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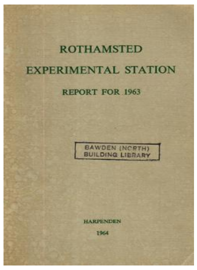

The Park Grass Experiment

R. G. Warren and A. E. Johnston

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THE PARK GRASS EXPERIMENT

R. G. WARREN
and A. E. JOHNSTON

The experiments Lawes and Gilbert started in the 1840s on Broadbalk, Barnfield, Agdell and Geescroft soon showed that different crops require different amounts and ratios of nitrogen (N), phosphorus (P) and potassium (K). Because of the special needs shown by cereals and legumes, they extended their experiments in 1856 to include the mixed plant population of old grassland. The site of the new experiment was part of the Park which had uniform herbage and had been in grass for several hundred years. The plots ranged from ½ to ¼ acre. After about 20 years Lawes and Gilbert found that the subsoil of a large part of plot 12, one of the two unmanured plots, contained more nitrogen than the other (plot 3) and concluded that this plot had received soil from elsewhere in the past. Plot 12 yielded 3 cwt more hay per acre from 1856 to 1875, and plot 3 should therefore be taken as the true unmanured plot. In 1959 the surface and subsoils of the two plots contained identical amounts of organic matter, total N and readily soluble K and had the same pH, but plot 12 contained more total P and $CaCl_2$-soluble P. A difference in P content would persist much longer than one in K and probably longer than small differences in organic matter and organic N. The small extra amount of P, at such small P content of the soil, could account for part at least of the 2 cwt extra hay per acre still obtained on plot 12 during the past 40 years.

At the beginning of the experiment there were three main groups of fertiliser treatments, no N, N as ammonium salts at 3 rates and N as sodium nitrate at 2 rates, supplying the same amounts of N as the 2 smaller rates of ammonium salts. Within the 3 groups there were comparisons of O and P with and without K Na Mg for some of the rates of N. All fertilisers were applied each year. Another group of treatments also applied each year, tested farmyard manure (FYM), FYM + fertiliser N, chaffed straw + N P K Na Mg and sawdust. The sawdust was applied to some of the plots in two of the groups of fertiliser treatments, no N and ammonium salts. The object was to increase the carbon dioxide content of the soil water by the decomposition of the sawdust. Liebig, in *Principles of Agricultural Chemistry*, 1855, stressed the importance of CO_2 for increasing the solvent action of the water on the soil minerals. The treatment with straw + N P K Na Mg was an attempt to simulate FYM. Neither straw nor sawdust had any effect on yield of hay during the first few years, and the sawdust treatment was stopped. Applications of straw, however, were continued for about 40 years, but the added organic matter accumulated as a peaty layer and began to injure the growth of the herbage, and in 1897 this treatment was also stopped. Although in the early years straw was without effect on yield, there was a benefit in later years, the average increase for the whole period was 7 cwt hay/acre (plot 9,

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TABLE 1

MANURIAL HISTORY OF THE PARK GRASS PLOTS, 1856–1963

PLOTS WITH UNCHANGED MANURING
or with only small changes before 1864

Plot	Treatment*	
NO NITROGEN GROUP starting 1856		
3	Unmanured	
12	Unmanured	
2	Unmanured from 1864	(farmyard manure 1856–63)
4/1	P (from 1859)	(sawdust 1856–58)
8	P Na Mg	(with K 1856–61, sawdust 1856–62)
7	P K Na Mg	
AMMONIUM-N GROUP starting 1856		
1	N_1	(with farmyard manure 1856–63)
4/2	N_2 P (from 1859)	(sawdust 1856–58)
10	N_2 P Na Mg	(with K 1856–61, sawdust 1856–62)
9	N_2 P K Na Mg	
11/1	N_3 P K Na Mg	
11/2	N_3 P K Na Mg Si (Si from 1862)	
NITRATE-N GROUP starting 1858		
17	N_1	
16	N_1 P K Na Mg	(P omitted 1866, 1867)
14	N_2 P K Na Mg	

PLOTS WITH MAJOR CHANGES IN MANURING

Plot	Treatment*	Period
AMMONIUM-N GROUP		
6	N_2 (with sawdust 1856–62)	1856–1868
	P K Na Mg	1869–1963
5/1	N_2	1856–1897
	Unmanured	1898–1963
5/2	N_2	1856–1897
	P K	1898–1963
13	N_2 P K Na Mg (and straw till 1897)	1856–1904
	Farmyard manure; fish guano	1905–1963
	(4-year cycle; farmyard manure in year 1, fish guano in year 3)	
18	N P K Na Mg Si	1865–1904
	N_2 K Na Mg	1905–1963
NITRATE-N GROUP		
15	N_2	1858–1875
	P K Na Mg	1876–1963
19	N_1 P K	1872–1904
	Farmyard manure once in 4 years	1905–1963
20	N_1 P K	1872–1904
	N P K farmyard manure	1905–1963
	Farmyard manure once in 4 years, fertilisers in other years.	

LIMING*

Between 1883 and 1897 lime was applied to all plots. From 1903 lime was made a test treatment on the south halves of thirteen plots (16 and 1–13 except 5/1, 5/2, 6, 12). Three more plots (14, 15, 17) were divided for the lime test in 1920, and since then the south halves of plots 1–17, except 5/1, 5/2, 6 and 12, have received lime every 4th year.

Plots 18, 19, 20 were also divided in 1920, but lime was applied at rates determined by two laboratory methods for measuring the lime requirements of soils. The dressings were repeated every 4th year.

* Rates of manures and lime are shown in Table 2.

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TABLE 2

DETAILS OF MANURES AND LIMING MATERIALS, PARK GRASS, 1856–1963

Fertilisers applied annually, except those on Plot 20, where they are omitted when farmyard manure (FYM) is given. FYM and fish guano applied once in 4 years except Plots 1 and 2, which received annual applications of FYM 1856–63. Sawdust and straw were annual applications. Lime applied once in 4 years since 1903 with two exceptions. P, K, Na and Mg applied in the winter (December–February), the nitrogen during March–April, the highest rate of ammonium-N (129 lb) and nitrate-N (86 lb) are given in two dressings (since 1883 ⅔ ammonium-N and ½ nitrate-N given in the first application). Before 1914 the ammonium-N applied 2–3 weeks before the nitrate-N dressings, since then both forms of nitrogen applied at the same time.

Rates per acre

NITROGEN

Ammonium sulphate at 210, 420, 630 lb. These three rates (N_1, N_2, N_3) supplied 43, 86, 129 lb N.

Exceptions	Plot 11	*1856–1858*	172 lb N
		1859–1861	86 lb N
		1862–1881	172 lb N
	Plot 18	*1865–1904*	35 lb N
	Plot 20	*1905–1963*	26 lb N

Before 1917 a mixture of equal weights of ammonium sulphate and ammonium chloride was used. In 1901 the mixed salts were compared with ammonium bicarbonate on halves of plots 5, 9, 10, 11/1, 11/2.

Sodium Nitrate at 275, 550 lb. These two rates (N_1, N_2) supplied 43, 86 lb N.

Exceptions	Plot 20	*1872–1904*	43 lb N as potassium nitrate

PHOSPHORUS

Superphosphate 392 lb containing 29–30 lb P (66–69 lb P_2O_5)

Exceptions	Plot 18	*1865–1904*	52 lb superphosphate
	Plot 20	*1905–1963*	200 lb superphosphate

From 1856 to 1888 superphosphate was made on the Farm from 200 lb bone ash and 150 lb sulphuric acid. After 1888 it was supplied ready made and the weight was adjusted to give the same amount of phosphorus as in the first period. 1897–1902 basic slag (400 lb) used instead of superphosphate.

POTASSIUM

Potassium sulphate		1856–1878	300 lb containing 120 lb K (145 lb K_2O)
		1879–1963	500 lb containing 200 lb K (240 lb K_2O)
Exceptions	Plot 18	*1865–1897*	76 lb potassium chloride
		1898–1904	76 lb potassium sulphate
	Plot 19	*1872–1904*	290 lb potassium sulphate
	Plot 20	*1872–1904*	327 lb potassium nitrate
		1905–1963	100 lb potassium sulphate

Potassium dressings omitted 1917 and 1918.

