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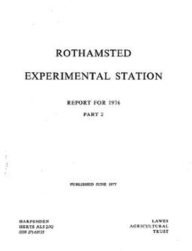

Full Table of Content

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Yields on the Exhaustion Land and Changes in the NPK Content of the Soils due to Cropping and Manuring, 1852–1975

A. E. JOHNSTON and P. R. POULTON

Introduction

The Exhaustion Land experiment now compares yields of barley grown on soil without P or K since 1852 with those on soils containing residues from PK manuring given during 1856–1901. Few visitors to Rothamsted Farm fail to appreciate the significance of the results which show that these residues, accumulated from dressings of either fertilisers or farmyard manure (FYM), have doubled yields of barley during 1949–74 when adequate N was given. Soils enriched with residues gave yields at least equal to the average of all barley crops grown in Great Britain. The experiment, which occupies 1·01 ha on the north side of Hoosfield, derived its name in the early part of this century. At that time unmanured cereal cropping, which started in 1902, measured the residual effects of manures applied in previous experiments. Warren and Johnston (1960) gave reasons for starting the three experiments made between 1852 and 1901 and discussed the results. They also gave yields for the period 1902–53. This paper summarises the early experiments and gives some previously unpublished data. Yields and NPK uptakes during 1949–74 are given in detail. We also discuss analyses of the soils including % N, and relate changes in total, soluble and isotopically exchangeable P and exchangeable K to the amounts of these nutrients removed in the crops.

There are two Classical experiments on Hoosfield and in both barley is now grown continuously; the Hoosfield Continuous Barley experiment started in 1852 and what is now the Exhaustion Land experiment started in 1856. Because we make some comparisons between the two experiments we shall refer, in this paper, to the first experiment as the Continuous Barley experiment and to the second as the Exhaustion Land, even though on occasions we give results from the latter from before 1902.

Experiments made between 1852 and 1901

1852–55. The 'Lois Weedon' plots. This experiment tested methods of husbandry suggested by the Rev. Samuel Smith. On the heavy land of his small farm at Lois Weedon, near Towcester, Mr. Smith grew large crops of winter wheat without using fertiliser or manure. His fields were divided into 3 ft wide strips which were alternately cropped and fallowed, cropping and fallowing being reversed in succeeding years. Only three rows of wheat, at 12 in. spacing, were drilled on the cropped strips, the fallow strips were intensively cultivated, especially the subsoils by double digging. Although Mr. Smith got good yields of wheat for that time, about 34 bushels acre^{-1} (2·29 t ha^{-1}), with this method of husbandry, yields at Rothamsted were less than those on continuously cropped unmanured soil on Broadbalk. Lawes and Gilbert were convinced that the difference was due to amounts of available N in the two soils. There was a difference in total N in the soils; that at Lois Weedon contained 0·154% N, that at Rothamsted 0·132% N but they knew that available N was not necessarily related to total N. These results, obtained recently by the Kjeldahl method, do not agree with those given by Lawes and Gilbert (1856), see p. 67.

Recently we have determined total P and P soluble in 0·5M-$NaHCO_3$ solution in the two

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soils, samples of which still exist. There was much more of both in the soil from Lois Weedon:

	Lois Weedon	Rothamsted
Total P(a) mg kg^{-1}	1080	494
$NaHCO_3$-P mg kg^{-1}	41	10

(a) Determined by perchloric acid digestion; results given later in this paper for the Rothamsted soils were obtained by Na_2CO_3 fusion, which gives slightly larger values.

Lawes and Gilbert eventually ascertained that the Lois Weedon soil had only been cultivated for a few years after a long period in permanent grass. This would explain why it contained more N and P. In addition, sufficient N was probably mineralised each year from soil organic matter to produce good yields of wheat when wheat and fallow were alternated.

1856–75. The winter wheat experiment. Lawes and Gilbert superimposed four plots on the Lois Weedon treatments to test their conclusion that lack of N was responsible for the poor yields of wheat on Hoosfield and included equal areas of cropped and fallowed land in each plot. They tested four treatments: unmanured, N only, PKNaMg and NPKNaMg, which were identical with the treatments on plots 3, 10, 5 and 16 respectively on Broadbalk in 1856. N was given as ammonium N. Yields in 1856 on Hoosfield were very similar to those on Broadbalk and led Lawes and Gilbert (1856) to conclude that adequate available N was more important than deep cultivation for wheat on Hoosfield. During the next four years yields on Hoosfield and Broadbalk were much the same. Average yields of dressed grain, in bushels acre^{-1}, during 1856–60, were:

	Wheat grain, bushels acre^{-1}			
	Unmanured	N only	PKNaMg	NPKNaMg
Hoosfield	16	29	18	37
Broadbalk	16	24	20	36

Subsequently, yields on Hoosfield declined and the response to nitrogen diminished but Lawes and Gilbert never commented on this difference between the two experiments. Field notes made annually show that in 1870 the Hoosfield plots were very foul with weeds. As competition from weeds increased wheat yields decreased and greater efforts to achieve satisfactory weed control were probably made on Broadbalk. The crops sown on Hoosfield in autumn 1870 and 1871 were so poor and weed infested that both were ploughed in in the following spring. Crops were harvested in 1873 and 1874; all plots were fallowed in 1875. Yields for three five-year periods and for 1873–74 are summarised in Table 1.

TABLE 1

Yields of wheat on Smith's Wheat Plots, Exhaustion Land, 1856–75

Mean annual yield of grain and straw, t ha^{-1}, at 85% dry matter

	Unmanured (plot 4)		Ammonium salts(a) (plot 3)		PKNaMg(a) (plot 1)		NPKNaMg(a) (plot 2)	
Period	grain	straw	grain	straw	grain	straw	grain	straw
1856–60	1·12	1·76	1·97	3·34	1·23	1·94	2·51	4·62
1861–65	0·72	1·09	1·27	2·03	0·95	1·34	2·54	3·96
1866–70	0·75	1·13	0·92	1·41	0·93	1·40	1·44	2·31
1873–75(b)	1·08	2·02	1·65	2·89	1·18	2·16	1·72	3·10
Total in 17 years	15·11	23·94	24·10	39·68	17·91	27·72	25·89	60·65

(a) See Table 4 for fertiliser dressings
(b) Experiment fallowed in 1871, 1872 and 1875

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1876–1901. The potato experiment. On the north side of the wheat experiment a strip of unmanured wheat was grown each year during 1856–74. In 1876 this strip was widened to make it almost the same width as the other four strips. The five strips were then halved to make ten plots on each of which potatoes were grown every year from 1876 to 1901. More fertiliser treatments were tested on the potatoes than on the wheat and a test of farmyard manure (FYM) was introduced. Table 2 shows the plot numbers and treatments for the wheat experiment and the corresponding plot numbers and treatments for the potato experiment.

TABLE 2

Corresponding plot numbers and treatments[a] *in the Smith's Wheat (1856–75) and Potato (1876–1901) experiments, Exhaustion Land*

Wheat experiment		Potato experiment			
Plot 1	P K Na Mg	Plot 9	P	Plot 10	P K Na Mg
Plot 2	N P K Na Mg	Plot 7	N P K Na Mg	Plot 8	N* P K Na Mg
Plot 3	N	Plot 5	N	Plot 6	N*
Plot 4	Unmanured	Plot 3	FYM	Plot 4	FYM
Plot 5	Unmanured[b]	Plot 1	Unmanured	Plot 2	Unmanured

(a) See Table 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(b) Not included in the wheat experiment but cropped each year with wheat given no manures

During the potato experiment the land was usually ploughed, probably only to about 12 cm, as soon as possible after the crop was lifted and then again in spring. All field work following spring ploughing was done as quickly as possible. First the fertilisers were applied and in some years the FYM was also spread before the land was bouted into ridges and furrows. If the FYM was not applied before the ridges were made it was placed in the bottoms of the furrows. The potatoes were then planted by hand in the furrows, in some years the seed was set directly on the FYM. The ridges were then split back over the seed. Planting was usually in April.

During the first six years FYM only, FYM plus P and FYM plus NP were tested on plots 2, 3 and 4 respectively. The same fertilser and FYM treatments were also tested for mangolds, swedes and turnips on Barnfield after 1856 and FYM plus NP was a treatment in the Rotation II experiment at Saxmundham which started in 1899 (Mattingly, Johnston & Chater, 1970). Yields given by FYM residues were measured on plot 2 which received no fresh dressings of FYM after 1881. After 1882 FYM only was applied on plots 3 and 4 so the effect of FYM residues, on plot 2, could be compared with that of a fresh dressing.

Gilbert (1888) discussed the yields for the first two six-year periods and Warren and Johnston (1960) summarised yields for the remaining 14 years. Table 3 shows yields for three periods; treatment effects should be compared only in the same period as the variety of potato grown changed during the experiment.

During 1876–81 unmanured soil yielded 5·72 t ha^{-1} potatoes and PKNaMg fertilisers almost doubled yield, 10·40 t ha^{-1}. N alone (96 kg N ha^{-1}) as ammonium or nitrate N gave smaller yields, 6·30 and 8·04 t ha^{-1} respectively, than the PKNaMg fertilisers. The effects of N and PKNaMg fertilsers on potatoes were quite different from those on winter wheat on Broadbalk. During 1872–81 wheat yields on unmanured, PKNaMg- and N-treated soils were 0·72, 0·84 and 1·20 t grain ha^{-1} respectively (Garner & Dyke, 1969).

Complete NPKNaMg fertilisers to potatoes, supplying 96 kg N ha^{-1} either as NH_4-N or NO_3-N gave, on average, 19·21 t ha^{-1}. This yield was not only above the national average at that time (15·42 t ha^{-1}, Gilbert, 1888) but also 6·08 t ha^{-1} larger than the yield given by FYM. Table 3 shows that adding P to FYM had little effect but that when 96 kg N ha^{-1}, as sodium nitrate, was also given yields were almost equal to those given by

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TABLE 3

Yields of potatoes grown continuously, the Potato experiment, Exhaustion Land, 1876–1901

Mean annual yield of total tubers, t ha⁻¹

Plot	Treatment[(a)]	1876–81	1882–87	1888–1901
1	Unmanured	5·72	4·24	2·11
5	N	6·30	5·20	2·99
6	N*	8·04	5·12	4·24
9	P	9·99	8·41	4·80
10	P K Na Mg	10·40	8·51	5·45
7	N P K Na Mg	18·88	14·92	10·40
8	N* P K Na Mg	19·54	13·86	11·00
2	FYM[(b)]	13·13	7·66	3·72
3	FYM P[(c)]	14·01	10·67	11·60
4	FYM N* P[(d)]	17·85	10·07	11·90

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate

(b) 1876–81, FYM; 1882–1901, unmanured

(c) 1876–82, FYM and superphosphate; 1883–1901, FYM only

(d) 1876–81, FYM, sodium nitrate and superphosphate; 1882, FYM and superphosphate; 1883–1901, FYM only

NPK fertilisers. This suggests that the FYM at that period was much more deficient in N than in P but gives no indication of the K status of the manure. The test of FYM plus N ceased after the first six years of the experiment. During the second six-year period yields with all treatments were less than during the first six years. Yields with FYM continued to be less than with NPK fertilisers and residues of FYM applied during the first six years gave smaller yields than fresh dressings of PKNaMg fertilisers.

Yields declined even more during the second half of the experiment where fertilisers were given. However between 1888 and 1901 fresh FYM added to FYM-treated soils gave slightly larger yields than fertilisers. Over the whole period of the experiment yields declined less on FYM-treated soils than on those treated with fertilisers.

We do not know why potato yields decreased so dramatically. We believe that wheat yields declined during the preceding experiment because of competition from weeds, but there are no records suggesting that the potatoes were also infested. It is possible that there may have been a build-up of soil-borne pests and diseases because potatoes were grown year after year on the same land for so long. Soil samples taken in 1903–04 were examined in 1970 for cyst-forming nematodes which, even in this heavy soil, might have built up to damaging populations. Unfortunately not only had the soils been stored for many years but they had also been very finely ground and Jones (personal communication) found only a few remnants of recognisable cyst cases and no eggs.

Hall, appointed Director after Gilbert died in 1901, stopped the potato experiment after the 1901 crop was harvested. He considered that the physical condition of soils not treated with FYM was poor and unsuitable for potatoes.

Experiments made between 1902 and 1975

In most of their experiments Lawes and Gilbert applied much more N, P and K in both fertilisers and manure than was removed in the harvested crops. They made many single plot tests to measure the effect of the residues on succeeding crops (Johnston, 1970). The Agricultural Holdings Act, 1875 gave an outgoing farm tenant a statutory right to compensation for unexhausted manurial residues and Lawes and Gilbert became principally concerned with estimating the 'manure value', in cash terms, of many foods at that time fed to stock. Compensation for the unexhausted manurial value of some artificial manures was allowed under certain circumstances by the Act of 1875. How-

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ever it was not until 1913 that Voelcker and Hall published suggested scales of compensation for some fertilisers and liming materials.

