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**MODERN DEVELOPMENTS IN AN EXPERIMENT
ON PERMANENT GRASSLAND STARTED IN 1856 :
EFFECTS OF FERTILISERS
AND LIME ON BOTANICAL COMPOSITION
AND CROP AND SOIL ANALYSES**

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SUMMARY

Different combinations of fertilizers have been applied annually since 1856 to permanent grassland cut for hay each year, and their effects compared with those of farmyard manure and an unfertilised treatment. Three amounts of nitrogen as ammonium sulphate (48, 96 and 144 kg N ha⁻¹) and two as sodium nitrate (48 and 96 kg N ha⁻¹) are tested together with P K Na Mg but not all treatment combinations are included. P K Na Mg is also applied without N. Between 1903 and 1964 half-plots of most treatments were limed at 2 240 kg CaO ha⁻¹ every fourth year. In 1965 a new liming scheme was introduced, eventually to produce soils at pH of 4, 5, 6, 7 on the four subplots of each treatment. Yields have been recorded annually and the herbage has been analysed botanically and chemically in some years. Occasional assessments have also been made of the pH and nutrient content of the soils. This paper describes results for 12 of the 20 plots and includes a brief summary of recent work on the ecological genetics of *Anthoxanthum odoratum* which occurs on most plots.

Yields of hay varied with treatment from the start of the experiment. Differences due to treatment were accentuated during the first sixty years even though yield on most plots declined. Then during 1920-1960 yields remained relatively stable, except with the smallest amount of ammonium sulphate, when yields continued to decline. The unmanured plot continued to yield little and the largest yield was with most nitrogen plus P K Na Mg. Where P K Na Mg was given with equivalent amounts of nitrogen, as sodium nitrate without lime, or as ammonium sulphate with lime, yields were the same. P K Na Mg alone and also farmyard manure alternating with fish meal gave a moderate yield. Since 1960 estimates of yield have been larger because they have been taken before, and not after, the losses incurred during hay-making. Yields were increased on previously-unlimed acid soils following liming between 1965 and 1968; extra lime on previously-limed soils had little effect.

The vegetation on unmanured soil is diverse, about 50 plant species equally distributed between grass and dicotyledons; lime has only small effects on the botanical composition. Where P K Na Mg is given, diversity is maintained but legumes increased especially where lime is also given. Where ammonium sulphate has acidified the soil, the herbage is dominated by acid-tolerant grasses — either *Agrostis*, *Anthoxanthum* or *Holcus*, depending on the amount of N and other nutrients applied. Lime applied with the two larger amounts of ammonium sulphate allows more productive grasses like *Arrhenatherum* and *Alopecurus* to prevail. At equivalent rates of N,

sodium nitrate without lime produces a sward similar to ammonium sulphate with lime. Of great interest is the fact that the flora of many plots changes slowly despite unchanging fertiliser treatment. *Agrostis* or *Anthoxanthum*, now dominant on some plots, did not become so until the 1930s and 1950s respectively. The relative abundance of *Alopecurus* and *Arrhenatherum* has also fluctuated with time on many plots. Liming under the new scheme has caused large changes in botanical composition on previously unlimed acid soils; acid-tolerant grasses have usually decreased, but without K, *Festuca* has increased greatly. *Holcus* has unexpectedly increased with 96 kg N ha⁻¹ and decreased with 144 kg N ha⁻¹, but *Arrhenatherum* and other grasses have also increased. Occasional plants of many dicotyledonous species have established on the plots. Increased amounts of lime on previously limed soil have enabled *Arrhenatherum* to increase, mainly at the expense of *Alopecurus*. Studies of morphological and physiological variation in *Anthoxanthum* by Dr. SNAYDON *et al.* of Reading University, have shown population differentiation with respect to morphological characteristics and response to mineral nutrients. The differences have developed quickly and locally and appear adaptive.

The variation in percentage N in the different crops was small and the amounts of N removed by the crops on different plots were largely dependent on yield. Percentage P and percentage K in the crops were both much greater where they were applied than where they were not and the total uptake of both ranged widely. The crops contained little Na and this was decreased where K was applied. Percentage Mg decreased as yield increased and its uptake was greatest where K was not applied. Percentage Ca was largest in crops grown without manure and the amount removed was only slightly increased by lime. Herbage grown on acid soil contained little Mg and Ca.

The pH of the unmanured soils and those given P K Na Mg are now about 5. Those receiving sodium nitrate range from 6 to 7 but on all plots receiving ammonium sulphate the soils are very acid (pH 3.7-4.0). On soils receiving most ammonium sulphate much of the chalk applied since 1903 has been lost. Where chalk has been applied in the new scheme, changes in pH have been slow; Ca appears to be held in the surface « mat » of partly decomposed organic matter. Percentage organic matter in the soil was largest in soil where ammonium sulphate was given but there was no more in soils given sodium nitrate than in unmanured soil. For most treatments, percentage N in soil varied little between 1913 and 1959 and an equilibrium value appears to have been reached. Residues of P have accumulated in the surface soil, and on soils with much organic matter, some has moved into the sub-soil. K residues have also accumulated where more has been applied than was removed by the crop.

Since 1965 a micro-plot experiment (sited on a plot given P K Na Mg from 1870 to 1963) has tested larger amounts of nitrogen and more frequent cutting than in the main experiment. Yields of herbage and recovery of N have been larger than in the main experiment and *Trifolium* species much encouraged.

INTRODUCTION

The Park Grass experiment on manuring grassland for hay was started in 1856 by LAWES and GILBERT on a level field at Rothamsted which had been in grass for longer than 100 years (LAWES and GILBERT, 1880). There was no record of the field being sown, but slight, regular undulations in part of it suggest that it was once ploughed in the ridge-and-furrow system. The soil is classified as Batcombe Series by the Soil Survey of England and Wales. It is a flinty silt loam or loam developed on Clay-with-flints overlying Upper Chalk. Probably because Park Grass has not been ploughed for so long the surface soil contains few flints. Complete agricultural and meteorological records for the duration of the experiment are available (see PENMAN, 1974, for a summary of Rothamsted weather).

Scope of this paper

It is impossible to discuss in detail the distribution of about 60 species which have been found on 20 plots during 120 years. We have therefore selected certain plots (table 2), and used the results from them to show botanical composition has

changed with changing soil reaction and impoverishment and enrichment of plant nutrients. These are all plots which have received unchanged treatments for about 100 years and only changes in the more abundant species are discussed.

TREATMENTS AND EXPERIMENTAL METHOD

Botanical nomenclature and units of measurement

The current Latin names for species occurring on the plots have changed, some of them several times, since this experiment began. In this paper we have followed CLAPHAM, TUTIN and WARBURG (1962). These names are not necessarily those of earlier publications *e.g.* *Helictotrichon pubescens* = *Avena pubescens* (table 7).

Similarly, plot-areas, fertiliser dressings and yields have been converted from the original imperial to the equivalent metric units, sometimes rounded up where this could be done without introducing gross errors. The conversion accounts for some apparently unusual quantities, all of which are per hectare, abbreviated ha⁻¹.

Fertilisers

The object of the experiment was to see how hay yields could be improved by applying fertilisers. Figure 1 shows a plan of the experiment and table 1 gives the treatments. Two plot-widths were used for the original series of plots, giving areas of 0.2 or 0.1 ha approx (1/2 or 1/4 acre). Because of the field boundary and the presence of three large oak trees within it, plots 1 to 3 and 14 to 17 (added in 1858), and 19 and 20 (added in 1872) were smaller than the others. Plot 18 was started in 1865. Two of the oak trees have now been removed.

LAWES and GILBERT replicated the unmanured plots, one at each end of the field (LAWES and GILBERT, 1859) but replication and randomisation of all treatments were still to come. However, figure 1 shows that the treatments in this experiment are arranged in a sequence which facilitates direct comparison and demonstration of the effects of including and omitting plant nutrients. LAWES and GILBERT also included two plots (plots 1 and 2) which received farmyard manure (F.Y.M.) every year. However, F.Y.M. residues soon began to accumulate on the surface, because incorporation into the soil was so slow; yields were diminished and the treatment discontinued after eight years. It was not until 1905 that an F.Y.M. treatment was again introduced, this time on plot 13, and then F.Y.M. was applied once every four years (table 1).

Before 1856 LAWES and GILBERT had demonstrated convincingly that cereals would yield well if given annual dressings of fertiliser N. Because permanent grassland contained so many Gramineae the fertiliser treatments tested were divided into three main groups: No N, N at three rates as ammonium salts and N at two rates as sodium nitrate (from 1858). Within the three groups there were comparisons of O and P with and without K Na Mg (applied as their sulphates) for some of the rates of N. All fertilisers were applied each year; P K Na Mg usually in late winter, nitrogen in spring.

Plot 11 (N₃ P K Na Mg) was halved in 1862 to test silicate (plot 11², fig. 1) in addition to the other fertilisers. Until 1872 equal weights of Ca and Na silicates were used after which it was all sodium silicate. Silicate was tested, in the hope that it would prevent lodging of crops given much N; it did not do so. However, the silicate dressing raised soil pH where lime was also given (table 12) and this affected the yield and botanical composition of the hay.

Treatments were altered on several plots in the first few years of the experiment. Plots 5 and 6 originally tested ammonium sulphate which rapidly eliminated legumes from the sward. After 13 years the N dressing was replaced by three treatments, PK, PKNaMg and unmanured, to observe which would encourage the return of legumes. The legumes, eliminated within three years by the N dressing, took 40 years to return to their original amount where P and K were applied.

Table 2 shows the starting-dates of treatments discussed in this paper.

Liming

JOHNSTON and MATTINGLY (1976) have explained why the soils of Park Grass, unlike those on which arable experiments were made at Rothamsted, contained no free calcium carbonate when the experiment began and soon started to become more acid. Chalk at 2.8 t ha⁻¹ was tested in 1881, on a narrow strip of plots 1 to 13, but there was no large effect on yield.

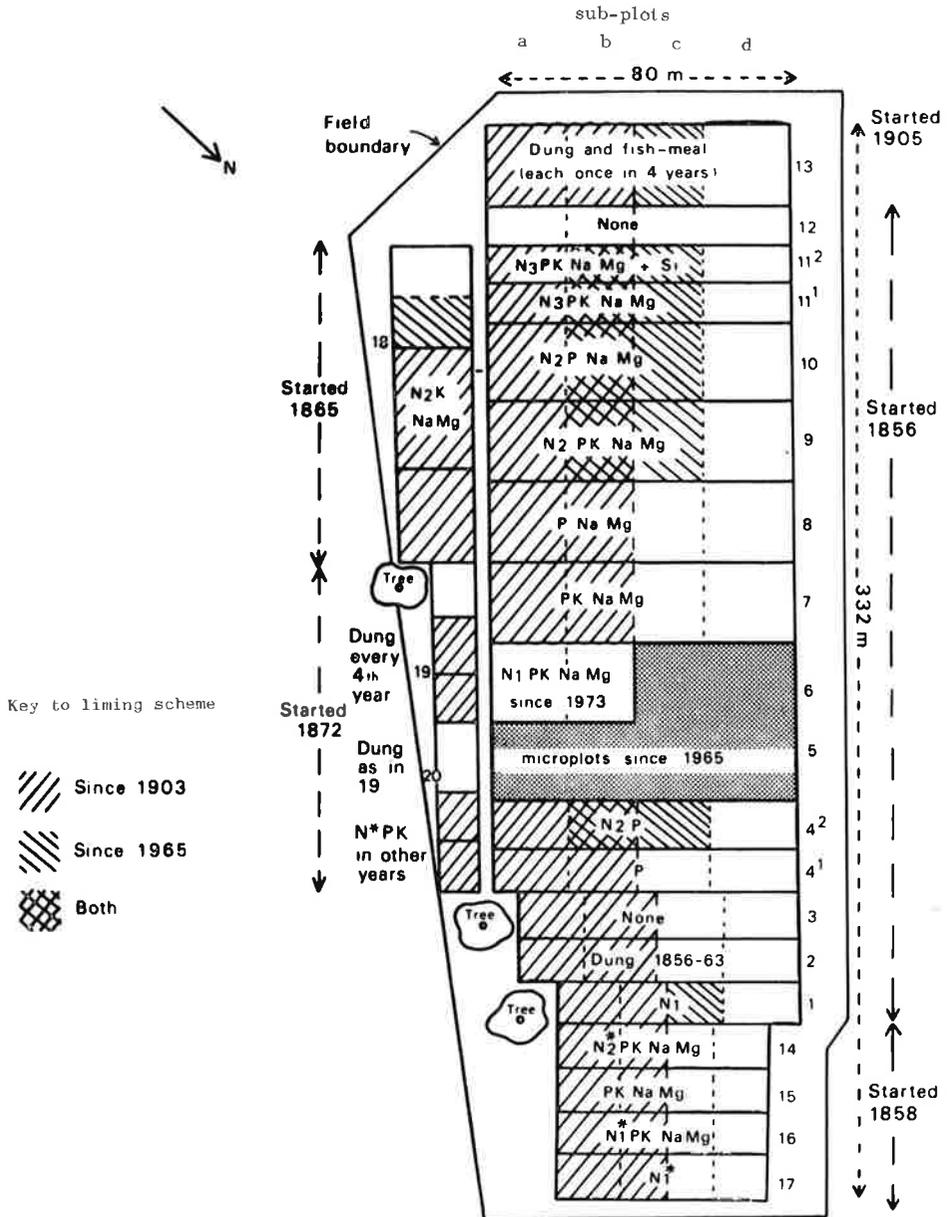


FIG. 1. — Plan of the Park Grass experiment on manuring of grassland for hay

Plot number	Area (approximate)
Largest e. g. 7 to 10	0.2 ha = 1/2 acre
Half plots e. g. 11 ¹ , 4 ¹	0.1 ha = 1/4 acre
Smaller 14 to 17	0.07 ha = 1/6 acre
Smaller 19 and 20	0.05 ha = 1/8 acre

For amounts and dates of lime see text and tables 1 and 13.

For fertiliser amounts and changes see text and table 1.

For soil pH see text and table 12.

Dung = FYM = farmyard manure (table 1).

TABLE 1

Fertilisers and lime applied to Park Grass plots for at least 50 years to 1975
(Treatments given annually except as indicated)

Nitrogen applied in spring.

N 1, N 2, N 3 ammonium sulphate supplying 48, 96, 144 kg N per ha (= ha⁻¹)

N 1*, N 2* sodium nitrate supplying 48, 96 kg N ha⁻¹

(Throughout this paper N = ammonium sulphate, N* = sodium nitrate)

PKNaMgSI applied in winter.

P 35 kg P ha⁻¹ as powdered superphosphate

K 225 kg K ha⁻¹ as potassium sulphate (50 p. 100 K₂O)

Na 15 kg Na ha⁻¹ as sodium sulphate (14 p. 100 Na)

Mg 11 kg Mg ha⁻¹ as magnesium sulphate (10 p. 100 Mg)

Si 450 kg ha⁻¹ of water soluble powdered sodium silicate (to plot 11² only)

Plot 20 (in years when FYM not applied)

30 kg N, 15 kg P, 45 kg K ha⁻¹

Organic each applied every fourth year.