SODIUM

Sodium sulphate		1856–1863	200 lb containing 28 lb Na
		1864–1963	100 lb containing 14 lb Na
Exceptions	Plots 8, 10	*1862–1863*	500 lb
		1864–1904	250 lb
	Plot 18	*1865–1870*	50 lb sodium silicate
		1871–1904	100 lb sodium silicate

MAGNESIUM

Magnesium sulphate 100 lb containing 10 lb Mg

Exceptions	Plot 18	*1865–1904*	35 lb of the sulphate

Magnesium dressings omitted 1917 and 1918.

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TABLE 2—continued

SODIUM SILICATE

Plot 11/2	1862–1870	200 lb sodium silicate + 200 lb calcium silicate
	1871–1963	400 lb sodium silicate
Plot 18	1865–1870	50 lb sodium silicate + 50 lb calcium silicate
	1871–1904	100 lb sodium silicate

Analysis of sodium silicate: the chemical composition of the mixed silicates is not known, but the sodium silicate used since 1904 was a water-soluble powder with a weight ratio $SiO_2 : Na_2O$ of approximately 3.

FARMYARD MANURE, 14 tons

Plots 1 and 2 1856–63 annual applications, none since.
Plots 13, 19, 20 first application 1905 and then every 4th year except 1917.

FISH GUANO

6 cwt in 1907, 1910, 1915 and then every 4th year until 1955. From 1959 onwards the weight of fish meal was adjusted to supply 56 lb N.

SAWDUST

2,000 lb.

STRAW

2,000 lb chaffed wheat straw.

LIMING MATERIALS

In 1881 dried sieved (¼ in.) chalk was applied at 2,500 lb/acre to a strip 50 links wide at the north end of plots 1–13. From 1883 to 1896 slaked lime was applied first to one half of each plot and later to the other half, so at the end of the period the whole of each plot had received 2,000 lb CaO/acre, except plots 5, 11/1, 11/2, where the total dressing was 4,000 lb.

In January 1903 plots 16 and 1–13 except 5/1, 5/2, 6 and 12 were halved in length and the south half of each plot dressed with ground lime (2,000 lb CaO/acre). The dressing was repeated in 1907 and 1915. In 1920 plots 14, 15, 17 were also divided for liming, and in that year the rate was increased to 2,500 lb CaO. Since then the south halves of the plots 1–17 except 5/1, 5/2, 6 and 12 have been limed every 4th year at the equivalent of 2,000 lb CaO/acre.

Another scheme of liming was introduced in 1920 on plots 18, 19, 20. Each plot was divided into three, and two of the sub-plots were limed at rates determined by two laboratory methods for measuring the lime requirements of soils, Hutchinson and MacLennan (1915): Fisher (1921).

The dressings given were:

Sub-plot	Method	Plot 18	Plot 19	Plot 20
		CaO (lb/acre)		
1	—	0	0	0
2	Hutchinson	6788	3151	2775
3	Fisher	3951	571	571

These dressings were repeated every 4th year.

From 1960 the equivalent amounts of ground chalk have been used in place of the slaked or ground lime on all limed plots.

N P K Na Mg, 54 cwt; plot 13, straw + N P K Na Mg, 61 cwt). Hall (1919) ascribed the increase partly to the shelter that the chaffed straw provided in the early spring (for it was noticed that growth started earlier on this plot) and partly to the extra water retained by the humus formed by its decay.

Trouble also arose with annual applications of FYM because unrotted material accumulated on the surface, and the treatment was discontinued in 1863 after eight applications (plots 1 and 2). From the results of the 8

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years Lawes and Gilbert concluded that the benefit from FYM came solely from the nutrients it contained and that yields could be further increased by giving fertiliser N along with FYM. One of the plots was then used to measure the residual effect of the organic manure. During the next 12 years this plot gave an average of 13 cwt more hay per acre than the unmanured plot. Unlike the experiments on Broadbalk, Hoosfield and Barnfield, there is now no treatment with FYM on Park Grass dating back to the beginning of the experiment. The present FYM treatments, which are applied only once in 4 years, started soon after the beginning of this century and all were applied to plots which had received other manurial treatments in the preceding 30–50 years. Their earlier treatments much altered the herbage and the soil by the time the FYM was applied. The acidity on the unlimed part of the FYM plot (13) is *not* from FYM applied since 1905 but from the ammonium salts applied before then. The difference in acidity between the unlimed half of the FYM plot (13) and the unlimed unmanured plot (3) is slowly diminishing; it was 1·2 pH units in 1923 and 0·5 in 1959.

Lawes and Gilbert were much concerned about the function of silica in plants, and to test the hypothesis that silica increases the stiffness of the straw and makes cereals less liable to lodge, they introduced a silicate treatment in the Hoos Barley experiment and also in Park Grass on plot 11, which grew a lush crop of grass. Changes were made in other treatments, principally to plots treated with only N fertilisers. Ammonium salts had not only changed the kinds of grass but also eliminated legumes; sodium nitrate also decreased the proportion of legumes. The N fertilisers were replaced by P K or P K Na Mg to measure the rates at which legumes reappeared. Because the repeated heavy dressing with ammonium salts was beginning to damage the herbage by the accumulation of a peaty layer, Lawes and Gilbert limed half of every plot in 1883, observed the effects and limed the remainder between 1887 and 1897. Hall, who succeeded Lawes and Gilbert in 1902, altered several of the treatments. He started the treatment with lime applied every fourth year on halves of most of the plots, and this produced remarkable changes in the botanical composition of the herbage. In 1920 three more plots were divided and used to test two laboratory methods for measuring the lime requirement of soils. Tables 1 and 2 show the history of the plots and details of the rates of manuring and liming.

The Effect of Manuring and Liming on Soil Reaction

The first set of determinations of the soil reaction (pH) of all the Park Grass plots was made by Crowther in 1923 at the end of a 4-year liming cycle. The pH values of surface soil, 0–9 in., and subsoils, 9–18 in., were measured by the hydrogen electrode method using a 1 : 5 soil–water suspension. In 1959, again at the end of a liming cycle, the plots were re-sampled and pH measured. On both dates the mat, about 1½ in., on the very acid plots was removed before taking the soil samples. In 1959 the glass electrode and 1 : 2·5 soil–water suspension were used. Crowther (1925) showed that doubling the amount of water increased pH by approxi-

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mately 0·1 unit, and this correction can be applied where necessary when comparing the results of the two sets of soil samples. A greater source of error may arise from differences in the amounts of soluble salts present in a soil at different times of sampling. This error is eliminated by Schofield's (1955) method in which 0·01*M*-$CaCl_2$ is used instead of water. In 1959 pH was determined by this method also, and values were uniformly smaller than with water, 0·4 units for the very acid soils and 0·5–0·6 for the less acid and near neutral soils. This consistency in the differences between the two methods gives added confidence when comparing the results of the 1923 and 1959 soil samples. Table 3 shows the pH values (in water) on the two occasions for plots without major changes in manuring. During