Having stopped the potato experiment in 1901, Hall decided to measure the residual value of the fertiliser and FYM dressings applied during 1856–1901. Table 4 shows the amounts of NPKNaMg and FYM applied in each dressing. Table 5, which corrects some

TABLE 4

Amounts of N, P, K, Na, Mg and FYM applied in each dressing, Exhaustion Land, 1856–1901

	Amount of element, kg ha^{-1}
Nitrogen	96 kg N as ammonium salts (N) or as sodium nitrate (N*)
Phosphorus	33·5 kg P as superphosphate. From 1856 to 1888 the superphosphate was made on Rothamsted Farm from calcined bone and sulphuric acid. From 1889 to 1896 ready made superphosphate, bought from a factory, was applied and from 1897 to 1901 448 kg basic slag was used
Potassium	135 kg K as potassium sulphate except from 1859 to 1875 when the K dressing to the wheat was decreased to 90 kg, as it was on Broadbalk
Sodium	16 kg Na as sodium sulphate except from 1856 to 1858 when the dressing supplied 31 kg Na
Magnesium	11 kg Mg as magnesium sulphate
Farmyard manure	35 t ha^{-1} thought to supply 224 kg total N ha^{-1}

TABLE 5

Number of annual dressings of fertiliser and farmyard manure and the estimated amounts of P and K applied, Exhaustion Land, 1856–1901

	Plot number									
	1	2	3	4	5	6	7	8	9	10
	Number of dressings									
FYM	—	6	26	26	—	—	—	—	—	—
PK	—	—	—	—	—	—	42	42	17	42
P only	—	—	7	7	—	—	—	—	25	—
N	—	—	—	6	43	43	43	43	—	—
	Nutrients applied, kg ha^{-1}									
P as superphosphate	0	0	235	235	0	0	1410	1410	1410	1410
P in FYM	0	235	1025	1025	0	0	0	0	0	0
K as potassium sulphate	0	0	0	0	0	0	5040	5040	1570	5040
K in FYM	0	900	3920	3920	0	0	0	0	0	0

previously published values (Warren, 1956; Warren & Johnston, 1960) shows the number of dressings applied to each plot. The largest number, 42, does not agree with the total length of the two experiments, 46 years, because some dressings were not given between 1870 and 1875 when the wheat crops failed or were not sown. PKNaMg fertilisers applied for the 1875 wheat crop which was not sown, were not reapplied for the first potato crop in 1876 so the first crop of potatoes received 90 rather than 135 kg K ha^{-1}. Table 5 also shows estimates of the total amounts of P and K applied in both fertilisers and FYM.

We have estimated the amounts of P and K removed in the wheat and potatoes (Table 6). For wheat we have used concentrations of P and K found in similarly manured crops at Rothamsted. For potatoes we have based our calculations on uptakes given by Gilbert (1888) for the first 12 years of the experiment. Results in Table 5 and 6 show that only about 7·5 and 14·5% of the P and 25 and 32% of the K added in FYM and fertilisers respectively were removed in the wheat and potatoes combined.

Plants may take up nutrients from soil reserves and residues of previous dresssings as well as from a fresh dressing. The percentage recovery of a fresh dressing is often calculated as:

$$\frac{\text{amount in treated crop } \textit{minus} \text{ amount in untreated crop}}{\text{amount applied}} \times 100$$

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TABLE 6

Estimates of P and K uptakes[a] *by crops grown on the Exhaustion Land, 1856–1974*

Period	Crop	Plot number and treatment to potatoes,[b] 1876–1901									
		1 None	2 None[c]	3 FYM[d]	4 FYM[e]	5 N	6 N*	7 NPK	8 N*PK	9 P[f]	10 PK
	P uptake, kg ha^{-1}										
1856–75	Wheat (grain + straw)	66	66	66	66	93	93	160	160	81	81
1876–1901	Potatoes (tubers only)	48	90	159	166	45	58	169	182	107	117
1902–40	Barley (grain + straw)[g]	73	106	200	212	131	146	235	239	179	190
1941–50	Barley (grain + straw)	44	45	104	108	49	50	91	97	90	101
1951–57	Barley (grain + straw)	28	32	63	71	33	33	58	64	54	66
1958–74	Barley (grain + straw)	76	78	207	203	76	72	172	165	167	177
	K uptake, kg ha^{-1}										
1856–75	Wheat (grain + straw)	211	211	211	211	311	311	622	622	271	271
1876–1901	Potatoes (tubers only)	347	778	1456	1468	387	452	1690	1683	912	1007
1902–40	Barley (grain + straw)[g]	202	294	457	484	533	600	933	975	551	616
1941–50	Barley (grain + straw)	168	175	366	389	200	203	387	417	293	472
1951–74	Barley (grain + straw)	293	329	641	639	310	335	626	633	481	749

(a) See text for procedure adopted for calculating uptakes
(b) For plot numbers and treatment in winter wheat experiment, 1856–75, see Table 2; N, ammonium salts; N*, sodium nitrate
(c) FYM, 1876–81
(d) Plus superphosphate, 1876–82
(e) Plus N and P, 1876–81, plus P only 1882
(f) K applied 1856–75
(g) Clover also grown on plots 5, 6, 7, 8, 9 and 10 between 1906–11

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TABLE 7

Estimates of the P and K balance, additions minus removals, kg element ha^{-1}, in 1902, 1951, 1958 and 1975, Exhaustion Land

		Plot numbers and treatment,(a) 1856–1901				
	Period	1, 2, 5, 6 Unmanured	3, 4 FYM	7, 8 NPK	9 P(b)	10 PK
Phosphorus						
Applied (Table 5)	1856–1901	60	1260	1410	1410	1410
Removed in crops (Table 6)	1856–1901	140	229	336	188	198
	1902–57	193	379	392	323	357
	1958–74	76	205	169	167	177
Balance in	1902	−80	+1031	+1074	+1222	+1212
	1958	−273	+652	+682	+899	+855
	1975	−349	+447	+513	+732	+678
Potassium						
Applied (Table 5)	1856–1901	225	3920	5040	1570	5040
Removed in crops (Table 6)	1856–1901	752	1673	2309	1183	1278
	1902–50	594	848	1356	844	1088
	1951–74	317	640	630	481	749
Balance in	1902	−527	+2247	+2731	+387	+3762
	1951	−1121	+1399	+1375	−457	+2674
	1975	−1438	+759	+745	−938	+1925

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) K applied 1856–75

TABLE 8

Yield of barley grain, %N in grain and total N uptake in grain plus straw, Exhaustion Land, 1902–22

	Mean annual yield of grain, t ha^{-1}, at 85% dry matter					%N in grain					Mean annual total N uptake, kg ha^{-1}, grain plus straw				
	Plot number and treatment(a) 1876–1901														
Year	1, 2 None	3, 4 FYM	5, 6 N	7, 8 NPK	9, 10 PK	1, 2 None	3, 4 FYM	5, 6 N	7, 8 NPK	9, 10 PK	1, 2 None	3, 4 FYM	5, 6 N	7, 8 NPK	9, 10 PK
1902	2·07	4·19	3·64	3·84	1·74	1·60	2·04	2·10	2·07	1·48	34·4	95·8	86·0	87·5	28·3
1903	0·71	2·68	1·12	1·62	0·76	1·57	1·68	1·72	1·57	1·46	12·1	50·7	20·8	27·9	13·2
1904	1·08	2·85	1·12	1·53	1·06	1·50	1·60	1·54	1·56	1·46	17·3	47·5	18·4	25·2	16·2
1905	0·38	1·81	—(e)	—	—	1·52	1·60	—	—	—	6·6	30·6	—	—	—
1906	0·89	2·66	—	—	—	1·32	1·40	—	—	—	12·8	39·2	—	—	—
1907–11(b)	0·54	1·29	—	—	—	1·38	1·51	—	—	—	11·1	26·7	—	—	—
1912–16(c)	0·80	1·26	1·07	1·72	1·44	1·52	1·53	1·56	1·53	1·52	15·8	25·1	18·8	29·8	25·0
1917–22(d)	0·75	1·24	0·98	1·20	1·08	1·50	1·51	1·55	1·47	1·47	9·3	14·4	10·4	14·8	11·4

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) %N in grain and total N in crop 1907–09 only
(c) %N in grain and total N in crop 1913–16 only
(d) %N in grain and total N in crop 1917–19 only; all plots fallowed in 1920
(e) — indicates that clover was grown

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and this is often used as a measure of fertiliser efficiency. In long-term experiments it is often more meaningful to calculate the nutrient balance, additions minus removals, on treated and untreated soils. This we have done for P and K in this experiment (Table 7) using the data in Table 6. The P and K balance is used later to calculate the percentage recovery of the P and K residues and to relate to changes in soil analysis. However plants grown on enriched soil may have removed as much P and K from the soil reserves as did plants on soil given no P or K in which case the residues of the applied P and K may be larger than those shown in Table 7. The effect of this would be to decrease our estimate of the % recovery of the residues during 1902–74 but it would not affect the relationship between changes in soil analysis and PK uptake. We have no way of apportioning uptake between the two sources, soil reserves and residues of applied dressings, but the enriched soils should still contain P and K equal to that removed by crops grown on unmanured soil.

1902–40. The first period of the Exhaustion Land experiment. No manures were applied in this period and cereals, mainly barley, were grown except on plots 5–10 which grew clover during 1906–11. Table 8 shows cereal yields in individual years 1902–06 and average yields for three five-year periods between 1907 and 1922. Barley yielded well, 3·84–4·19 t ha^{-1}, in 1902, the first year after manuring ended, on plots previously treated with NPK fertilisers or FYM. Even where N alone had been applied the yield was 3·64 t ha^{-1}. However only FYM-treated soils continued to yield well (2·77 t ha^{-1}) in the next two years although the NPK residues still gave small increases. Hall (1905) commented on the fact that the N and NPK residues gave yields almost equal to that with FYM residues in the first year but their effect rapidly diminished. He considered the extra yield came from N mineralised from increased crop residues remaining in these soils and not from any unchanged NH_4-N or NO_3-N left from the 96 kg N ha^{-1} fertiliser dressing. Table 8 shows that by 1912–16 yields were small and there was little apparent effect of fertiliser or FYM residues. It is of interest that after the 1920 barley crop failed, the land was ploughed, fallowed and drilled to winter wheat that autumn. Nitrogen accumulated during the fallow gave almost the same increase in yield, 0·63 t ha^{-1}, on plots with PK residues from either fertilisers or FYM. No yields were recorded between 1923 and 1940.

We have recently found some unpublished results for %N in grain and straw of most of the cereals grown from 1902 to 1922. These are summarised in Table 8 which also gives uptakes of N in the harvested crop. N residues from either fertilisers or FYM not only increased yield but also %N in grain in 1902. Percentage N in grain was only slightly increased by FYM residues during the next three years; thereafter previous treatment had little effect.

N in the harvested crop varied according to yield; on the unmanured soil the range was from 9 to 17 kg N ha^{-1} year^{-1}. Offtakes in 1912–16 show that N residues which accumulated in soil where legumes were grown between 1906 and 1911 increased the amount of N available to barley, especially where good crops of clover were grown on soils containing PK residues.

Clover yields varied considerably from year to year; the range was 1·41–7·09 t dry matter ha^{-1} on soils without PK and from 2·04 to 12·10 t ha^{-1} on soils with PK residues. Average dry matter yields during 1906–11 were 3·91 and 5·67 t ha^{-1} on soils without and with PK residues respectively. Estimates of the P and K removed by the clover are included in Table 6.

1941–75. The second period of the Exhaustion Land experiment. The method of measuring residual effects in the period 1902–40 continued the procedure adopted by

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Lawes and Gilbert. Without new additions of any of the three nutrients, N, P or K it was not possible to get any information on the contribution to yield of any one of the nutrients contained in the residues. However, starting in 1941, N has been given to all plots, except when they were fallow, and yields, recorded since 1949, have measured the combined effects of P and K residues. From 1941 to 1960 ammonium sulphate was used, from 1961 to 1975 an ammonium nitrate–calcium carbonate mixture ('Nitro-Chalk'). Starting in 1963 the 'Nitro-Chalk' was combine-drilled with the seed.

In 1954 parts of plots 2, 4, 6, 8 and 10 were found to be acid (see p. 69) and chalk was applied in winter 1954–55. Barley continued to be grown on all plots during 1954–56.

In 1957 the value of the P and K residues were tested separately for six crops, spring barley, spring wheat, potatoes, sugar beet, swedes and kale. This was done by dividing plots 1, 3, 5, 7 and 9 into 240 microplots, 120 were cropped in 1957, the remainder in 1958. Where P was tested NK fertilisers were given, where K was tested NP fertilisers were given. The experiment has been described and the results given in detail by Johnston, Warren and Penny (1970) and will not be discussed further here. Barley was grown only on part of the even numbered plots during 1957–58.

Since 1959 only barley has been grown; the variety has changed twice and the amount of N has been appropriate to the variety. The seed has been treated with ethirimol seed dressing each year since 1972. Occasionally all, or part of the plots have been fallowed to control rhizomatous grass weeds not readily controlled by the herbicides applied each spring. Plots without PK residues are usually most affected by grass weeds because the poor barley crops provide little competition.

Yields have only been recorded since 1949, some have been published previously (Warren, 1956; Warren & Johnston, 1960). We have given all grain and straw yields since 1949 in Appendix Tables 1 and 2 respectively. The appendix tables also show the variety, N dressing and years in which the plots were fallowed. This account ends with the 1975 harvest year but no crop was grown on the Exhaustion Land that season so all yields and nutrient uptakes end with the 1974 crop; soil samples were also taken from all plots in autumn 1974.

