt	Exhaustion Land	1957 & 1958	26·6	28·2	1·6
	Wheat Site, Woburn	1960 & 1962	26·7	26·4	−0·3
	Barley Site, Woburn	1960 & 1961	23·2	26·6	3·4
Spring wheat grain, cwt	Exhaustion Land	1957 & 1958	26·4	23·8	−2·6
Potatoes tubers, tons	Exhaustion Land	1957 & 1958	6·8	11·0	4·2
	Wheat Site, Woburn	1960 & 1962	11·4	14·8	3·4
	Barley Site, Woburn	1960 & 1961	11·4	14·4	3·0
Sugar beet sugar, cwt	Exhaustion Land	1957 & 1958	38·8	49·0	10·2
	Wheat Site, Woburn	1962	34·8	43·8	9·0
	Barley Site, Woburn	1961	21·8	30·2	8·4
Swedes roots, tons	Exhaustion Land	1957 & 1958	15·0	18·6	3·6
Kale tons	Exhaustion Land	1957 & 1958	20·2	21·1	0·9

Potassium concentration in the crops

Tables 12, 13 and 14 give the percentages of potassium in the dry matter of the crops.

Cereals. Johnston (1969) showed that the mineral composition of the grain and straw of winter wheat grown recently on Broadbalk confirmed Lawes and Gilbert's view that fully ripened grain has a consistent mineral composition whereas the composition of the straw varies considerably. Table 12 shows that the concentration of K in the grain grown on the starved soils on the Exhaustion Land and on the Barley Site at Woburn was 0·50%, slightly less than in the barley on the Hoosfield Continuous Barley plots. Barley on the Wheat Site at Woburn contained much less K (0·40%) for unknown reasons. K residues in the soil increased the concentration of K in the grain, but less on the Wheat Site than on the other two sites. On the enriched Exhaustion Land soil, the % K in the grain almost equalled that in the grain from the Hoosfield Continuous Barley Experiment. Dressings of fresh K did not increase the % K in grain from either the starved or enriched soils. The K concentration in the straw from the Exhaustion Land (1·16% in the enriched soil without new K) was nearly equal to that in the straw from the Hoosfield Continuous Barley Experiment, but the straw at Woburn contained only about half as much. Both the residual K in the soil and new dressings increased the % K in the straw by about the same amount, 0·1 to 0·3%.

Potatoes. Table 13 shows that the % K in dry matter of potato tubers from the Exhaustion Land was affected much more by new K than by K residues in the soil. However, the effect of the residues was not lessened by new K. At Woburn, in 1960, with larger concentrations of K in the

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TABLE 12

Effect of K residues and new K on the percentage of K in the grain and straw of cereals grown at Rothamsted and Woburn, 1957–62

% K in dry matter

	Rothamsted Exhaustion Land mean 1957 & 1958 K to seedbed				Woburn							
					Wheat Site 1962				Barley Site 1961			
	Barley		Spring wheat		K to seedbed Barley		K ploughed in Barley		K to seedbed Barley		K ploughed in Barley	
	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
No new K given to soil with												
No residues	0·48	0·84	0·37	0·40	0·43	0·50	0·39	0·34	0·50	0·40	0·50	0·46
K residues	0·54	1·16	0·42	0·48	0·39	0·52	0·41	0·49	0·53	0·61	0·52	0·61
Effect of residues	0·06	0·32	0·05	0·08	−0·04	0·02	0·02	0·15	0·03	0·21	0·02	0·15
56 lb new K given to soil with												
No residues	0·50	1·12	0·38	0·45	0·40	0·42	0·40	0·47	0·49	0·50	0·48	0·59
K residues	0·54	1·32	0·40	0·53	0·41	0·64	0·41	0·60	0·53	0·65	0·53	0·62
Effect of residues	0·04	0·20	0·02	0·08	0·01	0·22	0·01	0·13	0·04	0·15	0·05	0·03
Effect of 56 lb new K in the												
Absence of residues	0·02	0·28	0·01	0·05	−0·03	−0·08	0·01	0·13	−0·01	0·10	−0·02	0·13
Presence of residues	0·00	0·16	−0·02	0·05	0·02	0·12	0	0·11	0	0·04	−0·01	0·01

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TABLE 13

Effect of K residues and new K on the percentage of K in potatoes grown at Rothamsted and Woburn, 1957–62

% K in tuber dry matter

	Rothamsted Exhaustion Land mean 1957 & 1958	Woburn		Woburn			
		Wheat Site 1960	Barley Site 1960	Wheat Site 1962		Barley Site 1961	
	K in furrows	K to seedbed	K to seedbed	K to seedbed	K ploughed in	K to seedbed	K ploughed in
No new K given to soil with							
No residues	1·08	1·28	1·33	1·26	1·19	1·13	1·30
K residues	1·16	1·42	1·69	1·49	1·43	1·65	1·52
Effect of residues	0·08	0·14	0·39	0·23	0·24	0·32	0·22
New K[1] added to soil with							
No residues	1·40	1·68	1·82	1·85	1·61	1·74	1·59
K residues	1·50	1·92	2·20	1·92	1·79	2·04	2·04
Effect of residues	0·10	0·24	0·38	0·07	0·18	0·30	0·45
Effect of new K in the							
Absence of residues	0·32	0·40	0·49	0·59	0·42	0·41	0·29
Presence of residues	0·34	0·50	0·48	0·43	0·36	0·39	0·52

[1] 112 lb new K Exhaustion Land and Woburn 1960; 168 lb new K Woburn 1961–62.

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dry matter, the residues increased the % K more than at Rothamsted. Also at Woburn, 112 lb/acre of new K increased the % K more than the same dressing did at Rothamsted. This was true even though at Woburn the dressing was applied on the flat seedbed whereas at Rothamsted it was applied in the furrows. This again suggests that potato roots grow more easily and further in Woburn soil than in Rothamsted soil. This suggestion was supported when, in 1961–62, more K was tested at Woburn and seedbed dressings and ploughed-in new K increased the % K in dry matter similarly.

Sugar beet, swedes and kale. On the soil without residues or new K, swede tops and roots, sugar beet tops, and kale, all had nearly the same K concentration in the dry matter, but the sugar beet roots had much less (Table 14). K residues in the soil increased the % K in swede tops and roots

TABLE 14

Effect of K residues and new K on the percentage of K in sugar beet, swedes and kale grown on the Exhaustion Land, Rothamsted, 1957–58

	Swedes		Sugar beet		
	Tops	Roots	Tops	Roots	Kale
No new K given to soil with					
No residues	1·68	1·90	1·71	0·63	1·78
K residues	2·54	2·36	3·55	0·77	2·41
Effect of residues	0·86	0·46	1·84	0·14	0·63
New K[1] given to soil with					
No residues	2·19	2·21	2·30	0·74	2·31
K residues	2·62	2·55	3·66	0·90	2·54
Effect of residues	0·43	0·34	1·36	0·16	0·23
Effect of new K in the					
Absence of residues	0·51	0·31	0·59	0·11	0·53
Presence of residues	0·08	0·19	0·11	0·13	0·13

[1] 56 lb K to swedes, 112 lb K to sugar beet and kale.

and in kale by much the same amounts, but much less than in sugar-beet tops; however residues had little effect on the % K in sugar beet roots. New K increased the % K of all crops on starved soil much more than in the presence of residues.

Potassium content of the crops

Tables 15, 16, 17 and 18 give the uptakes of potassium by the harvested parts of the crops.

Cereals. Barley at Woburn and spring wheat at Rothamsted took up little more than 30 lb/acre K but the maximum uptake by barley at Rothamsted was twice as much (Table 15). More K was taken up from enriched than from starved soils and much of this extra K was in the straw. More K was taken up from newly applied K without than with residues, except for barley at Rothamsted, the uptake never exceeded 10% of the 56 lb/acre K newly applied.

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TABLE 15

Effect of K residues and new K on the amount of K in the grain and straw grown at Rothamsted and Woburn, 1957–62

lb K/acre/year

	Rothamsted Exhaustion Land mean 1957 & 1958 K to seedbed						Woburn: Wheat Site 1962						Woburn: Barley Site 1961					
	Barley			Spring wheat			K to seedbed Barley			K ploughed in Barley			K to seedbed Barley			K ploughed in Barley		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
No new **K** given to soil with																		
No residues	12	25	37	9	16	25	12	6	18	12	9	21	12	12	24	12	13	25
K residues	14	37	51	10	19	29	10	14	24	10	11	21	14	19	33	11	20	31
Effect of K residues	2	12	14	1	3	4	−2	8	6	−2	2	0	2	7	9	−1	7	6
56 lb new **K** given to soil with																		
No residues	13	36	49	10	20	30	12	12	24	13	15	28	12	15	27	12	18	30
K residues	15	42	57	9	22	31	10	18	28	11	15	26	13	18	31	13	19	32
Effect of K residues	2	6	8	−1	2	1	−2	6	4	−2	0	−2	1	3	4	1	1	2
Effect of 56 lb new K in the																		
Absence of residues	1	11	12	1	4	5	0	6	6	1	6	7	0	3	3	0	5	5
Presence of residues	1	5	6	−1	3	2	0	4	4	1	4	5	−1	−1	−2	2	−1	1

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TABLE 16

Effect of residues and new K on the amount of K in potato tubers grown at Rothamsted and Woburn, 1957–62

lb K/acre/year

	Rothamsted Exhaustion Land mean 1957 & 1958	Woburn					
		Wheat Site 1960	Barley Site 1960	Wheat Site 1962		Barley Site 1961	
	K in furrows	K to seedbed	K to seedbed	K to seedbed	K ploughed in	K to seedbed	K ploughed in
No new K given to soil with							
No residues	34	73	90	72	57	58	56
K residues	64	111	130	104	59	101	108
Effect of K residues	30	38	40	32	2	43	52
New K[1] given to soil with							
No residues	86	133	154	107	109	94	105
K residues	106	168	173	136	121	147	149
Effect of K residues	20	35	19	29	12	53	54
Effect of new K in the							
Absence of residues	52	60	64	35	52	36	49
Presence of residues	42	57	43	32	62	46	41

[1] 112 lb new K Exhaustion Land and Woburn 1960; 168 lb new K Woburn 1961–62.

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Potatoes. Uptake of K by potatoes on both sites (Table 16) varied very considerably, from 34 to 173 lb K/acre. Without new K, potato tubers from the starved soil on the Exhaustion Land contained about as much K as did the barley (grain plus straw), but tubers from the enriched soil contained more K than barley. At Woburn without new K, the potatoes took up more K than from the Exhaustion Land. The amount was about twice that taken up by the barley. Very much more K was taken up from the residues by potatoes than by barley. About 50% of the 112 lb/acre K tested on the Exhaustion Land and at Woburn in 1960 was taken up by potatoes. Increasing the dressings of new K to 168 lb K/acre at Woburn in 1961–62 did not increase K uptake from the fertiliser, so the apparent recovery of the added K by potatoes was only about 30% in 1961–62.

Sugar beet, swedes and kale. Without new K, sugar beet on the Exhaustion Land and at Woburn took up much the same amount of K (Table 17). By contrast potatoes took up less K on the Exhaustion Land than at Woburn, suggesting that they make less use of nutrients in Rothamsted soil than do sugar beet. From the starved soil without new K on the Exhaustion Land, sugar beet took up more than 100 lb K/acre and much more (180 lb) from the richer soil. Of the new K applied to the starved soil, the sugar beet took up 30 lb K (25%) but apparently none was taken up from the enriched soil. At Woburn the whole crop took up a maximum of 270 lb K. Possibly because the amount of new K tested was much more than at Rothamsted, more was taken up from the starved soil with new K than from the enriched soil without new K. However, maximum uptake was always with new K and residues. Apparent recoveries of added K were 30% from starved soils and 15% from enriched soils.

Swedes and kale on Exhaustion Land both resembled sugar beet, and took up much more K from the residues than from starved soil with fresh K fertiliser (Table 18). Without new K, kale extracted 13 lb more K from the

TABLE 18

Effect of K residues and new K on the amount of K in swedes and kale grown on the Exhaustion Land, Rothamsted, 1957–58

lb K/acre/year

	Swedes			
	Tops	Roots	Total	Kale
No new K added to soil with				
No residues	16	63	79	121
K residues	22	98	120	171
Effect of K residues	6	35	41	50
New K[1] added to soil with				
No residues	20	76	96	145
K residues	24	103	127	197
Effect of K residues	4	27	31	52
Effect of new K in the				
Absence of residues	4	13	17	24
Presence of residues	2	5	7	26

[1] 56 lb K to swedes; 112 lb K to kale.

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TABLE 17

Effect of K residues and new K on the amount of K in sugar beet grown at Rothamsted and Woburn, 1957–62

lb K/acre/year

	Rothamsted Exhaustion Land mean 1957 & 1958 K to seedbed			Woburn: Wheat Site 1962, K to seedbed			Woburn: Wheat Site 1962, K ploughed in			Woburn: Barley Site 1961, K to seedbed			Woburn: Barley Site 1961, K ploughed in		
	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total	Tops	Roots	Total
No new K added to soil with															
No residues	75	33	108	80	30	110	94	38	132	93	34	127	68	20	88
K residues	133	49	182	143	54	197	137	50	187	157	46	203	132	45	177
Effect of K residues	58	16	74	63	24	87	43	12	55	64	12	76	64	25	89
New K[1] added to soil with															
No residues	91	46	137	159	61	220	161	65	226	160	65	225	165	51	216
K residues	130	51	181	181	72	253	167	67	234	160	69	229	190	77	267
Effect of K residues	39	5	44	22	11	33	6	2	8	0	4	4	25	26	51
Effect of new K in the															
Absence of residues	16	13	29	79	31	110	67	27	94	67	31	98	97	31	128
Presence of residues	−3	2	−1	38	18	56	30	17	47	3	23	26	58	32	90

[1] 112 lb new K on Exhaustion Land; 336 lb new K at Woburn.

starved soil than did sugar beet and swedes 29 lb less. However, sugar beet extracted more K from the residues than did either kale or swedes. Apparent recovery of new K by swedes was altered by the residues; without them, 30% was taken up, with them, 12%. However, kale apparently recovered 20% of the new K from soils with and without residues.

Summary of the effects of K residues and new dressings of K fertiliser on K uptake

On the Exhaustion Land without new K, total uptake on the starved soil ranged from 25 lb by spring wheat to 121 lb/acre by kale, and on the enriched soil from 29 lb by spring wheat to 182 lb/acre by sugar beet. Thus, the recoveries from the residues ranged widely, from 4 lb by spring wheat to 74 lb by sugar beet. At Woburn there was a similar wide range of uptakes, 18 lb K by barley to 132 lb/acre K by sugar beet from the starved soil, and 21 lb K by barley to 203 lb/acre K by sugar beet from the enriched soil. In one comparison, barley obtained no extra K from the residues but sugar beet took up 89 lb K/acre. A large proportion of this extra K went into the straw of cereals, the tops of sugar beet and the roots of swedes. Except for potatoes and kale, the uptake from the residues was always decreased by new K fertiliser. Apparent recovery of new K was always less with than without residues, except for potatoes and kale. Apparent recoveries of the newly applied K ranged considerably, but the amounts of K tested were not the same in all experiments.

Summary

All crops tested gave larger yields on soils enriched with many past dressings of K fertilisers than on starved soils, when new K was not given but N and P fertilisers were.

Potatoes consistently responded well to new K on both starved and enriched soils, much more than the other crops.

All crops from soils enriched with residues contained more K than crops from starved soils. Thus, as for P, residues provide the growing plant with K throughout the cultivated soil. Except for potatoes, the concentration of K in each crop was increased more by residues than by the new dressings of fertiliser K. Much of the extra K taken up by cereals and sugar beet went into the straw and tops respectively.

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APPENDIX TABLE 1

Yields of cereals grown on the Exhaustion Land at Rothamsted and on the Wheat and Barley Sites at Woburn, 1957–62

cwt/acre at 85% dry matter

Exhaustion Land, Rothamsted

Classical Experiment plot	New K dressing to seedbed lb/acre	Barley grain				Barley straw			
		1957	1958	Mean	Response	1957	1958	Mean	Response
1 no K residues	0	26·7	26·4	26·6	—	22·4	37·5	30·0	—
	14	22·7	26·8	24·8	−1·8	19·6	40·2	29·9	−0·1
	28	22·2	26·5	24·4	−2·2	21·3	38·6	30·0	0·0
	56	30·2	26·5	28·4	1·8	27·0	39·8	33·4	3·4
7 with K residues	0	29·3	27·0	28·2	—	25·0	39·5	32·2	—
	14	27·5	26·3	26·9	−1·3	22·9	42·7	32·8	0·6
	28	28·9	28·6	28·8	0·6	25·3	39·2	32·2	0·0
	56	28·4	28·3	28·4	0·2	23·1	41·3	32·2	0·0
		Spring wheat grain				**Spring wheat straw**			
		1957	1958	Mean	Response	1957	1958	Mean	Response
1 no K residues	0	25·6	27·1	26·4	—	36·0	43·6	39·8	—
	14	21·4	26·7	24·0	−2·4	32·4	44·3	38·4	−1·4
	28	28·8	26·8	27·8	1·4	43·8	46·1	45·0	5·2
	56	23·6	27·8	25·7	−0·7	33·7	50·9	42·3	2·5
7 with K residues	0	22·5	25·0	23·8	—	31·2	45·0	38·1	—
	14	24·4	25·9	25·2	1·4	32·9	49·3	41·1	3·0
	28	24·7	27·2	26·0	2·2	35·2	49·4	42·3	4·2
	56	20·5	27·0	23·8	0·0	28·8	50·1	39·4	1·3

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Wheat Site, Woburn

Classical Experiment plot	New K dressing to seedbed lb/acre	Barley grain 1960	Barley grain 1962	Barley grain Mean	Barley grain Response	Barley straw 1960	Barley straw 1962	Barley straw Mean	Barley straw Response
7 no K residues	0	24·5	28·9	26·7	—	27·8	13·5	20·6	—
	14	25·9	31·9	28·9	2·2	26·0	27·7	26·8	6·2
	56	26·2	32·1	29·2	2·5	30·6	30·7	30·6	10·0
8 with K residues	0	19·0	26·9	23·0	—	24·2	21·1	22·6	—
	14	18·7	26·4	22·6	−0·4	26·5	23·7	25·1	2·5
	56	17·9	27·4	22·6	−0·4	27·1	24·5	25·8	3·2
9 with K residues	0	24·2	28·5	26·4	—	28·5	28·0	28·2	—
	14	24·5	—	—	—	29·9	—	—	—
	56	26·4	26·5	26·4	0·0	32·4	29·6	31·0	2·8

Barley Site, Woburn

Classical Experiment plot	New K dressing to seedbed lb/acre	Barley grain 1960	Barley grain 1961	Barley grain Mean	Barley grain Response	Barley straw 1960	Barley straw 1961	Barley straw Mean	Barley straw Response
7 no K residues	0	20·6	25·9	23·2	—	21·9	30·1	26·0	—
	14	21·3	25·6	23·4	0·2	22·0	29·1	25·6	−0·4
	56	23·0	26·2	24·6	1·4	23·9	31·8	27·8	1·8
8 with K residues	0	23·4	25·3	24·4	—	24·4	33·3	28·8	—
	14	24·0	27·9	26·0	1·6	23·9	31·5	27·7	−1·1
	56	23·8	25·7	24·8	0·4	26·4	33·5	30·0	1·2
9 with K residues	0	25·0	28·1	26·6	—	27·1	33·1	30·1	—
	14	27·3	27·3	27·3	0·7	28·1	30·4	29·2	−0·9
	56	26·9	25·7	26·3	−0·3	28·7	29·7	29·2	−0·9

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APPENDIX TABLE 2

Yields of potatoes grown on the Exhaustion Land at Rothamsted and on the Wheat and Barley Sites at Woburn, 1957–62

Tubers, tons/acre

Classical Experiment plot	New K dressing to seedbed lb/acre	Exhaustion Land, Rothamsted 1957	1958	Mean	Response
1 no K residues	0	4·7	8·8	6·8	—
	28	7·9	9·7	8·8	2·0
	56	11·5	12·1	11·8	5·0
	112	10·9	13·9	12·4	5·6
7 with K residues	0	10·0	12·1	11·0	—
	28	11·4	13·8	12·6	1·6
	56	14·0	14·9	14·4	3·4
	112	14·1	15·2	14·6	3·6
		Woburn			
		Wheat Site 1960	Barley Site 1960	Mean	Response
7 no K residues	0	11·9	14·3	13·1	—
	28	14·2	17·0	15·6	2·5
	112	17·0	18·2	17·6	4·5
8 with K residues	0	15·2	16·9	16·0	—
	28	14·9	17·2	16·0	0·0
	112	16·2	18·8	17·5	1·5
9 with K residues	0	16·3	16·4	16·4	—
	28	17·7	16·0	16·8	0·4
	112	19·3	18·2	18·8	2·4

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The Residual Value of Farmyard Manure and Superphosphate in the Saxmundham Rotation II Experiment, 1899–1968

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Introduction

The Rotation II experiment on Harwood's field at Saxmundham started in autumn, 1899, in the same year and tested the same 4-course rotation (wheat, roots, barley and a legume), as Rotation I. It was designed by Sir William Somerville, the first Drapers Professor of Agriculture at Cambridge, to determine how limited amounts of farmyard manure (FYM), nitrogen (as sodium nitrate) and phosphorus (as superphosphate) could best be distributed throughout the rotation. There were four blocks, one for each crop, and ten manurial treatments in each block. The history, including changes in manuring and results from the experiment were described by Oldershaw (1941) and Boyd and Trist (1966).

By 1952, although the cropping and manuring were no longer relevant to East Anglian farming, it was decided to keep seven of the original treatments on two of the four blocks for a further three rotations. The arrangement of these 14 plots, in relation to Rotation I, is shown schematically by Trist and Boyd (1966). They were manured and cropped, continuing the original rotation on the blocks known as Victors and Neals, until 1964.

In 1965 a new experiment was started on these plots to assess the value of soil P analysis on this soil. The adjacent two plots of treatment 8 of the original experiment, to which no P was added between 1952 and 1964, were included in the new experiment.

The sequence of cropping during the 4 years was barley, potatoes, turnips or sugar beet and barley. In 1969, the main plots of the experiment were divided into microplots to test, between 1969 and 1972, the value of the 'old' (1899–1964) and 'new' (1965–68) phosphate residues for three crops, potatoes, sugar beet and barley grown each year.

In this paper we describe:

1. the analysis of the soils, at the end of the original (1899–1964) manuring,
2. the changes in soil analysis between 1964 and 1968 and
3. the crop yields and nutrients removed between 1965 and 1968.

Methods of analysis

Soils were sampled 0–8 in. deep during autumn 1964 and 0–10 in. during autumn 1966 and 1968. These depths represented the plough layer, which was deepened in winter 1964/65 to improve the drainage and water-holding capacity of the surface soil.

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The methods of analysis used were those described for soils from Rotation I (Cooke, Mattingly & Williams, 1958), except that:

1. ***$CaCO_3$*** was measured by the method of Tinsley, Taylor and Moore (1951).
2. ***Total P*** was determined after fusion with Na_2CO_3 (Mattingly, 1970).
3. ***Exchangeable-K*** was measured by successively extracting 6·25 g of soil with *N*-ammonium acetate (250 ml).
4. ***Labile P*** (***Pe***) was measured by isotopic exchange in 0·02*M* KCl (Arambarri & Talibudeen, 1959) using a soil : solution ratio of 1 : 200 and a period of 150 hours for exchange.

Treatments, 1899–1964

Table 1 lists the treatments and mean yields of all crops, which were given previously by Boyd and Trist (1966). Although different crops in the rotation were dressed with FYM (10 tons/acre), sodium nitrate (26 lb N/acre) and superphosphate (73·5 lb P/acre), treatments 3 to 7 received the same total amounts of FYM, N and P in each 4-course rotation; treatment 8 received twice the amount of superphosphate (until 1952), treatment 2 received only FYM and treatment 1 was always unmanured.

Boyd and Trist stated in 1964:

'Perhaps the most important lesson to be learnt from the results of Rotation II came from the evidence it provided of the value of FYM and P fertiliser in raising yields of all crops in the rotation, not only those to which they were applied. Thus a single dressing of 10 tons FYM applied to wheat (treatment 2) not only increased the wheat yield by about a third compared with the unmanured plots (treatment 1) but also doubled the yield of mangolds, increased barley yield by almost a quarter and the yield of beans and clover, three crops later, by about a third. The application of P in addition to FYM gave further large increases in yield for all crops of the rotation whether or not the P fertiliser was applied directly to them. Indeed it is obvious from a study of the yields of treatments 3 to 7 that profitability of the rotation as a whole was only slightly influenced by the particular crop of the rotation to which the P was applied.'

The small differences between yields of treatments 3 to 7 are important to the subsequent use of the site which, in 1964, consisted of large areas of two blocks (Victors and Neals) that had received the same manuring for 65 years and from which almost the same quantities of crops had been removed.

The exact amounts of P applied to this soil are not known as neither the FYM nor superphosphate were analysed. Table 2 gives the total weights of FYM and superphosphate applied between 1899 and 1964 and estimates of the total P and K applied. These estimates are based on the following assumptions:

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TABLE 1

Treatments 1 to 8 and mean yields[a] Rotation II, 1899–1952

Treatment	Manuring per acre 1899–1952 (per 4 years)	Yields/acre: Wheat Treatment[b]	Wheat Grain (cwt)	Mangolds Treatment[b]	Mangolds Roots (tons)	Barley Treatment[b]	Barley Grain (cwt)	Beans Treatment	Beans Grain (cwt)
1	None	—	11·7	—	4·7	—	9·2	—	12·5
2	10 tons FYM	FYM	15·9	—	11·3	—	11·8	—	16·6
3		FYM	17·7	NP	19·3	—	13·4	—	20·6
4		NP	19·5	FYM	18·4	—	14·0	—	22·1
5	10 tons FYM plus 7½ cwt super-	N	19·6	FYM	18·8	—	14·2	P	22·6
6	phosphate (P) (5 cwt before 1921)	FYM + N	21·0	P	17·6	—	14·2	—	21·6
7		FYM	18·3	P	17·7	N	18·4	—	21·9
8	10 tons FYM plus 15 cwt superphosphate (10 cwt before 1921)	FYM	18·8	NP	21·7	½P	15·4	½P	22·8

[a] From Boyd and Trist (1966). [b] N, sodium nitrate (N), 1½ cwt/acre (1 cwt before 1921).

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1. that superphosphate contained 8·75% P, which very much overestimates the amounts applied in the early years of the experiment;

2. that FYM contained 44 lb P/10 tons, a value used previously for Rotation I (Cooke, Mattingly & Williams, 1958), which agrees well with analyses of the FYM applied in 1965 and 1966 (Table 6).

TABLE 2

Total amounts of FYM and superphosphate, and estimates of total P and K applied to Rotation II, 1899–1964

Treatment	Manuring per acre 1899–1964 (per 4 years)	Treatment symbol	Total applied per acre: FYM (tons)	Total applied per acre: Superphosphate (cwt)	Estimated P applied (lb/acre): FYM	Estimated P applied (lb/acre): Superphosphate	Estimated P applied (lb/acre): Total	Estimated K applied (lb/acre): FYM
1	None	None	None	None	None	None	None	None
2	10 tons FYM	FYM	160	None	705	None	705	1600
3	10 tons FYM plus 7½ cwt superphosphate (P) (5 cwt before 1921)	FYM + P	160	107·5	705	1050	1755	1600
4		FYM + P	160	107·5	705	1050	1755	1600
5		FYM + P	160	107·5	705	1050	1755	1600
6		FYM + P	160	107·5	705	1050	1755	1600
7		FYM + P	160	107·5	705	1050	1755	1600
8	Manuring stopped in 1952; until then 10 tons FYM plus 15 cwt superphosphate (2P) (10 cwt before 1921)	FYM + 2P	130	170	575	1665	2240	1300

Soil analysis, 1964

Table 3 gives analyses of the soils taken from the experiment in 1964, as means of the two blocks. Analyses from the two blocks were similar except for values of $NaHCO_3$-soluble P, labile P and $\frac{1}{2}pCa + pH_2PO_4$, some of which are given for the separate blocks (Table 4) and are discussed further below.

All plots contain free $CaCO_3$ (0·3 to 0·6%) and pH values (in 0·01 M $CaCl_2$), greatest on treatment 1, range only from 7·05 to 7·36. Farmyard manure alone (treatment 2) increased %C, %N, total P, all values of soluble P and exchangeable K and decreased $\frac{1}{2}pCa + pH_2PO_4$. Where superphosphate was given once in the rotation, in addition to FYM (treatments 3 to 7), or twice until 1952 (treatment 8), the %C was slightly (0·10%) larger, the mean %N was the same and total soil P about 180 ppm more than with only FYM. The $NaHCO_3$-soluble P and labile P values for treatments 3 to 8 (averaging both blocks) range from 38 to 44 and 108 to 120 ppm P respectively and are approximately three times larger than on the FYM only plot (treatment 2). The monocalcium phosphate potentials ranged from 6·90 to 6·98 and are about 0·8 units less than on treatment 2.

The mean analyses of the two blocks (Table 3) conceal the differences between soluble and labile P analyses because of the year when the last dressings of superphosphate were applied. Table 4 shows values of $NaHCO_3$-soluble P, labile P, P concentrations in 0·01 M $CaCl_2$ and $\frac{1}{2}pCa + pH_2PO_4$ in 1964, for single plots given superphosphate in either autumn 1963 or autumn 1960. There was more soluble and labile P in soils given superphosphate one year before sampling than in soils given

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TABLE 3

Chemical analyses of air-dry soils (0–8 in.) from Rotation II in 1964

Treatment	Manuring,[a] 1899–1964	Total C[b] (%)	Total N (%)	C/N ratio[b]	$CaCO_3$ (%)	pH in 0·01 *M* $CaCl_2$	Total P (ppm)	Labile P (ppm)	$NaHCO_3$-P (ppm)	$\frac{1}{2}pCa + pH_2PO_4$	Exchange-able K (ppm)
1	None	0·82	0·127	6·4	0·49	7·36	434	20	6	8·36	149
2	FYM	1·08	0·160	6·8	0·42	7·17	505	44	12	7·79	182
3	FYM + P	1·13	0·160	7·1	0·32	7·04	648	109	40	6·91	167
4	FYM + P	1·15	0·152	7·6	0·40	7·08	683	118	42	6·91	161
5	FYM + P	1·23	0·170	7·2	0·35	7·07	706	108	38	6·98	173
6	FYM + P	1·19	0·166	7·2	0·40	7·05	684	112	40	6·92	159
7	FYM + P	1·18	0·162	7·3	0·56	7·15	712	120	44	6·90	162
8	FYM + 2P	1·20	0·170	7·1	0·51	7·06	720	116	38	6·98	136

[a] For full details, see Tables 1 and 2. [b] Walkley-Black, uncorrected.

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TABLE 4

Soil analysis in relation to the application of FYM and superphosphate

Block	Treatment	FYM last applied	Superphosphate last applied	$NaHCO_3$-P (ppm)	Labile P (ppm)	P concentration (μM P/l.)	$\frac{1}{2}$pCa + pH_2PO_4
Victors	2	1962	None	10	41	0·5	7·81
Neals	2	1963	None	12	48	0·5	7·77
Victors	3	1962	1963	52	132	6·3	6·69
Neals	3	1963	1960	28	86	2·0	7·13
Victors	7	1962	1963	54	136	6·4	6·75
Neals	7	1963	1960	35	105	2·7	7·06

phosphate four years before. Values of $NaHCO_3$-soluble P ranged from about 50 ppm, in the year when P was applied, to about 30 ppm three years later. The yields of cereals and mangolds, however, increased only slightly when P was given (Table 1), probably because small crops were grown with the little N (26 lb/acre in addition to FYM) applied in the old rotation.

Unlike Rotation I, which tested K, potassium fertilisers were not given in Rotation II but some K was applied in the FYM given to treatments 2 to 8. If the FYM applied between 1899 and 1964 contained the same amount of K (100 lb K/10 tons FYM) as that applied in 1965 and 1966, then only 25 lb K was given on average each year. Most of this small amount of K was probably removed by the crops because increases in exchangeable K in the soils shown in Table 2 were small. Cooke and Williams (1966) showed by crop analysis that in Rotation I in 1964 and 1965 nearly all the K (50 lb K/acre) applied annually as potassium chloride was removed in the crops when N and P were also given.