FYM 35 t ha⁻¹ farmyard manure (bullocks) (1973, 1977)

Fish meal (about 6.5 p. 100 N) to supply 63 kg N ha⁻¹ (1975, 1979)

about 950 kg ha⁻¹ meal.

Lime

Started 1903 2 240 kg CaO ha⁻¹ as slaked lime or finely ground CaCO₃

Started 1965 See table 13.

TABLE 2

Plots of the Park Grass experiment discussed in this paper

Plot number	Treatment	Unchanged since
	No nitrogen group	
3	Unmanured.....	1856
8	P Na Mg.....	1862 but amount of Na has varied
7	P K Na Mg.....	1856
	Ammonium-N group	
1	N ₁	1863
10	N ₂ P Na Mg.....	1862 but amounts of fertilisers have varied
9	N ₂ P K Na Mg.....	1856
11 ¹	N ₃ P K Na Mg.....	1881
11 ²	N ₃ P K Na Mg Si.....	1881
	Nitrate-N group	
17	N ₁ *.....	1858
16	N ₁ * P K Na Mg.....	1858
14	N ₂ * P K Na Mg.....	1858
	Organic	
13	Farmyard manure } alternating at Fish meal } 2-year intervals	1905

In 1883-4, one half of each plot received 2.2 t CaO ha⁻¹ as slaked lime and in 1887-8 the other halves were similarly treated. Plots receiving most ammonium sulphate were given twice as much lime. There was no immediate effect from the dressing applied in 1883 but during 1885-87 small benefits, 0.63-0.88 t hay ha⁻¹, were recorded on plots given NPK fertilisers. It was not until 1903 that a scheme of regular liming was gradually introduced. Since 1924 the south halves of most plots have been limed every 4th year at the equivalent of 2.24 t CaO ha⁻¹. In 1920, another scheme of liming testing two laboratory methods for measuring the lime requirement of soils was introduced on plots 18, 19 and 20; subsequently these dressings were repeated every 4th year.

By 1965 it was realised that some of the interactions between soil reaction and nutrients on the botanical composition of the sward could not be measured, and a new liming scheme was introduced (WARREN, JOHNSTON and COOKE, 1965). Each plot was divided into 4 sub-plots, 2 on the limed, 2 on the unlimed half plots; it is intended that eventually the sub-plots will have soils with pH's of approximately 4.0, 5.0, 6.0 and 7.0 (in water) (fig. 1). Treatment started immediately on all sub-plots which had become sufficiently acid to require corrective liming (fig. 1, table 13) but even the unmanured plots are acidifying slowly and will eventually come into this scheme. This has provided the first opportunity in living memory for us to assess changes in the vegetation (WILLIAMS, 1974) as soil reaction has changed (JOHNSTON, 1972). These are the modern developments discussed in this paper.

Methods of harvesting, sampling and recording yields

a) The first crop.

This was always cut and made into hay on the plot on which it grew; hay yields were recorded and samples were often taken for botanical and, less frequently, chemical analysis. Until 1873 the herbage was cut with a scythe, then with a mowing machine. Since 1960 yields were recorded as dry herbage calculated after determining the dry matter content of fresh herbage cut by a flail forage harvester from sample strips on each plot. Thus, total dry matter at cutting, not the dry matter after hay making, was recorded and yields have been larger since 1960 because dry matter losses due to hay-making no longer occur. After the sample cuts are taken the bulk of the herbage is mown and made into hay on its own plot as previously, thus continuing the annual supply of fresh seeds of the appropriate species. This is particularly important on plots with much *Holcus lanatus*, many old plants of which die in severe winters and are replaced by seedlings in spring.

There is no record of the nutritive value or palatability of the hay having been investigated, although LAWES and GILBERT were very interested in animal nutrition (LAWES and GILBERT, 1895)

b) Second crop.

In 15 years during 1856-75 the regrowth after the first cut was grazed by sheep, penned on each plot separately and given no other food. Notes were made on their grazing habits e.g. in 1868 they ate the fine grasses (*Festuca* etc. first, then *Dactylis glomerata*, but *Arrhenatherum elatius* was only tipped, not eaten right down. Legumes and « weedy herbage » were apparently eaten indiscriminately. Because of the difficulty of deciding what is a weed in the mixed flora of permanent grassland we now describe plants which are neither grasses nor legumes as « other species » (STAPLEDON, 1939). Some of these other species are palatable and even beneficial though low-yielding. The number of sheep and the length of time they grazed on each plot were recorded and equivalent hay yields were calculated approximately by assuming that one sheep would eat 7.26 kg of hay in one week. Because the sheep often suffered from the change from better food, or from bad weather, or both, grazing was discontinued (LAWES and GILBERT, 1880)

During the next eight seasons the herbage of the second crop, and third if any, was mown, spread and left to decay on its respective plot to simulate grazing. However, leaving a thick layer of vegetation on the more fertile plots resulted in patches of retarded growth and some dead plants in the sward. Since 1887 all of the second cut has been carted, weighed and yield given as hay, or since 1960 as herbage dry matter.

Hay samples, and observations on botanical composition of the growing crop

The numerical results on percentage composition of the hay were obtained by taking representative samples of fresh herbage from each plot immediately after cutting. Handfuls of fresh herbage were taken at regular intervals along the undisturbed windrows until a suitable volume of material was collected, brought to the laboratory and made into hay by drying and turning, care being taken to avoid excessive breakage or bleaching by strong sunlight (BRECHLEY, 1924;

BRENCHLEY and WARINGTON, 1969). Since 1960, tedding the grass immediately after cutting has left it too fragmented for botanical analysis and in 1973 and 1974 samples were cut by hand from the standing crop bordering the forage-harvester strips; these samples were made into hay as before.

Because neither LAWES nor GILBERT were botanists, they sought the temporary help of skilled botanists to train and supervise Rothamsted staff doing the hay separations. The first University-trained botanist joined the Rothamsted staff in 1906. However, sorting, identifying and weighing the species in hay samples is very time-consuming and cannot be done every year, so visual observations are made on the standing crop. Since 1920 notes have been made on every plot just before the first cut and again at some time during the autumn before the second cut. In the early years of the experiment these botanical notes vary greatly in the amount of detail, depending on who did them.

Visual surveys showed that the new liming scheme, introduced in 1965, caused large changes in the botanical composition of many sub-plots. To quantify these changes more precisely, samples of hay were taken in 1973 and 1974 from all sub-plots (*i.e.* *a*, *b*, *c* and *d*) of plots which had received lime under the new scheme (fig. 1). In 1973 samples were taken from the *c* (limed for the first time) and *d* (permanently unlimed) sub-plots and in 1974 from the *a* (limed under the old scheme) and *b* (receiving increased rates of lime) sub-plots. Comparisons of the botanical compositions of sub-plots *a* and *d* in 1973-74 (table 8) with the limed and unlimed halves respectively of the same plots at the previous hay analysis in 1948-49 (table 7) assess the changes during 25 years on sub-plots with unchanged treatment. Comparisons of sub-plots *a* with *b* and of *c* with *d* assess changes due to the new liming scheme. Because these analyses showed large botanical changes in some of the plots with unchanged treatments, other plots *e.g.* unmanured, P K Na Mg and the sodium nitrate plots, also with unchanged lime and fertiliser treatments are now being analysed.

Soil-sampling

Few soil samples were taken in the early years of the experiment. LAWES and GILBERT appreciated that their conventional method of sampling, which removed a block of soil 15 × 15 cm by 23 cm deep at each sampling point, was not really suitable for sampling plots on permanent grassland because of the disturbance to the sward. So all plots were sampled only once, in 1876, though a few plots were sampled to 137 cm in 1870 when the water content of the soil was investigated after a severe drought. Recently soil sampling has been more frequent. Samples for chemical analysis are usually taken with a 2 cm diameter semi-cylinder sampling tool, which does not open up the closed sward of the plots. Cores required for the extraction of soil animals have to be larger, about 5 cm diameter.

Additional information on the flora and fauna

Members of departments other than Botany and Chemistry have used material from the Park Grass plots in their investigations. The presence of nitrifying bacteria in the soils, especially the relation of species to soil pH and to the presence of host-plants in the vegetation, has been discussed by NUTMAN and ROSS (1970). The invertebrate soil-fauna (EDWARDS and LOFTY, 1975), invertebrate surface fauna (EDWARDS, BUTLER and LOFTY, 1976), and earthworms (SATCHELL, 1955) have also been investigated. The number of soil invertebrates decreased with an increase in added nitrogen and a decrease in soil pH. The effects of fertilisers on surface-living arthropods are more indirect and much less distinct than on soil arthropods. Earthworms are most numerous on plots with the most plant-species, which in turn depends on fertiliser-treatment; they avoid very acid plots. When moles invade the field, they make most mole-hills where worms are numerous and none on the acid plots.

Workers from outside Rothamsted also use plant material from the Park Grass plots (see below).

RESULTS

Yields

1856-1926. Table 3 shows that yields of hay differed from the start of the experiment due to treatments. During 1856-58 the yields without manure (plot 3), with P K Na Mg (plot 7), P K Na Mg plus 96 kg N ha⁻¹ (plot 9) and P K Na Mg plus

TABLE 3

Mean yield of hay (t ha⁻¹) on some *Park* Grass plots during 1856-65, 1886-95 and 1916-25

Treatment	1856-65	1886-95	1916-25 ^a
No nitrogen group			
Unmanured	2.84	2.11	1.49
^b P Na Mg	4.22	2.07	2.32
P K Na Mg	4.26	3.40	3.44
Ammonium-N group			
^c N ₁	6.08	2.99	2.00
^b N ₂ P Na Mg	6.63	4.46	3.28
N ₂ P K Na Mg	6.73	4.93	4.42
N ₃ P K Na Mg	7.75	5.98	5.21
N ₃ P K Na Mg Si	8.34	7.78	6.39
Nitrate-N group			
N ₁ *	4.31	3.39	3.16
N ₂ * P K Na Mg	6.67	5.72	6.89

(a) : unlimed half-plot only ;
 (b) : also received K during 1856-61 ;
 (c) : also received FYM during 1856-63.

192 kg N ha⁻¹ (plot 11) were 2.9, 4.2, 7.5 and 8.0 t hay ha⁻¹. This effect of treatment on yield persisted during the first sixty years or so (LAWES and GILBERT, 1880 ; BRENCHLEY and WARINGTON, 1969) ; but during this time yields of many plots decreased, some more than others. The largest decrease was on the N₁ plot ; but yields also declined on the unmanured plot and on those which did not receive K fertiliser (plots 8 and 10) where the mean yield of hay during 1916-25 was about half what it had been during 1856-65. Decreases also occurred on plots given ammonium sulphate plus P K Na Mg and these were associated with decreasing soil pH and increasing dominance of less productive acid-tolerant grasses. The only treatment which continued to give the same yield was P K Na Mg with 96 kg N ha⁻¹ as sodium nitrate. No treatments increased yields (table 3).

1920-1959. With the exception of the N₁ plot, total yields, first plus second crop, were relatively stable during 1920-59 (table 4). Manuring and liming remained unchanged and the depletion and enrichment of soil N, P and K no longer affected yield. But when considering treatment effects on yield during this period it must be remembered that the crops are not botanically identical. Because the plots were cut earlier in June during 1940-59 than during 1920-39 the contribution of the first crop to the total yield decreased during the second 20 years of this period. In general, the first crop contributed about 70 p. 100 of the total annual yield, except on the N₁ and N₃ P K Na Mg plots where it was about 60 p. 100. These two plots are dominated by *Agrostis* and *Holcus* respectively which make much growth late in the growing season.

TABLE 4

*Mean annual yield of dry herbage (t ha⁻¹)
on some of the Park Grass plots during 1920-59*

Treatment	1st crop		2nd crop		Total	
	Unlimed	Limed	Unlimed	Limed	Unlimed	Limed
No nitrogen group						
Unmanured	1.03	1.22	0.45	0.41	1.48	1.63
P Na Mg	1.90	1.52	0.80	0.64	2.70	2.16
P K Na Mg	2.57	3.39	1.09	1.04	3.66	4.43
Ammonium-N group						
N ₁	1.05	1.77	0.65	0.60	1.70	2.37
N ₂ P Na Mg	2.11	3.57	0.93	0.89	3.04	4.46
N ₂ P K Na Mg	3.39	4.58	1.28	1.05	4.67	5.63
N ₃ P K Na Mg	3.40	5.26	2.15	1.47	5.55	6.73
N ₃ P K Na Mg Si	4.27	5.55	2.11	1.84	6.38	7.39
Nitrate-N group						
N ₁ *	1.91	2.22	0.74	0.66	2.65	2.88
N ₂ * P K Na Mg	4.82	4.63	1.39	1.04	6.21	5.67
FYM and fish meal	3.48	3.30	1.24	1.12	4.72	4.42

The unmanured plot continued to yield least dry herbage; P and Na plus Mg doubled yield, and adding K as well increased yield even more. Yield was greatly increased by nitrogen together with P K Na Mg. With 96 kg N ha⁻¹ (N₂) sodium nitrate outyielded ammonium sulphate by 1.5 t ha⁻¹ but this result is confounded with the effects of treatment on soil pH and botanical composition. F.Y.M. plus fish meal gave a moderate yield (4.7 t ha⁻¹). Lime greatly increased yield from soils treated with P K Na Mg and ammonium sulphate, but it had little effect on the unmanured soil or where sodium nitrate or F.Y.M. were given. Lime decreased yields with P Na Mg and N₂* P K Na Mg. In contrast to the unlimed halves of the plots, the yields with N₂ P K Na Mg and N₂* P K Na Mg with lime were similar.

1965-73. Yields of dry herbage in this period (table 5) were much larger than those during 1920-59, probably because dry matter yields were estimated before, and not after, losses incurred during hay-making. Yields without fertilisers and with P Na Mg, where the vegetation is short and difficult to make into hay, were almost twice as large, and those of most other treatments were almost 50 p. 100 greater during 1965-73 than during 1920-59; only the N₁ plot yielded less during the later years probably because of increasing soil acidity and depletion of P and K, especially P. Nevertheless, the pattern of differences between treatments has been maintained. The test of lime started in 1903 was continued on the *a* and *d* sub-plots. In contrast to its effect during 1920-59, lime decreased yield on the N₁* plot but increased that of the F.Y.M. plot during 1965-73.

