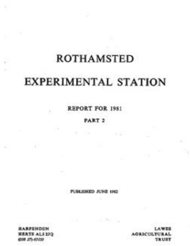
Rothamsted Experimental Station Report for 1981 Part 2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Results from the Woburn Reference Experiment. III. Yields of the crops and recoveries of N, P, K and Mg from manures and soil, 1975–79

F. V. WIDDOWSON, A. PENNY and M. V. HEWITT

Abstract

The experiment, begun in 1960 on sandy-silty loam at Woburn, tested N, P, K and Mg fertilisers alone and with FYM on five arable crops and a long ley. Results from the fourth 5-year cycle (1975–79) and yield and crop uptake over 20 years are summarised. N increased yields greatly, P little and K more than N for sugar beet, potatoes and the clover-grass ley. Yields were largest where both FYM and NPK fertilisers were given. Nutrient balance sheets from 1975–79 showed that removals (kg ha^{-1}) ranged from 171 to 698 of N, 29 to 105 of P and 131 to 1101 of K. The soil supplied (kg ha^{-1}) 39 of N, 10·4 of P and 29 of K per annum in the final 5 years.

Introduction

The experiment was begun in 1960 on the sandy-silty loam (overlying Lower Greensand) of Stackyard Field at Woburn, Beds and continued with no change to the rotation and little change to the manuring until 1979. Its objective was to measure the effects of N, P and K fertilisers and of farmyard manure (FYM) applied alone and together on yields, crop nutrient uptakes and nutrient balances in the soil. Five arable crops (spring barley, clover-grass ley, potatoes, winter oats and sugar beet) were grown each year and in that sequence, so that during each 5-year cycle of the experiment each crop was grown once in each block. There were also blocks of long ley and soft fruit, The results obtained from 1960 to 1969 (Widdowson & Penny, 1967, 1972; Widdowson, Penny & Williams, 1967; Williams, 1973) and from 1970 to 1974 (Widdowson & Penny, 1979) have already been published and should be read in conjunction with the data given here, which are from the fourth and final 5-year cycle of the experiment. The test of magnesium fertiliser on sugar beet and potatoes, begun in 1967 following the confirmation of Mg deficiency in foliage, was continued.

This paper presents the data briefly and is intended to be used in conjunction with our previous results. However, it includes a crop nutrient balance sheet constructed from the data obtained during the entire 20-year life of the experiment.

Design and measurements

The five arable crops, the long ley and the soft fruit each received all combinations of two amounts (0 *v.* 1) of N, P and K fertilisers in the standard eight-plot factorial combination, and also a double amount of N (N2) with P and K. Farmyard manure (FYM) was also tested alone (Code D), and together with fertilisers supplying either the single or double amount of N (DN1PK and DN2PK). However, the FYM was applied only for potatoes and sugar beet and not for the other three arable crops, which therefore measured its residues; it was applied annually for the long ley and the soft fruit. The arrangement

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of the twelve treatments in each block was restricted by using six rows of a 12×12 Latin Square. Individual plots were small (5·8 m²).

Each year the yields of each crop were measured and samples taken to measure dry matter and N, P and K contents. These values then were used to calculate dry matter yields and the amounts of N, P, K and Mg that the crops removed. These, together with the amounts of N, P, K and Mg added in fertilisers and in FYM were used to construct nutrient balance sheets over each 5-year cycle of the experiment. The amount of each nutrient that each crop removed was used to calculate the apparent efficiency of uptake of the N, P and K in the fertilisers and in the FYM. These uptakes also allowed us to measure the quantities of N, P and K supplied by this soil and to determine whether these changed with time. Additionally, the penultimate leaflets were removed from 20 stems on each half-plot of potatoes in July, to measure Mg concentrations, which also were measured in potato tubers and in sugar-beet tops at harvest.

Experimental method

Appropriate blocks of the arable rotation were dug in autumn after applying FYM for potatoes and sugar beet; it was applied to the long ley and to the fruit in spring. P and K were broadcast during winter and N and Mg in spring. The crop varieties chosen were: barley, Julia (ethirimol dressed); rotation ley, RVP Italian ryegrass and Hungaropoly red clover; potatoes, Pentland Crown; oats, Peniarth; sugar beet, Klein E. The long ley was a composite mixture of grasses and clovers; the strawberries, Cambridge Vigour; blackcurrants, Wellington XXX and gooseberries, Careless.

Manuring. 63 kg P_2O_5 ha^{-1} (27·4 kg P) as triple superphosphate and 251 kg K_2O ha^{-1} (208·5 kg K) as potassium bicarbonate were applied to appropriate plots of each crop in each year. Amounts of N (as ammonium nitrate) differed with crop and were (in kg ha^{-1});

	Spring barley	Rotation ley	Potatoes	Winter oats	Sugar beet	Long ley	Soft fruit
N1	63	31	126	63	126	188	63
N2	126	63	251	126	251	376	126

The N was applied in one dressing for the rotation ley, but was divided into two equal dressings for barley, potatoes, oats and sugar beet and into three for the long ley. Epsom salts ($MgSO_4.7H_2O$) were broadcast (50 kg Mg ha^{-1}) over one half of each sugar-beet and potato plot in spring and to the other half after the crops had been harvested. Thus 100 kg Mg ha^{-1} were applied in each 5-year cycle to every plot in the arable rotation; the same quantity was also given to the long ley and fruit. Basal calcium carbonate was broadcast in autumn 1974 to maintain soil pH at or near 7·0 and basal boron (5 kg ha^{-1}) was sprayed over sugar beet each spring after singling.

Chemical analyses of the crops

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

Phosphorus was measured by AutoAnalysis using the method of Fogg and Wilkinson (1958) after ashing and dissolving in 0·06 N-HCl.

Potassium was measured by Unicam SP.90A after dry ashing and solution in 0·06 N-HCl.