TABLE 3

Soil reaction, Park Grass, 1923 and 1959

Surface soils 0–9 in., subsoils 9–18 in.: U = unlimed, L = limed

		pH in water							
		1923				1959			
		Surface soils		Subsoils		Surface soils		Subsoils	
Plot	Treatment	U	L	U	L	U	L	U	L
No nitrogen group									
3	Unmanured	5·7	6·9	6·2	6·6	5·2	7·2	5·3	6·8
12	Unmanured	5·6	—	6·1	—	5·2	—	5·4	—
2	Unmanured	5·9	7·2	—	—	5·2	7·3	5·3	6·8
4/1	P	5·7	7·1	6·0	6·8	5·2	7·1	5·3	6·6
8	P Na Mg	5·7	7·0	—	—	5·2	7·0	5·3	6·6
7	P K Na Mg	5·4	6·7	5·9	6·2	4·9	7·0	5·0	6·3
Ammonium-N group									
1	N_1	4·8	6·5	6·2	6·4	4·0	7·2	5·2	6·6
4/2	N_2 P	3·9	4·8	5·1	6·1	3·7	5·7	4·2	5·6
10	N_2 P Na Mg	3·9	4·7	—	5·6	3·8	5·6	4·4	5·6
9	N_2 P K Na Mg	4·0	4·5	4·8	5·2	3·8	5·3	4·3	5·2
11/1	N_3 P K Na Mg	3·8	4·1	4·4	4·7	3·7	4·2	4·1	4·4
11/2	N_3 P K Na Mg Si	3·8	4·6	4·3	4·8	3·7	4·6	4·3	4·7
Nitrate-N group									
17	N_1	6·3	6·8	6·2	6·8	5·7	7·5	5·5	6·9
16	N_1 P K Na Mg	5·9	7·2	—	—	5·4	7·1	5·6	6·9
14	N_2 P K Na Mg	6·4	6·7	6·8	7·0	6·0	7·3	6·1	6·9

the 36 years the surface and subsoils of the unlimed plots without N have slowly increased in acidity (pH value decreasing from 5·7 to 5·2 and 6·0 to 5·3). The surface soil and subsoil of unlimed plots receiving nitrate-N (sodium nitrate) have both undergone similar changes in pH. In 1923 these plots were less acid than the plots without N, and the differences were maintained unchanged in the next 36 years. The differences for the surface soils on the two dates are:

Increases in pH from sodium nitrate

Plots, unlimed	1923	1959
17 (N_1)–3 (nil)	0.6	0.5
16 (N_1 P K Na Mg)–7 (P K Na Mg)	0.5	0.5
14 (N_2 P K Na Mg)–7 (P K Na Mg)	1.0	1.1

No explanation can be offered for sodium nitrate increasing pH before but not after 1923.

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Ammonium sulphate has made the soils very acid and its acidifying effect must now extend well below 18 in. From the 1923 results Crowther concluded that pH 3·8 represents the maximum acidity of the Park Grass soil. This is confirmed by the 1959 results, the pH value (3·7) of the surface soil of the unlimed plot receiving the most ammonium-N (plot 11/1) has not changed after annual applications of 630 lb ammonium sulphate per acre for 36 years. Ammonium sulphate at the middle rate (420 lb) has now also brought the pH to 3·7, and with the smallest rate (210 lb) the pH is but little higher (pH 4·0). The subsoils of these plots, except plot 1 (N_1) are nearly as acid (pH 4·1–4·4). In very acid soils, as on these plots, aluminium becomes an important exchangeable cation, and this change alters the shape and position of the titration curve of the soil. Russell (1961) quotes Schofield's results showing that the curve, obtained by measuring the pH values for increasing amounts of base, for the soil of plot 12 (unmanured) after treatment with aluminium chloride closely resembled the curve for the ammonium sulphate plot (11/1). By the treatment of the soil of plot 11/1 first with dilute acid and then with hard water for several days the new titration curve closely resembled that of plot 12.

Lime or its equivalent at 2,000 lb CaO/acre every fourth year increased the pH of the surface and the subsoil of plot 1, receiving ammonium sulphate at rate N_1 and the surface soil now contains 0·1% $CaCO_3$. At rate N_2, lime since 1923 has increased the pH of the surface soil but not the subsoil. Both surface and subsoil values have not changed, or only slightly, where most ammonium sulphate was given. Table 4 summarises the changes since 1923 in the pH values of the limed and unlimed plots receiving ammonium sulphate. For this table the 1923 values were adjusted for the difference in the soil–water ratio used in the determinations by subtracting 0·1 pH unit from the 1923 figures.

TABLE 4

Changes in pH between 1923 and 1959 from ammonium sulphate and lime

	Unlimed		Limed	
Ammonium sulphate	Surface soil	Subsoil	Surface soil	Subsoil
N_1	−0·7	−0·9	+0·7	+0·4
N_2	−0·1	−0·6	+0·9	−0·1
N_3	0·0	−0·1	+0·1	−0·1

The lime dressing, equivalent to 2,000 lb CaO/acre every fourth year, is more than is needed to maintain the soils of the no N and nitrate-N plots at pH 7. The excess has given only a small accumulation of $CaCO_3$ in the surface soils, 0·2–0·3% $CaCO_3$ in 36 years. Much Ca, equivalent to 6–7 cwt $CaCO_3$/acre each year, has therefore been lost. This is lost mainly in the drainage water, as the crops remove relatively little Ca. On the plot getting the most ammonium sulphate (plot 11/1, 630 lb/acre) the whole of the Ca in the lime dressing (equivalent to 8 cwt $CaCO_3$/acre each year) was lost from the top 18 in. of soil; the mean pH value of surface and subsoil has barely changed since 1923.

The manurial and liming treatments in the Park Grass experiment do not provide satisfactory estimates of the loss of calcium by the acidifying

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action of ammonium sulphate, or of the amounts of lime needed to maintain the soils between moderate acidity and neutrality.

In 1920 three plots (18, 19, 20) were used to test the laboratory methods of Fisher (1921) and Hutchinson–MacLennan (1915) for measuring the lime requirements of acid soils. Fisher's estimates of the lime needed for the soils of these plots were based on titration curves, using indicators. In the Hutchinson–MacLennan method the estimates were obtained from the interaction of the soils and a standard calcium bicarbonate solution. Table 5 shows the amount of lime (CaO) applied and the pH values of the soils in 1923 and 1959 (4 and 40 years later) with lime applied

TABLE 5

Soil reaction, plots 18, 19, 20, Park Grass, 1923 and 1959

Surface soils 0–9 in., subsoils 9–18 in.

Plot	Lime dressings (lb CaO/acre once in 4 years)	pH in water 1923 Surface soil	1923 Subsoil	1959 Surface soil	1959 Subsoil
18/1	0	4·5	5·7	4·1	4·4
/3	3,951	4·7	5·6	7·1	6·6
/2	6,788	5·2	6·1	7·5	7·1
19/1	0	5·8	—	5·2	5·2
/3	571	5·7	—	5·8	5·4
/2	3,151	6·2	—	7·4	6·9
20/1	0	6·0	—	5·4	5·7
/3	571	6·2	—	6·2	5·9
/2	2,775	6·6	—	7·2	6·9

every fourth year. The first application of the lighter dressings of lime prescribed by Fisher's method had only small effects on the reaction of the soils. The calcium bicarbonate method was more successful, but failed on the very acid soil of plot 18 (pH 4·5). The tests on plot 18 give but little information on the effects of lime and ammonium sulphate because of the long interval between the two occasions of soil sampling. The results on plots 19 and 20 cannot be linked with the main section of the Park Grass experiment because the manuring was different.

Botanical Composition of the Herbage

Full details of the botanical composition of the herbage during the course of the experiment are given in the following accounts, Lawes, Gilbert and Masters (1882), Hall (1919), Brenchley (1924 and 1935), Warington (1958).

The fertilisers quickly changed the proportions of grasses, legumes and weeds in the herbage. Nitrogen fertilisers suppressed legumes and weeds and P K fertilisers without N encouraged legumes. Table 6 shows the extent and rapidity of the changes. In 1858, two years from the start of the experiment, P K fertilisers increased the legumes from 5 to 20% (dry weight basis) and weeds were rare (all plants other than grasses and legumes are classed as weeds). Ammonium sulphate alone or with P K fertilisers eliminated the legumes and most of the weeds, leaving a herbage with 90% or more grasses. This large proportion has continued through

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TABLE 6

Botanical composition of hay, Park Grass, 1858 and 1877

Percentage of grasses, legumes and weeds

		Grasses		Legumes		Weeds	
Plot	Treatment	1858	1877	1858	1877	1858	1877
3	Unmanured	76	71	5	8	16	21
7	P K Na Mg	72	74	23	14	2	12
9	N_2 P K Na Mg	97	95	0	0	2	5
14	N_2* P K Na Mg	—	88	—	1	—	11
5	N_2 (till 1897)	89	94	2	0	6	6
15	N_2* (till 1875)	—	83	—	2	—	15

N* Sodium nitrate since 1858. N Ammonium salts since 1856.

the succeeding years, but the types of grasses have changed. The increases in grasses on the sodium nitrate plots, first manured in 1858, were nearly as large and the legumes had disappeared by 1862 when the next botanical analysis was made. Manuring with N ceased on plot 15 in 1875 and on plot 5 in 1897; it was replaced in 1876 and 1898 respectively by P K. Legumes began to reappear, they were 30% of the herbage after 30 years on plot 15 and after 50 years on plot 5/2.