TABLE 5

Mean annual yield of dry herbage (t ha⁻¹)
on some of the Park Grass plots during 1965-73

Treatment	1st crop				2nd crop				Total									
	a	b	c	d	a	b	c	d	a	b	c	d						
No nitrogen group																		
Unmanured	1.93		1.53		1.35		1.44		3.28		2.97							
P Na Mg	2.28		2.80		1.85		2.30		4.13		5.10							
P K Na Mg	5.32		3.28		3.03		2.34		8.35		5.62							
Ammonium-N group																		
N ₁	1.91		1.46		0.87		1.52		0.69		0.66		3.43		2.15		1.53	
N ₂ P Na Mg	4.33	4.59	4.27	3.15	1.78	1.60	1.35	1.46	6.11	6.20	5.62	4.61						
N ₂ P K Na Mg	6.76	6.50	5.90	5.02	2.88	2.67	1.72	1.68	9.62	9.17	7.62	6.70						
N ₃ P K Na Mg	7.17	6.99	7.30	4.69	3.24	2.61	2.70	3.26	10.41	9.60	10.00	7.95						
N ₃ P K Na Mg Si	7.41	7.72	7.38	5.48	4.07	3.98	2.96	3.41	11.48	11.70	10.34	8.89						
Nitrate-N group																		
N ₁ *	2.38		2.60		1.63		2.18		4.01		4.78							
N ₂ * P K Na Mg	5.69		6.14		2.27		3.04		7.96		9.19							
FYM and fish meal	4.74		4.99		4.32		3.94		3.46		3.08		8.68		8.45		7.40	

In 1965, the unlimed halves of plots were split into sub-plots *c* (where the pH is being raised to 5.0) and *d* which continues to be unlimed; the limed halves were split into *a* (limed under old scheme) and *b* (where the pH is being raised to 6.0). On those plots where differential liming has not yet started the means of *a* and *b* or *c* and *d* are given.

Lime, applied in the new test started in 1965, increased yields of the previously unlimed *c* sub-plots, mainly since 1968. The size of the increase depended on treatment. With N₁, the yield of *c* relative to *d* increased progressively from 6 p. 100 more in 1965 to 207 p. 100 more in 1973; with N₂ P K Na Mg and N₂ P Na Mg yields were 20-40 p. 100 greater on *c* than on *d* sub-plots. With N₃ P K Na Mg the effects of recent lime have been more variable: the mean increase during 1965-73 was due mainly to very large differences in yield (60-120 p. 100) in 1968 and 1969, when the *d* sub-plots yielded very little. In all comparisons the extra yield was due mainly to increase in the first crop, lime often decreased yield of *c* relative to *d* sub-plots of second crops.

Increased rates of lime on *b* sub-plots have had, as might be expected, less effect than on the previously unlimed *c* sub-plots. On N₂ P K Na Mg and N₃ P K Na Mg the yield of *b* was slightly less than on *a* but little different on the N₂ P Na Mg and on the N₃ P K Na Mg plus silicate.

The yield of the crops on all plots is influenced by the rainfall between mid-March and early July. Statistical examination of the effect of an extra 25 mm rain

in the years 1858-1902 showed that the effect was greatest when the rain came during the second half of April ; it was also greater on the ammonium sulphate than on the sodium nitrate plots (CASHEN, 1947).

Botanical composition

Changes due to treatment have occurred continuously throughout the experiment ; tables 6 and 7 give results for the botanical composition in 1948-49.

i) *Changes due to treatment between 1856 and 1949.*

The Latin names of the species are given fully in table 7 but in the text the generic name only, except where two species occur in the same genus. This avoids confusion between the numerous genera beginning with A. Species have been divided into 3 groups, grasses, legumes and other species, some of which are useful components of hay. Full details of the results of botanical analyses are given by LAWES and GILBERT, 1859 ; LAWES, GILBERT and MASTERS, 1882 ; HALL, 1905 ; BRENCHLEY, 1924, 1925, 1930, 1935 a, 1935 b and BRENCHLEY and WARINGTON, 1969.

Botanical analyses of seven plots were made in 1858 (LAWES and GILBERT, 1859). Grasses, legumes and other species contributed 76, 5 and 16 p. 100 respectively to the yield of the unmanured plot in that year. P K Na Mg fertilisers increased the legumes to 23 p. 100 and decreased other species to 2 p. 100 ; where ammonium salts were also applied the grasses were increased to 97 p. 100, legumes were eliminated and other species much decreased. Sodium nitrate, not tested until 1858, had similar effects. These large initial differences in the proportion of the three main groups of plants have persisted throughout the duration of the experiment but changes have occurred in the composition of the groups themselves. The main grasses on most plots in 1858 were *Lolium* and *Holcus* ; *Arrhenatherum* was also abundant on the P K Na Mg and F.Y.M. plots.

Further, more detailed analyses of all plots were done in 1862 — by then the plots had become botanically more distinct. Botanical separations were repeated at five-year intervals until 1877 (LAWES, GILBERT and MASTERS, 1882). Fifty species of higher plants were identified in the hay from the unmanured plots in these analyses, compared to 20 in 1858. Grasses contributed 70 p. 100 to the yield. *Agrostis* and *Festuca rubra* were most plentiful, but *Lolium* and *Holcus* remained important constituents. During the first twenty years other species contributed about 22 p. 100 to the yield ; there was no single dominant species but *Plantago* was prominent during 1862-67. Many species have persisted on this plot ; the changes that have occurred are associated with the depletion of nutrients and the consequent decrease in yield (table 3). Between 1877 and 1903 the number of species decreased from about 50 to about 40 ; grasses decreased while other species, especially *Leontodon*, *Plantago* and *Poterium*, increased. In 1948, thirty-six species of higher plants were recorded (table 6) ; *Agrostis* and *Festuca rubra* were the main grasses ; legumes, mainly *Lotus* and *Trifolium pratense*, contributed 7 p. 100 of the yield and the twenty-one other species, 40 p. 100. Plants characteristic of poor land e.g. *Briza media* and *Primula veris* occur on this plot and there are some species which are rare in other localities near Rothamsted. All the species found on the other plots grow on this plot, which remains the closest approximation to the state of the whole field in 1856. Liming the unma-

TABLE 6

Number of species and percentage of total produce of grasses, legumes and other species on some of the Park Grass plots in 1948-49

Treatment	Unmanured		PNaMg		PKNaMg		N ₁		N ₂ PNaMg		N ₃ PKNaMg		N ₃ PKNaMgSi		N ₁ *		N*PKNaMg		FYM + fish meal	
	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L
No. of grasses	41	14	14	14	6	41	5	12	7	2	6	6	5	9	15	10	10	9	12	
Percentage	53	53	57	47	95	63	99	90	100	94	100	99	98	71	83	92	94	74	67	
No. of legumes	4	4	4	4	0	3	0	1	0	0	0	0	0	1	1	1	1	2	3	
Percentage	7	16	7	11	0	5	0	3	0	0	0	0	0	0	3	2	3	1	11	
No. of others	21	16	15	16	5	14	1	7	1	4	1	2	3	40	13	5	6	12	13	
Percentage	40	48	40	35	5	32	1	7	t	6	t	2	2	29	14	6	3	25	22	
Total No. of species ..	36	32	33	34	41	28	6	20	8	11	3	8	8	20	29	16	17	23	23	

U : Unlimed ; L : Limed ; N as ammonium sulphate ; N* as sodium nitrate ; t : trace (< 0.5 p. 100). For full explanation of treatments see tables 1 and 2.

TABLE 7. — Percentage contribution (a) by weight of the principal species on some of the Park Grass plots during 1948-49

Treatment (b)	Unmanured		PNaMg		PKNaMg		N ₁		N ₂ PKNaMg		N ₂ PNaMg		N ₃ PKNaMg		N ₃ PKNaMg		N ₃ PKNaMg		N ₁ *		N ₂ * PKNaMg		FVM and fish meal		
	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	U	L	
<i>Agrostis tenuis</i>	16	1	3	1	4	1	75	1	8	4	1	52	1	—	—	—	—	—	—	1	1	—	—	16	t
<i>Alopecurus pratensis</i>	8	6	4	13	8	3	t	2	—	38	t	29	2	82	t	—	—	—	—	14	7	—	—	32	10
<i>Anthoxanthum odoratum</i>	1	1	2	1	4	4	t	1	—	4	4	10	1	—	—	—	—	—	—	9	1	—	—	6	t
<i>Arrhenatherum elatius</i>	t	t	14	15	2	12	—	3	1	15	5	4	—	—	—	—	—	—	—	—	2	—	—	3	26
<i>Bromus mollis</i>	—	—	t	t	t	2	—	—	—	t	—	t	—	—	—	—	—	—	—	—	—	—	—	t	—
<i>Diactylis glomerata</i>	4	3	13	6	16	13	3	18	—	—	12	t	—	—	—	—	—	—	—	25	24	—	—	9	21
<i>Festuca rubra</i>	17	4	5	2	5	1	16	15	t	4	40	55	—	t	t	—	—	—	9	22	13	—	4	4	1
<i>Festuca pratensis</i>	—	—	t	7	t	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Helictotrichon pubescens</i> ..	3	13	2	11	1	5	t	42	—	t	—	—	—	—	—	—	—	—	2	20	5	—	—	—	t
<i>Holcus lanatus</i>	4	2	7	2	3	1	—	6	91	3	21	t	t	100	3	2	2	—	—	1	2	—	—	2	4
<i>Lolium perenne</i>	—	—	t	t	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Poa pratensis</i>	t	2	1	1	3	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1	2	—	—	—	t
<i>Poa trivialis</i>	—	—	t	t	t	1	t	t	—	9	3	—	—	—	5	—	—	—	—	1	2	—	—	1	2
<i>Trisetum flavescens</i>	t	1	t	2	1	1	—	—	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	t	1
<i>Lathyrus pratensis</i>	1	2	1	2	11	16	2	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	t
<i>Lotus corniculatus</i>	4	7	3	6	t	t	—	2	—	4	—	—	—	—	—	—	—	—	—	—	—	—	—	t	8
<i>Trifolium pratense</i>	2	6	3	4	5	3	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2
<i>Trifolium repens</i>	t	1	1	t	3	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	t
<i>Achillea millefolium</i>	1	1	7	4	14	1	—	2	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	t
<i>Centaurea nigra</i>	1	2	2	3	4	t	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
<i>Cerastium holosteoides</i>	t	t	t	t	t	t	t	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	t
<i>Conopodium majus</i>	2	t	1	t	1	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Heracleum sphondylium</i>	—	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Knautia arvensis</i>	1	2	1	4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Leontodon hispidus</i>	18	12	4	6	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Plantago lanceolata</i>	6	13	15	13	7	5	20	—	—	—	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Potentilla reptans</i>	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Poterium sanguisorba</i>	6	12	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Ranunculus acris</i>	t	3	6	2	1	2	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Rumex acetosa</i>	2	1	3	2	2	2	2	2	—	—	5	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Taraxacum officinale</i>	t	t	t	t	t	2	—	1	—	3	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—

a) Only those species contributing at least 2 p. 100 on at least one plot are listed. This explains why most columns do not add up to 100 p. 100. The percentage contribution of all species contributing more than 0.5 p. 100 has been rounded to the nearest whole number, and those contributing less than this are denoted by 't'.
 b) U = Unlimed; L = Limed Half Plots; N as Ammonium Sulphate; N* as Sodium Nitrate (See tables 1 and 2).

nured plot had a relatively small effect on yield and on the botanical composition except that *Agrostis* and *Festuca rubra* usually decreased and *Helictotrichon* increased. *Plantago* and *Poterium* were increased but *Conopodium* and *Leontodon* decreased (table 7). During the last fifty years lime has also increased the proportion of legumes.

When P K Na Mg were added without N, the vegetation remained diverse, but less so than when the soil was unmanured. The large proportion of legumes, mainly *Lathyrus* and *Trifolium pratense*, which established in the early years, has persisted. Percentage grasses, especially *Festuca rubra*, decreased but *Dactylis* and *Alopecurus* increased. Other species, particularly *Achillea* and *Plantago*, also increased at the expense of the grasses. In 1948 *Dactylis* and *Alopecurus* were also plentiful on the limed half of this treatment and *Arrhenatherum* and *Helictotrichon* were much increased. Except for *Heracleum* most of the « other species » were decreased by lime.

When only P Na Mg were given (*i.e.* K was omitted) legumes usually, but not always, decreased. In 1948 *Lathyrus* contributed less than 1 p. 100 of the herbage, but *Lotus* was more abundant without than with K. Grasses contributed about 50 p. 100 on both plots (7 and 8) but *Arrhenatherum* was more plentiful without than with K. *Plantago*, *Ranunculus* and *Leontodon* were more, and *Centurea* less, prominent without than with K. Liming the P Na Mg treated soil greatly increased the percentage of *Helictotrichon* but, as on the P K Na Mg plot, discouraged *Agrostis*, *Anthoxanthum* and *Holcus*. The main difference between the grasses on the limed halves of the P K Na Mg and P Na Mg plots was a greater prominence of *Alopecurus* and *Dactylis* when K was given.

The effects of nitrogen on botanical composition have depended on the source and amount of N as well as on what other nutrients were applied. In the absence of P K Na Mg, 48 kg N ha⁻¹ (N₁) as ammonium sulphate (Plot 1) acidified the soil to such an extent that the number of grass and other species progressively declined between 1877 and 1948. *Agrostis* increased greatly from the 1920s onwards and by 1948 it made up three-quarters of the herbage. Legumes were eliminated early and *Rumex* and *Potentilla* became the main other species. Liming increased the range and type of grasses, allowed some legumes to re-establish and *Plantago* to flourish.

When 96 kg N ha⁻¹ (N₂) was given as ammonium sulphate together with P K Na Mg (Plot 9), legumes were eliminated, other species became less frequent and the number of grasses decreased gradually between 1856 and 1948. *Arrhenatherum* was plentiful on this plot until about 1920; afterwards *Holcus* increased rapidly and was dominant for about 30 years. Our records, however, do not allow us to determine whether there is a critical soil pH below which only *Holcus* can thrive. Apart from *Agrostis* (8 p. 100) no other grass contributed significantly to the herbage in 1948. Liming this treatment allowed *Alopecurus*, *Arrhenatherum* and *Dactylis* to dominate the herbage but many other grasses also occurred. Lime also enabled *Lathyrus* to establish; it remained in small amounts until 1940 but then increased more rapidly. Seven other species, mainly *Taraxacum* and *Heracleum*, contributed 7 p. 100 to the yield in 1948. On plot 10, K was omitted after 1862 and giving only N₂ P Na Mg caused an increase in *Alopecurus*, *Agrostis* and *Festuca* by 1877. In contrast to the N₂ P K Na Mg treatment, *Arrhenatherum* did not increase after 1877, but *Alopecurus* remained plentiful until the 1920s. After that it rapidly decreased and only a small

percentage occurred in 1948. *Agrostis* increased rapidly during the 1920s and by 1948 it dominated the herbage on this plot but there was also much *Anthoxanthum*, which had always been plentiful; *Holcus* also was plentiful in 1948. Liming allowed *Alopecurus* to re-establish and become dominant on the limed half of the plot between 1914 and 1940 but it then declined as *Festuca rubra* increased; by 1948 there was almost twice as much *Festuca rubra* (55 p. 100) as *Alopecurus* (29 p. 100).