Magnesium was measured by atomic absorption, with strontium as releasing agent using a Unicam SP.90A flame spectrophotometer, after dry ashing and solution in 0·06 N-HCl.

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Yields

Effects of N, P and K fertilisers and FYM. To allow direct comparisons between the abilities of the different crops to obtain nutrients from this soil, and between their relative responsiveness to added nutrients, most yields are presented as dry matter. However, to be able to judge the yields in conventional terms, Appendix Table 1 shows fresh yields of potato tubers and sugar beet roots and tops, the yield of sugar from the sugar beet and the yields of oats and barley grain at 15% moisture content. Though maximum yields were never large, they were largest where both FYM and fertilisers were given. The increases in yield from giving FYM were especially large for potatoes and sugar beet. Appendix Table 2 compares yields of the different crops as dry matter. The FYM and NPK fertilisers together increased yields of potatoes, sugar beet and the rotation ley four-fold and those of oats and barley grain three-fold, though straw yields were increased by more. The largest total dry matter yield (15·21 t ha^{-1}) was obtained from sugar-beet tops plus roots; winter oats grain plus straw (11·38 t ha^{-1}) outyielded spring barley (9·53 t ha^{-1}) and all three crops out-yielded the potatoes (tubers only), the rotation ley and the long ley.

Main effects and interactions of N, P and K fertilisers. The data in Table 1 were obtained in the conventional way by subtracting yields from four of the eight factorial treatments

TABLE 1

Main effects and interactions of N, P and K fertilisers on five arable crops, 1975–79

	Dry matter (t ha^{-1})								Coefficient of variation
	N	P	K	NP	NK	PK	NPK	s.e.	(%)
Oats									
grain	1·45**	0·22	0·01	0·18	0·06	0·04	0·02	±0·150	21·9
straw	1·97**	0·39	0·59*	0·26	0·38	0·20	0·10	±0·180	20·3
Barley									
grain	1·16**	0·03	0·71**	−0·01	0·55**	0·30	0·28	±0·122	19·2
straw	1·53**	0·04	0·57**	0·04	0·46**	0·12	0·16	±0·089	13·7
Potato									
tubers	0·97	0·49	2·79**	0·18	0·82	0·44	0·16	±0·439	44·2
Sugar-beet									
roots	1·69**	−0·36	1·81**	−0·30	1·06*	0·16	0·32	±0·344	28·3
tops	1·55**	−0·15	0·31	−0·09	0·30	0·12	0·23	±0·156	18·5
Rotation									
ley	1·29*	0·53	2·75**	0·08	0·00	0·46	0·22	±0·379	24·7

*, ** Significant at probability level of 1 and 0·1% respectively

(2^3) from the other four. There were highly significant main effects from N on oats, barley and sugar beet, but not on potatoes, which followed the grass-clover rotation ley. The main effects of P were always small and never significant, whilst those of K were large for some part of each crop and especially so for potato tubers and sugar-beet roots. The main effect of K was larger than that of N on the two root crops. The NP interaction was always small and sometimes negative, whereas the NK interaction was mostly positive and significant for barley and for the sugar beet roots. Whilst the PK and the NPK interactions were always positive they never reached significance, though they were sometimes of the same order of magnitude as their standard error.

Responses to N, P and K. Table 2 shows yields of the crops during the period 1975 to 1979 from soil completely unmanured since 1960, and the increases in yield given by N,

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TABLE 2

Responses to N, P and K fertilisers (means for 1975–79)

	Yields without fertiliser or FYM	Increases in the yield of dry matter (t ha^{-1}) from N1 (N1PK−PK)	N2−N1 (N2PK−N1PK)	N2-N1 (in presence of D) (DN2PK−DN1PK)	P (N1PK−N1K)	K (N1PK−N1P)
Barley						
grain	1·34	1·98	0·74	0·45	0·60	1·84
straw	1·20	2·18	1·15	0·97	0·36	1·31
Oats						
grain	1·46	1·70	0·65	1·11	0·45	0·13
straw	1·70	2·71	1·15	1·95	0·95	1·28
Potato tubers	1·66	2·14	0·95	0·97	1·29	4·20
Sugar-beet						
tops	1·67	2·06	1·11	1·17	0·18	0·96
roots	2·40	3·46	0·76	1·06	0·29	3·47
Rotation ley	2·74	1·58	0·21	0·92	1·28	3·42
Long ley	3·57	2·09	1·14	1·38	0·28	1·01

D=FYM was applied at 50 t ha^{-1} for sugar beet and potatoes and at 25 t ha^{-1} for long ley

by P and by K fertilisers on plots given the other two nutrients. Yields of all the crops were increased by the first increment of fertiliser N, but less by the second, which enhanced straw yields more than grain and the yield of sugar-beet tops more than roots. Where FYM also was given the second increment of N still increased yields even though yields then were larger, and it increased yields both of the rotation ley and of the long ley more than where fertilisers were given alone. Presumably this enhanced response to N in the presence of FYM was due to the large amount of additional K that the FYM added (Table 6). By comparison fertiliser P increased yields little, though all the crops responded to it, the largest responses being with oats, potatoes and the rotation ley. Shortage of K limited yields far more than shortage of P and responses to K were as large as or larger than those to N. Potassium was particularly important for potatoes, sugar-beet roots and the rotation ley; for potatoes the K reponse (4·20 t ha^{-1}) was roughly double that for N (2·14 t ha^{-1}).

Responses to farmyard manure. Table 3 shows that without fertilisers, FYM greatly increased the yield of every crop, especially in the year of application, though it very greatly increased yields of the grass-clover rotation ley two years afterwards. The increases in yield from FYM were greatly diminished when NPK fertilisers were also given, but doubling the amount of fertiliser N sometimes enhanced the benefit from the FYM. This happened with both root crops and with the long ley and oats, and may be explained by an interaction between the extra N given as fertiliser and the potassium supplied by the FYM. This implies that 251 kg K_2O ha^{-1} added in fertiliser may have been too little for both sugar beet and potatoes, because the largest yields were obtained where FYM was dug down in autumn and NPK fertilisers were given in spring (Appendix Table 1).

