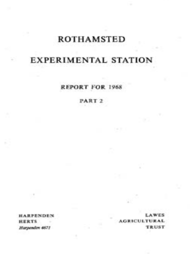
Rothamsted Experimental Station Report for 1968 - Part 2


ROTHAMSTED
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PART 2

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4. The Plant Nutrients in Crops Grown on Broadbalk

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4. THE PLANT NUTRIENTS IN CROPS GROWN ON BROADBALK

A. E. JOHNSTON

A sample of grain and straw from each plot on Broadbalk was kept each year, but some early ones were lost because the containers were damaged. Not all the samples were analysed and tables of composition and uptake of nutrient elements cannot be made to compare with the yield tables. Lawes and Gilbert (1858) published the analyses of the produce from six or eight plots for the individual years 1844, 1845 and 1846. Later they did full analyses on proportionately bulked samples from ten plots representing the four ten-year periods from 1852–91. They published, in detail, results for the crops grown in 1852–71 (Lawes & Gilbert, 1884), but only the results for P, K and Na for four of the ten plots for the second period 1872–91 (Gilbert, 1895); however the results for the other six plots are in manuscript in the Rothamsted archives. No further systematic analyses have been made except that nitrogen was determined in the grain only till about 1910, and Chambers (1946) analysed samples from nine plots up to 1921 for K, Na, Ca and Mg, thus extending the analyses Lawes and Gilbert had tabulated up to 1891. For this article, N, P, K, Na, Ca and Mg were measured in the grain and straw of the last two crops of Squarehead's Master grown in 1966 and 1967, on samples taken from all plots in the continuous wheat section, last fallowed in 1951, and from the section carrying the first crop after fallow.

Most of the analyses for nitrogen were made at Rothamsted. During the 1840s, the soda-lime method of Will and Varrentrapp (Watt, 1963) was used. The dry sample, intimately mixed with soda-lime (1 part NaOH, 2 parts CaO), was heated in a combustion tube. The nitrogen was converted to ammonia, which was expelled from the tube and absorbed in an excess of HCl. Platinum dichloride was then added to the acid ammonium chloride solution and ammonium chloroplatinate precipitated. The whole solution was evaporated to dryness and the residue taken up with mixed alcohol (2 volumes) and ether (1 volume) which dissolved only the platinum dichloride. The ammonium chloroplatinate was then filtered, washed, dried at 130°C and weighed. Manuscript notes at Rothamsted show that Gilbert had to pretreat the soda-lime to remove impurity and that he tried both glass and iron combustion tubes. By the 1860s the method had been modified, the ammonia was absorbed in dilute H_2SO_4 and the excess acid was back titrated with standard NaOH. Manuscript notes show that determining the ammonia gravimetrically gave rather larger values than the volumetric method. Later the Kjeldahl digestion procedure was adopted, the ammonia was distilled from the total digest into standard acid and excess acid back titrated. The 1966–67 analyses were done by a macro-Kjeldahl digestion of the sample and the ammonia in the digest was determined colorimetrically as the indophenol complex on a Technicon AutoAnalyzer.

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Lawes and Gilbert determined the total ash or mineral constituents in the crop to show how this was affected by the P, K, Na and Mg manuring. The ash samples were usually prepared by burning 20 oz of grain or 12·5 oz of straw on platinum dishes, 12 in. long by 4·5 in. wide, which were fitted into cast-iron muffles in a solid fuel furnace. The muffles were arranged so that they were heated mainly from the top (to avoid fusing the ash) and enough air was supplied to the sample without contaminating it by fuel dust from the furnace. Some of these ash samples were then analysed for P, K, Na, Ca, Mg, Fe, S, Cl and Si. Nearly all these analyses were made by Mr. R. Richter, some when he worked in the Rothamsted laboratory, the remainder after he started his own analytical laboratory at Charlottenburg (Berlin). Lawes and Gilbert eventually sent more than 700

TABLE 4·1

Yields of dry matter (lb/acre) of Squarehead's Master winter wheat grown on Broadbalk