The number of species decreased most rapidly where the largest amount of N (144 kg ha⁻¹) was given as ammonium sulphate with P K Na Mg. *Agrostis* (29 p. 100), *Holcus* (20 p. 100), *Dactylis* (17 p. 100), *Arrhenatherum* (15 p. 100) and *Alopecurus* (10 p. 100) were the main components of the herbage on this plot in 1877. *Holcus*, *Alopecurus* and *Arrhenatherum* increased between 1877 and 1903; *Holcus* continued to increase, became dominant during the next ten years, and has remained so ever since. The limed half of this plot was dominated by *Alopecurus* (82 p. 100) in 1949; no legumes and few other species occurred.

The botanical composition of the plot given N₃ P K Na Mg plus silicate has been similar to that without silicate but *Holcus* became dominant later: in 1914, when *Holcus* (91 p. 100) dominated the N₃ P K Na Mg plot, *Arrhenatherum* and *Alopecurus* still contributed 40 p. 100 where the same treatment was given with silicate. When lime and silicate were given, *Alopecurus* contributed 57 p. 100 to the yield and *Arrhenatherum*, *Poa pratensis* and *Dactylis* were also abundant.

Where nitrogen was given as sodium nitrate the surface soils, even of the unlimed half-plots remained less acid than those given ammonium sulphate and this, in turn, gave large differences in the swards. Where 48 kg N ha⁻¹ was given as sodium nitrate (N₁*) the sward did not change as much as where it was given as ammonium sulphate. *Alopecurus*, *Agrostis*, *Festuca rubra* and *Holcus* were the main grasses in the early years and, with the exception of *Agrostis*, they were also important constituents in 1949, when *Dactylis* (25 p. 100) was the most abundant grass. By 1948 the main effect of lime had been to increase *Helictotrichon* and *Festuca rubra*, to increase *Lotus* and to decrease other species from 29 to 14 p. 100.

With 96 kg N ha⁻¹ as sodium nitrate plus P K Na Mg grasses were encouraged and legumes and other species greatly discouraged. Comparing the effects of N₂ as sodium nitrate and ammonium sulphate on the unlimed halves of plots 14 and 9 respectively shows that different species of grasses have been encouraged on the two plots. On the unlimed half of plot 14 (N₂* P K Na Mg) *Poa trivialis* and *Holcus* were prominent in the early years but afterwards declined, *Holcus* to such an extent that it was absent after 1914. *Alopecurus* increased during the first twenty years and remained at 20-30 p. 100 until 1948. *Arrhenatherum* has increased greatly since the beginning of this century and *Dactylis*, which had been prominent in the early years and had then declined, became prominent again from about 1920 onwards. In 1948, therefore, the main components of the herbage on plot 14 without lime were very similar to those of plot 9 with lime. Lime decreased *Alopecurus* and increased *Festuca* on plot 14.

On the plot given F.Y.M. and fish meal since 1905, grasses — mainly *Alopecurus*, *Agrostis* and *Dactylis* — contributed 74 p. 100 and twelve other species, but mainly *Plantago*, *Achillea* and *Rumex*, 25 p. 100. Lime decreased percentage *Alopecurus* but increased *Arrhenatherum*, *Dactylis*, *Lathyrus*, *Taraxacum* and *Ranunculus*.

ii) *Changes due to treatment since 1949.*

a) *Changes on sub-plots with unaltered lime treatments.*

The botanical composition of sub-plots *a* and *d* in 1973-74 (table 8) can be compared with that of the limed and unlimed halves respectively of the same plots in 1948-49 (table 7) to assess changes during 25 years.

On the unlimed sub-plot given only ammonium sulphate (plot 1) *Agrostis* continued to dominate the herbage but *Anthoxanthum* has increased with a corresponding decrease in *Festuca*. *Holcus* remains dominant on the N₃ P K Na Mg plots with and without silicate. *Anthoxanthum*, however, now contributes 5 p. 100 to the yield of the N₃ P K Na Mg plot without silicate. On the unlimed sub-plots of the N₂ P K Na Mg and N₂ P Na Mg plots *Anthoxanthum* has increased to such an extent that it is now dominant. *Holcus* has decreased on the N₂ P K Na Mg plot from 91 to 13 p. 100. As in the past, *Agrostis* remains an important constituent of the N₂ P Na Mg plot.

The changes that have occurred under the old liming scheme on the *a* sub-plots of these five plots have been similar. The percentage contribution of *Alopecurus* has been at least halved and that of *Arrhenatherum* has increased greatly. *Holcus* has increased but *Poa pratensis*, *Dactylis* and *Festuca* have decreased. On the N₂ P Na Mg plot *Anthoxanthum* has greatly increased. The increase in *Lathyrus* on the N₂ P K Na Mg plot, noted earlier, has continued and *Anthriscus sylvestris* and *Heracleum* have increased on this and on the N₃ P K Na Mg plots. These species are still absent on the N₂ P Na Mg plot, where *Rumex* has declined but *Taraxacum* increased. On the F.Y.M. plot the relative proportions of *Alopecurus* and *Agrostis* have been reversed and *Holcus* has increased.

b) *Changes since 1965 on sub-plots which have received lime in the new scheme (table 8).*

Comparing the botanical composition of sub-plots *a* with *b* and *c* with *d* permits an assessment of the effects of the new liming scheme introduced in 1965. As might be expected, liming the previously unlimed *c* sub-plots has caused large changes in the botanical composition of the swards (WILLIAMS, 1974) but changes resulting from increased rates of lime on the previously limed half-plots have been smaller, but nevertheless significant.

By 1973, 12.5 t ha⁻¹ of calcium carbonate, applied between 1965 and 1968, to sub-plot 1 *c*, had decreased percentage *Agrostis* from 85 to 20 p. 100 and increased percentage *Festuca rubra* from 2 to 49 p. 100. Since the yield of the *c* sub-plot at the first cut in 1973 was three times larger than that of the *d* the decrease in the absolute amount of *Agrostis* was less, but the increase in *Festuca rubra* much more, than the percentage figures alone would suggest. Liming allowed legumes to establish on this sub-plot, especially *Lathyrus* which invaded from the neighbouring N₂* P K Na Mg plot, and thirteen other species which in total contributed 16 p. 100 to the yield. These were mainly *Plantago*, *Rumex*, *Cerastium* and *Centaurea*.

On the N₂ P K Na Mg and N₂ P Na Mg plots, lime at 18 and 20 t ha⁻¹ greatly discouraged *Anthoxanthum*, decreasing it from about 70 p. 100 to about 9 p. 100. On the N₂ P K Na Mg plot *Anthoxanthum* was replaced mainly by *Holcus* and *Poa pratensis*; however, on the N₂ P Na Mg plot *Festuca rubra* was increased as much as *Holcus* but *Poa pratensis* less than on the N₂ P K Na Mg plot. Small amounts of

TABLE 8

Number and percentage contribution by weight of grasses, legumes and other species on those Park Grass plots which have received lime under the new scheme

Treatment	N ₁				N ₂ PKNaMg				N ₂ PNaMg				N ₃ PKNaMg				N ₃ PKNaMgSi				FYM + fish meal	
	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
Number of grasses	6	3	10	9	9	4	7	8	9	7	7	6	7	7	8	7	9	3	8	7	9	9
Percentage	82	98	82	75	91	100	94	97	98	100	100	95	94	99	95	96	98	100	95	96	98	85
<i>Agrostis tenuis</i>	20	84	—	—	11	15	2	3	36	31	—	—	—	—	—	t	2	2	—	t	2	19
<i>Alopecurus pratensis</i>	—	—	15	8	1	t	8	7	t	t	30	—	—	9	29	15	7	—	—	—	7	32
<i>Anthoxanthum odoratum</i>	10	11	t	2	11	72	16	18	8	69	—	—	—	—	t	—	t	t	t	—	6	15
<i>Arrhenatherum elatius</i>	—	—	53	51	3	—	20	22	t	t	38	64	30	30	50	61	28	—	—	—	28	7
<i>Diactylis glomerata</i>	—	—	2	4	t	—	—	—	1	—	2	2	2	6	1	5	6	—	—	—	3	2
<i>Festuca rubra</i>	49	3	t	2	4	—	39	37	24	t	—	—	t	2	t	—	4	—	—	—	1	3
<i>Helictotrichon pubescens</i>	—	—	1	2	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Holcus lanatus</i>	1	—	7	6	44	13	4	7	21	t	22	7	7	37	11	3	31	—	—	—	14	20
<i>Poa pratensis</i>	2	—	2	1	16	—	6	3	7	t	2	3	3	12	1	2	13	—	—	—	t	—
<i>Poa trivialis</i>	t	—	2	—	1	—	—	—	t	—	1	1	1	3	3	10	8	—	—	—	—	t
Number of legumes	2	—	1	2	2	—	1	—	—	—	1	—	—	—	1	1	—	—	1	1	—	2
Percentage	2	—	11	16	3	—	t	—	—	—	t	—	—	t	t	t	—	—	t	t	—	9
<i>Lathyrus pratensis</i>	1	—	11	16	3	—	t	—	—	—	t	—	—	—	t	t	—	—	t	t	—	5
<i>Trifolium pratense</i>	1	—	—	t	t	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4
Number of other species	14	2	5	4	4	—	6	8	3	1	4	4	4	4	4	4	5	—	4	4	5	8
Percentage	16	2	7	9	6	—	6	3	2	t	5	6	1	1	4	4	2	—	4	4	6	11

Sub-plots *c* and *d* were analysed in 1973 and *a* and *b* in 1974. See table 5 for explanation of *a*, *b*, *c*, *d* and *t*.

Arrhenatherum and *Dactylis* also occurred on both plots. Legumes and *Anthriscus* and *Heracleum* also established on the N₂ P K Na Mg but not on the N₂ P Na Mg plot; *Taraxacum* established on both plots. The changes that have occurred on the N₃ P K Na Mg plots have been similar. Following the application of lime at 20 t ha⁻¹, *Holcus* has declined from 97 to 35 p. 100 and *Arrhenatherum* (28 p. 100), *Alopecurus* (8 p. 100), *Dactylis* (6 p. 100) and *Poa pratensis* and *Poa trivialis* have established as well as small amounts of four other species. The main effect of recent lime on the previously unlimed part of the F.V.M. plot has been to decrease *Agrostis* and to increase *Arrhenatherum* and the legumes.

Because the limed halves of the N₃ P K Na Mg plots were more acid and needed more lime than the N₂ P K Na Mg and N₂ P Na Mg plots to change the pH to 6, the changes in the botanical composition have been correspondingly larger on the *b* sub-plots of the former than on those of the latter group. On the N₃ P K Na Mg plots extra lime has increased the contribution of *Arrhenatherum*, but halved that of *Alopecurus*, decreased *Holcus*, but slightly increased *Heracleum* and *Anthriscus*. On the N₂ P K Na Mg plot, lime decreased percentage *Alopecurus* and further increased the legumes, mainly *Lathyrus*, from 11 to 16 p. 100. On sub-plot *b* of the N₂ P Na Mg plot, which needed only 3.7 t ha⁻¹ of lime, changes in the botanical composition have been negligible.

Ecological genetics of Anthoxanthum odoratum and other plant species

Anthoxanthum has always been one of the most widely-distributed plant species occurring on both limed and unlimed, fertilised and unfertilised plots. Recently, it has been one of the most abundant species on some of the more acid plots. Its wide distribution could be due to the fact that morphologically and physiologically different populations have evolved on the various plots. This possibility has been investigated by measuring, under uniform conditions, morphological and physiological attributes of plants collected from many contrasted plots. Information has been obtained on the extent, rate and significance of changes within the species. Morphological differences exist between populations (SNAYDON, 1970; SNAYDON and DAVIES, 1972); these differences are usually correlated with environmental conditions on the plots from which they were collected, and are apparently adaptive. Populations also differ in their response to mineral nutrients; again the differences appear adaptive (DAVIES and SNAYDON, 1973 *a* and *b*, 1974; DAVIES, 1975). The adaptive nature of the differences between populations was confirmed by growing them under uniform conditions for several years and then transplanting them back into either their own or other plots. Each population survived and grew fastest in its own plot (DAVIES and SNAYDON, 1976).

Similar studies of *Anthoxanthum* populations from the recently-limed sub-plots have indicated that genetic changes have occurred within seven years and that populations collected less than 1 m apart but from opposite sides of plots boundaries differ both morphologically and physiologically (SNAYDON and DAVIES, 1976). These differences have developed despite appreciable gene flow, caused by pollen drift and seed dispersal.

Differences have also been demonstrated between populations of *Lolium perenne* (GOODMAN, 1969), *Holcus lanatus* and *Dactylis glomerata* (REMISON, 1976)

collected from the Park Grass experiment. Such differences probably also exist between populations of many other species that occur in this experiment. RICHARDS (personal communication) recognised 12 species of *Taraxacum officinale* agg. on the plots, one or two species on each plot where *Taraxacum* was abundant, the taller species on the plots with the tallest hay and the flattest rosettes on the plots with the shortest vegetation.

Chemical composition of the crops

Results are given for three 4-year cycles, 1920-23, 1940-43 and 1956-59 of the liming scheme introduced in 1903. The crops grown during 1856-1873 were analysed chemically (LAWES and GILBERT, 1900) but the changing botanical composition

TABLE 9

Percentage N P K Na Ca Mg in the dry matter of the first crop of herbage, Park Grass, means of 12 years 1920-23, 1940-43, 1956-59

U = unlimed, L = limed half of each plot

Plot	Treatment	Percentage element in dry matter							
		U		L		U		L	
		N		P		K			
	No nitrogen group								
3	Unmanured	1.87	1.82	0.14	0.16	1.47	1.34		
8	P NaMg	1.75	1.72	0.38	0.36	1.20	1.22		
7	PKNaMg	1.76	1.72	0.32	0.30	2.90	3.17		
	Ammonium-N group								
10	N ₂ P Na Mg	2.24	1.88	0.29	0.33	0.66	0.55		
9	N ₂ PKNaMg	1.69	1.50	0.26	0.27	2.72	2.76		
11/1	N ₃ PKNaMg	2.02	1.76	0.25	0.27	2.67	3.04		
	Nitrate-N group								
16	N ₁ *PKNaMg	1.52	1.44	0.29	0.28	2.80	2.65		
14	N ₂ *PKNaMg	1.46	1.46	0.26	0.25	2.57	2.66		
	No nitrogen group	Na		Ca		Mg			
3	Unmanured	0.35	0.34	0.97	1.03	0.24	0.33		
8	P NaMg	0.49	0.40	0.83	0.78	0.24	0.26		
7	PKNaMg	0.05	0.03	0.52	0.70	0.14	0.18		
	Ammonium-N group								
10	N ₂ P NaMg	0.53	0.54	0.18	0.51	0.16	0.26		
9	N ₂ PKNaMg	0.06	0.02	0.15	0.36	0.11	0.13		
11/1	N ₃ PKNaMg	0.10	0.05	0.16	0.26	0.12	0.12		
	Nitrate-N group								
16	N ₁ *PKNaMg	0.18	0.11	0.39	0.50	0.14	0.15		
14	N ₂ *PKNaMg	0.27	0.21	0.28	0.36	0.12	0.13		

of the herbage during that period partly invalidates comparison with later ones. Table 9 shows the percentages of N, P, K, Na, Ca and Mg in the first crops and table 10 the amounts (kg ha⁻¹) of these elements in the total produce. Any comparison of the effects of treatment on chemical composition is limited by the fact that the botanical composition of the herbage was also much affected by treatment.