Responses to Mg by potatoes and sugar beet. Appendix Table 3 shows the effects of giving Mg fertiliser to half of each sugar-beet and potato plot. Magnesium increased potato yields most where K, or N and K was given; doubling N diminished its effect. As Mg had been applied after harvesting each root crop to half-plots not given Mg in spring, each year from 1967 onwards, it is surprising that the response to Mg was so large on the

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TABLE 3

The mean increases in yield (t ha^{-1} of dry matter) from FYM (D) tested with and without NPK fertilisers from 1975–79

	Without NPK fertiliser (D−0)	With NPK fertiliser: N at single rate (DN1PK−N1PK)	With NPK fertiliser: N at double rate (DN2PKN−2PK)
Direct effects			
Potato tubers	4·52	1·52	1·54
Sugar-beet			
tops	1·47	0·77	0·83
roots	3·94	2·18	2·48
Long ley	1·96	0·75	0·99
Residual effects (1 year later)			
Barley			
grain	0·87	0·45	0·16
straw	0·84	0·64	0·46
Oats			
grain	0·76	−0·07	0·39
straw	1·19	0·49	1·29
Residual effects (2 years later)			
Rotation ley	3·90	0·60	−1·31

plots given fertiliser. However, the potatoes also responded to Mg on the plots given FYM, which supplied about 40 kg Mg ha^{-1} twice in 5 years (Table 6). Thus these plots received a total of 180 kg Mg ha^{-1}, in each 5-year cycle of the experiment. Yields of sugar-beet roots, though not tops, were also appreciably increased by magnesium fertiliser, with a maximum response of 2·34 t ha^{-1} where N2PK fertilisers were given. FYM diminished the response to magnesium by the sugar-beet roots. Table 4 shows

TABLE 4

Mean effects of Mg fertiliser on the yields of potatoes and sugar beet 1975–79 in the presence and absence of N, P and K fertilisers

Fertiliser tested: N1 Without	N1 With	P Without	P With	K Without	K With
Mean effects of Mg					
Potatoes, total tubers (t ha^{-1}) fresh weight					
0·31	1·06	0·64	0·73	−0·06	1·43
Sugar-beet roots (t ha^{-1}) fresh weight					
0·04	0·48	0·43	0·06	−0·32	0·82
Sugar-beet tops (t ha^{-1}) fresh weight					
0·10	−0·02	−0·31	0·39	−0·17	0·25

how N, P and K fertilisers affected the mean response to magnesium on the eight plots testing them in factorial combination (2^3). For potatoes, both N and K greatly enhanced the response to magnesium, whilst P little affected it. This relationship applied also to sugar-beet roots, but the effect of P on Mg response was inconsistent.

Amounts of N, P, K and Mg applied 1975–79

By fertilisers. The amounts of N, P, K and Mg applied each year have been given previously.

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By FYM. Table 5 shows the percentage of dry matter and of N, P, K and Mg in each batch of FYM (always made by cattle in yards at Rothamsted) and Table 6 the amounts

TABLE 5

Chemical analyses of FYM, 1975–79

Cropping year	Dry matter %	% in dry matter of N	P	K	Mg
1975	22·62	3·51	0·530	3·76	0·310
1976	20·63	3·16	0·429	3·76	0·340
1977	24·50	3·18	0·586	5·00	0·371
1978	25·88	2·88	0·487	4·24	0·336
1979	22·01	2·75	0·467	5·14	0·324
Mean	23·13	3·10	0·500	4·38	0·336

TABLE 6

Annual amounts (kg ha^{-1}) of N, P, K and Mg supplied by 50 t ha^{-1} of FYM 1975–79

Cropping year	N	P	K	Mg
1975	399	60	427	35
1976	327	44	389	35
1977	392	72	615	46
1978	374	63	550	44
1979	304	52	568	36
Mean	359	58	510	39

added by the standard 50 t ha^{-1} dressing. Both the dry matter and the nutrient content varied from year to year, but on average the two dressings of FYM in 5 years supplied amounts of P and K (116 kg P and 1020 kg K ha^{-1}) almost equal to those added in fertilisers over the same period. The magnesium in the FYM enhanced not only the yield, but also the concentration of Mg in the potato and sugar-beet tops (Appendix Table 5).

Amounts of N, P and K removed from the soil by individual crops, 1975–79. Table 7 shows the amounts of nutrient removed from the soil by crops given the other two major

TABLE 7

The mean annual amounts of N, P and K (kg ha^{-1}) removed from the soil by crops given the other two elements as fertiliser 1975–79

	N	P	K
Barley			
grain	20	8·0	8
straw	5	1·1	6
Oats			
grain	22	8·5	14
straw	6	2·1	14
Potato			
tubers	51	8·4	22
Sugar-beet			
tops	29	6·3	23
roots	24	6·7	15
Rotation ley	123*	11·0	41
Mean	39**	10·4	29
Long ley	102*	14·4	53

* Includes contribution by clover
** Excluding clover ley

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elements. The mean annual amounts of N, obtained from the soil alone by four arable crops (excluding the rotation ley) and of P and K by all five arable crops were only 39·3, 10·4 and 28·6 kg ha^{-1} respectively, thus explaining the large responses to N and to K shown in Table 1. The ability of this soil to supply N where none was given declined with time, the supply of P changed little until the final 5-year cycle, whilst that of K fell dramatically from 120 kg K ha^{-1} in 1960 and in 1961 to 62 kg K ha^{-1} in 1964 and finally to only 28 kg K ha^{-1} (Table 8).

