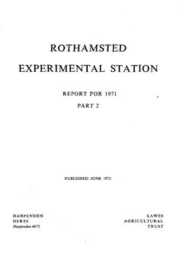
ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1971 Part 2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Results from the Woburn Reference Experiment, 1960–69

F. V. WIDDOWSON and A. PENNY

The experiment, sited on the sandy–silty loam (overlying Lower Greensand) of Stackyard Field at Woburn, Beds., was begun in spring 1960 to test whether very small plots (0·00145 acre) could be used, not only to demonstrate, but also to measure the effects of N, P and K fertilisers and of FYM (applied alone and with fertilisers) on a range of crops. Such experiments have advantages where suitable land is scarce (as at Woburn), but have the disadvantage that boundaries between plots may become blurred by the movement of soil from one plot to another.

We chose to grow sugar beet, barley, a clover–grass ley, potatoes and oats, each year (and in this sequence) and also a long ley and soft fruit. Each crop was given two amounts (0 *v* 1) of N, P and K in the standard 8-plot factorial layout; also tested was a double amount of N (N_2), but only with P and K. Farmyard manure (FYM) was tested alone (Code D) and with fertilisers supplying both single and double amounts of N (DN_1PK and DN_2PK).

Each year the yields of each crop were measured and samples taken to estimate their contents of N, P and K. From these values the ability of the different crops to obtain N, P and K from the soil could be compared and the effects of N, P and K fertilisers on each crop measured. Also, the effects of the N, P and K in FYM could be compared with effects from fertilisers, and the combined effects of each measured. In effect, where both FYM and fertilisers were applied the results showed that we were conducting a maximum yield experiment. The yields from the first cycle of the experiment (1960–64) were published by Widdowson and Penny (1967) and the amounts of N, P and K removed by the crops by Widdowson, Penny and Williams (1967). This paper gives comparable results for the second cycle of the experiment (1965–69), compares the two sets, and shows: (1) how the responses to N, P and K by the five arable crops changed during the ten years; (2) how the amounts of N, P and K obtained from the soil by the same crops changed.

In 1965 the leaves of the sugar beet showed chlorosis typical of Mg deficiency, so Bolton (1966) measured their Mg contents and found these ranged from a minimum of 0·11% Mg (in dry matter) where K was given, to a maximum of 0·48% where FYM was given. From 1966 onwards each plot of sugar beet was split to test Mg (0 *v* 1). Similarly, because the potato leaves showed signs of Mg deficiency in 1967, each plot of potatoes also was split to test Mg in 1968 and 1969.

Experimental method

Appropriate blocks of the arable rotation were dug late in autumn after applying FYM; it was applied to the long ley and the fruit in early spring. The P and K for the arable crops were cultivated into the soil before sowing. Half of each N dressing was also cultivated in for the spring oats in 1965 and for the other arable crops each year; the other half was given as a top-dressing in May. Winter oats replaced spring oats from 1966 and were given half of each N dressing in March and half in May. All of the N, P and K for the rotation ley and the fruit was given in spring. The long ley was given its P and K in spring and one-third of its N for each of three cuts. The Mg for the sugar beet was applied in May (after singling) in 1966, half in the seedbed and half in May in 1967, but all in the seedbed in 1968 and 1969. The Mg for the potatoes was always applied in the seedbed. Methods of cultivating, sowing, harvesting and sampling were described by Widdowson and Penny (1967). The varieties of the crops grown were barley, Maris Badger; rotation ley, mixture of red clover (Dorset Marl) and Italian ryegrass (S22); potatoes, King Edward; oats, Condor in 1965, Maris Quest in 1966 and 1967, Pendrwm in 1968 and 1969; sugar beet, Klein E. The long ley was a composite mixture and the varieties of soft fruit were strawberries, Cambridge Vigour; blackcurrants, Wellington XXX and gooseberries, Careless.

Manuring. The same amounts of P and K were applied for each crop each year, 0·5 cwt P_2O_5/acre as triple superphosphate and 2·0 cwt K_2O/acre as potassium bicarbonate, but the amounts of N, as ammonium nitrate, differed with crop and were, in cwt N/acre:

	Barley	Rotation ley	Potatoes	Oats	Sugar beet	Long ley	Fruit
N_1	0·5	0·25	0·75	0·5	0·75	1·5	0·5
N_2	1·0	0·50	1·50	1·0	1·50	3·0	1·0

Epsom salts was applied to give 0·2 cwt Mg/acre for the sugar beet in 1966 and 0·4 cwt Mg/acre for later crops of sugar beet and for the potatoes. These dressings were also applied after harvest to the half-plots not given Mg during spring, so that basal Mg was finally being given two years in five. In the rotation, only the potatoes and the sugar beet were given farmyard manure (20 tons/acre). The long ley and the fruit were given 10 tons/acre annually. By 1964 gooseberry bushes not given K were nearly dead, so a basal dressing of 0·2 cwt K_2O/acre was applied to the whole of each plot of fruit each year, and in 1967 many strawberry plants showed signs of Mg deficiency, so 0·4 cwt Mg/acre was given to them in 1968 and 1969. Calcium carbonate (25 cwt/acre) was applied in January 1967 to all the soils except that growing the long ley, to maintain soil pH at or near 7·0; the long ley did not require lime then.

Yields

Effects of N, P and K fertilisers and FYM. Appendix Table 1 shows yields of potatoes, sugar beet, barley and oats in agricultural terms and Appendix Table 2 yields as dry matter, so that the production of each crop can directly be compared.

Simple comparison of FYM with fertilisers. Appendix Table 2 shows that yields of potatoes and sugar-beet roots were slightly larger with 20 tons/acre of FYM (D) than with N_2PK, but yields of the oats and barley that followed the roots were much smaller with the FYM residues than with N_1PK. However, the yield of the rotation ley (two years after sugar beet), was only 8 cwt/acre less with FYM residues than with N_1PK, partly because it was undersown in the barley (which grew poorly without N) and partly because the K-rich FYM residues encouraged the clover in the mixture. Fresh FYM at only 10 tons/acre was much less effective than N_1PK on the long ley.

Relative outputs of the different crops. Without fertilisers or FYM, potatoes and barley (grain plus straw) produced least dry matter and sugar beet (tops and roots) and the rotation ley most. With the most manure given (DN_2PK) however, although barley still produced least, and sugar beet most dry matter, potato tubers yielded more dry matter than the sugar beet roots.

Fruit. Appendix Table 1 also gives yields of gooseberries and strawberries. The blackcurrants became infested with big bud (*Phytoptus ribis* Nal.) and so their yields are not given. K was easily the most important nutrient for gooseberries and the only one that increased yields in the absence of the other two; it nearly quadrupled yields with N, and more than trebled it with N and P. P was far less important and the single amount of N was enough. FYM outyielded fertilisers, but a combination of both gave maximum yields. Yields of strawberries were erratic, but were largest with N_1PK, and decreased by FYM, especially where N_1PK and N_2PK were also given.

Responses to N, P and K. Table 1 shows that N_1PK more than doubled the yield of barley grain and trebled that of barley straw. Oats were less responsive; their grain yield was increased by three-quarters and straw by one and a half. N_1PK also more than doubled potato yield and doubled that of sugar beet and the long ley, but it increased the yield of the rotation ley by only a half.

TABLE 1

Responses to N, P and K fertilisers (means for 1965 to 1969)

	Yields without fertiliser or FYM	Increases in the yield of dry matter (cwt/acre) from					
		N_1PK (N_1PK-O)	N_1 (N_1PK-PK)	P (N_1PK-N_1K)	K (N_1PK-N_1P)	N_2-N_1 (N_2PK-N_1PK)	N_2-N_1 (in presence of D) (DN_2PK-DN_1PK)
Barley							
grain	12·2	15·3	14·4	1·6	8·4	3·4	1·9
straw	10·7	20·0	18·9	2·4	12·3	8·6	7·9
Oats							
grain	17·5	12·9	13·0	−0·5	−0·9	6·7	2·0
straw	15·2	22·2	20·2	3·2	6·4	11·8	11·3
Potato tubers	18·4	29·5	15·2	2·7	28·1	12·6	17·8
Sugar beet							
tops	18·5	15·4	13·9	1·6	5·3	7·8	11·4
roots	29·6	30·9	21·2	4·6	26·7	3·4	6·0
Rotation ley	53·3	27·4	9·7	3·0	26·1	0·6	8·0
Long ley	30·9	37·0	25·3	2·4	15·6	7·0	15·6

Response to N. Table 1 also shows that yields of barley and oats were increased almost as much by the single amount of N (N_1PK-PK) as by N_1PK (N_1PK-O), showing that even with ample P and K yields were small without N. Although the other crops all responded greatly to this first dose of N, its effects were less dominant.

The second increment of N (N_2PK-N_1PK) had less effect than the first; it increased potato yields most (it was three-quarters as effective as the first increment) and the rotation ley (rich in clover) least. FYM residues diminished its effect (DN_2PK-DN_1PK) on barley and on oats, but increased it on the rotation ley. Newly applied FYM increased the effect of the double amount of N on potatoes, sugar beet and the long ley, so that its benefits were larger with than without FYM.

Response to P. Table 1 also shows that the effects of P (N_1PK-N_1K) were small; it slightly decreased the yield of oats grain, but increased yields of all the other crops, expecially of sugar-beet roots.

Response to K. By contrast, K greatly increased all yields except of oats grain (which again were decreased). Its benefits were very large on potatoes, sugar-beet roots and the rotation ley, large on the barley and long ley, and least on sugar-beet tops and oats straw.

