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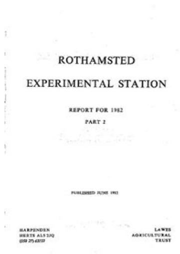

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The Broadbalk Wheat Experiment 1968–78: Yields and Plant Nutrients in Crops Grown Continuously and in Rotation

G. V. DYKE, B. J. GEORGE, A. E. JOHNSTON, P. R. POULTON and A. D. TODD

Abstract

Modifications made to the Broadbalk Wheat experiment in 1968 included growing wheat in 2 three-course rotations, potatoes, beans, wheat and fallow, wheat, wheat to compare yields of wheat grown in rotation with those of wheat grown continuously. The major change in manuring was to apply all N in spring as 'Nitro-Chalk' and introduce a test of 192 kg N ha^{-1}.

Average yields for all crops and all treatments during 1970–78 are given here. Wheat yields are now larger than at any time since 1843, even on soils which have been unmanured since then. Wheat after beans gave the largest grain yield. Potatoes and wheat responded differently to unbalanced manuring.

Nitrogen response curves were fitted to the 1970–78 average yields of wheat grown continuously, as first and second crops after fallow and following beans. It was possible to bring the curves for the three rotational wheats into coincidence with that for the continuous wheat by vertical and horizontal shifts. Relative to wheat grown continuously, the vertical shifts were equivalent to increased yields for wheat after beans (0·51 t ha^{-1}) and second wheat after fallow (0·38 t ha^{-1}), but decreased yield for first wheat after fallow (−0·36 t ha^{-1}). The horizontal shifts were equivalent to increases in available N for wheat after beans (23 kg ha^{-1}) and first wheat after fallow (53 kg ha^{-1}), but a slight decrease for second wheat after fallow (−9 kg ha^{-1}).

The percentage of N, P, K, Ca, Mg and Na in grain and straw of wheat after beans and continuous wheat, potatoes and bean grain for each treatment averaged over 1970–75 (1978 for N) and offtakes of these nutrients in the harvested crops are given. Wheat grain after beans and from continuous wheat contained, on average, 1·94 and 1·92% N in dry matter respectively. Of the total offtake by wheat in grain plus straw the proportion in the grain was 82% for N, 85% for P, 44% for K, 16% for Ca, 71% for Mg and 40% for Na.

Compared to earlier periods %N in grain has changed little but N offtakes are now larger, because yield has increased, and apparent recoveries of fertilizer N have improved. Percentage P in grain has decreased by about 25% but offtakes are now larger, again because yield has increased. There has been no or very little change in %K in grain but there were large seasonal differences in %K in straw. The concentrations of Ca, Mg and Na in grain and straw have changed very little.

Symbols and conventions used in all tables

Treatment symbols, rates, materials, etc. are given in Table 1.

17/18 indicates the mean of plots 17 and 18.
* = the plot does not extend to this section.
WC(1), WC(9): wheat after continuous wheat on sections 1, 9 respectively.
W1F, W2F: wheat as first, second crop after fallow in rotation fallow, wheat, wheat respectively.
W1Be: wheat as first crop after beans in rotation potatoes, beans, wheat.

All yields of grain, including beans, and of straw are at 85% dry matter.
All fertilizer rates and the amounts of nutrients in crops are per hectare.

