ROTHAMSTED RESEARCH

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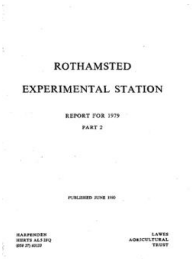

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Results from the Rothamsted Reference Experiment II. Yields of the Crops and Recoveries of N, P and K from Manures and Soil, 1971-75

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Results from the Rothamsted Reference Experiment II. Yields of the crops and recoveries of N, P and K from manures and soil, 1971–75

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Abstract

Results are given from the fourth 5-year cycle of an experiment begun in 1956 testing N, P and K fertilisers and FYM on five arable crops and permanent grass. N increased yields of all crops but those of kale and permanent grass the most. P increased yields of the arable crops, but not the permanent grass; largest increases were with potatoes, the clover–grass ley and kale. K increased the yields of all crops, but was particularly important for wheat, the clover–grass ley and potatoes, which responded three times as much to K as to N. Shortage of K limited yields more than N on this soil.

Farmyard manure was applied alone and with NPK fertilisers. The response by potatoes to FYM was outstanding. By contrast, yields of wheat grain were diminished when fertiliser N was also applied.

Nutrient balances showed that FYM supplied 1008 kg K ha^{-1} and 128 kg P ha^{-1}. Amounts of P removed by the crops were always less than those given, so sizeable balances remained in the soil. K balances were proportionally smaller, though four times as much K as P was given. Crops given N2PK fertiliser removed 40% of the P and 67% of the K given.

P and K balances were larger where both FYM and fertilisers were used although the larger crops removed more P and K. Total amounts (kg ha^{-1}) of N, P and K removed by the arable crops from 1971–1975, ranged from 270 to 840 of N, 37 to 132 of P and 160 to 1200 of K. The largest uptakes and the largest crops were where both FYM and fertilisers were applied.

Amounts of N, P and K supplied by this soil were 65, 9·4 and 34 kg ha^{-1} respectively.

The experiment was begun in spring 1956 on a clay-loam overlying Clay-with-flints (Batcombe series) in Great Field IV at Rothamsted. Its purpose was to measure the long-term effects of N, P and K fertilisers and of farmyard manure (FYM), applied both alone and with fertilisers, on growth and nutrient content of five arable crops and of permanent grass using very small plots (5·2 m^2).

This paper is intended to be read in conjunction with our earlier papers (Widdowson & Penny, 1973; Williams, 1973), and so gives only a brief and factual account of results from 1971 to 1975; thus in total, results for four 5-year cycles have now been published.

Design and measurements

We continued with the cropping sequence: winter wheat, kale, spring barley, clover-grass ley, potatoes, and each crop occurred each year. An adjacent strip of the original permanent pasture was also included in the experiment. Each crop was given all combinations of two amounts (0 and 1) of N, P and K in the standard eight-plot factorial design, and also a double amount of N (N2) with P and K. FYM was tested alone (Code D) and with fertilisers, supplying both single and double amounts of N (DN1PK and DN2PK). The treatments were allocated to five rows of a 12 × 12 Latin Square. Each

year the yields, dry matter and N, P and K contents of each crop were measured. From these values the amounts of N, P and K removed by the crops were calculated and used to construct a nutrient balance sheet over the 5-year cycle and to calculate the apparent recovery of the nutrients in FYM and in fertilisers.

Experimental method

The FYM was dug down each autumn for kale and for potatoes, but spread in spring over the permanent grass. P and K fertilisers were broadcast during winter and N in spring. The crop varieties were: barley Deba Abed, 1971–74, Maris Mink, 1975; rotation ley, Dorset Marl red clover 1971–72, Hungaropoly red clover 1973–75 plus RVP Italian ryegrass; potatoes, King Edward; winter wheat, Maris Nimrod; kale, Thousand-headed.