Comparisons between the relative responsiveness of the crops to N, P and K. Table 2 compares the responsiveness of the crops to fertilisers by expressing the responses to N, P and K in the presence of the other two, as a percentage. Thus, for N_1, this implies (N_1PK-PK/PK) × 100. The response to the second increment of N was calculated in the presence of N_1PK, thus: (N_2PK-N_1PK/N_1PK) × 100. The two cereals were conspicuously responsive to N, especially the barley. The two root crops were only about half as responsive as the cereals; sugar-beet roots and potato tubers responded similarly to the first increment of N, but only the potatoes to the second; beet tops were increased more than roots, especially with the double amount of N. The long ley was as responsive

TABLE 2

Relative responsiveness of five arable crops and a long ley to each nutrient tested in the presence of the other two nutrients

	Percentage increase in dry matter produced			
	from N_1	from N_2 over N_1	from P	from K
Barley				
grain	110	12	6	44
straw	160	28	8	67
Oats				
grain	75	22	−2	−3
straw	117	32	9	21
Potato tubers	46	26	6	142
Sugar beet				
tops	70	23	5	18
roots	54	6	8	79
Rotation ley	14	1	4	48
Long ley	59	10	4	30

as the root crops to the first increment of N, but less so to the second; it responded four times more than the rotation ley (which contained red clover and so needed N little). Except for oats grain, all crops benefited a little from P; there was very little difference between their responsiveness, but the leys responded least. By contrast all crops (oats grain again excepted) responded greatly to K. The response by potatoes was outstanding (yields increased 1½ times) and this was by far the best test crop for K. Sugar-beet roots also responded greatly to K, but less than potatoes, but the tops responded only little (about one-quarter as much as the roots). Both barley grain and, especially, straw responded well to K, but only oats straw did, and only by one-third as much as the barley straw. Thus barley was the most responsive crop to N, no crop (not even potatoes) was particularly responsive to P, and potatoes were easily the most responsive to K, though all the crops (except oats) were suitable tests for K.

Main effects and interactions of N, P and K fertilisers. Table 3 shows the main effects and interactions of N, P and K fertilisers obtained from the mean yields of the five crops in the rotation. The main effects of N were all positive and very highly significant. They confirmed that the cereals were the most, and the rotation ley the least responsive to N, and that sugar beet benefited more than potatoes, presumably because potatoes followed the clover–grass ley. The main effects of P were negligible, non-significant, and positive only for oats straw, potatoes and sugar beet tops. K had no effect on the yield of oats grain, but all other main effects of K were positive and all except one (sugar-beet tops) very highly significant (at 1 in 1000 level); they were exceptionally large on potatoes and the rotation ley, and very large on sugar beet roots. The NP interactions were small, non-significant and frequently negative, whereas the NK interaction was large and very

TABLE 3

Main effects and interactions of N, P and K fertilisers on five arable crops grown from 1965 to 1969

	Dry matter (cwt/acre)								Coeff. of variation (%)
	N	P	K	NP	NK	PK	NPK	S.E.	
Barley									
grain	10·9†	−0·1	3·5†	−0·4	2·8†	1·0	1·1	±0·67	11·8
straw	13·3†	−0·2	5·3†	−0·1	4·2†	1·2	1·6	±0·80	14·0
Oats									
grain	13·2†	0·0	−0·1	0·2	−0·1	−0·4	−0·2	±0·48	6·3
straw	17·1†	0·6	3·2†	0·6	1·2	0·7	1·2	±0·62	7·9
Potato tubers	8·1†	1·0	19·5†	−0·4	6·5†	1·2	0·9	±1·02	10·9
Sugar beet									
tops	12·0†	0·2	2·1*	−0·5	1·3	0·9	1·0	±0·62	7·7
roots	11·7†	−0·1	14·9†	−1·1	6·1†	1·3	4·5*	±1·39	10·5
Rotation ley	6·2†	−0·7	20·6†	0·2	2·0	2·2	1·3	±1·17	5·7

*, † Significant at probability levels of 1% and 0·1% respectively.

highly significant on potatoes and sugar-beet roots and, although smaller, also very highly significant on barley; it was non-significant on oats straw, sugar-beet tops and the rotation ley. The PK interaction was never significant, but was largest for the rotation ley. The NPK interaction was large and highly significant with sugar-beet roots, but was otherwise non-significant (though often larger than the NP or the PK interactions) showing that, at least for sugar beet there were benefits from applying N, P and K together, even though N and K were the dominant nutrients on this site.

Responses to farmyard manure. Table 4 shows that the fresh yields of potatoes and of sugar beet (roots and tops) were far larger with than without FYM, whether or not fertilisers also were given, and that the increase in yield from the FYM was decreased only a little by also giving fertilisers (N_1PK or N_2PK).

TABLE 4

Mean yields (tons/acre) of potato tubers and of sugar beet roots and tops without and with FYM from 1965 to 1969

	FYM applied (tons/acre)					
	0	20	0	20	0	20
	Potato tubers		Sugar beet			
Fertilisers			Roots		Tops	
None	3·61	13·18	6·47	14·23	5·68	12·82
N_1PK	10·04	17·66	13·15	17·68	10·91	16·56
N_2PK	12·88	22·11	14·15	19·54	14·80	21·72

Newly applied FYM greatly increased the dry matter yields of potatoes and sugar beet, but less with than without fertiliser (Table 5). The 10 tons/acre given to the long ley (half as much as to the potatoes and sugar beet) increased its yields much less; NPK again decreased the response to FYM. Without fertilisers, residues of FYM applied for sugar beet and potatoes increased the yields of the barley and oats (which followed them) little, and with fertilisers less. The residues of FYM applied for the sugar beet increased the yield of the rotation ley (two years afterwards) much more than they did the yield of barley (which preceded the ley), presumably because the residues were rich in K which

TABLE 5

Mean increases in yield (cwt/acre of dry matter) from FYM (D) tested with and without NPK fertilisers from 1965 to 1969

	Without NPK fertiliser (D-O)	With NPK fertiliser: N at single rate (DN_1PK-N_1PK)	With NPK fertiliser: N at double rate (DN_2PK-N_2PK)
Direct effects			
Potato tubers	45·2	30·1	35·3
Sugar beet			
tops	17·0	11·4	15·0
roots	36·3	21·7	24·3
Long ley	16·2	3·7	12·3
Residual effects			
Barley			
grain	6·3	2·1	0·6
straw	7·1	5·2	4·5
Oats			
grain	5·0	3·8	−0·9
straw	6·3	5·6	5·1
Rotation ley	19·4	2·3	9·7

benefited the red clover in the ley more than it did the barley. The yield of the rotation ley was increased more by the residues of FYM than was the yield of the long ley by giving 10 tons/acre of FYM each year, presumably reflecting the dominance of the red clover in the rotation ley and of grass in the long ley. The benefits from FYM were greater for both root crops and for both leys with N_2PK than with N_1PK, presumably because shortage of N was the main factor limiting their yield, but were smaller with the two cereals, suggesting that straw weakness and not shortage of N limited their yields.

Effects of time on yields and on responses to N, P and K and to FYM. Fig. 1 shows that, except for the large yields in 1961 and small ones in 1960 and in 1962 (both were duller and cooler summers than average) yields without FYM have declined slowly since 1963, though with it they have been as large as or larger than they were then. Fig. 1 also shows that by 1969 yields with and without N, with and without P, and without K were smaller than in 1960, though those with K were a little larger. In spite of this, mean yields with N and K were very similar. The effect of N was larger in 1960 than in 1961, but then steadily increased until 1966; it declined slightly in 1967, but then increased again in 1968 and in 1969, so the general effect was for it to increase with time. The effect of P was always small, it was negative in 1967 and in 1969. Evidently the soil was supplying almost enough for the crops, even though none had been given for ten years. The effect of K increased more than ten-fold between 1960 and 1963 (the large increase between 1962 and 1963 corresponded to doubling the amount tested, from 1·0 to 2·0 cwt K_2O/acre per year). Since 1963 the effect of K has been fairly constant, but it reached a maximum in 1968. So, in general, the effects of N, P and K were almost independent of season. Fig. 1 also shows that until 1963 yields with FYM (D) followed the same contours as those with N, P and K. Thereafter, both absolute yields with and effects of dung increased, until they reached a sort of equilibrium in 1966. The effect of FYM varied from year to year, presumably because its nutrient content varied, but was smallest in 1962 (when the summer was colder, duller and drier than average) and largest in 1965 (when rainfall of the previous winter was much less than average). In general, dry matter yields were 10–15 cwt/acre larger with FYM than without, with a range of from 7·6 (in 1962) to 25·4 (in 1965) cwt/acre over the ten years.