Comparison of soil analyses of Rotation I (1957) and Rotation II (1964)

Total C, N and P. All plots of Rotation I were sampled (0–8 in.) and analysed in March, 1957 (Cooke, Mattingly & Williams, 1958), when the experiment was still ploughed to the same depth as Rotation II. Table 5

TABLE 5

Comparison of soil analyses (0–8 in.) on Rotation I[a] *(in 1957) and Rotation II (in 1964)*

Rotation	Treatment	Treatment/acre/4 years	%C	%N	Total P (ppm)	$NaHCO_3$-P (ppm)	Labile P (ppm)	$\frac{1}{2}$Ca + pH_2PO_4
	6	None	0·94	0·135	460[b]	2	28	8·60
I	1	24 tons FYM	1·55	0·199	750[b]	33	145	6·64
	10	Sodium nitrate, 8 cwt superphosphate, 8 cwt potassium chloride, 4 cwt	1·01	0·144	600[b]	19	92	7·60
	1	None	0·82	0·127	434	6	20	8·36
	2	10 tons FYM	1·08	0·160	505	12	44	7·79
	3–7	10 tons FYM plus 7½ cwt superphosphate, sodium nitrate, 1½ cwt	1·18	0·162	687	41	113	6·92

[a] Some analyses of Rotation I are from Cooke, Mattingly and Williams (1958).
[b] Measured by $HClO_4$ digestion (P_p) and calculated for fusion analysis (P_f) using the following relation $P_f = 38{\cdot}8 + 1{\cdot}0021\, P_p$ (Mattingly, 1970).

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compares some analyses of soils taken from the two experiments in 1957 and 1964 respectively. The %C, %N and total P contents of the unmanured soils from both experiments were very similar. The *increases* in %C, %N and total P contents (Δ%C, Δ%N, ΔP_t) of soils given FYM in both rotations (Rotation I, treatment 1; Rotation II, treatment 2) were:

	Δ%C	Δ%N	ΔP_t (ppm)
Rotation I	+0·61	+0·064	+290
Rotation II	+0·26	+0·033	+71
Ratio I/II	2·3	1·9	4·1

The ratio of the increases in %C and %N are very close to the ratio (2·2) of the total amounts of FYM applied to the two rotations, which suggests that, *for the same rotation*, the accumulation of organic matter is proportional to the amounts applied and is the same at Saxmundham whether FYM is given each year (Rotation I) or every 4 years (Rotation II).

In contrast to the good agreement between the accumulation of C and N and the amounts of FYM added in both rotations, proportionally more P remained in the soil from the larger amounts of FYM given to Rotation I. The amounts of P applied in FYM to Rotations I and II can be estimated assuming that a ton of FYM contained 4·4 lb P. The total amounts of P removed by crops in each experiment were estimated from the difference between the total applied and the increase in total soil P in the plough layer. Using a bulk density of 1·6 g/cm^3 (Williams, 1966), the total weight of soil in an 8 in. plough layer is $2{\cdot}8 \times 10^6$ lb.

On the basis of the above assumptions, the amounts of P applied to and recovered from both rotations were:

Treatment/acre/rotation		Total P applied (lb/acre)	Total P recovered lb/acre	%
Rotation I (1899–1957)	FYM 24 tons	1530	710	46
Rotation II (1899–1964)	FYM 10 tons	705	505	72
Rotation II (1899–1964)	FYM 10 tons, Superphosphate 7½ cwt	1755	1045	60

Despite the small amounts of N given in both rotations, between 46% and 72% of the total P applied has been recovered by cropping. Much less P would presumably remain in these soils had more N been used and larger crops grown.

Soluble and labile P. Figs. 1, 2 and 3 show the changes in labile P, $NaHCO_3$-soluble P and $\frac{1}{2}$pCa + pH_2PO_4 in the soils of both rotations in relation to the net increase in total soil P (ΔP_t)) between 1899–1957 (Rotation I) or 1899–1964 (Rotation II). Values for the two rotations agree well. Soil P increased most (+290 ppm P) on FYM plots of Rotation I, which also contained the most labile P and maintained the smallest values of $\frac{1}{2}$pCa + pH_2PO_4. The $NaHCO_3$-soluble P (33 ppm) was less on these

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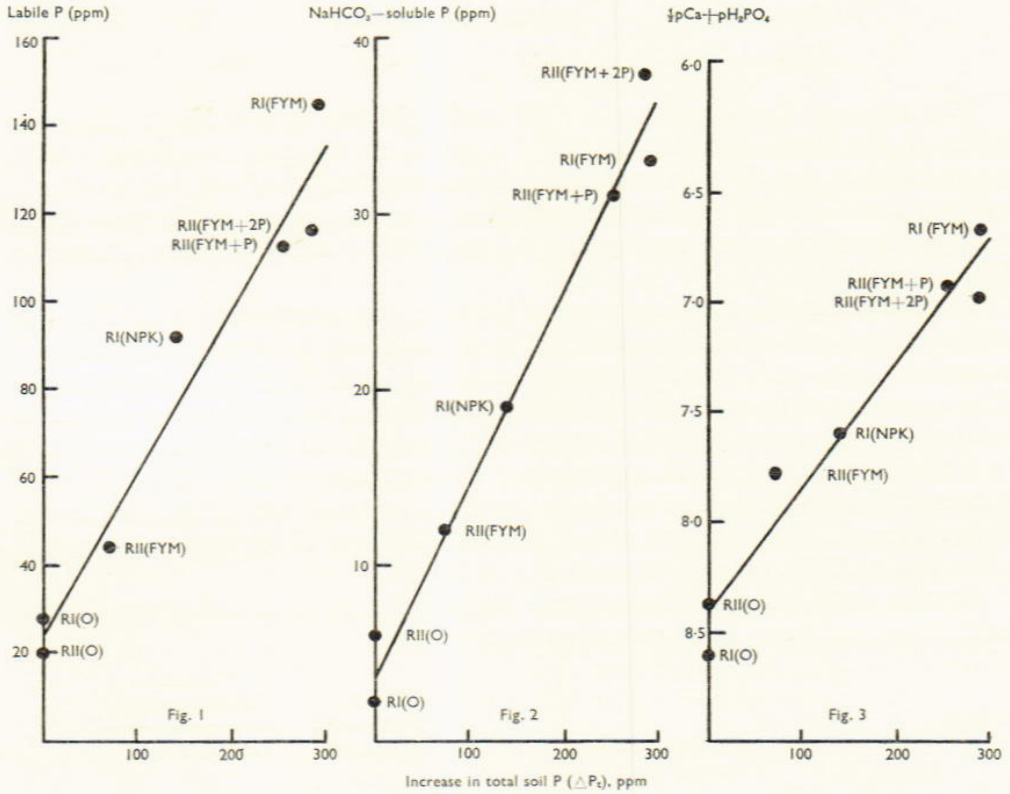
plots than the *mean* value (41 ppm) for Rotation II (treatments 3 to 7), given in Table 3, which was derived from analyses of all 10 plots given 73·5 lb P/acre as superphosphate during the three years before the soils were sampled. The $NaHCO_3$-soluble P in the 4 plots, last given P in 1960 or 1961 (31 ppm), probably more nearly represents an equilibrium value for this treatment and is used in the calculations below and in Fig. 2.



FIGS. 1, 2 and 3. Relationships between labile P (Fig. 1), 0·5*M* $NaHCO_3$-soluble P (Fig. 2) and $\frac{1}{2}pCa + pH_2PO_4$ (Fig. 3) and increases in total soil P (ΔP_t) for soils from Rotation I (1899–1957) and Rotation II (1899–1964).

Rotation	Symbol	Manuring	Treatment
I	RI(FYM)	FYM, 6 tons/acre annually	1
	RI(O)	Unmanured	6
	RI(NPK)	NK plus superphosphate, 2 cwt/acre, annually	10
II	RII(O)	Unmanured	1
	RII(FYM)	FYM, 10 tons/acre, once in 4 years	2
	RII(FYM + P)	FYM, 10 tons/acre, plus superphosphate, 7½ cwt/acre, once in 4 years	3–7
	RII(FYM + 2P)	FYM, 10 tons/acre, plus superphosphate, 15 cwt/acre, once in 4 years until 1952	8

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TABLE 6

FYM and superphosphate applied in Rotation II, 1965–68

(No FYM or superphosphate in 1968)

		1965		1966		1967		Total P applied (lb/acre) 1965–68		
Treatment	Manuring 1899–1964	FYM tons/acre	Super-phosphate lb P/acre	FYM tons/acre	Super-phosphate lb P/acre	FYM tons/acre	Super-phosphate lb P/acre	FYM	Super-phosphate	Total
1	None	None	None	None	None	None	None	None	None	None
2	FYM	None	None	None	None	None	None	None	None	None
3	FYM + P	None	None	None	None	None	None	None	None	None
4	FYM + P	None	None	20[a]	None	20[c]	None	206	None	206
5	FYM + P	None	73·5	20[a]	73·5[b]	20[c]	73·5[d]	206	220	426
6	FYM + P	None	73·5	None	73·5[b]	None	73·5[d]	None	220	220
7	FYM + P	None	147	None	147[b]	None	147[d]	None	440	440
8	FYM + 2P	None	None	None	None	None	None	None	None	None

[a] Applied autumn, 1965.
[b] Half in autumn, 1965; half in spring, 1966.
[c] Applied autumn, 1966.
[d] Half in autumn, 1966; half in spring, 1967.

(All autumn dressings before ploughing.)

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TABLE 7

Yields of barley and nutrient uptakes in 1965

Treatment	Manuring, 1899–1964	Manuring[a] in 1965 (lb P/acre)	Yields, cwt/acre: Green crop in July (dry matter)	Yields, cwt/acre: Grain at harvest (85% dry matter)	Total nutrients in grain plus straw, lb/acre: N	P	K
1	None	None	23·5	15·9	29	4·7	12
2	FYM	None	50·7	31·3	58	12·2	23
3	FYM + P	None	54·8	34·6	71	15·2	29
4	FYM + P	None	54·1	34·2	71	15·2	31
5	FYM + P	73·5	56·7	34·3	75	15·7	28
6	FYM + P	73·5	56·6	34·1	74	15·8	28
7	FYM + P	147	62·8	33·2	75	15·9	29
8	FYM + 2P	None	52·8	31·4	72	14·5	26

TABLE 8

Yields of potatoes and nutrient uptakes in 1966

Treatment	Manuring, 1899–1964	Manuring[a] in 1966: P (lb/acre)	FYM (tons/acre)	Yields, tons/acre: Total tubers	Dry matter	Total nutrients in tubers, lb/acre: N	P	K
1	None	None	None	7·45	2·02	60	5·7	75
2	FYM	None	None	14·56	4·11	98	14·3	152
3	FYM + P	None	None	16·85	4·74	112	20·2	172
4	FYM + P	None	20	20·47	5·42	129	24·3	214
5	FYM + P	73·5[b]	20	20·34	5·55	136	24·8	211
6	FYM + P	73·5[b]	None	18·23	4·98	114	21·7	181
7	FYM + P	147[b]	None	18·60	5·16	118	23·6	189
8	FYM + 2P	None	None	16·28	4·61	108	19·9	148

[a] All plots received N and K manuring (see p. 101). [b] The same dressings were applied for barley in 1965.

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Fitted regression lines give the following changes in $\frac{1}{2}$pCa + pH_2PO_4, $NaHCO_3$-soluble P and labile P for every 1 ppm (about 2·8 lb P/acre) that accumulates in the soil from residues of FYM or superphosphate.

(a) $\Delta(\frac{1}{2}pCa + pH_2PO_4)/\Delta P_t = -57 \pm 5{\cdot}3 \times 10^{-4}$
(b) $\Delta NaHCO_3\text{-soluble } P/\Delta P_t = +0{\cdot}11 \pm 0{\cdot}007$
(c) $\Delta P_e/\Delta P_t = +0{\cdot}37 \pm 0{\cdot}038$

These measurements provide an *approximate* guide to the changes in $\frac{1}{2}$pCa + pH_2PO_4, $NaHCO_3$-soluble P and labile P in Saxmundham soils, and probably also in similar Chalky Boulder-Clay soils, as P residues accumulate in them. The proportion of the total applied P that remains isotopically labile ($\approx$ 40%) is about the same (30–40%) as in Rothamsted soils (Mattingly & Talibudeen, 1961). $NaHCO_3$-soluble P increased in about 60 years by about one-tenth of the total P remaining in the soil.

Yields and nutrient uptakes, 1965–68

After the deeper ploughing in autumn, 1964, new dressings of FYM and/or superphosphate were given from 1965 to 1967 to produce 'new' P residues to compare with the 'old' P residues on treatments 2, 3 and 8. Treatments 4 and 5 were given 40 tons FYM/acre between 1965 and 1966; treatments 5 and 6 were given a total of 220 lb P/acre, and treatment 7 a total of 440 lb P/acre as triple superphosphate (21% P) between 1965 and 1967. P was not given in 1968, to ensure mixing and equilibration of the new P throughout the plough layer. Table 6 gives the amounts of FYM, superphosphate and P added between 1965 and 1968.

The plots of the old experiment (1899–1964) were 132 ft long and 18 ft wide. Each plot was divided at harvest in 1965 into two halves, each 66 ft long and 18 ft wide. Between 1965 and 1968 yields were taken from each half-plot, making four replications for each treatment. Barley was drilled along the plots and rows of potatoes (at 28 in. spacing) and sugar beet and turnips (in split plots at 18 in. spacing) were planted across the plots. The varieties grown and basal manuring were:

			lb/acre	
Year	Crop	Variety	N	K
1965	Barley	Proctor	90	93
1966	Potatoes	Pentland Dell	135	186
1967	Sugar beet	Klein E	135	111
	Turnips	Green	135	111
1968	Barley	Zephyr	84	45

Tables 7 to 11 give the crop yields and nutrients removed. Barley (grain and straw), potato tubers and sugar beet roots were all removed from the plots. Sugar beet tops and turnips (tops and roots) were all ploughed in on the plots where they grew.

Barley, 1965. Grain yields (Table 7) ranged from 16 to 34 cwt/acre. The residues of FYM given once every 4 years from 1899–1964 doubled yields (treatment 2) and the residues of FYM + P (treatments 3 and 4) gave slightly better yields (34·4 cwt/acre). Fresh superphosphate given in 1965 (treatments 5, 6 and 7) gave no extra yield.

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TABLE 9

Yields of turnips and nutrient uptakes in 1967

Treatment	Manuring, 1899–1964	Manuring[a] in 1967: P (lb/acre)	Manuring[a] in 1967: FYM (tons/acre)	Yields, tons/acre: Fresh roots	Yields, tons/acre: Dry matter: Roots	Yields, tons/acre: Dry matter: Tops	Total nutrients in tops plus roots, lb/acre: N	P	K	Na	Ca	Mg
1	None	None	None	2·22	0·29	1·16	91	5·7	102	7·0	100	10·0
2	FYM	None	None	5·00	0·68	1·30	81	10·6	144	6·7	93	9·6
3	FYM + P	None	None	6·84	0·91	1·51	96	17·6	169	11·3	96	9·4
4	FYM + P	None	20[c]	7·71	0·94	1·73	134	26·9	217	21·1	109	11·1
5	FYM + P	73·5[b]	20[c]	8·13	1·00	1·89	144	30·0	234	25·6	117	11·8
6	FYM + P	73·5[b]	None	7·92	0·97	1·51	107	22·7	181	22·8	98	9·5
7	FYM + P	147[b]	None	7·88	1·02	1·64	112	24·7	187	15·8	112	10·3
8	FYM + 2P	None	None	7·25	0·91	1·35	92	17·5	157	19·2	89	8·4

TABLE 10

Yields of sugar beet and nutrient uptakes in 1967

Treatment	Manuring, 1899–1964	Manuring[a] in 1967: P (lb/acre)	Manuring[a] in 1967: FYM (tons/acre)	Yields/acre: Roots: Fresh (tons)	Yields/acre: Roots: Dry (tons)	Yields/acre: Tops dry (tons)	Yields/acre: Sugar (cwt)	% sugar	Total nutrients in tops plus roots, lb/acre: N	P	K	Na	Ca	Mg
1	None	None	None	8·30	1·91	1·15	26·2	15·7	89	5·1	133	30	63	19·8
2	FYM	None	None	13·50	3·22	1·00	47·5	17·6	83	9·0	140	26	44	18·1
3	FYM + P	None	None	16·88	3·96	1·04	59·4	17·6	96	15·3	149	34	42	20·2
4	FYM + P	None	20[c]	19·55	4·44	1·30	67·2	17·2	125	20·9	182	50	43	24·6
5	FYM + P	73·5[b]	20[c]	19·51	4·40	1·24	67·3	17·3	128	22·8	179	55	39	23·5
6	FYM + P	73·5[b]	None	18·35	4·12	1·28	63·4	17·3	117	19·6	166	64	45	22·1
7	FYM + P	147[b]	None	18·61	4·24	1·17	64·4	17·3	111	21·0	153	43	44	20·8
8	FYM + 2P	None	None	17·44	4·03	1·19	60·1	17·3	104	16·2	151	43	44	19·5

[a] All plots received N and K manuring (see p. 101).
[b] The same dressings were applied for barley (1965) and potatoes (1966).
[c] 20 tons FYM to potatoes, 1966.

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Potatoes, 1966. Potatoes, which were planted in an excellent seedbed and grew well throughout the season, gave yields ranging from about 7·5 to more than 20 tons tubers/acre (Table 8). Yields were doubled by residues of farmyard manure (treatment 2) and increased by a further 1·7 to 2·3 tons/acre where FYM + P was given before 1964 (treatments 3 and 8). In contrast to barley, potatoes gave bigger yields with new P in 1966 in the presence of residues. Compared to FYM + P residues (treatment 3), which gave 16·8 tons/acre, 73·5 and 147 lb P/acre as fresh superphosphate (treatments 6 and 7) both produced a further increase of about 2 tons/acre, whereas the largest yields, about 20·4 tons/acre, were on plots given 20 tons FYM/acre the previous autumn, either without (treatment 4) or with (treatment 5) fresh superphosphate.

The following table compares yields and uptakes of N, P and K with and without FYM.

		Total P applied 1966 (lb P/acre)	Yield (tons/acre)	Uptake (lb/acre) N	P	K
With FYM	4	111	20·47	129	24·3	214
	5	184	20·34	136	24·8	211
	Mean	147	20·40	132	24·6	212
Without FYM	6	73·5	18·23	114	21·7	181
	7	147	18·60	118	23·6	189
	Mean	110	18·42	116	22·6	185

Potato tops remained greener throughout the season on plots given FYM and this better growth, which may have increased yield, was associated with larger uptakes of N, P and K.

Turnips and sugar beet, 1967. Early growth of both crops was good, but during the dry weather later the turnips flowered before lifting and were dry and poor quality when harvested in July. Yields of turnip roots (Table 9) increased from 2·2 tons/acre (treatment 1) to 7 tons/acre on plots with old residues (treatments 3 and 8). Adding fresh P, either as FYM or superphosphate (treatments 4, 5, 6 and 7), gave only 1 ton/acre more roots. As the potatoes, turnips removed more N, P and K (Table 9) from plots given fresh FYM than from those given fresh superphosphate but, in contrast to potatoes in 1966, or sugar beet in 1967, yields were not larger.

Sugar-beet yields (Table 10) ranged from 8·3 to 19·6 tons of roots/acre and sugar yields from 26 to 67 cwt/acre. 'Old' residues of FYM (treatment 2) and of FYM + superphosphate (treatment 3) increased sugar yields by 21 and 33 cwt/acre respectively. Compared to treatment 3 (59 cwt/acre), fresh superphosphate (treatments 6 and 7) increased yields by a further 4 to 5 cwt/acre, and fresh FYM, alone or with superphosphate (treatments 4 and 5), gave a further 3 cwt sugar/acre. The larger yields of tops and roots with fresh FYM contained more N and K and slightly more P and Mg.

Barley, 1968. The yield without P (treatment 1) in 1968, 24 cwt/acre (Table 11) was 8 cwt/acre more than in 1965 (Table 7). The crop, especially on treatments 4 to 8, lodged and yields with 'old' and 'new' P residues were

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TABLE 11

Yields of barley and nutrient uptakes in 1968

(No FYM or superphosphate applied in 1968)

Treatment	Manuring, 1899–1964	Manuring[a] in 1965–67 P (lb/acre)	FYM (tons/acre)	Yields at 85% dry matter cwt/acre Grain	Straw	Total nutrients in grain plus straw, lb/acre N	P	K
1	None	None	None	24·2	12·3	49	7·7	22
2	FYM	None	None	29·7	15·8	56	10·7	26
3	FYM + P	None	None	34·3	24·2	67	13·2	30
4	FYM + P	None	40	32·0	22·2	68	13·3	30
5	FYM + P	220	40	31·1	23·7	68	13·8	31
6	FYM + P	220	None	31·4	21·5	64	13·2	25
7	FYM + P	440	None	32·7	21·2	65	14·0	26
8	FYM + 2P	None	None	32·2	21·9	66	12·7	24

[a] All plots received N and K manuring (see p. 101).

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TABLE 12

Chemical analyses of air-dry soils (0–10 in.) from Rotation II in 1966

Treat-ment	Manuring[a] per acre 1965–68	Total C[b] (%)	Total N (%)	C/N[b]	$CaCO_3$ (%)	pH in 0·01 *M* $CaCl_2$	Total P (ppm)	Labile P (ppm)	$NaHCO_3$-P (ppm)	½pCa + pH_2PO_4	Ex-change-able K (ppm)
1	None	0·76	0·118	6·4	0·61	7·36	390	22	6	8·24	159
2	None	0·95	0·139	6·8	0·38	7·19	455	40	11	7·90	194
3	None	0·97	0·138	7·0	0·34	7·14	520	76	25	7·34	170
4	FYM, 40 tons	1·05	0·154	6·8	0·31	7·04	585	105	35	7·09	190
5	FYM, 40 tons + 220 lb P as superphosphate	1·06	0·154	6·9	0·41	7·12	601	123	46	6·93	184
6	220 lb P as super-phosphate	1·03	0·150	6·9	0·38	7·10	610	106	37	7·03	173
7	440 lb P as super-phosphate	1·03	0·156	6·6	0·69	7·20	645	146	58	6·78	174
8	None	1·06	0·156	6·8	0·55	7·22	591	103	36	7·22	160

TABLE 13

Chemical analyses of air-dry soils (0–10 in.) from Rotation II in 1968

Treat-ment	Manuring[a] per acre 1965–68	Total C[b] (%)	Total N (%)	C/N[b]	$CaCO_3$ (%)	pH in 0·01 *M* $CaCl_2$	Total P (ppm)	Labile P (ppm)	$NaHCO_3$-P (ppm)	½pCa + pH_2PO_4	Ex-change-able K (ppm)
1	None	0·80	0·119	6·7	0·61	7·45	402	28	3	8·58	176
2	None	0·97	0·136	7·1	0·32	7·32	450	44	7	8·35	189
3	None	1·04	0·134	7·8	0·36	7·25	530	81	21	7·69	187
4	FYM, 40 tons	1·21	0·156	7·8	0·50	7·16	644	123	39	7·20	213
5	FYM, 40 tons + 220 lb P as superphosphate	1·24	0·157	7·9	0·42	7·19	696	152	54	6·94	198
6	220 lb P as super-phosphate	1·09	0·153	7·1	0·50	7·24	631	123	44	7·13	171
7	440 lb P as super-phosphate	1·14	0·148	7·7	0·61	7·28	692	166	67	6·84	185
8	None	1·05	0·149	7·0	0·62	7·33	582	90	28	7·68	161

[a] All plots received N and K manuring (see p. 101). [b] Walkley-Black, uncorrected.

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2 to 3 cwt smaller in 1968 than in 1965. Straw yields in 1968 were doubled by 'old' residues of FYM and superphosphate (treatment 3), but were not increased further by 'new' residues (treatments 4 to 7).

Soil analyses, 1966 and 1968

Changes in total P and exchangeable K. Tables 12 and 13 give analyses of soils from all treatments sampled before ploughing in 1966 and 1968. It is impossible to compare them quantitatively with those from 1964 (Table 2) without allowing for the increase in the depth of ploughing (from about 8 to about 10 in.) between 1964 and 1966. Table 14 shows that deeper ploughing diluted the mean concentration of soil C, N and P on treatments 1, 2, 3 and 8 (to which no P was added between 1965 and 1968) by a factor of 0·85 to 0·89. In contrast, ploughing increased % $CaCO_3$ in the surface soil because the soil below 8 in. is calcareous. There was no further significant change between 1966 and 1968.

TABLE 14

Mean %C, %N, total P (ppm) and %$CaCO_3$ in soils from treatments 1, 2, 3. and 8 in 1964, 1966 and 1968

				Ratio	
	1964	1966	1968	1966/1964	1968/1966
%C	1·06	0·94	0·97	0·89	1·03
%N	0·154	0·138	0·134	0·89	0·97
Total P (ppm)	577	489	491	0·85	1·00
% $CaCO_3$	0·44	0·47	0·48	1·07	1·02

Between 1965 and 1968 the amounts of both P and K applied as fertilisers and in FYM exceeded the amounts removed by cropping. Table 15 gives a balance for the additions and removals of P and K and the changes in total P and exchangeable K in the soils between 1964 and 1968. In these calculations we assume:

1. the effective plough depth was 8·0 in. in 1964 and 9·5 in. in 1968. (This is consistent with the dilution factor of 0·85 for total P measured between 1964 and 1968).
2. The weight of soil per acre per in. = $0{\cdot}35 \times 10^6$ lb, corresponding to a bulk density of 1·6 g/cm^3.
3. No P and K in turnip tops and roots and sugar beet tops was lost before they were ploughed back into the soil.

Except for treatments 1 and 2, the net loss or gain of P by manuring and cropping agreed well with the change in total soil P in the plough layer, and the average of the two values for all 8 treatments differed by only 30 lb P/acre.

Fig. 4 shows the decline in the total P content of all the soils between 1964 and 1966 as a result of deeper ploughing. Where P was not given (treatments 1, 2, 3 and 8), there was little further change between 1966 and 1968, but where it was total soil P increased, especially where the most

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TABLE 15

Changes in total P and exchangeable K in surface soils between 1964 and 1968 and net gains or losses of P and K

Treatment	Manuring[a] per acre 1965–68	Total P, lb/acre 1964 (to 8 in.)	Total P, lb/acre 1968 (to 9·5 in.)	Total P, lb/acre Increase (1968–1964)	P applied *minus* P removed	Exchangeable K, lb/acre 1964 (to 8 in.)	Exchangeable K, lb/acre 1968 (to 9·5 in.)	Exchangeable K, lb/acre Increase (1968–1964)	K applied *minus* K removed
1	None	1215	1340	+125	−19	417	585	+168	+306
2	None	1415	1500	+85	−40	510	629	+119	+204
3	None	1815	1760	−55	−54	468	622	+154	+168
4	FYM, 40 tons	1910	2140	+230	+147	450	710	+260	+526
5	FYM, 40 tons + 220 lb P as superphosphate	1980	2320	+340	+366	484	659	+175	+528
6	220 lb P as superphosphate	1915	2100	+185	+163	445	570	+125	+163
7	440 lb P as superphosphate	1995	2300	+305	+380	454	615	+161	+153
8	None	2020	1935	−85	−52	381	535	+154	+201

[a] All plots received N and K manuring (see p. 101).

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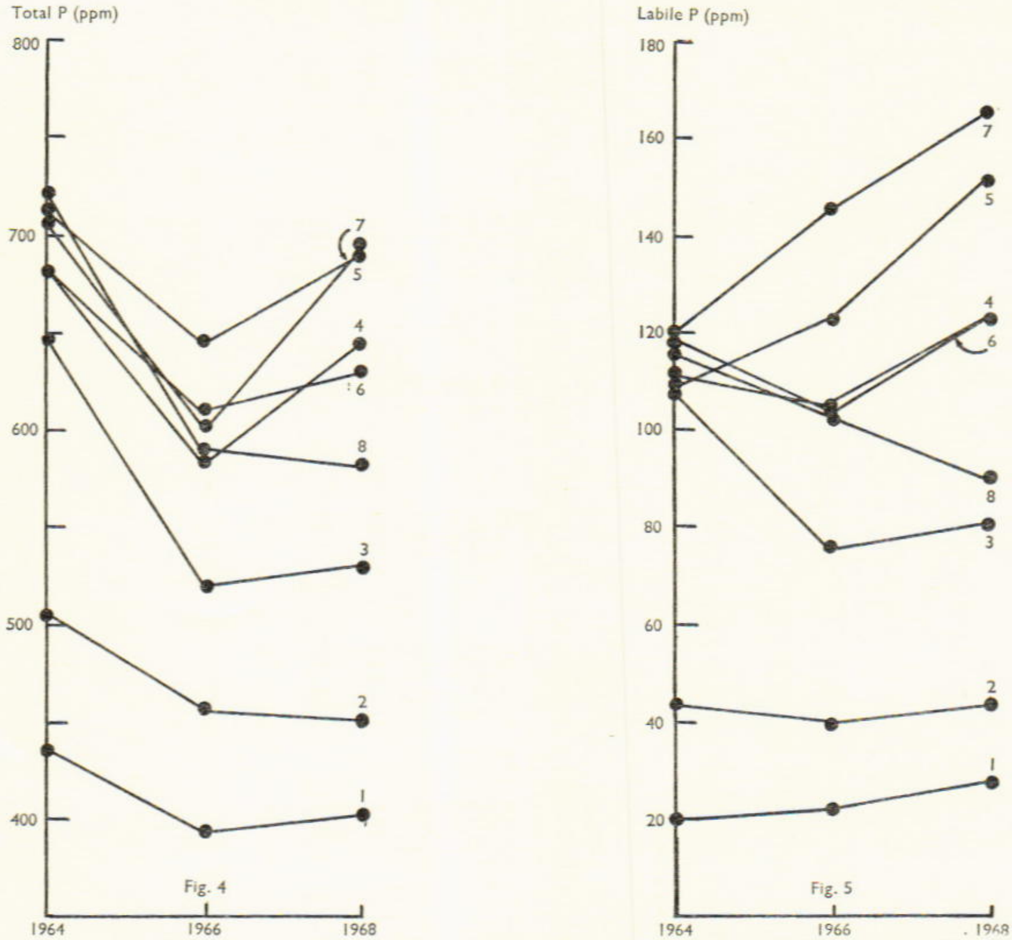

FIGS. 4 and 5. Changes in total soil P (Fig. 4) and labile P (Fig. 5) in Rotation II between 1964 and 1968.

Treatment	Manuring, 1899–1964[a]	P applied (lb/acre), 1965–68[b]
1	None	None
2	FYM	None
3	FYM + P	None
4	FYM + P	206
5	FYM + P	426
6	FYM + P	220
7	FYM + P	440
8	FYM + 2P	None

[a] For details, see Table 1. [b] For details, see Table 6.

FYM and superphosphate were given (treatments 5 and 7). However, the largest P contents in 1968 (696 ppm) were still smaller than in 1964, even though 440 lb P/acre was given as superphosphate (treatment 7) and 426 lb P/acre as FYM and superphosphate (treatment 5).

In contrast, the exchangeable K in the plough layer increased less than the net gain in applied K. Where FYM was given the increase in exchangeable K in the top 9·5 in. of soil was only one-half and one-third of the gain in K from manuring on treatments 4 and 5 respectively. Much of the apparent loss probably reflected fixation in non-exchangeable forms

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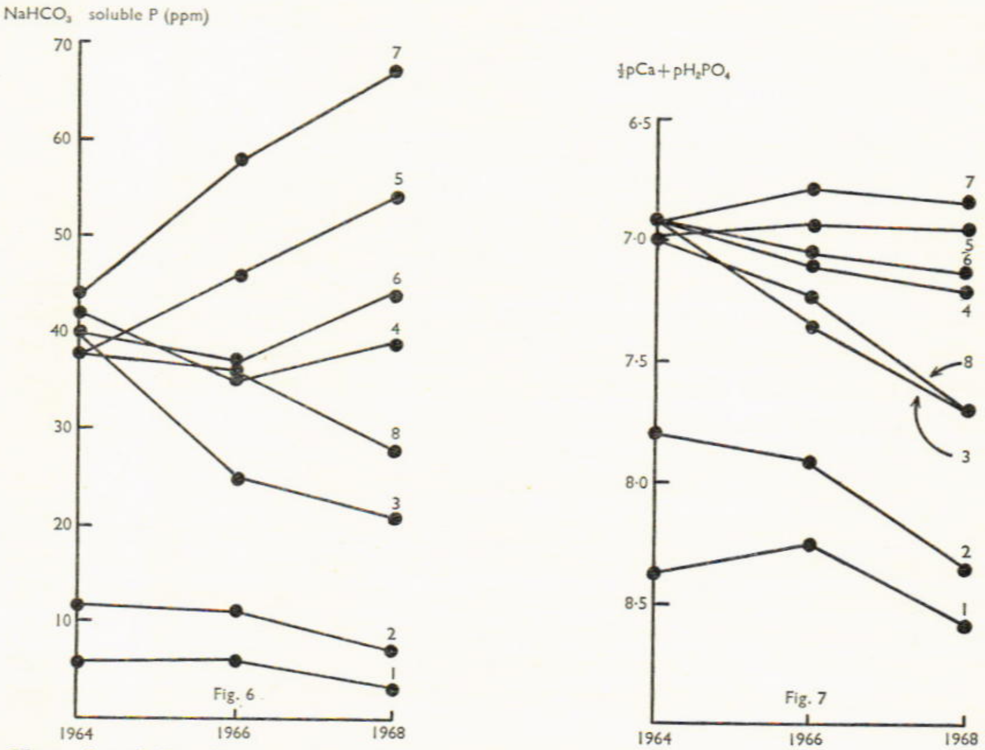

FIGS. 6 and 7. Changes in 0·5*M* $NaHCO_3$-soluble P (Fig. 6) and $\frac{1}{2}$pCa + pH_2PO_4 (Fig. 7) in Rotation II between 1964 and 1968.
(For key to treatments, see Figs. 4 and 5.)