TABLE 8

Mean amounts of N, P and K supplied by the soil (kg ha^{-1}) in each 5-year cycle of the experiment 1960–79

	1960–64	1965–69	1970–74	1975–79
N*	59	49	43	39
P	14	14	14	10
K	89	53	37	29

* Values for N exclude grass-clover rotation ley

The values for the individual crops (Table 7) show that the potatoes (which followed the clover-grass ley) obtained almost twice as much N from this soil as did the two cereal crops. However, the sugar beet (which followed the barley) obtained as much N from the soil as the potatoes, presumably because the deep tap-roots of the sugar beet were able to take up NO_3-N in the subsoil. The rotation ley apparently fixed more than 100 kg N ha^{-1}, for roughly this amount was removed in the foliage. No proper estimate can be made of the amount of N fixed by the clover nodules that remained in the soil but the non-significant effect of fertiliser N on potato yields suggests that an appreciable part of the 51 kg ha^{-1} shown in Table 7 came from the clover. Removal of P differed little with crop, whilst that of K varied appreciably. Spring barley obtained less K from this soil than winter oats, and sugar beet more than any other crop (48 kg K ha^{-1}).

Recovery of N, P and K from the fertilisers. Table 9 gives the apparent recoveries by the crops of N, P and K from fertilisers, calculated by subtracting the amounts of each

TABLE 9

The apparent (%) recoveries of N, P and K from fertilisers by five arable crops and a long ley, 1975–79

	Percentage recovery of			
Test crop	N1	N2	P	K
Barley (grain and straw)	60	56	12	22
Oats (grain and straw)	62	58	7	33
Potato tubers	32	21	8	48
Sugar-beet (tops and roots)	54	54	14	66
Rotation ley	—	—	16	60
Long ley	—	—	11	43
Mean (arable crops)	52	47	11	46

nutrient in crops grown without it, but with the other two, from amounts in crops given all three, and then expressing this difference as a percentage of that given as fertiliser.

The recovery of N by the two leys cannot be given because the plots given P and K, but not N, contained a large proportion of clover, which fixed 80–100 kg N ha^{-1} per annum (Appendix Table 4). The recoveries of fertiliser N by oats and by barley were similar and both recovered almost the same proportion of the double as of the single dressing of N (57 and 61% respectively). Sugar beet recovered more of the applied N

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than the potatoes appeared to do, but as we did not harvest the potato tops, we do not know the total amount of N recovered by the potatoes. No more than 16% of the fertiliser P was recovered by any crop, with a mean value of only 11%. By contrast the crops recovered fertiliser K far more completely. Sugar beet apparently recovered 66% of the K applied for it, and the clover-grass rotation ley and the potatoes 60 and 48% respectively. The two cereals recovered far less, presumably because much of the K in the leaves and stems returned to the soil before harvest. Mean recovery of K was as large as that of N.

Recovery of N, P and K from FYM. In this experiment FYM was applied at 50 t ha^{-1} for potatoes and sugar beet, but none was given for the other three arable crops; the long ley was given 25 t ha^{-1} annually. The potatoes and the sugar beet recovered proportionally far less of the N and K applied in the FYM (Table 10) than they did from fertilisers

TABLE 10

The apparent recoveries (%) of the N, P and K in FYM (D) by five arable crops and a long ley, 1975–79

	FYM applied					
	Alone (D−0)			With N2PK fertilisers (DN2PK−N2PK)		
% recovery of	N	P	K	N	P	K
FYM newly applied for						
Potatoes (tubers)	16	14	23	8	6	17
Sugar-beet (roots and tops)	16	17	24	8	11	24
Long ley	—	11	16	—	—	—
FYM applied for root crops 1 year ago						
Barley (grain and straw)	4	6	4	4	13	10
Oats (grain and straw)	4	7	10	3	10	14
FYM applied for potatoes 2 years ago						
Rotation ley	22	16	23	2	7	7

(Table 9), but rather more of the P. However, even though more N was added in the FYM than in the fertilisers, yields from FYM and N1PK fertilisers were similar (Appendix Table 1) and total uptakes, especially of K, also were similar (Appendix Table 4). Thus, although much of 359 kg N ha^{-1} applied in the FYM was apparently leached from the soil during winter, the K added in the two dressings of FYM was as effective as the K in fertiliser given annually, when judged by recovery during the 5-year arable rotation. Applying fertilisers with the FYM diminished the efficiency of uptake by the root crops of the N and P in the FYM, but hardly changed that of K. The oats and barley that followed the root crops recovered little of the N added in the FYM and this amount was not diminished by also giving N2PK fertilisers. However, the residues of the P and K from FYM were used more efficiently by the two cereal crops given N2PK fertilisers than by those that were not (Table 10).

Amounts of N, P and K taken up by individual crops. These are shown in Appendix Table 4. The amounts of nitrogen removed by barley and by oats ranged from 24 to 111 kg ha^{-1}, the largest values occurring on plots given both FYM and fertilisers, which also gave the largest yields (Appendix Table 1). Similar ranges in uptake occurred with sugar beet and potatoes, though the amounts removed were larger, because the ranges in yield were larger. Sugar-beet tops removed far more N than the roots and, with N2PK fertilisers, more than potato tubers. The amounts of P removed by the crops varied by a factor of five, with sugar beet and the long ley removing most (26·9 and 26·0 kg ha^{-1}

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TABLE 11

The total amounts (kg ha^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) applied for and removed by five crops grown in rotation at Woburn, 1975–79

	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
Nitrogen												
Added*	0	408	0	408	0	408	0	408	816	718	1126	1534
Removed	171	295	181	277	262	406	280	463	605	392	557	698
Difference	−171	+113	−181	+131	−262	+2	−280	−55	+211	+326	+569	+836
Phosphorous												
Added	0	0	137	137	0	0	137	137	137	116	253	253
Removed	29	40	34	46	36	52	45	68	78	64	90	105
Difference	−29	−40	+103	+91	−36	−52	+92	+69	+59	+52	+163	+148
Potassium												
Added	0	0	0	0	1042	1042	1042	1042	1042	1020	2062	2062
Removed	131	171	134	143	372	557	406	620	734	560	888	1101
Difference	−131	−171	−134	−143	+670	+485	+636	+422	+308	+460	+1174	+961

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

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year^{-1} respectively). Maximum uptakes on the N2PK plots corresponded to 80% of the P applied. Because shortage of soil K greatly limited yields, uptakes of K were large only where either fertiliser K or FYM was given, then they were larger than the corresponding uptakes of N. Sugar-beet roots and tops together removed a maximum of 349, the long ley more than 250 and the potato tubers more than 210 kg K ha^{-1}.