TABLE 9

Yields of barley, Exhaustion Land, 1949–74

Grain and straw, t ha^{-1} $year^{-1}$, at 85% dry matter

	Plot numbers and treatment,[a] 1856–1901									
	1, 2, 5, 6 Unmanured		3, 4 FYM		7, 8 NPK		9 P[b]		10 PK	
Period	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw
1949–53	1·59	1·88	3·03	3·30	2·87	2·99	2·72	2·83	3·05	3·19
1954–59[c]	1·80	1·92	3·32	3·05	3·10	2·94	2·81	3·06	3·08	2·97
1960–62	2·02	1·31	3·09	2·02	2·62	1·71	2·59	1·69	2·73	1·84
1963	1·90	1·24	3·27	2·23	2·86	2·04	3·21	2·23	2·99	2·20
1964–69[d]	1·71	1·35	4·28	3·06	3·61	2·49	3·59	2·54	3·61	2·36
1970–75[e]	1·83	1·38	4·75	3·11	4·22	2·90	3·76	2·62	4·53	3·12

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) K applied 1856–75
(c) 1954–59: mean of four years for the odd numbered plots which were used for a microplot experiment in 1957 and 1958 (see text); mean of five years for even numbered plots which were split for fallowing in 1957–58 (cropped area in 1957 was fallow in 1958), the average yield for 1957–58 was used to calculate the four year mean. 1959: plots 5 and 9 were harvested by the microplots used in 1957–58; the yield used is the mean of 1954, 1955 and 1956 only. The yield for 1956 was used to derive a mean yield for the period to calculate nutrient uptakes
(d) The whole experiment was fallowed in 1967
(e) The whole experiment was fallowed in 1975

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Warren and Johnston (1960) showed that during 1949–53 soil without PK residues yielded 1·59 t grain ha^{-1} and PK residues from fertilisers or FYM almost doubled yield. The increases (1·34 and 1·43 t ha^{-1} respectively) were due to the combined effects of P and K residues but Warren (1956) concluded from the analysis of the crops grown during 1949–53 that much of the extra barley yield resulted from the P residues. The large increases on FYM-treated soils in this period compared to the small ones in 1917–22 (Table 8) suggest that after a long period of cereal cropping without any fertilisers the organic manure residues contained available P and K residues but very little available N.

Table 9 summarises the yields for various periods. We are not able to give five-year means for consecutive periods because of changes in variety and the necessity to exclude years when the plots were fallowed or barley followed the multiple cropping in 1957–58. Between 1949 and 1974 the average annual yield of barley on soils without PK residues was 1·76 t grain ha^{-1} (range 0·98–3·30) and 1·56 t straw ha^{-1}; changing variety and N dressing had little effect, suggesting that yield was controlled by shortage of P and K. Variation in yield from year to year probably reflected the ability of the roots to search the soil for these nutrients rather than large seasonal changes in the solubility of the P and K. On soils with P and K residues yields increased between 1949 and 1974 especially when more productive varieties, Maris Badger and Julia, were grown:

		Plot and treatment		
		1, 2, 5, 6 no P no K	7, 8 PK residues	3, 4 FYM residues
Period	Variety		grain, t ha^{-1}	
1949–53	Plumage Archer	1·59	2·87	3·03
1970–74	Julia	1·83	4·22	4·75

Yields during 1970–74 on soils containing residues of P and K dressings, which were at least 70 years old, were almost equal to the average barley yield in England and Wales in the same period. Table 9 also shows that soils with FYM residues have yielded more than soils with fertiliser residues and that the difference in yield has been larger since 1960 than it was before.

On plot 9 K was only applied to the wheat (1856–75) and we estimate that K residues were smaller on this plot than on plots 7 and 8 (Table 7). When barley yields on plot 9 are compared with those on plots 7 and 8 they are similar until 1969 (Table 9). This suggests that the soil with less K residues did nevertheless supply sufficient K for both Plumage Archer and Maris Badger. Since 1970, Julia, which has a larger yield potential than the other two varieties, has yielded about 0·46 t grain ha^{-1} more on plots 7 and 8 than on plot 9. Soil on plot 9 may not now be supplying sufficient K for Julia.

Nutrients in the crop

Nitrogen was applied to all plots after 1941 and Table 10 shows % N in grain and N in the harvested crop for two periods, 1949–53 and 1970–74. In the first of these 63 kg N ha^{-1} was applied to Plumage Archer, in the second Julia received 88 kg N ha^{-1}. Percentage N in grain tended to be small and with Plumage Archer PK residues had little effect; Julia contained most N when grown on impoverished soils which produced least grain. Apparent recoveries of applied N cannot be calculated because all plots received N fertiliser. A total of 315 and 440 kg N ha^{-1} was applied in the first and second five-year periods respectively. Total uptake ranged from 175 to 305 kg N ha^{-1} in the first period and from 206 to 374 kg N ha^{-1} in the second.

https://doi.org/10.23637/ERADOC-1-11 pp 11

TABLE 10

%N in barley grain and total N uptake, kg ha⁻¹, 1949–53 and 1970–74, Exhaustion Land

N dressings: Plumage Archer, 63 kg N ha^{-1}; Julia, 88 kg N ha^{-1}

Plot	Treatment[a] 1856–1901	Mean % N in grain each year: 1949–53 Plumage Archer	1970–74 Julia	Total N uptake in five years: 1949–53 Plumage Archer	1970–74 Julia
1, 2, 5, 6	Unmanured	1·79	1·96	175	206
3, 4	FYM	1·82	1·57	305	374
7, 8, 10	PK	1·67	1·64	277	357

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings

Phosphorus. In the barley crops grown between 1949 and 1974 % P in grain and straw was, on average:

	Plot and treatment: 1, 2, 5, 6 Unmanured	3, 4 FYM residues	7, 8 PK residues	9 P(K)[a] residues	10 PK[b] residues
	%P in dry matter				
Grain	0·278	0·356	0·342	0·347	0·343
Straw	0·057	0·052	0·050	0·057	0·050

[a] K was applied only between 1856 and 1875
[b] PK applied without N 1856–1901

P residues either from superphosphate or FYM increased %P in grain but not in straw. This and the larger yields on soils with residues meant that more P was removed from the enriched than from the impoverished soils. Table 11 shows the total P removed in five years in grain plus straw for three periods, 1949–53, 1964–69 (the experiment was fallowed in 1967) and 1970–74 when Plumage Archer, Maris Badger and Julia respectively were grown. Much larger amounts of P were removed in the grain than in the straw. Barley

TABLE 11

P uptake, kg ha⁻¹, in barley grain and straw, Exhaustion Land, 1949–74

Plot	Treatment[a] 1856–1901		1949–53	1964–69[b]	1970–74	Total P uptake 1949–74
1, 2, 5, 6	Unmanured	grain	18·8	19·7	17·6	98·9
		straw	4·7	3·5	3·2	17·5
		total	23·5	23·2	20·8	116·4
3,4	FYM	grain	44·5	66·4	65·3	261·7
		straw	8·5	6·3	6·7	31·2
		total	53·0	72·7	72·0	292·9
7, 8	NPK	grain	39·7	53·3	53·5	222·0
		straw	7·4	5·4	4·9	26·1
		total	47·1	58·7	58·4	248·1
9	P[c]	grain	38·1	55·9	49·0	211·2
		straw	7·0	6·3	5·4	28·1
		total	45·1	62·2	54·4	239·3
10	PK	grain	43·0	52·1	59·0	235·6
		straw	7·6	4·4	6·0	27·7
		total	50·6	56·5	65·0	263·3

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) Fallow 1967
(c) K applied 1856–75

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grown on soils without P residues removed almost the same amount of P, 23·5 and 23·2 kg P ha^{-1}, in the first two periods and slightly less, 20·8 kg P ha^{-1} in the third period. It will be interesting to see if the amount of P removed from this soil decreases further and yields then decline as the experiment continues. The amount of P removed from soils enriched with residues increased in the second and third periods compared to the first because yields were larger (Table 9). The crops grown on plot 9 removed almost as much P as those grown on plots 7 and 8.

The total P removed during 1949–75 from the impoverished soils was 116·4 kg Pha^{-1}, equal to an average annual uptake of 4·66 kg P ha^{-1}. Barley removed 292·9 kg P ha^{-1} from soils with FYM residues and a little less, 248·1 kg P ha^{-1}, from soils enriched with fertiliser P residues on plots 7 and 8. Thus barley grown between 1949–75 recovered 176·5 kg P ha^{-1} from soils with FYM residues and 131·7 kg P ha^{-1} from soils where the residues were derived from superphosphate. These recoveries represent about 25 and 18% of the residue of the applied P we estimate remained in these soils in 1949 and at their present rate of recovery they could last for another 70 years or more.

Potassium. Any effect of K residues on the concentration of K in barley would be measured in the straw rather than the grain. During 1949–75, %K in grain and straw was, on average:

	Plot and treatment				
	1, 2, 5, 6 Unmanured	3, 4 FYM residues	7, 8 PK residues	9 P(K)[a] residues	10 PK[b] residues
	%K in dry matter				
Grain	0·47	0·49	0·50	0·49	0·51
Straw	0·60	0·57	0·67	0·46	0·83

[a] K was only applied between 1856 and 1875
[b] PK fertilisers were applied without N and in 1902 residues were larger than on plots 7 and 8 (Table 7)

The residues had little effect on %K in grain. The straw grown on soil with most residues (plot 10) contained most K. There was least K in straw grown on plot 9, this is discussed later.

There were differences in the amounts of K removed in the harvested crops because yields differed. Table 12 shows the K removed in five years in grain plus straw for three periods, 1949–53, 1964–69 (the experiment was fallowed in 1967) and 1970–74 when Plumage Archer, Maris Badger and Julia respectively were grown. Grain grown on soil without K residues removed much the same amount of K, 33–37 kg ha^{-1}, in five years in all three periods. In the first period, grain removed about twice this amount of K from enriched soils and the amount increased in the second and third periods because yields were larger. Table 12 shows that there was less K in the harvested straw in 1964–69 and 1970–74 than in 1949–53 on all soils. Not all of this decrease was because of a decline in available soil K, a change in the method of harvesting was partly responsible. During 1949–53 experimental cereal crops were cut by binder, stooked and carted to be threshed during the winter. By 1964 the crop was harvested by combine harvester and as the straw remained in the field longer, K appears to have been lost by leaching. Johnston (1969a) noted a similar change in %K in wheat straw on Broadbalk. Table 12 shows that much of the variation in total K uptake from soils with residues was due to differences in the amounts of K removed in the straw.

About 354 kg K ha^{-1} was removed from the impoverished soils during 1949–75, an average of only 14·2 kg K ha^{-1} year^{-1}. This amount may be compared with the K removed each year by barley in the Continuous Barley experiment, 19·3 kg K ha^{-1}, and by wheat on

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TABLE 12

K uptake, kg ha^{-1}, in barley grain and straw, Exhaustion Land, 1949–74

Plot	Treatment[a] 1856–1901		1949–53	1964–69[b]	1970–74	Total K uptake 1949–74
1, 2, 5, 6	Unmanured	grain	32·6	37·3	36·8	165·1
		straw	60·7	31·7	39·5	188·9
		total	93·3	69·0	76·3	354·0
3, 4	FYM	grain	66·4	94·3	98·5	368·0
		straw	122·4	59·3	72·5	348·0
		total	188·8	153·6	171·0	716·0
7, 8	NPK	grain	63·1	82·8	86·1	330·5
		straw	137·8	58·9	77·7	379·4
		total	200·9	141·7	163·8	709·9
9	P[c]	grain	57·6	80·4	76·0	301·1
		straw	88·8	39·2	43·6	238·6
		total	146·4	119·6	119·6	539·7
10	PK	grain	67·2	82·9	94·8	354·7
		straw	168·6	71·8	108·8	488·4
		total	235·8	154·7	203·6	843·1

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) Fallow 1967
(c) K applied 1856–75

Broadbalk, 34·7 kg K ha^{-1}, where these crops are manured with N and P fertilisers but no K has been given for more than 100 years. More K was removed from soils enriched with FYM and fertiliser K residues, 716 and 710 kg K ha^{-1}, respectively. Thus, on average, an extra 359 kg K ha^{-1} was taken up from residues of applied K which we estimate to have been about 1387 kg K ha^{-1} in 1951 on plots 3, 4, 7 and 8 (Table 7). About 26% of the K residue was therefore recovered between 1949 and 1975.

Percentage K in straw and total K uptake by barley on plot 9 during 1949–74 is of interest. Table 6 shows that K residues accumulated during 1856–75 when the wheat received potassium sulphate. The potatoes which followed during 1876–1901 were given P and no K but nevertheless they removed only 10% less K than those manured with P and K (plot 10). In 1902 K residues were therefore much smaller on plot 9 than on plot 10. We estimate that by the 1930s the crops grown on plot 9 had removed K equal to the amount of the residues but by 1951 this soil had probably lost less 'native' soil K than that on the unmanured plots (1, 2, 5, 6). During 1949–74 barley yielded more (Table 9) and took up more K (Table 12) on plot 9 than on plots 1, 2, 5 and 6. Much of the increased yield was due to the P residues and the extra P probably produced plants with a better root system capable of searching the soil for K. However the extra K uptake suggests that the K manuring during 1856–74 helped to conserve 'native' soil K and this was available to barley grown in 1949–74.

Calcium, magnesium and sodium. The concentrations of these three elements (Table 13) were determined in both grain and straw and the results are discussed briefly for the same three five-year periods used previously. Sodium was not determined in the 1949–53 samples.

Percentage calcium in straw was much larger than that in grain but neither was affected by residues of FYM or PK fertilisers. Julia, grown in 1970–74, contained a larger proportion of Ca than the other two varieties. The offtake of Ca in straw was about five times that in grain. Grain plus straw removed, on average, about 6 kg Ca ha^{-1} year^{-1} from soils without PK residues. The larger crops grown on enriched soils removed more, about 9 kg Ca ha^{-1} year^{-1}.