Manuring. 63 kg P_2O_5 ha^{-1} (27·4 kg P) as single superphosphate and 251 kg K_2O ha^{-1} (208·5 kg K) as muriate of potash were applied to each crop. Amounts of N (as 'Nitro-Chalk, 25') differed with crop and were (in kg ha^{-1}):

	Spring barley	Rotation ley	Potatoes	Winter wheat	Kale	Permanent grass
N1	57	19	75	75	126	126
N2	113	38	150	150	252	252

The N was applied as one dose for all arable crops, but one third was given to each of three cuttings of permanent grass. Fifty kg Mg ha^{-1} was applied after each potato crop, and basal calcium carbonate in 1971 to maintain soil pH at or near 7·0.

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 was determined by Technicon AutoAnalyzer using the method of Fogg and Wilkinson (1958), after ashing and dissolving in 0·06 N-HCl.

Potassium was determined by Unicam SP90A after dry ashing and solution in 0·06 N-HCl.

Yields

Yields of the different crops in Appendix Table 1 are shown as dry matter, to facilitate comparisons. However, to provide an agricultural context, yields of potatoes and of kale are shown in the lower part of Appendix Table 1 as fresh produce, together with grain yields at 85% dry matter. Mean maximum yields of dry matter from potatoes and from kale were smaller than from winter wheat (grain plus straw), but all three produced more than the other crops. Production of total dry matter was greatest for all six crops where both FYM and fertilisers were given. However, the yield of wheat grain was largest with fertilisers alone and that of barley grain increased very little by FYM. Evidently nitrogen was too abundant on plots given the DN2PK treatment, for the wheat crop there generally lodged, and this may explain the loss in yield.

Responses to N, P and K. All the crops, other than the clover-grass ley, needed nitrogen fertiliser to yield well, though only permanent grass responded as much to the second increment of N as to the first (Table 1). FYM residues diminished the response to N by wheat and by barley. By contrast FYM (containing much K, Table 6) greatly increased the effectiveness of the N fertiliser for potatoes, whilst not greatly changing it for kale or

ROTHAMSTED REFERENCE EXPERIMENT, 1971–75

TABLE 1

Responses to N, P and K fertilisers (means for 1971–75)

	Yields (t ha^{-1}) of DM without fertiliser or FYM	Increases in the yield of dry matter (t ha^{-1}) from N1 (N1PK-PK)	N2-N1 (N2PK-N1PK)	N2-N1 (DN2PK-DN1PK)	P (N1PK-N1K)	K (N1PK-N1P)
Wheat						
grain	2·98	1·73	0·87	−0·48	0·62	4·17
straw	3·85	2·66	1·38	0·90	1·19	4·21
Barley						
grain	2·35	1·10	0·86	0·31	0·94	1·73
straw	2·06	1·45	1·07	0·36	0·70	1·29
Potato tubers	2·08	2·52	0·84	1·49	1·99	8·87
Kale	2·95	3·94	1·69	1·47	7·24	2·14
Ley	4·32	0·46	−0·29	0·09	3·02	4·53
Permanent grass	2·53	2·25	3·03	2·58	−0·15	0·88

D = FYM applied at 50 t ha^{-1} for kale and potatoes and 37·5 t ha^{-1} for permanent grass

permanent grass, suggesting that we applied too little fertiliser K for our potatoes. This conclusion is supported by the responses to K (also Table 1) which were far larger for potatoes and wheat than those to N. All the crops responded to fertiliser P, but the response of kale was greatest, being thrice that of potatoes to P and larger than its own response to N.

Main effects and interactions of N, P and K fertilisers. N significantly increased the yields of both wheat and barley straw and of kale, but had less effect on grain yields, on potato tubers, or on the ley. (Table 2). Neither grain nor straw yields were significantly

TABLE 2

Main effects and interactions of N, P and K fertilisers on five arable crops, 1971–75

	Dry matter (t ha^{-1}) N	P	K	NP	NK	PK	NPK	s.e.	Coeff. of variation (%)
Wheat									
grain	0·32	−0·01	2·09**	−0·19	1·26**	0·48	0·34	0·201	17·8
straw	1·24**	0·16	2·06**	−0·09	1·04**	0·64*	0·47	0·227	14·3
Barley									
grain	0·41	0·29	0·67*	−0·08	0·34	0·31	0·43	0·213	22·7
straw	0·83**	0·17	0·47*	0·01	0·30	0·22	0·30	0·134	15·8
Potato tubers	0·89	0·93*	6·53**	−0·04	1·24**	0·67	0·42	0·323	18·5
Kale	1·48**	3·88**	−0·06	1·45**	0·30	1·20**	0·72	0·280	19·7
Rotation ley	1·01	1·75**	3·29**	−0·28	−0·31	1·51**	0·03	0·400	18·3