Mean for two seasons, 1966–67

		Continuous wheat			1st crop after fallow		
Plot	Treatment[1]	Grain	Straw	Total	Grain	Straw	Total
3	None	847	1052	1899	1738	1832	3570
2A	FYM since 1885	2076	2770	4846	3194	4584	7778
2B	FYM	1970	2828	4798	3294	4865	8159
19	Castor meal	1680	1970	3650	2428	2861	5289
5	P K Na Mg	966	1204	2170	2042	2470	4512
6	N_1 P K Na Mg	1604	1990	3594	2318	2713	5031
7	N_2 P K Na Mg	2290	3142	5432	2442	3132	5574
8	N_3 P K Na Mg	2680	3403	6083	2666	3727	6393
15	N_2†P K Na Mg	1376	2337	3713	2384	2685	5069
17	N_2	1961	2628	4589	2499	3022	5521
18	P K Na Mg	714	910	1624	1904	1956	3860
9	N_1*P K Na Mg	1828	2698	4526	2338	2898	5236
16	N_2*P K Na Mg	2004	3337	5341	3099	4170	7269
10	N_2	1095	1618	2713	1652	1794	3446
11	N_2 P	2032	2490	4522	2014	2323	4337
12	N_2 P Na	2214	2537	4751	2318	2552	4870
13	N_2 P K	2128	2718	4846	2804	3565	6369
14	N_2 P Mg	2404	2780	5184	2623	3037	5660
20	N_2 K Na Mg	1390	2023	3413	(1599)[2]	(2075)	(3674)

[1] For full details see Tables 2·1 and 2·2.
[2] 1967 only.

N Nitrogen as ammonium salts.
N* Nitrogen as sodium nitrate.
N† All nitrogen as ammonium sulphate in autumn.

animal and vegetable ash samples to Charlottenburg for complete analysis. Because each element was determined gravimetrically, this large number of analyses took many years and during this time many of the analytical procedures were improved and it was realised that there were errors in some of the very early analyses. Chambers used the Lundegårdh flame method of spectrographic analysis in the 1940s to determine K, Na, Ca and Mg in cold HCl extracts of dried ground plant material. The 1966–67 analyses for P, K, Na, Ca and Mg were made after the samples had been

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ashed in silica dishes and the ash dissolved in dilute HCl. P was determined colorimetrically as the molybdenum blue complex using a Technicon AutoAnalyzer, K, Na and Ca by flame photometry, and Mg by atomic absorption.

It is proposed to discuss the 1966–67 results (dry matter yields for these two years are in Table 4·1) and relate them where possible to earlier figures.

Nitrogen

The nitrogen removed by the crops grown in 1966–67 is shown in Table 4·2. For all comparisons more nitrogen was removed in the first crop

TABLE 4·2

Amount of nitrogen removed in Squarehead's Master winter wheat grown on Broadbalk

Mean for two seasons, 1966–67

lb N/acre/year

Plot	Treatment	Continuous wheat Grain	Straw	Total	1st crop after fallow Grain	Straw	Total
3	None	18·4	4·2	22·6	34·5	6·5	41·3
2A	FYM since 1885	45·0	9·8	54·8	78·2	19·8	98·0
2B	FYM	44·5	12·1	56·6	84·0	23·6	107·6
19	castor meal	32·3	6·6	38·9	51·2	11·9	63·1
5	P K Na Mg	18·8	4·2	23·0	41·4	8·9	50·3
6	N_1 P K Na Mg	30·2	6·6	36·8	47·6	10·1	57·7
7	N_2 P K Na Mg	44·8	12·1	56·9	55·4	14·2	69·6
8	N_3 P K Na Mg	55·1	14·1	69·2	60·4	19·8	80·2
15	N_2†P K Na Mg	28·4	9·6	38·0	49·2	10·4	59·6
17	N_2	37·6	9·6	47·2	49·0	11·6	60·6
18	P K Na Mg	14·0	4·3	18·3	37·8	7·8	45·6
9	N_1*P K Na Mg	35·2	8·6	43·8	47·8	11·4	59·2
16	N_2*P K Na Mg	40·8	18·5	59·3	64·9	17·6	82·5
10	N_2	22·4	6·5	28·9	36·2	8·5	44·7
11	N_2 P	41·0	9·8	50·8	43·4	11·2	54·6
12	N_2 P Na	44·4	9·8	54·2	47·4	10·0	57·4
13	N_2 P K	42·6	12·0	54·6	59·2	12·8	72·0
14	N_2 P Mg	46·0	10·5	56·5	54·3	11·6	65·9
20	N_2 K Na Mg	27·6	9·4	37·0			

N Nitrogen as ammonium salts.
N* Nitrogen as sodium nitrate.
N† All nitrogen as ammonium sulphate in autumn.

after fallow than in the continuous wheat; this was not only because the crop was larger but also because in nearly all comparisons for both grain and straw the percentage of N in the dry matter was larger. The reason for this increase in %N is not known, but possible factors are:

1. the roots of the first crop after fallow grew better;
2. fallowing may have improved soil structure and allowed the roots to search better for the nutrients in the soil;
3. N accumulated in the soil during the fallow may have been mineralised and taken up throughout the growing season.

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Table 4·3 shows that the 1966–67 results largely confirm those of Lawes and Gilbert for the effect of N and PKNaMg on the nitrogen content of the harvested crop. Without manure, the N content changed little between the two periods. PKNaMg given without N had little effect on the N content as soon as readily mineralised N reserves originally present in the soil were used. With full N_2PKNaMg manuring, the N content changed little, but the crops given N without PKNaMg contained less N by 1966–67 because the diminishing amounts of available P and K in the soil limited yield more.