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TABLE 13

%Ca, %Mg, %Na in, and Ca, Mg and Na uptakes by, barley grain and straw, Exhaustion Land, 1949–74

Plot	Treatment[(a)] 1856–1901	Period	Calcium Grain % Ca	Calcium Grain Uptake	Calcium Straw % Ca	Calcium Straw Uptake	Calcium Total uptake kg Ca ha⁻¹	Magnesium Grain % Mg	Magnesium Grain Uptake	Magnesium Straw % Mg	Magnesium Straw Uptake	Magnesium Total uptake kg Mg ha⁻¹	Sodium Grain % Na	Sodium Grain Uptake	Sodium Straw % Na	Sodium Straw Uptake	Sodium Total uptake kg Na ha⁻¹
1, 2, 5, 6	Unmanured	1949–53	0·058	3·9	0·434	34·6	38·5	0·100	6·8	0·071	5·7	12·5	—[(b)]	—	—	—	—
		1964–69[(c)]	0·056	4·1	0·390	22·3	26·4	0·093	6·8	0·056	3·2	10·0	0·053	3·9	0·352	20·1	24·0
		1970–74	0·077	6·0	0·501	29·3	35·3	0·087	6·8	0·058	3·4	10·2	0·040	3·1	0·240	14·1	17·2
		1949–74[(c)]	0·063	22·3	0·401	124·9	147·2	0·097	34·3	0·057	17·8	52·1	—	—	—	—	—
3, 4,	FYM	1949–53	0·053	6·8	0·414	58·0	64·8	0·112	14·4	0·054	7·6	22·0	—	—	—	—	—
		1964–69[(c)]	0·056	10·2	0·345	44·9	55·1	0·107	19·4	0·035	4·6	24·0	0·028	5·1	0·206	26·8	31·9
		1970–74	0·068	13·7	0·490	64·8	78·5	0·103	20·8	0·041	5·4	26·2	0·026	5·2	0·149	19·7	24·9
		1949–74[(c)]	0·058	43·2	0·379	223·1	266·3	0·109	81·2	0·043	25·3	106·5	—	—	—	—	—
7, 8	NPK	1949–53	0·055	6·7	0·421	53·5	60·2	0·109	13·3	0·058	7·4	20·7	—	—	—	—	—
		1964–69[(c)]	0·054	8·3	0·313	33·1	41·4	0·104	16·0	0·034	3·6	19·6	0·027	4·1	0·213	22·5	26·6
		1970–74	0·074	13·3	0·475	58·5	71·8	0·098	17·6	0·039	4·8	22·4	0·025	4·5	0·166	20·5	25·0
		1949–74[(c)]	0·059	39·1	0·367	193·9	233·0	0·106	70·3	0·042	22·2	92·5	—	—	—	—	—
	P[(d)]	1949–53	0·064	7·4	0·454	54·6	62·0	0·108	12·5	0·065	7·8	20·3	—	—	—	—	—
		1964–69[(c)]	0·054	8·2	0·366	39·5	47·7	0·106	16·2	0·038	4·1	20·3	0·044	6·7	0·358	38·6	45·3
		1970–74	0·070	11·2	0·519	57·8	69·0	0·097	15·5	0·042	4·7	20·2	0·037	5·9	0·228	25·4	31·3
		1949–74[(c)]	0·061	37·6	0·412	207·5	245·1	0·104	64·2	0·047	23·7	87·9	—	—	—	—	—
10	PK	1949–53	0·055	7·1	0·386	52·3	59·4	0·110	14·3	0·056	7·6	21·9	—	—	—	—	—
		1964–69[(c)]	0·051	7·8	0·286	28·7	36·5	0·102	15·7	0·031	3·1	18·8	0·020	3·1	0·101	10·1	13·2
		1970–74	0·079	15·2	0·438	58·1	73·3	0·100	19·3	0·039	5·2	24·5	0·022	4·2	0·082	10·9	15·1
		1949–74[(c)]	0·059	41·4	0·342	191·6	233·0	0·106	74·3	0·041	23·0	97·3	—	—	—	—	—

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(b) Na not determined 1949–53
(c) Fallow in 1967
(d) K applied 1856–75

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Barley grain always contained more magnesium than straw. There is some indication that %Mg in grain grown on each group of soils has declined during the three periods (Table 13). We do not know whether this is due to changes in variety or to a dilution effect on soils with PK residues where grain yields were increased. Barley grain grown on soils with PK residues from fertilisers or FYM contained about 10% more Mg than grain grown on impoverished soils. On the Continuous Barley experiment barley was given 11 kg Mg ha^{-1} each year during 1970–75 in addition to NPK fertilisers but the grain only contained, on average, 0·114% Mg, little different to that in the Exhaustion Land barley grain. This suggests that barley grown on the Exhaustion Land and yielding about 5 t grain ha^{-1} gets sufficient Mg. Total offtake of Mg from soils with and without PK residues was about 4 and 2 kg Mg ha^{-1} $year^{-1}$ respectively. Williams (1976) showed that during 1969–73 rainfall at Rothamsted supplied 2·6 kg Mg ha^{-1} $year^{-1}$, almost enough to supply the requirements of the barley in this experiment.

There was more sodium in barley straw than in grain. Both grain and straw grown on soils with most K residues, either from FYM or fertilisers, contained only half the Na found in crops grown on unmanured soils (plots 1, 2, 5 and 6) or on plot 9 which did not receive K during the potato experiment, 1876–1901. On average the crop removed between 3 and 9 kg Na ha^{-1} $year^{-1}$; this is less than the amount, 12 kg Na ha^{-1}, supplied annually in rain (Williams, 1976).

Yield and uptake of P and K. Warren (1956) discussed yield and P and K uptake by barley during 1949–53. Fig. 1a shows his results. For K he said that, 'the extra amounts of potassium in the crops above 0·25 cwt K/acre (32 kg K ha^{-1}) did not increase the yields of dry matter . . .'. We give similar data for 1970–75 in Fig. 1b, the relationship between yield and P uptake was much the same in the two periods. For K the change in the relationship between yield and K uptake in the second period may be due to the smaller K removals in the straw already mentioned or it could be because soil K levels have decreased and there is now little luxury uptake of K.

These good relationships suggest that the soluble P and K were well mixed throughout the plough layer and were the factors limiting yield. If, in other experiments, such relationships are poor it would suggest that factors other than amounts of P and K are limiting yield.

Soil analysis

Soil sampling. Lawes and Gilbert took some soil samples from Broadbalk as early as 1846 and they gradually developed techniques for sampling and sample preparation which, in their final form, were described by Warington (1892) and Dyer (1902). The first systematic soil sampling was made in 1856; these samples were taken with a 9 × 9 × 9 in. (23 × 23 × 23 cm) metal box sampler. At that time the depth of ploughing was probably not greater than 13 cm so that about half the sample was subsoil. Five plots on Broadbalk and the four Smith's Wheat plots on Hoosfield were sampled and the N content of the soils was discussed by Lawes and Gilbert (1856). We doubt the accuracy of these values which we think are too large. However, we cannot explain this because two possible sources of error would both have given low results. In 1856 it was not appreciated that moist soil samples should be dried as quickly as possible to minimise the effect of biological activity which usually causes a loss of N and C from the soil. In addition the N content of the soil was determined by the soda-lime method which usually gives smaller values than the Kjeldahl method. In 1902 Dyer published many N analyses made on Rothamsted soils between 1865 and 1893, he did not include the 1856 values for Broadbalk. Most of the data had been obtained by Lawes and Gilbert and

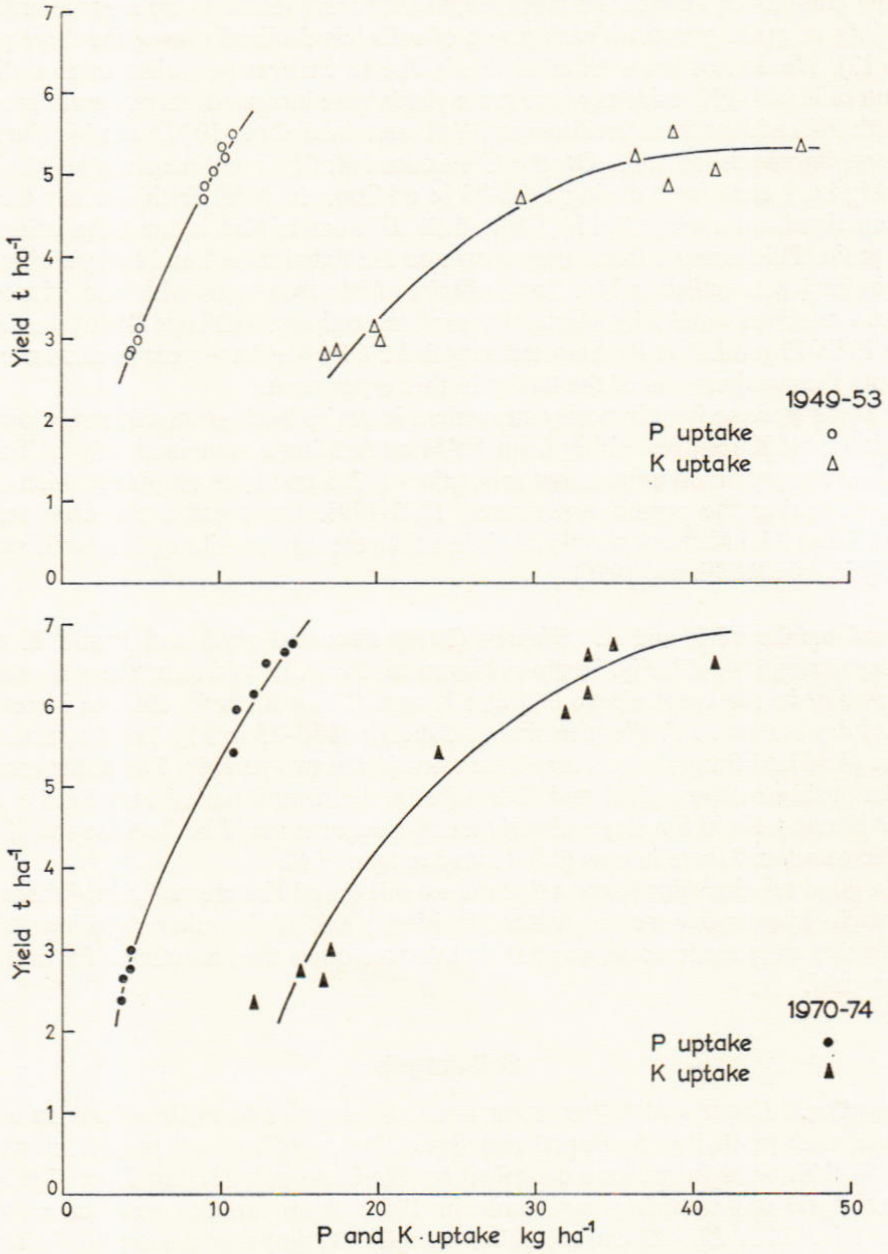

FIG. 1. The relationship between the total amounts of P and K removed each year and the yield of barley, t ha^{-1} dry matter, grain plus straw. P uptake, kg ha^{-1}: ○, 1949–53; ●, 1970–74. K uptake, kg ha^{-1}: △, 1949–53; ▲, 1970–74.

the published values were agreed with them before their deaths. This suggests that they had doubts about the accuracy of the procedures used for the analyses made in 1856.

We have a bulked sample, comprising eight subsamples, two from each of the four Smith's Wheat plots. We have analysed this sample for nitrogen and other plant nutrients to determine changes due to cropping and manuring since 1856.

The soils, except those of plots 7 and 8, were next sampled by Hall in 1903–04. In 1903 samples were taken from plots 1, 3, 5, 6, 9 and 10, plots 2 and 4 were sampled in 1904;

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throughout this paper we have referred to all the samples as 1903 for convenience. These samples were taken with a 15 × 15 × 23 cm metal box, there were two sub-samples from each main plot.

The soils were not sampled again until 1951: since then, sampling has been more frequent, in 1954, 1958, 1965, 1968 and 1974. All recent samples were taken with semi-cylindrical sampling tools, varying in diameter from 1·2 to 2·5 cm; there were usually 20 cores per sample. On each occasion the east and west halves of the plots, and in 1958 the north and south sides of each half plot, were sampled separately. In 1954 individual cores were taken on a gird pattern. The pH of each sample was determined, a soil reaction map prepared, and recommendations then made to correct acidity by differential chalk dressings. The 0–23 cm depth was sampled in 1968 and 1974, this was then about the depth of ploughing. In 1958 the soil was sampled to 15 cm, and then by 7·5 cm horizons down to 53 cm. Samples taken in 1951, 1954 and 1965 were from the top 15 cm, which includes the plough layer, but we have no record of the depth of ploughing. Horses were used for ploughing until the early 1920s and it is probable that ploughing depth changed little until about that time. Since then ploughing depth has increased gradually as tractor power has increased. From both the total N and P content of the 0–15, 15–23 and 23–30 cm horizons, sampled in 1958, we have calculated that ploughing was about 21 cm in 1958.

Weight of soil per hectare. Jenkinson and Johnston (1977) gave weights per hectare of soil from the 0–23 cm depth from a number of plots in the eastern half of the Continuous Barley experiment. They noted that the weight of fine soil was larger on plot 1–0, at the northern end, than on the remainder, and for plot 1–0 they adopted a soil weight of 2·91 Mkg ha^{-1} compared with 2·62 Mkg ha^{-1} for the other plots. These were weights of oven dry soil less than 6·25 mm (6·25 mm was used because Lawes and Gilbert made all their estimates of soil weights on soil passing a quarter inch sieve; on average 1 kg dry fine soil $<$ 6·25 mm contains 20 g stones $>$ 3 mm and $<$ 6·25 mm).