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

increased by P, but they were by K, outstandingly on winter wheat. P significantly increased yields of potatoes, of kale and of the clover-grass ley, whilst K increased greatly the yields of potato tubers and clover-grass, but negligibly those of kale. As expected, several of the NK and PK interactions were positive and highly significant, whilst the NP interaction was always negative (except for kale) showing the dependence of the other four crops on fertiliser K to yield well.

Responses to FYM. These were measured either in the year of application or one or two years later (Table 3). The effects FYM had were always positive except for wheat

TABLE 3

Mean increase in yield (t ha^{-1} of dry matter) from FYM (D) tested with and without NPK fertilisers from 1971 to 1975

	Without NPK fertiliser (D-O)	With NPK fertiliser: N at single rate (DN1PK-N1PK)	With NPK fertiliser: N at double rate (DN2PK-N2PK)
Direct effects			
Potato tubers	9·38	1·82	2·47
Kale	5·02	3·35	3·13
Permanent grass	3·41	2·56	2·11
Residual effects (1 year later)			
Wheat			
grain	1·87	0·15	−1·20
straw	2·43	1·30	0·82
Barley			
grain	1·69	0·68	0·13
straw	1·15	1·05	0·34
Residual effects (2 years later)			
Ley	5·67	0·61	0·99

grain when N2PK was given. The K in the FYM greatly enhanced the yield of clover-grass ley 2 years after its application, and its high content of K (Table 6) almost certainly explains why the FYM increased the yield of potato tubers more where N2PK rather than where N1PK fertilisers were also given. The yields of potatoes and kale were far larger with combinations of FYM and fertilisers than with fertilisers alone (Table 4).

TABLE 4

Mean yields (t ha^{-1}) of fresh potato tubers and of kale without and with FYM, 1971–75

	Mean amount of FYM applied (t ha^{-1}): Potato tubers 0	Potato tubers 50	Kale 0	Kale 50
Fertilisers				
None	8·77	44·19	13·34	34·44
N1PK	44·68	53·83	40·98	63·47
N2PK	47·65	60·15	54·76	75·59

Nutrient balance, 1971–75

Added in fertilisers. Amounts applied over the whole period are shown in Table 5.

TABLE 5

Amounts (kg ha^{-1}) of nitrogen, phosphorus and potassium supplied annually by fertilisers to crops grown in rotation and to permanent grass at Rothamsted, 1956–75

	Nitrogen 1956–75: N1	Nitrogen 1956–75: N2	Phosphorus 1956–75	Potassium 1956–60	Potassium 1961–65	Potassium 1966–70	Potassium 1971–75
Wheat	75	150			156		
Barley	57	113			104		
Potatoes	75	150	27·4	104	260	208	208
Kale	126	252			104		
Ley	19	38			208		
Total in 5 years	352	703	137	520	832	1040	1040
Permanent grass	126	252	27·4	104	260	208	208

Added in FYM. The percentages of N, P, K and Mg in each batch each year and the amounts added by the standard dressing are shown in Table 6. The quantity of K supplied

TABLE 6

Chemical analysis of FYM, 1971–75

Cropping year	Dry matter %	% in dry matter of N	P	K	Mg
1971	22·25	3·12	0·52	4·56	0·34
1972	25·05	3·37	0·52	4·48	0·31
1973	24·65	3·14	0·52	4·28	0·32
1974	22·06	3·08	0·67	4·43	0·36
1975	22·62	3·51	0·53	3·76	0·31
Mean	23·33	3·24	0·55	4·30	0·33

Amounts (kg ha^{-1}) of N, P, K and Mg supplied by 50 t ha^{-1} of FYM

	N	P	K	Mg
1971	349	58	510	38
1972	424	65	564	39
1973	389	64	530	40
1974	341	74	491	40
1975	399	60	427	35
Mean	380	64	504	38

by two dressings of FYM in 5 years almost exactly equalled that supplied by the five annual dressings of K fertiliser, i.e. about 1000 kg K ha^{-1}. These data are summarised over the life of the experiment in Table 7.