TABLE 4·3

Uptake of nitrogen by grain + straw of winter wheat grown continuously on Broadbalk

Means for 1852–61 and for 1966–67

	Uptake lb N/acre/year					
	Without N		With N(N_2)		N_2 minus N_0	
	1852–61	1966–67	1852–61	1966–67	1852–61	1966–67
Without PKNaMg	23·1	22·6	38·3	28·9	15·2	6·3
With PKNaMg	28·7	23·0	57·3	56·9	28·6	33·9

Table 4·4 shows the apparent recovery of nitrogen added as ammonium-N, nitrate-N and organic-N in castor meal was better by the continuous wheat than by the first crop after fallow; this was because the first crop after fallow took up proportionately more N when given PKNaMg. However, the first crop after fallow recovered much more nitrogen from FYM than did the continuous wheat. This difference between the two

TABLE 4·4

Percentage recovery of added nitrogen by Squarehead's Master winter wheat grown on Broadbalk

Total uptake by grain + straw, mean of 1966 and 1967
Uptake on plot 5 (PKNaMg) taken as standard

		% recovery of added N	
Plot	Treatment per acre	by continuous wheat	by 1st crop after fallow
6	43 lb NH_4–N P K Na Mg	32·1	17·2
7	86 lb NH_4–N P K Na Mg	39·4	22·4
8	129 lb NH_4–N P K Na Mg	35·8	23·2
15	86 lb NH_4–N P K Na Mg (all N given in autumn)	17·4	10·8
9	43 lb NO_3–N P K Na Mg	48·4	20·7
16	86 lb NO_3–N P K Na Mg	42·2	37·4
2	198 lb total N in FYM	16·6	26·5
19	86 lb total N in rape cake	18·5	14·9

forms of organic nitrogen suggests that residues of FYM continue to produce worthwhile amounts of nitrogen, but nitrogen in castor meal is so quickly mineralised that the residues provide very little. Table 4·4 also shows that, when given 43 or 86 lb N/acre, both crops recovered more N from nitrate (all given in spring) than from ammonium (some given in autumn, some in spring). The apparent recovery from 86 lb NH_4-N given

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all in autumn (plot 15) was only about half that from the same amount of N divided between autumn and spring dressings.

In 1844 and 1845 Lawes and Gilbert applied nitrogen to Broadbalk in units of 112 lb/acre of ammonium sulphate. In 1846 they used a mixture of equal weights of ammonium sulphate and ammonium chloride. In 1847 they changed the weight unit to 100 lb of this mixture and 400 lb of the mixed salts contained 100 lb ammonia, equivalent to 82 lb N. The salts available commercially became purer so that, by the late 1850s, when applied at 400 lb/acre the nitrogen applied had increased to 86 lb N/acre. Thus there are some slight discrepancies between figures in early publications for the nitrogen recoveries by crops according to which value was used for the N applied. Table 4·5 shows some comparisons between the N recoveries published by Lawes and Gilbert and those for continuous winter wheat grown in 1966–67. Without PKNaMg the crops recovered less N in 1966–67 because deficiencies of P and K limited growth. With FYM (always ploughed-in, in autumn), or sodium nitrate (always applied all in spring), the crops recovered the same amount of N during both periods. (See also note on recovery of P on page 56.)

TABLE 4·5

Percentage recovery of added nitrogen by grain + straw of winter wheat grown continuously on Broadbalk

Means for three periods, 1852–71, 1852–81, 1966–67
extra uptake over that on plot 5 (PKNaMg)

Treatment	N added lb/acre/year 1852–71	N added lb/acre/year 1966–67	% recovery of added N 1852–71[1]	% recovery of added N 1966–67
N_1 as NH_4–N P K Na Mg	41	43	32·4	32·1
N_2 as NH_4–N P K Na Mg	82	86	32·9	39·4
N_3 as NH_4–N P K Na Mg	123	129	31·5	35·8
N_4 as NH_4–N P K Na Mg[2]	164	—	28·5	—
N_2 as NO_3–N P K Na Mg	82[3]	86	45·3	42·2
14 tons FYM	200	198	14·6	16·6
All N as NH_4–N	N added lb/acre		1852–81[4]	1966–67
N_2	86		14·4	6·9
N_2P	86		20·6	32·3
N_2P Na	86		25·8	36·3
N_2P K	86		27·2	36·7
N_2P Mg	86		28·0	39·0
N_2P K Na Mg	86		30·1	39·4

[1] Lawes & Gilbert 1873.
[2] 1852–64 only.
[3] 82 lb N 1855–71 only.
[4] Lawes, Gilbert & Warington 1882.