(which were not measured) in this slightly calcareous soil, but some K may have leached below plough depth.

Changes in $NaHCO_3$-soluble and labile P. Values of labile P (Fig. 5) either declined or remained almost constant, and $NaHCO_3$-soluble P values (Fig. 6) all declined where fresh P was not given (treatments 1, 2, 3 and 8), not only between 1964 and 1966 but also between 1966 and 1968. Soluble and labile P increased where most fresh FYM or superphosphate were given (treatments 5 and 7) and were maintained at the 1964 amounts in treatments 4 and 6. This increase occurred even though the residues of 'fresh' FYM and superphosphate did not increase total soil P content (ppm) because they were distributed through more soil in 1968 than in 1964. The increases in $NaHCO_3$-soluble P and labile P between 1964 and 1968 were:

		Increase 1964–68			
		ppm		lb P/acre	
Treat-ment	Manuring 1965–67	$NaHCO_3$ soluble-P	Labile P	$NaHCO_3$ soluble-P	Labile P
5	FYM, 40 tons plus 220 lb P/acre as superphosphate	+16	+44	+76	+203
7	440 lb P/acre as superphosphate	+23	+46	+100	+207

The net gains in total P in the top 9·5 in. of soils from new residues (treatments 5 and 7) were 340 and 305 lb P/acre respectively (Table 15). The

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increases in $NaHCO_3$-soluble P and labile P (Pe), per unit increase in total soil P, for 'old' and 'new' residues were:

	$\Delta NaHCO_3$-soluble $P/\Delta P_t$	$\Delta P_e/\Delta P_t$
'Old' residues, 1899–1964	0·11	0·37
'New' residues, 1965–68	0·25	0·60

Changes in the solubility of soil P. Values of $\frac{1}{2}pCa + pH_2PO_4$ (Fig. 7) show that the solubility of soil P declined (treatments 1, 2, 3 and 8) between 1964 and 1968 and was maintained, but not appreciably increased, (treatments 4, 5, 6 and 7) where fresh P was given. In contrast to soils from some of the Classical Experiments at Rothamsted (Aslyng, 1954), all the Saxmundham soils from Rotations I or II are undersaturated with octacalcium phosphate.

Soil analysis and crop response

Table 16 summarises yields of barley, potatoes, turnips and sugar beet between 1965 and 1968 in relation to soil P analysis. Yields of barley, grown on soils with 20–40 ppm $NaHCO_3$-soluble P and adequate N and K, were not increased by fresh superphosphate (73·5 lb P/acre) in 1965 or by fresh residues of cumulative dressings (1965–67) in 1968. Yields of potatoes, turnips and sugar beet, however, were all more with fresh superphosphate than with residues alone.

TABLE 16

Yields and responses of barley, potatoes, turnips and sugar beet in relation to soil analysis, 1965–67

	Soil analysis			Yields/acre				
							Sugar beet	
Treatment	$NaHCO_3$-soluble P (ppm)	Labile P (ppm)	$\frac{1}{2}pCa + pH_2PO_4$	Barley[a] grain (cwt)	Potatoes tubers (tons)	Turnips roots (tons)	Roots (tons)	Sugar (cwt)
1	4–6	20–25	8·4–8·2	15·9	7·4	2·2	8·3	26
2	9–12	40–45	8·1–7·8	31·3	14·6	5·0	13·5	48
3	20–40	75–110	7·5–6·9	34·6	16·8	6·8	16·9	59
	Increase from 73·5 lb P/acre (treatment 6 *minus* 3)			−0·3	+1·4	+1·1	+1·7	+4

[a] At 85% dry matter.

At the end of 1968 the soils ranged widely in $NaHCO_3$-soluble P (about 3 to 67 ppm) and in labile P (about 28 to 166 ppm). Residues of 'old' and 'new' FYM and P are now being evaluated, relative to fresh superphosphate applied in the seedbed, in a crop rotation of potatoes, barley (without P), sugar beet and barley (without P) to compare crop response and soil analysis on the Chalky Boulder-Clay soil at Saxmundham with crop response at Rothamsted and Woburn.

Conclusions and Summary

1. Between 1899 and 1964 more P was applied in FYM alone (10 tons/acre/rotation) and in FYM (10 tons/acre/rotation) plus superphosphate

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(about 74 lb P/acre/rotation) than was removed by cropping. $NaHCO_3$-soluble P and isotopically-exchangeable (labile) P were directly proportional, and $\frac{1}{2}pCa + pH_2PO_4$ inversely proportional, to the increase in total P(ΔP_t) in the soil. $NaHCO_3$-soluble P and labile P increased by the same amounts, per unit increase in total soil P, in Rotation I (when sampled in 1957) as in Rotation II in 1964, and were about 10% and 40% respectively of the increases in total soil P that accumulated from 'old' P residues.

2. $NaHCO_3$-soluble P, labile P and $\frac{1}{2}pCa + pH_2PO_4$ in 1964 were 6 ppm, 20 ppm and 8·36 on plots without P, 12 ppm, 44 ppm and 7·79 where FYM only was given (treatment 2) since 1899 and 41 ppm, 113 ppm and 6·92 where FYM and superphosphate were given (treatments 3 to 7) in the old rotation.

3. The only K applied in the old rotation came from FYM which supplied about 100 lb K/acre/rotation. Negligible amounts remained in the soil as exchangeable K in 1964.

4. Between 1964 and 1968, deeper ploughing (from about 8 to 10 in.) lessened the total P content of the soil by a factor of about 0·85 where further P was not applied (treatments 1, 2, 3 and 8). Where FYM (40 tons/acre containing 206 lb P) or superphosphate (220 lb P/acre) were given between 1965 and 1967 (treatments 4 and 6), total P was less in 1968 than in 1964; where FYM plus superphosphate (total P 426 lb/acre) or 440 lb P/acre were given as superphosphate (treatments 5 and 7), the extra P applied just maintained the original P content (in ppm) of the soil. The 'fresh' P given between 1965 and 1967 was incorporated within the deeper (9·5 in.) plough layer and increased both the concentration of $NaHCO_3$-soluble P and labile P (ppm) and the total amounts (lb P/acre) in the plough layer. The increases in $NaHCO_3$-soluble P and labile P were about 25% and 60% respectively of the increases in total soil P that accumulated from 'new' P residues.

5. Between 1965 and 1968 more K was applied as FYM and/or inorganic K than was removed by cropping. Exchangeable K (in ppm) increased during this period despite dilution by ploughing.

6. Yields of barley in 1965 and 1968, with adequate NK fertiliser, ranged from 16 to 35 cwt/acre and increased in the order: no P < FYM residues < FYM + superphosphate residues. Fresh superphosphate in 1965 did not increase yields further. Yields of potatoes in 1966, given NK fertilisers, ranged from 7·4 to 20·5 tons/acre. Yields with FYM + P residues (treatment 3) were 16·8 tons/acre and 'fresh' superphosphate (74 lb P/acre) increased yields by 1·4 tons/acre and 'fresh' superphosphate (74 lb P/acre) plus FYM (20 tons/acre) by 3·5 tons/acre. Yields of turnips (2 to 8 tons/acre) and sugar beet (8·3 to 19·6 tons/acre), given NK fertilisers were greater by 1·3 and 2·6 tons roots/acre respectively with 'fresh' FYM plus superphosphate than with only residues of 'old' dressings.

7. The treatments given between 1965 and 1968 modified the soils which now contain different amounts of soluble P. The range of soils include 'no P' since 1899 (treatment 1), P residues from FYM alone or

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with superphosphate, applied between 1899 and 1964 (treatments 2, 3 and 8), P residues from 'old' FYM and superphosphate with (i) new FYM alone (treatment 4); (ii) new superphosphate alone (treatments 6 and 7); (iii) new FYM and superphosphate together (treatment 5).

Cultivations have ensured, and soil analyses have confirmed, that both P and K residues are distributed throughout a plough layer of about 0–10 in. These residues will be evaluated, relative to fresh superphosphate, in a crop rotation of potatoes, barley (without P), sugar beet and barley (without P) between 1969 and 1972.

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The Effects of Partially Sterilising Agricultural Soils with Formalin, and of Applying Nitrogen Fertilisers, on the Yields and N Contents of Spring and Winter Wheat, of Barley and of Grass

F. V. WIDDOWSON and A. PENNY

Partial sterilization with steam or with formalin solutions has for long been used in horticulture to maintain yields in glasshouses where the same crops have been grown frequently. Russell (1961), quoting from work done in the early 1900s, stated that the larger yields after partial sterilization resulted not only from killing soil-borne pathogens, but also from an increase in mineralisable soil nitrogen, but that the full explanation of the better yields was lacking.

Benzian (1965) showed that in forest nurseries formalin and other soil sterilants greatly increased the height and vigour of conifer seedlings which otherwise were stunted. All other treatments, which included fungicides, soil conditioners, composts and inorganic fertilisers were ineffective unless the soil was drenched with formalin not less than 3 weeks before the seeds were sown. The fact that fungicides did not improve growth, whereas the formalin drench did, showed that more than killing soil fungi was involved and tests showed that the sterilised soils contained more ammonia and the trees grown on them more manganese. These experiments also showed that the increase from formalin was larger where it was given for the first time than where it had been given the year before, so that the benefits of successive treatments were not cumulative.

Cooke (1963) considered problems of growing cereals on some light soils in Hertfordshire and Lincolnshire, where promising crops had failed during dry weather in June, and summarised work then done to try to solve them. Similar problems with cereals had also occurred on light land at Woburn Experimental Station, where, as at the other centres, they were associated with generous N manuring, with dry weather before ear emergence, and with fungi causing root rots. Because the stunted growth in forest nurseries had been overcome by applying formalin to these soils we decided to test formalin for wheat, and included with it tests of other treatments that might help to overcome the problem. In our first experiment we used (1) a non-phytotoxic fungicide (Nabam) to control *Fusarium* spp. (2) irrigation during dry weather to prevent a moisture deficit and (3) a range of nitrogen dressings to apply stress. It was made in 1964 with spring wheat at Woburn; formalin trebled yields. In 1965 we extended the work to Rothamsted where, on heavier soils, cereals had not been harmed, so far as we knew, and we chose one site that had previously grown cereals for many years and another recently ploughed from grass. In 1967 another experiment with formalin was begun on Chalky Boulder Clay at Saxmundham (Suffolk), because barley in a long-term rotation experiment there had yielded disappointingly; the amount of pathogens in the soil was unknown. Also in 1967 another

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experiment was begun with newly sown meadow fescue and timothy at Rothamsted, to establish whether a crop less likely to be damaged by soil pathogens benefited from drenching the soil with formalin before sowing and, if it did, for how long.

The main purposes of the experiments therefore were:

(1) to measure the effect of formalin on the yield of cereals;

(2) to examine the effect of formalin on the nitrogen content of the crops and so the need for fertiliser N;

(3) to examine the effects of formalin and fertiliser nitrogen on the take-all fungus (*Ophiobolus graminis*) and other soil-borne pathogens (D. B. Slope and G. A. Salt), and hence the amount of N needed by uninfected and infected crops.

Also, because D. B. Slope's root samples showed that cereal cyst eelworm (*Heterodera avenae*) was abundant on Butt Close, Williams (1969) measured the effects of the treatments on its incidence.

Experimental methods and treatments

Butt Close, Woburn, 1964–65. This field previously had grown many arable crops; the soil is a light sandy loam over Lower Greensand, holding less than 1 in. of water per foot of soil. In 1963 winter wheat following beans became stunted during dry weather in late May and June, especially on plots given much N; on these plots many ears failed to emerge normally and at harvest yields were small.

In 1964 spring wheat tested these four factors in all combinations:

(1) 38% formaldehyde (at 250 cc/sq yd) applied in water as a drench.
(2) Nabam (a fungicide) sprayed over the seedbed and over the crop.
(3) Water applied to give, with rain, 1 in. of water per week.
(4) Nitrogen fertiliser ('Nitro-Chalk') to give 0·6, 1·2 or 1·8 cwt N/acre.

These 24 treatments were arranged in two blocks of 12 plots; there were two replicates; individual plots were 7 ft wide and 20 ft long (0·0032 acre).

The formalin was applied by watering-can in December 1963 and repeated in February 1964 because too little rain fell after the first drench to wash it in. Then, in March, basal PK fertiliser (0-20-20 at $2\frac{1}{2}$ cwt/acre) and half of each N dressing were broadcast by hand, Nabam (at 10 lb/acre) was sprayed over appropriate plots and then the wheat (Jufy I) was sown with a hand-drill in rows 6 in. apart. The seedbed was made with hand-rakes to limit the movement of sterilised and unsterilised soil from plot to plot. Nabam (at 5 lb/acre) was sprayed over the wheat at the 3-leaf stage and again when it covered the ground completely; the other half of the N was applied in early May. From 18 May to 27 July water was applied weekly by hand-hose to give, with the rain that fell, 1 in. of water per week (4·7 in. of water was applied). At harvest the centre 13 rows of wheat on each plot were cut by hand and threshed, and the grain and straw were weighed. Samples of grain and straw were taken to measure dry matter and % N.

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In 1965 formalin was applied again (in December 1964) in all combinations with the 1964 treatments giving a single replicate of each combination. Nabam was not tested again, calcium nitrate replaced Nitro-Chalk (to eliminate any effect formalin might have on nitrification) and Opal wheat replaced Jufy I. The 1965 summer was wet and water was applied for the wheat only from 25 May to 16 June (1·2 in. of water was added), because after that ample rain fell each week. Other treatments and methods were the same.

Little Knott and Pastures, Rothamsted, 1965–68. The Little Knott experiment was made on a field that had been ploughed from grass in 1943 and then had grown cereals in 19 of the next 21 years; the Pastures experiment was made on a field that had grown grass for 10 years and then was ploughed for spring wheat in 1964. In 1965 the effect of a formalin drench (250 cc of 38% formaldehyde per sq yd) was tested on spring wheat without N and with 0·5, 1·0 or 1·5 cwt N/acre (as calcium nitrate). The eight treatments were arranged in a randomised block; there were four blocks on Little Knott and two on Pastures. Individual plots were 7 ft wide and 20 ft long (0·0032 acre).

The formalin drench was applied by watering-can and basal PK by hand over spring-tined land in February. The first half of the N was applied during March and then Opal wheat was sown by hand-drill in rows 6 in. apart. The remaining N was applied in May. At harvest the wheat was cut by sickle and threshed.

In 1966 the same amount of formalin was tested again in all combinations with the 1965 drench, on whole plots on Little Knott and on half plots on Pastures. The same amounts of N were given to the same plots and at the same times to Kloka spring wheat. The wheat was cut by sickle and threshed.

In September 1966 formalin was applied again (in all combinations with the 1965 and 1966 drenches) either to the stubble, or shortly after ploughing; the N dressings again were cumulative. Basal PK was given and winter wheat (Cappelle) was sown by hand drill in late October. In spring, N (at 0·5, 1·0 or 1·5 cwt/acre) was re-applied to appropriate plots, half of each dressing in March and half in May. On Little Knott the wheat was combine-harvested, but on Pastures it was cut by sickle and threshed.

In September 1967, after ploughing, formalin was again applied in all combinations with the three previous drenches. In October, Cappelle wheat was sown and in spring N was applied to appropriate plots. Both experiments were combine-harvested. Each year the grain and straw were weighed and sampled for dry matter and % N.

Grove Plot, Saxmundham, 1967–68. The experiment was made to test factors that may limit yield on this sandy clay soil with a poor structure. Formalin, lime and two amounts of nitrogen (applied in either March or May) were tested in all combinations on two barley varieties (Maris Badger and Deba Abed). The 32 treatments were arranged in two blocks of 16 plots; individual plots were 7 ft wide and 14 ft long (0·0022 acre).

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In February 1967 a formalin drench (500 cc of 38% formaldehyde per sq yd) and lime where appropriate and basal PK were applied over the ploughed land. In March the soils were sampled and then the barley was sown by hand-drill in rows 7 in. apart; N at 0·6 or 1·2 cwt/acre (as calcium nitrate) was broadcast by hand either on the seedbed or in May over appropriate plots. At harvest the barley was cut by sickle, threshed, and the grain and straw weighed and sampled for dry matter and % N.

In 1968 formalin was tested again in all combinations with the 1967 drench. All the other treatments were repeated on the same plots to give a half replicate of 32 plots. In March the soils were sampled again for mineralisable N. The results given here are averaged over varieties, lime and times of applying N.

Fosters, Rothamsted, 1967–68. This experiment was made on a field that had grown many arable crops. It measured the effects of a February soil drench of formalin (at 500 cc/sq yd) without nitrogen and with 0·3, 0·6 or 0·9 cwt N/acre/cut (as calcium nitrate) on the yield of a March-sown timothy (Scots) and meadow fescue (S.53) ley. The eight treatments were arranged in a randomised block; there were four blocks. Individual plots were 6 ft wide and 12 ft long (0·0016 acre). In 1967 the grass was cut three times (in July, September and November) and in 1968 twice (in May and July); N was re-applied for each cut. The grass was weighed and sampled for dry matter and % N.

Observations

Butt Close, Woburn, 1964–65. On 6 May 1964, wheat growing on soil drenched with formalin was taller and more vigorous than wheat on untreated soil and also was almost weed-free, whereas the other wheat was infested with many weed seedlings (mainly *Matricaria* and *Polygonum* sp.). It was all sprayed to kill the weeds. On 9 June irrigated wheat had larger broader leaves than unirrigated, even though 1·5 in. of rain had fallen the week before, but with so much rain in June none of the wheat failed, and the expected symptoms of scorching did not occur, even though July was dry and sunny.

On 22 April 1965 we observed that wheat growing on soil drenched with formalin in 1964 was inferior to wheat growing on untreated soil; much of it was stunted and had yellow leaves. Also, the large benefits from the new formalin drench were diminished by the residues of the 1964 drench, so that the formalin was most beneficial where it had not been used the year before; these differences persisted until harvest.

Little Knott and Pastures, Rothamsted, 1965–68. On 3 May 1965 wheat on Little Knott growing on soil drenched with formalin was much superior to wheat growing on untreated soil, but on Pastures the wheat showed no benefit, presumably because this soil contained few pathogens, and was rich in N.

In 1966, freshly applied formalin improved growth greatly on Little

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Knott, but only slightly on Pastures. There was no visible benefit or harm, on either field, from the residues of the formalin given in 1965.

In 1967, formalin applied the previous autumn did not visibly benefit the wheat on Little Knott until mid-June, but did after then. By contrast, formalin given the year before was harmful, for in July the wheat growing on nine plots was stunted, had bluish stems and leaves, and the leaves were erect and rolled inwards from the margins; all had been given formalin in February 1966. On Pastures new formalin improved growth during March, but the drench applied over the stubble improved growth less than the drench given after ploughing. The benefits from the formalin persisted until severe lodging occurred well before harvest; the most vigorous wheat lodged most.

In 1968, freshly applied formalin benefited the wheat greatly on Pastures, but had little effect on growth on Little Knott (by contrast to the first two years), but losses from giving formalin the year before were not evident. The wheat responded greatly to N on Little Knott, but there was less visual response on Pastures. At harvest there was little lodging on Little Knott, but on Pastures all the wheat given N was flat.

Grove Plot, Saxmundham, 1967–68. In 1967, formalin improved growth only a little and in 1968 little more; its benefits were evident only with 0·6 cwt N/acre and not when 1·2 cwt N/acre was given. By contrast, N greatly increased growth each year and so the visual effects were mainly from rates and times of N.

Foster's, Rothamsted, 1967–68. The grasses established only slowly during wet weather in May and so, in June, they were topped and a second dressing of N given. Then they grew quickly and growth was better with formalin than without. In 1968 there was little visible benefit from the formalin.

Results

Butt Close, Woburn, 1964–65. Appendix Table 1 shows that in 1964 grain yields (averaged over Nabam) ranged from 9·1 (with 0·6 cwt N/acre) to 37·2 cwt/acre (with 1·2 cwt N/acre, formalin and water). Trebling the amount of nitrogen (to 1·8 cwt N/acre) increased grain yields by 5·7 cwt/acre without irrigation or formalin, by 11·8 cwt/acre with irrigation alone, by only 0·2 cwt/acre with formalin alone, but 5·9 cwt/acre when both formalin and water were given, so that water increased and formalin decreased the need for nitrogen. Appendix Table 1 also shows that in 1964 straw yields ranged from 14·3 (with 0·6 cwt N/acre) to 53·0 cwt/acre (with 1·8 cwt N/acre, water and formalin), so that the straw benefited from one more increment of N than the grain. However, the gains from formalin and from water were proportionally as large for straw as for grain. The table also shows that applying formalin did not consistently change the percentage of N in the wheat grain, but, because it increased yields so much, it more than doubled the amount of N removed by wheat given 0·6 cwt N/acre, and increased by a half the amount of N removed by wheat given 1·8 cwt N/acre. Applying water decreased % N in the grain in five of six

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comparisons, presumably because it increased yields without increasing the amount of mineralisable N in the soil, whereas formalin probably increased it. However, watered wheat removed approximately one fifth more N than unwatered, so that water increased its ability to use N. Nabam increased yields little and so its results are not shown.

Appendix Table 1 shows that in 1965 grain yields ranged from 6·0 (with 0·6 cwt N/acre alone) to 37·4 cwt/acre (with 1·2 cwt N/acre, formalin in 1965 and water), so that although the range was greater in 1965 than in 1964 maximum yields were almost the same in the two years. The Table also shows that formalin was most effective where none had been applied the year before, so that there was a negative interaction between the fresh application and the residues of that given the year before.

The table also shows that giving the wheat 1·8 rather than 1·2 cwt N/acre decreased yields where formalin had been given that year, but that it increased them a little where it had not, showing again the interaction between nitrogen and formalin. Also, the benefits from giving extra N were made larger by giving water, providing that formalin also had been given, but not where it had not. Evidently the residual effects of water were harmful on this sandy soil, because in 1965 water increased grain and straw yields (in 9 or 12 comparisons) where formalin was also newly given and decreased yields (in 9 or 12 comparisons) where it was not. Presumably the water given in 1964 allowed cereal cyst eelworm to multiply faster and so decrease yields in 1965, unless formalin was newly given (Williams, 1969). Appendix Table 2 also shows that straw yields ranged from 11·8 (with 0·6 cwt N/acre and water) to 44·8 cwt/acre (with 1·2 cwt N/acre, water and formalin only in 1965). There was no obvious relationship between the increases from the largest amount of N and formalin.

Formalin tended to diminish % N in the grain, presumably because yields with it were larger, and water also tended to do so, whether or not it increased yields. Formalin greatly increased the amount of N removed by the wheat; it more than trebled the amount by wheat given 0·6 cwt N/acre and almost doubled the amount by wheat given 1·8 cwt N/acre; water increased the amount only where it also increased yields.

Table 1 shows that, in 1964, mean grain and straw yields were almost doubled by formalin, but that the residues of this drench decreased the yields of the wheat that followed in 1965. By contrast the formalin given in 1965 more than doubled grain and straw yields, but, even so, mean yields were smaller than in 1964 (maximum yields were not (Appendix Table 1)). Table 1 also shows that the second increment of 0·6 cwt N/acre increased grain and straw yields in both years, but the third increased only straw yields. Water significantly increased yields during dry weather in 1964, but had little effect in 1965.

Table 2 shows that giving formalin in 1964 increased yields slightly in 1965, but the plots drenched in both 1964 and 1965 yielded less than those drenched in 1965 only, i.e., drenches in two successive years had less effect than one drench immediately before the wheat crop. On this soil, formalin was more effective than N in increasing yield but, even with formalin newly applied, maximum yield needed 1·2 cwt N/acre, which is usually regarded as a large dressing.

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TABLE 1

Mean yields (cwt/acre) of spring wheat (at 15% moisture content) without and with formalin, with three amounts of nitrogen, and without and with irrigation on Butt Close, Woburn, 1964 and 1965

	Formalin in 1964			Formalin in 1965			Nitrogen (cwt/acre/year)				Water		
	Without	With	S.E.	Without	With	S.E.	0·6	1·2	1·8	S.E.	Without	With	S.E.
Yields in 1964													
Grain	15·4	30·8	±0·54	—	—	—	19·2	24·9	25·1	±0·66	20·1	26·0	±0·54
Straw	25·3	44·8	±0·70	—	—	—	27·9	36·6	40·7	±0·86	32·0	38·1	±0·70
Yields in 1965													
Grain	21·4	19·1	±0·36	12·2	28·3	±0·36	16·0	22·4	22·3	±0·44	20·3	20·1	±0·36
Straw	29·4	26·0	±0·68	19·4	36·1	±0·68	22·9	29·3	31·0	±0·83	27·5	28·0	±0·68

TABLE 2

The residual and the direct effects of formalin on the yields (cwt/acre) of spring wheat (at 15% moisture content) given three amounts of nitrogen, on Butt Close, Woburn, 1965

	Formalin in 1964					
	Without			With		
	N cwt/acre/year					
Formalin in 1965	0·6	1·2	1·8	0·6	1·2	1·8
Grain						
Without	6·6	10·5	13·8	8·8	16·5	16·9
With	29·1	35·8	32·6	19·6	26·7	25·8
Straw						
Without	11·9	17·7	22·5	17·8	23·0	23·4
With	37·4	43·5	43·4	24·3	33·2	34·5

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Little Knott, Rothamsted, 1965–68. Appendix Table 2 shows that, in 1965, grain yields ranged from 17·0 (without N or formalin) to 35·4 cwt/acre (with 1·0 cwt N/acre and formalin), and that formalin increased yields with each amount of N. Although 0·5 cwt N/acre increased yield of grain by approximately 11 cwt/acre and straw by even more, there was little or no advantage from giving the wheat more N, whether or not formalin also was given. % N in the grain was increased by each increment of N; wheat given 1·5 cwt N/acre contained approximately 50% more N than wheat given none. By contrast, formalin did not consistently change % N in the grain, but, because it increased yields so much, it increased the amount of N removed (in the grain plus straw) by approximately a quarter, at each rate of N tested. Wheat given 0·5 cwt N/acre and formalin together recovered as much N as wheat given 1·5 cwt N/acre alone, so that the effect of formalin then was approximately equivalent to giving the wheat 1·0 cwt more N/acre.

Appendix Table 2 shows that, in 1966, the residual effects of formalin applied in 1965 greatly decreased yields and that, although these losses were diminished by applying N, they were not eliminated by the largest amount given (1·5 cwt N/acre). The table also shows that these harmful residual effects were diminished by a formalin drench in 1966, which gave larger yields than on plots not drenched in either year. However, the largest yields of grain and straw were obtained by formalin applied for the first time in 1966. The table also shows that this treatment tended to increase % N in the grain; as in 1965, it consistently increased the amount of N recovered by the wheat, and again its effect was approximately equivalent to giving the wheat 1·0 cwt more N/acre.

Appendix Table 2 shows that in 1967 winter wheat on soil not given formalin either in 1966 or in 1967 yielded the most grain, and that it gave approximately the same yield as the spring wheat grown before it. The residual effects of the formalin given in 1966 greatly diminished yields of grain and of straw and the wheat not given N almost failed. A formalin drench repeated in 1967 only partly overcame the harmful residual effects, for even with formalin in both years, both grain and straw yields were smaller than from untreated soil. However, straw yields were increased by formalin applied in 1967 only, and this also increased grain % N, but it did not consistently increase the amount of N recovered by the wheat.

Appendix Table 2 shows that, again in 1968, grain yields tended to be larger without than with newly applied formalin, so that the effectiveness of formalin seemed to be diminishing on this site. Also, by contrast to results in 1967, straw yields were not increased by newly applied formalin. The residual effects of formalin again decreased yields, but much less than in 1967, and their harmful effects were diminished by applying formalin again for the 1968 wheat. The newly applied formalin consistently increased grain % N, but it did not consistently increase the amount of N recovered by the wheat. However, by 1968, only two of the 32 plots in the experiment had not been given any formalin during the four years, which suggests that subsequent applications given to some plots in 1967 and in 1968 were less beneficial than the initial ones.

Table 3 shows that although formalin increased yields each year on

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TABLE 3

Mean yields (cwt/acre) of wheat (at 15% moisture content) without and with formalin on Little Knott Field, Rothamsted, 1965–68

Yield in		Formalin given in: 1965 Without	1965 With	1966 Without	1966 With	1967 Without	1967 With	1968 Without	1968 With	S.E.
1965	Grain	24·5	31·7	—	—	—	—	—	—	±0·61
	Straw	41·8	49·7	—	—	—	—	—	—	±0·77
1966	Grain	33·2	29·9	26·7	36·5	—	—	—	—	±0·64
	Straw	44·8	40·8	34·1	51·5	—	—	—	—	±0·83
1967	Grain	23·6	24·2	30·0	17·7	23·1	24·6	—	—	±1·10
	Straw	35·7	38·4	41·5	32·6	34·0	40·1	—	—	±0·94
1968	Grain	31·0	32·5	30·1	33·4	32·2	31·3	31·1	32·4	±1·15
	Straw	34·2	34·3	32·6	35·9	36·6	31·9	32·9	35·6	±1·55

TABLE 4

Mean yields (cwt/acre) of wheat (at 15% moisture content) without and with formalin on Pastures Field, Rothamsted, 1965–68

Yield in		Formalin given in: 1965 Without	1965 With	1966 Without	1966 With	1967 Without	1967 With	1968 Without	1968 With	S.E.
1965	Grain	27·2	27·8	—	—	—	—	—	—	±0·83
	Straw	55·1	58·3	—	—	—	—	—	—	±1·02
1966	Grain	36·3	36·6	35·7	37·2	—	—	—	—	±0·82[1] ±0·86[2]
	Straw	56·2	57·1	50·8	62·5	—	—	—	—	±0·89[1] ±0·62[2]
1967	Grain	30·4	29·6	31·6	28·4	29·1	30·9	—	—	±0·87[3]
	Straw	62·6	62·4	66·2	58·8	57·8	67·2	—	—	±1·28[3]
1968	Grain	24·6	25·0	24·8	24·8	24·7	25·0	27·1	22·5	±0·73[4] ±0·62[5]
	Straw	37·1	38·7	37·6	38·2	39·2	36·6	38·1	37·7	±1·07[4] ±0·86[5]

[1] Applies to yields from 1965 formalin.
[2] Applies to yields from 1966 formalin.
[3] Does not apply to yields from 1965 formalin.
[4] Applies to yields from 1965 formalin.
[5] Applies to other yields in 1968.

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Little Knott, it increased them more in 1965 and 1966 (when applied in February for spring wheat) than in 1967 and 1968 (when applied in September for winter wheat). However, the losses from the residues of formalin given the year before were as large, or larger, with winter wheat than with spring wheat, so that, in contrast to its direct effects, its residual effects were the same for both spring and winter wheat. In 1967 and 1968 the experiments also measured the effects of giving formalin two years earlier, and Table 3 shows that grain yields were a little larger with than without these formalin treatments. In 1968 the wheat also measured the residual effects of formalin given three years earlier; these also slightly increased yields.

Pastures, Rothamsted, 1965–68. Appendix Table 3 shows what happens when wheat is grown on a nitrogen-rich soil and given too much N. In 1965 N consistently decreased yields of grain, which with 1·5 cwt N/acre were almost halved. By contrast, 0·5 cwt N/acre increased straw yields by more than 10 cwt/acre, but giving more N than this decreased them. Formalin increased grain yields provided that N was not given, but had no consistent effect when it was, although formalin consistently increased the yields of straw. The large amount of N in the soil was confirmed by the large % N in the grain and by the fact that unmanured wheat recovered twice as much N here as on Little Knott (Appendix Table 2) in the same year.

Appendix Table 3 also shows that, in 1966, yields were not diminished by residual effects of the formalin given in 1965 (in contrast to Little Knott). Grain yields were sizeably increased by the new formalin drench only when N was not given, but straw yields were increased independently of N. Yields without N fertilisers were smaller than in 1965 and grain yields were greatly increased by giving 0·5 cwt N/acre (except where formalin also had been given in 1965 and 1966), but not further by giving more. Straw yields also were greatly increased by 0·5 cwt N/acre (whether or not formalin was given), but little more with more N.

The fact that yields of straw, but not of grain, were larger when formalin and nitrogen were given together, suggests that potential grain yield was lost through lodging. Hence, effects were better judged by straw than by grain. The table also shows that newly applied formalin did not consistently increase % N in the grain, but that it did increase the total amount of N removed by the grain and straw in seven of eight comparisons.