Because of this variability and because the Exhaustion Land is only 100 m north of the Continuous Barley experiment, we decided to check the weight of soil on the Exhaustion Land. In autumn 1976 we took one sample from each plot which had never received organic manures and two from each of the FYM plots, using a 15 × 15 × 23 cm metal box. The weights of oven-dry fine soil $<$ 6·25 mm were 2·97 Mkg ha^{-1} (range 2·80–3.14) on soils which received FYM from 1876 to 1901 and none since and 3·01 Mkg^{-1} (range 2·75–3·17) on soils without organic manures. The mean value, 2·99 Mkg ha^{-1} of oven-dry fine soil to 23 cm depth, is very similar to that for plot 1–0 on the Continuous Barley experiment. We have made most of our analyses on air-dry soil and have used a weight of 3·03 Mkg ha^{-1} of soil; this allows 2% for the weight of small stones and 3% for the moisture in air-dry soil.

The bulk density of the *whole* soil on the Exhaustion Land experiment was 1450 kg m^{-3}. This is less than that of the Continuous Barley soil, 1520 kg m^{-3}, because the Exhaustion Land contains many fewer stones.

Calcium carbonate content and pH of the soils. $CaCO_3$ in the surface soil of arable fields at Rothamsted originated from man-made applications of chalk. The practice of sinking pits to extract the underlying chalk was well established by the eighteenth century (Young, 1813; Russell, 1916). Warren and Johnston (1967) showed that there was more $CaCO_3$ in surface soils on the east side of the Continuous Barley experiment than in soils on the west side, which suggests that the chalk was dug from 'bell pits' to the east of the experiment and that applications were heavier nearer the pit. Table 14 shows the same pattern of distribution on the Exhaustion Land, which lies only a little to the north of the

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TABLE 14

%$CaCO_3$ and soil[(a)] pH (in water), Exhaustion Land

1856 sample: 3·17% $CaCO_3$; pH 7·8 in water

Plot	Treatment[(b)] 1856–1901	% $CaCO_3$ 1903	% $CaCO_3$ 1951	pH in water 1903	pH in water 1951	pH in water 1958	pH in water 1968	pH in water 1974
1	Unmanured	2·34	0·90	8·0	8·0	—[(c)]	8·3	8·0
2	Unmanured	0·86	0·00	7·8	7·1	7·8	7·7	7·4
3	FYM	2·46	0·85	7·7	8·0	—[(c)]	8·3	8·1
4	FYM	0·77	0·00	7·8	7·1	7·7	7·6	7·4
5	N	1·19	0·67	8·0	7·9	—[(c)]	8·2	7·9
6	N*	0·88	0·00	8·0	6·2	7·8	7·5	6·9
7	NPK	—[(d)]	0·70	—[(d)]	7·9	—[(c)]	8·3	8·0
8	N*PK	—[(d)]	0·00	—[(d)]	6·8	7·7	7·5	7·1
9	P[(e)]	1·83	1·46	7·9	8·0	—[(c)]	8·3	8·1
10	PK	1·04	0·12	8·0	7·4	7·5	7·3	7·0

(a) All soils 0–23 cm; except 1951 when the plough layer only was sampled
(b) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(c) Not determined
(d) Not sampled
(e) K applied 1856–75

Continuous Barley experiment. In 1903 soils from the odd-numbered plots in the east half of the experiment, contained much more $CaCO_3$ than those from the even-numbered plots.

All soils lost $CaCO_3$ between 1903 and 1951 and, by 1951, those from plots 2, 4, 6 and 8 contained no free $CaCO_3$. For about three-quarters of the period these losses of $CaCO_3$ were not due to manuring but to 'natural' loss. This would have been enhanced during 1941–51 by the annual application of 310 kg ha^{-1} of ammonium sulphate. Unfortunately, we cannot calculate an average annual loss of $CaCO_3$ from these soils. Sampling in 1903 was to 23 cm, that in 1951 was only to plough depth and we have least information on ploughing depth in 1951. It is almost certain that the soil below plough depth would have contained no $CaCO_3$ so %$CaCO_3$ in the 0–23 dm depth in 1951 would have been less than that given in Table 14. Table 14, however, shows that those soils with most $CaCO_3$ in 1903 (plots 1 and 3) had lost most by 1951. Compared with these soils, those on plots 5 and 10, which contained only about half as much $CaCO_3$ in 1903, lost much less by 1951.

All soil reaction values given here have been determined in recent years using soil water suspensions and glass electrodes. In 1903 all soils had pHs above 7·5 but by 1951 soil on plots 6 and 8 had values less than 7·0. In 1954 the pH of individual soil cores showed how variable soil acidity was on the even-numbered plots; the original chalk spreading must have been very uneven the further it was away from the 'bell-pit'. In winter 1954–55 various amounts of chalk, ranging from 5 to 12·5 t ha^{-1}, were applied to correct acidity. Plot 2 received a further dressing of 2·6 t ha^{-1} chalk in September 1959. Table 14 shows that the soils have remained at a satisfactory pH (i.e. 7·0–8·0) during 1958–74.

Nitrogen and carbon. Table 15 shows %N in air-dry soil in 1856, 1903, 1951, 1958, 1965 and 1974. All soils, other than those given FYM, lost N between 1856 and 1903 and this loss was much larger than that in the Continuous Barley experiment (Jenkinson & Johnston, 1977) or on Broadbalk (Johnston, 1969b) during the same period. We can offer no explanation for this greater loss but suggest it may have occurred during 1876–1901 when potatoes were grown. As in other experiments at Rothamsted the addition of N fertilisers alone (plots 5 and 6) did not increase soil N by 1903. The effects of NPK fertilisers cannot be measured because plots 7 and 8 were not sampled in 1903.

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TABLE 15

Total N in the soil[(a)], *Exhaustion Land*

1856 sample: Surface soil, 0–23 cm, 0·132% N
Subsoil, 23–46 cm, 0·062% N

Plot	Treatment[(b)] 1856–1901	%N 1903	1951	1958	1965	1974
1	Unmanured	0·093	0·111	0·112	0·112	0·101
2	Unmanured	0·097	0·119	0·113	0·122	0·108
3	FYM	0·159	0·138	0·128	0·130	0·122
4	FYM	0·155	0·142	0·128	0·134	0·125
5	N	0·096	0·114	0·110	0·112	0·102
6	N*	0·099	0·117	0·109	0·114	0·097
7	NPK	—[(c)]	0·117	0·109	0·114	0·106
8	N*PK	—[(c)]	0·120	0·112	0·113	0·094
9	P[(d)]	0·089	0·111	0·106	0·107	0·107
10	PK	0·098	0·116	0·111	0·111	0·098

(a) All soils 0–23 cm; except 1951, when the plough layer only was sampled
(b) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(c) Not sampled
(d) K applied 1856–75

Less N accumulated in FYM-treated soils in this experiment than in similarly treated soils on Broadbalk and the Continuous Barley experiment. During the early years of both the Continuous Wheat and Barley experiments N accumulated at about 85 kg N ha^{-1} $year^{-1}$ when 35 t FYM ha^{-1} $year^{-1}$ were applied (Jenkinson & Johnston, 1977). If N had accumulated at the same rate during the potato experiment, 1876–1901, on the Exhaustion Land, 2·21 t N ha^{-1} would have remained in the soil and increased the N content by 0·072% N (using 3·09 Mkg ha^{-1} as the soil weight in 1903 since these soils contained fine stones $< 6{\cdot}25$ mm). Unfortunately, we have to estimate the %N in soils that were to be treated with FYM because no soil samples were taken in 1876 before the first dressing was given. We have made this calculation in two ways: (1) If N was lost at the same rate on plots 3 and 4 as on plots 1, 2, 5 and 6 between 1856 and 1903 then 0·015% N would have been lost in the 20 years before the soil was first treated with FYM in 1876. (2) If the rate of loss was the same as on the unmanured soil on the Continuous Barley experiment (Jenkinson & Johnston, 1977) then 0·007% N would have been lost in 20 years. We have taken the average of these two extremes and assumed a loss of 0·012% N. Therefore soil which received FYM from 1876 to 1901 would have contained about 0·120% N in 1876 and this should have increased to 0·192% N in 1901 with the residual N from the FYM. However the observed value in 1903 was only 0·157% N so that FYM given to potatoes increased soil N much less than when given to cereals. This may be due to the fact that the FYM was normally applied in the bouts immediately before planting the potatoes, usually in early April. In consequence the FYM was not mixed into the soil and the higher soil temperatures of late spring may have increased biological activity in this unprotected organic matter and made the losses of N and C larger than when incorporation was better. FYM applied to the cereal experiments was normally ploughed in and was therefore mixed with more soil at a time when soil temperatures were declining on Broadbalk or were very low, in early spring, on the Continuous Barley experiment.

FYM was not applied after 1901 on the Exhaustion Land; by then 26 dressings each of 35 t ha^{-1} had been given. Since then soil N has gradually decreased. The rate of decline can be compared with that on similarly manured soil on the Continuous Barley experiment where plot 7-1 received 20 dressings of FYM (35 t ha^{-1} $year^{-1}$) between 1852–71 and none since. In that experiment Jenkinson and Johnston (1977) showed that the

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turnover of organic N could be described by the equation:

$$N = N_E + (N_O - N_E)\, e^{-rt}$$

where N is the total N content of the soil and r the fraction of this N which decomposes each year; N_O and N_E are the N contents initially and at equilibrium. For the Exhaustion Land results we took N_O as 4·85 t N ha^{-1} in 1903 and N_E as 2·98, the predicted N content to which unmanured soils will eventually decline on the Continuous Barley experiment and one to which the unmanured Exhaustion Land soils will probably fall. For the 1958, 1965 and 1974 results (Table 15) the mean value for r was 0·011 agreeing with Jenkinson and Johnston's value (0·011 ± 0·001) for plot 7–1 on the Continuous Barley experiment. The value for r for soils sampled in 1951 was much smaller because the samples were taken only from the plough layer and %N was larger than it would have been if the 0–23 cm depth had been sampled. The equation was used to produce fitted curves for N content in soil against time using values for N_O of 5·33 and 4·85 for the Continuous Barley and Exhaustion Land experiments respectively. During the period over which soil N has been declining (70–100 years) the curve for the Exhaustion Land could be superimposed on that for the Continuous Barley if the former was shifted horizontally by 20 years. Thus it appears that once the soils contained the same amount of soil N, the N decreased at the same rate in both soils.

There is further support for the suggestion that there was an additional loss of N on the Exhaustion Land during the period that FYM was being applied. Once FYM was no longer given barley yields were increased by the FYM residues for 12 or 15 years (Table 8) on the Exhaustion Land whilst on the Continuous Barley experiment the FYM residues gave small but measurable increases in yield for about 40 years. The difference in time (about 25 years) over which the FYM residues were effective agrees with the observation above that 20 years were required for the N content of plot 7–1 on the Continuous Barley experiment to fall to that on the Exhaustion Land.

We only determined %C on bulked samples from plots with the same treatments using Tinsley's method (Bremner & Jenkinson, 1960). Table 16 shows %C in air-dry soil and C/N ratios. Percentage C, like %N, appeared to increase between 1903 and 1951, probably because only the plough layer was sampled in 1951 and this was shallower than the 0–23 cm horizon sampled on other occasions. Otherwise % C and C/N ratio changed little on the unmanured and fertiliser-treated soils. On the FYM-treated soils %C declined, as did %N, after FYM additions ceased in 1901.

TABLE 16

Total C and C/N ratios in surface soil[(a)], Exhaustion Land

1856 sample: 1·127%C; C/N ratio 8·54

Plot	Treatment[(b)] 1856–1901	1903 %C	1903 C/N ratio	1951 %C	1951 C/N ratio	1958 %C	1958 C/N ratio	1965 %C	1965 C/N ratio	1974 %C	1974 C/N ratio
1, 2, 5, 6	Unmanured	0·848	8·83	1·030	8·96	0·973	8·77	0·918	7·98	0·881	8·64
3, 4	FYM	1·447	9·22	1·381	9·86	1·172	9·16	1·149	8·70	1·103	8·90
7, 8, 9, 10[(c)]	NPK	0·795	8·46	1·013	8·73	0·964	8·76	0·934	8·41	0·881	8·72

(a) All soils 0–23 cm, except 1951 when the plough layer only was sampled
(b) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(c) Plots 9 and 10 only in 1903

Phosphorus. *Total P* was determined by Na_2CO_3 fusion and colorimetric analysis on the Technicon AutoAnalyzer. Table 17 shows that soils without P additions apparently

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lost little P before 1958 although some P was obviously removed in the crops. The discrepancy may be due to sampling and analytical error and there is the possibility that some P-enriched soil has moved into the unmanured plots during ploughing and cultivations. Jenkinson and Johnston (1977) also found that total soil P changed little in soils given no P for more than 100 years on the Continuous Barley experiment.