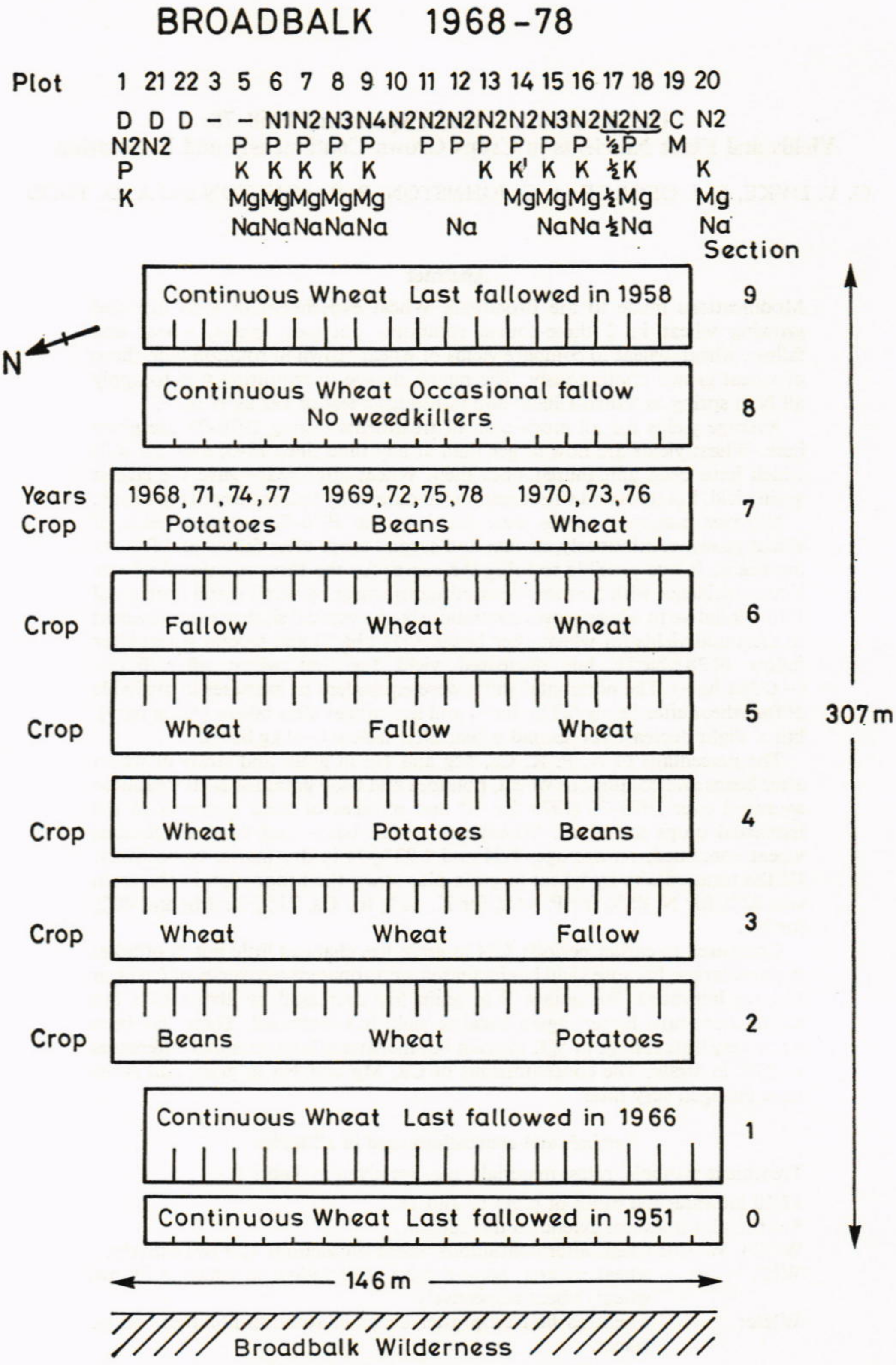

FIG. 1. Plan of the Broadbalk Wheat experiment showing sections, plots, manuring and crop ping from 1968. For details of treatments see Table 1.

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THE BROADBALK WHEAT EXPERIMENT 1968–78

Introduction

The continuous wheat experiment on Broadbalk field started in autumn 1843 and, though there were changes in the treatments of some plots in early years, from 1852 to 1967 the plot treatments continued with negligible variation. Wheat, always sown in autumn except in rare seasons when this was not possible, was grown on the whole area of each plot until the 1890s. From then until 1925 occasional fallows were taken on parts of the experiment to control weeds. From 1926 to 1967 the area was divided into five sections, I to V at right angles to the length of the plots and at least one section was bare fallowed each year. For most of this period there was a 5-year rotation with 1 year of fallow and 4 years of wheat. From 1952, however, a short length of each plot at the West end of the field was cropped with wheat each year, and from 1959 a similar length at the East end was sown to wheat each year.