Appendix Table 3 shows that, in 1967, wheat yields were diminished by formalin given in 1966, but that most of this loss was prevented either by drenching with formalin again in 1967 or by giving the wheat more than 0·5 cwt N/acre. A new drench greatly increased the yields of grain where the wheat was not given N, and slightly increased them when only 0·5 cwt N/acre was given, but, with more N than this, formalin decreased grain yields. It consistently increased straw yields. The largest yields of grain and of straw were obtained by giving formalin to soil that had been given none the year before, but the best amount of N for each was different. New formalin increased % N in the grain in 7 of 8 comparisons and it also increased the total amount of N removed by the grain and straw, except when 1·5 cwt N/acre was also given. The effect of this new drench on the

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amount of N removed by the wheat was less than that of giving the wheat 0·5 cwt N/acre.

Appendix Table 3 shows that the formalin given for the 1968 wheat consistently decreased grain yields and slightly decreased those of straw, presumably because it made lodging worse in this wet summer. By contrast, the residual effects from the 1967 drench increased grain yields, presumably because this wheat was poorer, lodged less and so yielded more. Nitrogen increased yields a little providing that only 0·5 cwt N/acre was given. With more N, grain yields were consistently diminished and straw yields were irregular. Newly applied formalin usually increased grain % N, but because it decreased yields it usually decreased the total amount of N recovered by the wheat, although fertiliser N consistently increased it.

Table 4 shows that newly applied formalin (averaged over N) increased grain and straw yields only a little each year from 1965 to 1967, and that it greatly decreased yields of grain and slightly decreased yields of straw in 1968.

The residual harmful effects of formalin the year after it was given were far less than on Little Knott; they appreciably diminished yields of grain only in 1967 and of straw in 1967 and in 1968. Formalin given two or three years previously had only small effects on yields, but they were positive in four of six comparisons.

Grove Plot, Saxmundham, 1967–68. The 1967 barley followed a summer fallow. Appendix Table 4 shows that, without formalin, 0·6 cwt N/acre increased grain yields by 14·1 cwt/acre, but with it, by 17·9 cwt/acre. Applying 1·2 cwt N/acre rather than 0·6 increased grain yields further (by 4·9 cwt/acre), but then formalin slightly diminished yields. Formalin also increased straw yields, but more with the single than with the double amount of N, and it also increased % N in the grain, however much N was given. Thus, more total N was always removed by the barley with than without formalin.

Appendix Table 4 shows that, in 1968, yields without N were smaller than in 1967, but that the response to N was larger, so that maximum yields were nearly the same in the two years. As in 1967, newly applied formalin increased yields a little, but more with 0·6 than with 1·2 cwt N/acre. The residual effects from the formalin given in 1967 also increased yields, but

TABLE 5

Mean yields (cwt/acre) of spring barley (15% moisture content) without and with formalin at Saxmundham in 1967 and 1968

	Formalin in 1967			Formalin in 1968		
	Without	With	S.E.	Without	With	S.E.
			Yields in 1967			
Grain	38·5	40·2	±0·68	—	—	—
Straw	40·1	42·7	±0·87	—	—	—
			Yields in 1968			
Grain	37·8	38·8	±0·62	37·6	39·0	±0·62
Straw	42·7	42·8	±0·77	42·5	43·1	±0·77

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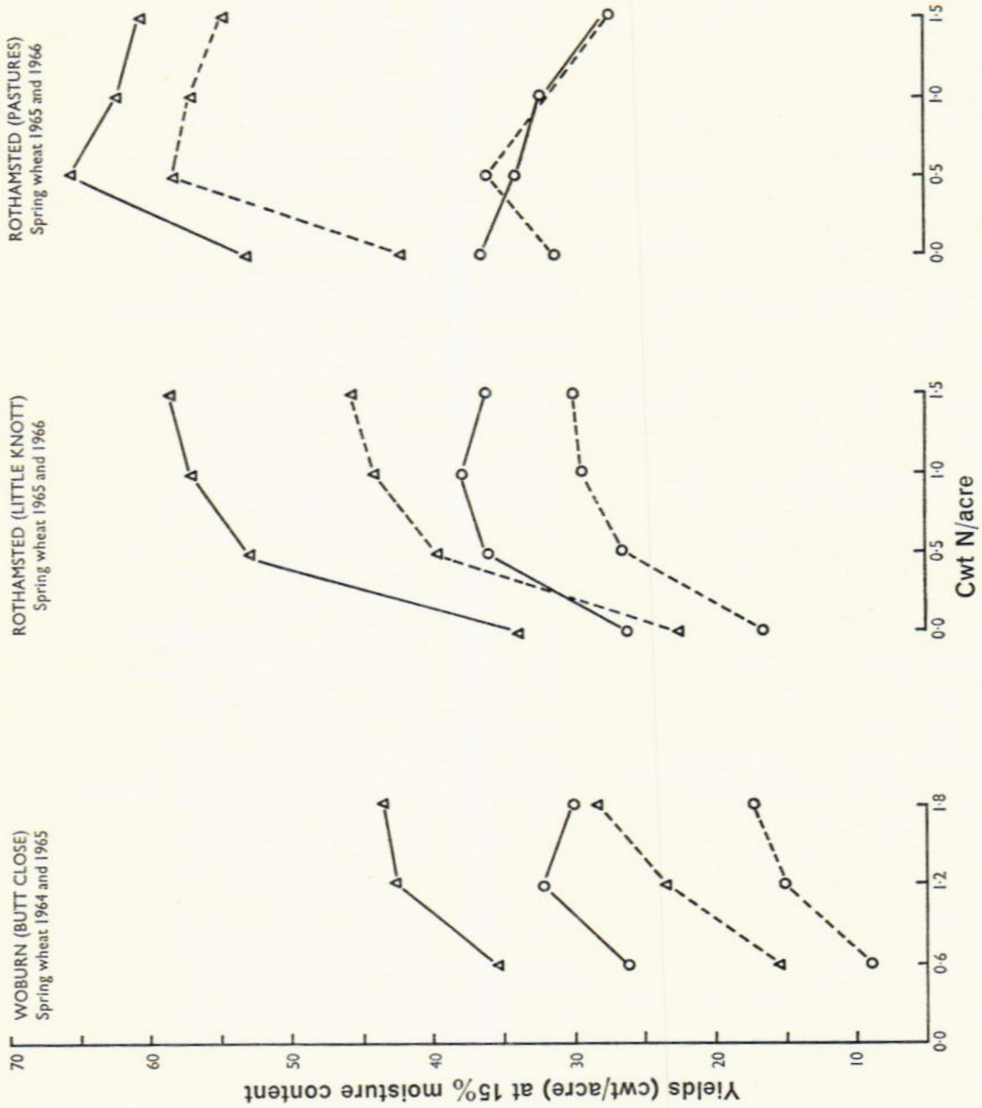

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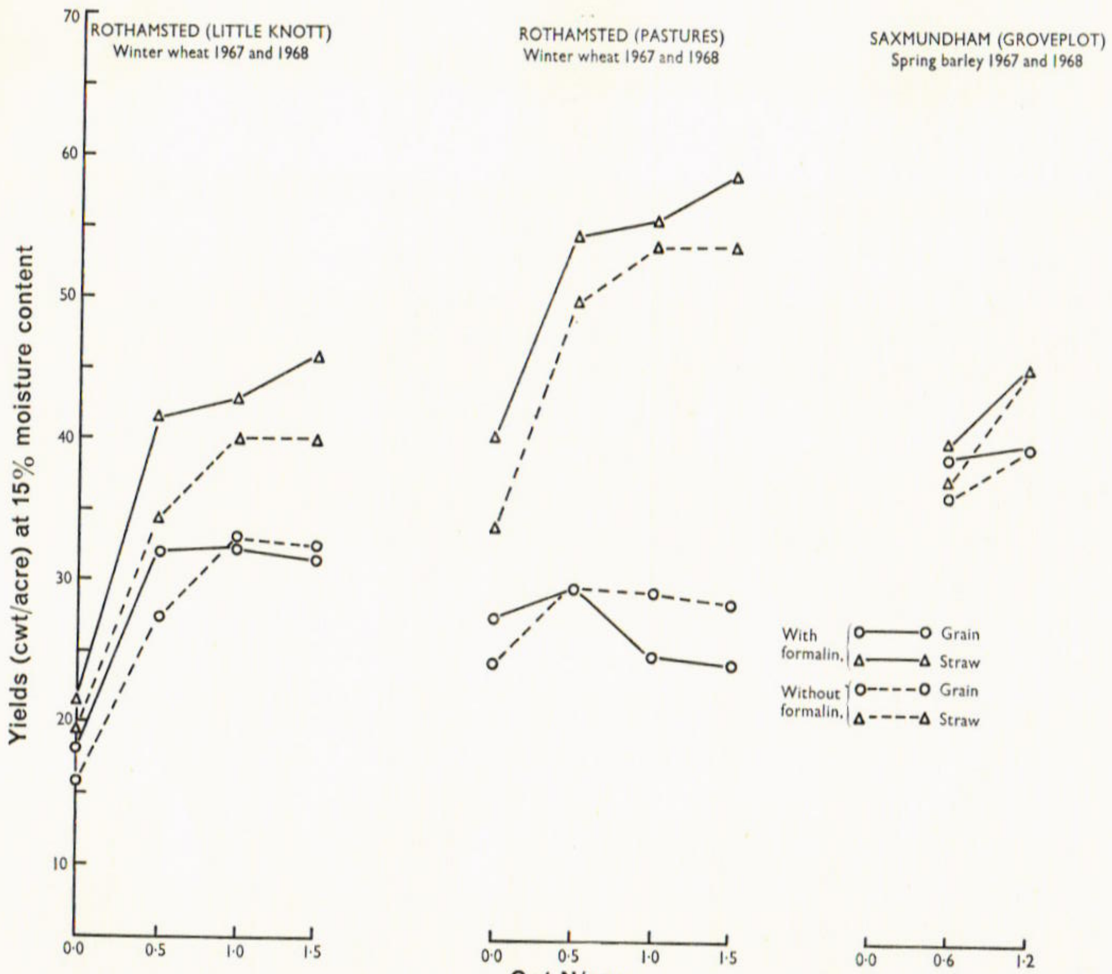

FIG. 1. The mean effects (in pairs of years) of applying formalin and nitrogen separately and together in four cereal experiments, 1964–68.

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usually less than did the new drench. Formalin applied in either year increased % N in the grain, but the combined effect of both drenches was not consistently greater than that of a drench in 1968 only.

Table 5 shows that newly applied formalin increased mean grain and straw yields each year, though by much less than on soils with a long history of arable crops at Woburn (Butt Close) and at Rothamsted (Little Knott). Also, in contrast to the other experiments, the residual effects of formalin were beneficial rather than harmful, which suggests that at Saxmundham the effects of formalin were mainly from an increase in mineral N and not from a decrease in soil pathogens. Table 6 shows the amounts of mineralisable N in soil samples taken just before the barley was sown in March 1968 and then incubated in the laboratory for 24 days at 25°C (by J. K. R. Gasser). These show that the soil contained little mineral N; formalin increased the amount of N mineralised after incubation, either when it had been given in 1967 or in 1968, but giving it in both years increased mineral N most. Judged by yields, this increase in mineral N was

TABLE 6

The total amounts of mineralisable N in Saxmundham soils in March, 1968

	Formalin applied			
	None	1967	1968	1967/68
		ppm N (NO_3+NH_4)		
Mineral N in fresh soil	7·3	6·9	4·5	3·1
Mineral N after incubation	16·6	17·4	19·3	26·4
Increase (Δ mineral N)	9·3	10·5	14·8	23·3

probably equivalent to giving the barley only another 10 lb N/acre; the extra N from giving formalin in 1967 and in 1968, rather than in 1968 alone, was not reflected in larger yields or in larger amounts of N removed by the barley.

Fosters, Rothamsted, 1967–68. Appendix Table 5 shows that, in 1967, formalin greatly increased the yields of grass at the first cutting and slightly increased them at the second and third cuttings. At the first cut, % N was

TABLE 7

Total yields (cwt/acre) of dry grass from five cuts, the mean percentage of N in dry grass and the total amounts (cwt/acre) of N taken up (in five cuts) in an experiment testing nitrogen and formalin for grass, 1967–68

	Total yields		Mean % N in dry grass		Total N taken up	
cwt N/acre/cut	—	F	—	F	—	F
0·0	35·0	46·0	1·81	1·73	0·62	0·77
0·3	90·2	104·8	2·18	2·20	1·76	2·09
0·6	116·6	125·4	2·69	2·67	2·80	3·03
0·9	118·6	127·7	3·05	2·97	3·34	3·49

— = No formalin in 1967.
F = Formalin in 1967.

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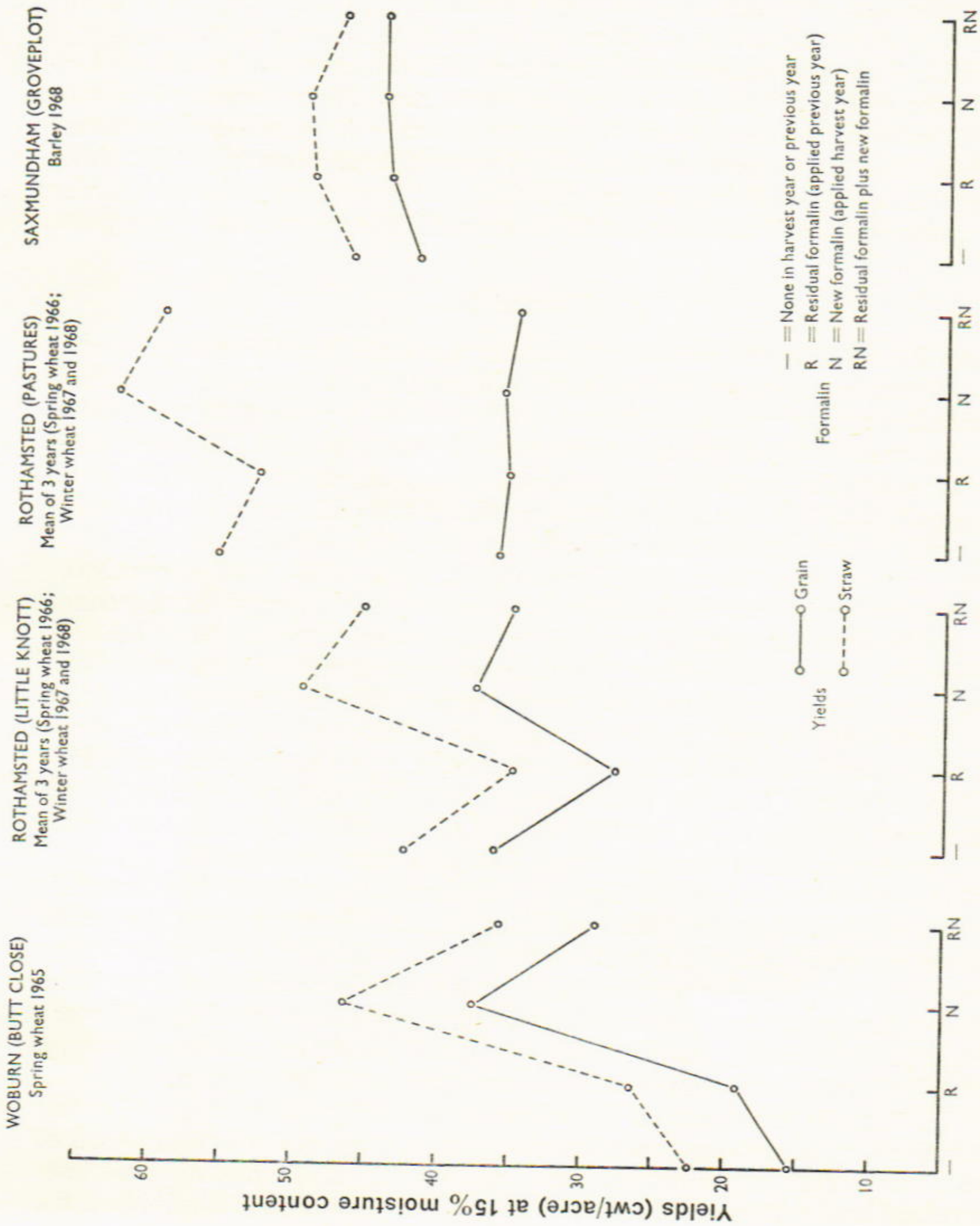

FIG. 2. The residual, direct and cumulative effects of formalin on yields of cereals in four experiments, 1965–68.

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decreased, but total N increased, whereas at the second and third cuttings formalin increased both % N and the total amount removed by the grass.

In 1968 the residual benefits of formalin were small but consistent. They increased yields at the first and the second cuttings (16 months after the formalin had been applied), but they increased % N and the yield of nitrogen only at the first, and of grass not given N at the second cutting.

Table 7 shows that over the two years formalin increased yields by 11·0 cwt/acre without N and by 9·1 cwt/acre with most N, so formalin had proportionally most effect when N was not given. Nitrogen alone increased yields by 83·6 cwt/acre, so that its effect was approximately eight times larger than that of formalin. Formalin did not consistently change % N in the grass, but it did increase the total amount of N recovered by the grass.

Discussion

The results illustrated well the problems involved in making experiments with formalin and other sterilants, for not only did the formalin control soil pathogens and so produce bigger crops, but it also increased the amounts of N recovered by the crops and so presumably the amounts of N mineralised in the soils (Gasser & Peachey, 1964). However, because of these interactions and because we did not measure the effects of formalin on mineralisable soil N (except at Saxmundham) we cannot tell whether the healthier crops grown with formalin (Slope, 1966; Salt, 1966) used the existing reservoir of soil N more efficiently, or whether their larger yields depended partly on the additional N provided by the partial sterilisation of the soil. However, except at Woburn (where cereal cyst nematode was abundant) fertiliser nitrogen and formalin were to some extent interchangeable, when each was tested alone. At Rothamsted the effect of giving formalin alone was comparable to that of giving nitrogen alone, but it never exceeded that of giving 0·5 cwt N/acre. Nevertheless, when formalin and 0·5 cwt N/acre were given together, they interacted, and it was seldom possible to obtain as large a yield from nitrogen alone, however much was given.

Fig. 1 shows mean results for pairs of years in each cereal experiment. It is very evident that the effects of nitrogen and formalin were far better measured by the straw than by the grain, for the yields of straw were always larger with formalin than without, whereas formalin sometimes diminished grain yields, presumably because the larger crop that it gave lodged more severely. Apparently lodging did not diminish straw yields, otherwise formalin would have diminished these as well as those of grain.

Fig. 2 shows mean results (averaged over nitrogen dressings) of giving formalin for the previous crop, for the current crop or for both, in each of the four cereal experiments. Residual effects of formalin sometimes increased and sometimes decreased yields, but they always diminished the benefit from freshly applied formalin, which consistently increased yields. Formalin had similar effects on grain and on straw yields, except on the Pastures experiment, where lodging spoilt the comparison for grain. So again the effects of formalin were best measured by yields of straw.

This paper is intended to give the yields obtained from the experiments in full, and to show and discuss the interactions between nitrogen fertiliser and

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formalin. It also shows the amounts of N recovered by the crops and that formalin increased this whether or not soil pathogens were abundant. It does not discuss the effects of formalin on cereal cyst nematode (*Heterodera avenae*) in the Butt Close experiment, because these have already been published (Williams, 1969); nor effects on take-all (*Ophiobolus graminis*) and other soil fungi, because D. B. Slope and G. A. Salt will give their results in other papers.

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APPENDIX TABLE 1

Yields of spring wheat grain and straw, the percentage of N in grain, and the amounts of N taken up by grain plus straw on Butt Close field at Woburn, 1964 and 1965

Year	1964		1965			
			Without formalin in 1964 or 1965	With formalin in		
cwt N/acre/year	Without formalin	With formalin		1964	1965	1964 and 1965
			Yields (cwt/acre) of grain at 15% moisture content			
			Without water			
0·6	9·1	26·3	6·0	11·6	29·0	19·7
1·2	15·1	29·1	10·1	17·7	34·2	23·5
1·8	14·8	26·5	16·2	18·8	34·0	23·0
			With water			
0·6	11·6	29·9	7·2	6·0	29·1	19·6
1·2	18·3	37·2	11·0	15·3	37·4	29·8
1·8	23·4	35·8	11·3	15·0	31·4	28·7
S.E.	±1·33				—	
			Yields (cwt/acre) of straw at 15% moisture content			
			Without water			
0·6	14·3	37·8	12·0	23·8	35·6	23·6
1·2	25·2	43·0	16·4	24·0	42·2	28·9
1·8	28·4	43·0	25·2	26·8	42·0	29·4
			With water			
0·6	17·6	41·8	11·8	11·8	39·3	25·0
1·2	28·1	50·0	19·0	22·0	44·8	37·5
1·8	38·1	53·0	19·8	20·1	44·8	39·6
S.E.	±1·72				—	
			Percentage of N in grain			
			Without water			
0·6	1·96	1·77	2·14	1·84	1·82	1·94
1·2	2·23	2·24	2·40	2·44	2·32	2·19
1·8	2·61	2·58	3·00	2·68	2·64	2·79
			With water			
0·6	1·88	1·96	2·08	2·01	1·84	1·70
1·2	2·02	2·12	2·51	2·16	2·07	2·24
1·8	2·31	2·31	2·77	2·55	2·52	2·41
			N (cwt/acre) in grain plus straw			
			Without water			
0·6	0·200	0·487	0·168	0·271	0·590	0·433
1·2	0·377	0·704	0·336	0·451	0·883	0·632
1·8	0·457	0·767	0·576	0·574	1·043	0·772
			With water			
0·6	0·240	0·624	0·189	0·160	0·593	0·375
1·2	0·405	0·850	0·304	0·413	0·879	0·733
1·8	0·599	0·911	0·392	0·462	1·015	0·849

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APPENDIX TABLE 2

Yields of wheat[1] grain and straw, the percentage of N in grain, and the amounts of N taken up by grain plus straw on Little Knott field, Rothamsted, 1965–68

Year	1965		1966				1967				1968			
				With formalin in				With formalin in				With formalin in		
cwt N/ acre/ year	Without formalin	With formalin	Without formalin in 1965 or 1966	1965	1966	1965 & 1966	Without formalin in 1966 or 1967	1966	1967	1966 & 1967	Without formalin in 1967 or 1968	1967	1968	1967 & 1968
					Yields (cwt/acre) of grain at 15% moisture content									
0·0	17·0	23·9	19·4	13·0	29·2	27·6	21·6	4·4	24·1	9·4	20·3	17·5	21·4	18·2
0·5	28·3	34·9	27·1	21·9	36·2	38·4	28·6	14·7	31·9	22·8	37·0	29·0	32·6	41·0
1·0	26·6	35·4	36·3	28·2	42·5	38·1	39·6	20·8	25·0	26·8	39·6	31·4	37·6	39·2
1·5	26·2	32·5	34·6	32·7	40·1	39·3	33·6	22·0	36·0	21·1	36·3	37·8	32·6	36·5
S.E.	±1·21			±1·81					—				—	
					Yields (cwt/acre) of straw at 15% moisture content									
0·0	27·0	34·1	20·6	16·0	34·8	32·7	24·6	11·2	25·0	22·0	24·7	17·0	22·0	16·8
0·5	46·8	52·5	37·0	28·0	53·6	53·3	38·0	32·8	50·0	36·4	39·5	27·6	36·6	42·6
1·0	45·9	56·8	45·2	39·1	59·0	55·2	46·0	40·0	45·0	37·2	44·0	29·8	46·8	42·1
1·5	47·7	55·4	44·0	43·2	64·0	59·2	46·2	33·2	57·2	48·0	39·6	41·1	39·6	38·4
S.E.	±1·53			±2·34					—				—	
						Percentage of N in grain								
0·0	1·87	1·93	1·73	1·71	1·83	1·85	1·70	2·02	1·62	1·74	1·69	1·65	1·84	1·74
0·5	2·09	2·14	1·71	1·83	1·81	1·94	1·79	1·96	1·88	1·82	1·83	1·84	1·96	1·85
1·0	2·36	2·27	1·89	1·89	2·14	1·92	2·05	2·27	2·14	2·20	2·29	2·25	2·37	2·31
1·5	2·81	2·70	2·03	2·18	2·03	1·95	2·42	2·54	2·61	2·70	2·61	2·51	2·62	2·51
S.E.	±0·069			—					—				—	
						N (cwt/acre) in grain plus straw								
0·0	0·386	0·528	0·367	0·224	0·551	0·545	0·378	0·152	0·400	0·252	0·404	0·312	0·446	0·333
0·5	0·755	0·918	0·495	0·438	0·684	0·697	0·569	0·422	0·634	0·480	0·734	0·569	0·723	0·795
1·0	0·794	1·072	0·706	0·547	0·925	0·733	0·839	0·564	0·620	0·649	1·039	0·739	1·049	0·998
1·5	0·933	1·123	0·694	0·686	0·916	0·943	0·916	0·670	1·082	0·770	1·055	1·068	1·039	1·042
S.E.	±0·0449			—					—				—	

[1] Spring wheat in 1965 and 1966, winter wheat in 1967 and 1968.

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APPENDIX TABLE 3

Yields of wheat[1] grain and straw, the percentage of N in grain, and the amounts of N taken up by grain plus straw, on Pastures field, Rothamsted, 1965–68

Year	1965		1966				1967				1968			
			Without formalin in 1965 or 1966	With formalin in			Without formalin in 1966 or 1967	With formalin in			Without formalin in 1967 or 1968	With formalin in		
cwt N/acre/year	Without formalin	With formalin		1965	1966	1965 & 1966		1966	1967	1966 & 1967		1967	1968	1967 & 1968
	Yields (cwt/acre) of grain at 15% moisture content													
0·0	33·6	35·9	24·6	32·2	34·5	39·3	21·4	19·4	33·1	30·6	25·2	31·6	23·4	23·3
0·5	32·7	28·5	39·4	39·0	39·7	39·3	35·4	21·6	37·8	32·6	30·4	31·6	24·6	24·0
1·0	24·1	25·1	39·7	38·8	39·0	39·0	32·8	35·0	26·9	28·9	23·6	26·6	22·8	21·5
1·5	18·5	21·7	39·2	32·9	34·2	32·7	34·2	33·0	31·0	26·0	26·2	21·4	21·2	19·6
S.E.	±1·65			±2·37[2] ±2·43[3]				—			—			
	Yields (cwt/acre) of straw at 15% moisture content													
0·0	50·0	54·1	31·3	36·6	50·7	53·1	38·4	32·7	55·2	47·3	34·6	29·8	33·3	25·4
0·5	61·2	64·3	54·6	55·6	64·3	69·7	66·5	48·2	71·4	64·6	44·6	40·4	43·4	39·0
1·0	56·6	59·0	57·8	57·0	64·8	66·4	65·2	68·6	72·4	66·7	41·2	41·1	45·0	39·2
1·5	52·8	56·0	59·6	54·0	66·5	64·3	72·8	70·2	87·4	72·2	37·5	35·4	34·4	42·2
S.E.	±2·05			±2·18[2] ±1·77[3]				—			—			
	Percentage of N in grain													
0·0	2·15	2·13	1·86	1·83	1·79	1·70	1·70	1·66	1·77	1·59	1·83	1·92	1·91	2·07
0·5	2·35	2·30	1·80	1·82	2·00	2·04	1·88	1·82	1·94	1·96	2·20	1·92	2·23	2·17
1·0	2·34	2·51	2·14	1·90	2·16	2·22	2·25	2·08	2·44	2·31	2·40	2·43	2·54	2·50
1·5	2·46	2·49	2·24	2·19	2·18	2·14	2·50	2·58	2·71	2·68	2·74	2·54	2·56	2·66
S.E.	±0·036				—			—			—			
	N (cwt/acre) in grain plus straw													
0·0	0·844	0·969	0·511	0·641	0·699	0·764	0·395	0·348	0·616	0·512	0·536	0·660	0·544	0·516
0·5	1·054	1·015	0·812	0·811	0·932	0·986	0·764	0·468	0·810	0·795	0·766	0·710	0·690	0·638
1·0	1·065	1·123	1·041	0·915	1·068	1·128	0·826	0·913	0·890	0·766	0·748	0·826	0·791	0·726
1·5	0·958	1·014	1·077	0·992	1·064	1·047	1·113	1·016	1·111	1·098	0·922	0·742	0·772	0·770
S.E.	±0·0520				—			—			—			

[1] Spring wheat in 1965 and 1966, winter wheat in 1967 and 1968.
[2] For use in comparing columns 1 with 2 or 4, 2 with 3, and 3 with 4 in 1966.
[3] For use in comparing columns 1 with 3 or 2 with 4 in 1966.

APPENDIX TABLE 4

Yields of barley grain and straw, the percentage of N in grain, and the N taken up by grain plus straw at Saxmundham (Suffolk), 1967 and 1968

Year	1967		1968			
			Without formalin in 1967 or 1968	With formalin in		
cwt N/acre/year	Without formalin	With formalin		1967	1968	1967 and 1968
	Yields (cwt/acre) of grain at 15% moisture content					
0·0	21·9 (±1·36)	—	11·8	—	—	—
0·6	36·0	39·8	35·6	37·8	39·6	37·5
1·2	40·9	40·5	37·7	39·5	38·4	40·3
S.E.	±0·96			±1·24		
	Yields (cwt/acre) of straw at 15% moisture content					
0·0	21·0 (±1·74)	—	10·8	—	—	—
0·6	35·9	40·4	36·2	41·3	41·4	37·4
1·2	44·3	45·0	46·2	46·4	47·2	46·2
S.E.	±1·23			±1·53		
	Percentage of N in grain					
0·0	1·44 (±0·084)	—	1·70	—	—	—
0·6	1·38	1·58	1·67	1·78	1·86	1·84
1·2	1·70	1·79	2·25	2·26	2·26	2·30
S.E.	±0·060			±0·052		
	N (cwt/acre) in grain plus straw					
0·0	0·342 (±0·0504)	—	0·214	—	—	—
0·6	0·535	0·682	0·668	0·784	0·843	0·747
1·2	0·794	0·829	1·068	1·156	1·099	1·150
S.E.	±0·0357			±0·0346		

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APPENDIX TABLE 5

Yields of, and the percentages and amounts of N in dry grass from a timothy/meadow fescue ley at Rothamsted in 1967 and 1968

Year	1967						1968			
cwt N/acre/cut	1st cut	2nd cut Without formalin	3rd cut	1st cut	2nd cut With formalin	3rd cut	1st cut Without formalin	2nd cut	1st cut With formalin	2nd cut
					Yields (cwt/acre) of dry grass					
0·0	5·0	17·5	0·7	12·9	18·4	1·2	5·0	6·8	6·0	7·6
0·3	12·2	29·7	6·2	20·1	29·0	6·6	22·7	19·4	27·6	21·5
0·6	16·5	32·4	7·9	23·6	32·9	7·8	36·6	23·3	37·2	23·9
0·9	18·3	32·1	6·4	23·1	32·9	7·2	40·9	20·8	43·2	21·2
S.E.	±1·05	±0·99	±0·40	±1·05	±0·99	±0·40	±0·63	±0·63	±0·63	±0·63
					Percentage of N in dry grass					
0·0	2·40	1·81	1·97	1·77	1·79	2·21	1·62	1·25	1·64	1·26
0·3	2·90	1·90	2·98	2·47	2·07	3·34	1·76	1·36	1·75	1·37
0·6	3·19	2·34	3·88	2·76	2·54	4·12	2·09	1·96	2·14	1·79
0·9	3·27	2·89	4·05	2·92	2·69	4·21	2·51	2·54	2·56	2·46
S.E.	±0·070	±0·058	±0·060	±0·070	±0·058	±0·060	±0·042	±0·077	±0·042	±0·077
					N (cwt/acre) in dry grass					
0·0	0·116	0·319	0·015	0·226	0·328	0·026	0·081	0·086	0·099	0·095
0·3	0·347	0·562	0·185	0·491	0·600	0·219	0·401	0·264	0·484	0·293
0·6	0·521	0·757	0·307	0·647	0·835	0·321	0·764	0·456	0·796	0·428
0·9	0·593	0·927	0·258	0·672	0·882	0·304	1·030	0·527	1·105	0·523
S.E.	±0·0326	±0·0219	±0·0149	±0·0326	±0·0219	±0·0149	±0·0216	±0·0195	±0·0216	±0·0195

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Chemical Control of Plant Growth

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That the form of plants, and the relative proportions of their different parts, can change greatly is evident from the differences between plants of one variety when grown in different environments. The sequence of environmental changes that gives the greatest yield of either total dry matter or the economically important parts of the plant can be discovered experimentally, but the scope for increasing yield of field crops by changing the environment is small. There is more scope in changing the morphology and development of the plant to suit the environment, and the larger potential yield of new than of old varieties of some crop plants reflect the success of the plant breeder in doing this. However, plant breeding is a slow process, and with the knowledge that the effects of the environment are mediated by the changes in the content and distribution of endogenous growth substances (chemicals produced within the plant that affect such processes as cell division and extension), there comes the possibility of altering the growth and morphology of existing varieties in ways that will increase yield.

This paper discusses this possibility and describes how growth regulators affect plant form; a growth regulator is defined as either a naturally occurring or a synthetic chemical that, when applied to plants in small amounts, changes their form by altering the relative proportions of its component parts (Humphries, 1967).