Table 7 shows the average composition of the herbage of 4 plots (3, 7, 9, 14, limed and unlimed) for each of two 4-year periods in recent times,

TABLE 7

Botanical composition of hay, Park Grass, 1936–39, 1944–47

Percentage of grasses, legumes and weeds

			Grasses		Legumes		Weeds	
Treatment	Plot		1936–39	1944–47	1936–39	1944–47	1936–39	1944–47
Unmanured	3	Unlimed	42	53	7	10	51	37
		Limed	44	31	15	18	41	51
P K Na Mg	7	Unlimed	49	36	30	29	21	35
		Limed	63	62	20	20	17	18
N_2 P K Na Mg (ammonium-N)	9	Unlimed	100	99	0	0	0	1
		Limed	96	92	1	2	3	6
N_2 P K Na Mg (nitrate-N)	14	Unlimed	94	94	1	2	5	4
		Limed	89	88	3	9	8	3

1936–39 and 1944–47. The two main effects are that N decreased the legumes and weeds and P K increased the legumes, as in the early years, 1858 and 1877. Since 1877 on the unlimed halves of the plots without N, weeds increased at the expense of grasses, legumes increased on the P K plot, but otherwise the results for the later years differ little from the early figures. Lime, since the beginning of the century, has changed the proportion of grasses, legumes and weeds on only one of the four plots, the grasses on the P K plot increasing from about 40 to 60%. Both legumes and weeds were less, but as the yield of hay on this plot was increased by liming (about 30%), the weight of legumes per acre altered little.

Lime and fertiliser also produced remarkable differences in the species within each of the three broad groups of plants. To assess the separate effects of the two factors, even on the main species, a greater range of treatments is needed in the experiment, especially rates of lime. Some

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indications on the effects of these factors on the species of grasses are in Table 8, where the dominant species are expressed as percentages by weight of the total grasses. On soils with pH values 3·7–4·1 and where the

TABLE 8

Effect of manuring and soil reaction on grass species, Park Grass, 1947–49

Each species expressed as per cent by weight of the grass fraction: species present in amounts less than 10% are omitted from the table.

Plot	Treatment	Soil reaction pH 3·7–4·1		pH 4·2–6·0		pH 6·0–7·5	
1	N_1	Fine bent	79			Cocksfoot	29
		Red fescue	16			Red fescue	24
						Downy oat	19
17	N_1*			Cocksfoot	36	Red fescue	27
				Meadow foxtail	20	Cocksfoot	25
				Red fescue	13	Downy oat	25
				Sweet vernal	12		
				Yorkshire fog	12		
18	N_2 K Na Mg	Fine bent	88			Cocksfoot	50
		Red fescue	10			Tall oat	30
4/2	N_2 P	Fine bent	36	Red fescue	60		
		Red fescue	35	Meadow foxtail	25		
		Yorkshire fog	18				
		Sweet vernal	10				
10	N_2 P Na Mg	Fine bent	52	Red fescue	58		
		Yorkshire fog	22	Meadow foxtail	30		
		Sweet vernal	10				
		Red fescue	10				
9	N_2 P K Na Mg	Yorkshire fog	91	Meadow foxtail	42		
				Tall oat	16		
				Cocksfoot	13		
				Smooth stalked meadow grass	10		
11/1	N_3 P K Na Mg	Yorkshire fog	100	Meadow foxtail	84		
11/2	N_3 P K Na Mg Si	Yorkshire fog	93	Meadow foxtail	59		
				Tall oat	18		
				Smooth stalked meadow grass	11		
				Cocksfoot	10		
14	N_2* P K Na Mg			Tall oat	39	Tall oat	48
				Meadow foxtail	34	Cocksfoot	14
				Crested dogstail	15	Crested dogstail	14
						Meadow foxtail	13

Cocksfoot	*Dactylis glomerata*
Crested dogstail	*Cynosurus cristatus*
Downy oat	*Heliototrichon pubescens*
Fine bent	*Agrostis tenuis*
Meadow foxtail	*Alopecurus pratensis*
Red fescue	*Festuca rubra*
Smooth stalked meadow grass	*Poa pratensis*
Sweet vernal	*Anthoxanthum odoratum*
Tall oat	*Arrhenatherum elatius*
Yorkshire fog	*Holcus lanatus*

N* as sodium nitrate, all other plots receive ammonium sulphate.

manuring was deficient in P, the main grass was Fine bent. When P was given along with ammonium-N Fine bent was still the dominant species, but the grass fraction of the herbage contained about 20% Yorkshire fog.

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With full manuring (N P K) all or nearly all of the grass was Yorkshire fog. With the same full manuring but on less acid soils, pH 4·2–6·0, this grass was replaced chiefly by Meadow foxtail and small amounts of Tall oat. Omitting K decreased the Meadow foxtail on this class of soil (pH 4·2–6·0), and Red fescue became the dominant grass, except on plot 17 (43 lb N as sodium nitrate), where Cocksfoot replaced the Meadow foxtail. In the third soil class (pH 6·0–7·5), where P and K were omitted, Meadow foxtail was replaced by Cocksfoot, Red fescue and oat grasses. With N_2PK (plot 14) Meadow foxtail was present, but there was also much Tall oat and Cocksfoot. The results showed that Meadow foxtail needs P K in addition to N fertiliser, and that there is a critical limit of soil acidity (pH 4·2) below which it does not grow, but less is known about its growth in neutral and slightly calcareous soils.

The botanical analyses of the grasses on the FYM plots (13, 19, 20) are not discussed because two of them also receive fertilisers or fish guano. None started before the beginning of this century, and the soil of one of them was extremely acid before it received FYM, because of ammonium sulphate applied previously.

Yield of Herbage

Until 1958 the grass on the whole of each plot was made into hay, and samples were taken to determine dry matter. From 1959 a part of each plot was cut at the hay stage by flail harvester, the herbage was weighed green and yields, unaffected by haymaking losses, were recorded as dry matter. To maintain the traditional procedure, which may have contributed to the botanical composition of the herbage by reseeding, the remainder of the crop was cut by mower and made into hay. The aftermath was grazed by sheep until 1874, but later was cut and weighed green, though occasionally made into hay. The yield results for the green grass were until recently converted to equivalent "hay" weights (80% dry matter), but after 1958 were recorded as dry matter.

The hay results have been reported during the course of the experiment by Lawes and Gilbert (1880), Hall (1919), Brenchley (1924 and 1930), Cashen (1947) and Warington (1958). Warington included 10 years' averages till 1949 for the hay crops in the most recent account of the botanical composition of the herbage.

Because the manurial treatments rapidly changed the type of herbage, Lawes and Gilbert realised that weight was not a satisfactory measure of the worth of a crop, and they therefore gave more emphasis to the results of the botanical composition. The effects of the manures can be assessed practically only from the nutritional values of the crops. When considering treatment effects on yield in this experiment it must be remembered that the crops are not botanically identical.

Cashen (1947) made a statistical examination of the effect of 1 in. extra rain, between mid-March and early July, on the yield of hay in the years 1858–1902. The crops on all plots benefited by the extra rain, and its effect was greatest when it came in the second half of April. Maximum benefit from 1 in. was $4\frac{1}{2}$ cwt hay/acre on the ammonium sulphate plots

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and 3 cwt where sodium nitrate was given. Extra rain did not alter the botanical composition of the crop in that year or in the one after. Cashen also examined the hay results for deterioration of yield and concluded that it was much less during the period 1920–40 than before 1900.