TABLE 7

Total amounts (kg ha^{-1}) of N, P and K supplied by FYM in each 5-year cycle of the experiment, 1956–75

Years	N	P	K
1956–60	951	177	1255
1961–65	664	123	716
1966–70	676	175	1072
1971–75	760	128	1008

Amounts of N, P and K removed from the soil by individual crops, 1971–75. Table 8 shows the amounts of N removed from the soil by crops given P and K, of P by crops given

TABLE 8

Mean annual amounts (kg ha^{-1}) of N, P and K removed from the soil by crops given the other two elements as fertiliser, 1971–75

	N	P	K
Wheat			
grain	54	12·8	8
straw	16	1·5	10
Barley			
grain	47	8·6	14
straw	10	1·4	9
Potato tubers	83	10·9	26
Kale	51	1·8	46
Ley	220*	10·1	56
Mean (excluding ley for N)	65	9·4	34
Permanent grass	56	9·0	29

* Includes contribution by clover

N and K, and of K by crops given N and P fertilisers. The mean annual amounts of N, P and K removed by the five arable crops from this soil were 65, 9·4 and 34 kg ha^{-1} respectively as compared with 61, 11·2 and 43 in the previous 5-year cycle. Potatoes (which followed the clover-grass ley) obtained 83 kg N ha^{-1} from the soil, i.e., only 13 kg ha^{-1} more than winter wheat and 26 kg ha^{-1} more than barley did, after a non-leguminous crop. Crop analyses showed (Appendix Table 2) that the crops given NPK fertilisers took up N and K in roughly equal proportions and hence had equal need of each nutrient, but the soil provided little K, hence the large responses to K shown in Table 2.

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

TABLE 9

The apparent recoveries of N, P and K fertilisers by five arable crops and by permanent grass, 1971–75

	Percentage recovery of			
Test crop	N1	N2	P	K
Wheat (grain and straw)	51	52	30	40
Barley (grain and straw)	47	56	27	36
Potato tubers	53	47	37	84
Kale	40	38	49	46
Ley	—	—	44	89
Mean	48	48	37	59
Permanent grass	34	49	18	46

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

The recovery of N in the harvested portions of the crops did not exceed 56%, but was at least as large with the double as with the single amount of N. The kale and the permanent grass were given most N (252 kg N ha^{-1}) and responded most to it (5·64 and 5·28 t ha^{-1} of dry matter respectively); but they recovered proportionally less N than the other crops did. Some of the residual N was undoubtedly recovered by the following crops, but we have no measurements of this.

The small amount of P applied annually (27·4 kg ha^{-1}) was recovered relatively efficiently by the arable crops, but the permanent grass recovered only half as much.

The large amount of K given each year (208 kg K ha^{-1}) was recovered less well by barley and by wheat than by the clover-grass ley, which was harvested green, because a large part of the K in the foliage of the wheat and barley is returned to the soil as the crops mature. However, the potato tubers recovered a very large part of the K given for them, confirming the very large K requirement of potatoes and the inability of this soil to supply more than 26 kg K ha^{-1} to the tubers.

Recovery of N, P and K from FYM. In this experiment FYM is applied at 37·5 t ha^{-1} annually for the permanent grass and at 50 t ha^{-1} for potatoes and for kale, but not for the other three arable crops, which therefore measure residues. Potatoes and kale recovered proportionately less N and K from FYM than they did from fertilisers (Tables 9 and 10), but the absolute uptakes from FYM and from N1PK fertilisers (Appendix Table 2) were very similar. The small efficiency of the 380 kg ha^{-1} of N given in FYM for potatoes and kale is not surprising, because the FYM was dug-in during autumn and hence part of the N in it was subject to leaching during winter. Because of this its value

TABLE 10

The apparent recoveries (%) of the N, P and K in FYM (D) by five arable crops and by permanent grass, 1971–75