Hormone weedkillers are growth regulators, but I shall not consider them though they represent by far the largest use yet of growth regulators in agriculture. I shall deal only with chemicals applied to change the form and growth of crop plants directly. Research on such chemicals was stimulated by the discovery of gibberellic acid, gibberellin A_3, first identified as a metabolic product of the fungus *Fusarium moniliforme*. This greatly increased the growth of some plants, especially of their stems, but sometimes also of leaves, and increased total dry weight. Regrettably the early promise that gibberellic acid could be used to increase crop yield has not been realised, although only few tests have been made on field crops because it is expensive. However, a claim that cheaper unrefined preparations increase yields of sugar cane (Tanimoto & Nickell, 1966) implies the need for further tests.

The chemicals whose effects and interactions I shall consider are:

Gibberellic Acid, a naturally occurring growth regulator that increases both cell division and cell growth.

CCC (2-chloroethyl-trimethylammonium chloride), a synthetic chemical that inhibits gibberellin synthesis, slows cell division, lessens apical

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dominance, causing more branches to develop, and strengthens stems of cereals.

B9 (N-dimethylaminosuccinamic acid), a synthetic chemical that stunts plant growth, probably by interfering with auxin synthesis (e.g. Cooper *et al.*, 1968).

Morphactins, which are synthetic derivatives of fluorene carboxylic acid, and chemically related to the gibberellins, but with very different properties. The morphactins stunt plant growth at smaller concentrations than CCC or B9.

Ethrel (2-chloroethylphosphonic acid), a chemical that causes growth changes by liberating ethylene in the plant.

Effects of growth regulators on potatoes

The yield of potatoes could be increased if a greater proportion of the total dry weight could be made to pass into the tubers, or if the dry weight could be increased by increasing the leaf area or by prolonging the life of the haulm. Gibberellic acid usually increases stem extension, but not of potato plants except when nitrogen is deficient (Humphries & French, 1960) or when potato seed pieces are soaked in concentrated solutions (Dyson & Humphries, 1966). It increased the areas of some leaves and increased the yield of dry matter, (Humphries & French, 1960, 1961, 1963) and sometimes tuber yield (Humphries & French, 1963). Treated leaves had larger cells and more cells per leaf (Humphries & French, 1963). Apparently gibberellic acid affected only growing leaves or those that had reached a minimum size in the apical primordium, but by enough to increase dry matter. It also increased tuber number but made them smaller and shortened the dormant period (Humphries, 1958; and Humphries & French, 1960). Gibberellic acid increases the activity of hydrolysing enzymes and this may be why treated potato leaves have less total nitrogen and protein per unit area than untreated (Humphries & French, 1961). As gibberellic acid also makes the root system smaller, the paler colour of the leaves could imply that the roots were not absorbing enough nitrogen, but spraying the leaves of treated plants with urea did not affect their appearance (Humphries & French, 1963).

The ability of gibberellic acid to break tuber dormancy could be an advantage if the precocious growth were subsequently checked by applying inhibitors. Krug (1963) found a balanced combination of the inhibitor CCC and gibberellic acid produced compact plants in the dim light of winter, but Dyson (1965) found that applying CCC to soil containing seed pieces soaked in 50 mg/l gibberellic acid did not counteract the effect of GA. Effects depend on the concentration of the growth substances and when they are applied. For instance, Dyson and Humphries (1966) found that CCC or B9 had different effects on Majestic potato plants treated with gibberellic acid when applied at different times. When growth of lower lateral branches was retarded, upper laterals often grew more than in untreated plants. However, Bruinsma and Swart (1966) controlled the growth of potato plants from tuber buds by giving gibberellic acid and B9 simultaneously.

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The effects of applying gibberellic acid at different concentrations and times and its interaction with growth inhibitors, are still far from fully known, but none has yet proved to be useful. However, it might be better to treat a plant with a gibberellin that occurs naturally in it. Gibberellic acid itself is not a common constituent of most plants but Gibberellin A_5 is; Wheeler and Humphries (1963) found when potato plants were sprayed with gibberellic acid it was converted to another gibberellin, possibly A_5.

Stimulating the growth of one plant part at the expense of another may lead to compensating effects later when the stimulation stops. This happens with gibberellic acid and is one reason why it is not useful. An effective stimulator should accelerate the growth of all plant parts equally, so that its effects would resemble those of increasing temperature on plant growth. This could be achieved if the substance increased cell division in all parts of the plant so that their relative growth rates were maintained. This seemed possible with the discovery of the phytokinins, but although they stimulate cell division and growth in isolated plant parts they have little effect when applied to intact plants (e.g. Humphries, 1958), perhaps because they do not penetrate or move easily in the intact plant. Small amounts of some herbicides (especially triazole compounds) seem to have the desired properties of a growth stimulator and need further study.

Increasing leaf growth, especially at first, increases yield but when crops become dense part of their leaf area is inefficient and uses dry matter that might otherwise have been diverted to increase the economic part of the plant (e.g. see Humphries & Wheeler, 1963). As already mentioned the relative distribution of dry matter in different parts of a plant is determined by the environment working through endogenous growth substances, but the distribution is altered by applying growth regulators. CCC and B9 slow growth of stems and leaves and divert assimilates to other parts. Such diversion could be valuable in the potato. Humphries and Dyson (1967a) showed that a potato crop can have more leaf area than is necessary for maximum tuber yield; some leaves contribute little to useful dry matter production, for Majestic potato plants sprayed with B9 (5 g/l) at tuber initiation and two weeks later had 20% less leaf area than unsprayed plants at the time of maximum leaf area index, but yielded the same weight of tubers. B9 speeded tuber growth and increased the number of tubers. This result suggests potential uses of growth regulators in potato culture, and in preliminary tests, Humphries, French and Williams (1967) found that different potato varieties may respond differently and that yield increased more in early than in main crop varieties. Whereas CCC increased tuber yields of Arran Pilot by 37% and B9 of Craigs Alliance by 28%, neither chemical increased the yield of Maris Peer or Pentland Dell by more than 5% (Table 1). Whether such effects can be obtained consistently remains to be seen. Bodlaender and Algra (1966) found that B9 also increased yield of the variety Alpha. Shibles and Weber (1966) concluded that converting as little as 8% of the top vegetative dry matter of the soybean plant to beans would increase yields by about 15%.

CCC hastens tuber growth (Dyson, 1965) and this earlier development of tubers increases sinks for carbohydrate and increases net photosynthesis of the leaves (Dyson & Humphries, 1966; Gifford & Moorby, 1967). The

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TABLE 1

Effect of the growth regulators CCC and B9 on % change in (a) total fresh weight of tubers, and (b) tuber number of some potato varieties

	(a) Fresh weight		(b) Tuber number	
	CCC	B9	CCC	B9
Ulster Prince	5	−7	4	5
Arran Pilot	37	12	−12	11
Craigs Alliance	5	28	1	15
Maris Peer	4	3	6	13
Pentland Dell	7	6	−9	41

factors determining the number of tubers that a potato variety produces are not fully understood but it is certain that the potential number is greater than the actual number. For instance, Nösberger and Humphries (1965) found that removing tubers caused more to form. In the variety Epicure, 98 tubers formed on a plant when they were continually cut off, but only 45 formed when they were undisturbed. This result suggests that tuber number can be altered by appropriate treatments and this might have practical benefits. For instance the potato-seed grower requires the maximum number of tubers in the seed-size range, and the canner small evenly-shaped tubers. These requirements are met, to some extent, by suitable varieties or cultural practices, but growth regulators can also change tuber size and number. Thus, B9 increased mean tuber number in Majestic by nearly 30% (Humphries & Dyson, 1967b). In this experiment, seed tubers of different sizes were planted and, as expected, the smaller seed produced plants with fewest tubers, but B9 also affected tuber number, so the number of tubers per plant in this experiment ranged widely. B9 increased tuber number in some other varieties but CCC did not, and sometimes decreased the number. The effect of a growth regulator depends on whether it is applied before or at the time of tuber initiation.

Preliminary results with potatoes grown in pots show that Morphactin slows haulm growth, and this has beneficial effects on stolon and tuber development. Sprays of 1 or 10 mg/l completely stopped growth of new leaves and stimulated growth of axillary shoots, especially at the base of the main stem, and increased the leafy stolons i.e. branches originating beneath the soil and emerging to bear leaves. In the field, with greater depth of soil and more competition for light, these branches might have remained in the soil and produced tubers. Increase in growth activity at the base was also reflected by greater weight and length of stolons. Morphactin also increased the number of small tubers (Humphries & Pethiyagoda, 1969).

Effect of CCC on white mustard (*Sinapis alba*)

CCC increases leafiness in some plants—for example length and dry weight of the main stem of white mustard decreases with increasing amounts of CCC, whereas leaf weight may increase. The net effect of moderate amounts of CCC is a greater total leaf area (Humphries, 1963a), a good example of how a growth regular may be used to increase the useful part of the plant (leaf) and decrease the less desirable part. CCC and B9 also

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delay the decrease with age in total-N and protein-N of bean leaves, probably because the shoot grows more slowly and demands less nitrogen (Humphries, 1968a).

Effect of CCC and gibberellic acid on sugar beet

CCC hastened leaf production by sugar beet and gibberellic acid slowed it. Both changed the shape of the crown of the plant, CCC flattening it and gibberellic acid elongating it, and this change was associated with the rate leaves were produced (Humphries & French, 1965). More leaves on the sugar-beet plants did not affect the dry matter produced because they were smaller; nor did the fewer leaves of plants treated with gibberellic acid, because they were larger and persisted longer than on untreated plants. The result showed that dry weight can depend more on size and longevity of leaves than on total number of leaves.

Although CCC hastened leaf production of sugar beet, it had no such effect on potatoes or cereals. When CCC was applied to sugar-beet seedlings with only two leaves, its effect persisted for the rest of the season, as do the effects of environment in which sugar-beet seedlings are raised, (Humphries, 1966; French & Humphries, 1969; Humphries & French, 1969a, 1969b). Suitable growth regulators might change the relative proportions of plant parts in the same way as environment does. If this is done at an early stage it may be possible to increase yield in other plants with organs that store carbohydrate (Humphries, 1969). For example, CCC applied to sweet potato (*Ipomoea batatus*) grown in pots increased the weight of tubers. Possibly some growth substances may also increase net photosynthesis in leaves, for there is evidence that the leaves of sugar beet do not always photosynthesise to full capacity.

CCC and cereals

Up to now the growth regulator most studied on cereals is CCC. Soon after it was described by Tolbert in 1960 it was used to prevent lodging of cereals and many papers show its practical value (see Humphries, 1968b). Although its main effect is to shorten and strengthen the stems, and so lessen losses caused by lodging, it has other effects that increase yield.

In the first experiments with CCC on wheat on Rothamsted farm in 1964, the untreated crops did not lodge, but CCC increased grain yield by 2 cwt/acre, mainly by increasing the number of ears; a decrease in grain size by CCC was offset by more grains/ear (Humphries, Welbank & Witts, 1965a). Leaf area index of sprayed plants was 70–80% of unsprayed. With less leaf more light penetrated the canopy of crops sprayed with CCC than of unsprayed crops, and at first this was thought to be the reason why more shoots survived, but later experiments did not support this explanation.

In the following years, experiments were done mainly to see how CCC affected lodging and yield of crops given different amounts of nitrogen fertiliser, spaced at different row widths or irrigated. Some experiments also

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studied the effects of CCC on leaf area, the number of ear-bearing shoots, grains per ear and grain size.

Spacing experiments. In 1965, spring wheat, Opal, was sown in rows 4 in. or 8 in. apart at usual and twice usual seed rates, with 0·5 or 1·0 cwt nitrogen/acre. Yield was slightly increased by CCC at 4 in. spacing, but not at 8 in.; however, the interaction was not significant (Humphries & Bond, 1969a). Yield was less with the larger seed rate, although it increased leaf area duration after anthesis.

Similar results were obtained in 1968, when CCC was tested on both winter wheat (Cappelle) and spring wheat (Kolibri) grown at different spacings. Nitrogen fertiliser was applied at 0·8, 1·6 or 2·4 cwt N/acre. The winter wheat did not lodge and mean yield of grain was 28·8 cwt/acre; closer spacing increased it by 0·9 cwt/acre and spraying with CCC increased it by 1·9 cwt/acre, but there was no indication that CCC had a greater effect with closer spacing.

The mean yield from Kolibri was 31·8 cwt/acre and closer spacing increased grain yield by 1·3 cwt/acre, spraying with CCC increased it by 4·7 cwt/acre but, as before, there was no interaction between CCC and row width. Thus, although the shortened shoots of CCC plants allow more light to penetrate to the base of the plants (Humphries, Welbank & Witts, 1965b), this seems to have little effect on yield (Humphries & Bond, 1969b).

Irrigation experiments. In 1964 and 1965, CCC-treated plants pulled by hand from the soil had more attached roots than untreated plants. Hanus (1967) found that CCC usually increased the amount of wheat roots at all soil depths. Others have reported similarly and it can be accepted that CCC usually makes root systems larger, especially of spring wheat, whose stems are shortened more by CCC than are stems of winter varieties. The enlarged root suggested that CCC may increase yield by enabling shoots to avoid water stress during the period near ear emergence, so that more survive to produce ears. CCC increases tillering of wheat growing in pots (Humphries, 1963b, Tolbert, 1960); but in a field crop, where competition causes many tillers to die before maturing, CCC presumably increases the number of fertile tillers by allowing some tillers to survive that otherwise would have died. Humphries, Welbank and Witts (1965b) showed that the shoot number of an untreated crop declined from about 700/m^2 in mid-May to 450/m^2 at the end of June. The survival of an additional 20 ears/m^2 would increase grain yielded about 2 cwt/acre (Humphries, 1968c). The dependence of yield on the number of ear-bearing shoots per acre is illustrated by results obtained in 1966 from the Woburn Irrigation Experiment (see Fig. 1, which shows the partial regression of yield on shoot number at constant ear weight). Yields ranged from about 25 cwt/acre with 300 shoots/m^2 to about 50 cwt with more than 500 shoots/m^2.

Soil moisture deficits at Rothamsted for the 3 weeks after ear emergence, calculated by Penman's method, were more than 2 in. in 1964 and 1966, when CCC increased yield, but less than 1 in. in 1965 when CCC had no effect on yield of a normally spaced crop. The conclusion that the enlarged root system of CCC plants is important in drought was

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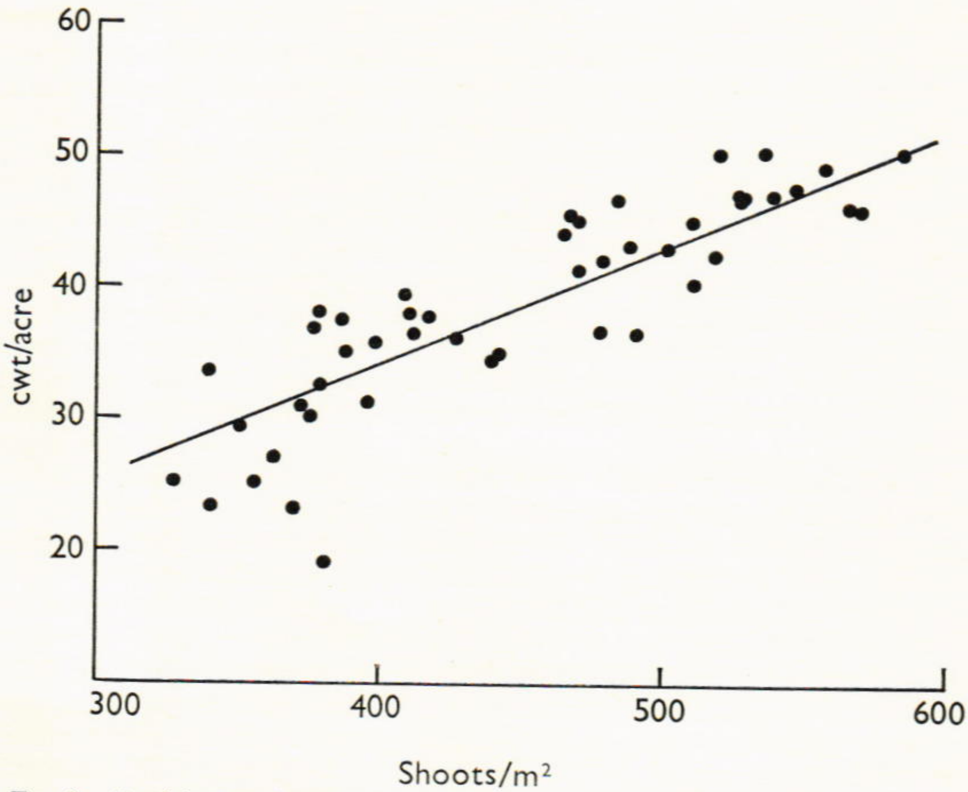

FIG. 1. Partial regression of yield on shoot number. Woburn Irrigation Experiment, 1966.

further tested in 1966 on the Irrigation Experiment at Woburn Experimental Farm by spraying half of each irrigated and unirrigated plot of spring wheat with $2\frac{1}{2}$ lb/acre CCC at 5-leaf stage. The experiment also tested N at 0·4, 0·8, 1·2 or 1·6 cwt/acre in all combinations with CCC and irrigation.

Both irrigation and CCC increased grain yield, but CCC had no effect on irrigated plots and the effect of irrigation was less on plots sprayed with CCC. On plots receiving 1·2 or 1·6 cwt N/acre, CCC increased grain yield by 6 cwt/acre, and irrigation by 10 cwt/acre, mainly by increasing ear number (Humphries, Welbank & Williams, 1967; Humphries, 1968c). In an identical experiment in 1967, irrigation increased yield but CCC did not, possibly because the dry spell in June and July was longer than in 1966. Root sampling showed that CCC without irrigation increased total root weight by 14%, and in the subsoil (25–60 cm) by 37%, but very little with irrigation (Humphries & Bond, 1969b). Thus, CCC increased the root system most in the subsoil, where water would not be lacking during a brief dry spell but might during a longer one.

Interaction of CCC with nitrogen supply. Several experiments were made to test the possibility that shortening the straw of a wheat crop with CCC may allow larger N dressings to be given and the yield increased more without risk of lodging (Humphries & Bond, 1969b). In 1966 at Rothamsted, Kloka

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wheat was given 0, 0·8, 1·6 or 2·4 cwt N/acre. Plots without CCC did not lodge, even with 2·4 cwt N, but CCC increased grain yield by an average of 2 cwt/acre as in 1964. Tests on grain from this experiment (Evers & Kent, 1968) show that CCC did not affect protein content. In 1967, when both winter (Cappelle) and spring wheat (Kloka) were given the same amounts of nitrogen as in 1966, CCC increased yield of Cappelle without N by 12 cwt/acre but by only 0·6 cwt/acre when N was given. The increase in yield with CCC came mostly from more ears and more grains per ear, offset to a small extent by smaller grains. More grains per ear is a usual effect of CCC but the cause is still in doubt and requires further investigation. That the slower development of CCC-treated plants allows more grains to form seems the most probable explanation. CCC did not affect grain yield of Kloka in 1967 and the maximum yield was obtained with 0·8 cwt N.

In 1968, more experiments were done with large N amounts, both on Cappelle and the new spring variety Kolibri; for the first time we could assess the benefits of CCC in conditions favouring lodging. Lodging occurred on all untreated plots of Kolibri, in amounts that increased with increasing N. Spraying with CCC increased the mean yield of grain by 4·7 cwt. Early lodging on untreated plots caused slower development of grains than on treated plots, so by delaying and decreasing lodging CCC increased grain size. It makes grains smaller in unlodged crops. There were also more grains per ear on CCC-treated plots, so more, larger grains account for the increased yield. Cappelle did not lodge and CCC increased yield only with 1·6 cwt N, by increasing the number of ears.

TABLE 2

Summary of results of CCC experiments 1964–69; Rothamsted and Woburn

				Yield cwt/acre			
Year		Variety		Nil	CCC	S.E.	Mean of
1964	R	Phoebus*	SW	39·7	41·9	1·21	3 N amounts and 2 CCC amounts
1965	R	Opal*	SW	32·5	33·1	0·89	1 cwt N/acre
1966	R	Kloka*	SW	31·8	33·8	0·71	4 N amounts
1966	W	Kloka*	SW	37·5	43·5	0·86	2 N amounts
1967	R	Kloka†	SW	45·8	45·8	0·65	4 N amounts
1967	R	Cappelle†	WW	56·1	60·8	1·32	4 N amounts
1967	R	Champlein*	WW	54·9	59·0	1·00	3 spraying dates
1967	W	Kloka*	SW	44·7	44·9	0·84	4 N amounts
1968	R	Kolibri‡	SW	32·1	39·2	0·45	3 N amounts
1968	R	Cappelle†	WW	27·8	29·7	0·50	3 N amounts
1968	R	Champlein‡	WW	37·4	40·6	0·53	2 N amounts and autumn and spring spray of CCC
			Mean	40·0	42·9		

R = Rothamsted
W = Woburn
SW = Spring Wheat
WW = Winter Wheat

* not lodged
† slightly lodged
‡ severely lodged

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Table 2 summarises the results of experiments on wheat at Rothamsted and Woburn between 1964 and 1968. In ten out of eleven experiments CCC increased yields. In some experiments yield was increased when no lodging occurred on untreated plots, in others the yield was increased because lodging was delayed or prevented. The mean increase in yield by CCC in all experiments was 7%. There was no evidence that yields increased by giving more than the usual amount of nitrogen when CCC was applied to prevent lodging. I have done no experiments in which CCC was mixed and applied with herbicide spray, but this has been shown to be a practical procedure, and the extra cost of CCC is then only that of the chemical. The Rothamsted results suggest that the use of CCC would have been profitable in most years.

Effect on wheat diseases. In spite of modern stiff-strawed varieties, lodging often limits grain yield. The likelihood of lodging is increased when the eyespot fungus, *Cercosporella herpotrichoides*, invades and weakens the base of straws. CCC increases the resistance of infected crops to lodging, but opinions differ on how it acts. Some claim it decreases the incidence of the disease, others that it acts merely by strengthening the straws, so experiments were done at Rothamsted to try and resolve the conflict. In an experiment with the susceptible variety Squarehead's Master grown in pots (Slope & Humphries, 1966) CCC applied to the soil lessened the number of lesions by the fungus but field experiments done in three years have not confirmed this effect. In 1966, CCC did not alter the number of eyespot lesions on Rothwell Perdix but it prevented lodging. In 1967 Champlein winter wheat was sprayed with CCC at the 3-leaf stage, the 5-leaf stage and the 6-leaf stage. CCC had no effect on severity of lesions but although only 4% of the unsprayed crop lodged, it increased yield by 4 cwt/acre. Even when the crop of Champlein was treated with CCC in autumn, when eyespot is most likely to spread, there were as many lesions as on spring treated or untreated plants, (Slope, Humphries & Etheridge, 1969). Thus, CCC did not affect the incidence of eyespot or the severity of its lesions. It decreases lodging of infected crops as of uninfected crops by shortening the straw. CCC is said to increase the incidence of ear diseases such as *Septoria culmorum* and *Fusarium* in some climates, but this has not been critically studied.

Semi-dwarf wheats. Dwarf wheat varieties that are less likely than taller ones to lodge may make the use of CCC unnecessary. However, CCC could benefit the yield of dwarf cereals by increasing the root system and increasing grains per ear, just as it does in current varieties. In a trial done in 1966 with several dwarf wheats grown in pots, CCC at a dilution of 1 in 200 (equivalent to 2 lb/acre) shortened the straws of all but one of the varieties and none as much as of Opal or Kloka (Table 3). However, effects in field crops have yet to be tested.

Effects on barley and oats. A treatment that shortens straw would be useful with barley which is more susceptible than wheat to lodging, but many experiments at Rothamsted and elsewhere show that CCC has little effect

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TABLE 3

Effect of CCC on straw length of some semi-dwarf wheat varieties (cm)

	CCC	Untreated	Straw length % of untreated
843–6	49·7	59·4	83
843–7	47·4	50·4	94
Gaines	43·4	46·5	93
Chilean 13573	30·2	28·0	106
Mexico 120	24·6	28·0	86
NBJ 115	43·6	51·4	85
PC 81 EEE	44·7	50·9	88
Cappelle	61·2	64·0	95
Opal	44·3	60·2	74
Kloka	44·6	57·5	77

on barley. In tests with six varieties grown in pots, CCC shortened the shoots of the old long-strawed variety Plumage Archer but not of Proctor, Maris Badger, Europa, Cambrinus or Impala (Humphries, Welbank & Witts, 1965a). Whether the lack of effect is because CCC does not penetrate into the plant readily, is not translocated, or is metabolised once inside the plant, was not determined. When dimethylsulphoxide, which aids penetration of chemicals into plant and animal tissues, was added to CCC spray, the mixture shortened barley plants grown in pots in the glasshouse more than CCC spray alone, suggesting that more CCC entered the plant. However, when the ears were ripe, the plants treated with CCC alone or together with dimethylsulphoxide were nearly as tall as untreated plants. The same result was obtained in the field; soon after spraying, plants were shorter but afterwards grew faster than untreated plants (Humphries & Williams, 1968). The peduncle and highest internode at maturity were longer on sprayed than unsprayed shoots, but the lower internodes, which were elongating when sprayed, were shorter (Humphries, 1968d). Why barley plants treated with CCC eventually grew faster than untreated plants is not known, but the effect suggests that CCC may increase the gibberellin content of barley. Apparently if enough CCC can be maintained in the barley plant the shortening achieved is comparable with that in wheat. Thus, Larter (1967) who sprayed successively at the 3-leaf, 5-leaf and flag-leaf stages reported that stems were shortened by 25% and lodging was prevented. Successive sprayings are neither practical nor desirable because of the risk of increasing harmful residues in the grain. Stoy (1968) showed that tetraploid rye responds to CCC much more than diploid strains. So genotype is probably concerned with response of cereals to CCC, but perhaps this is only a part of the problem because I have shown that strains of wheat that are unresponsive in the hot climates of Egypt and Kenya show the expected shortening when tested here.

To shorten oat straw would be very valuable, for oats are very susceptible to lodging, but unfortunately CCC is not a general help because it affects only some varieties (Humphries, 1968b). When tested on the responsive variety Maris Quest in 1968, given 0·5, 1·0 or 1·5 cwt N/acre, the effect of 2½ or 5 lb/acre CCC was to shorten straws by 11% or 15% respectively; the effect decreased with increasing N supply. Slight lodging in July on plots

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given 0·5 cwt N/acre was decreased by spraying with CCC, but plots with more N were severely lodged whether sprayed with CCC or not. On plots with 0·5 cwt N/acre, spraying with CCC at $2\frac{1}{2}$ lb or 5 lb/acre increased grain yields 2 cwt and 9 cwt/acre respectively, mainly by increasing grains per panicle. With more N, CCC did not affect yield (Humphries & Bond, 1969a).

A new growth regulator 'Ethrel' (2-chloroethylphosphonic acid) was tested on barley and oats in 1969. Plots of each crop sprayed with 1 lb or 2 lb/acre of active ingredient at 5–6 leaf stage lodged sooner than unsprayed plants but yields were not affected.

Effect of growth regulators on field beans

The first growth regulator experiments on field crops at Rothamsted were done by Moffatt and Hill (1960) between 1955 and 1957. They tested the effect of 4-chloro-phenoxyacetic acid and α-(2,4,5-trichlorophenoxy) propionic acid at 5 ppm on set of pods of spring-sown tick beans (*Vicia faba* var. *minor*). Two applications of the propionic acid decreased yield in 1955 and four applications of the phenoxy acid increased it in 1956. In 1957, it increased flower set on dunged plots and decreased it on irrigated plots.

In trials on field beans (McEwen, 1969), CCC did not shorten the stems and lessened yield by 1·9 cwt; B9 greatly affected growth and shortened stems by as much as 30%, depending on time and amount applied. A single application in early June was most effective. However, B9 affected yields inconsistently; without fertiliser nitrogen it increased yield by about 2·5 cwt in 1966 and 1968 but decreased it by 2·1 cwt in 1967. The main effects of B9 were to increase the number of stems and pods per acre and lessen 1000 bean weight. Plants given B9 in 1968 produced half a million more beans per acre than untreated plants.

Conclusion

Applying chemicals to crops to alter their character and make them better able to withstand adverse conditions, or to alter their growth to produce more of the useful parts, is a new departure in agriculture but the success of CCC on cereals shows promise of future practical benefits. The search for growth-regulating chemicals has been intensified and there are now several promising compounds that warrant thorough testing. Experience with CCC and other growth regulators shows that when a chemical is selected for a particular property, such as stem shortening, it is soon found to have other apparently unrelated effects. For instance, CCC usually also increases the number of grains, stem diameter and the root system in wheat. Such multiple effects make it important that each growth regulator be tested on many species in different conditions.

It would be an advantage if a regulator also controlled pests and diseases, but the claim that CCC lessened eyespot disease of wheat has not been sustained, and it is now certain that it decreases lodging because it strengthens infected straws.

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There are other ways in which chemical regulators may aid crop production in the future. We still know little about the causes of flowering. The productivity of some crops, e.g. cereals, depends on time and amount of flowering, and perhaps suitable chemicals will be found to hasten flowering and seed set and shorten the crop cycle.

Little attention has yet been given to shortening the time a crop occupies the ground. Chemical regulators may eventually enable us to grow more crop in a shorter time. Yields of some crops in this country are limited by the length of the growing season. Potato plants for instance are easily frosted and a treatment to increase resistance to cold could increase yield by allowing earlier sowing. Both CCC and B9 are said to increase frost resistance of plants, including potatoes, but so far there is little reliable evidence.

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Rhizobium in the Soils of the Rothamsted and Woburn Farms

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Introduction

This paper reports counts made of root nodule bacteria in the classical field experiments (except Broadbalk field, the results for which were given in Part 2 of *Rothamsted Report for 1968*), in the long-term fallow plots and in fields where legumes have been inoculated. Some other counts are summarised in the *Rothamsted Reports for 1960* (p. 68), *for 1962* (p. 79) and *for 1965* (p. 86).

Species of nodule bacteria cannot with certainty be identified by cultural characteristics and so counted by plating. Enumeration depends on the nodulation of an appropriate host, grown in a sterile medium, from inocula of serially diluted samples of soil. The estimate of the number of nodules in the original sample is then obtained from the distribution of nodulated plants in the test, and rests on the assumption, verified by experiments with pure cultures (Date & Vincent, 1962), that a single cell of the appropriate *Rhizobium* introduced into the plant culture can suffice to produce nodules. Technical details and cultural methods are given by Date and Vincent (1962).

Serial dilutions used as inocula usually differed by a factor of 10, but occasionally by 4; 2–4 replicate samples of soil were used and each dilution was inoculated to 2–4 plants. Because test plants are sometimes attacked by fungi introduced in the soil suspension, each plant culture was classified as + (nodulating), − (not nodulating) or blank (dead or severely damaged), and the maximum likelihood method for estimating the most probable number of bacteria (MPN) in the original suspension was modified to take account of blank readings. In the tables and figures results are given as logarithms (base 10) of numbers per g dry soil. Variances of the estimated log densities have two independent components, the dilution series variance and the sampling variance. The dilution series variance depends mainly on the dilution factor and the number of tubes per dilution, and for two tubes in a tenfold dilution series averages 0·15, although the variance exceeds this figure if some plants die. The sampling variance and dilution series variance combined can be estimated from the sub-plot error in a replicated trial, which for Broadbalk over the four species averaged 0·30; results for Barnfield were similar (0·28). Where the range of dilutions chosen missed either the starting or end points for nodulation, numbers are given as fewer than, or more than, specified values. The counts recorded as zero in the tables are to be interpreted as fewer than one organism per 0·5 g dry soil. Rhizosphere counts are related to the dry weight of the soil adhering to the roots.

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The four common species of *Rhizobium* found in arable farmland were separately counted by using different test legumes: viz *Vicia hirsuta* for *Rhizobium leguminosarum*, *Trifolium pratense* for *Rhizobium trifolii*, *Medicago sativa* or *M. lupulina* for *Rhizobium meliloti*, and *Lotus corniculatus* or *L. uliginosus* for *Rhizobium lupini*.

Test plants were grown on a N-free mineral salts agar medium (Jensen, 1942) so that their growth can be used to estimate the effectiveness with which the most numerous representatives of the bacteria present fixes nitrogen. This estimate may be affected by other soil micro-organisms introduced in the soil suspension and by the presence of both effective and ineffective (non nitrogen-fixing) nodules on the same root. For this reason effectiveness is best judged from plants nodulating with the most dilute inoculum or by supplementary tests using bacteria re-isolated from single nodules taken from such plants.

Barnfield

The 0–1 in. soil layer was sampled in February 1967 before Barnfield was sown for the first time to field beans (*Vicia faba*). To count *R. leguminosarum* and *R. trifolii* four samples of soil were taken from each of the original plots (see Table 1). Two of the samples were taken from each half plot sown in the previous year to mangolds (a) or potatoes (b), one from the sub-plot given no fertiliser (N_0) and one from the sub-plot (N_1) given 1·8 cwt ammonium sulphate per acre (except in the 0 and 3 strips which were not subdivided for the new fertiliser dressings). *R. lupini* and *R. meliloti* were not counted in the samples taken from the N_1 sub-plots.