TABLE 9

Mean annual yield—Park Grass plots, 1920–59

Dry matter (cwt/acre)

Plot	Present treatment	Unlimed 1st crop	Unlimed 2nd crop	Unlimed Total	Limed 1st crop	Limed 2nd crop	Limed Total
	Plots with unchanged manuring since 1864						
No nitrogen group							
3	Unmanured	8·2	3·6	11·8	9·7	3·3	13·0
12	Unmanured	10·1	4·9	15·0	—	—	—
2	Unmanured	9·4	4·2	13·6	10·8	4·0	14·8
4/1	P	12·5	4·6	17·1	11·7	4·2	15·9
8	P Na Mg	15·1	6·4	21·5	12·1	5·1	17·2
7	P K Na Mg	20·5	8·7	29·2	27·0	8·3	35·3
Ammonium-N group							
1	N_1	8·4	5·2	13·6	14·1	4·8	18·9
4/2	N_2 P	11·9	4·5	16·4	23·6	5·8	29·4
10	N_2 P Na Mg	16·8	7·4	24·2	28·4	7·1	35·5
9	N_2 P K Na Mg	27·0	10·2	37·2	36·5	8·4	44·9
11/1	N_3 P K Na Mg	27·1	17·1	44·2	41·9	11·7	53·6
11/2	N_3 P K Na Mg Si	34·0	16·8	50·8	44·2	14·7	58·9
Nitrate-N group							
17	N_1	15·2	5·9	21·1	17·7	5·3	23·0
16	N_1 P K Na Mg	26·9	7·9	34·8	27·5	7·9	35·4
14	N_2 P K Na Mg	38·4	11·1	49·5	36·9	8·3	45·2
	Plots with major changes in manuring						
6	P K Na Mg	20·6	8·2	28·8	—	—	—
5/1	Unmanured	7·2	3·3	10·5	—	—	—
5/2	P K	14·4	6·0	20·4	—	—	—
13	FYM, fish guano	27·7	9·9	37·6	26·3	8·9	35·2
15	P K Na Mg	18·1	7·1	25·2	21·4	6·6	28·0

TABLE 10

Mean annual yield, plots 18, 19, 20, Park Grass, 1920–59

Dry matter (cwt/acre)

Plot	Lime dressings (lb CaO/acre once in 4 years)	1st crop	2nd crop	Total
18/1	0	11·7	7·9	19·6
3	3,951	20·8	6·2	27·0
2	6,788	23·3	6·4	29·7
19/1	0	21·4	8·4	29·8
3	571	21·4	7·2	28·6
2	3,151	19·9	6·8	26·7
20/1	0	28·2	8·6	26·8
3	571	28·4	8·0	36·4
2	2,775	27·4	7·4	34·8

The present account of the yields deals with the results for the years 1920–59 when manuring and liming remained unchanged. Tables 9 and 10 show for this period the mean yields of dry matter for the 1st and 2nd

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crops and their total. Yields of the 2nd crop received little attention in the earlier accounts of the experiment, but they contributed appreciably to the total dry matter, especially on the unlimed plots getting most ammonium sulphate (plots 11/1, 11/2). The 2nd crops were 17 cwt dry matter/acre, compared with 1st crops of 27 cwt (11/1) and 34 cwt (11/2). On all other plots the 2nd crops were one-third to one-quarter of the 1st crops. Yorkshire fog (unlimed halves of plots 11/1, 11/2) differs therefore from Meadow foxtail and the mixed plant species in the distribution of growth between the early and late crops.

Table 11, which summarises the effects of lime on the yields of the unmanured and fertiliser plots, shows that lime benefited the crop on the

TABLE 11

Increases from lime, Park Grass, 1920–59

Dry matter (cwt/acre)

		Nitrogen fertiliser	
Other fertilisers	None	Ammonium	Nitrate
None	1·2, 1·2	5·3	1·9
P or P Na Mg	−1·2, −4·2	13·0, 11·3	—
P K Na Mg	6·1	7·7, 9·4, 8·1	0·6, −4·3

P K plot, where legumes are plentiful. There were substantial increases from lime where ammonium sulphate was given, but none with sodium nitrate, reflecting the difference between the effects of these fertilisers on soil reaction. Extra yields were not always obtained from lime applied to acid soils, on two FYM plots (13, 19) at pH 4·7 and 5·2 lime decreased yields by 2 cwt.

Nitrogen increased the yield greatly. Where equal amounts of fertiliser N (86 lb/acre) were given on the limed plots the yields from ammonium sulphate and sodium nitrate were identical (45 cwt), but sodium nitrate outyielded ammonium sulphate by 12 cwt where lime was omitted. Measurement of the effect of increasing levels of fertiliser N is limited to the differences between the N_2 and N_3 rates of ammonium sulphate and the N_1 and N_2 rates of sodium nitrate. To measure the effect of the first 43 lb of fertiliser N (N_1) in the presence of P K Na Mg is impossible, because the crop on plot 7 (P K Na Mg) contained 30–40% legumes which fixed N. The yields of dry matter on plot 7 with lime and plot 16 N_1 P K Na Mg (N as nitrate) were the same.

Both P and K are needed on the Park Grass soil to produce good crops of grass–legume herbage and also of grassy herbage when fertiliser N is used.

The Amounts of N, P, K, Na, Ca and Mg in the Herbage

The crops were analysed chemically by Lawes and Gilbert (1900) during the period up to 1873, when the botanical composition of the herbage was changing. The lime treatment was introduced in the experiment in 1903, and since then crops were analysed for three 4-year periods, 1920–23, 1940–43, 1956–59. Tables 12 and 13 show for some of the plots with un-

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changed fertiliser treatments the percentages of N, P, K, Na, Ca and Mg in the first and second crops and Tables 14 and 15 the amounts per acre of these elements in the total produce. Comparisons are much limited for reasons given in the discussion of yields, and only a short summary is given for each element.

TABLE 12

Percentage N, P, K in dry matter of herbage, Park Grass, means of 12 years, 1920–23, 1940–43, 1956–59

U = unlimed, L = limed

Plot	Treatment	N U	N L	P U	P L	K U	K L
			1st crop				
No nitrogen group							
3	Unmanured	1·87	1·82	0·14	0·16	1·47	1·34
8	P Na Mg	1·75	1·72	0·38	0·36	1·20	1·22
7	P K Na Mg	1·76	1·72	0·32	0·30	2·90	3·17
Ammonium-N group							
4/2	N_2 P	2·50	2·15	0·32	0·36	0·69	0·64
10	N_2 P Na Mg	2·24	1·88	0·29	0·33	0·66	0·55
9	N_2 P K Na Mg	1·69	1·50	0·26	0·27	2·72	2·76
11/1	N_3 P K Na Mg	2·02	1·76	0·25	0·27	2·67	3·04
Nitrate-N group							
16	N_1 P K Na Mg	1·52	1·44	0·29	0·28	2·80	2·65
14	N_2 P K Na Mg	1·46	1·46	0·26	0·25	2·57	2·66
			2nd crop				
No nitrogen group							
3	Unmanured	1·75	1·68	0·13	0·15	1·20	1·02
8	P Na Mg	1·80	1·84	0·38	0·39	0·99	1·06
7	P K Na Mg	2·01	1·94	0·33	0·36	2·57	2·63
Ammonium-N group							
4/2	N_2 P	2·37	1·98	0·31	0·35	0·60	0·57
10	N_2 P Na Mg	2·34	1·91	0·29	0·33	0·59	0·56
9	N_2 P K Na Mg	1·79	1·74	0·25	0·30	2·31	2·02
11/1	N_3 P K Na Mg	1·90	1·58	0·25	0·24	2·60	1·93
Nitrate-N group							
16	N_1 P K Na Mg	1·72	1·59	0·31	0·29	2·07	1·86
14	N_2 P K Na Mg	1·62	1·51	0·29	0·27	1·97	1·74

Nitrogen. On plots without N or where N was given as sodium nitrate, the % N in the crop was not altered by lime and the differences in the amounts of N (lb/acre) reflected effects of lime on yield. Lime decreased the % N in the crops grown with ammonium sulphate.