For the crop-season of 1968 major changes were made; they were accommodated by dividing each existing section into two to make ten shorter sections 0–9 (Fig. 1). The main object was to compare wheat grown continuously, wheat after a 2-year break and

TABLE 1

The Broadbalk Experiment

Treatments 1970–78

Plot	Symbol	Notes
1	FYM+N_2PK	Treatment started 1968: plot extends over sections 2 to 7 only
21	FYM+N_2	
22	FYM	
3	None	
5	PKMg(Na)	
6	N_1PKMg(Na)	
7	N_2PKMg(Na)	
8	N_3PKMg(Na)	
9	N_4PKMg(Na)	
10	N_2	
11	N_2P	
12	N_2PNa	
13	N_2PK	
14	N_2PK′Mg	K first applied 1968
15	N_3PKMg(Na)	
16	N_2PKMg(Na)	
17	$N_2\frac{1}{2}$[PKMg(Na)]	Until 1967: N_2 and PKMgNa in alternate years
18	$N_2\frac{1}{2}$[PKMg(Na)]	Until 1967: N_2 and PKMgNa in alternate years
19	Castor meal	
20	N_2KMg(Na)	Plot extends over sections 0 and 1 only

Materials and rates per hectare

(applied annually unless otherwise stated)

FYM	Farmyard manure, made by bullocks in covered yards, then clamped in the open, during the summer, at 35 t; this supplied on average a total of 248 kg N, 43 kg P and 325 kg K.
N	Ammonium nitrate/calcium carbonate fertilizer ('Nitro-Chalk') to supply 48, 96, 144, 192 kg N. (N_1, N_2, N_3, N_4).
P	Superphosphate (about 20% P_2O_5) to supply 35 kg P (triple superphosphate, about 47% P_2O_5, in 1974 only)
K	Potassium sulphate (about 50% K_2O) to supply 90 kg K.
K′	As above, but only since 1968.
Mg	Until 1973: magnesium sulphate annually (about 10% Mg) to supply 11 kg Mg (except plot 14, which received 31 kg Mg). From 1974: kieserite (about 15% Mg) to supply 35 kg Mg every 3rd year (1974, 1977 etc.) (except plot 14 which received 30 kg Mg annually).
Na	Plot 12 only. Sodium sulphate (about 14% Na) to supply 57 kg Na (from 1974, 55 kg Na).
(Na)	Until 1973, sodium sulphate to supply 16 kg Na.
$\frac{1}{2}$[PKMg(Na)]	P, K, Mg and (until 1973) Na at half standard rates.
Castor meal	(About 5% N) to supply 96 kg N.

General notes

1. All dates are of the years of harvest; for example plot 1 first received FYM in autumn 1967.
2. The table indicates changes made in 1968 to manuring with FYM, P, K, Mg and Na. For changes in manuring with nitrogenous fertilizers, and for all changes before 1968, see Report for 1968, Part 2, pages 19–25.
3. From 1968 all manures and fertilizers except 'Nitro-Chalk' were applied in autumn, before ploughing 'Nitro-Chalk' was applied in spring, in a single application, top-dressed to wheat, to flat land before planting potatoes and before sowing beans; no 'Nitro-Chalk' was applied to fallow.
4. Major variations in husbandry were:
   (a) in autumn 1977 the whole area was subsoiled using a single-tine subsoiler working West/East along the plots at 38 cm deep, 1·6 m spacing.
   (b) wheat seed was treated with dieldrin 1970–75, chlorfenvinphos 1976–78, for protection against wheat bulb fly (*Delia coarctata*).
   (c) wheat on section 9 in 1976 was sprayed with dimethoate against *Agriphila straminella*.
   (d) wheat on section 6 in 1978 (first after fallow) was sprayed with omethoate against wheat bulb fly.
   (e) all wheat was sprayed in 1976 and 1977 with pirimicarb against aphids.