Amounts of N, P and K added to and removed from the soil in 5 years. Table 11 shows the total amounts of each of the nutrients added by FYM and by fertilisers and the amounts removed by the five arable crops in one cycle of the experiment (1975–79). The nitrogen balance sheet takes no account of the fact that a large part of the total N removed by the five arable crops was in the clover-grass rotation ley (47–127 kg ha^{-1} annually, Appendix Table 4). As this soil provided only 39 kg N ha^{-1} per annum to the other four arable crops in the rotation (Table 8) and the clover-grass ley given P and K but no N removed 123 kg N ha^{-1} it appears that the clover nodules fixed at least 84 kg N ha^{-1}. This is far less than the 160 kg N ha^{-1} recorded in the previous 5-year cycle of the experiment, but may simply reflect the effect of seasons less favourable for the growth and development of the clover plants (the variety and cultural management were unchanged). Thus the negative nitrogen balance shown on plots given PK fertilisers alone should be diminished by more than 84 kg N ha^{-1}; also our data take no account of the N dug down in the clover roots and nodules. Wherever FYM was given there were large apparent balances of N remaining in the soil. However, the value of these N residues was small, whether judged by crop response (Table 3) or by N uptakes (Table 10) and so either this N was lost by leaching during winter or remained in the soil in a form unavailable to the crops. Balances of P and K are less difficult to interpret. Those of P were always positive where 27 kg P ha^{-1} was given annually even for crops given N2PK fertilisers, though this amount of P was far less than usually would be given. By contrast, the amount of K that we applied each year (208·5 kg K ha^{-1} = 1042 kg ha^{-1} in 5 years) was far more than would usually be recommended. Crops given the N2PK fertiliser dressing removed a total of 734 kg K ha^{-1} in 5 years, of which 145 kg ha^{-1} was provided by the soil, leaving the balance (589 kg ha^{-1}) presumably to be provided by fertiliser. This represents an apparent recovery of 56% of the fertiliser given, almost identical with that obtained in the previous 5 years of the experiment (57%), but larger than that shown in Table 9 for crops given N1PK fertilisers. The data in Table 11 show that K uptakes by the larger crops, grown where both FYM and NPK fertilisers were given, were roughly 30% larger than with NPK alone. However, because the FYM was so rich in K (Table 6) it was then evidently no longer necessary to apply so much fertiliser K. The use of FYM should therefore have allowed considerable economy in the use of fertiliser K, had the experimental design allowed us to do so, and farmers with access to FYM should consider K balances in their farming systems carefully, to determine whether they can make savings.

Mg in potato leaves and tubers and in sugar-beet tops. Appendix Table 5 shows that % Mg in potato leaves was diminished by K, either in fertiliser or in FYM, and was increased only a little by applying Mg fertiliser to the seedbed. Table 12 shows how the N, P and K fertilisers changed % Mg in the potato leaves and tubers. Evidently the concentration in the leaves was a far better guide to Mg availability in the soil than % Mg in the tubers, which was diminished by giving K fertiliser, but not changed at all by giving Mg fertiliser.

The concentration of Mg in sugar-beet tops was decreased by the K in fertilisers and in FYM just as it was in potato leaves (Appendix Table 5), but giving Mg fertiliser did not always increase % Mg in the tops, in particular where FYM was given. Table 11

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TABLE 12

Mean percentages of Mg in potato leaves in July, in the mature potato tubers and in mature sugar-beet tops, together with mean uptakes, 1975–79

	N Without	N With	P Without	P With	K Without	K With
			% Mg in potato leaves			
Without Mg	0·35	0·34	0·34	0·36	0·50	0·20
With Mg	0·40	0·40	0·39	0·41	0·57	0·23
			% Mg in potato tubers			
Without Mg	0·07	0·07	0·07	0·07	0·06	0·08
With Mg	0·07	0·08	0·07	0·08	0·06	0·08
			Mg (kg ha^{-1}) in potato tubers			
Without Mg	2·0	2·7	2·2	2·6	1·1	3·7
With Mg	2·2	3·0	2·4	2·9	1·1	4·1
			% Mg in sugar-beet tops			
Without Mg	0·28	0·37	0·32	0·34	0·42	0·24
With Mg	0·29	0·40	0·35	0·35	0·45	0·25
			Mg (kg ha^{-1}) in sugar-beet tops			
Without Mg	4·7	12·0	8·5	8·2	10·0	6·6
With Mg	4·9	12·5	8·8	8·5	10·6	6·8

shows that the increases in Mg concentration from giving N and the decreases from giving K were far larger than the increases from Mg fertiliser. However, because Mg fertiliser increased yields, it also increased Mg uptakes.