TABLE 10

*Average yearly content of N P K Na Ca Mg
in the herbage (1st plus 2nd crops),
Park Grass, mean of three periods 1920-23, 1940-43, 1956-59*

U = unlimed, L = limed half of each plot

Plot	Treatment	kg element per hectare							
		U		L		U		L	
		N		P		K			
	No nitrogen group								
3	Unmanured.....	27	31	2	2	20	21		
8	P NaMg.....	49	41	11	9	31	28		
7	PKNaMg.....	67	76	11	13	103	129		
	Ammonium-N group								
10	N ₂ P NaMg.....	73	83	9	14	20	25		
9	N ₂ PKNaMg.....	81	86	12	16	122	146		
11/1	N ₃ PKNaMg.....	116	118	14	18	156	189		
	Nitrate-N group								
16	N ₁ *PKNaMg.....	68	74	12	13	114	121		
14	N ₂ *PKNaMg.....	94	84	17	14	152	140		
	No nitrogen group	Na		Ca		Mg			
3	Unmanured.....	4	6	12	19	3	6		
8	P NaMg.....	13	9	24	20	7	7		
7	PKNaMg.....	2	1	21	31	6	8		
	Ammonium-N group								
10	N ₂ P NaMg.....	18	22	8	24	6	11		
9	N ₂ PKNaMg.....	2	1	9	22	6	7		
11/1	N ₃ PKNaMg.....	6	2	12	20	7	8		
	Nitrate-N group								
16	N ₁ *PKNaMg.....	8	4	18	27	7	8		
14	N ₂ *PKNaMg.....	14	10	20	22	8	7		

Nitrogen

Although fertiliser nitrogen was given only in the spring, percentage nitrogen in the second crop was nearly the same as in the first crop for all treatments (table 9). Lime decreased the percentage N in the crops grown with ammonium sulphate. On

plots without N, or where N was given as sodium nitrate, the percentage N was not altered by giving lime and the differences in the amounts of N in the crops reflected the effects of lime on yield (table 10).

The crop grown on the unmanured soil removed 29 kg N ha⁻¹. About the same amount is removed by other crops grown at Rothamsted on soils unmanured for longer than 100 years (JOHNSTON, 1976). Where P K Na Mg was given, the crop removed more N (72 kg N ha⁻¹) because legumes, mainly *Lathyrus pratensis*, fixed N. However, the extra 43 kg N ha⁻¹ is small compared to the amounts that can be fixed by legumes. We do not know whether this was because these legumes naturally fix little N or whether it was because they were growing in competition with other plants. When 96 kg N ha⁻¹ was applied as ammonium sulphate or sodium nitrate, the crops removed 84 and 90 kg N ha⁻¹ respectively. When the percentage recovery of applied N is calculated as shown in table 17, note *b*, then these crops recovered 57 and 64 p. 100 of the 96 kg N ha⁻¹ dressing. With 48 kg N ha⁻¹ as sodium nitrate, the crop apparently recovered 90 p. 100 of the applied N but the few legumes on this plot may have contributed some of the total N in the crop. With 144 kg N ha⁻¹ as ammonium sulphate, 60 p. 100 of the N was recovered.

Phosphorus

The unmanured crop contained only 0.15 p. 100 P but where much P fertiliser had been given for longer than 60 years the crop contained 0.25 to 0.35 p. 100 P. The amount of P removed yearly ranged from 2 to 18 kg P ha⁻¹; the largest extra uptake represented an apparent recovery of about 50 p. 100 of the applied P.

Potassium

Potassium was the only nutrient of which there was always more in the first crop than in the second, probably because K was applied only once each year, in winter. Where K fertiliser was given the crops removed 100 to 190 kg K ha⁻¹ each year; the largest amount removed was about three-quarters of the added K. The percentage K in crops given K fertiliser was about twice that in unmanured crops and the unmanured crops contained more K than those grown on soils given N P fertilisers only. Herbage given only N P removed so much extra K before 1920 that the annual K uptake had decreased to about 20 kg K ha⁻¹ between 1920-60. This small amount is much the same as that removed by winter wheat and spring barley grown at Rothamsted and similarly manured for the same length of time.

Sodium, magnesium and calcium

Results in tables 9 and 10 show how much fertiliser K depressed the concentration of Na in the dry matter and the uptake of Na by the herbage. Even when much sodium (184 kg Na ha⁻¹) was given as sodium nitrate and sodium sulphate (plot 14), less than 10 p. 100 was removed by the crop.

Magnesium was always applied with sodium and only in small amounts (11 kg Mg ha⁻¹). Percentage Mg in the dry herbage exceeded 0.2 p. 100 only if yields were small; with larger yields Mg levels were often only 0.11 to 0.13 p. 100 Mg. Where

Mg was given, the crops removed 6 to 8 kg Mg ha⁻¹ on all plots (limed and unlimed), except on the limed half of plot 10 (N₂ P Na Mg) where they removed 11 kg Mg ha⁻¹. This large value without K fertiliser may be due to K : Mg interaction.

Percentage calcium was largest when no manures were given and decreased with all manurial treatments. The amounts of calcium removed in the crops were only slightly increased, by 14 kg Ca ha⁻¹ at most, by the application of about 1 700 kg Ca ha⁻¹ as lime every fourth year.

The nutrient composition of different crops

The feeding value of herbage depends not only on its yield but also on its chemical composition. The results from Park Grass show that although crops given different combinations of fertiliser and lime may yield similarly their mineral element composition may vary greatly. Table 11 shows the percentages of N, P, K, Na, Ca and Mg in the first and second crops of five plots which all yielded 4.39 to 4.64 t ha⁻¹ of dry herbage.

TABLE II

The composition of crops grown on plots which yielded 4.39 to 4.64 t ha⁻¹ of dry herbage, Park Grass 1920-59

(3.39 to 3.51 t ha⁻¹ as 1st crop : 0.88 to 1.26 t ha⁻¹ as 2nd crop (a))

Plot	Treatment	Percentage element in dry matter					
		1st crop	2nd crop	1st crop	2nd crop	1st crop	2nd crop
		N		P		K	
7L	PKNaMg	1.7	1.9	0.30	0.36	3.2	2.6
10L	N ₂ P NaMg	1.9	1.9	0.33	0.33	0.6	0.6
9U	N ₂ PKNaMg	1.7	1.8	0.26	0.25	2.7	2.3
16L	N*PKNaMg	1.4	1.6	0.28	0.29	2.6	1.9
16U	N ₁ *PKNaMg	1.5	1.7	0.29	0.31	2.8	2.1
		Na		Ca		Mg	
7L	PKNaMg	0.03	0.03	0.70	0.88	0.18	0.18
10L	N ₂ P NaMg	0.54	0.35	0.51	0.66	0.26	0.23
9U	N ₂ PKNaMg	0.06	0.06	0.15	0.26	0.11	0.11
16L	N*PKNaMg	0.11	0.07	0.50	0.68	0.16	0.16
16U	N ₁ *PKNaMg	0.18	0.12	0.39	0.54	0.14	0.14

a) 1st and 2nd crop ; hay and aftermath respectively.

b) N ammonium sulphate, N* sodium nitrate ; PKNaMg fertilisers applied late winter, N fertiliser applied in spring.

The analyses of the first and second crops (hay and aftermath respectively) were similar. Where K was given, percentage K was less, but percentage Ca was greater, in the second cut than in the first. There were three large differences in the composition of the crops :

1. Herbage grown on very acid soil with $N_2 P K Na Mg$ (plot 9 U) contained very little Mg (0.11 p. 100) but where K was omitted, $N_2 P Na Mg$ (plot 10 U), it contained more than twice as much Mg (0.26 p. 100 and 0.23 p. 100 in the hay and aftermath respectively).

2. Percentage Ca was very small (0.15 and 0.26 p. 100) in herbage grown on very acid soil (plot 9 U).

3. The herbage of all plots given K fertiliser contained little sodium even though on plot 16 extra sodium (84 kg Na ha^{-1}) was given as sodium nitrate.

Magnesium, calcium and sodium are all implicated in certain metabolic disorders of ruminants. These results well show that the concentration of these elements may depend on fertiliser and lime treatments.

The concentrations of some free amino acids in the herbage of some Park Grass plots are also affected by potassium fertiliser and lime (NOWAKOWSKI, JOHNSTON and LAZARUS, 1975). Where lime was given, K fertiliser did not affect the percentage of protein N in the total N of the grass but it increased glutamic and aspartic acid concentrations. On soils of pH 3.8, K fertiliser increased protein N and the concentration of aspartic and glutamic acids, but decreased that of serine, basic amino acids, asparagine and glutamine. Lime, with or without K, had a large effect. Without lime the herbage contained only 0.12 p. 100 Ca and asparagine, glutamine and proline all accumulated in the plant.

The effect of manuring and liming on soil reaction

When the Park Grass experiment started some soils were described as 'sour', a property defined by the type of plants growing on them, but the concept of acidity and the use of a pH scale to measure it had not then been developed. In the 1920s Crowther at Rothamsted investigated various methods of measuring the pH of soil water suspensions. In 1923 he determined the soil reaction (pH) of all the surface and sub-soils on the Park Grass plots using the hydrogen electrode method and a 1 : 5, soil : water suspension (CROWTHER, 1925). In 1959 the pH was measured again using a glass electrode and a 1 : 2.5, soil : water suspension, and in 1975 the pH of the *a* sub-plot soils were measured. WARREN and JOHNSTON (1964) gave the pH values for samples taken in 1923 and 1959 and discussed in detail the changes due to liming and manuring.

Table 12 shows the pH values for the surface soils in 1923, 1959 and 1975. Between 1923 and 1959 both surface and sub-soils of plots given no fertiliser N or sodium nitrate without lime slowly became more acid. Compared to soils without N, sodium nitrate increased soil pH by 0.5 to 1.0 pH unit by 1923 and this difference persisted unchanged during the next 36 years (table 12). It is not known why sodium nitrate increased pH before but not after 1923.

Ammonium sulphate without lime greatly acidified the soils, even below 23 cm. CROWTHER (1925) concluded that pH 3.8 represents the maximum acidity of the Park Grass soil and the 1959 results confirm this: the pH value (3.7) of the surface soil of the unlimed plots getting most ammonium sulphate (706 kg ha^{-1} each year) did not change during 36 years. Soils receiving 471 kg ha^{-1} ammonium sulphate were also at pH 3.7-3.8 in 1959 while the smallest amount of ammonium sulphate (235 kg ha^{-1}) had decreased the pH to 4.0. Except with the smallest amount of ammo-

mium sulphate, the soil between 23 to 46 cm deep on these plots was almost as acid (pH 4.1 to 4.4). In these very acid soils aluminium and manganese are important exchangeable cations.

TABLE 12

Soil reaction, Park Grass, 1923, 1959 and 1975
Surface soils, 0-23 cm

U = unlimed, L = limed half of each plot (a)

Plot	Treatment	pH in water				
		1923		1959		1975
		U	L	U	L	L
No nitrogen group						
3	Unmanured.....	5.7	6.9	5.2	7.2	7.1
8	P NaMg.....	5.7	7.0	5.2	7.0	6.9
7	PKNaMg.....	5.4	6.7	4.9	7.0	6.6
Ammonium-N group						
1	N ₁	4.8	6.5	4.0	7.2	6.6
10	N ₂ P NaMg.....	3.9	4.7	3.8	5.6	5.5
9	N ₂ PKNaMg.....	4.0	4.5	3.8	5.3	5.0
11/1	N ₃ PKNaMg.....	3.8	4.1	3.7	4.2	4.3
11/2	N ₃ PKNaMgSi.....	3.8	4.6	3.7	4.6	5.1
Nitrate-N group						
17	N*.....	6.3	6.8	5.7	7.5	—
16	N* PKNaMg.....	5.9	7.2	5.4	7.1	6.8
14	N* PKNaMg.....	6.4	6.7	6.0	7.3	7.0
FYM group						
13	FYM ^b	4.6	5.8	4.7	7.0	6.9

a) Lime applied every fourth year since 1903

b) FYM applied only every fourth year since 1905, N₂PKNaMg each year 1856-1904.

— Not measured.

Any consideration of the effect of lime must take account of the fact that it was not applied regularly until 1903 whereas ammonium sulphate has been applied each year since 1856. The lime given every fourth year has been equivalent to 4.3 t CaCO₃ ha⁻¹, except in 1971 and 1975 when the *a* sub-plots received half this rate. Liming the plot given 235 kg ha⁻¹ ammonium sulphate increased the pH of the top 23 cm of soil by 0.7 pH unit between 1923 and 1959 but for some unknown reason the soil became more acid again during 1960-75. Lime increased the pH of soils receiving 471 kg ha⁻¹ ammonium sulphate from 4.7 to 5.5 during 1923-59 but the pH of the sub-soils remained unchanged. Between 1960 and 1975 12.9 t CaCO₃ ha⁻¹ maintained these soils at pH 5.4. Where most ammonium sulphate was given (plots 11¹ and 11²) the pH of both surface and sub-soils did not change during 1923-59. Between 1960

and 1975, while the pH of plot 11¹ remained unchanged that of plot 11², given silicate as well, increased by 0.5 pH unit.

Table 12 shows that the unlimed and limed soils of plot 13 (FYM and fish meal since 1905) were quite acid (pH 4.8 and 5.8 respectively) in 1923 as a result of applying 471 kg ha⁻¹ ammonium sulphate each year from 1856 to 1904. Between 1923-59 FYM did not change the pH on the unlimed half-plot, but where lime was given the pH increased considerably.

For the period 1923-59 two estimates can be made of the loss of Ca from these soils. The first is that, even on soils receiving no N or sodium nitrate, much calcium, equivalent to 0.75 to 0.88 t CaCO₃ ha⁻¹, was lost each year from the surface soil. The second is that where most ammonium sulphate was given all the calcium in the lime dressing, equivalent to more than 1 t CaCO₃ ha⁻¹ each year, was lost from the top 46 cm of soil. Most of this loss must be in the drainage water because the crops removed relatively little calcium. Between 1959-75 all the CaCO₃ applied (equivalent to 0.8 t ha⁻¹ year⁻¹) on the *a* sub-plots was lost from the soils receiving 471 kg ha⁻¹ ammonium sulphate.