The crop on plot 7 (P K Na Mg) where legumes, mainly Meadow vetchling, fixed N contained 38 lb N/acre more than the unmanured crop: the increases from fertiliser N at 86 lb N/acre (N_2) were 48 lb with ammonium sulphate and 54 lb with sodium nitrate. With the smallest rate of sodium nitrate, 43 lb N/acre, much of the N (38 lb) was recovered, but whether the few legumes on this plot contributed much is not known.

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TABLE 13

Percentage Na, Ca, Mg in dry matter of herbage, Park Grass, means of 12 years, 1920–23, 1940–43, 1956–59

U = unlimed, L = limed

Plot	Treatment	Na U	Na L	Ca U	Ca L	Mg U	Mg L
				1st crop			
No nitrogen group							
3	Unmanured	0·35	0·34	0·97	1·03	0·24	0·33
8	P Na Mg	0·49	0·40	0·83	0·78	0·24	0·26
7	P K Na Mg	0·05	0·03	0·52	0·70	0·14	0·18
Ammonium-N group							
4/2	N_2 P	0·32	0·34	0·21	0·61	0·14	0·28
10	N_2 P Na Mg	0·53	0·54	0·18	0·51	0·16	0·26
9	N_2 P K Na Mg	0·06	0·02	0·15	0·36	0·11	0·13
11/1	N_3 P K Na Mg	0·10	0·05	0·16	0·26	0·12	0·12
Nitrate-N group							
16	N_1 P K Na Mg	0·18	0·11	0·39	0·50	0·14	0·15
14	N_2 P K Na Mg	0·27	0·21	0·28	0·36	0·12	0·13
				2nd crop			
No nitrogen group							
3	Unmanured	0·21	0·21	0·99	1·18	0·22	0·31
8	P Na Mg	0·52	0·35	0·86	0·95	0·26	0·32
7	P K Na Mg	0·07	0·03	0·71	0·83	0·15	0·18
Ammonium-N group							
4/2	N_2 P	0·33	0·23	0·33	0·69	0·15	0·24
10	N_2 P Na Mg	0·56	0·35	0·37	0·66	0·19	0·23
9	N_2 P K Na Mg	0·06	0·02	0·26	0·54	0·11	0·13
11/1	N_3 P K Na Mg	0·10	0·03	0·26	0·39	0·12	0·12
Nitrate-N group							
16	N_1 P K Na Mg	0·12	0·07	0·54	0·68	0·14	0·16
14	N_2 P K Na Mg	0·13	0·07	0·44	0·58	0·13	0·12

TABLE 14

Average yearly content of N, P and K in the herbage, Park Grass, mean of three periods 1920–23, 1940–43, 1956–59, sum of 1st and 2nd crops

lb element/acre

Plot	Treatment	N U	N L	P U	P L	K U	K L
No nitrogen group							
3	Unmanured	24	28	2	2	18	19
8	P Na Mg	44	37	10	8	28	25
7	P K Na Mg	60	68	10	12	92	115
Ammonium-N group							
4/2	N_2 P	51	70	7	12	14	20
10	N_2 P Na Mg	65	74	8	13	18	22
9	N_2 P K Na Mg	72	77	11	14	109	130
11/1	N_3 P K Na Mg	104	105	13	16	139	169
Nitrate-N group							
16	N_1 P K Na Mg	61	66	11	12	102	108
14	N_2 P K Na Mg	84	75	15	13	136	125

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Phosphorus. The % P in the unmanured crop was very little (0·15); values where fertiliser P was given were 0·25–0·35, and amounts of P in these crops were mainly determined by the yields. The greatest recovery of fertiliser P by the crop was 14 lb (plot 11/1 limed half).

Potassium. The % K in the unmanured crop was half as much as in those given K fertiliser, but double as much as in those given N P fertilisers alone. Crops grown without K extracted only 20 lb K/acre from the starved Park Grass soil; where fertiliser K was given the crops contained 90–170 lb K/acre: the most extracted was nearly three-quarters of the added K.

TABLE 15

Average yearly content of Na, Ca and Mg in the herbage, Park Grass, mean of three periods 1920–23, 1940–43, 1956–59, sum of 1st and 2nd crops

		lb element/acre					
		Na		Ca		Mg	
Plot	Treatment	U	L	U	L	U	L
No nitrogen group							
3	Unmanured	4	5	11	17	3	5
8	P Na Mg	12	8	21	18	6	6
7	P K Na Mg	2	1	19	28	5	7
Ammonium-N group							
4/2	N_2 P	7	10	5	21	3	9
10	N_2 P Na Mg	16	20	7	21	5	10
9	N_2 P K Na Mg	2	1	8	20	5	6
11/1	N_3 P K Na Mg	5	2	11	18	6	7
Nitrate-N group							
16	N_1 P K Na Mg	7	4	16	24	6	7
14	N_2 P K Na Mg	13	9	18	20	7	6

Sodium and magnesium. The outstanding feature of the analysis for Na (Table 15) is the extent to which K fertiliser depressed the uptake of Na, applied as sodium sulphate (= 14 lb Na/acre) (plots 7, 8 and 9, 10). Even from the much larger dressing of 163 lb Na (sodium nitrate with sodium sulphate), less than 10% was recovered in the crop. Mangolds on Barnfield showed the same effect.

On Park Grass, as in the Hoosfield and Barnfield experiments, there was no separate test of Mg, which was applied with Na. The uptakes of Mg were similar (5–7 lb Mg/acre) on all plots (limed and unlimed) where Mg fertiliser was applied, except on the limed part of plot 10 (10 lb Mg). The larger value on this plot with N P fertiliser and without K may reflect the interaction of K and Mg.

Calcium. The % Ca in the herbage of the plots is influenced by the genera and species, and increases with increases in legumes (plot 7) or "weed" species (plot 3). The crop of Yorkshire fog on the unlimed part of plot 11/1 contained 0·2% Ca; lime changed the grass on this plot to Meadow foxtail with 0·3% Ca. These results add nothing that is new; Gardner and Garner (1953) deal fully with the effects of lime on hay and the Ca contents of legumes, grass species and weeds.

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The lime treatment, which supplied about 1,400 lb Ca/acre every fourth year, only slightly increased Ca in the crops: average gains, lb Ca/acre, were: plots without N, 4; with ammonium sulphate, 12; with sodium nitrate, 5.

Although yield of herbage is important the value of grass to stock that eat it depends largely on the concentration and balance of various chemical constituents it contains. The same yield of dry matter can be obtained by different fertiliser and lime treatments but the composition may differ greatly. The results of the chemical analysis of the herbage from the Park Grass plots provide good examples of the ways in which treatments alter composition. Table 16 shows the percentages of N, P, K, Na, Ca and Mg in the crops of 5 plots which yielded 35–37 cwt total dry matter/acre (27–28 cwt in hay crop and 7–10 cwt as aftermath).

TABLE 16

Park Grass, 1920–59

Composition of crops from plots yielding 35–37 cwt. dry matter/acre (27–28 cwt. as hay: 7–10 cwt. aftermath)

% in dry matter

Plot	Treatment	N Hay	N aftermath	P Hay	P aftermath	K Hay	K aftermath
7L	PK Na Mg	1·7	1·9	0·30	0·36	3·2	2·6
10L	N_2 P Na Mg	1·9	1·9	0·33	0·33	0·6	0·6
9U	N_2 PK Na Mg	1·7	1·8	0·26	0·25	2·7	2·3
16L	N_1* PK Na Mg	1·4	1·6	0·28	0·29	2·6	1·9
16U	N_1* PK Na Mg	1·5	1·7	0·29	0·31	2·8	2·1

Plot	Treatment	Na Hay	Na aftermath	Ca Hay	Ca aftermath	Mg Hay	Mg aftermath
7L	PK Na Mg	0·03	0·03	0·70	0·88	0·18	0·18
10L	N_2 P Na Mg	0·54	0·35	0·51	0·66	0·26	0·23
9U	N_2 PK Na Mg	0·06	0·06	0·15	0·26	0·11	0·11
16L	N_1* PK Na Mg	0·11	0·07	0·50	0·68	0·16	0·16
16U	N_1* PK Na Mg	0·18	0·12	0·39	0·54	0·14	0·14

N—Ammonium sulphate. N*—Sodium nitrate.