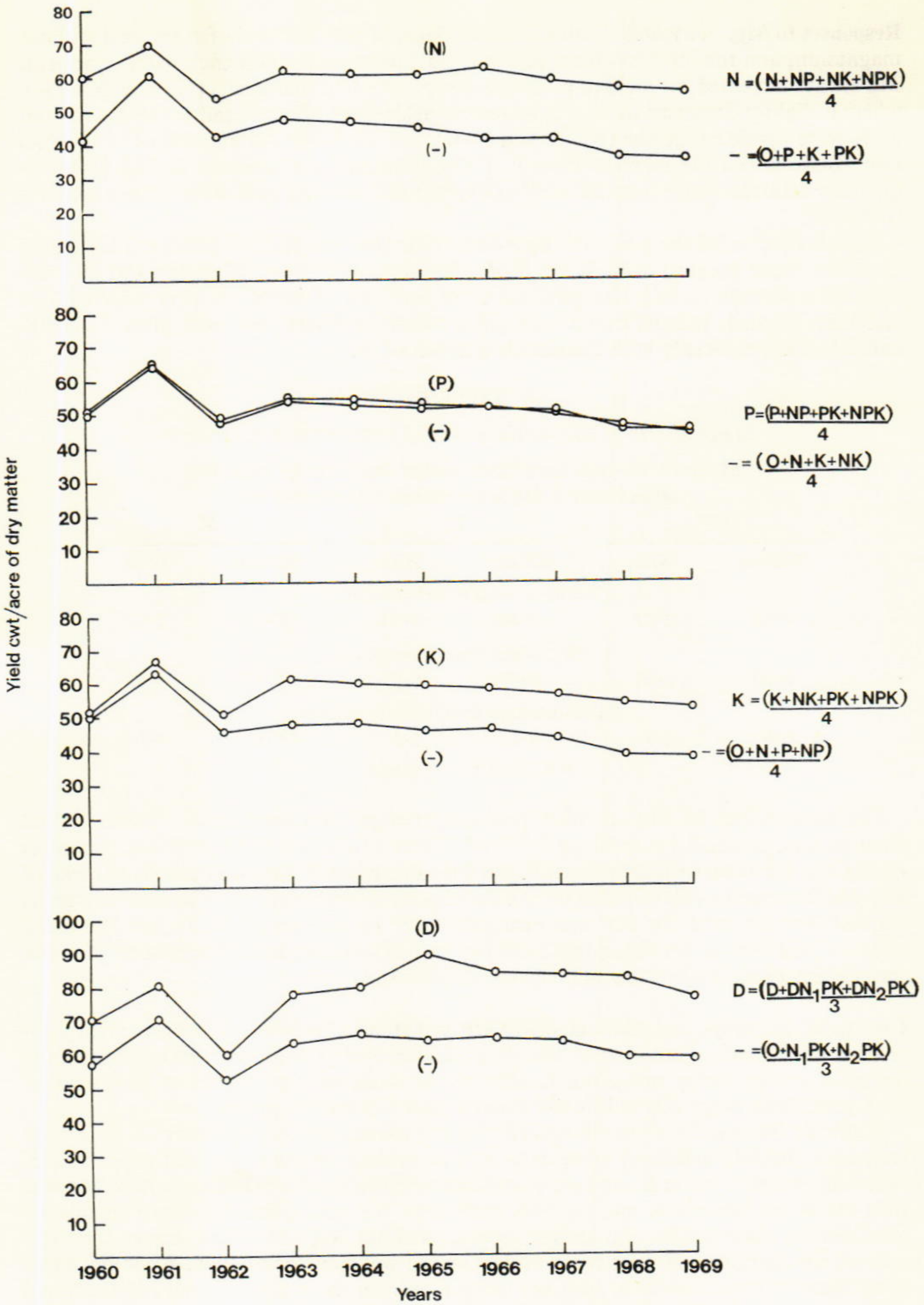

FIG. 1. Mean yields of dry matter from five arable crops with and without N, P and K fertilisers and with and without FYM (D) each year from 1960 to 1969.

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Responses to Mg. Appendix Table 3 shows yields of potatoes and of sugar beet without magnesium and the increases from giving it (as Epsom salts) with each main treatment. Mg always increased the yield of potatoes, except with two treatments (NP and DN_2PK), where it slightly decreased them. Mg increased yields most where K and the single amount of N were applied together (N_1PK and N_1K), but doubling the amount of N (N_2PK) more than halved the increase from it. FYM decreased the response to Mg by three-quarters with the single amount of N (DN_1PK) and eliminated it with double amount (DN_2PK).

Mg also increased the yields of sugar-beet roots (but less than of potatoes) and again its effects were greatest with K or N_1K. The double amount of N (1·5 cwt N/acre) eliminated its effects. Mg also gave an extra half ton of roots per acre where FYM had been applied, but decreased root yields when fertilisers also were given (DN_1PK and DN_2PK), especially with the double amount of N.

TABLE 6

Mean effects of Mg on the yields of potatoes and sugar beet

Means of two years for potatoes and of four years for sugar beet

Mean effects of Mg in the absence and presence of:

N_1*		P		K	
Without	With	Without	With	Without	With
Potatoes, total tubers (tons/acre)					
0·72	2·07	1·44	1·34	0·10	2·68
Sugar-beet roots (tons/acre)					
0·50	1·08	0·59	0·98	0·12	1·45
Sugar-beet tops (cwt/acre dry matter)					
0·6	2·9	1·2	2·3	−0·6	4·1

* N_1 = 0·75 cwt N/acre

The mean effects of Mg on either potatoes or sugar beet were small without N, but were at least doubled by applying 0·75 cwt N/acre (Table 6). With potatoes, the effect of Mg was the same with or without P, but with sugar beet P almost doubled the effect of Mg. Mg increased yields of either crop little without K but greatly with K, and the results showed that the need for Mg was increased more by K than by N. In fact the mean effect of Mg with K on sugar beet tops (4·1 cwt dry matter/acre) was greater than the mean effect of K (2·1 cwt dry matter/acre) (Table 3).

Growth of the crops and nutrient deficiency symptoms, 1965–69. Nitrogen greatly increased the growth of both barley and oats; K increased growth much less, although the leaves of young barley not given K showed the whitened tips typical of K deficiency each year. Both crops ripened slowly where P and K were not given.

N greatly increased the growth and yield of sugar-beet tops. Symptoms of K deficiency were rare, but Mg deficiency symptoms became evident on the sugar beet tops in 1965, especially on plots given K, and were confirmed by leaf analysis (Bolton, 1966). Mg was then tested on half-plots, and by May each year the beet given Mg could readily be identified by their larger and darker leaves. Without Mg the yellow leaves scorched around the margins and were most evident in the wet summer of 1968. Although these symptoms were not shown by beet not given K nor on those given FYM, Mg increased yields on some of these plots (Appendix Table 3).

The haulms of potatoes given neither K nor FYM (O, N_1, P and N_1P) developed symptoms of acute K deficiency by the end of June and died by the end of July or mid-August. Haulms on the other plots grew until the end of September, when the potatoes were dug. By 1967 potatoes also showed symptoms of Mg deficiency, mostly on plots given K, so in 1968 and 1969 Mg was tested on half-plots. In 1968 the symptoms were evident by the end of May (first on the lower leaves) and especially on plots given K. By mid-July the symptoms had appeared on all half-plots not given Mg, except those given FYM plus N, P and K fertilisers, and by late July were severe. In 1969 the summer was drier and the potatoes were grown on plots where sugar beet was given Mg in 1966. The deficiency symptoms appeared later and were slighter, but otherwise developed progressively as in 1968.

The red clover in the rotation ley mixture grew well only where K had been given and developed the marginal leaf scorch typical of K deficiency where it had not. N greatly increased the growth of the long ley and soon made the taller grasses (cocksfoot and timothy) dominant. In 1966 the combination of fertilisers and FYM killed many plants; much of the cocksfoot died and was replaced by timothy and meadow fescue, sown directly into the existing swards. With N, but without K, the grasses had bronzed leaf tips typical of K deficiency.

The gooseberries showed such acute K deficiency (many terminal branches died) that they had to be given a little K (0·2 cwt K_2O/acre) each year to allow them to survive. Similarly the strawberries were given basal Mg, because they showed severe Mg deficiency.

Discussion

One of the main advantages of long-term experiments with small plots is the opportunity afforded regularly to observe the effects of a large range of treatments on several crops grown close together, and so to recognise problems as they occur. This was illustrated well when Mg deficiency first showed on the sugar-beet leaves in 1965 and on the potato leaves in 1967, especially on plots given K (but not FYM) since 1960.

Comparisons of mean yields of the five arable crops grown with all combinations of N, P and K (Table 7) show that yields of barley and of oats were approximately 25% larger during the second than during the first five-year cycle of the experiment. By contrast, yields of potatoes were approximately 20%, and of sugar beet 25%, smaller than during the first five years. We presume this was because in 1960 and in 1961 shortage of K was less limiting than subsequently and so yields of these K-demanding crops were larger then than afterwards.

TABLE 7

Mean yields of five arable crops grown in rotation with all combinations of N, P and K fertilisers from 1960 to 1964 and from 1965 to 1969

	Mean yield (cwt/acre) of dry matter	
	1960–64	1965–69
Barley (grain plus straw)	29·8	36·2
Oats (grain plus straw)	39·1	49·2
Potato tubers	36·2	29·5
Sugar beet (tops plus roots)	92·6	67·3
Rotation ley	72·4	64·8
Mean	54·0	49·4

The cereal yields depended on N and were larger during the second cycle because of larger responses to N; without N, yields in the two cycles were similar. Only a little more

N was given during the second than the first cycle, so the larger responses probably reflect the change to more responsive varieties of oats and barley.

Only with FYM plus fertilisers was the production from the soil fully maintained. Thus mean yields of dry matter (averaged over the five crops in the rotation) from the eight fertiliser treatments of the standard N × P × K factorial arrangement were 54·0 cwt/acre during the first cycle, but only 49·4 cwt/acre in the second; from all nine fertiliser treatments (N_2PK included) they were 56·1 cwt/acre in the first, but only 52·8 cwt/acre in the second, whereas from all 12 treatments (D, DN_1PK and DN_2PK included) mean yields were 60·7 during the first and 60·4 cwt/acre during the second cycle.

N, P, K and Mg removed by the crops

Amounts of N, P, K and Mg applied, 1965–69

Fertilisers. The amounts of N (as ammonium nitrate), P (as triple superphosphate) and K (as potassium bicarbonate) applied to individual crops each year were (in lb/acre):

Crop	Amount N_1	N_2	P	K
Barley	56	112	24·4	186
Oats	56	112		
Potatoes	84	168		
Sugar beet	84	168		
Rotation ley	28	56		
Long ley	168	336	24·4	186

Epsom salts supplied 22·4 lb Mg/acre for sugar beet in 1966 and 44·8 lb for sugar beet from 1967, and for potatoes from 1968.