	FYM applied					
	Alone (D-O)			With N2PK fertilisers (DN2PK-N2PK)		
% recovery of	N	P	K	N	P	K
FYM newly applied for						
Potatoes (tubers)	21	28	43	7	8	21
Kale	10	17	20	13	20	22
Permanent grass	18	20	29	15	19	38
FYM applied for root crops one year ago						
Wheat (grain and straw)	7	14	11	1	8	8
Barley (grain and straw)	7	15	10	2	4	5
FYM applied for potatoes two years ago						
Ley	—	20	33	—	6	11

as a source of N for the cereal crops one year later was small, as shown in Table 10 and Appendix Table 2. Thus the winter wheat recovered only 18 and spring barley 17 kg N ha^{-1} from the FYM, as compared with 39 from 75 and 26 from 57 kg of fertiliser N ha^{-1} respectively. Table 10 also shows how giving N2PK fertilisers with FYM tended to decrease the proportion of nutrients that were taken up from the FYM. However the permanent grass recovered more K from FYM where fertilisers were also given than where they were not, presumably because shortage of N limited yield when FYM was given alone. Although the residual value of the N in FYM was small, the P and K in it were evidently as valuable as newly applied dressings of P and K fertilisers, because the uptakes of P and K from D plots (Appendix Table 2), were larger than those from plots given P and K fertilisers alone.

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 fertilisers and by FYM, and the amounts removed by the five arable crops in one cycle of the experiment. The nitrogen balance sheet takes no account of the fact that a large proportion of the total N removed was in the clover-grass ley (70–220 kg N ha^{-1} per year, Appendix Table 2). As this soil provided on average 65 kg N ha^{-1} to other crops (Table 9) and the grass-clover ley given P and K fertilisers, but no N, removed 220 kg N ha^{-1} (Appendix Table 2), it appears that the clover nodules fixed annually at least 155 kg N ha^{-1} on these plots, a value very near to that obtained at Woburn in the comparable experiment (Widdowson & Penny, 1979). Neither the amount of N in the clover roots nor its availability to the following potato crop is known, but Appendix Table 2 shows that, on plots given K, these residues enhanced nitrogen uptake by at least 30 kg N ha^{-1}. If we assume that the N in the clover nodules was utilised as efficiently as fertiliser N by the potato crop (Table 9), then this level of recovery implies that the clover roots contained at least 60 kg N ha^{-1} of mineralisable N. Wherever FYM was applied there were large apparent positive balances of N in soil. Data in Table 10 shows however that the following wheat and barley recovered little of this residual N and so it either was leached from the soil during winter, or remained in the soil as a slow acting source of N.

Balances of P and K are less difficult to interpret. Where P was given annually they were always positive, even though the amount added (27 kg P ha^{-1}) was far less than would usually be given on soils like this one; balances were three to four times as large where FYM also was used. The amount of K given annually as fertiliser (208 kg ha^{-1}) was far larger than that usually applied commercially, so that the K balance sheet was

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 Rothamsted, 1971–75

	O	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
Nitrogen												
Added*	0·0	351·6	0·0	351·6	0·0	351·6	0·0	351·6	703·2	760·0	1111·6	1463·2
Removed	269·4	352·9	285·8	331·8	356·0	456·1	482·7	624·7	744·9	563·7	743·4	841·7
Difference	−269·4	−1·3	−285·8	+19·8	−356·0	−104·5	−482·7	−273·1	−41·7	+196·3	+368·2	+621·5
Phosphorus												
Added	0·0	0·0	136·9	136·9	0·0	0·0	136·9	136·9	136·9	128·0	264·9	264·9
Removed	37·1	38·5	56·5	53·6	45·2	47·1	79·5	98·5	107·4	96·9	125·8	132·1
Difference	−37·1	−38·5	+80·4	+83·3	−45·2	−47·1	+57·4	+38·4	+29·5	+31·1	+139·1	+132·8
Potassium												
Added	0·0	0·0	0·0	0·0	1041·8	1041·8	1041·8	1041·8	1041·8	1008·0	2049·8	2049·8
Removed	156·9	171·7	217·9	167·0	461·9	545·9	632·5	782·6	866·7	747·6	1103·6	1207·7
Difference	−156·9	−171·7	−217·9	−167·0	+579·9	+495·9	+409·3	+259·2	+175·1	+260·4	+946·2	+842·1