Given P and either K, Na or Mg, or PKNaMg, more of the added NH_4-N was recovered in 1966–67, when some was applied in spring, than when all the N was applied to the seedbed in autumn between 1852 and 1871.

A satisfactory estimate cannot be made of the amount of nitrogen that accumulates during a fallow year and can be used by a winter wheat crop on Broadbalk. Small amounts of P and K on plot 3 probably limit growth so that 18 lb, the extra uptake, is probably an under-estimate, whereas mineralisation of N residues from leguminous weeds on plots 5, 17 and 18 (see p. 189) probably means that the extra uptake of 27 lb on these plots is an over-estimate.

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Phosphorus, Potassium, Sodium, Magnesium

Lawes and Gilbert published analyses for the mineral constituents of the wheat grown on Broadbalk in three papers, which are still one of the most extensive studies of their kind (Lawes & Gilbert 1858; Lawes & Gilbert 1884; Gilbert 1895). In the first two the results were presented in three ways:

1. the composition of the ash;
2. the amount per 1000 of dry substance;
3. uptake in lb/acre in grain, straw and total produce.

In the first paper (Lawes & Gilbert, 1858) were 23 analyses including some of the products from grain milling, flour and bran. The second paper (Lawes & Gilbert, 1884) gave results, set out in three groups, for both grain and straw.

1. The first group was of three plots, FYM, unmanured and N only for 16 consecutive seasons, 1848 (5th season) to 1863 (20th season). The results showed seasonal fluctuations under very different manuring.
2. The second group was for nine different treatments, FYM, unmanured, PKNaMg, N_2PKNaMg, N_2, N_2P, N_2PNa, N_2PK and N_2PMg each in two unfavourable (1852 and 1856) and two favourable (1858 and 1863) seasons. The results extended those of group 1 to a wider range of manurial treatments for the extremes of good and bad seasons.
3. The third group was for the analyses of bulked samples, mixed in proportion to the annual yields, for two 10-year periods, 1852–61 and 1862–71 from ten differently manured plots. The analyses in this last group were not done until after 1871 when Richter had established satisfactory methods of analysis. They showed the effect of accumulation and exhaustion of mineral constituents in the soil on the mineral composition of the wheat plant.

In a third paper, Gilbert (1895) published the uptakes of P, K and Na by the crops on plots 11, 12, 13 and 14 for the two ten-year periods 1872–81 and 1882–91.

The first paper showed that the ash of wheat grain had about 50% P_2O_5, 30% K_2O, 10% MgO, 3% CaO and established that the percentages of N, P, K, Ca and Mg increased from the finer to the coarser flours and were much larger in the bran. The first two papers showed that better matured grains contained smaller percentages of nitrogen and total mineral matter, for favourable growing conditions enhanced the accumulation of starch. In good seasons, the dry matter of both grain and straw contained slightly larger percentages of K and slightly less P and Mg than in bad seasons; the total uptake of all three nutrients was, however, greater in the better seasons. The compositions of grain and straw ash from the three plots given no fertiliser, FYM and N only, when compared over 16 consecutive seasons, showed that seasonal differences caused larger variations in the percentage of P and K in the ash from any one treatment than existed between the means for each treatment. The range of seasonal variation was

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much greater for straw ash than for grain ash; fully ripened grain had a very uniform mineral composition.

From early analyses Lawes and Gilbert found that grasses and cereals contained much silica and, on Broadbalk, Hoosfield and Park Grass, they tested additions of silica in various forms. They supposed that the silica made the straw stronger and prevented lodging. However, the accumulated analyses showed that the percentage of silica in the straw was larger in bad than in good seasons, when the large yields of organic material diluted the silica. In seasons when harvesting was difficult straw containing much silica was brittle and unsuitable for use in the local straw-plait industry.

TABLE 4·6

Amount of phosphorus removed in Squarehead's Master winter wheat grown on Broadbalk

Mean for two seasons, 1966–67

lb P/acre/year

		Continuous wheat			1st crop after fallow		
Plot	Treatment	Grain	Straw	Total	Grain	Straw	Total
3	None	3·4	0·6	4·0	6·7	0·8	7·5
2A	FYM since 1885	9·0	2·1	11·1	13·6	3·8	17·4
2B	FYM	8·5	2·9	11·4	14·2	4·6	18·8
19	Castor meal	6·8	1·1	7·9	9·8	1·6	11·4
5	P K Na Mg	4·1	1·0	5·1	8·2	1·6	9·8
6	N_1 P K Na Mg	6·4	1·3	7·7	9·4	2·0	11·4
7	N_2 P K Na Mg	9·4	2·0	11·4	10·2	2·2	12·4
8	N_3 P K Na Mg	11·2	2·1	13·3	10·7	2·9	13·6
15	N_2†P K Na Mg	5·8	2·0	7·8	9·8	1·6	11·4
17	N_2	7·8	1·6	9·4	9·6	1·4	11·0
18	P K Na Mg	2·9	0·8	3·7	7·7	1·2	8·9
9	N_1*P K Na Mg	7·5	1·6	9·1	9·3	1·9	11·2
16	N_2*P K Na Mg	8·1	2·7	10·8	12·5	2·5	15·0
10	N_2	3·7	0·6	4·3	5·8	0·9	6·7
11	N_2 P	6·0	1·8	9·8	7·4	1·6	9·0
12	N_2 P Na	9·0	1·9	10·9	9·0	1·6	10·6
13	N_2 P K	8·6	2·1	10·7	11·2	1·8	13·0
14	N_2 P Mg	9·9	2·0	11·9	10·0	1·6	11·6
20	N_2 K Na Mg	4·7	1·0	5·7			