TABLE 17

Total P[(a)], mg kg^{-1}, in surface soil[(b)], Exhaustion Land

1856 sample, 528 mg P kg^{-1}

Plot	Treatment[(c)] 1856–1901	1903	1951	1958	1965	1974
1, 2, 5, 6	Unmanured	530	523	532	509	478
3, 4	FYM	862	719	698	662	630
7, 8	NPK	—[(d)]	689	684	649	617
9, 10	PK	886	711	702	640	596

(a) Total P was determined on individual plots for each year, and on samples prepared by bulking together groups of plots with similar treatments. The results given are means of the individual and bulked samples
(b) All soils 0–23 cm; except 1951, when the plough layer only was sampled
(c) See Tables 2 and 4 for full details of FYM and fertiliser dressings
(d) Not sampled

By 1903 there were large gains in total P in soils treated with either superphosphate or FYM; since then, total P has gradually diminished. The differences in total P between the enriched and impoverished soils in 1974 was about half what it was in 1903.

In 1958 soil samples were taken from the 0–15 cm depth and then by 7·5 cm layers down to 53 cm. Total P was determined in all soils by perchloric acid digestion and we have converted these results to those given by fusion analysis using Mattingly's (1970) conversion factor. We have calculated that ploughing depth was about 21 cm at that time so that the total P content of the 23–46 cm depth was that of undisturbed subsoil. Subsoil from umanured, FYM and superphosphate treated plots contained 444, 500 and 464 mg P kg^{-1} respectively. Thus there had been little movement of P into the subsoil where superphosphate was given, more where FYM was applied.

0·5M-NaHCO$_3$ and 0·01M-CaCl$_2$ soluble P are in Table 18. Values for 0·5M-NaHCO$_3$ soluble P correct some previously published results (Warren, 1956) which we now believe are incorrect because when they were made in 1954, we had little experience of the method.

Bicarbonate soluble P was increased considerably by P residues from both superphosphate and FYM dressings applied during 1856–1901. In 1903 the enriched soils contained about eight times as much soluble P as the umanured soils although total P was increased by less than twice. After 1903 soluble P diminished slowly on unmanured soils, much more rapidly on enriched soils.

Only about 2% of the total P was bicarbonate-soluble in 1856 and P residues increased soluble P to about 8% of the total in 1903. However the solubility of the extra P in the soil (Table 17) was much larger than this. About 16% of the superphosphate residues which accumulated during 1856–1901 and 18% of the P residues from FYM dressings, 1876–1901, remained bicarbonate-soluble in 1903. Solubilities of 16 and 18% for residues varying in age from 48 to 3 years may be compared with the solubilities of other P residues accumulated in various experiments at Rothamsted, Woburn and Saxmundham (Johnston, 1975; Johnston & Chater, 1975; Johnston, Mattingly & Poulton, 1976). Their results showed that very recent P residues (six months to three years old) increased soluble P by between 20 and 36% and that percentage solubility then declined as the

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TABLE 18

P soluble in 0·5M-$NaHCO_3$ and 0·01M-$CaCl_2$ in surface soil, Exhaustion Land

Plot	Treatment[a] 1856–1901	NaHCO₃ soluble P mg kg⁻¹ (1856 sample, 9·8) 1903	1951	1958[b]	1965	1974	CaCl₂ soluble P g mol litre⁻¹ (1856 sample, not determined) 1903	1951	1965	1974
1	Unmanured	7·1	7·3	11·9	6·6	2·7	0·28	0·30	0·18	0·18
2	Unmanured	11·4	5·5	5·6	5·0	2·0	0·23	0·26	0·15	0·05
3	FYM	69·2	27·9	30·5	18·9	12·4	10·49	1·24	0·55	0·44
4	FYM	63·9	25·3	21·7	17·2	11·9	8·72	1·16	0·46	0·20
5	N	8·2	9·3	10·3	5·7	3·0	0·25	0·24	0·19	0·05
6	N*	6·9	6·7	5·1	4·8	2·2	0·22	0·12	0·21	0·11
7	NPK	—[c]	22·6	26·4	12·9	7·9	—[c]	0·66	0·32	0·20
8	N*PK	—[c]	19·9	15·3	12·0	7·5	—[c]	0·66	0·42	0·16
9	P[d]	60·1	27·8	23·1	15·9	10·5	5·33	0·99	0·42	0·18
10	PK	69·8	25·5	17·6	14·5	8·9	5·91	0·69	0·28	0·15

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(b) Values for the odd numbered plots are too large, for explanation see text
(c) Not sampled
(d) K applied 1856–75

age of the residues increased. Only 4 and 6% of the P applied before 1901 as superphosphate and FYM respectively to the Exhaustion Land was bicarbonate-soluble in 1974.

Table 18 shows that in 1958 the amounts of $NaHCO_3$ soluble P in soil from plots with odd numbers were all larger than in 1951, whilst on even numbered plots the amounts were the same or less. The increases are explained by the fact that the 1958 samples had to be taken from the microplots used for the multiple cropping experiment in 1957 (see p. 61). These microplots received either basal or test dressings of P and this recently applied P gave measurable increases in $NaHCO_3$ soluble P. We have estimated what the values might have been in two different ways: (1) by using the decrease on each comparable even number plot; (2) by subtracting from the observed value the expected increase in soluble P as a result of applying 56 kg P ha^{-1}. The two estimates agreed closely so we used the mean value. The corrected amounts of $NaHCO_3$ soluble P, mg kg^{-1}, for 1958 are: plots 1, 2, 5, 6—6·6; plots 3, 4—23·4; plots 7, 8—17·8; plots 9, 10—18·3. These corrected values were used to calculate the decreases in $NaHCO_3$ soluble P between 1903 and 1958 used in Table 24. Bicarbonate soluble P values as determined in 1958 (Table 18) were used to calculate decreases for the 1958–74 period in Table 24.

The build up and decline of $CaCl_2$ soluble P was very similar to that of bicarbonate soluble P.

Isotopically exchangeable P. We are indebted to Margaret Chater for determining the isotopically exchangeable P in the 1856, 1903, 1958 and 1974 soil samples. Both rapidly exchanging phosphate P_{e24}, the amount exchanging in 24 h and the 'total' exchangeable P, P_{e168}, the amount exchanging in 168 h were determined. The semi-empirical constant P_{e24}/P_{e168} was calculated; this has been used by Talibudeen (1958) and Mattingly and Talibudeen (1961) to characterise the phosphate status of soils. Table 19 shows our results; the rapidly exchanging P was usually more than half of P_{e168} but only in 1958 was the ratio consistently larger on soils with residues than on those without. There are some anomalies, particularly the values for P_{e24} for the unmanured soils on plots 5 and 6 in 1974. These values are too large and are omitted from Table 19 because the amount of P in the soil extract was below the limit of accurate estimation using our present analytical procedure. The ratio P_{e24}/P_{e168} for plots 5 and 6 in 1903 is somewhat

TABLE 19

Amounts of isotopically exchangeable P, mg kg⁻¹, in surface soil, Exhaustion Land

P exchanging in 24 h, P_{e24}, and in 168 h, P_{e168}, and ratio P_{e24}/P_{e168}.
1856 sample: P_{e24} 25·3 mg P kg⁻¹; P_{e168} 42·5 mg P kg⁻¹; P_{e24}/P_{e168} 0·595

Plot	Treatment[(a)] 1856–1901	1903 mg P kg⁻¹ P_{e24}	1903 mg P kg⁻¹ P_{e168}	1903 P_{e24}/P_{e168}	1958 mg P kg⁻¹ P_{e24}	1958 mg P kg⁻¹ P_{e168}	1958 P_{e24}/P_{e168}	1974 mg P kg⁻¹ P_{e24}	1974 mg P kg⁻¹ P_{e168}	1974 P_{e24}/P_{e168}
1	Unmanured	29·2	42·6	0·685	25·1	50·0	0·502	17·1	26·6	0·643
2	Unmanured	34·1	54·1	0·630	17·3	35·4	0·489	15·6	18·8	0·830
3	FYM	139·5	207·5	0·672	54·0	99·3	0·544	43·5	63·4	0·686
4	FYM	133·5	204·0	0·654	55·2	95·2	0·580	42·8	69·5	0·616
5	N	31·5	42·4	0·743	23·7	47·9	0·495	—[(d)]	24·0	—
6	N*	33·4	40·5	0·825	16·4	34·5	0·475	—[(d)]	18·6	—
7	NPK	—[(b)]	—	—	44·2	77·5	0·570	35·3	52·0	0·679
8	N*PK	—[(b)]	—	—	41·2	76·2	0·541	39·4	50·1	0·786
9	P[(c)]	132·5	184·0	0·720	54·4	79·5	0·684	38·1	53·4	0·713
10	PK	143·0	220·5	0·649	50·8	82·8	0·614	48·0	73·4	0·654

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(b) Not sampled
(c) K applied 1856–75
(d) The values for P_{e24} are too large and are omitted, see text

greater than on the other unmanured plots, 1 and 2, which suggests there may have been some recent P enrichment in the soil of 5 and 6. These plots are between 3 and 4, treated with FYM and 7 and 8, treated with superphosphate. If the samples were taken near the plot boundary there may have been contamination with enriched soil from adjacent plots.

There were large increases in both P_{e24} and P_{e168} whilst P residues, either from FYM or superphosphate, were accumulating. Both total and rapidly exchangeable P has diminished during the period of exhaustion but the amounts are not yet as small as those in unmanured soils. We discuss these changes in relation to the P balance later.

Exchangeable cations. K exchangeable to 1N ammonium acetate has been determined in most soils (Table 20). Over the whole period of the experiment exchangeable K has diminished slightly where no K has been applied. On these soils exchangeable K is

TABLE 20

Exchangeable K, mg kg⁻¹, in surface soil, Exhaustion Land

1856 sample, 91 mg K kg⁻¹

Plot	Treatment[(a)] 1856–1901	1903	1951	1958	1965	1968	1974
1	Unmanured	94	74	77	86	72	64
2	Unmanured	85	68	73	85	73	66
3	FYM	293	108	109	116	98	90
4	FYM	236	104	110	112	95	84
5	N	109	79	92	90	81	75
6	N*	92	74	80	92	79	70
7	NPK	—[(b)]	118	115	120	95	89
8	N*PK	—[(b)]	124	126	124	104	89
9	P[(c)]	146	84	92	94	84	76
10	PK	454	150	154	158	121	112

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate
(b) Not sampled
(c) K applied 1856–75

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now almost the same as on similarly cropped soils given N and P but no K on the Continuous Barley experiment and less than in similarly manured soils on Broadbalk (about 80 mg K kg^{-1}) and Barnfield (120 mg K kg^{-1}).

Exchangeable K was much increased by K manuring during 1856–1901. Unfortunately we have no samples for plots 7 and 8 in 1903 but plot 10 was given the same amount of K fertiliser and contained most exchangeable K in 1903. The increase was less on plots 3 and 4 where FYM was given only between 1876 and 1901 and smaller still on plot 9 where K was given only for wheat during 1856–1875 and not for the following potato experiment. Between 1903 and 1941 exchangeable K diminished considerably on all soils containing residues but, since 1951, the decrease has been much less. Soils which received K either as fertilisers or FYM still contain more exchangeable K than unmanured soil.

Exchangeable Mg, Na and Ca were determined only in soils sampled in 1974 (Table 21).

TABLE 21

Exchangeable Mg, Na and Ca in surface soil in 1974, Exhaustion Land

Plot	Treatment[(a)] 1856–1901	mg element kg^{-1} Mg	Na	Ca
1	Unmanured	29·9	10·9	4520
2	Unmanured	34·7	13·7	2650
3	FYM	35·7	13·8	5840
4	FYM	39·1	13·7	2970
5	N	31·3	14·7	3860
6	N*	40·1	12·7	2380
7	NPK	28·3	11·5	4630
8	N*PK	35·6	13·6	2560
9	P[(b)]	33·0	19·0	6160
10	PK	38·9	11·1	2520

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium salts; N*, sodium nitrate

(b) K applied 1856–75

Both magnesium and sodium were applied as sulphates with the PK fertilisers and in FYM. Exchangeable Mg was, on average, 35 mg Mg kg^{-1}. The old manurial treatments now have little effect, the amount in soil given FYM is a little larger than on the other soils. Similarly, exchangeable Na is not now affected by previous treatment; there was only about 14 mg Na kg^{-1}. On page 67 we show that more Na is now supplied in rain than is removed in the crops. Exchangeable Ca, however, was affected by the varying $CaCO_3$ content of the soil (p. 70). The odd-numbered plots which have always contained free $CaCO_3$ contained 5000 mg Ca kg^{-1} exchangeable to NH_4^+. This was about twice the amount on the even-numbered plots which did become acid but were subsequently limed.

Nutrient balance and its relationship to exchangeable P and soluble P and K in the soil

We have related changes in total and bicarbonate soluble P and exchangeable K in soil to the P and K balance, additions minus removals, during 1856–1901 and 1902–74. In the first period residues were accumulating in some soils, in the second period all soils lost P and K.