wheat after a fallow. Fertilizer treatments, mainly N rates, to a few plots were changed; plots 15 and 16 had N rates which made them replicates of plots 8 and 7 respectively (Table 1), and a test of N at 192 kg ha^{-1} was reintroduced. From 1974 the small annual dressings of sodium sulphate were discontinued but the larger dressing given to plot 12 was continued. The small annual Mg dressing was replaced by triennial dressings of kieserite supplying treble the earlier rate of Mg (plot 14 continued to receive Mg annually at the larger rate applied up to 1967, but as kieserite). P and K dressings remained unchanged except that rates were slightly adjusted to 35 kg ha^{-1} and 90 kg ha^{-1} respectively when metric measures were introduced in 1974. Plot 14 (which had previously received no K) was given K at the standard rate from 1968. From 1968 all inorganic N has been applied as 'Nitro-Chalk' and, in contrast to the practice of earlier years, farmyard manure (FYM), castor meal and fertilizers except 'Nitro-Chalk' were applied (ploughed down) to the whole plot including the section to be fallowed in the next season.

The ten shorter sections were numbered from West to East 0 to 9 (Fig. 1). The cropping systems adopted from 1968 were as follows:

Sections 0, 1 and 9:	Continuous wheat.
Section 8:	Continuous wheat without chemical weedkillers.
Sections 2, 4 and 7:	3-year rotation potatoes, spring beans, wheat.
Sections 3, 5 and 6:	3-year rotation bare fallow, wheat, wheat.

All wheat was sown in autumn and the variety from 1968 to 1978 was Cappelle Desprez. Potatoes were Majestic (1968–69), King Edward (1970–75), Pentland Crown (1976–78); beans were Maris Bead (1970–74), Minor (1975), Minden (1976–78).

The new rotations began as follows (Be = beans, W = wheat, P = potatoes, F = bare fallow):

Section	2	4	7	3	5	6
1968	Be	W	P	W	W	F
1969	W	P	Be	W	F	W
1970	P	Be	W	F	W	W

From 1979 the rotation potatoes, beans, wheat was abandoned, mainly because of a persistent infestation of the bean crops by stem eelworm (*Ditylenchus dipsaci*): the present scheme includes the rotation fallow, potatoes, wheat.

This paper gives yields and N, P, K, Ca, Mg, Na compositions of, and uptakes by, all crops in the period 1970–75, plus yields, % N and N uptake in the crops grown in 1976–78.

Changes of practice during the period 1970–78 are listed in Table 1 together with the treatment to each plot. For fuller information on the history of the Broadbalk experiment see Rothamsted Experimental Station (1969) and for recent changes in treatments and husbandry see Rothamsted (1978).

Methods and yields

The recorded yields of grain and straw of wheat, of grain of beans (all at 85% dry matter) and the total yields of potato tubers have been used. Yields of bean straw which, being taken after baling, may be somewhat unreliable and relatively unimportant have not been considered. Sections 1 and 9 (last fallowed in 1966 and 1958 respectively) have been used to represent continuous wheat. Section 0, which is adjacent to the Wilderness (part with trees 20 m or more tall) and section 8, without chemical weedkiller, are dealt with briefly. All yields in 1968 and 1969 have been omitted because the rotation potatoes, beans, wheat was not fully established. The sequence of yields considered ends in 1978; from 1979 a new crop rotation was followed and a new variety of wheat was introduced. There are yields for all crops in all nine seasons 1970–78 except for one plot of section 8 in 1971 which was excessively weedy and was cut green in July. Plot 1 however, spans only sections 2 to 7, and plot 20 spans only sections 0 and 1 (Fig. 1).