Farmyard manure (FYM). Table 8 shows the percentages of dry matter and of N, P, K and Mg. in the FYM (always made by cattle in yards at Rothamsted) used in different years, and Table 9 how the differences affected the nutrient content of the standard

TABLE 8

Chemical analyses of FYM (in dry matter)

Cropping year	Dry matter %	N %	P %	K %	Mg %
1965	25·75	2·81	0·48	3·96	0·295
1966	22·50	2·99	0·72	4·32	0·438
1967	26·97	2·84	0·64	4·64	0·348
1968	22·80	2·29	0·55	4·30	0·280
1969	21·90	2·83	0·94	4·64	0·472

TABLE 9

Amounts (lb/acre) of N, P, K and Mg supplied by 20 tons/acre of FYM

Year	N	P	K	Mg
1965	324	55	457	35
1966	301	73	435	44
1967	343	77	561	42
1968	234	56	439	29
1969	278	92	455	46
Mean	296	71	469	39

dressings given. The 20 tons given to potatoes and sugar beet supplied most N (343 lb/acre) in 1967 and least (234 lb/acre) in 1968 so there was a range of almost a half in the amounts of N given. Similarly the P applied ranged from a maximum of 92 lb/acre in 1969 to a minimum of 55 lb/acre in 1965. The K supplied by the FYM ranged only from 561 lb/acre in 1967 to 435 lb/acre in 1966. On the conventional oxide basis, the 20-ton dressings of FYM supplied mean amounts of 296 lb N, 162 lb P_2O_5 and 562 lb K_2O/acre. The Mg supplied by 20 tons/acre of FYM ranged from 46 lb/acre in 1969 to 29 in 1968, so that finally the mean amount applied (39 lb/acre) was slightly less than that in 4 cwt of Epsom salts (44·8 lb Mg/acre).

Chemical analyses of the crops

Nitrogen was determined after Kjeldahl digestion using $CuSO_4$ and K_2SO_4 as catalysts by 'Technicon AutoAnalyzer', using Varley's (1966) method modified by adding citrate tartrate buffer.

Phosphorus by 'Technicon AutoAnalyzer' using the method of Fogg and Wilkinson (1958) after ashing with magnesium acetate and solution in dilute HCl.

Potassium by 'EEL' flame photometer after dry ashing and solution in dilute HCl.

Magnesium by atomic absorption, with strontium as releasing agent (Elwell & Gidley, 1961), using a 'Unicam' SP.900 flame spectrophotometer, after dry ashing and solution in dilute HCl.

Amounts of N, P and K removed from the soil by individual crops, 1965–69. Table 10 shows the amounts of N removed from the soil by crops given P and K, of P by crops given N and K, and of K by crops given N and P fertilisers.

TABLE 10

Nitrogen, phosphorus and potassium (lb/acre) removed from the soil

Crop	Mean of five years 1965–69					
	N		P		K	
Barley						
grain	20	28	9·2	10·5	12	18
straw	8		1·3		6	
Oats						
grain	31	39	10·9	13·0	18	40
straw	8		2·1		22	
Potato						
tubers	47		9·2		22	
Sugar beet						
tops	37	59	7·2	14·3	50	70
roots	22		7·1		20	
Rotation						
ley	204		20·2		83	
Long ley	95		15·8		54	

Nitrogen. The yearly amounts of N removed from the soil by the arable crops ranged from 1 : 1·5 for potatoes to 1 : 3·6 for oats. The amounts removed by oats ranged widely because the spring oats grown in the cool wet summer of 1965 yielded much more, and removed three to four times more N, than the winter oats sown in later years. Sugar beet (tops plus roots) removed most, on average 59 lb/acre, and barley (grain plus straw) least (28 lb/acre) N. Potatoes (tubers only), which followed the rotation ley, removed more than the sugar-beet roots and oats more than barley. The amounts of N removed by these four crops did not change consistently between 1965 and 1969. The rotation ley included Broad red clover, and the long ley white clover, and their cuts contained 204 and 95 lb N/acre respectively, but how much of this N was fixed by the clover and how much came from the soil is unknown. With both crops the amounts of N removed differed greatly between years. Thus, from 1965 to 1968 the rotation ley given P and K removed 200 to 300 lb of N/acre, but in 1969, because much of the clover died in the previous winter, it removed only 90 lb. Similarly the amounts of N in the long ley ranged from 130 lb N/acre in 1965 to 34 lb N/acre in 1969.

Phosphorus. The amounts of P removed from the soil differed little between years. The range was largest (1 : 2) with the rotation ley and sugar beet, and smallest (1 : 1·3) with barley. On average, the rotation ley obtained most P (20 lb/acre/year) from the soil, and barley and potato tubers least (10 and 9 lb/acre respectively). Although three crops (barley, oats and long ley) took their most P from the soil in 1965 and three (barley, rotation ley and long ley) their least in 1969, there was no obvious decrease in the amounts of P taken from the soil by the crops.

Potassium. Except for the oats, which yielded far more in 1965 than later, the ranges in the amounts of K taken up by the crops from year to year were small (1 : 1·6 for potato tubers and the two leys, 1 : 1·7 for barley, 1 : 1·8 for sugar beet). The rotation ley obtained most K from the soil (83 lb/acre per year), perhaps because the red clover was deep rooted; the sugar beet (also deep rooted) obtained 70 lb/acre per year. By contrast, the potatoes (tubers) obtained only 22 lb K/acre and barley (grain plus straw) only 18. We do not know how much K the potato tops contained. There was only a small decline in the amounts of K supplied by the soil after 1965, but the three crops most responsive to K (potatoes, sugar beet and the rotation ley) obtained only between one-half and two-thirds of the amounts that they obtained during the previous rotation (1960–64).

Mean amounts of N, P and K removed from the soil (1960–69). Fig. 2 shows the mean annual amounts of N, P and K taken from the soil from 1960 to 1969 by the five arable crops grown in rotation. The mean amounts of N are in only four crops (rotation ley excluded). The mean amounts of P and K are in all five crops (except in 1964, when the barley was destroyed by rooks).

Nitrogen. The crops obtained rather more N from the soil in 1961 than in 1960 (57 and 43 lb/acre respectively), presumably because the clover–ley dug down in 1960 decayed and released N. The supply of N from the soil was maintained until 1963, after when it gradually declined to a minimum of only 39 lb/acre in 1967, after when it increased to 41 lb N/acre. Evidently under this cropping system, crops can obtain roughly 40 lb N/acre per year from this soil, some of which must have been fixed by the red clover in the ley. We suggested earlier in this paper that barley and oats yielded more during 1965 to 1969 than during 1960 to 1964 because the varieties grown during the second cycle were more responsive to N fertiliser; our results show that both obtained more N from the soil from 1965–69 than previously. By contrast, both potatoes and sugar beet obtained less soil N during the second cycle of the rotation.

Phosphorus. Fig. 2 also shows that the amounts of P obtained by the crops varied little. None responded much to P fertiliser, so the small amounts of P provided by the soil (11·5–15 lb/acre) were obviously enough.

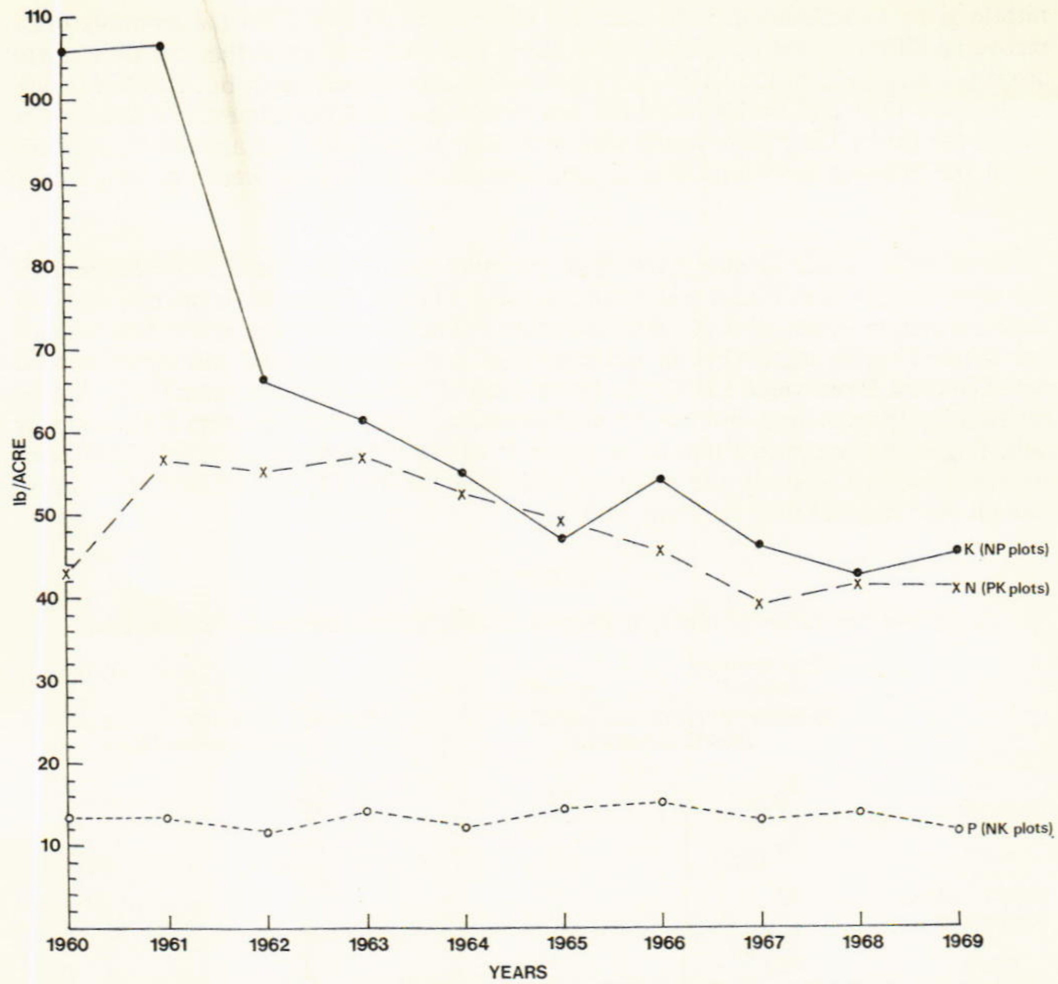

FIG. 2. The mean annual amounts (lb/acre) of N, P and K taken from the soil by five arable crops grown on the Woburn Reference plots from 1960 to 1969. Mean of five crops for P and K, mean of four (excluding ley) for N.