N Nitrogen as ammonium salts.
N* Nitrogen as sodium nitrate.
N† All nitrogen as ammonium sulphate in autumn.

Phosphorus. Table 4·6 shows that in 1966–67 the first crop after fallow contained more P than the continuous wheat, but this was because of the increase in yield and not because of an increase in the percentage of P in the dry matter. Table 4·7 shows that the percentage of P in the dry matter of the grain in 1966–67 was very similar to that between 1862 and 1871, but the straw contained less in 1966–67 where N, P or NP were not given. However, the total uptakes of P on all plots except 10 (N_2) (which was less) were closely similar in the two periods. It is worth emphasising that the uptake of both N and P has remained much the same over the whole period of the experiment where NPK have been given. For N this might be explained by the fact that there has been no accumulation of total

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TABLE 4·7

Percentage P in grain and straw of winter wheat grown continuously on Broadbalk and the total uptake of P

Means for 1862–71 and for 1966–67

		% P in dry matter				Total P in crop lb/acre	
		Grain		Straw			
Plot	Treatment	1862–71	1966–67	1862–71	1966–67	1862–71	1966–67
2B	FYM	0·436	0·437	0·098	0·103	11·9	11·4
3	None	0·439	0·411	0·091	0·063	4·2	4·0
5	P K Na Mg	0·452	0·430	0·124	0·079	5·4	5·1
10	N_2	0·344	0·343	0·066	0·039	6·1	4·3
7	N_2P K Na Mg	0·414	0·409	0·066	0·065	10·2	11·4

inorganic N in the soil but it is remarkable that there has been no luxury uptake of P by the crop grown on those plots where large residues of inorganic P have accumulated.

Table 4·8 shows the apparent recovery by the whole crop from the 30 lb P/acre added each year; the figures for 1852–71 are calculated from those given by Lawes and Gilbert. For 1966–67 the recoveries by the continuous wheat and the first crop after fallow include analyses on crops given N_2PKNaMg and N_2KNaMg; this comparison could not be made before 1906 when A. D. Hall started the present plot 20. Without fertiliser N during both periods, continuous wheat recovered less than 5% of

TABLE 4·8

Apparent recovery of phosphorus by grain and straw of winter wheat grown on Broadbalk

Means for 1852–71 and for 1966–67

30 lb P/acre/year added as superphosphate

	without N		with N			with N	
Treatment	—	PK	—	P	PK	KNaMg	PKNaMg
Plot	3	5	10	11	13	20	7
1852–71							
amount in crop, lb/acre	4·4	5·9	5·8	8·2	10·1		
% recovery		5		8	14		
1966–67							
Continuous wheat							
amount in crop, lb/acre	4·0	5·1	4·3	9·8	10·7	5·7	11·4
% recovery		4		18	21		19
1st crop after fallow							
amount in crop, lb/acre	7·5	9·8	6·7	9·0	13·0	5·9	11·3
% recovery		8		8	21		18

the P applied; but the nitrogen accumulating in the fallow year increased crop yield so that 8% of the P was recovered. When N was given the recovery of P in 1852–71 increased from 8% without K to 14% with. In 1966–67 the continuous wheat with and without fertiliser-K recovered 21% and 18% respectively of the added P. This apparent extra recovery during the second period is only partly because extra fertiliser-P was taken up; there was also less taken up on plot 10 (N_2). The first crop after fallow recovered 18–21% of the P applied only where K was given.

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Cations, K Na Ca Mg. Analyses of the crops were published by Lawes & Gilbert (1884) and by Gilbert (1895). Manuscript tables in the Rothamsted archives give analyses of the crops in the two ten-year periods 1872–81 and 1882–91. Chambers (1946) used these and his own analyses of crops for the two periods 1902–11 and 1912–21, to study the uptake of K, Na, Ca and Mg by winter wheat. These results are for harvested crops. Work by Knowles & Watkin (1931), Chambers (1953b) and Widdowson, Penny & Williams (1967) showed that cereals may take up more of some elements during active growth than appears in the harvested crop.