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

always positive. The amounts of K added for and removed by crops given either N1PK or FYM were similar, so evidently the K in both sources was of equivalent value. The difference between the amount of K removed by crops given N1PK fertilisers (783 kg ha^{-1}) and that provided by the soil (170 kg ha^{-1}, Table 8) presumably came from the fertiliser dressing (i.e. 613 kg K ha^{-1}). Of the 866 kg K ha^{-1} in crops given N2PK fertilisers, roughly 700 kg K ha^{-1} would have been provided by fertiliser. Using a 60% efficiency factor for fertiliser K (Table 9), this implies that a fertiliser dressing of 1160 kg K ha^{-1} would be required for this amount of uptake. As this is 120 kg ha^{-1} more than we added we must assume that the dressing given was justified. Because the K uptakes from FYM and from fertiliser K were similar it appears that a large part of the K requirements of arable crops like these could usefully be met by rotational dressings of FYM, for as at Woburn (Widdowson & Penny, 1979) the main merit of FYM was as a source of K. FYM had less value as a source of N because little of the N in it was recovered by the crops. However the combinations of FYM and fertilisers not only produced the largest uptakes, but also the largest yields (Table 4) and so it is difficult to argue that the additional nutrients supplied by FYM were not utilised efficiently. Appendix Table 3 gives the nutrient balance sheet over the four, 5-year cycles of this experiment. The two largest balances of K in this table are smaller than those shown in Table 11 for 1971–75, because less fertiliser K was given from 1956–60 (Table 5) than later, though rates of N and P remained the same. The amounts of N, P and K removed by the largest crops (with FYM and NPK fertilisers) have evidently increased little with time, for the maximum values in Table 11 are little larger than those shown in Appendix Table 3, even though P and K residues in these soils have increased with time. Since the relationship between yield and treatment has not changed we must assume that FYM residues are not enhancing N supply to crops appreciably. This argument is supported by the data in Table 12 which shows that the yields of crops given N, P and K fertilisers increased until

TABLE 12

Mean yield of dry matter of five crops in each 5-year cycle of the experiment

Years	1956–60	1961–65	1966–70	1971–75
Without FYM				
N1PK	8·96	10·05	10·55	10·34
N2PK	9·49	10·78	11·82	11·63
With FYM				
N1PK	10·53	11·38	12·63	12·14
N2PK	11·14	12·15	13·17	12·96

1970, but not afterwards. This applied whether or not FYM was also given, so on this evidence, enhanced residues of nutrients failed to increase yields further.

Summary and discussion

Results are given from the fourth 5-year cycle (1971–75) of an experiment begun in 1956 on a clay loam soil at Rothamsted using very small plots, which previously had grown grass for many years. It tested N, P and K fertilisers and also FYM on five arable crops grown in rotation and also on permanent grass.

N greatly increased yields of all crops other than the clover-grass ley, but those of kale and permanent grass the most. P increased yields of all the arable crops, but not the permanent grass. It increased yields of potatoes, the clover-grass ley and kale most, and was the nutrient most needed by kale on this soil. K increased the yields of all crops, but was particularly important for wheat, the clover-grass ley and potatoes, which responded

three times as much to K as to N. Shortage of K limited yields more than shortage of N on this soil.

Farmyard manure was applied alone and with NPK fertilisers for potatoes, kale and the permanent grass; the other crops measured its residues. Yields of all the crops were increased by FYM and by its residues, but by more when given alone than with NPK fertilisers. The response by potatoes to FYM was outstanding; its value was enhanced by doubling the amount of fertiliser N given. By contrast yields of wheat grain were diminished by FYM residues when the double dose of fertiliser N was also applied.

Nutrient balances over the five years showed that two 50 t ha^{-1} dressings of FYM supplied nearly as much K (1008 kg K ha^{-1}) as in five annual fertiliser dressings (1040 kg K ha^{-1}) and similar amounts of P (128 kg ha^{-1} v. 137 kg ha^{-1} in fertilisers). The amounts of P removed by the crops were always less than those given, even with most N (N2PK), so sizeable balances of fertiliser P remained in the soil. K balances were also always positive, but proportionally smaller than those for P, even though four times as much fertiliser K as P was given. Crops given most fertiliser (N2PK) removed 40% of the P and 67% of the K given, after allowing for that provided by the soil.