Potassium. Fig. 2 also shows the large fall in the amount of K provided by the soil after 1961. In 1960 and in 1961 the crops removed mean amounts of 106 and 107 lb/acre respectively, but in 1962 only 66 lb, so 'available' K had decreased by more than one-third after only two years. It then decreased year by year, until in 1965 the soil provided only 47 lb K/acre. Thereafter it fluctuated a little, but seemed to be settling around 44 lb K/acre per year. The yield response to K increased more than ten-fold between 1960 and 1963, but afterwards remained fairly constant (except that it was larger in 1968 than in other years) so there was a good negative correlation between the amount of K obtained from the soil and the response to fertiliser-K.

Recovery of N, P and K from the fertilisers. Table 11 gives the apparent recoveries by the crops of the N, P and K applied as fertilisers, calculated by subtracting the amounts of each nutrient in crops grown without it, but with the other two, from amounts in crops given all three, both directly and expressed as a percentage of that given as fertiliser.

Nitrogen. Values for the two leys cannot be given because the amounts of N 'recovered' by them include N fixed by the clover. Although amounts of ammonium nitrate given to individual crops were the same from 1965 to 1969 the amounts of N recovered differed greatly between years. Sugar beet recovered more than the other three crops (71 and 64% of the single and double amounts respectively), but two-thirds was in the tops. Oats and barley recovered less than sugar beet, but almost two-thirds of it was in the grain. The potato tubers recovered only two-fifths of the applied N, but how much the growing crop recovered is unknown because the tops were not weighed or sampled.

Phosphorus. Table 11 also shows that not more than 5·0 lb P/acre was recovered by any crop though 24 lb P/acre was given annually. The dry matter from the two leys and from the potato tubers always contained more P when fertiliser was given than when it was not, but barley and oats grain and sugar beet roots sometimes did and sometimes did not. The most P recovered (20%) was by the long ley and the second most (16%) by the rotation ley (presumably because the shallow-rooted grass took up more P than clover did). Sugar beet recovered almost as much P as the rotation ley, but its yields were increased more. Curiously the potatoes recovered far less (4%) than any other crop, though they respond to P on many soils.

TABLE 11

Apparent recoveries of nitrogen, phosphorus and potassium applied as fertiliser

	Mean recovery (lb/acre)		% recovery	Mean recovery (lb/acre)		% recovery
	Recovery of single amount of N (N_1PK minus PK)			Recovery of double amount of N (N_2PK minus PK)		
Barley						
grain	20	29	52	34	54	48
straw	9			20		
Oats						
grain	20	31	55	41	61	54
straw	11			20		
Potato tubers	32		38	67		40
Sugar beet						
tops	38	60	71	72	107	64
roots	22			35		
	Recovery of phosphorus (N_1PK minus N_1K)			Recovery of potassium (N_1PK minus N_1P)		
Barley						
grain	1·4	1·8	7	7	29	16
straw	0·4			22		
Oats						
grain	0·5	1·5	6	1	49	26
straw	1·0			48		
Potato tubers	1·1		4	81		44
Sugar beet						
tops	2·1	3·6	15	98	126	68
roots	1·5			28		
Rotation ley	3·8		16	136		73
Long ley	5·0		20	137		74

Potassium. Table 11 also shows the apparent recoveries of K by crops given 186 lb K/acre annually. All crops except oats grain always contained more K when fertiliser-K was given, but the oats were inconsistent, perhaps because K seldom increased their yield. The long ley and the rotation ley recovered the largest mean amounts of K, slightly more than sugar beet (tops and roots). However, the amounts removed by the crops differed greatly between years, and were minimum in 1965 with sugar beet, when Mg deficiency was first diagnosed (Bolton, 1966) and in 1969 with the rotation ley when the red clover almost failed. Maximum amounts recovered were 160 lb K/acre by the long ley in 1965 and 1968 and by the sugar beet in 1968 and 1969, and 187 lb/acre by the rotation ley in 1967. Almost four-fifths of the K recovered by the sugar beet was in the tops but, even so, K increased the yield of tops little and of roots greatly (5–7 times more than the tops). Potatoes responded more than any other crop, but the tubers recovered only 44% of the K; i.e. only two-thirds as much as by the leys or sugar beet. We do not know how much was in the tops, but, in July 1969 leaves of potatoes on the Rothamsted Reference Plots without K fertiliser contained only 0·8% K, but 3·4% K with it (Widdowson, Penny & Flint, 1970), so that the tops probably used as much K as the tubers did, much of which would be returned to the soil. Oats and barley recovered much less K than the other crops, and most of it was in the straw. Recoveries ranged from 16% with barley to 74% with the leys.

Recovery of N, P and K from fresh FYM. Table 12 shows apparent recoveries of N, P and K from the FYM applied to the long ley, potatoes and sugar beet, calculated by subtracting the amounts in completely unmanured crops from those in crops given FYM only (D-O) and the amounts in crops given fertilisers only from those in crops given both fertilisers and FYM (DN_1PK-N_1PK and DN_2PK-N_2PK). These calculations are subject to some error because in calculating the recovery of one nutrient from the FYM they ignore the effects of the other two in it (e.g. recovery of N from FYM might better be calculated as D-PK instead of D-O).

TABLE 12

The apparent recoveries of the nitrogen, phosphorus and potassium from FYM (D) applied without and with fertilisers, 1965 to 1969

	Without fertiliser (D-O)		With single amount of fertiliser-N (DN_1PK-N_1PK)		With double amount of fertiliser-N (DN_2PK-N_2PK)	
	Mean recovery (lb/acre)	% recovery	Mean recovery (lb/acre)	% recovery	Mean recovery (lb/acre)	% recovery
			Nitrogen			
Potato tubers	48	16	42	14	64	22
Sugar beet						
tops	40 } 64	22	31 } 51	17	43 } 66	22
roots	24		20		23	
Long ley	30	20	15	10	22	15
			Phosphorus			
Potato tubers	10·3	14	7·9	11	9·4	13
Sugar beet						
tops	5·2 } 11·9	17	3·3 } 8·5	12	6·2 } 11·1	16
roots	6·7		5·2		4·9	
Long ley	5·6	16	3·9	11	8·5	24
			Potassium			
Potato tubers	129	28	100	21	126	27
Sugar beet						
tops	104 } 139	30	84 } 111	24	112 } 149	32
roots	35		27		37	
Long ley	88	38	48	20	121	51

The mean annual amounts of N, P and K added in 20 tons/acre of FYM were 296, 71 and 469 lb/acre respectively. Without fertilisers, the potatoes apparently recovered 48 lb of the N, 10·3 lb of the P and 129 lb of the K given; the sugar beet recovered 64 lb of the N, 11·9 lb of the P and 139 lb of the K. When fertilisers supplying the single amount of N (DN_1PK) were also given the potatoes recovered only slightly less of the N and P, but only three-quarters as much of the K from the FYM; sugar beet recovered between one-quarter and one-fifth less of each. With twice as much N (DN_2PK), the potatoes apparently recovered 64 lb of the N in the FYM (one-third more than without fertilisers) and approximately the same amounts of P and K, so that nitrogen fertiliser increased the amount of N taken from the FYM. Similarly, doubling the N increased the efficiency of the FYM for the sugar beet, for then it recovered the same amounts of N and P and slightly more K (149 lb/acre) than when FYM was used alone. Thus, the recovery of the nutrients in FYM was increased rather than decreased by also giving fertiliser for these two crops.

The long ley was given mean annual amounts of 148 lb of N, 35 lb of P and 235 lb of K in the 10 tons/acre of FYM applied. Without fertilisers, 30 lb of the N, 6 lb of the P and 88 lb of the K were removed in the herbage, but with fertilisers also (DN_1PK), the long ley recovered only half as much N, three-quarters as much P and half as much K from the FYM. With the double amount of N (DN_2PK) however, it recovered more of each than with the single amount, and more P and K, though less N, than when FYM was given alone. Hence, fertilisers again increased the recovery of the P and K from FYM.

Relative efficiencies of the N, P and K in FYM and fertilisers. Tables 11 and 12 allow the relative value of the two sources of nutrients for potatoes, sugar beet and the long ley to be compared directly. For potatoes, the N in FYM was never more than half as effective as that in ammonium nitrate when judged by percentage recovery, but when judged by the absolute yield of N in the tubers similar amounts were recovered from each source. For sugar beet, the N in the FYM was about one-third as effective as the N in ammonium nitrate when judged by percentage recovery and less effective also in absolute terms. We could not measure the relative value of the two sources of N for the long ley, because it contained clover.