Potassium. The amount of potassium taken up by the crops grown in 1966–67 is in Table 4·9. The first crop after fallow contained more K

TABLE 4·9

Amount of potassium removed in Squarehead's Master winter wheat grown on Broadbalk

Mean for two seasons, 1966–67

lb K/acre/year

		Continuous wheat			1st crop after fallow		
Plot	Treatment	Grain	Straw	Total	Grain	Straw	Total
3	None	4·2	4·1	8·3	8·8	11·0	19·8
2A	FYM since 1885	10·4	20·3	30·7	15·2	49·8	65·0
2B	FYM	9·6	24·2	33·8	15·4	55·6	71·0
19	Castor meal	8·5	7·5	16·0	11·4	14·8	26·2
5	P K Na Mg	4·8	6·0	10·8	9·8	14·8	24·6
6	N_1 P K Na Mg	8·4	11·0	19·4	11·4	16·5	27·9
7	N_2 P K Na Mg	11·8	18·7	30·5	11·8	21·0	32·8
8	N_3 P K Na Mg	13·8	21·1	34·9	13·0	26·6	39·6
15	N_2†P K Na Mg	7·4	16·8	24·2	11·8	17·2	29·0
17	N_2	10·1	14·6	24·7	12·1	19·0	31·1
18	P K Na Mg	3·6	8·0	11·6	9·5	10·8	20·3
9	N_1*P K Na Mg	9·4	15·8	25·2	11·4	20·5	31·9
16	N_2*P K Na Mg	10·6	23·8	34·4	14·9	26·4	41·3
10	N_2	5·6	4·5	10·1	8·2	10·1	18·3
11	N_2 P	10·4	6·8	17·2	9·9	10·0	19·9
12	N_2 P Na	11·8	7·4	19·2	11·7	9·6	21·3
13	N_2 P K	11·3	17·0	28·3	14·0	23·4	37·4
14	N_2 P Mg	13·0	7·4	20·4	13·0	9·8	22·8
20	N_2 K Na Mg	6·6	11·8	18·4	(7·4)[1]	(13·5)	(20·9)

[1] 1967 only.

N Nitrogen as ammonium salts.
N* Nitrogen as sodium nitrate.
N† All nitrogen as ammonium sulphate in autumn.

than wheat grown continuously, both in grain and straw. However, the percentage of K in the grain was changed little either by treatment or by position in the cropping cycle, confirming Lawes and Gilbert's views about the composition of ripe grain. There was more K in the dry matter of the straw of the first crop after fallow (range 0·32% to 1·18%) than in the straw of the continuous wheat (range 0·28% to 0·85%); the large variation was related to treatment. The percentages of K in the grain for the two seasons, 1966 and 1967, do not support Chambers' (1953a) prediction that the %K would diminish. Table 4·10 shows that %K in grain in 1966–67 was roughly the same as the mean for the period 1852–1921. Chambers also

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showed that, whereas the percentage of K in the straw grown on plots given K was increasing, it was decreasing where K was not given. However, Table 4·10 shows that straw harvested in 1966–67 contained only half as much K as straw from crops in the earlier period, 1852–1921. This large difference is probably because of the change in the method of harvesting. When the crop was cut slightly green with the binder, and the sheaves left in stooks to dry, there was much less chance for K to be leached from the straw than when the crop stood in the field to ripen fully before being harvested by the combine. Also the straw sample from the combine con-

TABLE 4·10

Percentage K in the grain + straw of winter wheat grown continuously on Broadbalk

Means for 1852–1921 and for 1966–67

80 lb K/acre/year applied as potassium sulphate since 1859

% K in dry matter

Plot	2B	3	5	7	10	11	12	13	14
Period					Grain				
1852–1921[1]	0·50	0·52	0·53	0·50	0·48	0·48	0·50	0·51	0·49
1966–1967	0·50	0·50	0·50	0·52	0·50	0·51	0·54	0·52	0·54
					Straw				
1852–1921[1]	1·18	0·82	1·04	1·12	0·63	0·51	0·68	1·10	0·70
1966–1967	0·78	0·39	0·51	0·58	0·29	0·27	0·28	0·63	0·26

[1] Omitting decade 1892–1901.

tains no chaff and pieces of leaf, which were certainly weighed and may have been sampled as straw when the plot produce was threshed in a stationary thresher.