Total P. Table 22 shows that during 1856–1901 the net loss or gain of P by manuring and cropping agreed well with the change in total P in the 0–23 cm depth of soil. The agreement between the decrease in soil P and P removed in the crops during 1903–58 and 1958–74 was not quite so good. However, when the differences between P removed and decreases in soil P are expressed as a percentage of the total soil P most of the errors are

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TABLE 22

Changes in total P in surface soil during 1856–1903, 1903–58 and 1958–74 and the P balance, net gains or losses of P, due to cropping and manuring, Exhaustion Land

Plot	Treatment	Total P in soil, kg ha^{-1}			P balance kg ha^{-1}	Difference between change in soil P and P balance as a % of total P in soil
During period of manuring 1856–1901[(a)]		1856	1903[(a)]	Increase 1856–1903	P applied minus P removed[(b)]	
1, 2, 5, 6	None	1600	1606	+6	−80	5
3, 4	FYM	1600	2612	+1012	+1031	1
9, 10	PK	1600	2685	+1085	+1217	5
During period of exhaustion (a) 1903–58		1903	1958	Decrease 1903–58	P removed	
1, 2, 5, 6	None	1606	1612	+6	193	11
3, 4	FYM residues	2612	2115	−497	379	6
9, 10	PK residues	2685	2127	−558	340	10
(b) 1958–74		1958	1974	Decrease 1958–74		
1, 2, 5, 6	None	1612	1448	−164	76	6
3, 4	FYM residues	2115	1909	−206	205	0
9, 10	PK residues	2127	1809	−318	172	8
7, 8	PK residues	2073	1870	−203	169	2

(a) Fertilisers applied until 1901, soils sampled in 1903
(b) See Table 7 for P applied and removed

less than 10%. The larger errors for 1903–58 compared to 1958–74 may be because we had to estimate the P removed in the crops during 1902–48. An error of 10% is probably within the combined error of sampling and analysis for total P. This means that residues are not easily estimated as differences between total P in enriched and impoverished soils, especially if their amount is small in relation to the total P. The results given here are similar to those given by Mattingly, Johnston and Chater (1970) for changes in total P and net gains or losses of P in the Rotation II experiment at Saxmundham.

Isotopically exchangeable P. We have restricted this discussion to the 'total' exchangeable P, that exchangeable in 168 h, because these values were larger and more consistent than those for P_{e24} which were difficult to determine with accuracy. Changes in P_e on unmanured soils accounted for only a very small proportion ($< 10\%$) of P uptake between 1856 and 1958 (Table 23). During 1958–74 these soils were stressed to provide P, because barley was given N fertiliser, and about 80% of the uptake was accounted for by the decline in P_e. Table 19 shows that P_e remained reasonably constant on these soils until 1958 and then decreased considerably; it will be interesting to see whether this decline continues.

The increase in P_e on soils, in which P residues accumulated during 1856–1901, only accounted for about 45% of the residues. This may be compared with an increase of about 15% in the amount of $NaHCO_3$ soluble P (Table 24). Therefore much of the P residues were present as reserves which we do not measure by present techniques other than increases in total P which may be associated with fairly large errors, as mentioned in the previous section. Our evidence that 45% of the P residues remains isotopically exchangeable agrees well with others for Rothamsted soils given by Mattingly (1958) and

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TABLE 23

Changes in isotopically exchangeable P, P_{e168}[(a)], in surface soil during 1856–1903, 1903–58, 1958–74 and the P balance, net gains or losses of P, due to cropping and manuring, Exhaustion Land

Plot	Treatment	Isotopically exchangeable P in soil, kg ha^{-1}			P balance kg ha^{-1}	Change in isotopically exchangeable P as a percentage of the P balance
During period of manuring, 1856–1901[(b)]		1856	1903[(b)]	Increase 1856–1903	P applied minus P removed[(c)]	
1, 2, 5, 6	None	129	136	+7	−80	9
3, 4	FYM	129	623	+494	+1031	48
9, 10	PK	129	613	+484	+1217	40
During period of exhaustion (a) 1903–58		1903	1958	Decrease 1903–58	P removed	
1, 2, 5, 6	None	136	127	9	193	5
3, 4	FYM residues	623	295	328	379	87
9, 10	PK residues	624	246	378	340	111
(b) 1958–74		1958	1974	Decrease 1958–74		
1, 2, 5, 6	None	127	67	60	76	79
3, 4	FYM residues	295	201	94	205	46
9, 10	PK residues	246	192	54	172	31
7, 8	PK residues	233	155	78	169	46

(a) P_{e168}, P which is isotopically exchangeable over a period of 168 h
(b) Fertiliser applied until 1901, soils sampled 1903
(c) See Table 7 for P applied and removed

Posner and Chater (1976). In their experiments they took samples from impoverished and enriched soils and determined exchangeable and total P. The difference in exchangeable P was expressed as a percentage of the difference in total P. Mattingly, using soils taken in 1955 from Broadbalk, Continuous Barley and Barnfield experiments, at Rothamsted, found that 32–44% of the residues remained isotopically exchangeable. Posner and Chater gave a value of 40% for the residues in the Continuous Barley soils.

Since 1902 the enriched soils have lost P as it was removed in the crops. For most of the period 1903–58 the barley was given no N, the crops were small and presumably there was little demand on soil P. Table 23 shows that during these years the decrease in P_e accounted for all the P removed in the barley. After 1958, because N was applied to the barley, the demand for P increased. Under these conditions the decline in isotopically exchangeable P accounts for only about 40% of the P uptake. Much P must, therefore, have come from non-isotopically exchangeable reserves which accumulated during 1856–1901.

Bicarbonate soluble P. We have calculated changes in $NaHCO_3$ soluble P as kg P ha^{-1} to see how much of the residues remained soluble and how much of the P uptake after 1903 could be accounted for by the decrease in soluble P. Table 24 shows that changes in soluble P on soils given no P since 1856 were very small. The plants probably took up P from the bicarbonate-soluble fraction which was apparently replenished so quickly from non-bicarbonate soluble reserves that it appears that P uptake came from non-soluble P fractions.

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TABLE 24

Changes in bicarbonate soluble P in surface soil during 1856–1903, 1903–58 and 1958–74 and the P balance, net gains or losses of P due to cropping and manuring, Exhaustion Land

Plot	Treatment	$NaHCO_3$ soluble P in soil, kg ha^{-1}			P balance kg ha^{-1}	Change in $NaHCO_3$ soluble P as a percentage of the P balance
During period of manuring, 1856–1903[a]		1856	1903[a]	Increase 1856–1903	P applied minus P removed[b]	
1, 2, 5, 6	None	30	25	−5	−80	6
3, 4	FYM	30	202	+172	+1031	17
9, 10	PK	30	197	+167	+1217	14
During period of exhaustion (a) 1903–58		1903	1958[c]	Decrease 1903–58	P removed	
1, 2, 5, 6	None	25	20	5	193	3
3, 4	FYM residues	202	71	131	379	35
9, 10	PK residues	197	55	142	340	42
(b) 1958–74		1958	1974	Decrease 1958–74		
1, 2, 5, 6	None	25	8	17	76	22
3, 4	FYM residues	79	37	42	205	20
9, 10	PK residues	62	29	33	172	19
7, 8	PK residues	63	23	40	169	24

(a) Fertilisers applied until 1901, soils sampled 1903
(b) See Table 7 for P applied and removed
(c) For derivation of 1958 values see p. 74

The increase in bicarbonate soluble P during 1856–1901 accounted for only about 15% of the differences between the P applied as fertiliser or FYM and that removed in the crop. Much of the P residues must have become non-$NaHCO_3$ soluble during the 46 years they were accumulating.

The period 1902–74 can be divided into two, 1903–58 and 1958–74, according to the years in which soil samples were taken. During the first and second periods the decrease in $NaHCO_3$ soluble P accounts for about 40 and 20% respectively of the P removed in the crops. In both periods, therefore, much non-bicarbonate soluble P contributed to P in the crops, which agrees with other results reported recently by Johnston, Mattingly and Poulton (1976) from an experiment at Woburn. Since 1902 $NaHCO_3$ soluble P has declined steadily on soils with P residues but sufficient P was supplied for the larger annual offtakes in the second period.

Exchangeable K. Changes in exchangeable K, as kg K ha^{-1}, are related to the K balance, additions minus removals, in Table 25. On soils given no K only a small proportion of the K uptake came from the decrease in exchangeable K, a result similar to that for P uptake and change in bicarbonate soluble P. While K was being added each year during 1856–1901 the increase in exchangeable K accounted for only about 26% of the K balance on plots 3, 4 and 10. On plot 9 the K balance was smaller than on plots 3, 4 and 10. and the increase in exchangeable K was a much larger proportion (43%) of the K balance. During the period of exhaustion after 1901 the decreases in exchangeable K accounted for more of the K uptake in the first period, 1903–50, than in the second, 1951–74, although the average annual uptake was larger in the second period. Much non-exchangeable K became available to crops each year especially in the second period.

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TABLE 25

Changes in exchangeable K in surface soil during 1856–1903, 1903–51 and 1951–74 and the K balance, net gains or losses of K due to cropping and manuring, Exhaustion Land

Plot	Treatment	Exchangeable K in soil, kg ha^{-1}			K balance kg ha^{-1}	Change in exchangeable K as a percentage of the K balance
During period of manuring, 1856–1901[(a)]		1856	1903[(a)]	Increase 1856–1903	K applied minus K removed[(b)]	
1, 2, 5, 6	None	276	288	+12	−527	—
3, 4	FYM	276	801	+525	+2247	23
9	P[(c)]	276	442	+166	+387	43
10	PK	276	1376	+1100	+3762	29
During period of exhaustion (a) 1903–51		1903	1951	Decrease 1903–51	K removed	
1, 2, 5, 6	None	288	223	65	594	11
3, 4	FYM residues	801	321	480	848	57
9	P[(c)]	442	255	187	844	22
10	PK residues	1376	455	921	1088	85
(b) 1951–74		1951	1974	Decrease 1951–74		
1, 2, 5, 6	None	223	208	15	317	5
3, 4	FYM residues	321	264	57	640	9
9	P[(c)]	255	230	25	481	5
10	PK residues	455	339	116	749	15
7, 8	PK residues[(d)]	367	270	97	630	15

(a) Fertilisers applied until 1901, soils sampled 1903
(b) See Table 7 for K applied and removed
(c) K applied 1856–75
(d) NPK fertilisers applied 1856–1901 so that K residues were smaller than on plot 10

P and K uptake related to soil analysis. The enriched soils contain more soluble P than the impoverished ones but there is not a sufficient range of values within each group to relate yield or P uptake to soluble P. There is, however, a sufficient range of exchangeable K and Fig. 2 shows the relationship between K uptake and exchangeable K for two periods, 1949–53 and 1970–74. In both periods K uptakes and soil K were well related. Fig. 2 shows the relationships were not identical, exchangeable K was smaller in the second period especially on the enriched soils and, on each plot, K uptake was a little less in the second period although dry matter yields were larger on the enriched soils.

The measurement of soil reserves. The results in Fig. 2 show that exchangeable K relates well to K uptake by current crops. In this experiment we do not have a sufficient range of soil P values to relate yield to bicarbonate soluble P but other results (Johnston, Mattingly & Poulton, 1976) and unpublished data show that good relationships exist. However, results given in this paper demonstrate clearly that during long periods of cropping the amounts of P and K removed were larger than the decreases in soluble P or K in the soils. The methods of analysis we used did not measure reserves of P or K which became available to crops over a long period, and these reserves may give economically worthwhile increases in crop yield. We know that on soils such as those at Rothamsted which contain about 25% clay, changes in total K do not always measure K residues because the amount of K varies more with changes in clay content than with K residues.

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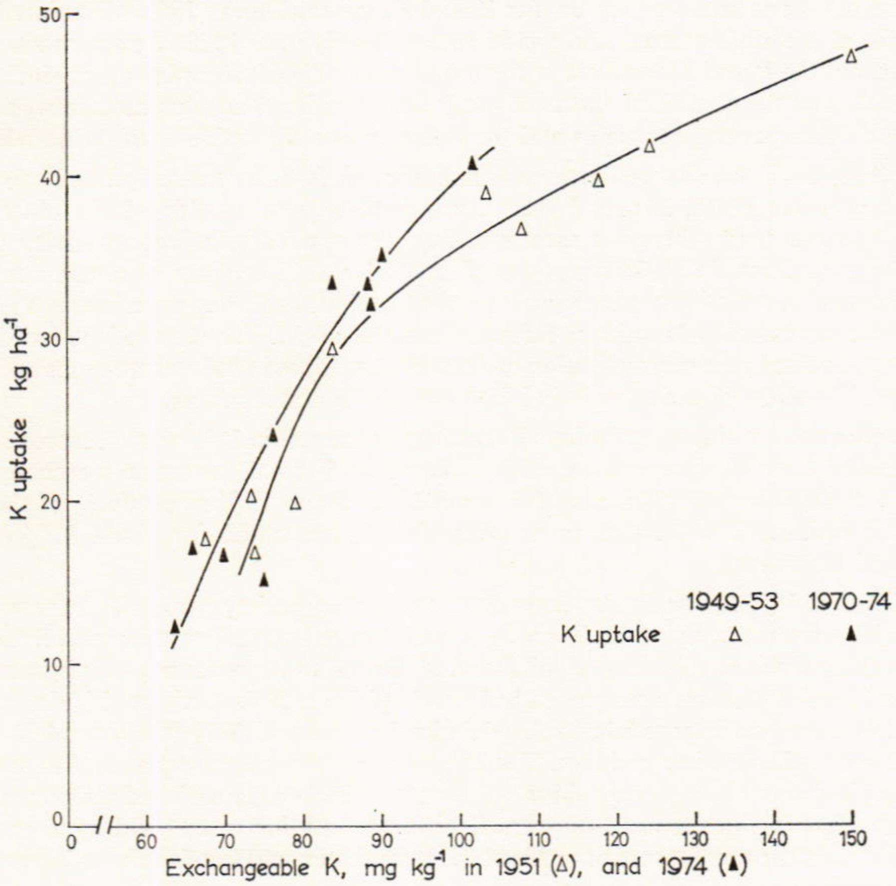

FIG. 2. The relationship between K uptake, kg ha^{-1}, each year and exchangeable K in soil, mg kg^{-1}. △, K uptake 1949–53, soil sampled 1951; ▲, K uptake 1970–74, soil sampled 1974.