The beans sown in Barnfield after February were inoculated with a peat culture of *Rhizobium leguminosarum* from Dr. D. A. van Schreven, Kampen, Holland, except those for strip 3 which were sown with uninoculated seed. In May 1967 bacteria in the rhizosphere and soil (between rows) were counted in duplicate samples taken from the 3 and 8 (no PKNaMg) and 0 (no nitrogen fertilisers), and A (ammonium sulphate) combinations only, and from winter beans growing in the neighbouring allotment field.

Table 1 shows the average numbers of the four *Rhizobium* species for each plot, combining (a) and (b) and (N_0) and (N_1) sub-plots.

Rhizobium trifolii and *R. leguminosarum* were about equally frequent, with average numbers per plot ranging several hundredfold. *R. lupini* and *R. meliloti* were very scarce; many samples contained none and no sample contained as many as 100/g dry soil. Analysis of variance showed significant differences between plots of each series (1–8 and O–C) and a highly significant interaction between series. FYM seemed to decrease numbers, and nitrate and ammonium sulphate to increase numbers more than did rape cake, but because there is no true plot replication the interpretation of these effects is uncertain. The analysis also showed no effects of previous cropping or of supplementary dressings of nitrogen fertiliser recently applied.

Rhizobium numbers were quite unrelated to the long-term mangold yields, which ranged from 3 to 28 cwt/acre (Watson & Russell, 1943)

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TABLE 1

Numbers of Rhizobium *in Barnfield soil, before and after inoculation of beans, and in neighbouring allotment field*

Log estimated no./g dry soil

February 1967 (before sowing beans)

	R. trifolii				*R. leguminosarum*				*R. lupini*				*R. meliloti*			
Plots[1]	1	3	4	8	1	3	4	8	1	3	4	8	1	3	4	8
O	3·06	1·04	0·70	1·83	1·17	1·92	2·39	2·80	0[2]	0	0·48	0	0·60	0·78	0·48	1·92
N	3·40	1·08	0·60	2·55	2·65	2·61	3·54	2·65	0·42	0	0·78	0	0·30	1·08	0·48	0·70
A	2·35	1·20	2·64	2·06	1·71	3·06	3·67	3·12	0	0·70	1·04	0	0	0	0	0·60
C	1·76	2·06	2·40	3·37	1·86	2·47	2·72	2·86	1·10	0	1·40	1·81	0·78	1·08	0	1·94

	R. trifolii	*R. leguminosarum*	*R. lupini*	*R. meliloti*
(a) after mangolds	2·29	2·63	0·48	0·88
(b) after potatoes	1·77	2·51	0·49	0·46
(N_0) no supplementary ammonium sulphate		2·58		
(N_1) with supplementary ammonium sulphate		2·57		

May 1967, *R. leguminosarum*

Barnfield Plots		Inoculated 3	Not inoculated 8	Allotment beans rhizosphere
O	soil	1·52	1·95	5·18
	rhizosphere	5·18	4·96	
A	soil	2·51	3·47	
	rhizosphere	5·30	5·46	

[1] Key to plot numbering: 1, FYM; 3, nil; 4, PKNaMg; 8, nil; 0, nil; N, nitrate of soda; A, ammonium sulphate; C, rape cake.
[2] Less than one nodule bacterium per 0·5 g soil.
Standard errors of all values approx. ±0·3.

and so provided very different amounts of roots to indicate any rhizosphere stimulation.

The rhizosphere counts on the first bean crop grown in this field showed that large populations of *R. leguminosarum* developed rapidly in the root zone, where numbers resembled those in the adjoining allotment field where beans have been frequently grown. Inoculation had no effect on the rhizosphere population but slightly increased the soil population, indicating that some of the peat inoculum was introduced into the inter-row soil.

No isolates were taken for separate tests of the effectiveness of the bacteria in fixing nitrogen but the responses of the plants used in the counts showed that fewer than 5% of the most numerous bacteria present of *R. leguminosarum* and *R. lupini* were ineffective with *Vicia hirsuta* and *Lotus corniculatus* respectively. However, 15% of the clover bacteria and about 20% of the medick bacteria were poorly effective or ineffective with *Trifolium pratense* and *Medicago sativa* respectively.

Long-term bare fallows

Continuous fallows were begun in 1960 in sections of Highfield (Rothamsted) and in 1959 in Stackyard (Woburn). The site on Highfield was ploughed from permanent grass, the Woburn site from potatoes after an arable sequence without legumes since 1944.

Counts were begun at Woburn in June 1960 and at Rothamsted in December 1960. Because numbers in the surface (0–1 in.) and sub-surface (3–4 in.) soil were similar, counts for the two samples were combined. Table 2 shows the logarithms of the mean numbers per g dry soil at each time of sampling. Initially numbers of *R. trifolii* and *R. leguminosarum* were similar in the two fields but there were more *R. meliloti* at Woburn than at Rothamsted. During 1961, which was very dry during early summer, numbers fell sharply, especially of *R. meliloti* at Woburn, but later the rates of decline of each species were less; at Rothamsted numbers of *R. trifolii* and *R. leguminosarum* tended to fluctuate rather than decline.

At Woburn *R. trifolii* remained slightly more numerous than *R. leguminosarum* whereas at Rothamsted *R. trifolii* was constantly about 100 × more abundant than *R. leguminosarum*. In both fields the *R. meliloti* were few. Many samples from both sites taken since 1961 contained no recoverable cells.

The increase in the numbers of *R. trifolii* and *R. leguminosarum* immediately after the drought in 1961 and in 1963 may have been caused by leguminous and other weeds that grew when cultivations were impossible because of soil conditions (at Woburn 8 cultivations were done in 1960 and 1961, 4 in 1962 and 3 in 1963). The possible effect of weed growth was examined in soil sampled from the plots in August and December 1963 into pots, and kept moist. *R. trifolii* and *R. leguminosarum* were counted in the soil and in the rhizospheres of some of the weeds that developed (and in the rhizoid zone of the moss layer that formed on some of the pots). Table 3 shows the logarithms of numbers in the rhizosphere and the ratios of numbers in the rhizosphere to numbers in soil (R/S). Fifteen of

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TABLE 2

Numbers of Rhizobium *in Long-term Fallow Plots at Rothamsted and Woburn*

Log estimated no./g dry soil

	June 1960	Dec. 1960	April 1961	July 1961	Nov. 1961	Mar. 1962	Nov. 1962	April 1963	June 1963	Sept. 1964	Jan. 1967
ROTHAMSTED HIGHFIELD											
Rhizobium trifolii	—	5·32	5·07	2·93	3·97	4·60	4·93	5·54	5·50	4·86	4·53
Rhizobium leguminosarum	—	3·03	3·22	1·24	2·38	2·96	3·05	3·24	3·05	2·57	2·87
Rhizobium meliloti	—	1·20	1·24	0·22	<0·25	0	0	<0·42	<0·25	0	0
WOBURN STACKYARD											
Rhizobium trifolii	5·14	—	3·86	—	2·81	3·80	2·64	3·39	1·76	1·47	—
Rhizobium leguminosarum	2·55	—	3·54	—	2·50	3·50	2·62	0·69	2·58	1·23	—
Rhizobium meliloti	3·64	—	1·53	—	<0·24	0	0	1·31	<0·26	<0·53	—

Standard error $\pm 0{\cdot}3$

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TABLE 3

The stimulation of Rhizobium trifolii *and* R. leguminosarum *in the rhizosphere of weed species in Woburn and Rothamsted fallow soils*

Log estimated no./g dry rhizosphere soil and ratio of numbers in rhizosphere (R) and soil (S)

		Rhizobium trifolii		*Rhizobium leguminosarum*	
		Rhizosphere	R/S	Rhizosphere	R/S
Experiment 1	August, 1963				
Rothamsted	*Urtica urens*	5·65	14	5·04	180
	Poa annua	5·48	<1	4·48	50
Woburn	*Gnapthalium uliginosum*	3·16	<1	4·88	6300
	Poa annua	3·50	2	2·17	12
Experiment 2	December, 1963				
Rothamsted	*Stellaria media*	4·15	3	2·85	10
	Medicago lupulina	5·82	67	3·17	22
	Moss rhizoid zone	5·31	21	3·29	28
Woburn	*Spergularia* sp.	4·58	27	2·47	7
	Moss rhizoid zone	4·43	19	1·62	<1

the eighteen R/S values were greater than unity, and in most comparisons the rhizosphere effect was appreciable, indicating that some plants other than members of the *Leguminosae* stimulate the multiplication of nodule bacteria. Most *R. trifolii* were found among the roots of the single medick plant that grew in these pots (which, however, was not nodulated, indicating the absence of *R. meliloti*). Most *R. leguminosarum* was found in the rhizosphere of *Urtica urens*. That seeds of leguminous weeds are scarce at the Woburn site was also shown by Thurston, who found only three viable seeds each of *Medicago lupulina* and *Trifolium repens* in 30/Kg of soil sampled between 1960 and 1962, and none in 1963 (personal communication).

Miscellaneous counts in arable fields

Table 4 summarises counts of *R. leguminosarum* and *R. meliloti* made in fields before starting inoculation experiments.

R. leguminosarum. This species occurred in all fields sampled, but numbers were very few in the acid soil of Sawyers III, where beans were not known to have been grown before. The rhizosphere of young bean plants during early spring (in Delafield and Great Field I) already contained as many bacteria as recorded in the much older plant's rhizosphere (Table 1); numbers in soil under cereals after beans were about one-tenth as large as in the bean rhizosphere.

R. meliloti. In fields growing good trefoil (Stackyard A in 1960 and Stackyard C in 1962), *R. meliloti* was abundant, specially in the rhizosphere.

Butt Close field, which is not known to have been sown to trefoil but probably contains medick weeds had a small population of *R. meliloti* in

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TABLE 4

Miscellaneous counts

A *Rhizobium leguminosarum* Field and history		pH	Estimated log no. *Rhizobium* per g soil
Delafield	Feb. 1962. In winter beans after four years cereals	...	6·79
Great Field I	Feb. 1962. In winter beans after two years beans	...	6·36
Long Hoos III	Feb. 1962. In cereal after spring beans	7·8	5·09
Great Field II	Feb. 1962. In cereal after spring beans	7·3	5·79
Butt Close	Feb. 1962. After spring beans	6·9	5·79
Sawyers III	Feb. 1962. No record of beans		
"	"	5·8	1·76
"	"	5·8	2·07
"	"	5·6	2·23
"	"	5·6	1·16
B *Rhizobium meliloti*			
Woburn Stackyard A	Oct. 1960. In well established trefoil (*Medicago lupulina*)	...	7·85*
	"	...	>7·87*
	"	...	>9·16*
	"	...	>7·22*
Woburn Stackyard C	Feb. 1962. In trefoil	...	5·31
	"	...	4·00
	"	...	4·37
	"	...	5·06
Butt Close	Feb. 1962		
	Cottage end	6·7	3·18
	"	6·6	1·46
	"	6·7	3·23
	"	6·6	1·75
	Irrigation end	6·9	2·77
	"	6·9	3·22
	"	6·9	2·33
	"	7·1	3·59
Sawyers I	No record of sown legumes	4·9	0
	"	5·1	0
	"	5·2	0
	"	5·1	0

1962. The field was slightly less acid at one end than the other, and populations were larger in the less acid areas.

Counts were made in Stackyard C and Lansome fields in 1960 to investigate the poor establishment of trefoil grown from uninoculated seed in land not previously known to have grown trefoil. Soil from plots in the experiment growing ryegrass contained either none or very few *R. meliloti*, but the rhizosphere of the trefoil contained *R. meliloti* in numbers ranging from fewer than 100 to more than 100 million per g of dry soil. Stackyard C seemed to be more favourable than Lansome to the bacteria and to nodulation. Numbers of nodules were correlated with rhizosphere populations at Lansome but not at Stackyard C, and in both fields neither nodules nor rhizosphere populations were related to vigour of growth of the plants. The poor growth of individual plants was probably caused by late, and consequently ineffective, nodulation from the small scattered population of *R. meliloti* present in these fields, and did not recur when inoculated seed was sown (*Rothamsted Report for 1962*, p. 79).

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TABLE 4 (*continued*)

Miscellaneous counts

		No. of nodules on plant sampled	Estimated log no. *Rhizobium* per g soil
Woburn Stackyard C	Oct. 1960. Not known to be sown previously to trefoil. In ryegrass	...	0
	,,	...	0·78
	,,	...	0
	,,	...	1·36
	In trefoil (not inoculated). Well-grown plants	62	>6·45*
		6	6·79*
	,,	50	7·85*
	,,	90	>6·57*
	In trefoil. Poorly-grown plants	0	3·36*
	,,	58	7·85*
	,,	50	>8·50*
	,,	36	>8·60*
Woburn Lansome	Oct. 1960. Not known to be sown previously to trefoil. In ryegrass	...	0
	,,	...	0
	,,	...	0
	,,	...	0
	In trefoil. Well-grown plants	9	2·80*
	,,	5	6·00*
	,,	0	1·43*
	,,	0	3·96*
	In trefoil. Poorly-grown plants	1	4·57*
	,,	0	3·36*
	,,	30	>9·00*
	,,	2	4·79*

* Rhizosphere counts; remainder soil counts
Each soil count mean of 4 or 8 samples
... = no observations

Garden Clover

The garden clover plot, measuring 8 × 12 ft, was established in 1854 to grow red clover continuously on rich garden soil at Rothamsted Manor. The equivalent of more than 20 tons/acre of green matter was harvested per year from this plot at first. But yields then declined, sometimes to less than 1 ton/acre, and for many years the plot has been resown or partly resown annually. The plot or part of the plot has been given dressings of lime, fertilisers (including molybdenum) and treated with formalin, carbon bisulphide, clover nodule bacteria and soil extract but without appreciably increasing yields.

Two soil samples were taken in February 1967 from the sub-plot given molybdenum and not treated with formalin. These contained averages of 154 000 cells per g dry soil of *R. trifolii*, 9 cells of *R. leguminosarum*, (capable of fixing nitrogen on *T. pratense* and *Vicia hirsuta* respectively) and none of *R. lupini* or *R. meliloti*. The numbers of clover nodule bacteria have probably been sustained partly by inoculation and partly by the continuing presence of the host, and the poor growth of clover cannot be attributed to lack of effective bacteria.

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TABLE 5

Numbers of Rhizobium trifolii, R. leguminosarum, R. lupini *and* R. meliloti, *and occurrence of their hosts in plots of the Park Grass Experiment*

Log estimated no./g dry soil

Plot	Liming	pH 0–3 in.	*R. trifolii* r	*R. trifolii* 0–1 in.	*R. trifolii* 3–4 in.	Occurrence of *Trifolium*	*R. leguminosarum* r	*R. leguminosarum* 0–1 in.	*R. leguminosarum* 3–4 in.	Occurrence of *Lathyrus*	*Rhizobium lupini* r	*Rhizobium lupini* 0–1 in.	*Rhizobium lupini* 3–4 in.	Occurrence of *Lotus*	*R. meliloti* r	*R. meliloti* 0–1 in.	*R. meliloti* 3–4 in.	Occurrence of *Medicago*
3 No manure	L	7·2	>8·51	8·40	6·21	+	4·19	4·56	4·28	++	3·02	5·18	>6·50	++	0	0	0	−
	U	5·1	>9·32	5·90	5·07	+	>3·97	4·55	>4·41	± to −	>4·97	>6·58	>6·40	+	0	0	0	−
5 N 1856–97 5/1 No manure since 1898	U	4·4	>8·64	<2·70	<2·79	±	3·28	2·56	<2·42	−	2·73	>6·68	5·55	+	0	0	0	−
5/2 PK since 1898	U	4·9	>9·50	3·64	4·24	±	...	...	...		2·99	4·71	2·39	+	0	0	0	−
7 PKNaMg	L	7·0	6·91	4·37	6·75	+	3·89	5·13	5·78	++	2·44	3·35	2·80	± to −	...	0	0	−
	U	4·8	7·75	5·13	3·94	+ to ±	3·14	3·88	4·56	+	<1·65	3·15	2·68	± to −	...	0	0	−
6 N_2 (1856–62) PKNaMg	U	4·8	>10·85	6·59	<6·47	+	3·62	<4·41	<4·47	±	4·53	>6·55	<5·49	+	0	0	0	−
1 N_1	L	7·2	>7·51	7·06	5·13	±	4·51	>65·9	5·41	+	4·31	3·86	5·44	−	0	0	0	−
	U	3·6	...	0	0	−	...	0	0	−	...	0	0	−	...	0	0	−
9 N_2 PKNaMg	L	5·3	6·28	3·89	4·20	± to −	5·36	4·10	3·47	+	0·92	2·29	>1·60	−	0	0	0	−
	U(A.t)	...	...	0	0	−	...	0	0	−	...	...	...	−	...	0	0	−
	U(H.l)	3·8	...	<2·06	1·08	−	...	0	0	−	...	...	...	−	...	0	0	−
18 N_2 KNaMg	HL	7·6	9·72	5·66	5·44	+	9·86	4·45	4·99	± to −	9·08	<4·41	4·66	± to −	0	0	0	−
	LL	7·3	10·76	4·97	5·12	+	10·29	5·47	6·06	± to −	9·17	4·66	6·21	± to −	0	0	0	−
	U	4·2	...	<1·80	3·39	± to −	...	<1·80	2·01	± to −	...	0·48	<1·60	± to −	...	0	0	−
17 N_1*	L	7·5	>10·58	5·22	5·08	+	>4·36	4·03	3·86	± to −	...	...	...	−	0	0	0	−
	U	5·7	>9·97	4·76	3·77	+	5·73	4·38	2·76	−	...	...	...	−	0	0	0	−
13 FYM and fish guano	L	7·0	7·98	6·51	5·32	+ to ±	6·35	5·90	4·65	+	<4·56	3·47	4·36	±	0	0	0	−
	U	4·7	11·21	3·32	4·77	±	<4·56	2·30	<4·65	± to −	<4·56	4·26	3·38	±	0	0	0	−

SYMBOLS USED

Liming

HL, heavy liming (6788 lb ground lime/acre every fourth year

LL, light liming (3951 lb ground lime/acre every fourth year)

L, liming to plots except plot 18 (2000 lb ground lime/acre every fourth year

U, not limed.

r, Numbers of *R. trifolii*, etc., counted per g of clover rhizosphere soil.

Occurrence of host species on scale: ++, abundant to −, absent.

... No count.

O, less than about 1 organism per 0·5 g.

Counts from areas of plots with dominant *Agrostis tenuis* (A.t) or *Holcus lanatus* (H.l) respectively.

N_1, N_2—43, 86 lb N/acre as ammonium sulphate

N_1*—43 lb N/acre as sodium nitrate

The standard error of each estimate is approximately ±0·30

Park Grass

Samples were taken during the winter from the limed and unlimed sections of certain of the plots given no manure or given nitrogenous, mineral or organic fertilisers (see Table 5). Each sample consisted of either the 0–1 in. (surface) or 3–4 in. (sub-surface) parts of ten half inch cores taken at random from each sub-plot. The ten part-cores were mixed and duplicate 2–3 g sub-samples taken for counting. In addition, some plots were sampled to a depth of 12 in. and samples of clover rhizospheres were taken from plots containing clover.

Table 5 shows the numbers of the four species of *Rhizobium* in the surface and sub-surface soil samples and in the clover rhizosphere (r), and also the occurrence and relative abundance of the leguminous species in each plot and the pH of the 0–3 in. layer of soil.

The most striking result is the absence (i.e. fewer than about 1 organism per 0·5 g soil) of *Rhizobium meliloti* from all plots sampled; this correlates with the fact that none of the hosts of this nodule bacterium—species of *Medicago*, *Melilotis* or *Trigonella*—has been recorded in the plots. Populations of the other three species in the soil of the different plots also depended on the presence of appropriate hosts, except (i) for *R. leguminosarum* in the nitrate plot without lime and in the mineral plot without PK, both of which adjoin plots containing *Lathyrus* or *Vicia* in their herbage, and (ii) for *R. lupini* in the limed halves of plots 1 and 9, both of which contain a few *R. lupini* but not their host plants. The average soil populations of *R. trifolii* were about ten times larger than those of *R. leguminosarum* or *R. lupini*.

Provided there are some host plants present, the populations of nodule bacteria in the soil are only slightly influenced or are unaffected by the abundance of the host. In view of this, the large effect of the clover rhizosphere was unexpected. This effect is restricted to *R. trifolii* except for the limed sections of plot 18 where *R. leguminosarum* and *R. lupini* are also stimulated. On all plots not given nitrogen fertiliser, the rhizosphere of clover seems to have fewer *R. lupini* than the soil. Some rhizosphere populations of *R. trifolii* were very large, and the dilution series used failed to give any negative readings for half of the samples. This rhizosphere stimulation of *R. trifolii* was greatest where the soil was somewhat acid, as in the unlimed half of plot 3 and in plots 5/1 and 5/2, although the largest populations were in the limed plots. The clover nodule bacteria of some of the limed plots were a major constituent of the total bacterial population of the soil counted on a soil-extract agar.

Populations of *R. trifolii* and *R. leguminosarum* but not *R. lupini* were usually 7–8 times larger in surface than in sub-surface soil. Table 6 shows additional counts made in samples from plots 7, 9 and 13 to a depth of 12 in. On the unlimed parts, specially of plots 9 and 13, numbers of *R. trifolii* and *R. leguminosarum* decreased regularly with depth, and at 11–12 in. were about one-hundredth of numbers in the surface soil. *R. lupini* occurred more irregularly through the profile, and showed no clear trend with depth. All species were irregularly distributed and not especially abundant in the top 1 in. of soil.

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TABLE 6

Distribution of nodule bacteria in the soil profiles of Park Grass plots 7, 9 *and* 13

Log estimated no./g dry soil

		Sample depth (in.)	*R. trifolii*	*R. leguminosarum*	*R. lupini*
Plot 7	Limed	0–1	4·37	3·89	2·39
		3–4	<1·63	6·07	2·81
		7–8	4·07	4·69	2·56
		11–12	3·81	4·08	1·25
	Unlimed	0–1	4·36	3·80	<0·57
		3–4	2·41	<1·63	<1·63
		7–8	>4·69	1·93	5·48
		11–12	2·76	2·32	1·76
Plot 9	Limed	0–1	3·89	4·05	2·29
		3–4	4·17	3·47	<0·60
		7–8	1·60	2·40	2·75
		11–12	0·86	1·68	1·51
Plot 13	Limed	0–1	5·50	5·01	<2·99
		3–4	4·87	4·83	3·76
		7–8	4·73	4·16	6·16
		11–12	4·25	3·07	2·20
	Unlimed	0–1	3·32	2·30	6·62
		3–4	4·77	<3·40	2·48
		7–8	<4·11	<3·02	1·71
		11–12	3·65	<2·92	2·66

Liming greatly increased *Rhizobium* numbers, probably partly indirectly by its effect in increasing the amount of host species in the herbage. Each host and its bacterium was found only in plots with soil less acid than pH 4·0 and they were usually more abundant on the alkaline plots. Plots sampled were either acid (pH 4·2–5·7) or slightly alkaline (pH 7·0–7·6). Between these groups, but not within them, there was a consistent effect of pH, with more nodule bacteria occurring in the soils (and in the clover rhizospheres) of the alkaline than of the acid group. The alkaline soils averaged 148 times more *R. trifolii*, 13 times more *R. leguminosarum* and 140 times more *R. lupini* than the acid soils.

The principal grasses of the unlimed part of plot 9 are *Holcus lanatus* in clumps, and *Agrostis tenuis*. Soil samples taken from the soil under the *Agrostis tenuis* areas yielded no nodule bacteria whereas soil under the *Holcus lanatus* area contained a few *R. trifolii*, which because of their unusual symbiotic characteristics (see next section) are probably indigenous to this plot.

The symbiotic characteristics of Park Grass strains of *Rhizobium trifolii*. The dominant (most numerous) members of the *Rhizobium* populations in the plots were obtained by isolating from nodules formed on test seedlings inoculated with the most dilute soil suspensions that produced nodules. These came from the limed and unlimed parts (when present) of Plots 1, 3, 5/1, 5/2, 7, 9, 13 and 18. Each isolate was tested on four replicated plants of *Trifolium pratense* grown aseptically on N-free mineral salts

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medium in test tubes kept in a glasshouse. Comparison was made with uninoculated plants, and with plants inoculated with either the effective strain 0403 or the outstandingly effective strain 5 (Rothamsted collection strain numbers). The extent of nodulation was recorded and growth measured by grading for size at intervals and by measuring dry weight at harvest (80 days).

Isolates did not differ in the time at which they formed nodules, but varied considerably in their symbiotic effectiveness and in numbers of nodules produced. Fig. 1 shows the distribution of effectiveness of isolates measured in relation to the dry weight produced by strain 0403 (100%). With the exceptions discussed below, dry weight was distributed normally for each set of isolates; the variation was predominantly of host origin and corresponded to that expected in tests with four replicated plants.

The most effective strains (equal to or more effective than strain 5) came from the limed halves of plots given ammonium sulphate (plots 1, 9 and 18 II), although some strains from other plots (e.g. the unlimed section of the PKNaMg and nitrate plots, plots 7 and 17) were of more than average effectiveness. Strains from limed plots given minerals only and from the heavily limed plot 18 II differed more. Most strains isolated from these plots were as effective (or slightly more effective) than strain 0403, but of 20 strains two were ineffective and 3 poorly effective.

Plot 5, which has not been limed was colonised by bacteria more effective than 0403, except for an ineffective isolate from the rhizosphere of a plant from the section given PK. Only two of the eight bulked samples yielded any rhizobia, and these were of average effectiveness.

Isolates from limed and unlimed halves of plot 17, which is given sodium nitrate, were slightly less effective than those from plots 1 and 9. The small lime dressing applied to plot 18 III had no influence on strain variability, but the heavy liming of 18 II increased it; of the 16 strains examined from 18 II, two were more effective than the average, one less and one very poorly effective.

The acidity of unlimed plots usually either eliminated the clover nodule bacteria altogether or left as survivors only ineffective or poorly effective strains. Of the 8 strains isolated from the very acid (pH 3·8) section of plot 9 (from a *Holcus lanatus* patch) 4 were completely ineffective, and of those isolated from plots given no manure or PKNaMg only (pH 5·1 and 4·8), about one-quarter were ineffective, one-quarter poorly effective and one-half effective.

Nevertheless, neither acidity nor absence of lime were invariably associated with a decline in effectiveness; strains from plot 5/2 (pH 4·4), from the unlimed half of plot 17 (pH 5·7) and from plot 18 I (pH 4·2), were of average or more than average effectiveness. In all plots, isolates from the soil and from the corresponding rhizosphere were of similar effectiveness.

The mean number of nodules formed by each strain provided criteria for further strain differentiation, as shown in Table 7. Ineffective and poorly effective strains from all plots, except 18 II, formed many more and smaller nodules than did their effective counterparts. Differences between effective ones isolated from one plot section were not larger (except in the limed section of plot 17) than those with the strains 0403 and 5, and can be

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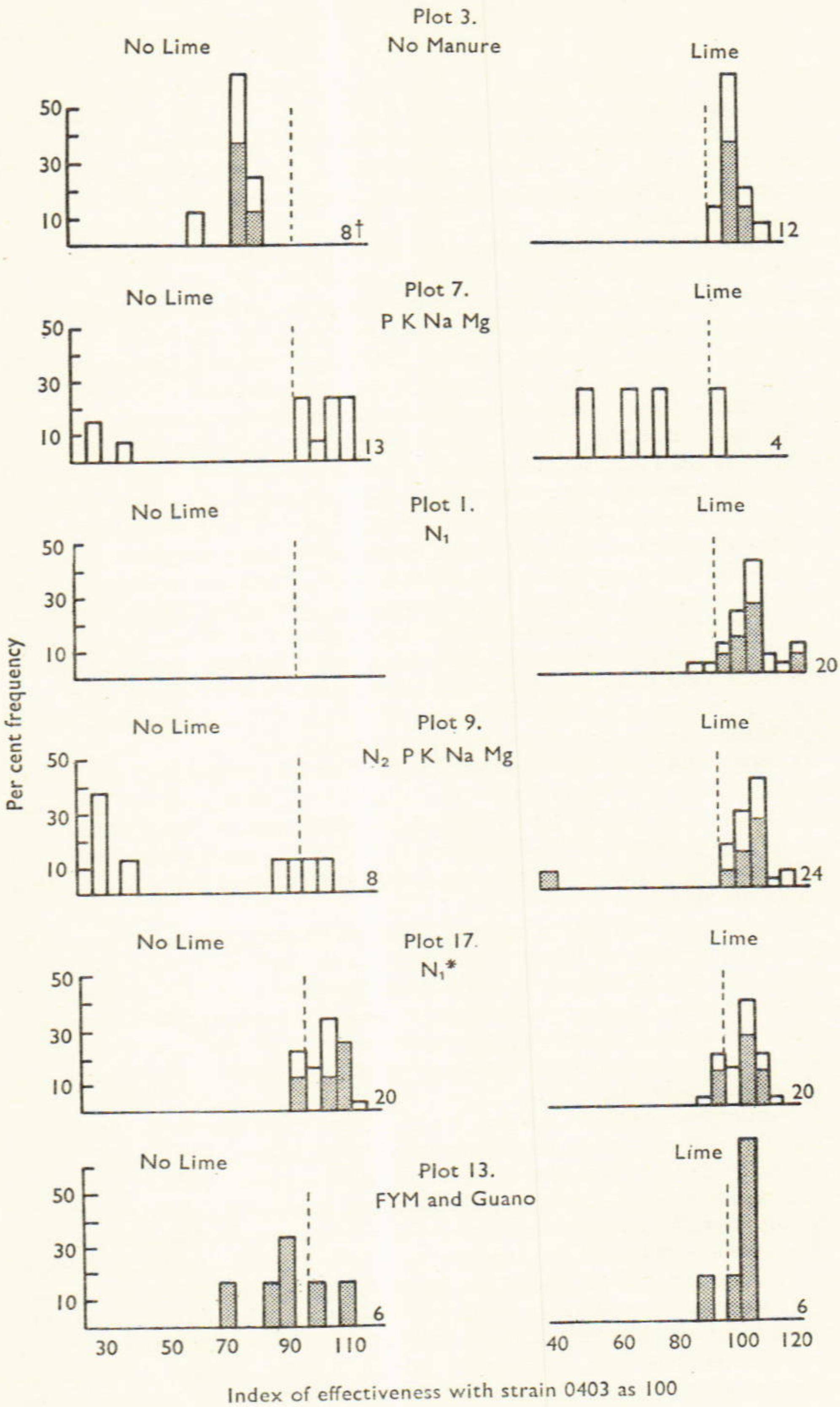

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attributed to host variation. However, there were large and significant differences in numbers between effective strains from different plots. Many more nodules were formed by effective strains from plot 5/2 (PK and no lime) and plot 7 (PKNaMg and lime) than by effective strains from the other plots. Strains from the limed sections of plot 13 (FYM) and plot 18 formed fewer nodules than strains from other plots. The single ineffective strain from plot 18 II was unique in its very sparse nodulation.