Practical implications

The value of FYM on a sandy soil. The fact, previously noted, that the combination of FYM and NPK fertilisers produced the largest yield of all six crops was substantiated in the final 5-year cycle of the experiment (Table 13). Thus, for sugar beet and potatoes,

TABLE 13

Mean yields (t ha^{-1}) of crops grown without and with FYM, 1975–79

	Potato tubers(1)		Winter oats grain(2)		Sugar beet roots(1)		Spring barley grain(2)		Clover-grass ley(3)		Long ley(3)	
FYM (D)	—	D	—	D	—	D	—	D	—	D	—	D
Fertilisers												
None	6·6	25·2	1·72	2·61	10·4	26·4	1·58	2·60	2·74	6·64	3·57	5·53
N1PK	25·0	34·3	3·71	3·62	25·9	35·3	4·14	4·67	7·52	8·12	6·88	7·63
N2PK	28·1	37·9	4·47	4·93	30·6	41·0	5·01	5·20	7·73	9·04	8·02	9·01

(1) = fresh weight; (2) = weight at 15% moisture content; (3) = dry weight

the increase in yield from the double dose of N (N2PK) was as large or larger where FYM was applied, than where it was not. The combined effect of the two sources of nutrients was to increase yields of potato tubers and sugar-beet roots by a third, as compared with yields from N2PK fertilisers alone. The residues from the FYM dressings given for potatoes and sugar beet also enhanced the yields of the following crops, presumably because they improved not only the nutrient content of the soil, but also its structure and permeability (Williams, 1973). After 20 years, soil on plots given FYM twice in each 5-year cycle of the experiment was darker in colour, less dense and more friable, than soil on plots given NPK fertilisers alone. It is difficult to avoid the conclusion that on poorly structured soils like this one, organic manures are of real value, even where, as

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here, short duration clover-grass leys are grown, partly with the intention of maintaining soil structure and organic matter content.

The effects of NPK fertilisers alone and with FYM through time. Twenty years is not long in the history of a soil. However, the relationship between the smaller yields with NPK fertilisers alone and the larger yields with NPK and FYM shown in the first cycle of the experiment (1960–64) was maintained throughout its life (Table 14). The benefit given by FYM in terms of dry matter was greater in the second cropping cycle than in the first, but subsequently remained unchanged, both in absolute and in relative terms. The percentage gain in dry matter yield from FYM on plots also given NPK fertilisers was remarkably consistent (Table 14), with little change, either with time or with single

TABLE 14

Mean annual production of dry matter (t ha^{-1}) from five arable crops, in each 5-year cycle of the experiment, where NPK fertilisers were given alone and where FYM also was given, together with the % increases in yield given by the FYM

Years	1960–64	1965–69	1970–74	1975–79	Mean
Without FYM					
N1PK	8·22	8·76	8·79	7·71	8·37
N2PK	9·07	10·61	10·08	9·05	9·70
With FYM					
N1PK	9·27	10·35	10·37	9·02	9·75
N2PK	10·53	12·49	11·89	10·74	11·41
% increase in yield from FYM with:					
N1PK	13	18	18	17	16
N2PK	16	18	18	19	18

and double amounts of fertiliser N (N1PK *v.* N2PK). FYM consistently increased mean annual dry matter production by 18%, over and above that obtained with N1PK or N2PK fertilisers alone. Since the additional response to N2 was far smaller than the response to N1 where fertilisers alone were given, we cannot assume that the nitrogen fertiliser dressings that we chose to give were too small. Table 1 shows that the response to N2 was larger where FYM was given than where it was not on four of the six crops, suggesting that some nutrient other than N was limiting yield, possibly K. However, we applied far more K for our crops than currently is recommended and our balance sheets showed that we always applied more K than the crops removed. We also applied magnesium basally twice in 5 years. This suggests that the FYM either enhanced the availability of nutrients already in this soil and of those in fertilisers (we measured increased uptakes of P where FYM was given, Tables 9 and 10) or so improved the soil structure that it allowed roots to make better use of available moisture. Certainly growth was much superior where both FYM and fertilisers were given, than where either was given alone. Clearly, an effect as large as this is important for evidently yields on soils like this, which initially contained only 0·68% C, will be limited unless organic manures are used. This experiment cannot fully explain the benefits that the FYM gave, but a larger and more comprehensive experiment on the same soil (Mattingly, 1974) has demonstrated that organic amendments have a large beneficial effect, for a range of arable crops, that cannot be explained by their crop nutrient contents alone.

Long-term nutrient balance sheets. Because both yield and nutrient content were measured each year for 20 years we have been able to construct a nutrient balance sheet averaged over the four complete 5-year cycles of the experiment (Appendix Table 6). This shows with considerable accuracy not only the amounts of N, P and K that the adequately manured crops removed and hence by inference required, but also the amounts of N, P and K that the crops were able to obtain from the soil alone. Thus the

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mean annual contributions (kg ha^{-1}) were 80 of N from soil and the activity of clover nodules together and 13·6 of P and 51·6 of K from soil alone. These values are larger than those obtained in the final 5-year cycle of the experiment (Table 8) and that for N is misleading, because it includes the contribution made by the clover-grass ley. However, the values given for P and K are probably the best estimates that we can make of soil supply in the absence of fertiliser residues.

Summary

The experiment was begun in 1960 on the sandy-silty loam of Stackyard Field at Woburn to test N, P, K and Mg fertilisers alone and with FYM on five arable crops grown in rotation and on a long ley and soft fruit. This paper gives results from the fourth and final 5-year cycle (1975–79) and summarises some yield and crop uptake data over the whole 20 years.

In this final cycle N continued greatly to increase yields of all crops except the clover-grass ley. P increased yields more than previously, but only little compared with K, which greatly enhanced yields of all 6 crops, but especially sugar beet, potatoes and the clover-grass ley, for all of which the effect of K was greater than that of N.

FYM was tested alone and with N1PK and N2PK fertilisers for potatoes, sugar beet and the long ley; the other crops valued its residues. Yields of all crops were largest where both FYM and NPK fertilisers were given and the effect of FYM was not diminished by doubling fertiliser N. Over the 20 years FYM increased mean yields by 16% with N1PK and by 18% with N2PK fertilisers.

Nutrient balance sheets for 1975–79 and for all 20 years showed that during each 5 years fertiliser K (1042 kg ha^{-1}) and the K applied in the FYM (1020 kg) were almost the same, as were amounts of P (137 *v.* 116 kg P ha^{-1} respectively). The total amounts of nutrients removed (in kg ha^{-1}) by the five crops from 1975–79, ranged from 171 to 698 of N, 29 to 105 of P and 131 to 1101 of K, the largest uptakes being by the largest crops.