Also we have shown in this paper that changes in total P are not easy to measure accurately. The search for laboratory methods able to distinguish between reserves which are only very slowly available and those we have measured by crop uptake over many years is worth pursuing. Long-term experiments will be needed to test the validity of any proposed techniques. To measure phosphate residues it may be necessary to allow for organic P which can be mineralised and may produce 1·5–3·5 kg P ha^{-1} year^{-1} (Mattingly, Chater & Johnston, 1975).

Summary

1. Since 1949 the Exhaustion Land at Rothamsted has shown that PK residues in soil have doubled barley yields when adequate N is given. The soil is a slightly calcareous flinty silt loam or loam over Clay-with-flints (Batcombe Series).

2. Experiments on this site started in 1852. There are two distinct periods; 1852–1901 when fertilisers and farmyard manure (FYM) were applied and residues accumulated in soil; 1902–75 when, because no P or K was given the residues have decreased. No N was given during 1902–40 and depletion was small but since 1941 when N has been given to all plots each year more of the residues have been removed.

3. Yields of wheat and potatoes grown before 1902 are summarised here and the P and K

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balance, additions minus removals, for 1856–1901 given. During 1902–40 mainly barley was grown, without fertiliser, and yields, recorded only until 1922, are summarised and estimates of the P and K removed in the crops given. Yields, recorded again since 1949, have measured the combined effects of the P and K residues accumulated between 1856 and 1901. This paper gives yields and the rate at which the residues are being released.

4. Total N in soil has changed little on unmanured or fertiliser treated plots. N accumulated only where FYM, 35 t ha^{-1} $year^{-1}$, was given to potatoes, 1876–1901, but the increase was less than where the same dressing was applied to wheat or barley grown continuously. Once FYM dressings ceased in 1901 soil N declined at a rate much the same as that on a similarly treated soil on the Continuous Barley experiment. Yields in 1903 were increased by N residues from fertilisers of FYM. The effect of the fertiliser N residues was due to the mineralisation of extra root residues in soils where crops had been given N. The effect of the extra N in FYM residues persisted longer.

5. The effect of P residues on various P fractions in the soil in 1903 was measured as was the effect of K residues on exchangeable K. Increases in total, isotopically exchangeable and $NaHCO_3$ soluble P accounted for about 100, 45 and 15% respectively of the estimated P residue. The increase in exchangeable K accounted for about 32% of the estimated K residues.

6. Yields since 1949 can be divided according to the barley variety grown. On impoverished soil yields were much the same in each period, seasonal variations are probably due to factors other than the solubility of soil P and K. On soils with residues yields increased as more productive varieties were grown. In 1970–75 yields of Julia, grain at 85% dry matter, were: 1·83 t ha^{-1} on impoverished soil, 4·75 t ha^{-1} on soil with FYM residues, 4·22 t ha^{-1} on soil with PK fertiliser residues. The largest yield was about equal to the national average yield for all barley crops. Much of the extra yield on the enriched soil comes from the P residues but in the last five years K residues have increased yield by about 0·5 t grain ha^{-1}. At the present rate of removal the P residues could last for about 70 years.

7. P removed in crops since 1902 is related to changes in isotopically exchangeable and $NaHCO_3$ soluble P. Before 1958 when, for most of the time, the soils were not stressed to supply P, the decrease in isotopically exchangeable and $NaHCO_3$ soluble P accounted for about 100 and 40% respectively of all the P removed. Between 1958 and 1974 barley, given N each year, yielded well and the decline in isotopically exchangeable and $NaHCO_3$ soluble P accounted for only about 40 and 20% of the P in the crops.

8. On soils with most K residues the decrease in exchangeable K between 1902–51 and 1951–74 accounted for about 70 and 15% of the K in the crop. Much K came from non-exchangeable reserves especially in the second period. K residues which accumulated in one soil during 1856–74 were probably exhausted by the 1930s but K uptake from this soil was larger in 1949–74 than from soil unmanured since 1852. It is possible that K in the soil in 1856 was conserved by the K manuring and contributed to recent K uptake by barley.

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APPENDIX TABLE 1

Yields of barley grain, t ha⁻¹, at 85% dry matter, Exhaustion Land, 1949–75

Year	Variety	N dressing kg ha⁻¹	Plot number and treatment to potatoes, 1876–1901[a] 1 None	2 None	3 FYM	4 FYM	5 N	6 N*	7 NPK	8 N*PK	9 P[b]	10 PK
1949	Plumage Archer	63[g]	0·98	1·28	3·42	3·26	1·09	1·65	2·96	3·61	2·96	3·42
1950	Plumage Archer	63	1·40	1·86	3·00	3·58	1·53	1·81	2·74	3·26	3·02	3·29
1951	Plumage Archer	63	1·58	1·48	2·67	2·92	1·79	1·33	2·82	2·79	2·72	3·07
1952	Plumage Archer	63	1·62	1·27	2·90	2·86	2·07	1·64	2·66	2·66	2·45	2·73
1953	Plumage Archer	63	1·98	1·46	2·80	2·85	2·16	1·84	2·67	2·50	2·45	2·72
1954	Plumage Archer	63	2·03	2·38	3·75	3·60	2·57	2·16	3·49	3·39	2·99	3·34
1955	Plumage Archer	63	1·19	1·56	3·40	3·18	1·48	1·00	3·09	2·86	2·62	3·00
1956	Plumage Archer	63	1·09	1·44	2·60	2·61	1·18	1·23	2·77	2·65	2·81	3·00
1957[c]	Plumage Archer	63	—	1·09	—	2·51	—	2·20	—	2·21	—	3·21
1958[c]	Plumage Archer	63	—	1·30	—	3·40	—	1·44	—	2·81	—	2·96
1959	Plumage Archer	63	3·30	2·65	4·02	3·58	—[d]	2·38	3·75	3·18	—[d]	2·95
1960	Plumage Archer	63	2·38	2·13	3·09	3·11	2·21	2·03	2·55	2·47	2·56	2·71
1961	Plumage Archer	63	2·20	1·98	3·00	3·20	2·13	1·96	2·70	2·74	2·81	2·96
1962	Plumage Archer	63	2·01	1·77	3·06	3·07	1·79	1·58	2·60	2·64	2·41	2·51
1963	Proctor	88[h]	2·36	1·78	3·38	3·15	1·73	1·72	3·12	2·60	3·21	2·99
1964	Maris Badger	88	1·67	1·28	4·47	4·12	1·57	1·49	4·00	3·39	3·61	3·56
1965	Maris Badger	88	1·82	1·56	4·17	3·69	1·52	1·49	3·64	3·39	3·73	3·36
1966	Maris Badger	88	1·49	1·63	4·24	4·04	1·53	1·34	3·83	3·50	3·48	3·65
1967	Fallow		—	—	—	—	—	—	—	—	—	—
1968	Maris Badger	88	1·23	1·57	3·66	4·30	1·15	1·19	2·40	3·07	2·57	3·39
1969	Maris Badger	88	2·75	2·68	5·10	4·94	3·04	2·26	4·48	4·42	4·57	4·08
1970	Julia	88	1·14	1·73	4·10	4·44	1·64	1·58	3·75	3·88	3·30	3·85
1971	Julia	88	1·72	1·84	4·69	4·69	1·89	1·87	4·05	4·18	3·56	4·45
1972[e]	Julia	88	2·54	3·17	5·80	5·06	3·04	2·76	5·39	4·71	4·92	5·35
1973	Julia	88	1·29	1·27	4·91	4·85	1·22	1·16	4·25	4·20	4·00	4·29
1974	Julia	88	1·65	1·74	4·48	4·46	1·91	1·39	4·12	3·61	3·02	4·71
1975	Fallow		—	—	—	—	—	—	—	—	—	—
Total yield 1949–75			41·42	42·71	86·71	88·52	41·42	40·68	77·83	78·21	72·58	82·47
Average annual yield[f]			1·80	1·78	3·77	3·69	1·80	1·70	3·38	3·26	3·16	3·44

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium sulphate; N*, sodium nitrate
(b) In addition K applied 1856–75
(c) Odd numbered plots in 1957–58 were used for a microplot experiment. On the even numbered plots barley was grown on part of the plot in 1957 and the remaining part in 1958, the parts not in barley being fallowed. Nutrient uptakes were calculated as for one harvest year using the mean yield for 1957 and 1958
(d) The barley was harvested by the microplots used in 1957 and 1958 to test for residual effects of P given in 1957 and 1958
(e) Seed treated with etherimol seed dressing in 1972 and each year since
(f) For odd numbered plots, 23 harvests; for even plots, 24 harvests, i.e. counting 1957 and 1958 as one harvest year
(g) N dressing to seedbed
(h) N dressing combine-drilled

APPENDIX TABLE 2

Yields of barley straw, t ha⁻¹, at 85% dry matter, Exhaustion Land, 1949–75

Year	Variety	N dressing kg ha⁻¹	Plot number and treatment to potatoes, 1876–1901[a] 1 None	2 None	3 FYM	4 FYM	5 N	6 N*	7 NPK	8 N*PK	9 P[b]	10 PK
1949	Plumage Archer	63[h]	1·05	1·56	3·72	3·61	1·49	1·98	2·80	3·25	2·89	3·76
1950	Plumage Archer	63	2·02	2·47	3·28	3·79	1·86	2·16	3·22	3·38	3·20	3·46
1951	Plumage Archer	63	1·64	1·55	2·40	2·61	1·65	1·00	2·59	2·44	2·35	2·60
1952	Plumage Archer	63	2·05	1·60	3·41	3·66	2·45	1·92	3·32	2·99	2·72	2·94
1953	Plumage Archer	63	2·25	2·21	3·19	3·30	2·39	2·26	3·01	2·90	2·99	3·19
1954	Plumage Archer	63	2·57	3·55	4·03	4·13	2·77	3·18	3·83	4·35	3·56	3·89
1955	Plumage Archer	63	1·57	2·08	3·58	3·39	1·77	1·43	3·43	3·12	2·82	3·35
1956	Plumage Archer	63	1·39	1·61	2·67	2·60	1·48	1·56	2·77	2·42	2·81	3·22
1957[c]	Plumage Archer	63	—	0·92	—	1·18	—	0·85	—	1·28	—	1·79
1958[c]	Plumage Archer	63	—	1·54	—	3·02	—	1·61	—	2·74	—	3·29
1959	Plumage Archer	63	2·01	1·69	2·57	2·22	—[d]	1·39	2·50	1·87	—[d]	1·87
1960	Plumage Archer	63	1·56	1·34	2·16	1·88	1·42	1·26	1·76	1·68	1·62	1·73
1961	Plumage Archer	63	1·38	1·26	1·84	1·93	1·28	1·26	1·68	1·61	1·66	1·53
1962	Plumage Archer	63	1·37	1·12	2·03	2·26	1·23	1·18	1·81	1·68	1·78	2·25
1963	Proctor	88[i]	1·43	1·19	2·35	2·11	1·18	1·14	2·30	1·78	2·23	2·20
1964	Maris Badger	88	1·47	1·17	3·35	3·11	1·28	1·12	2·76	2·33	2·56	2·11
1965	Maris Badger	88	1·83	1·57	3·25	2·77	1·26	1·39	2·54	2·41	2·41	1·94
1966	Maris Badger	88	1·97	1·83	3·18	3·05	1·53	1·62	2·87	2·50	2·85	2·56
1967	Fallow		—	—	—	—	—	—	—	—	—	—
1968	Maris Badger	88	1·15	1·47	3·41	3·74	1·24	1·20	2·72	3·12	2·80	3·40
1969	Maris Badger	88	0·95	1·00	2·36	2·38	0·97	0·85	2·06	1·52	2·10	1·78
1970	Julia	88	0·25	0·44	1·34	1·42	0·93	0·53	1·49	1·00	1·09	1·76
1971	Julia	88	0·69	1·14	2·97	2·98	0·99	1·34	2·60	2·62	2·58	2·83
1972[e]	Julia	88	1·55	1·76	3·57	3·57	1·58	1·83	3·49	3·19	3·03	3·49
1973	Julia	88	2·17	2·86	5·99	5·65	1·92	—[f]	5·49	5·61	5·22	5·21
1974	Julia	88	0·92	1·66	1·80	1·84	1·14	1·52	1·61	1·88	1·19	2·30
1975	Fallow		—	—	—	—	—	—	—	—	—	—
Total yield 1949–75			35·24	39·36	68·45	70·10	35·29	36·67	62·65	61·66	59·27	65·91
Average annual yield[g]			1·53	1·64	2·98	2·92	1·53	1·53	2·72	2·57	2·58	2·75

(a) See Tables 2 and 4 for full details of FYM and fertiliser dressings; N, ammonium sulphate; N*, sodium nitrate
(b) In addition K applied 1856–75
(c) Odd numbered plots in 1957–58 were used for a microplot experiment. On the even numbered plots barley was grown on part of the plot in 1957 and the remaining part in 1958, the parts not in barley being fallowed. Nutrient uptakes were calculated as for one harvest year using the mean yield for 1957 and 1958
(d) The barley was harvested by the microplots used in 1957 and 1958 to test for residual effects of P given in 1957 and 1958
(e) Seed treated with etherimol seed dressing in 1972 and each year since
(f) Yield of straw not recorded. A mean of the other three unmanured plots was used as a yield for this plot in the calculation of uptakes
(g) For odd numbered plots, 23 harvests; for even plots, 24 harvests, i.e. counting 1957 and 1958 as one harvest year
(h) N dressing to seedbed
(i) N dressing combine-drilled

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