Exceptions to the general similarity in nodule number produced by effective strains from within a plot were three strains from the limed half

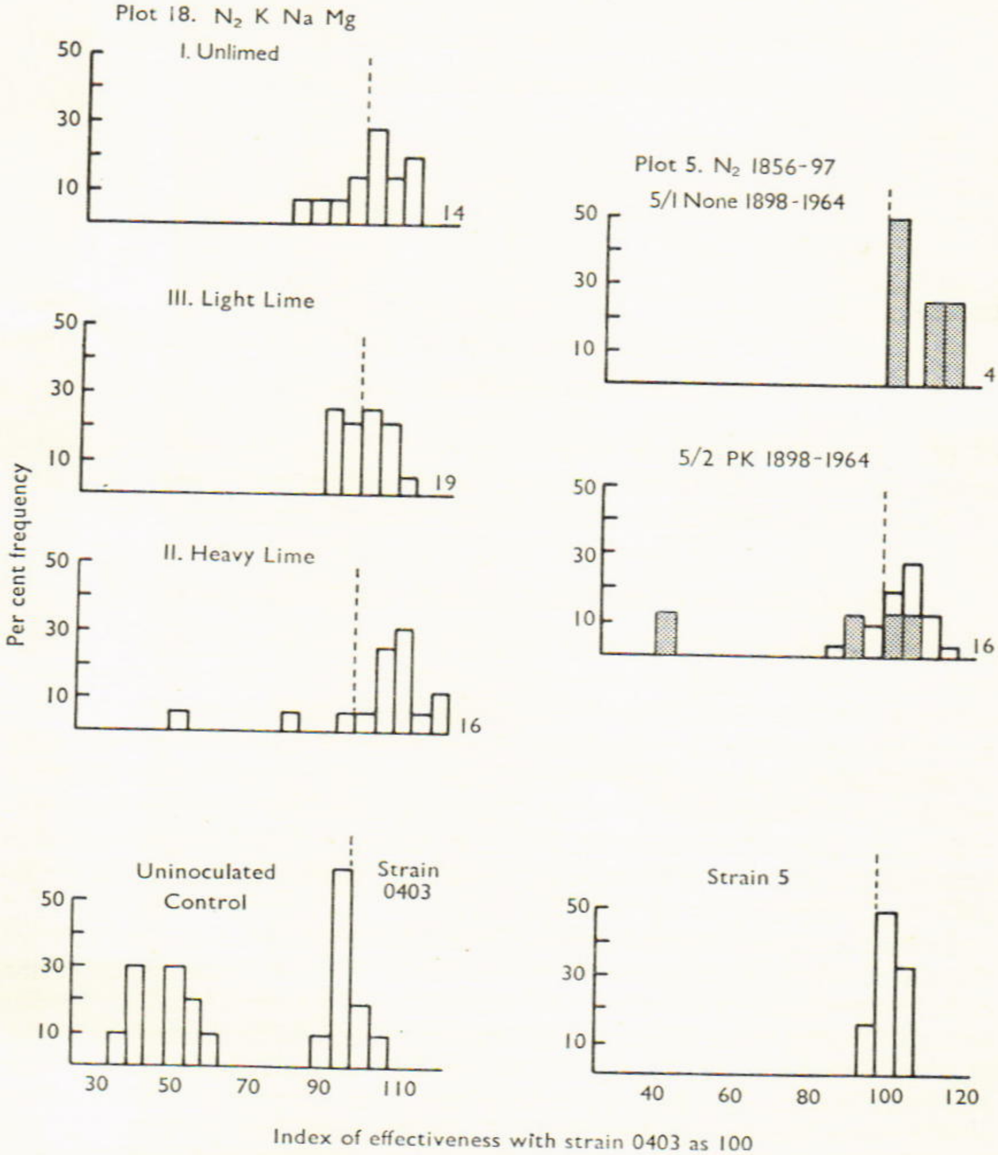

Fig. 1 Distribution of effectiveness of isolates of *Rhizobium trifolii* from Park Grass, tested on *Trifolium pratense*. Shaded areas refer to isolates from rhizospheres.

† Number of isolates tested.

TABLE 7

Numbers of nodules formed by Park Grass isolates in relation to effectiveness

Unlimed

Plot	30	40	50	60	70	80	90	100	110
3				74		68	67		
7	72	64						22	18
1									
9	65	81					18	21	
17							17	18	19
13					34		27	31	8

Limed

Plot	30	40	50	60	70	80	90	100	110	120
3								26	17	
7			108		37	58		68		
1							20	19	20	15
9		80						22	23	28
17							30	14	19	
13							10	9		

30–40–50–60–70–80–90–100–110 30–40–50 – 60–70–80–90–100–110–120

Relative effectiveness (Strain 0403 = 100)

Plot	30	40	50	60	70	80	90	100	110	120
18_{I}						17	15	12	11	
18_{III}							13	11	9	
18_{II}			12			12	6	16	19	13
5/1								18	21	
5/2		78				42	49	27	39	
Strain 0403							29	36		
Strain 5							29	25		

30 – 40 – 50 – 60 – 70 – 80 – 90 – 100 – 110 – 120

Relative effectiveness (Strain 0403 = 100)

of plot 17; although these seemed to conform to the normal effective group, as its least effective members, they produced many more nodules, *viz* 37, 38 and 52 compared with 16 for the remaining member of the group.

The distribution of nodulated plants in the dilution series

In the above counts no adjustment was made for 'skips', i.e. plants without nodules at lower dilutions than plants with nodules. The distribution of skips in the Barnfield, Broadbalk, Long-Term Fallows and Park Grass counts was examined by tabulating the number of skip tubes per dilution series (Table 8). A 'skip' tube is defined as any negative tube above a positive one in the dilution series. This simple definition somewhat over-estimates their true incidence, because where a 'skip' negative and a terminal positive are produced by adjoining dilutions, its normal probability of happening is up to 50%.

Because of the different lengths of the dilution series, statistical tests of the distribution of skips could not be made, but the results show some definite trends. Skips occurred in the counts of the four *Rhizobium* species in the following order of increasing frequency (neglecting manurial effects): *R. leguminosarum* or *R. trifolii*, *R. meliloti* and *R. lupini*. This order occurred in each field and was also observed in other experiments where results were too few to be tabulated. Skips were least prevalent in the Broadbalk samples. Long-term fallowing at Rothamsted and Woburn decreased the incidence of skips in the counts of *R. meliloti*, but seemed not to affect their frequency in counts of the other species. In Broadbalk,

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TABLE 8

Number of skip negatives per dilution series

A. Species differences

	Broadbalk	Barnfield	Rothamsted Fallow	Woburn Fallow	Park Grass
R. trifolii	0·23	0·56	0·24	0·57	0·47
R. leguminosarum	0·19	0·29	0·57	0·66	0·51
R. meliloti	0·50	0·67	3·30	3·08	—
R. lupini	0·66	—	—	—	0·96

B. Effect of duration of long-term fallowing

	1960–61	1962–63	1964–67
R. trifolii	0·78	0·25	0·40
R. leguminosarum	0·22	0·66	0·69
R. meliloti	4·87	1·87	1·50

C. Effects of manuring (combining test species)

Broadbalk

Plots		Sections	
3 (Unmanured)	0·44	I	0·22
5 (PKNaMg)	0·54	II	0·52
8 (PKNaMg and ammonium sulphate)	0·31	III	0·29
		IV	0·42
16 (PKNaMg and sodium nitrate)	0·15	V (fallow)	0·33

Barnfield

Sections		Sections	
1 (FYM)	0·56	O (nil)	0·31
3 (No manure)	0·16	N (sodium nitrate)	0·50
4 (PKNaMg)	0·36	A (ammonium sulphate)	0·36
8 (No manure)	0·54	C (rape cake)	0·34

Park Grass

Plots	Unlimed	Limed
3 (Unmanured)	1·4	0·30
7 (PKNaMg)	1·2	0·55
1 (2 cwt ammonium sulphate)	—	0·22
9 (4 cwt ammonium sulphate)	—	0·24
17 sodium nitrate	0·13	—
13 FYM and guano	0·71	0·59

neither one year's fallow nor applying herbicide affected the number of skips.

Combining results for the different *Rhizobium* species, both Broadbalk and Park Grass show very similar differences caused by manuring. Plots given nitrate provided dilution series with fewest skips, followed by those given ammonium sulphate or PKNaMg or left unmanured. On Park Grass FYM increased the incidence of skips and liming greatly decreased it in all except one set of the paired plots where skips were few. The results for Barnfield showed no consistent plot differences, but in view of the Park Grass results it is of interest that the FYM plot gave most skips.

Discussion

The counting method. The method gave consistent results but with large differences between replicates; the standard errors commonly ranged from 10 to 100% of the mean most probable number.

Estimates of numbers were affected by skips in the expected sequence of

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positives and negatives which led to sporadic and sometimes gross under-estimation of actual numbers present in the original suspension, and also increased replicate variation. Thompson and Vincent (1967) showed that skips in dilution tubes used for counting *R. trifolii* were unaffected by conditions of growth of the test seedlings, but were commoner with soil containing few bacteria than with soil containing many. Adding soil to a dilution series of a pure culture of nodule bacteria decreased the count, especially when the soil was added to the tubes some time before the bacteria. Thompson and Vincent also showed that the contents of skip tubes when used to inoculate fresh seedlings sometimes produced nodules and sometimes did not, indicating that the nodule bacteria may be suppressed or eliminated, presumably by microbial antagonism, lysogeny or predation. There is much evidence that rhizobia are subject to microbial antagonism in soil and in pure culture studies (Hely, Bergersen, & Brockwell, 1957; Wieringa, 1963; van Schreven, 1964; Visona & Tardieux, 1964; Hattingh & Louw, 1966a, 1966b; Holland & Parker, 1966; and Robinson, 1968).

The consistent differences between *Rhizobium* species in liability to this counting aberration, and of effects of manuring and liming, are interpretable in terms of microbial antagonism encouraged by dung and acidity and discouraged by nitrogen fertilisers. The fields at Rothamsted and Woburn provide valuable soils for further study of this phenomenon.

Populations of *Rhizobium* and their effectiveness. Populations of the four species of *Rhizobium* studied occurred widely in the arable fields of the Rothamsted and Woburn farms but in numbers that varied many-fold, usually in relation to the presence or recent presence of their respective host plants, and to soil acidity. *R. trifolii* was most widespread and usually most abundant, followed by *R. leguminosarum*, with *R. meliloti* and *R. lupini* much less abundant and more restricted in distribution.

At the time Broadbalk was surveyed (*Rothamsted Report for 1968*, Part 2, p. 180), this field had been cropped with nothing but wheat since 1843. Numbers were unaffected by manurial treatment or by fallow the previous year or by herbicide. Numbers were not simply related to the distribution or abundance of leguminous weeds, although the absence of clover may have been a contributory cause of the fewer *R. trifolii* found in Broadbalk than in other arable fields. There are no records of leguminous weeds on the plot area of Barnfield (J. M. Thurston, private communication), but clovers, vetches and medick are common on the field boundaries and in neighbouring fields.

In the continuously fallowed fields, numbers declined progressively in the early years but later more erratically, particularly at Rothamsted. That the host plant is not entirely necessary for multiplication of nodule bacteria in soil was shown by experiments on their stimulation by some non-leguminous weeds. Such multiplication was sporadic and uncertain and is probably unimportant in maintaining populations. This is also indicated by the absence of any correlation of populations with wheat yields on Broadbalk, or of mangolds or potatoes on Barnfield. The counts from all the arable fields indicate that nodule bacteria from areas where

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they are abundant are transferred to neighbouring fields, probably in soil blown by wind or brought on implements. Such agents probably suffice to provide inocula for clovers and beans, and possibly lotus, but not lucerne or trefoil grown on the farms. Adverse physical conditions, such as drought and heat accelerate decline of the soil population but when these do not operate, biological factors may be important, and it may not be coincidental that the species of *Rhizobium* most liable to decline in numbers are also most prone to show skips in their MPN count.

Development of appreciable populations from bacteria in the soil or from artificial inoculation, seems mainly to be restricted by soil acidity, with the four species again showing differential susceptibility to this factor in the environment. *R. trifolii* was occasionally isolated from soil more acid than pH 4·0, but *R. meliloti* very rarely from soil more acid than pH 6·0. Alkalinity stimulated rhizosphere increase, though whether directly or by increasing root exudation is not known. Loneragan and Dowling (1958) and Mulder and van Veen (1960) also showed that acidity was important in restricting multiplication.

The symbiotic effectiveness of strains occurring in the arable areas was not studied in detail but the response of the count-test plants showed that most of the rhizobia were effective in fixing nitrogen on their test hosts.

The distributions and relative abundance and effectiveness of *R. trifolii* and *R. meliloti* at Rothamsted and Woburn parallel those reported by Jensen (1969) for more than two hundred arable soils of Denmark, where abundance was clearly related to presence of host and to soil pH. By experiment Jensen also showed that *R. trifolii* only survived well in soil above pH 4·9 and *R. meliloti* only above pH 5·9.

The partial survey of the Park Grass plots demonstrated the dominating influences on rhizobia in pasture of host and soil reaction, for there was an almost exact correspondence between the occurrence of each species of *Rhizobium* in the soil and of its host, and indicated that a continuous plant cover prevents movement of bacteria from plot to plot. The survey also showed that the prolonged differential manuring had some effects on the symbiotic properties of *R. trifolii*. Where manures had not been given but lime had, strains were effective, but in plots without lime, and where pH had fallen to 5·1, strains were only poorly effective. Mineral fertilisers without nitrogen decreased effectiveness, even with liming. The use of nitrogenous fertilisers (nitrate of soda, ammonium sulphate or organic manures) over very long periods of time did not lessen ability of strains to fix nitrogen, provided that lime was also applied to the plots given ammonium sulphate.

Acidity tended to favour ineffective or poorly effective strains, although even acid plots contained some fully effective strains. Completely ineffective strains occurred irregularly and some were found in plots otherwise occupied by populations of strains of more than average effectiveness. Thornton (1954), Masterson (1961), Jones *et al.* (1964) and Jones (1966) showed that strains from hill pastures in the U.K. and Eire were often poorly effective. This was usually, but not always, associated with acidity. Holding and King (1963) attributed the poor effectiveness of strains from Scottish hill pastures to the soils being deficient in bases.

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The classical fields at Rothamsted and Woburn provide unique sites for ecological studies on the relationship between nodule bacteria, their host species and the soil, and for the collection of strains adapted to acidity and to nitrogen fertilisers, which could have agricultural value, but this still has to be assessed.

Summary

Rhizobium trifolii, *R. leguminosarum*, *R. meliloti* and *R. lupini* were counted in some of the arable fields of Rothamsted and Woburn, and in selected plots of the Park Grass experiment. All species were widely distributed throughout the arable areas, with *R. trifolii* and *R. leguminosarum* usually much more abundant than *R. meliloti* or *R. lupini*, especially in fields cropped by the host. When the host plants were not grown, numbers decreased in a few years from tens or hundreds of thousands per g dry soil to very few or none (as for example *R. meliloti* and *R. lupini* in most plots of Barnfield). Numbers were unaffected or only slightly affected by mineral or nitrogenous fertilisers or by moderate infestation with leguminous or other weeds but were reduced by acidity. The results suggest that numbers in arable soil without a recent legume crop are maintained by transfer by natural agents or farm implements from areas of abundance. Most nodule bacteria from these fields were effective in fixing nitrogen with the test hosts used.

The Park Grass survey showed striking correspondence between the occurrence of *Rhizobium* in the soil of each plot and the presence of a host species in the herbage. Numbers were few or absent in the acid plots and were more on the limed plots but were unaffected by mineral fertiliser. *R. trifolii* was strongly stimulated in the clover rhizosphere, even after more than a century of clover cover. The numbers of nodules produced and the nitrogen-fixing effectiveness of isolates of *R. trifolii* differed between plots and were affected by liming and fertilisers. The most effective isolates came from limed plots given nitrogen fertiliser and the least effective from unmanured or somewhat acid plots.

The MPN estimate of numbers varied in reliability according to the species enumerated and soil treatment and was best for limed soil given nitrogenous fertilisers and worst for acid plots or those given organic fertilisers.

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Rothamsted Insect Survey

L. R. TAYLOR and R. A. FRENCH

Suction traps

Three new traps operated in 1969, at the Rosewarne Experimental Horticultural Station, Camborne, in Cornwall, England, at the Welsh Plant Breeding Station, Plas Gogerddan, Nr. Aberystwyth, Wales, and at the Department of Agriculture and Fisheries for Scotland, East Craigs, Edinburgh 12, Scotland. The weekly bulletins listing 11 trap counts of 34 species, or groups, of aphids of economic interest was maintained with only one hiatus, during the third and fourth weeks of July when each week comprised only four days because full catches were too large to count in time to be included in the bulletin. This year the airflow characteristics of the trap were investigated and next year the volumetric air sample will be halved during July and August to lessen the risk of similar oversampling. The converse problem, that of increasing the sample size during April and May to increase sensitivity when incoming migrants are infesting crops, has proved to be less tractable because of the internal resistance of the trap at high air speeds; another attempt will be made to solve this problem during the coming season. It is hoped to complete the east/west transect next year with traps near Exeter, Bristol and Wageningen in Holland.

These tables are given here to publish records quickly, the final table being completed just in time for press. It may be possible to comment on them in Part 1 of the Report which is compiled later. The tables contain the same species as the bulletins. To save space, counts are given per 4-week period using the 'standard' weeks devised to coincide from year to year for convenience in analysis; the bulletin weeks are 'working' weeks from Monday through Sunday, chosen for convenience in despatching and sorting catches. The second trap at Rothamsted, formerly referred to as Rothamsted Farm, has been omitted from both bulletins and table to save space. Its function is entirely experimental and its adds little to the information on distribution on a large scale. A few days have been lost by accident or breakdown but, thanks to the lively co-operation of the operators and other members of staff to whom we are deeply indebted, there are no serious gaps in the record. Zero catches are left blank in the table for simplicity.

Light traps

In the *Rothamsted Report for 1968*, Part 1, 210–213, the annual catch of 26 species of moths of economic interest from light traps at 32 sites in Great Britain during 1967, and for some of these sites in 1966 and 1965 were tabulated. The catches of the same 26 species at sites in 1968 are given in Table 2 and those for 1967 repeated for comparison.

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Many more traps are now in operation, but only those that operated throughout the year are included in the table. Unlike the aphid records, it is not possible to publish these catches in the year they are obtained because most of the identification is done by voluntary workers and hence cannot be done immediately. Light traps give only a relative sample because their efficiency is subject to the behavioural response of the insect, so the catches of different species cannot be compared until the relative efficiency of the trap for the species has been assessed. At present, only the differences between sites and years can be usefully considered. The sites, which have been numbered sequentially as they began to operate, are arranged in latitude sequence, north to south, in the table. The species have been arranged according to their preferred latitude, north on the left to south on the right. The distribution of some species is erratic, and all are affected by the immediate environment of the trap, which ranges from urban streets through farmland to uncultivated moorland. Nevertheless, the latitudinal limits of some species are clearly defined and this may help to locate likely outbreak areas when we have more seasons' distributions. It is striking that the recognised pest species are not necessarily widespread nor generally common, some species being restricted to a fairly narrow band of latitudes. The spatial distribution of nearly all species in 1968 closely resembles that in 1967, except for *Plusia gamma*, an immigrant, *Gortyna micacea* and *Alsophila aescularia*, all of which were more common in 1968 than in 1967. Dashes indicate missing records; 0s record zero counts.

TABLE 1 *The Rothamsted Insect Survey—Suction Traps* is on pages 170–176.

TABLE 2 *The Rothamsted Insect Survey—Light Traps* is on pages 178–185.

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TABLE 1(a)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 17–20: 23 April–20 May

Sites / Species	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum						1				1	
Aphis fabae										1	
Aphis frangulae									1		
Aphis idaeii											
Aphis nasturtii											
Amphorophora spp.											
Aulacorthum solani								1			
Brachycaudus helichrysi											
Brevicoryne brassicae											
Cavariella aegopodii									3		
Cinara spp.											
Drepanosiphum platanoidis									1		
Dysaphis plantaginea											
Elatobium abietinum					9	1	1	18		9	
Eriosoma ulmi											
Hyalopterus pruni											
Hyperomyzus lactucae											
Macrosiphum euphorbiae									1	1	
Megoura viciae											
Metapolophium dirhodum											
Metapolophium festucae							3	2	2		
Myzus ascalonicus					2	3	11	5	4	5	5
Myzus ornatus											
Myzus persicae											
Nasonovia ribis nigri											
Pemphigus spp. } Prociphilines											
Phyllaphis fagi								2			
Pentatrichopus fragaefolii											
Phorodon humuli											
Rhopalosiphum insertum									1		
Rhopalosiphum maidis											
Rhopalosiphum padi					2			1		3	2
Sitobion avenae											1
Sitobion fragariae								1			
First aphid caught					May 5	May 4	May 5	May 8	May 4	May 11	May 5

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TABLE 1(b)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 21–24: 21 May–17 June

Species / Sites	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum						4	2	9	5	2	1
Aphis fabae		1	1	2		2	11	30		7	5
Aphis frangulae									1		
Aphis idaeii											
Aphis nasturtii								2		2	
Amphorophora spp.						1		4		2	
Aulacorthum solani					2	6		2	2	3	14
Brachycaudus helichrysi		3			121	11	300	370	5	147	61
Brevicoryne brassicae	1										
Cavariella aegopodii	1	1		3	44	412	597	1073	121	183	21
Cinara spp.				1			5	1			
Drepanosiphum platanoidis											
Dysaphis plantaginea						3	5	2			
Elatobium abietinum	13	3	38	3	211	5	45	160		171	12
Eriosoma ulmi	1					8	22	21	15	13	
Hyalopterus pruni					4		35	6	21	2	9
Hyperomyzus lactucae					6	4	12	28	3	4	3
Macrosiphum euphorbiae								7		2	2
Megoura viciae							1	2		1	
Metapolophium dirhodum		2			2		1	13	1	3	10
Metapolophium festucae					3	2	2	16	5	3	12
Myzus ascalonicus		2	1	2	7	5	13	24	8	18	5
Myzus ornatus								1			
Myzus persicae					1		1			1	3
Nasonovia ribis nigri	1				2			8	2		1
Pemphigus spp. } Prociphilines									2		
Phyllaphis fagi	5	14	14	3		4	4	23	2	3	4
Pentatrichopus fragaefolii											
Phorodon humuli					10	13	227	150		91	1
Rhopalosiphum insertum	1				4		3	2	6		3
Rhopalosiphum maidis	2				2				1		
Rhopalosiphum padi	6	27	2	10	108	72	175	93	8	40	46
Sitobion avenae					2	2	14	35	3	17	14
Sitobion fragariae						14	11	79		24	21
First aphid caught	May 26	Jun 5	Jun 7	May 25							

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TABLE 1(c)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 25–28: 18 June–15 July

Sites / Species	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum	1		1	3		80	13	45	56	71	1
Aphis fabae		4	1	6	7	133	106	416	268	608	3
Aphis frangulae					1	4		15	4	21	
Aphis idaeii							2	1		1	
Aphis nasturtii						2	2	13	6	10	
Amphorophora spp.			1			5	2	5		16	
Aulacorthum solani		1			2	5	3	2	2	5	1
Brachycaudus helichrysi	1	2	2	2	2	158	109	176	58	302	5
Brevicoryne brassicae						1			1		1
Cavariella aegopodii	3	6	3	40	2	662	356	274	243	283	3
Cinara spp.	4	6	4	1		15	2	4	2	22	
Drepanosiphum platanoidis	40	69	17	4	10	20	13	39		5	18
Dysaphis plantaginea			1			3	14	17	1	15	
Elatobium abietinum	16	2	58	1	1	1		1			
Eriosoma ulmi	69	43	7	16		201	60	59	9	84	2
Hyalopterus pruni	4	17	17	120	14	1286	1300	1336	403	2284	11
Hyperomyzus lactucae		3			8	67	19	43	39	37	
Macrosiphum euphorbiae					17	3	19	59	13	25	3
Megoura viciae		1	1		1	1	4	9		6	1
Metapolophium dirhodum	24	19	7	9	17	967	128	172	1207	351	19
Metapolophium festucae		1		1		23	15	12	19	21	4
Myzus ascalonicus	1	1				1	4	2	2	1	1
Myzus ornatus		1						2		8	1
Myzus persicae				1	6	76	61	49	309	325	6
Nasonovia ribis nigri			1	2		11	9	12	10	14	
Pemphigus spp. } Prociphilines }			1			2		9	44	5	
Phyllaphis fagi	5	4	15	7	3	91	38	236		46	
Pentatrichopus fragaefolii											
Phorodon humuli		1	1	2		182	167	525	22	978	
Rhopalosiphum insertum		2		19	6	546	1125	1347	164	559	14
Rhopalosiphum maidis	5	4	2	1		14	6	6	20	41	
Rhopalosiphum padi	8	9	22	43	14	275	29	123	286	558	18
Sitobion avenae		2	4	2	34	304	161	402	96	466	19
Sitobion fragariae	3			2		139	142	502	11	232	

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TABLE 1(d)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 29–32: 16 July–12 August

Species / Sites	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum	17	11	6	108	6	1595	524	150	10	83	2
Aphis fabae	31	191	124	877	102	3846	2177	1006	300	641	63
Aphis frangulae	2		4	7	4	83	41	16	28	35	
Aphis idaeii							1				
Aphis nasturtii		1	3	9	4	112	105	30	16	14	1
Amphorophora spp.	1	1				1	2	1			
Aulacorthum solani	1	5	1		1	4					
Brachycaudus helichrysi	12	49	14	23	3	403	107	95	24	39	4
Brevicoryne brassicae	2	3				50	62	8	1	2	14
Cavariella aegopodii	7	36	32	89	1	49	16	6	23	7	
Cinara spp.	2	4	6	2		2	1	2		5	
Drepanosiphum platanoidis	6	25	1	8	8	18	17	47		7	26
Dysaphis plantaginea	1	1	1			6	6	6	1	1	
Elatobium abietinum											
Eriosoma ulmi	24	20	9	4	1	14	5	1		4	1
Hyalopterus pruni	71	198	203	680	57	5366	3518	1476	1108	1857	26
Hyperomyzus lactucae	1	3	7	11	19	90	18	11	10	4	
Macrosiphum euphorbiae	19	70	12	18	62	73	77	82	37	29	1
Megoura viciae		1		3	1	27	20	7		6	1
Metapolophium dirhodum	638	1738	779	1590	39	5617	234	116	2143	36	11
Metapolophium festucae	1		15	28	3	21	5	5	3	4	
Myzus ascalonicus									7		
Myzus ornatus		1						2			
Myzus persicae	32	30	7	22	18	439	127	61	3603	281	4
Nasonovia ribis nigri			1		1	21	7	10	2	4	1
Pemphigus spp. } Prociphilines	5	3	2		4	7	3	2	28	1	
Phyllaphis fagi						6	1	13		12	
Pentatrichopus fragaefolii											
Phorodon humuli		2		10		614	243	58	12	117	
Rhopalosiphum insertum	39	246	247	960	114	2301	3652	3308	830	1423	45
Rhopalosiphum maidis	66	101	210	68	52	26	19	22	15	44	
Rhopalosiphum padi	603	427	429	1066	46	2803	370	585	3172	249	26
Sitobion avenae	109	293	292	693	278	3970	1916	1701	1284	499	39
Sitobion fragariae	1	11	17	70	3	741	394	253	60	111	11

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TABLE 1(e)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 33–36: 13 August–9 September

Sites / Species	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum	13	3	6	33	6	1	1	2			5
Aphis fabae	612	339	1821	509	266	7	11	5		11	7
Aphis frangulae	2	2		10	9	1			1	1	
Aphis idaeii											
Aphis nasturtii				4							
Amphorophora spp.	1										
Aulacorthum solani											
Brachycaudus helichrysi	98	27	8	15	48	10	64	7		16	17
Brevicoryne brassicae	2				3	7	8	20			5
Cavariella aegopodii	6	1	3	9							
Cinara spp.	4		3	1	1				1		
Drepanosiphum platanoidis	7	9	48	15	7	13	8	39		6	16
Dysaphis plantaginea	1							2			
Elatobium abietinum											
Eriosoma ulmi		2		3			10			2	2
Hyalopterus pruni	194	10	19	152	10	60	51	40	2	110	2
Hyperomyzus lactucae			2		1	1					
Macrosiphum euphorbiae	46	38	1	3	8						
Megoura viciae					1						
Metapolophium dirhodum	33	36	15	51	1						1
Metapolophium festucae		1	3								
Myzus ascalonicus											
Myzus ornatus				1							
Myzus persicae	60	20	4	27	10	1		2	2	4	3
Nasonovia ribis nigri				4							
Pemphigus spp. } Prociphilines	12	4	28	40	69	16	3	14	2	6	4
Phyllaphis fagi		1									
Pentatrichopus fragaefolii											
Phorodon humuli	1		1							6	1
Rhopalosiphum insertum	137	270	1584	1300	100	30	52	44		60	79
Rhopalosiphum maidis	1	1	2	3	12	4				2	
Rhopalosiphum padi	446	260	1004	405	48	24	7	19	21	25	97
Sitobion avenae	183	103	84	318	81	30	26	31	4	35	25
Sitobion fragariae	6	5	11	24	2		2	1	1	1	2

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TABLE 1(f)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 37–40: 10 September–7 October

Sites / Species	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum	1				4			2	2	7	5
Aphis fabae	180	60	93	1	112	12	2	7	3	98	19
Aphis frangulae					2	2					
Aphis idaeii											
Aphis nasturtii											
Amphorophora spp.											
Aulacorthum solani										1	
Brachycaudus helichrysi	21	62	6	3	68	25	44	20	1	40	18
Brevicoryne Brassicae	7			1		1	17	8		4	11
Cavariella aegopodii			5	1	2	1				2	
Cinara spp.			1								
Drepanosiphum platanoidis	21	33	23	13	8	3	10	4		4	63
Dysaphis plantaginea						10	9	35	2	28	2
Elatobium abietinum											
Eriosoma ulmi	3	1		1		14	10	12	3	35	6
Hyalopterus pruni	192	4		2		6	3	16	7	9	1
Hyperomyzus lactucae	2				5	2	2	2	2	16	1
Macrosiphum euphoribiae	9	4			1						
Megoura viciae											
Metapolophium dirhodum	10	4	2		2					4	
Metapolophium festucae		1			1						1
Myzus ascalonicus					6						
Myzus ornatus						1					
Myzus persicae	24	10		2	60	8	13	11	5	161	19
Nasonovia ribis nigri					17	1	1	6		3	1
Pemphigus spp. } Prociphilines	54	51	30	5	142	372	79	43	110	240	21
Phyllaphis fagi											
Pentatrichopus fragaefolii											
Phorodon humuli						1		10		1473	
Rhopalosiphum insertum	469	613	1242	183	3337	284	181	355	31	450	244
Rhopalosiphum maidis	11	8	9		24	1	2	2	2	6	
Rhopalosiphum padi	2456	1063	1402	151	2333	985	380	1082	816	3766	393
Sitobion avenae			4	1	10			5		12	5
Sitobion fragariae	1		1		8				2	3	

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TABLE 1(g)

The Rothamsted Insect Survey—Suction Traps: 4-weekly total catches of aphids of economic interest reported in the Weekly Bulletin

Week Nos 41–44: 8 October–4 November

Sites / Species	Dundee	Edinburgh	Newcastle	High Mowthorpe	Aberystwyth	Brooms Barn	Rothamsted	Silwood Park	Zeeland	Wye, Kent	Rosewarne
Acyrthosiphon pisum					2				4	5	
Aphis fabae	31	15	6	3	38	18	16	10	6	38	10
Aphis frangulae											
Aphis idaeii											
Aphis nasturtii										1	
Amphorophora spp.											
Aulacorthum solani						4		8		7	4
Brachycaudus helichrysi	6	8	2	3		13	21	10	4	20	6
Brevicoryne brassicae	13		1		1	1	12	22	1	26	9
Cavariella aegopodii	2	1	2		5	3	1		1	4	1
Cinara spp.		1	2				1	2		4	
Drepanosiphum platanoidis	23	27	3	18	23	5	18	21	1	3	10
Dysaphis plantaginea		2	3	3		2	8	13		9	11
Elatobium abietinum											
Eriosoma ulmi	15	31	18	3		16	22	6	5	28	1
Hyalopterous pruni	1					5	1	3	1	4	
Hyperomyzus lactucae	2	1	3	2	6	5	10	3		75	
Macrosiphum euphorbiae	2	1			9		1	1		7	
Megoura viciae											
Metapolophium dirhodum	12	11			7	1	1	3	5	48	2
Metapolophium festucae		2	2		7	1		1		3	
Myzus ascalonicus		1			10		2	2	1	2	2
Myzus ornatus							1				
Myzus persicae	38	48	6	11	130	65	44	48	46	331	27
Nasonovia ribis nigri		1		1	24	5	7	3		9	3
Pemphigus spp. / Prociphilines	170	159	275	36	55	1294	414	402	95	1027	46
Phyllaphis fagi		1									2
Pentatrichopus fragaefolii											
Phorodon humuli			1			1				67	
Rhopalosiphum insertum	2490	3134	3271	741	13317	1804	1057	1724	394	5304	1730
Rhopalosiphum maidis	4	5			7	3	4	1		5	3
Rhopalosiphum padi	3558	3987	2040	558	6431	3293	1758	2942	3176	9575	352
Sitobion avenae	2	2			12	3	17	9	2	55	7
Sitobion fragariae	6	6	4		217	8	7	58	10	188	24

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Table 2

The Rothamsted Insect Survey—Light Traps: two years' records of the moths of economic interest (1967 and 1968)

See pages 178–185

M

TABLE

The Rothamsted Insect Survey—Light Traps: two years'