The experiment also measured the mean annual amounts of N, P and K supplied by the soil alone. These were (in kg ha^{-1}) 39 of N, 10·4 of P and 29 of K in the final 5 years and 48 of N, 13·6 of P and 52 of K over 20 years.

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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, 1975–79

	Treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
	Fresh produce (t ha^{-1})											
Potato tubers*	6·64	7·37	6·74	7·76	13·44	19·71	16·53	24·99	28·14	25·18	34·29	37·91
Sugar-beet roots*	10·39	15·24	9·54	12·51	13·26	24·97	12·24	25·94	30·65	26·38	35·26	41·04
Sugar-beet tops*	7·96	16·54	8·27	14·11	8·44	18·66	8·54	20·57	28·98	17·80	26·35	35·98
	Grain (t ha^{-1}) at 15% moisture content											
Barley	1·58	2·64	1·61	1·98	1·74	3·44	1·81	4·14	5·01	2·60	4·67	5·20
Oats	1·72	3·16	1·74	3·55	1·64	3·18	1·71	3·71	4·47	2·61	3·62	4·93
	Sugar (kg ha^{-1})											
Sugar beet*	1631	2393	1486	1911	2180	4234	1975	4442	4974	4526	6060	6768
	Gooseberries, blackcurrants (kg per bush) and strawberries (kg per seven plants)											
Gooseberries	1·30	2·21	3·69	2·43	2·52	3·45	2·66	5·28	3·89	4·76	5·31	4·63
Blackcurrants†	2·40	2·11	2·47	3·25	3·08	3·18	3·42	4·75	3·52	3·10	3·45	5·32
Strawberries	0·70	0·74	0·89	1·40	0·95	1·29	1·31	1·30	1·07	1·27	1·11	0·57

* Averaged over without and with Mg on each treatment for all years (1975–79)
† Mean of 4 years (crop failure in 1977)

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APPENDIX TABLE 2

Mean yields of dry matter (t ha^{-1}) from combinations of N, P and K fertilisers and FYM (D) tested on five arable crops and a long ley in the Woburn Reference experiment, 1975–79

	Treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
Potatoes												
total tubers*	1·66	1·80	1·69	1·87	3·35	4·78	3·93	6·07	7·02	6·18	7·59	8·56
Sugar-beet												
tops*	1·67	3·17	1·67	2·78	1·78	3·56	1·68	3·74	4·85	3·14	4·51	5·68
roots*	2·40	3·51	2·20	2·82	3·11	6·00	2·83	6·29	7·05	6·34	8·47	9·53
Barley												
grain	1·34	2·24	1·37	1·68	1·48	2·92	1·54	3·52	4·26	2·21	3·97	4·42
straw	1·20	2·40	1·24	2·19	1·36	3·14	1·32	3·50	4·65	2·04	4·14	5·11
Oats												
grain	1·46	2·69	1·48	3·02	1·39	2·70	1·45	3·15	3·80	2·22	3·08	4·19
straw	1·70	3·13	1·74	3·47	1·81	3·80	2·04	4·75	5·90	2·89	5·24	7·19
Rotation ley	2·74	4·18	2·95	4·10	5·25	6·24	5·94	7·52	7·73	6·64	8·12	9·04
Total in 5 years	14·17	23·12	14·34	21·93	19·53	33·14	20·73	38·54	45·26	31·66	45·12	53·72
Long ley	3·57	5·78	2·89	5·87	4·75	6·60	4·79	6·88	8·02	5·53	7·63	9·01

* Averaged over without and with Mg on each treament for all years (1975–79)

APPENDIX TABLE 3

Mean yields of potatoes and of sugar beet without magnesium and the increases from applying magnesium in the Woburn Reference experiment, 1975–79

	Main treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
	Potatoes, total tubers (t ha^{-1}) fresh weight											
Yields without Mg	7·11	7·15	6·74	7·63	12·97	18·65	15·91	24·27	28·15	24·98	33·90	37·67
Increases from Mg	−0·93	0·44	−0·01	0·26	0·94	2·11	1·23	1·44	−0·02	0·41	0·78	0·48
	Sugar-beet roots (t ha^{-1}) fresh weight											
Yields without Mg	11·09	14·97	9·59	12·67	12·31	24·64	12·41	25·42	29·48	27·29	34·94	40·98
Increases from Mg	−1·40	0·54	−0·11	−0·33	1·90	0·68	−0·35	1·04	2·34	−1·82	0·64	0·12
	Sugar-beet tops (t ha^{-1}) fresh weight											
Yields without Mg	8·20	16·88	7·93	14·21	8·41	18·73	8·48	20·09	29·46	17·09	26·04	38·20
Increases from Mg	−0·48	−0·69	0·68	−0·20	0·06	−0·14	0·13	0·96	−0·96	1·43	0·61	−4·44

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APPENDIX TABLE 4

Mean annual amounts (kg ha^{-1}) 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) in the Woburn Reference experiment, 1975–79

	Treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
						Nitrogen						
Barley												
grain	18·7	38·5	19·2	29·3	20·3	43·7	20·4	50·7	73·2	30·9	60·2	81·4
straw	4·9	13·0	5·4	13·8	4·8	12·1	4·7	12·3	21·6	7·1	15·3	28·4
Oats												
grain	23·1	45·0	24·4	48·2	20·9	41·7	22·2	51·0	71·6	34·8	51·9	76·6
straw	5·2	11·1	5·7	12·4	5·8	12·8	5·9	16·2	29·1	8·8	22·4	35·1
Potatoes												
total tubers	22·5	31·2	23·0	34·0	43·5	67·9	50·6	90·4	104·1	78·2	117·2	133·2
Sugar beet												
tops	28·8	70·2	30·4	68·5	29·7	70·8	28·9	74·0	117·7	58·4	92·9	134·0
roots	18·1	29·4	20·2	23·4	28·2	52·4	24·1	46·4	70·8	46·1	74·3	84·5
Rotation ley	49·8	56·8	52·8	47·2	109·2	104·6	122·8	121·8	116·7	127·2	123·1	124·8
Long ley	72·7	102·8	56·5	100·9	100·1	106·3	102·2	114·3	161·5	100·3	122·3	182·3
						Phosphorus						
Barley												
grain	4·7	6·8	5·0	5·4	5·4	8·0	5·8	10·9	11·8	7·5	14·1	16·0
straw	1·0	1·2	1·4	1·6	1·0	1·1	1·4	1·6	2·0	1·6	2·8	5·6
Oats												
grain	5·1	8·2	5·5	10·5	5·1	8·5	5·2	10·2	13·2	7·9	11·2	15·8
straw	1·7	1·1	2·4	2·3	1·8	2·1	3·0	2·4	3·2	3·0	5·0	6·1
Potatoes												
total tubers	4·0	4·3	4·1	4·7	6·4	8·4	8·5	10·5	11·1	12·3	15·3	14·6
Sugar beet												
tops	3·5	6·7	4·8	8·3	3·3	6·3	4·3	9·1	11·9	7·9	11·7	14·3
roots	2·8	4·1	3·0	3·9	3·4	6·7	3·7	7·8	8·7	8·2	10·9	12·6
Rotation ley	5·9	8·1	7·9	9·4	9·7	11·0	13·5	15·5	15·9	15·1	18·9	19·8
Long ley	9·2	14·4	8·1	16·6	11·6	14·4	13·2	17·1	21·2	15·7	22·9	26·0
						Potassium						
Barley												
grain	7·2	10·7	7·8	8·5	8·8	14·2	9·2	17·9	21·4	12·3	21·5	24·9
straw	7·3	7·3	8·5	5·5	16·9	39·0	16·3	41·1	58·0	24·9	67·8	106·1
Oats												
grain	7·6	12·3	7·5	14·2	7·3	14·1	7·3	16·4	20·2	11·7	16·3	22·6
straw	13·8	16·0	13·9	13·7	39·5	68·5	43·8	80·8	119·1	61·0	126·6	189·8
Potatoes												
total tubers	21·8	22·8	23·0	22·5	73·3	99·8	90·3	121·8	129·8	137·0	190·4	214·8
Sugar beet												
tops	25·4	36·5	22·5	23·0	62·0	133·4	57·8	131·2	172·5	116·5	203·8	262·9
roots	14·8	20·6	13·3	14·8	23·8	45·8	23·0	43·5	53·1	47·8	66·3	86·0
Rotation ley	32·8	44·4	37·2	41·0	140·8	142·4	158·4	167·3	159·9	148·6	195·3	193·6
Long ley	59·5	56·2	45·7	52·9	108·0	144·8	113·3	143·5	168·0	141·1	208·9	250·7

APPENDIX TABLE 5

The mean percentages of magnesium and mean amounts (kg ha^{-1}) of magnesium in potato leaves, dry potato tubers, and dry sugar-beet tops, in the Woburn Reference experiment, 1975–79

	Main treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
	% Mg in leaves in July (1975–79)											
Potatoes												
Without Mg	0·51	0·44	0·52	0·51	0·19	0·20	0·19	0·22	0·27	0·26	0·24	0·28
With Mg	0·59	0·50	0·61	0·59	0·20	0·26	0·20	0·25	0·31	0·28	0·27	0·27
	% Mg in tubers											
Without Mg	0·06	0·06	0·06	0·06	0·08	0·08	0·09	0·08	0·08	0·09	0·09	0·09
With Mg	0·06	0·06	0·06	0·07	0·08	0·08	0·09	0·09	0·08	0·09	0·09	0·09
	Mg (kg ha^{-1}) in tubers											
Without Mg	1·1	1·1	1·1	1·1	2·6	3·8	3·4	4·9	5·8	5·9	6·9	8·2
With Mg	1·0	1·2	1·1	1·2	2·9	4·4	3·8	5·4	5·8	5·8	7·8	8·2
	% Mg in tops											
Sugar beet												
Without Mg	0·37	0·45	0·36	0·48	0·20	0·27	0·21	0·29	0·30	0·31	0·28	0·32
With Mg	0·36	0·55	0·37	0·51	0·20	0·28	0·23	0·28	0·37	0·29	0·27	0·30
	Mg (kg ha^{-1}) in tops											
Without Mg	6·3	14·8	5·6	13·4	3·5	9·3	3·4	10·3	14·2	9·1	12·4	19·2
With Mg	5·8	16·5	6·3	13·7	3·6	9·5	3·8	10·3	17·7	9·4	12·3	16·1

APPENDIX TABLE 6

The mean amounts (kg ha^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) applied for and removed by five arable crops during four 5-year periods of the experiment, 1960–79

	Main treatments											
	0	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	N1PKD	N2PKD
Nitrogen												
Added	0	369	0	369	0	369	0	369	738	699	1068	1437
Removed	301	417	296	396	391	523	402	567	700	508	682	850
Difference	−301	−48	−296	−28	−391	−154	−402	−198	+38	+191	+386	+587
Phosphorus												
Added	0	0	137	137	0	0	137	137	137	174	312	312
Removed	44	55	49	60	52	68	60	81	88	78	105	118
Difference	−44	−55	+88	+77	−52	−68	+77	+56	+49	+96	+207	+194
Potassium												
Added	0	0	0	0	964	964	964	964	964	960	1924	1924
Removed	239	281	242	258	485	638	505	681	757	634	952	1144
Difference	−239	−281	−242	−258	+479	+326	+459	+283	+207	+326	+972	+780

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