Since there was no replication of most treatments within years, all standard errors in the tables are based on differences between years. Unless otherwise stated, they are calculated directly from the annual values to which they refer and have 8 d.f. The detection of an apparently significant difference between two plots cannot be uniquely ascribed to the effects of the treatments applied to the plots. Because of the fixed location of any treatment, such a difference may be due to intrinsic differences due to position in the field.

Table 2A shows the mean yields of grain and potatoes over the nine seasons of each crop on each plot and the mean over all plots other than 1 and 20. Table 2B shows the corresponding standard errors and, for selected plots, the coefficients of variation (CV = 100 × SE/mean).

Table 3 shows mean yields of wheat straw for each plot, and the mean over all plots except 1 and 20. The standard errors of plot means are based on pooled mean squares over plots and have 144 d.f. Table 4 shows, for selected treatment comparisons, differences between yields with their standard errors.

Examination of the average grain yields over the 9 years, for plots receiving PKMg(Na) showed broadly similar forms of response to nitrogen, where the N_2 and N_3 levels are taken as the averages of plots 7/16 and 8/15 respectively. For first wheat after fallow and wheat after beans the yields had distinct maxima. For continuous wheat and second wheat after fallow the yields increased continuously over the five rates of application of nitrogen, but were almost constant at the higher rates.

To provide a convenient summary of the four sets of data, response curves of constant shape but differing locations were fitted. The form of curve chosen was exponential plus linear, i.e. $y = a + br^x + cx$, where y is the grain yield in t ha^{-1}, and x is the applied N in kg ha^{-1}. The values of r and c were constant for the four sets, and a and b varied between sets. The value of r was fixed at 0·99 since this was found to approximately optimize the overall fit, and variation in r between 0·985 and 0·995 produced negligibly different fits. The values of the other parameters, a, b, and c, were then estimated by least square fitting to the linearized equations.

There are insufficient points to justify the chosen form of curve in preference to other forms, but the resulting fit accounted for 97·3% of the overall variation and the residuals showed no strong pattern to suggest serious lack of fit. The fitted curves are shown in

TABLE 2A

Broadbalk 1970–78: mean yields of grain and potatoes, t ha^{-1}

Plot	Treatment	Wheat grain WC(1)	WC(9)	W1F	W2F	W1Be	Potato tubers	Bean grain
1	FYM+N_2PK	*	*	5·56	6·10	6·00	32·8	2·39
21	FYM+N_2	5·75	5·34	5·70	5·78	5·99	42·1	2·79
22	FYM	5·85	5·82	6·18	5·72	6·47	37·3	2·98
3	None	1·72	1·58	2·97	1·39	2·68	10·2	1·85
5	PKMg(Na)	1·67	1·88	3·56	1·53	3·13	14·9	2·70
6	N_1PKMg(Na)	3·48	3·56	4·60	3·57	5·08	24·2	2·65
7	N_2PKMg(Na)	4·81	4·86	5·10	5·27	6·02	32·1	2·67
8	N_3PKMg(Na)	5·13	5·51	4·96	5·66	5·66	37·0	2·94
9	N_4PKMg(Na)	5·49	5·49	4·79	5·77	5·51	40·1	2·92
10	N_2	3·53	2·61	3·71	3·46	4·94	9·9	1·52
11	N_2P	3·51	2·67	3·54	4·55	5·22	8·4	0·80
12	N_2PNa	4·57	3·83	3·97	4·94	5·60	11·9	0·80
13	N_2PK	5·01	4·65	4·68	5·21	6·07	23·0	2·53
14	N_2PK′Mg	5·18	4·83	4·84	5·31	6·33	24·4	2·36
15	N_3PKMg(Na)	5·42	5·24	4·76	5·73	5·92	35·4	2·81
16	N_2PKMg(Na)	4·78	4·71	4·93	5·03	5·97	30·8	2·70
17	$N_2\frac{1}{2}$[PKMg(Na)]	4·57	4·52	5·31	5·11	6·20	27·9	2·66
18	$N_2\frac{1}{2}$[PKMg(Na)]	4·67	4·91	5·25	5·12	6·15	28·5	2·75
19	Castor meal	4·05	3·63	5·15	4·18	5·41	19·2	1·75
20	N_2KMg(Na)	3·58	*	*	*	*	*	*
Mean (excluding plots 1, 20)		4·40	4·20	4·67	4·63	5·46	25·4	2·34