Chambers (1953a) calculated that crops given N recovered about 50% of the fertiliser K, but he ignored the K provided by the soil. Table 4·11 shows that if K taken up from soil not given fertiliser-K is allowed for, then, from the dressing of 80 lb K/acre, the crops recovered 29% in 1862–91 and 14% in 1966–67 where Na and Mg were not applied. A smaller proportion was recovered in 1966–67 because there was less K in the straw. When Na and Mg were given without K (plots 12, 14) in amounts chemi-

TABLE 4·11

Apparent recovery of potassium by grain + straw of winter wheat grown continuously on Broadbalk

Means for 1862–91 and for 1966–67

80 lb K/acre/year applied as potassium sulphate since 1859

K in crop lb/acre

Plot	Treatment	1862–91			1966–67		
13	N_2P K		40·6			28·3	
11	N_2P		17·3			17·2	
	13 minus 11		23·3			11·1	
	% recovery			29%			14%
13	N_2P K		40·6			28·3	
12	N_2P Na	26·2	26·6		19·2	19·8	
14	N_2P Mg	26·9			20·4		
13 minus (mean 12 and 14)			14·0			8·5	
% recovery				18%			11%

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TABLE 4·12

Amounts of sodium, calcium and magnesium removed in Squarehead's Master winter wheat grown on Broadbalk

Mean for two seasons 1966–67

lb element/acre/year

		Sodium						Calcium						Magnesium					
		Continuous wheat			1st crop after fallow			Continuous wheat			1st crop after fallow			Continuous wheat			1st crop after fallow		
Plot	Treatment	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
3	None	0·1	0·2	0·3	0·2	0·3	0·5	0·4	2·6	3·0	0·9	5·0	5·9	1·1	0·5	1·6	2·3	1·2	3·5
2A	FYM since 1885	0·2	0·4	0·6	0·4	0·6	1·0	1·2	5·1	6·3	1·4	10·4	11·8	2·9	1·2	4·1	4·7	2·9	7·6
2B	FYM	0·2	0·4	0·6	0·3	0·6	0·9	0·9	5·2	6·1	1·6	12·2	13·8	2·8	1·6	4·4	4·8	3·3	8·1
19	Castor meal	0·2	0·2	0·4	0·3	0·4	0·7	0·8	4·5	5·3	1·2	7·5	8·7	2·1	1·0	3·1	3·3	1·9	5·2
5	P K Na Mg	0·1	0·2	0·3	0·2	0·3	0·5	0·5	2·5	3·0	0·9	5·7	6·6	1·3	0·6	1·9	2·8	1·7	4·5
6	N_1 P K Na Mg	0·1	0·2	0·3	0·1	0·4	0·5	0·7	4·8	5·5	1·0	6·6	7·6	2·0	1·1	3·1	3·2	1·9	5·1
7	N_2 P K Na Mg	0·2	0·3	0·5	0·4	0·3	0·7	1·0	7·3	8·3	1·1	8·5	9·6	2·9	1·7	4·6	3·4	2·1	5·5
8	N_3 P K Na Mg	0·2	0·4	0·6	0·3	0·6	0·9	1·3	8·0	9·3	1·2	11·3	12·5	3·4	1·7	5·1	3·7	2·6	6·3
15	N_2†P K Na Mg	0·1	0·2	0·3	0·2	0·4	0·6	0·7	7·5	8·2	1·1	6·3	7·4	1·8	1·4	3·2	3·5	1·7	5·2
17	N_2	0·2	0·3	0·5	0·2	0·4	0·6	0·9	6·2	7·1	1·1	7·2	8·3	2·5	1·4	3·9	3·2	1·9	5·1
18	P K Na Mg	0·1	0·1	0·2	0·2	0·4	0·6	0·4	4·0	4·4	0·9	4·9	5·8	0·9	0·6	1·5	2·7	1·3	4·0
9	N_1*P K Na Mg	0·2	0·5	0·7	0·2	0·5	0·7	0·7	5·4	6·1	1·0	7·5	8·5	2·4	1·4	3·8	3·1	2·2	5·3
16	N_2*P K Na Mg	0·3	0·7	1·0	0·3	1·0	1·3	0·9	9·1	10·0	1·3	10·0	11·3	2·4	1·9	4·3	4·4	2·8	7·2
10	N_2	0·1	0·2	0·3	0·1	0·5	0·6	0·6	4·4	5·0	1·0	5·6	6·6	1·2	0·7	1·9	2·0	1·2	3·2
11	N_2 P	0·2	0·4	0·6	0·2	0·9	1·1	1·3	7·4	8·7	1·3	8·8	10·1	2·4	1·2	3·6	2·5	1·7	4·2
12	N_2 P Na	0·2	0·5	0·7	0·2	1·0	1·2	1·2	8·3	9·5	1·4	8·6	10·0	2·6	1·2	3·8	2·9	1·6	4·5
13	N_2 P K	0·2	0·3	0·5	0·2	0·5	0·7	0·9	7·3	8·2	1·3	8·7	10·0	2·5	1·2	3·7	3·7	1·9	5·6
14	N_2 P Mg	0·2	0·4	0·6	0·3	0·5	0·8	1·3	8·0	9·3	1·5	8·4	9·9	3·0	1·6	4·6	3·5	2·1	5·6
20	N_2 K Na Mg	0·1	0·2	0·3	(0·3)[1]	(0·2)	(0·5)	0·6	4·8	5·4	(0·8)	(5·2)	(6·0)	1·5	1·1	2·6	(2·1)[1]	(1·4)	(3·5)

[1] 1967 only.