By contrast, the P in the FYM was three times more effective for potatoes than the P in triple superphosphate was (on a percentage recovery basis) and ten times more effective when judged by the total amount of P removed. It was equally as effective as fertiliser-P for both sugar beet and the long ley, though in absolute terms the sugar beet recovered three times more P from FYM than from fertiliser. The K in the FYM was roughly half as effective as the K in potassium bicarbonate for all three crops (when judged on a percentage recovery basis) though potatoes recovered far more, and sugar beet a little more K from FYM. By contrast, the long ley made better use of fertiliser-K when judged by either standard.

Recovery of N, P and K from FYM residues. Table 13 shows apparent recoveries of N, P and K by barley and by oats from the residues of the FYM applied the year before, and of P and K by the rotation ley from FYM applied two years before. Unexpectedly, spring barley following sugar beet recovered more N (a mean of 14 lb/acre) than winter oats following potatoes (a mean of 10 lb/acre). These recoveries were roughly 5% of the N originally given. Taking fertiliser-N to be 50% efficient for cereals on this soil (Table 11), these N residues were equivalent to giving barley 24 to 32 lb fertiliser-N/acre and oats 16 to 26 lb N/acre. Table 13 also shows that the barley and oats recovered from 2·2 to 3·8 lb P/acre from the FYM residues, roughly twice as much as they recovered from fertiliser-P (Table 11), but still no more than 6% of that originally given. Hence, for both crops, the P in the FYM residues was at least as effective as freshly applied fertiliser P.

WOBURN REFERENCE EXPERIMENT, 1960–69

TABLE 13

The apparent recoveries of nitrogen, phosphorus and potassium from one-year-old and two-year-old residues of FYM

	Without fertiliser (D minus O)		With single amount of fertiliser-N (DN_1PK minus N_1PK)		With double amount of fertiliser-N (DN_2PK minus N_2PK)	
	Mean recovery (lb/acre)	% recovery	Mean recovery (lb/acre)	% recovery	Mean recovery (lb/acre)	% recovery
Recoveries from one-year-old residues (grain plus straw)						
			Nitrogen			
Barley	15	5	12	4	16	5
Oats	13	4	10	3	8	3
			Phosphorus			
Barley	3·6	6	2·8	4	3·8	6
Oats	2·8	4	2·2	4	3·3	5
			Potassium			
Barley	18	4	16	4	33	8
Oats	29	7	26	6	37	9
Recoveries from two-year-old residues						
			Phosphorus			
Rotation ley	6·3	10	1·6	3	4·1	7
			Potassium			
Rotation ley	103	25	30	7	47	12

The table also shows that the barley apparently recovered relatively little K (16 to 33 lb/acre) and the oats only a little more (26 to 37 lb/acre) from the FYM residues. So, when judged by fertiliser recoveries (Table 11), these K residues (from larger amounts) were less effective than fresh fertiliser, but were equivalent to giving at least 100 lb K/acre as fertiliser.

Table 13 also shows that without fertiliser the rotation ley recovered mean amounts of 6·3 lb/acre of P and 103 lb/acre of K from the residues of FYM given two years before, but that with fertiliser it recovered far less. The largest recoveries (without fertiliser) represented 10% of the P and 25% of the K originally given, so that the residues were less effective than fresh fertiliser. Nevertheless, the residues were equivalent to giving from 10 to 39 lb/acre of fertiliser P and from 41 to 141 lb/acre of fertiliser-K to the ley.

Amounts of N, P and K removed by the crops. Appendix 4 shows that the mean amounts of N, P and K removed by each crop differed greatly. Maximum yields of N ranged from roughly 100 lb/acre in barley and oats to 230 lb/acre in sugar beet and the long ley. The largest amounts of P removed ranged from about 30 lb/acre by fully manured sugar beet and leys, to about 20 lb/acre by fully manured cereals and potatoes. Maximum yields of K were larger even than those of N; sugar beet removed the most (370 lb/acre), the long ley about 300 lb and the rotation ley and the potato tubers about 250 lb K/acre. Barley removed a maximum of 94 lb K/acre.

Amounts of N, P and K added to and removed from the soil in five years. Appendix Table 5 shows the total amounts of N, P and K added in fertilisers and in FYM and the amounts removed by the five arable crops from 1965 to 1969. The manures added from

308 to 1208 lb N/acre (note that the FYM doubled the amount of N given) and the crops removed from 282 to 808 lb N/acre during five years. The rotation ley yielded from 111 to 218 lb N/acre (Appendix Table 4), so that the clover in it probably contributed from about 80 to 180 lb N/acre. The largest loss of N during five years was probably about 200 lb/acre (obtained by deducting 180 from the total amount of N removed on the K and PK plots) and the largest gain about 500 lb N/acre (obtained by deducting 80 from the total amount of N removed on the DN_2PK plots). Even allowing for the N fixed by the clover, the double amount of N was needed to give a positive balance, though how much was later leached is unknown. Soil given FYM alone probably gained about 240 lb N/acre during five years (ignoring leaching) and given also the double dose of N, about 500 lb N/acre (a similar total to that obtained in the first rotation).

Phosphorus. Appendix Table 5 also shows that the crops always removed less P (43 to 117 lb) than was added (122 lb P/acre) as fertiliser in five years. With fertilisers alone, most P was lost (67 lb/acre) when N and K were applied and the least gained (37 lb/acre) when the double amount of N (N_2PK) was given. The two dressings of FYM in five years added rather more P (141 lb/acre) than the fertilisers, so that when applied together the total gain was about 150 lb P/acre, i.e. about three-fifths of the total amount given.

Potassium. When K was not given the soil lost up to 265 lb/acre in five years (we suggested earlier, Fig. 2, that this soil can now provide 44 lb K/acre per year). With fertiliser-K (930 lb K/acre in five years) the crops given most fertiliser (N_2PK) removed seven-ninths of it (720 lb K/acre), so they apparently need to obtain 100 lb K/acre per year either from fertilisers or from FYM. There were sizeable gains in K when both FYM and fertilisers were given, even though the larger crops grown with the FYM removed more K. More than 900 lb K/acre accumulated in the DN_1PK plots and about 750 lb K/acre in the DN_2PK plots. These results suggest that 180 lb of fertiliser-K are needed annually to maintain the K concentrations of the largest crops grown here.

Mg in potato tubers and in sugar-beet tops. Appendix Table 6 shows that the percentage of magnesium in potato tubers was slightly increased (in 10 of 12 comparisons) by giving 45 lb Mg/acre (as Epsom salts) and that, except on the unmanured plots, the recovery of Mg was similarly increased. Applying FYM (supplying 40 lb Mg/acre) increased both the percentage and amount of Mg more than applying Epsom salts did. Percentage Mg was changed more by varying N, P and K fertilisers than by giving Mg. Because giving N, P and K increased tuber yields so much (from 18 to 96 cwt dry matter/acre) totals of Mg also ranged widely, from 1·0 lb/acre (with P alone) to 12·4 lb/acre with FYM and fertilisers together (DN_2PK). These values were increased little by also giving Mg, so the amount of Mg recovered by the tubers never exceeded 5% of that applied, though presumably the potato tops contained appreciable amounts.

Appendix Table 6 also shows that giving Epsom salts consistently increased % Mg in sugar beet tops grown with fertilisers alone, though they did not when FYM was given. % Mg was changed more by giving N, P and K fertilisers than by giving Mg, with K decreasing % Mg by roughly a third. Similarly, amounts of Mg were increased from 3·9 lb/acre (with K alone) to 17·8 lb/acre by FYM and fertiliser together, mainly because the range in yields was so large. By contrast, the increases in the uptake of Mg from applying it for the beet were small, but consistent; the most Mg apparently recovered (3·3 lb/acre) represented only 7% of the amount applied.

Table 14 shows the effects of giving N, P and K fertilisers (obtained in the usual way from the 8 plot contrasts) on the concentrations and amounts (lb/acre) of Mg both in

TABLE 14

Mean percentages of Mg and mean amounts (lb/acre) of Mg in dry potato tubers and dry sugar-beet tops in the absence and presence of N_1, of P and of K

Means of two years for potatoes and of four years for sugar beet

	N_1		P		K	
	Without	With	Without	With	Without	With
	% Mg in potato tubers					
Without Mg	0·077	0·072	0·075	0·073	0·058	0·091
With Mg	0·079	0·077	0·077	0·079	0·062	0·093
	Mg (lb/acre) in potato tubers					
Without Mg	2·4	2·7	2·5	2·6	1·2	3·9
With Mg	2·8	3·9	3·3	3·4	1·4	5·4
	% Mg in sugar-beet tops					
Without Mg	0·206	0·216	0·206	0·215	0·257	0·164
With Mg	0·223	0·268	0·247	0·244	0·302	0·188
	Mg (lb/acre) in sugar-beet tops					
Without Mg	4·7	7·6	6·2	6·1	7·5	4·8
With Mg	5·1	10·0	7·6	7·5	8·6	6·4

potato tubers and in sugar-beet tops. N slightly decreased % Mg in potato tubers, but increased it in sugar beet tops, but because it increased yields greatly it increased the total amount of Mg removed by both. P had little effect either on % Mg in the crops or on the amounts removed. Fertiliser-K increased % Mg in potato tubers by roughly a third; consequently, as K also greatly increased tuber yields, the amounts of Mg removed were more than trebled. By contrast, K diminished % Mg in the sugar-beet tops by more than a third, and because it did not increase yields, it also decreased the amounts removed by a third.

These effects were not changed by giving Mg though then both concentrations of Mg and amounts removed were larger.