With the current rates of fertilisers given to the plots the analyses of the hay and aftermath were similar, those for P and Mg were almost identical. The high K values for hay on the plots with K fertiliser decreased by 0·4–0·8% K in the aftermath. Ca however increased significantly by 0·1–0·2% Ca. There were three large differences in the composition of the crops, both for hay and aftermath:

(1) Very low values were found for Mg (0·11%) on plot 9U (N_2PKNaMg). Where K fertiliser was omitted from this mixture (plot 10L) the herbage contained over twice as much Mg (0·26% and 0·23%).

(2) There were two very low values for Ca (0·15% and 0·26%) in herbage on the very acid plot 9U.

(3) Herbage contained little Na on all plots where K fertiliser was given; even where still more Na (75 lb) was given as sodium nitrate on plots 16U, 16L values were much less than where K was omitted. A small

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amount of the extra Na was taken up by the hay crop to increase the percentage Na to 0·11 and 0·18, but this increase was not maintained in the aftermath in which the values decreased to 0·07 and 0·12% Na. Concentrations of Mg, Ca and Na in herbage are all known to be involved in certain metabolic disorders of ruminants. These data from Park Grass illustrate well how much the concentrations of these elements may depend on fertiliser and lime regimes.

Effects of the Manures and Lime on the contents of Organic Matter, N, P and K in the Soil

The Park Grass soil belongs to the Batcombe Series, as the soils of the Rothamsted Farm are classified by the Soil Survey of England and Wales. Most of the plots are on Series 3, deep phase, with a loam or silt loam surface soil containing few flints. Several plots at the south-west end are on Series 1, undifferentiated, with a flinty loam and silt loam surface soil.

From time to time action against moles was necessary. They were first reported on the plots in 1890. Since the liming was started the moles prefer this half of the plots, and only on plot 8 have they gone on an unlimed portion.

The 1959 soil samples were taken carefully to avoid compression, but even so they provide only very approximate estimates of the relative densities of the soils at different depths. Therefore no attempt was made to prepare a balance sheet for nutrients applied as manures, in crops and remaining in soil.

Organic matter and nitrogen. Before taking the soil samples the mats on the very acid plots were removed (unlimed plots, 1, 4/2, 9, 10, 11/1, 11/2: limed, 11/1, 11/2). They had the following weights and composition,

Organic matter (tons/acre)	15–22	(limed plot 11/2: 10)
pH	3·7–3·9	(limed plots: 11/1, 11/2: 5·2, 5·5)
% N	1·5–2·0	
% P	0·15–0·2	
% K	0·02–0·06	(soluble in ammonium acetate)

The mats were very similar except for the weight of organic matter on plot 11/2 and the higher pH values on the limed halves of 11/1 and 11/2. Richardson found that the very acid plots were free from worms and concluded that the mat formed because acidity affected worms rather than the microbiological decomposition of the organic matter. However, Shaw (1958), found that the acid mat decomposed slowly and decomposition was accelerated by adding lime.

Table 17 shows the organic C and total N contents of the surface soils and subsoils of the plots where manures were not changed.

The statement that lime accelerates the decomposition of organic matter is supported only by the results for the acid soils of the ammonium sulphate plots. It decreased the organic matter in the 0–9-in. depth of soil with all rates of ammonium fertiliser and prevented a mat forming with the

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TABLE 17

Organic carbon and nitrogen contents of Park Grass soils, 1959

		Organic carbon (%)				Total N (%)			
		Surface 0–9 in.		Subsoil 9–18 in.		Surface 0–9 in.		Subsoil 9–18 in.	
Plot	Treatment	U	L	U	L	U	L	U	L
No nitrogen group									
3	Unmanured	3·3	4·0	1·6	1·3	0·27	0·33	0·15	0·13
12	Unmanured	3·4	—	1·4	—	0·28	—	0·15	—
2	Unmanured	3·5	4·2	1·6	1·6	0·28	0·35	0·15	0·15
4/1	P	3·7	4·1	1·7	1·6	0·29	0·34	0·16	0·16
8	P Na Mg	3·0	3·7	1·3	1·4	0·24	0·31	0·14	0·15
7	P K Na Mg	2·8	3·4	1·4	1·5	0·23	0·30	0·14	0·15
Ammonium-N group									
1	N_1	3·0	3·5	1·1	1·6	0·24	0·30	0·12	0·16
4/2	N_2 P	4·1	3·6	1·2	1·2	0·30	0·29	0·11	0·13
10	N_2 P Na Mg	4·2	3·5	1·1	1·1	0·34	0·28	0·12	0·12
9	N_2 P K Na Mg	4·1	4·0	1·4	1·5	0·30	0·31	0·13	0·15
11/1	N_3 P K Na Mg	4·5	4·1	1·5	1·7	0·34	0·30	0·15	0·15
11/2	N_3 P K Na Mg Si	4·7	3·7	1·9	1·7	0·35	0·29	0·16	0·14
Nitrate-N group									
17	N_1	2·9	3·5	1·2	1·4	0·26	0·30	0·14	0·14
16	N_1 P K Na Mg	3·6	3·8	1·4	1·4	0·28	0·32	0·14	0·14
14	N_2 P K Na Mg	2·9	3·7	1·2	1·1	0·21	0·32	0·12	0·12

smaller rates. In contrast, lime increased the organic matter in the plots without N fertiliser and also with sodium nitrate. A further result, not in accord with expectation, is that the soils of the sodium nitrate plots, limed and unlimed, contain no more organic matter than the unmanured plots. Indeed, some contain less, although the crops were much larger. As an estimate of available N, however, the amount of organic matter is not a satisfactory guide, for Richardson (1938) showed that the soils of the sodium nitrate plots produced more ammonium and nitrate nitrogen by incubation than the unmanured soils.

Richardson investigated the nitrogen cycle in grassland soils with especial reference to the Park Grass plots. The following notes are based on his summary of the results.

1. When arable soil is put down to grass, the nitrogen content of the soil increases with age and, under Rothamsted conditions, it takes about 25 years to move half-way to the equilibrium content (that of old grassland).

2. The organic C and N contents of the Park Grass plots were increased by liming, except plot 9, where lime had no effect. (Richardson did not include in his tests other plots getting the same or more ammonium sulphate.)

3. Fresh soil contained more ammonium than nitrate, the amounts of both were small and sufficiently constant to suggest the existence of equilibrium conditions in the nitrogen cycle. The equilibrium levels of ammonium and nitrate were larger in old than in new grassland.

4. Mineralisable N (by incubation) tended to a maximum in winter and early spring and a minimum in summer and early autumn, corre-

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sponding to the addition and decay of organic residues in the soil. As much mineral N was produced by the soil of a very acid plot (9 unlimed) as by more normal soils.

5. Fertiliser N applied to the plots as ammonium sulphate or sodium nitrate disappeared rapidly; the half period is one or two weeks in winter or early spring and a few days in late spring.