The P and K balances were far larger where both FYM and fertilisers were used, even though the larger crops grown with both removed more P and K. The crop uptake (Appendix Table 2) data showed that the amounts of P and K taken up from FYM and from fertilisers were similar so evidently one application of FYM in 5 years, together with the fertilisers, would have met the additional needs of the larger crops, or, conversely, with two dressings of FYM, only half as much P and K fertiliser need have been given. The total amounts (kg ha^{-1}) of N, P and K removed by the arable crops from 1971–75 ranged from 270 to 840 of N, 37 to 132 of P and 160 to 1200 of K, the largest uptakes being associated with the largest crops, which were grown where both FYM and fertilisers were applied.

The amounts of N, P and K supplied by this soil, where the element was not given, were (in kg ha^{-1}) 77, 11 and 43 in the previous 5-year cycle of the experiment and 65, 9·4 and 34 in the present cycle. This suggests that the amounts supplied by the soil were declining, though the data obtained from 1956–75 showed some fluctuation between cycles of the experiment. Mean annual values over the 20 years of the experiment were (in kg ha^{-1}) 73 of N, 12·9 of P and 49 of K.

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APPENDIX TABLE 1

Mean yields ($t\ ha^{-1}$ of dry matter) from combinations of N, P and K fertilisers and FYM (D) tested on five arable crops, and on permanent grass in the Rothamsted Reference experiment, 1971–75

	Treatments											
	O	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
Wheat												
grain	2·98	2·55	3·02	1·55	3·67	5·10	3·99	5·72	6·59	4·85	5·87	5·39
straw	3·85	4·60	3·94	3·57	4·70	6·59	5·12	7·78	9·16	6·28	9·08	9·98
Barley												
grain	2·35	2·94	2·83	2·41	2·81	3·20	3·04	4·14	5·00	4·04	4·82	5·13
straw	2·06	2·88	2·32	2·55	2·31	3·14	2·39	3·84	4·91	3·21	4·89	5·25
Potato tubers	2·08	2·19	2·80	1·99	7·13	8·87	8·34	10·86	11·70	11·46	12·68	14·17
Kale	2·95	3·41	4·91	6·84	2·13	1·74	5·04	8·98	10·67	7·97	12·33	13·80
Ley	4·32	5·95	4·87	5·87	6·43	7·38	9·94	10·40	10·11	9·99	11·01	11·10
Permanent grass	2·53	3·64	1·99	4·77	2·77	5·80	3·40	5·65	8·68	5·94	8·21	10·79

Mean yield of agricultural produce from combinations of N, P and K fertilisers and FYM (D) on four arable crops in the Rothamsted Reference experiment, 1971–75

	Treatments											
	O	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
	Fresh produce ($t\ ha^{-1}$)											
Potato tubers	8·77	9·51	11·41	8·99	28·73	36·40	34·26	44·68	47·65	44·19	53·83	60·15
Kale	13·34	17·44	21·97	37·66	10·55	9·50	10·51	40·98	54·76	34·44	63·47	75·59
	Grain ($t\ ha^{-1}$) at 85% dry matter											
Barley	2·76	3·46	3·33	2·84	3·30	3·76	3·58	4·87	5·88	4·75	5·67	6·04
Wheat	3·50	3·00	3·55	1·82	4·32	6·00	4·69	6·73	7·75	5·70	6·90	6·34

APPENDIX TABLE 2

Mean annual amounts (kg ha^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) removed by five arable crops, and by permanent grass grown with combinations of N, P and K fertilisers and FYM (D) from 1971–75