Discussion

Comparing these results with those from the same plots during the first crop cycle (Widdowson, Penny & Williams, 1967), the most striking features were the steep decline in the amounts of K obtained from the soil and the occurrence of severe Mg deficiency. The decrease in soil K was most evident in the potatoes, sugar beet roots and the leys, which obtained little more than half as much K from the soil as during the previous cycle. In fact potato tubers obtained only 22 lb K/acre yearly from 1965 to 1969, but 49 lb K/acre previously.

By contrast, the amounts of N obtained from the soil decreased less (presumably because clover was in the rotation ley), and soil P did not change detectably. Consequently recoveries from fertiliser-N were a little larger from 1965–69 than previously, as were recoveries of fertiliser-P, though the amounts of P provided by the soil were apparently as large then as before and there was still no yield response.

Although more potassium bicarbonate was applied from 1965–69 than before, a much larger percentage of it was recovered by each crop, presumably because the soil K had been greatly diminished and yield responses became larger.

Although both fertilisers and FYM were applied cumulatively, and although the amounts of N, P and K given to DN_1PK and DN_2PK plots greatly exceeded the amounts removed (Appendix Table 5), the crops recovered slightly more of the N and one-third more of the P from the FYM than during the previous cycle. Similarly, the crops recovered the same percentage of K from the FYM during both cycles, but because the FYM given from 1965–69 was richer in K, they recovered larger absolute amounts than previously. Hence, the accumulation of nutrients in this soil seemed not to lead to any loss in their efficiency. However, N and K (and especially N) were less efficient when given in FYM than when given in fertiliser, though more K was given in the FYM. For potatoes at Woburn, FYM was a much better source of P than superphosphate, for during both cycles it was three times more effective, judged by crop content or by percentage recovery of P applied. For the other crops, it was no better than superphosphate.

Both cereals recovered roughly 5% of the N originally contained in the FYM. Hence they needed less N fertiliser than where fertilisers were given alone. For the cereals and the rotation ley, the P and K residues from FYM seemed as effective as fresh fertiliser. In conclusion, the dressings of FYM to sugar beet and potatoes together supplied almost as much N and a little more P and K than was in the largest fertiliser dressing (N_2PK) given. Hence one 20 tons/acre dressing of FYM every five years would almost meet the demand for P and go more than halfway towards meeting the demand for K by these five crops, thereby greatly diminishing the amounts of P and K fertilisers required and also supplying a valuable dressing of magnesium.

Giving K increased the need for Mg, partly because crops were larger with K than without and removed more Mg from the soil, and partly because of the antagonism between K and Mg which led to less Mg in sugar-beet tops (and probably in potato tops too). This did not happen with potato tubers, which contained a larger percentage of Mg with K than without, and because K increased tuber yields so much they also recovered more Mg, though the foliage showed acute symptoms of Mg deficiency.

Addiscott (1971) also found, with potatoes grown in pots, that the more K given the more Mg the tubers contained, but K decreased % Mg in the foliage. This also probably happened in our experiment, but analyses were not made to confirm it.

Summary

Yields. An experiment begun in 1960 to measure the effects of FYM (D) and N, P and K fertilisers on a five-course rotation of barley, grass–clover ley, potatoes, oats and sugar beet, and on permanent ley, continued to 1969. Mg was tested from 1966 on sugar beet and from 1968 on potatoes. Soft fruit (blackcurrants, gooseberries and strawberries) had the same FYM and N, P and K treatments.

N greatly increased yields of all agricultural crops except the rotation ley and K greatly increased yields of all except oats. Barley and oats were the most responsive to N and potatoes and sugar-beet roots and the long ley the most responsive to K. P increased yields little. Responses to both N and K were larger from 1965 to 1969 than from 1960 to 1964. The mean effects of N, P and K fertilisers from 1965–69 averaged over crops and in cwt dry matter/acre were (1) 18·5 for N, (2) 0·2 for P, and (3) 13·8 for K. Fresh dressings of FYM greatly increased yields of potatoes and sugar beet. The clover-rich rotation ley benefited more from two-year-old residues from FYM than barley and oats did from residues one-year old. Applying fertilisers (N_1PK or N_2PK) with the FYM decreased its benefits only little, especially when the double amount of N was given, and so the combination of fertilisers and FYM gave by far the largest yields of sugar beet and potatoes and larger yields than from fertilisers alone of all except oats grain.

Mg increased yields of potatoes and sugar beet most where K also was given, but had no effect on sugar beet yields when the double amount of N was given (N_2PK), or on those of either crop given the largest manuring (DN_2PK).

Mean yields of barley and oats (from all combinations of N, P and K) were larger

from 1965 to 1969 than from 1960 to 1964, but mean yields of potatoes, sugar beet and the rotation ley were smaller. Mean yields of the long ley also were smaller during the second cycle.

N, P, K and Mg. From 1965 to 1969 the percentages and recoveries of N, P and K were measured on the five arable crops and the long ley, and of Mg in sugar beet tops (from 1966) and in potato tubers (from 1968). From these measurements the amounts were calculated of nutrients removed by each crop from the soil. This differed between crops, but mean values (lb/acre) during the final three years (1967–69) were about 40 for N, 44 for K and 13 for P. The red clover in the rotation ley contributed roughly 80–180 lb N/acre and the white clover in the long ley 20–55 lb N/acre.

Little more than two-thirds of the fertiliser-N and one-fifth of the N in FYM was ever recovered by any crop. Very little fertiliser-P (maximum 20%) was recovered by any crop and no more than 24% of that in FYM. The P in FYM was three times as effective as fertiliser-P for potatoes, but no more so for sugar beet or the long ley. Fertiliser-K was recovered more completely (maximum 74%) than either N or P, but the larger amount of K in the FYM was used less completely (maximum 51%) than the smaller amount given as fertiliser. The residues from the FYM given for potatoes and sugar beet lessened the need for N by barley and oats (roughly by 25 lb fertiliser-N/acre) and seemed effective sources of P and K.

From the N, P and K contents of the FYM (20 tons supplied 296 lb N, 71 lb P and 469 lb K/acre) fertilisers and crops, a balance sheet was constructed for N, P and K. This showed ranges in offtake over the five years (in lb/acre) of from 300 to 800 of N, 40 to 120 of P and 200 to 1100 of K, with consequent maximum losses to the soil of about 200 of N, 70 of P and 250 of K and maximum gains of about 500 of N (ignoring leaching), 150 of P and 900 of K.

The concentrations and amounts (lb/acre) of Mg in sugar beet tops and potato tubers were increased appreciably by giving FYM (supplying 39 lb Mg/acre), but Epsom salts increased them only little. Neither N nor P fertilisers greatly changed % Mg in either sugar beet tops or potato tubers, but K increased % Mg in tubers and greatly decreased it in sugar-beet tops.

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APPENDIX TABLE 1

Mean yields of agricultural produce from combinations of N, P and K fertilisers and FYM (D) tested on four arable crops and on soft fruit in the Woburn Reference experiment from 1965 to 1969

	Treatments												
	—	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK	S.E.
	Fresh produce (tons/acre)												
Potato tubers*	3·61	4·31	3·80	4·02	6·47	9·52	6·90	10·04	12·88	13·18	17·66	22·11	±0·791
Sugar-beet roots*	6·47	9·05	7·44	7·52	8·89	12·11	8·60	13·15	14·15	14·23	17·68	19·54	±0·608
Sugar-beet tops*	5·68	10·10	6·14	9·23	6·39	10·36	6·05	10·91	14·80	12·82	16·56	21·72	±0·942
	Grain (cwt/acre) at 15% moisture content												
Barley	14·3	25·5	14·7	22·5	15·1	30·5	15·4	32·4	36·4	21·8	34·8	37·1	±1·56
Oats	20·6	35·9	20·7	36·8	20·9	36·4	20·4	35·8	43·6	26·4	40·2	42·5	±1·02
	Sugar (cwt/acre)												
Sugar beet*	20·4	27·4	23·1	22·3	29·3	39·9	27·9	42·7	45·0	47·3	58·3	63·5	±2·12
	Gooseberries (lb/bush) and of strawberries (lb/seven plants) (Yields are means of five years (1965 to 1969) for gooseberries and of three years (1965, 1968, 1969) for strawberries)												
Gooseberries	3·33	2·24	2·62	3·15	5·58	8·11	6·62	10·49	11·08	11·66	15·65	15·78	—
Strawberries	4·23	4·37	5·89	2·96	4·79	5·77	5·25	6·31	3·51	4·73	2·96	4·30	—

* Averaged over with and without Mg on each treatment for potatoes in 1968 and 1969 and for sugar beet from 1966 to 1969.

APPENDIX TABLE 2

Mean yields of dry matter (cwt/acre) from combinations of N, P and K fertilisers and FYM (D) tested on five arable crops and on a long ley in the Woburn Reference experiment from 1965 to 1969

	Treatments												
	—	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK	S.E.
Potatoes													
total tubers*	18·4	21·3	19·6	19·8	31·1	45·2	32·7	47·9	60·5	63·6	78·0	95·8	±3·24
Sugar beet													
tops*	18·5	30·8	19·3	28·6	19·6	32·3	20·0	33·9	41·7	35·5	45·3	56·7	±1·61
roots*	29·6	40·7	33·8	33·8	41·4	55·9	39·3	60·5	63·9	65·9	82·2	88·2	±2·75
Barley													
grain	12·2	21·7	12·5	19·1	12·8	25·9	13·1	27·5	30·9	18·5	29·6	31·5	±1·33
straw	10·7	21·5	11·1	18·4	12·3	28·3	11·8	30·7	39·3	17·8	35·9	43·8	±1·51
Oats													
grain	17·5	30·5	17·6	31·3	17·8	30·9	17·4	30·4	37·1	22·5	34·2	36·2	±0·87
straw	15·2	31·7	15·8	31·0	17·7	34·2	17·2	37·4	49·2	21·5	43·0	54·3	±1·77
Rotation ley	53·3	58·5	51·5	54·6	71·0	77·7	71·0	80·7	81·3	72·7	83·0	91·0	±3·52
Total in five years	175·4	256·7	181·2	236·6	223·7	330·4	222·5	349·0	403·9	318·0	431·2	497·5	—
Long ley	30·9	51·9	27·8	52·3	39·1	65·5	42·6	67·9	74·9	47·1	71·6	87·2	—

* Averaged over with and without Mg on each treatment for potatoes in 1968 and 1969 and for sugar beet 1966 to 1969.