Phosphorus. Table 18 shows the total P, and the P soluble in 0·01*M*-$CaCl_2$, 0·5*M*-$NaHCO_3$ and 0·3*N*-HCl, in surface soils. Residues of fertiliser P have accumulated in the surface soils, the amounts depending on how much the crop removed. There is indeed a straight-line relation between the two quantities. The average extra P from fertiliser is greater for Park Grass than for Barnfield, but because some of the values are similar for both fields the solubilities of extra P in grassland and arable soil can be compared. The increases in soluble P, in 0·01*M*-$CaCl_2$, for 60 mg more total P per 100 g soil are:

TABLE 18

Total and soluble phosphorus in the surface soils, Park Grass, 1959

		Total P (mg/100 g)		P soluble in 0·01*M*-$CaCl_2$ (g mols per litre × 10^{-6})		P soluble in 0·5*M*-$NaHCO_3$ (mg/100 g)		P soluble in 0·3*N*-HCl (mg/100 g)	
Plot	Treatment	U	L	U	L	U	L	U	L
No nitrogen group									
3	Unmanured	49	57	2·5	2	0·5	1	0·2	0·3
12	Unmanured	56	—	4·0	—	0·5	—	0·2	—
2	Unmanured	51	60	4·0	2	0·5	1	0·2	0·2
4/1	P	143	159	54	57	11	14	19	38
8	P Na Mg	134	153	41	55	14	11	18	33
7	P K Na Mg	132	134	23	24	13	10	16	22
Ammonium-N group									
1	N_1	52	59	0·5	1·5	0·5	1	0·3	0·3
4/2	N_2 P	156	128	49	29	24	10	30	22
10	N_2 P Na Mg	148	122	22	27	22	10	24	20
9	N_2 P K Na Mg	136	123	14	31	17	10	18	17
11/1	N_3 P K Na Mg	127	117	32	20	21	13	17	14
11/2	N_3 P K Na Mg Si	127	112	23	18	19	9	15	12
Nitrate-N group									
17	N_1	50	56	2·5	1·5	0·5	1	0·2	0·5
16	N_1 P K Na Mg	140	150	23	25	9	13	14	31
14	N_2 P K Na Mg	110	135	14	13	4	8	9	21

$$\left.\begin{array}{ll}\text{Barnfield} & 2\\ \text{Park Grass} & 17\end{array}\right\}\text{P g moles per litre} \times 10^{-6}$$

Solubility in 0·5*M*-$NaHCO_3$ is also greater for Park Grass soils than for Barnfield soil, but is only twice as much for 60 mg extra total P. The method of extraction using 0·3*N*-HCl is very simple and rapid. It is unsuitable on soils containing calcium carbonate, even small amounts (0·2%). But Table 18 indicates that, on acid soils, it extracts the same phosphorus compounds as 0·5*M*-$NaHCO_3$, a method that successfully

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estimates the availability of P in many soils. Although a change in soil reaction from pH 7·5–6 may increase solubility in $CaCl_2$, this effect does not account for the great solubility of P in Park Grass soil. The unlimed plots, at pH 5, and limed plots, at pH 7, in the group of soils without N fertiliser have similar values.

In arable soils at Rothamsted the movement of P into subsoil is detectable only where FYM has been given often, as on Broadbalk, Barnfield and Hoosfield. This movement is ascribed to P being much more soluble in the soils of the FYM plots. Considerable amounts of P have moved down on Park Grass. P is not confined to the top few inches as frequently stated, and some has passed into the subsoil below 18 in., as shown in Table 19.

TABLE 19

Distribution of total P in the soil, Park Grass, 1959

P (mg/100 g)

	Plots without P			Plots with P: without N			Plots with P: with NH_4-N			Plots with P: with NO_3-N	
Plot	3	1	17	4/1	8	7	4/2	9	11/1	14	16
Depth (in.)						Unlimed					
0–9	49	52	50	143	134	132	156	136	127	110	140
9–12	45	45	44	108	93	96	83	91	88	68	77
12–15	41	41	40	74	69	76	59	87	63	49	69
15–18	39	40	40	58	60	53	39	54	47	43	53
						Limed					
0–9	57	59	56	159	153	134	128	123	116	135	150
9–12	60	54	53	95	100	83	75	77	82	75	82
12–15	48	53	52	89	78	74	60	69	66	61	73
15–18	45	50	52	66	55	54	57	58	56	52	53

Potassium. Table 20 shows for surface soils, 0–9 in., the amounts of K soluble in $1N$-ammonium acetate, water and $0{\cdot}01M$-$CaCl_2$. As for P, the results for all methods of analysis reflect the removal of K by crops. The ratios of water-soluble K to K soluble in ammonium acetate for the Park Grass soils with pH values greater than 6·5, and the soils of Barnfield, pH 7–8, are similar. For Park Grass soils below pH 6·5 the ratio is greater than those above; none of Barnfield is under pH 7. In all the arable soils of the Classical Experiments, fertiliser K has passed down into the subsoil, appreciable amounts below 18 in. Table 21 shows the same movement of K for Park Grass. This loss of K points to the need for adjusting in practice the amounts of fertiliser K applied to balance crop removals.

The Park Grass experiment is best known for the changes in botanical composition of the herbage caused by continued manuring with fertilisers and dressings of lime. More information on the ways in which these factors operate could be obtained by introducing some extra treatments, especially new rates of lime. Table 8 indicates where information is lacking on the effect of soil reaction on grass species. Extra lime treatments are

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TABLE 20

Readily soluble potassium in surface soils, Park Grass, 1959

K, mg/100 g, soluble in

Plot	Treatment	1*N*-ammonium acetate U	1*N*-ammonium acetate L	Water U	Water L	0·01*M*-$CaCl_2$ U	0·01*M*-$CaCl_2$ L
No nitrogen group							
3	Unmanured	8	7	1·1	0·5	2·2	1·4
12	Unmanured	8	—	1·2	—	1·8	—
2	Unmanured	8	8	1·1	0·6	1·8	1·4
4/1	P	7	6	0·8	0·6	1·4	0·8
8	P Na Mg	8	8	0·8	0·5	1·3	0·9
7	P K Na Mg	67	61	11·3	9·9	25·8	19·6
Ammonium-N group							
1	N_1	6	6	1·2	0·5	1·8	0·9
4/2	N_2 P	5	6	1·0	0·8	1·4	1·0
10	N_2 P Na Mg	6	8	0·9	0·9	1·4	1·4
9	N_2 P K Na Mg	22	39	5·4	7·7	11·2	13·9
11/1	N_3 P K Na Mg	22	24	5·2	6·0	9·4	10·5
11/2	N_3 P K Na Mg Si	22	25	5·4	5·2	9·4	10·8
Nitrate-N group							
17	N_1	7	6	0·8	0·5	1·4	1·3
16	N_1 P K Na Mg	67	61	9·6	10·0	26·6	20·8
14	N_2 P K Na Mg	49	47	6·0	7·0	19·2	13·4

TABLE 21

Distribution of K, soluble in ammonium acetate, in Park Grass soil, 1959

K (mg/100 g)

	Plots without K			Plots with K: without N			with NH_4-N			with NO_3-N	
Plots	3	1	17	6	7	15	9	11/1	11/2	14	16
Depth (in.)						Unlimed					
0–9	8	6	7	66	67	70	22	22	22	49	67
9–12	7	6	7	53	55	55	20	17	20	43	52
12–15	6	6	7	50	56	55	21	18	18	34	52
15–18	6	7	8	49	53	50	27	19	20	34	46
						Limed					
0–9	7	6	6	—	61	62	39	24	25	47	61
9–12	6	6	5	—	43	49	30	22	21	36	49
12–15	5	5	5	—	40	50	32	23	20	33	49
15–18	7	6	6	—	38	44	31	21	21	33	44

preferable to a change in the current rate of liming to half plots. As the plot boundaries of Park Grass are still clearly defined after more than a 100 years, it is feasible to divide the present plots to accommodate new treatments. New lime treatments would provide useful information on factors affecting yield, especially on the plot that receives the most ammonium sulphate. The soil of this plot is still very acid (pH 4), even though limed at the equivalent of 2,000 lb CaO/acre every fourth year. It gives good yields at present, 80 cwt dry matter/acre in 1963, but quality is poor.

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In contrast, a better-quality hay is produced by the legume–grass herbage produced on plots given only P K fertiliser, but the yields are only moderate and the amount of nitrogen fixed is small, about 40 lb/acre.

The surface soils and subsoils of Park Grass are more acid, contain more organic matter and their amounts of P differ more than the arable soils at Rothamsted. Their content of organic matter rather than differences in soil reaction is thought to cause the P from superphosphate to remain very soluble in 0·01*M*-$CaCl_2$. On Barnfield (*Rothamsted Report* for 1961, p. 227) there was much soluble P only on FYM and rape cake plots. The Park Grass plots provide further soils for studying this effect of organic matter.

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