TABLE 13

Amounts of chalk applied in the new liming scheme on Park Grass and the pH (in water) of successive horizons of the soil profile in 1959, 1971 and 1974

Plot	pH, November 1959				Chalk applied t ha ⁻¹ 1965-68	pH, November 1971				pH, March 1974			
	'mat'	horizon ^a				'mat'	horizon ^a			'mat'	horizon ^a		
		1	2	3			1	2	3		1	2	3
Sub-plots without a 'mat' and soil pH intended to be 6													
4/2 ^b	— ^b	6.0	5.7	5.3	3.7	—	6.5	6.3	5.8	—	5.8	6.1	5.8
9 ^b	—	5.5	5.2	5.1	7.5	—	6.5	5.7	5.2	—	6.0	5.6	5.3
10 ^b	—	5.8	5.5	5.4	3.7	—	6.3	6.2	5.7	—	6.0	5.9	5.6
Sub-plots with a 'mat' and soil pH intended to be 6													
11/1 ^b	5.5	4.2	4.1	4.4	24.9	6.4	4.9	4.6	4.6	6.2	4.7	4.4	4.3
11/2 ^b	5.2	4.7	4.5	4.6	15.1	—	6.5	6.2	5.6	—	6.2	5.4	4.9
Sub-plots without a 'mat' and soil pH intended to be 5													
13 ^c	—	4.7	4.6	4.9	3.7	—	5.8	5.2	5.2	—	5.3	4.8	4.8
Sub-plots with a 'mat' and soil pH intended to be 5													
1 ^c	3.8	3.7	3.9	4.4	12.4	6.7	4.7	4.3	4.5	6.4	4.3	4.3	4.7
4/2 ^c	3.7	3.6	3.7	3.9	22.4	6.3	4.7	4.2	4.3	6.1	4.1	3.9	4.1
9 ^c	3.7	3.4	3.8	4.0	17.6	6.2	4.4	4.1	4.2	6.3	4.3	4.1	4.2
10 ^c	3.9	3.4	3.7	4.1	20.0	6.4	5.0	4.2	4.2	6.2	4.4	4.2	4.1
11/1 ^c	3.7	3.6	3.6	3.8	20.0	6.3	4.2	4.0	4.1	6.2	4.4	4.1	4.6
11/2 ^c	3.7	3.5	3.7	4.0	20.0	6.5	4.2	4.0	4.2	6.6	4.5	4.0	4.0

a) Horizons 1, 2, 3, are the 0 to 7.5, 7.5 to 15 and 15 to 22.5 cm depths of soil respectively.

b) — shows there was no 'mat' of partially decomposed organic material on the surface of the mineral soil.

One reason for modifying the liming treatments on Park Grass was to measure how much chalk was needed to maintain pH levels of 7, 6, 5 and 4 when manurial treatments differ as much as on Park Grass.

JOHNSTON (1972) gave in detail preliminary results for the changes in pH on soils of sub-plots *b* and *c* in the new liming scheme started in 1965. Table 13 gives the amounts of chalk applied during 1965-68 (none was given in 1971-75), and the pH values of the soils in 1959, 1971 and 1974. Evidently, when grassland is undisturbed and percolating water has to take calcium down the profile, soil pH changes only very slowly. On those sub-plots 4^a*b*, 9 *b*, 10 *b*, 13 *c*, which had no 'mat' (a layer of partially decomposed organic matter on the surface) the soil 0-7.5 cm deep (horizon 1) became slightly more acid between 1971 and 1974 and soils on these sub-plots will soon need more chalk to maintain the appropriate pH. On sub-plots which had 'mats' of organic material the pH of the 'mat' increased considerably by 1971 but that of the underlying mineral soil changed little even though much chalk was given. There was little change in the pH of either the 'mats' or the mineral soils on these sub-plots between 1971 and 1974 (table 13) suggesting that much of the added calcium had been held in the 'mat'. On sub-plot 11^a*b* the pH of the mineral soil increased rapidly after the 'mat' disappeared, presumably as a result of increased biological activity following the first chalk application.

The effects of the manures and lime on soil constituents

All soils were sampled from 0-23 cm depth. Detailed results for soils sampled in 1959 have been given previously (WARREN and JOHNSTON, 1964); these together with some earlier results are summarised here.

a) *Organic matter and nitrogen.*

Soil on the unlimed half of each plot was sampled in 1913, at which time the limed halves had received only three dressings of lime. All half-plots were sampled in 1959, when there was a 'mat' of partially decomposed organic material of varying thickness on the surface of the very acid soils (unlimed plots 1, 4^a, 9, 10, 11¹ and 11² and limed plots 11¹ and 11²). Attempts were made to separate the 'mat' which contained 1.5 to 2.0 p. 100 N, from the underlying mineral soil; percentage N in mineral soil is given in tables 14 and 15.

TABLE 14

Percentage N in top soil (0-23 cm), Park Grass 1913 and 1959
Unlimed half-plots only

Treatment	1913	1959
Unmanured.....	0.275	0.278
PK	0.250	0.255
Nitrate-N plus PK	0.269	0.271
Ammonium-N plus PK.....	0.286	0.325

Soil N changed very little between 1913 and 1959 (table 14) in three of the four groups of unlimed soils, suggesting that percentage N had reached an equilibrium value of about 0.27 p. 100 N. Only in very acid, ammonium sulphate treated soils had percentage N increased.

In 1959 there were large differences in pH between limed and unlimed soil (table 12) and also differences in amounts of C and N (table 15). Unlimed soils contain

TABLE 15

Organic carbon and nitrogen contents of Park Grass soils 1959
Surface soils 0.23 cm

U = unlimed, L = limed half of each plot

Plot	Treatment	Organic carbon (p. 100) ^a		Total N (p. 100)	
		U	L	U	L
No nitrogen group					
3	Unmanured	3.3	4.0	0.27	0.33
8	P NaMg	3.0	3.7	0.24	0.31
7	PKNaMg	2.8	3.4	0.23	0.30
Ammonium-N group					
1	N ₁	3.0	3.5	0.24	0.30
10	N ₂ P NaMg	4.2	3.5	0.34	0.28
9	N ₃ PKNaMg	4.1	4.0	0.30	0.31
11/1	N ₃ PKNaMg	4.5	4.1	0.34	0.30
11/2	N ₃ PKNaMgSi	4.7	3.7	0.35	0.29
Nitrate-N group					
17	N ₁ *	2.9	3.5	0.26	0.30
16	N ₁ *PKNaMg	3.6	3.8	0.28	0.32
14	N ₂ *PKNaMg	2.9	3.7	0.27	0.32
FYM group					
13	FYM ^b	3.1	3.8	0.25	0.32

(a) Percentage carbon was determined by the method described by WALKLEY (1947) and multiplied by a factor of 1.3.

(b) FYM applied only every fourth year since 1905, N₂PKNaMg each year 1856-1904.

ned less organic matter than limed soils except those given ammonium sulphate supplying 96 and 144 kg N ha⁻¹; these soils contained more. Where lime had been given, soils without N and with ammonium- and nitrate-N all contained on average about 0.30 p. 100 N (range 0.28-0.33 p. 100 N). This effect of liming is interesting; apparently it has slightly increased the equilibrium value for percentage N in many soils, especially those without N or treated with sodium nitrate. Limed soils had a pH about 7, compared with pH values ranging from 5 to 6 in similarly treated but unlimed soils.

The apparently inconsistent result is that percentage N was larger in some unlimed ammonium sulphate treated soils than in similarly treated limed soils (table 15), and that percentage N in these soils increased between 1913 and 1959 (table 14). All these unlimed soils were already very acid, pH less than 4.0, in 1923 and it is possible that at this pH the rate of mineralisation of organic matter in soil was considerably decreased. In addition there may have been some slight contamination of the mineral soil with 'mat' in 1959. RICHARDSON (1938) found that the very acid soils had no earthworms and concluded that the 'mat' formed because of the effect of acidity on earthworms rather than on the microbiological decomposition of the organic matter. However, a laboratory study by SHAW (1958) showed that the 'mat' decomposed slowly and that decomposition was faster when lime was added.

b) *Phosphorus and potassium.*

Table 16 shows the total P, P soluble in 0.5 M-NaHCO₃, and K exchangeable with 1N-ammonium acetate, in the top 23 cm of soil in 1959. Residues of fertiliser P have accumulated in the surface soils and the amount depends on how much the

TABLE 16

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

U = unlimed, L = limed half of each plot

Plot	Treatment	mg element kg ⁻¹					
		Total P		P soluble in 0.5M NaHCO ₃		K exchangeable with 1N ammonium acetate	
		U	L	U	L	U	L
No nitrogen group							
3	Unmanured	489	568	5	8	79	71
8	P NaMg	1 341	1 527	142	108	76	77
7	PKNaMg	1 319	1 339	126	98	670	609
Ammonium-N group							
1	N ₁	516	589	5	7	56	61
10	N ₂ PNaMg	1 484	1 222	222	95	65	82
9	N ₂ PKNaMg	1 364	1 226	174	103	218	388
11/1	N ₃ PKNaMg	1 274	1 166	211	134	220	240
11/2	N ₃ PKNaMgSi	1 267	1 124	187	94	220	252
Nitrate-N group							
17	N*	502	557	5	7	72	62
16	N ₁ *PKNaMg	1 399	1 502	88	128	668	612
14	N ₂ *PKNaMg	1 100	1 352	42	85	494	474
FYM group							
13	FYM ^a	915	1 021	49	43	101	113

a) FYM applied only every fourth year since 1905, N₂PKNaMg each year 1856-1904..

crop removed. There was relatively more bicarbonate-soluble P in the very acid than in the less acid soils. The amounts of exchangeable K reflect both K manuring and the removal of K in the harvested crops.

Where P has been applied, some is now found at depths below 23 cm (WARREN and JOHNSTON, 1964). Similar downward movement of P into sub-soils has not occurred on arable soils at Rothamsted except where annual dressings of FYM have been given for more than 100 years. We do not know why fertiliser P has moved downwards on Park Grass but there is a common factor in that P movement has occurred on soils rich in organic matter.

Where much potassium has been given and little has been removed in the crop, K also has moved downwards through the soil on Park Grass. Much of this sub-soil K cannot be recovered by shallow-rooting species. The amounts of fertiliser K applied to grassland should therefore be adjusted to balance that removed by the crop; otherwise fertiliser is wasted.

Recent experiments on the more efficient use of N fertilisers

Two features of the Park Grass experiment introduced by LAWES and GILBERT have persisted: the herbage is still cut for hay and all the nitrogen is applied in spring. However, where large yields are required the practice of manuring grassland has changed; grass is cut more frequently and solid nitrogen fertilisers are applied more than once each year. To assess how permanent grassland would respond to these management practices small plot experiments have been made on plots 5 and 6 (fig. 1) since 1965.

Plot 6 was divided into 40 small plots to test amounts and times of N application and the frequency of cutting. The largest amount of N tested was 450 kg N ha⁻¹,

TABLE 17

*Yield of dry herbage and uptake of N.
Rates of N experiment, Park Grass 1972-73*

N applied annually kg ha ⁻¹	0 ^a	0 sp ^a	75	150	225	300	375	450
Dry herbage t ha ⁻¹	6.20	1.82	6.33	7.94	9.78	11.57	11.75	12.49
N in dry herbage kg ha ⁻¹	171	35	154	185	231	300	339	379
Percentage recovery of applied N ^b	—	—	159 ^c	100	87	88	81	76

a) To measure the contribution of the legumes in the sward to yield and nitrogen fixation some plots without N were sprayed with herbicide to kill legumes; this allowed the uptake of non-legume N to be measured and the recovery of fertilizer N calculated.

b) Percentage recovery calculated as:

$$\frac{(\text{uptake on treated soil}) - (\text{uptake on untreated soil})}{\text{amount applied}} \times 100$$

c) Some legumes, still present in the sward on this plot, contributed N to the total N uptake, hence apparent recovery of fertiliser N exceeds 100 p. 100.

about three times that on the main experiment, and as many as six cuts per year have been taken. During the first years of the experiment the herbage responded up to the largest amount of N but with large amounts of N and infrequent cutting, bare patches occasionally developed in the sward. Since 1971 this experiment has been modified to test seven amounts of nitrogen, the plots are cut four times each year and a quarter of each amount of fertiliser N is given for each cut. Yields of dry herbage, N in the dry herbage and the apparent recovery of the applied fertiliser N in 1972-75 are shown in table 17.

Yields ranged from 1.8 to 12.5 t dry herbage ha⁻¹ and there has been no serious deterioration in the sward. The recovery of added nitrogen in this experiment was much larger than in the main experiment. About 90 p. 100 of the N applied (up to 300 kg N ha⁻¹) was recovered in the dry herbage. The apparent recovery of 159 p. 100 of the 75 kg N ha⁻¹ was due to extra N in the legumes in the sward. These large recoveries were probably because nitrogen was applied for each cut. Evidently large yields and recoveries of N can be obtained from permanent pasture on this soil-type and in this climate. Frequent cutting of herbage given no nitrogen has almost eliminated *Lathyrus pratensis* but encouraged *Trifolium pratense* and *Trifolium repens*. We hope to do complete botanical analyses for all treatments after the botanical compositions have stabilised.

DISCUSSION

This experiment quickly achieved its original object of determining how hay yields could be increased by the use of suitable fertilisers. However, as the experiment continued not only were there changes in yield but in the botanical composition of the swards, and these latter changes have continued until today there are large differences between swards, due to treatment. With few exceptions all the crops grown since 1856 have been removed and plant nutrients in the soil have either been depleted or enriched depending on manurial treatment and the size of the crop. In addition some treatments so acidified the soil that on some plots soil reaction is now less than pH 4. No studies have been made on minor elements but the very acid soils must contain much exchangeable aluminium and manganese. It is possible that the observed changes in the relative abundance of some species, e. g. *Alopecurus*, *Anthoxanthum* and *Holcus* on a few plots may be due to changes in amounts of minor elements. We hope that comparative studies on the response to minor elements of some selected species taken from these plots and from natural habitats will be studied soon by colleagues outside Rothamsted.

The decline in *Lolium* right from the start of the experiment could be due to the fact that the genotype present on Park Grass had developed under grazing and was, therefore, not well suited to a hay regime. It might also have failed to adapt to the impoverishment which occurred on the plots with incomplete or no fertiliser.

The studies of *Anthoxanthum*, which occurs on most plots, have shown that within this species there are strains or varieties differing in height and in nutrient requirements. These differences are related to plot treatment and the height of the vegetation on it, and are adaptive because plants raised from them thrive better

when transplanted back into their own plots than into others. Gene-flow across plot boundaries is limited to approximately 0.5 m in either direction for *Anthoxanthum*.

Taraxacum is abundant only on plots given K and lime (table 7) and was one of the genera which invaded the newly-limed section *c* of the very acid plots 11¹ and 11² (N₃ P K Na Mg). There are a number of plots with the correct nutrient requirements and pH for *Taraxacum* but with vegetation differing greatly in height and density. The mechanism of plasticity in *Taraxacum* differs from that of *Anthoxanthum*. In the grass, variation is intraspecific, but *Taraxacum* consists of hundreds of apomictic species, twelve of which have been identified on Park Grass. Usually only two or three occur on one plot, the combination of species depending on the height of the surrounding vegetation. *Taraxacum* spp. found in the tall, dense crops on the limed sections of N₃ P K Na Mg plots have long, broad, erect leaves whereas those found on the unmanured or low-fertility plots produce flat rosettes of small, deeply-indented leaves.