N Nitrogen as ammonium salts. N* Nitrogen as sodium nitrate. N† All nitrogen as ammonium sulphate in autumn.

cally equivalent to the amount of K on plot 13, the uptake of K on plots given Na or Mg increased and the apparent recovery of added fertilizer K decreased to 18% in 1862–91 and 11% in 1966–67. Chambers concluded that Na and Mg, when applied to soils not receiving K, released soil K which was taken up by the crop. Sodium behaves differently in the nutrition of wheat and sugar beet, sodium is essential for beet and seems to replace part of the potassium (Adams, 1961).

Sodium, Calcium, Magnesium. Table 4·12 shows the mean annual uptake of sodium, calcium and magnesium by the grain and straw of the crops grown in 1966–67. Table 4·13 shows the total uptake each year of each of the three elements during the four periods 1852–61, 1882–91, 1912–21 and 1966–67, average uptakes have been remarkably constant.

TABLE 4·13

Annual uptake of Na, Ca, Mg in the grain + straw of winter wheat grown continuously on Broadbalk

Means for 1852–61, for 1882–91, for 1912–21 and for 1966–67

lb element/acre/year

Plot	Treatment	Sodium 1852–61	1882–91	1912[1]–21	1966–67	Calcium 1852–61	1882–91	1912[1]–21	1966–67	Magnesium 1852–61	1882–91	1912[1]–21	1966–67
3	None	0·2	0·1	0·1	0·3	3·4	2·2	1·8	3·0	1·8	1·3	1·3	1·6
2	FYM	0·2	0·2	0·3	0·6	6·5	7·6	6·4	6·3	4·0	5·0	4·5	4·4
5	P K Na Mg	0·2	0·1	0·1	0·2	3·4	2·2	1·8	2·9	2·1	1·6	0·6	1·9
7	N_2 P K Na Mg	0·4	0·3	0·2	0·6	7·6	8·2	5·1	8·3	4·0	4·1	3·5	4·6
10	N_2	0·7	0·3	0·4	0·3	5·3	5·4	4·4	5·0	2·4	2·1	2·2	2·0
11	N_2 P	1·2	0·5	0·9	0·6	7·0	8·0	5·5	8·7	3·3	2·8	2·8	3·6
12	N_2 P Na	0·7	0·6	1·6	0·7	7·1	8·7	6·1	9·6	3·7	3·4	3·3	3·8
13	N_2 P K	0·3	0·1	0·2	0·5	7·2	7·3	5·6	8·2	3·6	3·6	3·3	3·7
14	N_2 P Mg	0·5	0·4	0·7	0·7	7·3	8·6	5·3	9·3	3·9	4·0	3·7	4·6

[1] Calculated from Chambers' figures for straw uptakes and Gilbert's figures (mean 1852–91) for grain uptakes.

Sodium. Little sodium was taken up; when the fertilisers supplied both NH_4-N and K, sodium uptake was only about $\frac{1}{50}$th of the K uptake, without fertiliser-K about $\frac{1}{25}$ of the K uptake. With NPK fertilisers, adding an extra 14 lb Na hardly affected the sodium content of the crop. Even when sodium nitrate was given, the extra 74 and 158 lb Na supplied by the N_1* and N_2* rates caused little further increase in the sodium taken up by the crop; the Na to K ratio was approximately 1 to 35. However, it is unexpected that the 51 lb per acre Na given without K on plot 12 had such a small effect on the Na content of the crop compared to that on plots 11 (N_2P) or 13 (N_2PK). Gilbert's figures for 1852–91 showed that less Na was taken up from plot 12 (N_2PNa) than from plot 11 (N_2P).

Calcium. The weight of calcium taken up was between a third and a quarter of that of the potassium; the extra taken up by the first crop after fallow mainly reflected the extra yield and not a larger percentage of Ca in the dry matter of the grain or straw.

Magnesium. Approximately half as much magnesium was taken up as calcium. The percentage of Mg in the dry matter was slightly but consistently larger in both the grain and straw of the first crop after fallow than

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in the continuous wheat, so the first crop after fallow took up more Mg. When extra Mg was applied on plot 14 (N_2 PMg, 28 lb Mg per acre) without fertiliser-K, neither the percentage in the grain and straw, nor the total uptake, differed greatly from that on plot 7 (N_2PKNaMg, 10 lb Mg), or plot 13, which had N_2PK but no Mg.

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