Pest Species	Year	89 Sandwick	57 Ardross	58 Newton	49 Fort Augustus	38 Killiecrankie	29 Rannoch	60 Aros	48 Kindrogan	47 Dundee	82 Dunblane	97 Rowardennan	98 Auchencruive
Gortyna micacea	1967	—	132	136	63	15	70	39	50	7	—	—	—
Rosy Rustic	1968	140	297	104	82	89	145	228	171	32	97	3	18
Bupalus piniaria	1967	—	0	—	2	0	0	0	0	0	—	—	—
Bordered white	1968	0	0	2	6	0	0	0	0	0	0	0	0
Panolis flammea	1967	—	0	0	5	38	29	0	0	0	—	—	—
Pine Beauty	1968	0	0	5	9	0	4	0	0	0	0	0	0
Cerapteryx graminis	1967	—	18	26	83	114	111	87	24	7	—	—	—
Antler Moth	1968	348	13	29	194	18	78	342	101	9	35	79	13
Erannis aurantiaria	1967	—	19	1	36	15	86	0	1	0	—	—	—
Scarce Umber	1968	0	32	3	103	37	146	2	23	0	0	17	0
Operophtera fagata	1967	—	3	0	4	10	146	0	0	0	—	—	—
Northern Winter Moth	1968	0	6	5	16	20	136	0	0	1	0	22	0
Apamea sordens	1967	—	0	0	0	1	0	0	4	8	—	—	—
Rustic Shoulder Knot	1968	0	1	0	3	3	0	0	0	3	3	0	1
Gortyna flavago	1967	—	0	0	0	0	0	0	0	0	—	—	—
Frosted Orange	1968	0	0	4	0	4	0	0	0	2	0	0	0
Mamestra brassicae	1967	—	0	0	0	0	0	0	0	0	—	—	—
Cabbage Moth	1968	0	0	0	0	0	0	0	0	8	5	0	0
Noctua pronuba	1967	—	0	16	3	35	0	13	0	5	—	—	—
Large Yellow Underwing	1968	0	4	20	4	35	0	5	20	14	24	10	12
Diataraxia oleracea	1967	—	0	13	0	2	0	6	0	1	—	—	—
Bright-line Brown-eye	1968	0	0	13	0	0	0	8	0	2	2	0	6
Euxoa nigricans	1967	—	0	0	0	0	0	0	0	0	—	—	—
Garden Dart	1968	0	0	1	0	0	4	0	1	1	1	0	0
Apamea secalis	1967	—	1	35	22	3	0	34	0	11	—	—	—
Common Rustic	1968	0	0	100	22	6	0	15	0	21	40	1	68

https://doi.org/10.23637/ERADOC-1-4

2(a)

records of the moths of economic interest (*1967 and 1968*)

100 Carlisle	39 Chester le Street	72 Castletown, I.O.M.	45 Malham Tarn	40 Lancaster	68 Harrogate	10 Bradford	85 Prestwich	35 Bangor	77 Maentwrog	79 Shardlow	61 Sutton Bonington	Year	Pest Species
—	3	—	0	7	39	24	—	1	—	—	—	1967	*Gortyna micacea*
10	4	64	0	7	44	17	4	0	7	30	3	1968	Rosy Rustic
—	0	—	0	0	0	0	—	0	—	—	0	1967	*Bupalus piniaria*
0	0	0	0	0	0	0	0	0	0	0	0	1968	Bordered white
—	0	—	0	0	0	0	—	0	—	—	0	1967	*Panolis flammea*
0	0	0	0	0	0	0	0	0	0	0	0	1968	Pine Beauty
—	0	—	17	0	2	0	—	3	—	—	0	1967	*Cerapteryx graminis*
2	0	7	24	1	0	0	0	5	98	6	0	1968	Antler Moth
—	0	—	1	0	0	0	—	0	—	—	0	1967	*Erannis aurantiaria*
0	0	0	47	0	3	0	0	1	87	0	1	1968	Scarce Umber
—	1	—	10	0	0	0	—	0	—	—	0	1967	*Operophtera fagata*
0	0	0	18	0	0	0	0	0	105	0	0	1968	Northern Winter Moth
—	0	—	1	0	0	2	—	0	—	—	0	1967	*Apamea sordens*
1	7	0	1	2	1	3	6	0	0	8	2	1968	Rustic Shoulder Knot
—	1	—	0	0	4	10	—	0	—	—	5	1967	*Gortyna flavago*
1	0	0	0	1	2	1	0	0	0	0	2	1968	Frosted Orange
—	11	—	0	1	1	5	—	11	—	—	9	1967	*Mamestra brassicae*
1	19	0	0	2	2	15	11	29	0	5	2	1968	Cabbage Moth
—	3	—	8	16	13	9	—	83	—	—	10	1967	*Noctua pronuba*
26	8	38	6	13	17	16	2	46	7	41	26	1968	Large Yellow Underwing
—	3	—	0	2	4	2	—	0	—	—	32	1967	*Diataraxia oleracea*
1	4	18	0	5	4	6	4	4	1	13	31	1968	Bright-line Brown-eye
—	2	—	0	0	1	0	—	0	—	—	0	1967	*Euxoa nigricans*
1	3	0	0	0	0	0	1	0	0	0	0	1968	Garden Dart
—	29	—	0	22	29	17	—	45	—	—	28	1967	*Apamea secalis*
7	18	66	0	27	31	4	5	44	2	191	162	1968	Common Rustic

https://doi.org/10.23637/ERADOC-1-4

TABLE

The Rothamsted Insect Survey—Light Traps: two years'

Pest Species	Year	23 St. Ives	88 Brooms Barn	18 Flatford Mill	31 Dunmow	1 Rothamsted (Barnfield)	34 Rothamsted (Allotments)	22 Rothamsted (Geescroft)	87 Writtle	17 Dale Fort	73 Orielton	90 Isleworth
Gortyna micacea	1967	—	—	6	1	5	27	1	—	—	19	—
Rosy Rustic	1968	1	2	23	17	2	0	1	4	6	99	0
Bupalus piniaria	1967	—	—	0	0	0	0	0	—	0	0	—
Bordered white	1968	0	0	0	0	0	0	0	0	0	0	0
Panolis flammea	1967	—	—	0	0	0	0	0	—	0	0	—
Pine Beauty	1968	0	0	0	0	0	0	0	0	0	0	0
Cerapteryx graminis	1967	—	—	0	0	0	1	0	—	0	4	—
Antler Moth	1968	0	0	0	0	0	0	0	0	0	22	0
Erannis aurantiaria	1967	—	—	0	0	1	0	8	—	0	—	—
Scarce Umber	1968	0	0	2	0	0	0	28	0	0	0	0
Operophtera fagata	1967	—	—	0	0	0	0	0	—	0	0	—
Northern Winter Moth	1968	0	0	0	0	0	0	0	0	0	0	0
Apamea sordens	1967	—	—	0	0	0	6	0	—	0	0	—
Rustic Shoulder Knot	1968	2	5	0	0	4	1	0	7	0	0	0
Gortyna flavago	1967	—	—	5	0	1	4	1	—	0	10	—
Frosted Orange	1968	0	0	4	6	2	0	3	3	1	22	3
Mamestra brassicae	1967	—	—	1	7	0	0	0	—	1	1	—
Cabbage Moth	1968	9	1	9	2	1	0	1	3	1	0	6
Noctua pronuba	1967	—	—	3	1	5	8	112	—	3	7	—
Large Yellow Underwing	1968	2	6	4	4	7	9	72	31	6	4	4
Diataraxia oleracea	1967	—	—	4	7	3	3	0	—	10	1	—
Bright-line Brown-eye	1968	4	6	10	7	4	4	2	31	39	0	1
Euxoa nigricans	1967	—	—	0	0	0	1	1	—	0	0	—
Garden Dart	1968	0	0	0	0	0	0	0	6	0	0	0
Apamea secalis	1967	—	—	25	17	17	21	21	—	37	44	—
Common Rustic	1968	18	20	65	16	21	9	29	43	28	29	4

https://doi.org/10.23637/ERADOC-1-4

2(b)

records of the moths of economic interest (1967 and 1968)

16 Mortimer	93 Newton St. Loe	69 Wisley	46 Alice Holt	62 Wye	92 Nettlecombe Court	33 Dungeness	76 Iwerne Minster	74 Cullompton	78 Ringwood	67 Slapton Ley	102 Helston	Year	Pest Species
1	—	6	14	2	—	10	—	—	—	20	—	1967	*Gortyna micacea*
4	6	8	0	7	7	20	8	2	8	9	72	1968	Rosy Rustic
0	—	0	0	0	—	0	—	—	—	0	—	1967	*Bupalus piniaria*
0	0	0	0	0	0	0	0	0	0	0	0	1968	Bordered white
0	—	0	1	0	—	0	—	—	—	0	—	1967	*Panolis flammea*
1	0	0	0	0	0	0	0	0	0	0	0	1968	Pine Beauty
0	—	1	3	0	—	0	—	—	—	0	—	1967	*Cerapteryx graminis*
0	0	0	3	0	0	3	0	0	0	0	1	1968	Antler Moth
6	—	16	16	0	—	0	—	—	—	0	—	1967	*Erannis aurantiaria*
7	0	3	10	0	2	0	1	0	12	0	0	1968	Scarce Umber
0	—	11	0	0	—	0	—	—	—	0	—	1967	*Operophtera fagata*
0	0	3	22	0	0	0	0	0	0	0	0	1968	Northern Winter Moth
0	—	2	0	0	—	5	—	—	—	0	—	1967	*Apamea sordens*
0	1	1	0	3	0	2	0	0	0	0	0	1968	Rustic Shoulder Knot
0	—	0	0	0	—	1	—	—	—	2	—	1967	*Gortyna flavago*
0	1	2	2	7	4	5	4	0	0	1	0	1968	Frosted Orange
1	—	0	0	0	—	1	—	—	—	8	—	1967	*Mamestra brassicae*
1	13	0	0	1	0	7	3	12	0	6	30	1968	Cabbage Moth
16	—	3	5	7	—	0	—	—	—	17	—	1967	*Noctua pronuba*
43	17	20	18	14	8	6	34	9	2	1	10	1968	Large Yellow Underwing
1	—	3	0	1	—	1	—	—	—	10	—	1967	*Diataraxia oleracea*
2	3	6	0	9	7	11	4	12	0	5	0	1968	Bright-line Brown-eye
0	—	0	0	0	—	0	—	—	—	0	—	1967	*Euxoa nigricans*
0	0	0	0	0	0	0	0	0	0	0	0	1968	Garden Dart
9	—	30	4	12	—	16	—	—	—	47	—	1967	*Apamea secalis*
46	96	64	12	7	29	49	16	15	6	12	0	1968	Common Rustic

https://doi.org/10.23637/ERADOC-1-4

TABLE

The Rothamsted Insect Survey—Light traps: two years'

Pest Species	Year	89 Sandwick	57 Ardross	58 Newton	49 Fort Augustus	38 Killiecrankie	29 Rannoch	60 Aros	48 Kindrogan	47 Dundee	82 Dunblane	97 Rowardennan	98 Auchencruive
Melanchra persicariae Dot Moth	1967 1968	— 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	— 0	— 0	— 0
Operophtera brumata Winter Moth	1967 1968	— 3	14 52	5 10	35 28	77 21	43 15	10 12	19 68	2 3	— 2	— 97	— 1
Abraxas grossulariata Magpie Moth	1967 1968	— 0	0 0	0 0	0 0	0 0	0 0	0 1	0 0	0 0	— 0	— 0	— 0
Agrotis segetum Turnip Moth	1967 1968	— 0	0 0	0 1	0 0	0 0	0 0	0 0	0 0	0 0	— 0	— 0	— 0
Erannis defoliaria Mottled Umber	1967 1968	— 0	3 9	1 8	42 47	20 5	16 9	0 0	33 119	2 1	— 0	— 75	— 0
Phlogophora meticulosa Angle Shades	1967 1968	— 0	0 0	0 0	0 0	0 0	0 1	0 1	0 0	0 0	— 0	— 0	— 0
Alsophila aescularia March Moth	1967 1968	— 0	2 4	4 10	0 2	1 0	0 0	1 1	0 0	0 1	— 1	— 198	— 0
Hepialus humuli Ghost Swift	1967 1968	— 0	0 1	0 0	1 0	2 1	2 1	0 0	0 2	0 0	— 3	— 0	— 1
Hepialus lupulina Common Swift	1967 1968	— 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 2	— 0	— 2	— 0
Agrotis ipsilon Dark Sword Grass	1967 1968	— 0	1 1	1 1	0 0	0 0	0 0	0 0	0 0	0 0	— 0	— 0	— 0
Euproctis chrysorrhoea Brown Tail	1967 1968	— 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	— 0	— 0	— 0
Agrotis exclamationis Heart and Dart	1967 1968	— 0	0 0	0 3	1 0	18 22	0 0	0 0	1 0	1 6	— 4	— 0	— 3
Plusia gamma Silver Y	1967 1968	— 4	0 1	0 3	1 3	0 2	0 1	0 4	1 3	0 0	— 1	— 0	— 1

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records of the moths of economic interest (1967 and 1968)

100 Carlisle	39 Chester le Street	72 Castletown, I.O.M.	45 Malham Tarn	40 Lancaster	68 Harrogate	10 Bradford	85 Prestwich	35 Bangor	77 Maentwrog	79 Shardlow	61 Sutton Bonington	Year	Pest Species
—	0	—	0	1	1	0	—	0	—	—	7	1967	*Melanchra persicariae*
0	0	0	0	0	1	1	2	0	3	11	8	1968	Dot Moth
—	1	—	30	0	11	0	—	1	—	—	9	1967	*Operophtera brumata*
1	0	1	68	0	2	0	0	0	78	2	4	1968	Winter Moth
—	47	—	0	1	13	105	—	3	—	—	3	1967	*Abraxas grossulariata*
0	18	11	0	1	28	59	2	0	3	9	7	1968	Magpie Moth
—	0	—	0	0	0	0	—	0	—	—	0	1967	*Agrotis segetum*
0	0	1	0	0	1	0	0	1	0	0	5	1968	Turnip Moth
—	0	—	4	0	4	0	—	0	—	—	0	1967	*Erannis defoliaria*
0	0	14	18	0	5	0	0	0	1844	3	0	1968	Mottled Umber
—	2	—	0	1	0	1	—	6	—	—	0	1967	*Phlogophora meticulosa*
0	0	21	0	1	2	4	0	13	8	6	0	1968	Angle Shades
—	0	—	0	0	6	0	—	0	—	—	2	1967	*Alsophila aescularia*
0	0	0	0	0	5	0	0	0	65	5	6	1968	March Moth
—	0	—	0	1	1	2	—	0	—	—	3	1967	*Hepialus humuli*
0	1	0	0	3	0	0	0	0	0	2	1	1968	Ghost Swift
—	0	—	0	0	40	4	—	0	—	—	9	1967	*Hepialus lupulina*
1	1	0	0	1	9	0	0	0	0	77	24	1968	Common Swift
—	0	—	0	0	0	2	—	0	—	—	0	1967	*Agrotis ipsilon*
1	0	9	0	0	1	0	0	4	8	0	0	1968	Dark Sword Grass
—	0	—	0	0	0	0	—	0	—	—	0	1967	*Euproctis chrysorrhoea*
0	0	0	0	0	0	0	0	0	0	0	0	1968	Brown Tail
—	5	—	0	2	13	0	—	16	—	—	37	1967	*Agrotis exclamationis*
7	5	59	0	15	20	0	6	25	2	314	121	1968	Heart and Dart
—	24	—	3	7	14	10	—	1	—	—	3	1967	*Plusia gamma*
8	47	60	12	5	13	8	3	7	13	15	14	1968	Silver Y

https://doi.org/10.23637/ERADOC-1-4

TABLE

The Rothamsted Insect Survey—Light Traps: two years'

Pest Species	Year	23 St. Ives	88 Brooms Barn	18 Flatford Mill	31 Dunmow	1 Rothamsted (Barnfield)	34 Rothamsted (Allotments)	22 Rothamsted (Geescroft)	87 Writtle	17 Dale Fort	73 Orielton	90 Isleworth
Melanchra persicariae	1967	—	—	3	25	6	1	1	—	3	3	—
Dot Moth	1968	1	11	3	34	3	0	0	6	9	1	0
Operophtera brumata	1967	—	—	5	0	2	1	114	—	6	6	—
Winter Moth	1968	0	1	11	2	2	1	107	0	3	10	10
Abraxas grossulariata	1967	—	—	8	13	10	43	123	—	74	23	—
Magpie Moth	1968	7	3	20	28	9	1	96	1	183	54	5
Agrotis segetum	1967	—	—	0	1	0	3	2	—	0	0	—
Turnip Moth	1968	6	14	0	0	6	5	3	61	0	0	0
Erannis defoliaria	1967	—	—	2	0	0	0	50	—	1	7	—
Mottled Umber	1968	0	1	2	0	0	0	48	0	0	6	0
Phlogophora meticulosa	1967	—	—	12	0	0	2	7	—	13	4	—
Angle Shades	1968	3	3	27	2	0	2	5	2	12	2	1
Alsophila aescularia	1967	—	—	6	0	0	0	11	—	0	9	—
March Moth	1968	3	4	23	6	4	1	35	6	1	6	0
Hepialus humuli	1967	—	—	0	0	3	1	1	—	0	1	—
Ghost Swift	1968	0	0	2	0	3	0	7	0	0	1	0
Hepialus lupulina	1967	—	—	1	1	12	18	3	—	23	2	—
Common Swift	1968	39	1	8	3	9	0	12	7	7	1	0
Agrotis ipsilon	1967	—	—	0	0	0	0	1	—	3	1	—
Dark Sword Grass	1968	0	1	2	0	0	0	0	0	9	2	0
Euproctis chrysorrhoea	1967	—	—	0	1	0	0	0	—	0	0	—
Brown Tail	1968	0	0	0	0	0	0	0	0	0	0	0
Agrotis exclamationis	1967	—	—	11	57	33	19	14	—	29	8	—
Heart and Dart	1968	93	83	33	105	66	33	24	599	27	32	6
Plusia gamma	1967	—	—	23	2	5	15	8	—	20	10	—
Silver Y	1968	12	16	21	4	4	4	31	73	48	30	0

https://doi.org/10.23637/ERADOC-1-4

2(d)

records of the moths of economic interest (1967 and 1968)

16 Mortimer	93 Newton St. Loe	69 Wisley	46 Alice Holt	62 Wye	92 Nettlecombe Court	33 Dungeness	76 Iwerne Minster	74 Cullompton	78 Ringwood	67 Slapton Ley	102 Helston	Year	Pest Species
2	—	2	1	8	—	0	—	—	—	49	—	1967	*Melanchra persicariae*
2	0	2	0	14	0	0	3	1	0	12	0	1968	Dot Moth
84	—	15	40	13	—	0	—	—	—	9	—	1967	*Operophtera brumata*
34	0	25	12	0	44	0	15	11	8	9	1	1968	Winter Moth
83	—	2	1	9	—	8	—	—	—	24	—	1967	*Abraxas grossulariata*
215	13	1	0	7	18	4	28	56	3	10	223	1968	Magpie Moth
1	—	0	1	0	—	3	—	—	—	0	—	1967	*Agrotis segetum*
0	0	0	0	1	5	2	0	4	0	0	4	1968	Turnip Moth
24	—	16	29	1	—	0	—	—	—	1	—	1967	*Erannis defoliaria*
24	5	21	19	0	15	0	4	1	11	2	2	1968	Mottled Umber
1	—	4	3	0	—	0	—	—	—	3	—	1967	*Phlogophora meticulosa*
4	3	2	0	3	25	1	7	3	1	4	5	1968	Angle Shades
0	—	26	7	7	—	0	—	—	—	19	—	1967	*Alsophila aescularia*
6	4	7	10	3	6	0	9	6	5	15	0	1968	March Moth
1	—	3	5	1	—	0	—	—	—	4	—	1967	*Hepialus humuli*
1	0	2	5	1	0	0	0	1	0	1	2	1968	Ghost Swift
9	—	1	1	1	—	39	—	—	—	0	—	1967	*Hepialus lupulina*
19	0	2	2	23	0	55	2	2	2	1	0	1968	Common Swift
1	—	0	1	1	—	3	—	—	—	2	—	1967	*Agrotis ipsilon*
0	1	1	0	0	12	1	0	1	1	1	8	1968	Dark Sword Grass
0	—	0	0	0	—	32	—	—	—	0	—	1967	*Euproctis chrysorrhoea*
0	0	0	0	0	0	83	0	0	0	0	0	1968	Brown Tail
4	—	28	23	34	—	84	—	—	—	97	—	1967	*Agrotis exclamationis*
30	57	66	48	361	56	139	19	25	0	44	68	1968	Heart and Dart
12	—	77	16	12	—	24	—	—	—	60	—	1967	*Plusia gamma*
26	155	112	37	45	119	22	132	120	2	35	30	1968	Silver Y

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CONVERSION FACTORS

Factors for the Conversion of Imperial to Metric Units

1 inch (in.)	= 2·540 centimetres (cm)
1 foot (ft) (=12 in.)	= 30·48 cm
1 yard (yd) (=3 ft)	= 0·9144 metre (m)
1 square yard (sq yd)	= 0·8361 sq m
1 acre (=4840 sq yd)	= 0·4047 hectare (ha)
1 ounce (oz)	= 28·35 grams (g)
1 pound (lb)	= 0·4536 kilogram (kg)
1 hundredweight (cwt) (=112 lb)	= 50·80 kg
1 ton (=2240 lb)	= 1016 kg = 1·016 metric tons (tonnes)
1 pint	= 0·5682 litre
1 gallon (gal) (=8 pints)	= 4·546 litre
1 fluid ounce = 1/20 pint	= 0·02841 litre = 28·41 ml
1 cubic foot	= 28·32 litre

To convert	*Multiply by*
oz/acre to g/ha	70·06
lb/acre to kg/ha	1·121
cwt/acre to kg/ha	125·5
cwt/acre to tonnes/ha	0·1255
tons/acre to kg/ha	2511
tons/acre to tonnes/ha	2·511
gal/acre to litre/ha	11·233

The following factors are accurate to about 2 parts in 100:

1 lb/acre = 1·1 kg/ha
1 gallon/acre = 11 litre/ha
1 ton/acre = 2·5 tonnes/ha

In general reading of the text there will be no great inaccuracy in regarding:

1 lb = 0·5 kg
1 lb/acre = 1 kg/ha

Temperatures

To convert °F into °C subtract 32 and multiply by $\frac{5}{9}$ (0·556)
To convert °C into °F multiply by $\frac{9}{5}$ (1·8) and add 32

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Factors for the Conversion of Metric to Imperial Units

1 centimetre (cm)	=	0·3937 inch (in.) = 0·03281 ft
1 metre (m)	=	1·094 yards (yd)
1 square metre (sq m)	=	1·196 square yards (sq yd)
1 hectare (ha)	=	2·471 acres
1 gram (g)	=	0·03527 ounce (oz)
1 kilogram (kg)	=	2·205 pounds (lb)
1 kg	=	0·01968 hundredweight (cwt) = 0·0009842 ton
1 metric ton (tonne)	=	0·9842 ton
1 litre	=	1·760 pints = 0·2200 gallon (gal)

1 litre = 1000 millilitres (ml) = 35·20 fluid ounces = 0·03531 cubic foot

To convert	*Multiply by*
g/ha to oz/acre	0·01427
kg/ha to lb/acre	0·8921
kg/ha to cwt/acre	0·007966
tonnes/ha to cwt/acre	7·966
ka/ha to tons/acre	0·0003983
tonnes/ha to tons/acre	0·3983
litre/ha to gal/acre	0·08902

Plant nutrients

Plant nutrients are best stated in terms of amounts of the elements (P, K, Na, Ca, Mg, S); the old 'oxide' terminology P_2O_5, K_2O, Na_2O, CaO, MgO, SO_3) is still used in work involving fertilisers and liming since Regulations require statements of P_2O_5, K_2O, etc.

For quick conversions

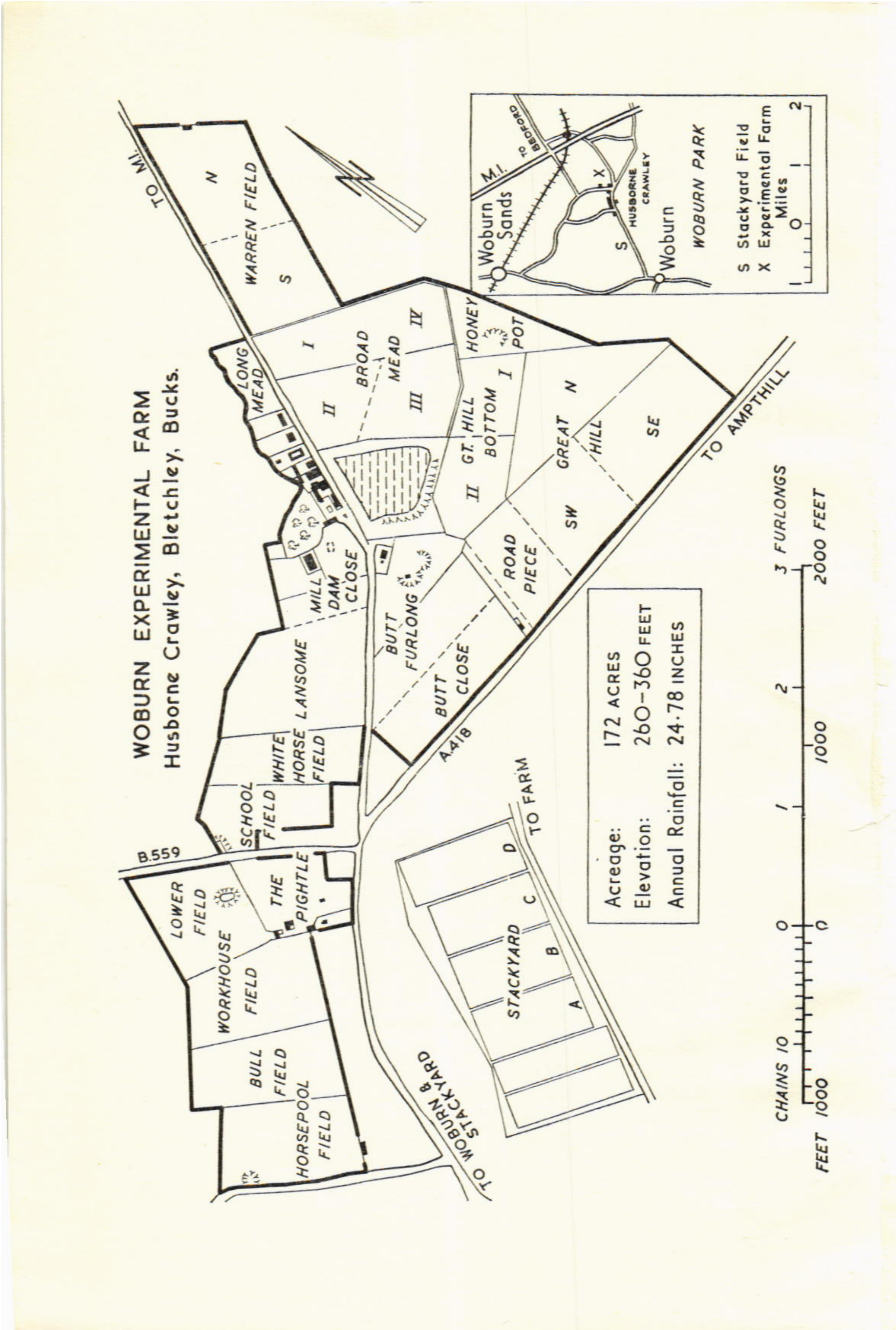
(accurate to within 2%) the following factors may be used:

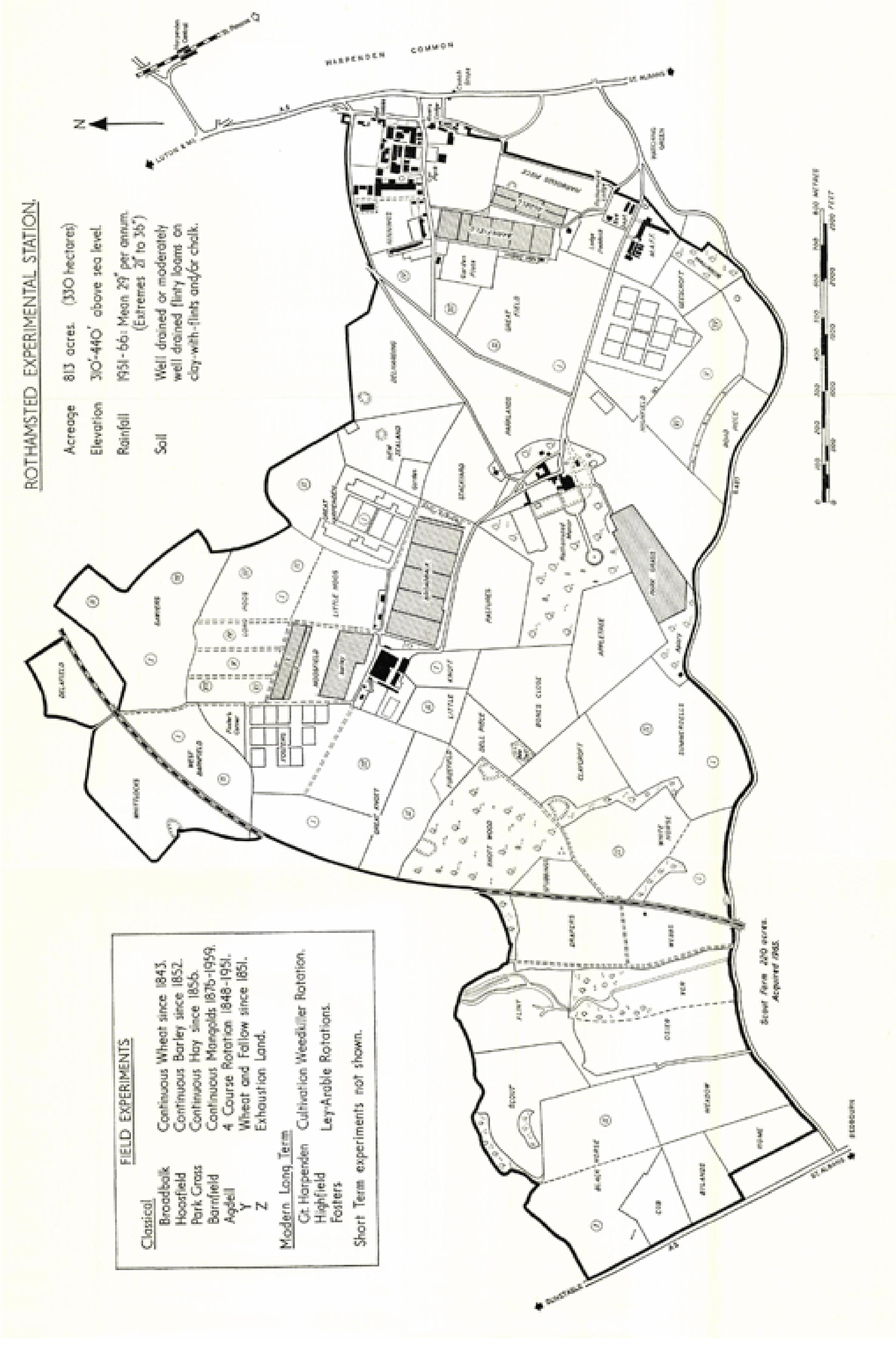
$2\frac{1}{3} \times P = P_2O_5$	$\frac{3}{7} \times P_2O_5 = P$
$1\frac{1}{5} \times K = K_2O$	$\frac{5}{6} \times K_2O = K$
$1\frac{2}{5} \times Ca = CaO$	$\frac{7}{10} \times CaO = Ca$
$1\frac{2}{3} \times Mg = MgO$	$\frac{3}{5} \times MgO = Mg$

For accurate conversions:

To convert	*Multiply by*	*To convert*	*Multiply by*
P_2O_5 to P	0·4364	P to P_2O_5	2·2915
K_2O to K	0·8301	K to K_2O	1·2047
CaO to Ca	0·7146	Ca to CaO	1·3994
MgO to Mg	0·6031	Mg to MgO	1·6581

https://doi.org/10.23637/ERADOC-1-4


WOBURN EXPERIMENTAL FARM
Husborne Crawley, Bletchley, Bucks.
Acreage: 172 ACRES
Elevation: 260–360 FEET
Annual Rainfall: 24·78 INCHES
TO M.I.
WARREN FIELD
N
S
LONG MEAD
BROAD MEAD
I
II
III
IV
HONEY POT
GT. HILL BOTTOM
GREAT HILL
N
SE
SW
ROAD PIECE
MILL DAM CLOSE
BUTT FURLONG
BUTT CLOSE
LANSOME
WHITE HORSE FIELD
SCHOOL FIELD
B.559
LOWER FIELD
THE PIGHTLE
WORKHOUSE FIELD
BULL FIELD
HORSEPOOL FIELD
A.418
TO AMPTHILL
TO FARM
STACKYARD
A
B
C
D
TO WOBURN & STACKYARD
M.I.
TO BEDFORD
Woburn Sands
HUSBORNE CRAWLEY
Woburn
WOBURN PARK
S Stackyard Field
X Experimental Farm
Miles
0
1
2
3 FURLONGS
2000 FEET
1000
CHAINS 10
FEET 1000


ROTHAMSTED EXPERIMENTAL STATION.
Acreage 813 acres. (330 hectares)
Elevation 310'-440' above sea level.
Rainfall 1931-66: Mean 29" per annum. (Extremes 21" to 35")
Soil Well drained or moderately well drained flinty loams on clay-with-flints and/or chalk.
FIELD EXPERIMENTS
Classical
Broadbalk Continuous Wheat since 1843.
Hoosfield Continuous Barley since 1852.
Park Grass Continuous Hay since 1856.
Barnfield Continuous Mangolds 1876-1959.
Agdell 4 Course Rotation 1848-1951.
Y Wheat and Fallow since 1851.
Z Exhaustion Land.
Modern Long Term
Gt. Harpenden Cultivation Weedkiller Rotation.
Highfield Ley-Arable Rotations.
Fosters
Short Term experiments not shown.
Scout Farm 220 acres. Acquired 1968.