No other species have yet been studied in detail on Park Grass, but it is possible to deduce nutrient requirements and acidity tolerances for some of them from their known distribution on the plots. *Agrostis* tolerates acid soil and deficiency of P and K; it does not require large amounts of nitrogen. On plot 1 (N₁) only *Anthoxanthum* tolerates these conditions as well as does *Agrostis*, and the flora is consequently much less varied than on the adjacent unmanured or N₃* P K Na Mg plots. However, although *Anthoxanthum* tolerates K deficiency it can benefit from added K; plants are taller on plot 9 (N₂ P K Na Mg) than on plot 10 (N₂ P Na Mg).

Holcus grows on unmanured and low-fertility soils but reaches its greatest density (100 p. 100) on the very acid (pH 3.7) soils of unlimed plots receiving N₃ PK Na Mg (table 7). Evidently it requires more nitrogen and is less tolerant of K-deficiency, than *Anthoxanthum*. The latter is presumably shaded out of plots where *Holcus* thrives. Fundamental studies comparing the habit and response to N and K of *Holcus* from different plots would help us to understand the principles underlying competition between species in the mixed flora of permanent grassland and why *Holcus lanatus* is dominant in some natural habitats *e.g.* hill-grazing in Yorkshire.

The species occurring on Park Grass differ in the time of year at which they make their vegetative growth and subsequently flower, and in the height to which they grow. The cutting-regime thus has a profound influence on their relative abundance. For example, *Alopecurus*, *Lolium* and *Dactylis* flower only before the first cut and *Agrostis* only before the second, but *Holcus* flowers abundantly both before and after the first cut. More frequent cutting affects many species. On the frequently-cut micro-plots, maintaining shorter vegetation favours the low-growing *Trifolium* species and is detrimental to *Lathyrus* which scrambles up among the stalks of taller species. Another example occurred on the main experiment in 1975. On some plots narrow, frequently-mown strips gave access to pitfall-traps for insects in 1973 and 1974. In 1975, on some plots *Bromus mollis* was far more abundant where these strips had been than in the surrounding crops, although no extra mowing was done in that year. Some alteration to the vegetation was expected due to this mowing so the strips were outside the areas to be sampled for yield. It will be interesting to see how long the difference persists and whether the copious seed-production of *Bromus* on the strips affects its abundance in adjacent areas in subsequent years.

The introduction of the new liming scheme in 1965 has added greatly to the

interest and value of this experiment, but the full effects will not be seen for some years. Some plots are not yet sufficiently acid for maintenance dressings of lime to be applied. In the first phase, when the *c* sub-plots of the unlimed halves of the more acid plots were limed, *Anthriscus*, *Heracleum* and several leguminous species have established on plot 9 *c* (N₃ P K Na Mg) but not on 10 *c* (without K). Raising the pH of the surface 'mat' of dead, partly-decayed vegetation, in the presence of K (plot 9 *c*) seems to have been more important in admitting new species than the improvement in pH of the underlying mineral soil in the 7.5 to 15.0 cm layer on the no-K plot 10 *c* (table 13). This is to be expected if the new species arrive as seeds which must germinate, and the seedlings establish, first in the surface layer of the plot. The presence of a thick 'mat' as on plot 11¹*d* and 11²*d*, leads to the establishment of young plants growing in it, before they root down into the mineral soil below. A severe drought, or rough treatment by agricultural machinery, can detach the 'mat' from the mineral soil. Plants growing only in the 'mat' then die.

Liming the previously very acid plots 11¹*c* and 11²*c* (N₃ P K Na Mg without and with Si) eventually allowed *Taraxacum* to establish. After the first application of lime, seeds germinated but the seedlings did not establish because the 'mat' was still too acid for them. By 1971, with the pH of the 'mat' raised to 6.3 or 6.5 (table 13) acidity was no longer a limiting factor and as the other requirement, sufficient K, was already met by the fertiliser treatment, *Taraxacum* plants became permanently established.

The spectacular alteration in the flora of small strips mown differently from the rest of the plots shows how difficult it is to do detailed experimentation on the plots without damaging them. Frequently inspected quadrats cause excessive trampling, especially when the hay grows tall. Removal of turf and large soil-cores admits alien species to the bare areas created. Nevertheless, this experiment provides data on, and ideas about, the differences in flora according to the fertiliser given, as described in the Results section, and on the behaviour of individual species, as discussed above. These ideas can and should be followed up in experiments elsewhere, as has been done for *Anthoxanthum*. In new experiments, randomised and replicated, fertiliser treatments can be tested outside the limits set by the old treatments. Plants can be taken from the plots as cuttings or seeds use in such experiments, and the scope for studies of our 60 genera or species and their interaction is vast.

Studies of the relative importance of some factors known to affect plant competition are difficult on these plots. Irrigation, shading and frequent sampling of small areas cannot be undertaken, and the diversity of the flora on some plots complicates the interpretation of variations seen in years with contrasting weather-conditions. Nevertheless, investigation elsewhere of the reactions of individual species or groups of species found on these plots can help in interpreting our records. Conservely, our records could provide a comparison under field conditions with the results of small-scale pot or plot experiments.

One practical use of the results, unforeseen when this experiment began, is their application to the management of roadside verges and amenity grassland. Excessive mowing and the use of herbicides can be avoided by using little or no nitrogenous fertiliser. This saves money, and helps to preserve desirable wild flowers. Park Grass has shown that decorative species such as *Primula veris*, *Ajuga reptans* and *Briza media* are eliminated from the flora by the use of any fertilisers. Unfortunately, often

new road verges are on agricultural soil of high fertility and containing weed-seeds; this makes it difficult to establish a flora resembling the unmanured plots of Park Grass. However, if the final aim is understood, mistakes in early management can be avoided. Photographs of the Park Grass plots are used in some University departments of architecture and landscape-planning, for teaching the principles of amenity-grassland management.

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RÉSUMÉ

OBSERVATIONS RÉCENTES CONCERNANT UN ESSAI SUR PRAIRIE PERMANENTE ÉTABLI EN 1856 :

EFFETS DES ENGRAIS ET DU CHAULAGE SUR LA COMPOSITION BOTANIQUE, LES RÉCOLTES ET LES ANALYSES DU SOL,

Différentes formules de fumure ont été utilisées annuellement depuis 1856 sur prairies permanentes fauchées chaque année pour le foin et on en a comparé les effets avec ceux du fumier de ferme et de traitements sans engrais. L'expérimentation porte sur trois doses d'azote, sous forme de sulfate d'ammoniaque (48,96 et 144 kg N ha⁻¹) et sur deux autres doses, sous forme de nitrate de sodium (48 et 96 kg N ha⁻¹) appliquées avec des engrais PK Na Mg, mais toutes les combinaisons de fumure ne sont pas réalisées. La fumure PK Na Mg a également été appliquée sans N. Entre 1903 et 1964 un chaulage a été effectué tous les quatre ans avec 2 240 kg Cao ha⁻¹ sur les demi-parcelles de la plupart des traitements. En 1965, on a introduit un nouveau plan de chaulage, pour amener en principe les sols à des pH de 4,5, 6,7 sur les quatre sous-parcelles de chaque traitement. On a enregistré annuellement les rendements et certaines années les analyses botaniques et chimiques de l'herbe ont été effectuées. On a également fait des déterminations périodiques du pH des sols et de leur teneur en éléments nutritifs.

Cet article présente les résultats de 12 de ces 20 parcelles et comporte un bref résumé des travaux récents sur l'étude écologique d'*Anthoxanthum odoratum* présent sur la plupart des parcelles.

Depuis le début de l'essai, les rendements en foin ont varié en fonction du traitement. Durant les soixante premières années les différences dues aux traitements furent plus prononcées, bien que les rendements aient diminué sur la plupart des parcelles. Par la suite, de 1920 à 1960, ces derniers restèrent relativement stables, sauf avec la plus petite quantité de sulfate d'ammoniaque pour laquelle les rendements continuèrent à diminuer.

La parcelle non fertilisée continua à peu produire et le rendement le plus élevé fut obtenu avec la plus grande quantité d'azote + PK Na Mg. Quand PK Na et Mg était apporté avec des quantités équivalentes d'azote sous la forme de Nitrate de sodium sans ajout de chaux ou de sulfate d'ammonium avec addition de chaux, les rendements étaient semblables. L'utilisation de PK Na Mg seul et aussi de fumier de ferme alternant avec de la farine de poisson amène à des rendements moyens. Depuis 1960, les rendements obtenus ont été plus importants car les prélèvements étaient faits avant et non pas après les pertes subies durant la fenaison. Les rendements ont été améliorés sur les sols acides non chaulés précédemment, ceci à la suite d'un chaulage effectué

entre 1965 et 1968 ; des doses supplémentaires de chaux, apportées à des parcelles précédemment chaulées, sont restées pratiquement sans effets.

La végétation sur les sols non fertilisés est variée et se compose d'environ 50 espèces, avec une proportion égale de graminées et de dicotylédones ; le chaulage affecte peu la composition botanique. Les apports de PK Na Mg permettent de maintenir la diversité, mais les légumineuses ont tendance à augmenter, en particulier sur les parcelles traitées aussi avec de la chaux ; sur les sols où des doses de sulfate d'ammoniaque ont provoqué une acidification, l'herbe est dominée par des plantes tolérant l'acidité, soit *Agrostis*, *Anthoxanthum*, soit *Holcus*, en fonction des doses d'N et des autres éléments nutritifs apportés.

Le chaulage associé aux deux doses les plus élevées de sulfate d'ammoniaque entraîne une prédominance d'herbes plus productrices, comme *Arrhenatherum* et *Alopecurus*. A doses égales de N, le nitrate de sodium sans chaulage produit une couche herbeuse semblable à celle que l'on peut obtenir avec des apports de sulfate d'ammoniaque associés à un chaulage. Il est particulièrement intéressant de noter que la flore de nombreuses parcelles se modifie lentement, alors que les traitements fertilisants restent inchangés. *Agrostis* et *Anthoxanthum*, qui sont maintenant dominantes sur certaines parcelles, ne l'étaient pas jusqu'en 1930 et 1950 respectivement. L'abondance relative de *Alopecurus* et d'*Arrhenatherum* a également été sujette à des variations dans le temps sur de nombreuses parcelles. Le chaulage introduit par le nouveau plan de fumure a provoqué des changements importants dans la composition botanique sur les sols acides précédemment non chaulés ; les herbes tolérant l'acidité ont en général régressé, mais sans apport de K, *Festuca* s'est beaucoup multipliée.

Un apport de 96 kg N ha⁻¹ a entraîné une augmentation inattendue de *Holcus* et une dose de 144 kg N ha⁻¹ une diminution, inattendue elle aussi, mais *Arrhenatherum* et d'autres plantes fourragères ont eux aussi, augmenté. Sporadiquement quelques dicotylédones de diverses espèces se sont établies sur les parcelles.

Des doses croissantes de chaux sur des parcelles ayant déjà reçu de la chaux ont permis à *Arrhenatherum* de s'étendre, surtout au détriment d'*Alopecurus*. Des recherches sur les variations morphologiques et physiologiques chez *Anthoxanthum*, effectuées par SHAYDON *et al.*, de l'Université de Reading, ont mis à jour des différences d'une population à l'autre dans les caractères morphologiques et dans la réponse à la fumure minérale. L'apparition de ces différences a été rapide et locale et semble indiquer qu'il y a eu adaptation.

Le taux d'azote des différentes cultures a peu varié et les quantités d'N exportées par celles-ci furent en grande partie dépendantes du rendement. Les teneurs en P et K des récoltes étaient beaucoup plus élevées sur les parcelles fertilisées avec ces deux éléments, et l'absorption totale de P et de K par les plantes présentait de fortes variations. Les cultures renfermaient peu de Na et les teneurs en Na étaient encore plus faibles sur les parcelles fertilisées avec K. La teneur en Mg a diminué parallèlement à l'augmentation des rendements et c'est dans les traitements sans K que l'absorption de cet élément par les plantes a été la plus élevée. La teneur la plus importante en calcium a été obtenue dans les cultures sans engrais et la quantité exportée n'a pu être que légèrement augmentée par le chaulage. L'herbe cultivée sur sols acides contenait peu de Mg et de Ca.

Le pH des sols non fertilisés et celui des sols ayant reçu une fumure PK Na Mg se situe actuellement autour de 5. Les sols fertilisés avec du nitrate de sodium ont un pH de 6 à 7, mais les sols de toutes les parcelles traitées avec du sulfate d'ammoniaque sont très acides (pH 3,7-4,0). Dans les sols recevant les plus fortes doses de sulfate d'ammoniaque, la chaux appliquée depuis 1903 a été en grande partie perdue. Sur les parcelles chaulées conformément au nouveau plan, les changements du pH ont été lents. Il semble que le calcium soit retenu dans le « mat » superficiel, composé de matière organique partiellement décomposée. C'est dans les sols traités avec du sulfate d'ammoniaque que le pourcentage de matière organique a été le plus élevé ; toutefois dans le traitement au nitrate de sodium ce pourcentage n'a pas été supérieur à celui du témoin sans engrais. Dans la plupart des traitements le taux d'N du sol a peu varié entre 1913 et 1959 et il semble qu'une valeur d'équilibre ait été atteinte. Des reliquats de P se sont accumulés dans la couche superficielle du sol et, dans les sols à teneur élevée en matière organique, une partie de ce P a migré dans le sous-sol. Des reliquats de K se sont également accumulés là où l'apport de K a été supérieur à l'exportation par les récoltes.

Depuis 1965, dans un essai en micro-parcelles (situé sur une parcelle fertilisée avec PK Na Mg entre 1870 et 1963), nous avons étudié les effets de doses d'azote plus importantes et de coupes plus fréquentes que dans l'essai principal. Les rendements en herbe et la récupération de l'N par les plantes ont été supérieurs à ceux de l'essai principal et les diverses espèces de *Trifolium* ont été très stimulées.

ZUSAMMENFASSUNG

GEGENWÄRTIGE NACHWIRKUNGEN EINES IM 1856 EINGESETZTEN VERSUCHS
AUF DAUERWIESEN WIRKUNGEN
DER DÜNGER UND DER KALKUNG AUF DIE BOTANISCHE ZUSAMMENSETZUNG
UND ANALYSEN DER KULTUREN UND BÖDEN

Seit 1856 wurden alle Jahre Düngerkombinationen einer Dauerwiese mit einer jährlichen Heuernte verabreicht und die Wirkungen dieser Behandlungen wurden den mit Stallmistgaben und ohne Düngung erzielten Wirkungen verglichen. Es wurden drei als Ammoniumsulfate (48, 96 und 144 kg N ha⁻¹) und zwei als Natriumperborat (48 und 96 kg N ha⁻¹) zugeführten Stickstoffgaben mit zusätzlicher P K Na Mg Zufuhr studiert, aber nicht alle Behandlungskombinationen wurden eingeschlossen. P K Na Mg sind auch ohne N verabreicht. Zwischen 1903 und 1964 erhielten die Halbparzellen der meisten Behandlungen 2 240 kg CaO ha⁻¹ alle vier Jahre. Im Jahre 1965 wurde ein neues Kalkungsplan eingeführt, um über Böden mit einem pH von jeweils 4,5, 6 und 7 auf den vier Unterparzellen jeder Behandlung zu verfügen. Die Erträge wurden alle Jahre berechnet und die botanische und chemische Kräuterezusammensetzung wurde manchmal auch bestimmt. Schätzungen des pH und der Bödenährstoffgehalte wurden von Zeit zu Zeit gemacht. Dieser Bericht liefert die Ergebnisse für 12 unter den 20 Parzellen und enthält eine kurze Zusammenfassung der letzten Untersuchungen über die ökologische Genetik von *Anthoxanthum odoratum*, das auf der meisten Parzellen vertreten ist.