	Treatments											
	O	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
						Nitrogen						
Wheat												
grain	45·4	49·7	46·2	29·8	52·4	79·8	54·4	83·0	111·2	68·1	95·7	99·0
straw	16·3	29·0	17·9	22·6	13·1	22·6	16·5	26·0	38·8	20·1	36·1	53·0
Barley												
grain	39·0	54·5	44·0	43·7	44·5	60·1	47·4	65·4	92·5	62·3	83·2	94·7
straw	11·2	19·9	10·1	18·4	11·0	21·2	10·5	18·8	28·3	13·1	23·9	31·9
Potato tubers	40·0	44·3	39·4	44·7	72·6	106·8	83·2	122·8	154·5	120·8	148·7	181·2
Kale	42·0	68·4	51·7	102·2	36·5	44·5	50·9	101·1	145·3	79·5	167·1	195·8
Ley	75·5	87·1	76·5	70·4	125·9	121·1	219·8	207·6	174·3	199·8	188·7	186·1
Permanent grass	42·8	84·1	33·6	106·6	46·7	108·6	56·0	98·9	179·0	111·6	174·7	236·8
						Phosphorus						
Wheat												
grain	9·6	7·6	10·8	5·3	10·7	12·8	13·9	18·7	21·5	17·0	20·4	18·2
straw	2·3	2·8	3·8	3·7	1·3	1·5	3·0	3·8	4·8	4·0	5·8	8·6
Barley												
grain	7·9	8·7	11·0	9·1	9·1	8·6	12·4	15·1	17·5	16·5	18·9	18·8
straw	1·3	1·6	2·1	2·5	1·1	1·4	1·8	2·3	2·9	2·4	3·7	4·1
Potato tubers	4·8	4·8	7·1	5·6	10·8	10·9	17·7	21·1	22·6	22·5	26·3	27·9
Kale	3·3	3·8	10·0	14·5	2·4	1·8	9·2	15·3	17·0	13·9	26·1	29·8
Ley	7·9	9·2	11·7	12·9	9·8	10·1	21·5	22·2	21·1	20·6	24·6	24·7
Permanent grass	5·8	6·2	6·1	15·4	5·4	9·0	10·5	13·9	20·4	18·3	25·4	32·7
						Potassium						
Wheat												
grain	13·9	12·1	15·0	7·6	16·1	21·5	18·8	27·2	30·6	23·3	28·6	25·7
straw	12·0	11·2	16·2	9·5	37·6	63·4	45·5	73·8	102·7	56·4	105·7	147·8
Barley												
grain	14·1	16·2	17·2	13·8	17·6	19·8	20·1	25·2	30·5	26·4	31·2	31·0
straw	12·9	15·4	17·6	9·0	50·3	69·5	45·3	73·6	94·5	50·7	109·4	118·0
Potato tubers	23·8	24·8	38·0	25·5	145·8	179·7	169·9	199·3	211·5	239·8	297·4	321·2
Kale	29·8	33·0	48·3	45·5	34·4	27·7	78·8	142·1	177·8	132·6	255·6	290·9
Ley	50·4	59·0	65·6	56·1	160·1	164·3	254·1	241·4	219·1	218·4	275·7	273·1
Permanent grass	24·2	19·7	16·8	29·4	55·4	134·7	74·3	125·7	179·1	171·6	275·0	370·1

APPENDIX TABLE 3

The mean amounts (kg ha^{-1}) of nitrogen (N), phosphorus (P) and potassium (K) applied for and removed by five crops during four 5-year periods of the experiment, 1956–75

	Treatments											
	O	N1	P	N1P	K	N1K	PK	N1PK	N2PK	D	DN1PK	DN2PK
Nitrogen												
Added	0	352	0	352	0	352	0	352	703	763	1114	1466
Removed	356	431	379	422	460	566	569	689	802	652	817	924
Difference	−356	−79	−379	−70	−460	−214	−569	−337	−99	+111	+297	+542
Phosphorus												
Added	0	0	137	137	0	0	137	137	137	151	288	288
Removed	41	44	63	61	52	54	81	96	102	93	120	126
Difference	−41	−44	+74	+76	−52	−54	+56	+41	+35	+58	+168	+162
Potassium												
Added	0	0	0	0	860	860	860	860	860	1013	1873	1873
Removed	192	215	240	205	465	518	588	687	750	717	1029	1117
Difference	−192	−215	−240	−205	+395	+342	+272	+173	+110	+296	+844	+756