APPENDIX TABLE 3

Mean yields of potatoes and of sugar beet without magnesium and the increases from applying magnesium (Epsom salts) in the Woburn Reference experiment*

(Yields are means of two years (1968 and 1969) for potatoes and of four years (1966 to 1969) for sugar beet)

	Main treatments											
	O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
Potatoes, total tubers (tons/acre)												
Yields without Mg	3·97	4·00	3·29	4·04	6·73	9·70	8·41	9·68	13·97	14·84	20·40	25·75
Increases from Mg	0·02	0·10	0·39	−0·10	1·75	3·90	0·71	4·37	1·80	1·95	1·07	−0·21
Sugar-beet roots (tons/acre)												
Yields without Mg	6·78	9·16	7·65	7·03	8·66	11·56	8·30	12·64	13·72	13·90	17·52	19·47
Increases from Mg	−0·21	0·28	−0·25	0·68	1·12	1·18	1·32	2·18	−0·13	0·51	−0·38	−1·13
Sugar-beet tops (tons/acre)												
Yields without Mg	5·79	10·50	6·75	9·03	6·56	9·92	5·82	10·26	14·74	11·54	16·17	20·80
Increases from Mg	−0·08	−0·62	−0·69	0·39	0·00	1·27	0·70	2·36	−0·42	1·66	−1·12	1·27
Sugar-beet tops, dry matter (cwt/acre)												
Yields without Mg	19·4	31·9	21·3	29·1	19·2	32·1	18·6	31·4	42·2	31·8	42·9	58·5
Increases from Mg	−0·6	−0·3	−1·8	0·3	1·8	3·9	3·1	7·6	−1·3	5·6	0·7	−3·5

* Two cwt/acre to sugar beet in 1966, otherwise 4 cwt/acre.

APPENDIX TABLE 4

Mean annual amounts (lb/acre) of nitrogen (N), phosphorus (P) and potassium (K) taken up by five arable crops and by a long ley grown with combinations of N, P and K fertilisers and FYM (D) from 1965 to 1969

	Treatments											
	O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
Nitrogen												
Barley												
grain	18·7	31·7	18·9	30·5	18·6	37·3	19·9	39·7	54·1	29·7	47·6	61·3
straw	4·7	11·1	5·0	9·6	5·4	13·2	7·5	16·2	27·3	8·6	20·1	36·2
Oats												
grain	32·2	52·8	32·6	53·3	32·5	50·3	31·3	51·1	72·6	41·8	59·2	75·2
straw	7·0	14·8	7·8	14·4	7·8	15·1	7·7	17·7	27·5	10·2	19·4	33·0
Potatoes												
total tubers	33·3	44·8	32·0	39·3	43·3	74·8	46·6	78·2	113·7	81·3	120·3	178·2
Sugar beet												
tops	37·7	75·9	44·0	70·4	38·1	71·3	37·3	75·3	109·6	77·7	106·3	152·6
roots	20·6	30·0	19·3	26·1	21·5	36·1	21·6	44·1	56·8	44·9	63·7	79·4
Rotation ley	135·3	124·0	122·1	110·7	218·3	190·0	204·2	202·6	173·4	206·9	199·9	192·5
Long ley	67·4	125·5	52·8	141·7	96·7	137·4	94·9	143·4	213·3	97·7	158·7	234·8
Phosphorus												
Barley												
grain	5·1	7·3	5·2	6·3	5·1	9·2	5·5	10·6	11·6	8·1	12·3	13·1
straw	0·7	1·0	1·0	0·9	0·8	1·3	1·1	1·7	2·3	1·3	2·8	4·6
Oats												
grain	6·8	10·3	7·0	11·4	6·7	10·9	6·9	11·4	13·3	8·3	12·3	14·5
straw	2·4	1·6	2·8	2·0	2·3	2·1	3·3	3·1	3·1	3·7	4·4	5·2
Potatoes												
total tubers	4·0	4·6	4·5	4·6	7·6	9·2	8·6	10·3	11·8	14·3	18·2	21·2
Sugar beet												
tops	4·9	7·5	6·0	8·7	4·6	7·2	5·4	9·3	10·5	10·1	12·6	16·7
roots	4·1	5·2	4·9	5·1	5·5	7·1	5·8	8·6	8·9	10·8	13·8	13·8
Rotation ley	15·4	15·5	17·6	17·7	19·9	20·2	21·9	24·0	23·4	21·7	25·6	27·5
Long ley	10·5	13·2	10·3	18·3	10·9	15·8	14·7	20·8	21·7	16·1	24·7	30·2
Potassium												
Barley												
grain	9·9	14·7	9·8	12·3	9·9	17·8	10·6	19·6	20·9	14·4	21·9	24·2
straw	6·4	7·8	7·1	6·5	13·6	26·2	14·0	28·6	41·2	19·6	41·8	70·5
Oats												
grain	11·0	16·8	10·9	17·9	10·5	18·6	10·6	18·4	21·3	14·7	22·3	23·5
straw	21·4	23·9	22·5	22·1	39·0	67·3	42·9	70·0	82·1	46·8	91·8	117·1
Potatoes												
total tubers	22·8	24·9	24·6	22·5	75·4	98·2	82·1	103·5	120·2	152·0	203·1	245·9
Sugar beet												
tops	45·4	69·7	45·7	50·2	91·4	140·9	88·3	148·6	172·7	149·3	232·8	285·0
roots	20·4	23·7	21·2	19·7	32·3	48·3	31·2	47·3	48·5	55·7	74·2	85·2
Rotation ley	82·7	83·5	88·7	83·2	217·8	215·5	208·2	218·9	214·4	185·5	248·4	261·0
Long ley	59·2	52·6	51·4	53·8	109·7	181·1	123·5	190·5	180·4	147·5	238·7	301·3

APPENDIX TABLE 5

The total amounts (lb/acre) of nitrogen (N), phosphorus (P) and potassium (K) applied for, and removed by, five crops grown in rotation at Woburn, 1965 to 1969

	Treatments											
	O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
Nitrogen												
Added*	0·0	308·0	0·0	308·0	0·0	308·0	0·0	308·0	616·0	592·0	900·0	1208·0
Removed	289·5	385·1	281·7	354·3	385·5	488·1	376·1	524·9	635·0	501·1	636·5	808·4
Difference	−289·5	−77·1	−281·7	−46·3	−385·5	−180·1	−376·1	−216·9	−19·0	+90·9	+263·5	+399·6
Phosphorus												
Added	0·0	0·0	122·2	122·2	0·0	0·0	122·2	122·2	122·2	141·2	263·2	263·2
Removed	43·4	53·0	49·0	56·7	52·5	67·2	58·5	79·0	84·9	78·3	102·0	116·6
Difference	−43·4	−53·0	+73·2	+65·5	−52·5	−67·2	+63·7	+43·2	+37·3	+62·9	+161·2	+146·6
Potassium												
Added	0·0	0·0	0·0	0·0	929·7	929·7	929·7	929·7	929·7	938·8	1868·3	1868·3
Removed	220·0	265·0	230·5	234·4	489·9	632·8	487·9	654·9	721·3	638·0	936·3	1112·4
Difference	−220·0	−265·0	−230·5	−234·4	+439·8	+296·9	+441·8	+274·8	+208·4	+300·8	+932·0	+755·9

* As fertiliser, excludes N added by clover in rotation ley.

APPENDIX TABLE 6

Mean percentages of Mg and mean amounts (lb/acre) of Mg in dry potato tubers and in dry sugar beet tops in the Woburn Reference experiment

(Data are means of two years (1968 and 1969) for potatoes and of four years (1966 to 1969) for sugar beet)

	Main treatments											
	O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
% Mg in potato tubers												
Without Mg*	0·060	0·056	0·056	0·058	0·098	0·087	0·094	0·085	0·080	0·097	0·099	0·104
With Mg	0·058	0·062	0·062	0·068	0·100	0·087	0·096	0·090	0·090	0·100	0·100	0·114
Mg (lb/acre) in potato tubers												
Without Mg*	1·4	1·2	1·0	1·2	3·2	4·2	4·0	4·2	5·6	7·4	9·4	12·4
With Mg	1·2	1·4	1·4	1·4	4·4	6·3	4·4	6·6	7·4	8·5	11·0	13·8
% Mg in sugar-beet tops												
Without Mg*	0·226	0·262	0·274	0·267	0·165	0·173	0·158	0·162	0·200	0·320	0·287	0·272
With Mg	0·268	0·336	0·283	0·323	0·177	0·206	0·164	0·206	0·258	0·279	0·282	0·326
Mg (lb/acre) in sugar-beet tops												
Without Mg*	5·0	9·6	6·7	8·7	3·9	6·4	3·3	5·8	9·9	11·4	14·0	17·8
With Mg	5·8	11·8	6·3	10·6	4·2	8·4	4·0	9·1	12·2	11·5	14·0	20·3

* FYM (D) supplied 38 lb/acre of Mg for potatoes and 40 lb/acre for sugar beet.