Die Heuerträge hängen von den seit dem Versuchsanfang durchgeführten Behandlungen ab. Die von der Behandlung bedingten Differenzen wurden während der sechsig ersten Jahren verstärkt, obgleich der Ertrag auf der meisten Parzellen abstieg. Dann, zwischen 1920 und 1960, sind die Erträge relativ beständig geblieben, ausser auf der Parzelle mit geringster Ammoniumsulfatgabe, auf der die Erträge weiter absanken. Die unverdüngte Parzelle hatte immer noch einen niedrigen Ertrag und der höchste Ertrag wurde für die höchste Stickstoffgabe mit PKNaMg verzeichnet. Die Erträge waren gleich für PKNaMg-Gaben mit gleichwertigen entweder als Natriumperborat ohne Kalk oder als Ammoniumsulfat mit Kalk verabreichten Stickstoffmengen. Die alleinige PKNaMg-Düngung und der wechselweise mit Fischmehl zugeführte Stallmist ergaben mittlere Erträge. Seit 1960 sind die Ertragsschätzungen höher, weil sie vor und nicht nach den während der Heuernte erzeugten Verlusten durchgeführt worden sind. Die Erträge wurden nach einer zwischen 1965 und 1968 gemachten Kalkzufuhr auf sauren nicht vorhergekalkten Böden erhöht; aber eine zusätzliche Kalkgabe auf schon gekalkten Böden wirkte wenig. Auf unverdüngten Böden ist die Vegetation vielfältig; ungefähr 50 unter einjährigen Pflanzen und Dikotyledonen ebenfalls verteilte Pflanzenarten sind vertreten; Kalk beeinflusst wenig die botanische Zusammensetzung. Im Falle von PKNaMg-Zufuhr hält die Mannigfaltigkeit an, aber die Leguminosen vermehren sich insbesondere mit zusätzlicher Kalkzufuhr. Wenn Ammoniumsulfat den Boden angesäuert hat, beherrschen die säurebeständigen einjährigen Pflanzen-entweder *Agrostis*, *Anthoxanthum* oder *Holcus* in Abhängigkeit von der Zufuhr von N und anderen Nährstoffen. Eine Kalkzufuhr mit den beiden höchsten Ammoniumsulfatgaben begünstigt die Beherrschung von ertragsreicheren einjährigen Pflanzen wie *Arrhenatherum* und *Alopecurus*. Für gleichwertige N-Gaben ergibt das Natriumperborat ohne Kalkzufuhr einen Rasen, der diesem mit Ammoniumsulfat und Kalk gleicht. Es ist bemerkenswert dass die Flora von vielen Parzellen sich langsam ändert obgleich die Düngung nicht variiert. *Agrostis* oder *Anthoxanthum*, die heute auf einige Parzellen beherrschen, beherrschen erst seit den dreißiger bzw den sechziger Jahren. Die relative Abundanz von *Alopecurus* und *Arrhenatherum* hat auch mit der Zeit auf vielen Parzellen variiert. Die Kalkung nach dem neuen Plan hat bedeutende Änderungen in der botanischen Zusammensetzung auf vorher ungekalkten sauren Böden hervorgebracht; säurebeständige Kräuter haben sich gewöhnlicherweise verringert, aber ohne K-Zufuhr hat sich *Festuca* sehr vermehrt. Mit 96 kg N ha⁻¹ hat sich *Holcus* unerwartet vermehrt und mit 144 kg ha⁻¹ nimmt es ab, aber *Arrhenatherum* und die anderen einjährigen Pflanzen haben sich auch vermehrt. Gelegentliche Pflanzen vieler Dikotyledonenarten sind auf der Parzellen hervorgetreten. Erhöhte Kalkgaben auf vorher gekalktem Boden haben die Vermehrung von *Arrhenatherum* hauptsächlich auf Kosten von *Alopecurus* begünstigt. Die Untersuchungen von Dr SNAYDON und *al* der Universität von Reading über die morphologischen und physiologischen Veränderungen in *Anthoxanthum* haben eine Bestandsdifferenzierung erweist, die die morphologischen Eigenschaften und die Rückwirkungen hinsichtlich der mineralen Nährstoffe betrifft. Die Differenzen haben sich schnell und örtlich geändert und scheinen einem Anpassungsvermögen zu entsprechen.

Die Schwankung des N-Prozentsatzes in den verschiedenen Kulturen war klein und die N-Aufnahme durch die Pflanzen auf den verschiedenen Parzellen hing im grossen Umfang vom Ertrag ab. Der P- und K-Prozentsatz in den Kulturen Waren viel grösser mit P- und K-Düngung als ohne und die gesamte Aufnahme von beiden Stoffen variierte weitgehend. Die Kulturen enthielten wenig Na und dieser Gehalt sank mit K-Zufuhr ab. Mg-Prozentsatz nimmt mit Ertragserhöhung ab und die Aufnahme war höher ohne Kalkzufuhr. Der Höchste Ca-Prozentsatz wurde in Kulturen ohne Düngung erzielt und die augenommene Menge war nur leicht durch Kalkung erhöht. Der auf sauren Böden gewachsene Rasen enthielt wenig Mg und Ca.

Die pH von ungedüngten und mit PKNaMg gedüngten Böden gleichen jetzt ungefähr 5. Die pH von Böden mit Natriumperboratzufuhr variieren zwischen 6 und 7, aber auf allen Parzellen mit Ammoniumsulfatzufuhr sind die Böden sehr sauer (pH 3.7-4.0). Auf den Böden mit der grössten Ammoniumsulfatgaben wurde ein grosser Teil des seit 1903 gebrachten Kalks verloren. Wo Kalk gemäss dem neuen Plan verabreicht worden ist, sind die änderungen des pH langsam vorgekommen, Ca scheint an der Oberfläche der teilweise zersetzten Stoffe zu bleiben. Der höchste Prozentsatz organischer Substanzen im Boden war auf den Böden mit Ammoniumsulfatzufuhr verzeichnet, aber es gibt nicht mehr organische Stoffe in den mit Natriumperborat verabreichten Böden als in unverdüngten Böden. In den meisten Behandlungen hat sich der N-Prozentsatz zwischen 1913 und 1959 wenig geändert und ein Gleichgewichtswert scheint erreicht zu sein. P-Rückstände werden in der Bodenoberfläche angehäuft und auf an organischen Stoffen reichen Böden haben einige davon in den Untergrund gewandert. K-Rückstände werden auch in den Böden angehäuft, die eine der Kulturaufnahme überlegene K-Gabe erhalten.

Seit 1965 werden grössere Stickstoffmengen und öftere Schnitte in einem Mikroparzellerversuch (auf einer Parzelle mit PKNaMg-Zufuhr zwischen 1870 und 1963) als in dem Hauptversuch getestet. Die Wieseerträge und N-Verwertung waren grösser als in dem Hauptversuch und *Trifolium* arten waren sehr begünstigt.

РЕЗЮМЕ

Модернизация опыта начатого в 1856-м году на постоянном лугу : влияние удобрения и известкования на ботанический состав, урожайность и анализы почв.

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На постоянных укосных лугах, скашивавшихся каждый год на сено, с 1856-го года применялись ежегодно различные формулы удобрения, и их действие сравнивалось с действием обработки навозом и с результатами полученными на делянках без удобрения. В опыте применялись 3 разных дозы азота в форме серноокислого аммония (48, 96 и 144 кг N/га⁻¹), и 2 дозы в форме нитрата натрия (48, и 96 кг N/га⁻¹) вносившиеся с PK, Na и Mg; но все возможные комбинации удобрений не были использованы полностью. Удобрение PK, Na, Mg, применялось также без азота. Между 1903-м и 1964-м годом, каждые 4 года, проводились также известкования в дозе 2 240 кг CaO/га⁻¹ на половинах делянок большей части обработок. В 1965-м году был реализован новый план известкований, для того чтобы довести рН почвы в принципе, от 4,5 до 6,7 на 4-х половинах делянок каждого варианта. Урожай регистрировался каждый год и в некоторые годы проводились ботанический и химический анализы травы. Периодически определялись также кислотность почв и содержание в них главных питательных элементов.

Данная работа заключает результаты, полученные на 12-ти из 20-ти делянок, и краткое описание недавно проведенных работ по экологии душистого колоска (*Anthoxanthum odoratum*), найденном на большинстве делянок.

С самого начала опыта урожай изменялся в зависимости от обработки. В течении первых 60-ти лет различия были более сильными, несмотря на уменьшение урожайности на большинстве из делянок. Позже, от 1920-го до 1960-го года, урожайность оставалась на одном и том-же уровне, за исключением варианта внесения максимальных количеств серноокислого аммония, в котором урожайность продолжала падать.

Неудобренная делянка продолжала приносить мало, а самый крупный урожай был получен при внесении самой крупной дозы азота, РК, Na и Mg. В случаях когда РК, Na и Mg вносились с эквивалентными количествами азота в форме нитрата натрия и без прибавления извести, или в форме серноокислого аммония с прибавлением этой последней, полученные урожаи были одного уровня. Применение РК, Na, и Mg без азота, и поочередное внесение навоза и рыбной муки, давало посредственные результаты. Начиная с 1960-го года урожаи стали больше, ибо пробы стали отбираться не после, а до потерь вызванных укосом. Улучшение урожайности было достигнуто на кислых почвах, предварительно не известкованных, но получивших известь между 1965-м и 1968-м годом; дополнительное-же известкование делянок, предварительно уже известкованных, не произвело практически никакого благоприятного действия.

На неудобренных почвах растительность очень разнообразна и включает около 50 видов, причем пропорция злаковых и двусеменодольных в ней более или менее одинакова; известкование мало влияет на ботанический состав трав. Внесение РК, Na и Mg позволяет поддерживать разнообразие, но с тенденцией к увеличению пропорции бобовых, в особенности на известкованных делянках; на почвах в которых высокие дозы серноокислого аммония вызвали увеличение кислотности, в разнотравьи господствуют растения хорошо выносящие кислотность: полевика (*Agrostis*) душистый колосок (*Anthoxanthum*) или бухарник (*Holcus*), в зависимости от применявшихся доз азота и других питательных элементов.

Известкование, комбинированное с двумя самыми крупными дозами серноокислого аммония, приводит к господству более продуктивных трав, как рай-грасс высокий (*Arrhenatherum*) и лисохвост (*Alopecurus*). При одинаковых дозах азота, нитрат натрия без известкования, дает слой травы того-же порядка что и сернокислый аммоний, комбинированный с известкованием. Но особенно интересно отметить, что флора многих делянок изменяется очень медленно, даже тогда, когда применяется одна и та-же обработка. Полевика (*Agrostis*) и душистый колосок (*Anthoxanthum*) преобладающие в настоящее время на некоторых делянках, не господствовали до 1930-го и 1950-го года соответственно. Относительное изобилие лисохвоста (*Alopecurus*) и рай-грасса высокого (*Arrhenatherum*) также изменилось со временем на многочисленных делянках. Известкование, введенное новым планом, вызвало очень сильные изменения ботанического состава трав на кислых, предварительно не известкованных почвах; отмечена была общая регрессия процента нечувствительных к кислотности трав, и в отсутствии калийного удобрения сильно распространилась овсяница (*Festuca*).

Внесение дозы в 96 кг N/га вызвало неожиданное увеличение процента бухарника (*Holcus*), а внесение дозы в 144 кг N/га, такое-же неожиданное уменьшение этого процента, в то время как пропорция рай-грасса высокого (*Arrhenatherum*) и других кормовых трав сильно увеличивалась. Спорадически появлялись на делянках и некоторые двусеменодольные, принадлежавшие к разным видам.

Увеличение доз извести на делянках уже известкованных, вызвало распространение рай-грасса высокого (*Arrhenatherum*), особенно за счет лисохвоста (*Alopecurus*). Исследование, посвященное морфологическим и физическим изменениям душистого колоска, проведенные Снайдоном и колл. в университете в Ридинге, выявили существование различий между популяциями этого вида в смысле морфологических характеристик и реакции на внесение минеральных удобрений.

Появляются эти различия очень быстро и локально и должно-быть указывают на применение растений. Процент азота изменялся мало в разных культурах и количества вынесенного ими элемента зависели в большинстве случаев от урожая. Сожание P и K в урожаях были гораздо выше на делянках удобренных этими элементами, но поглощение их растениями было очень разным. Культуры содержали мало натрия, и содержание его было еще более слабым на делянках получавших калий. Содержание магния уменьшалось параллельно увеличению урожайности и наиболее интенсивное поглощение этого элемента растениями наблюдалось на делянках не получавших калия. Наиболее высокое содержание кальция наблюдалось в культурах не получавших удобрения, и количество вынесенного растениями элемента увеличивалось только очень немного, после известкования. Травы культивируемые на кислых почвах содержали очень небольшие количества магния и кальция.

pH неудобранных почв и почв получивших удобрение PK, Na и Mg, не превышает в настоящее время 5. pH почв удобренных нитратом натрия находится между 6 и 7, но все почвы обработанные серноокислым аммонием имеют кислую реакцию (pH = 3,7-4,0). В почвах получавших самые крупные дозы серноокислого аммония, известь вносившаяся с 1903-го года, была, в большинстве случаев, — потеряна. На делянках, известкованных по новому плану, pH изменялся очень медленно. Кальций, кажется удерживался в поверхностном слое, составленном из частично разложившегося органического вещества. Процент органического вещества был наиболее велик в почвах получивших серноокислый аммоний, но в варианте с нитратом натрия содержание органического вещества не превышало его содержания в контрольных неудобранных делянках. С 1903-го до 1959-г. года процент почвенного азота менялся мало в зависимости от обработок, и здесь, кажется были достигнуты равновесные величины. Остаточные количества фосфора накапливались в поверхностном слое почв, а в почвах с повышенным содержанием органического вещества, часть этого фосфора мигрировала в под-почву. Остаточные количества калия также накапливались в тех местах, где количество внесенного элемента превышало вынос его урожаем.

С 1965-го года, в опыте на микро-делянках (расположенных на делянке получавшей удобрение PK, Na и Mg с 1870-го по 1963-ий год), изучалось действие более крупных доз азота, и более частых, чем в главном опыте, укосов. Урожай трав и рекуперация азота растениями были лучше и интенсивнее чем в главном опыте и, отмечалась, кроме того, сильная стимуляция некоторых видов клевера.

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