TABLE 2B

Broadbalk 1970–78: standard errors of means tabulated in Table 2A, each based on 8 d.f., t ha^{-1}

Plot	Treatment	Wheat grain WC(1)	WC(9)	W1F	W2F	W1Be	Potato tubers	Bean grain
1	FYM+N_2PK	*	*	0·378	0·325	0·380	4·15	0·403
21	FYM+N_2	0·391	0·377	0·328	0·362	0·485	4·77	0·399
22	FYM	0·354	0·383	0·434	0·363	0·399	4·21	0·460
3	None	0·084	0·114	0·165	0·127	0·140	0·97	0·341
5	PKMg(Na)	0·080	0·120	0·193	0·110	0·246	1·97	0·494
6	N_1PKMg(Na)	0·202	0·246	0·365	0·148	0·254	3·98	0·456
7	N_2PKMg(Na)	0·245	0·355	0·386	0·235	0·294	4·65	0·415
8	N_3PKMg(Na)	0·168	0·328	0·363	0·244	0·389	4·49	0·485
9	N_4PKMg(Na)	0·196	0·310	0·385	0·299	0·362	4·14	0·417
10	N_2	0·315	0·336	0·425	0·426	0·301	0·99	0·284
11	N_2P	0·291	0·296	0·437	0·263	0·314	0·97	0·122
12	N_2PNa	0·304	0·472	0·558	0·248	0·284	1·57	0·164
13	N_2PK	0·221	0·547	0·559	0·190	0·288	3·01	0·389
14	N_2PK′Mg	0·272	0·445	0·445	0·207	0·245	2·35	0·390
15	N_3PKMg(Na)	0·262	0·417	0·420	0·250	0·267	3·46	0·477
16	N_2PKMg(Na)	0·251	0·315	0·372	0·195	0·275	3·38	0·373
17	$N_2\frac{1}{2}$[PKMg(Na)]	0·243	0·393	0·293	0·200	0·276	3·37	0·378
18	$N_2\frac{1}{2}$[PKMg(Na)]	0·289	0·356	0·274	0·172	0·262	3·35	0·381
19	Castor meal	0·098	0·313	0·346	0·234	0·283	1·82	0·291
20	N_2KMg(Na)	0·348	*	*	*	*	*	*
Standard error of mean yield (excluding plots 1, 20)		0·202	0·304	0·326	0·178	0·246	2·78	0·346
	Coefficients of variation (%) for selected plots							
21	FYM+N_2	6·8	7·1	5·7	6·3	8·1	11·3	14·3
22	FYM	6·0	6·6	7·0	6·3	6·2	11·3	15·4
3	None	4·9	7·2	5·6	9·1	5·2	9·5	18·4
5	PKMg(Na)	4·8	6·4	5·4	7·2	7·9	13·3	18·3
9	N_4PKMg(Na)	3·6	5·6	8·0	5·2	6·6	10·3	14·3
10	N_2	8·9	12·8	11·5	12·3	6·1	10·0	18·7
12	N_2PNa	6·7	12·4	14·1	5·0	5·1	13·2	20·6
19	Castor meal	2·4	8·6	6·7	5·6	5·2	9·5	16·6
CV% of mean yield		4·6	7·2	7·0	3·9	4·5	11·0	14·8

TABLE 3

Broadbalk 1970–78: mean yields of wheat straw at 85% dry matter, t ha^{-1}

Plot	Treatment	WC(1)	WC(9)	W1F	W2F	W1Be
1	FYM+N_2PK	*	*	5·17	6·05	6·36
21	FYM+N_2	6·89	6·10	6·44	6·64	7·30
22	FYM	6·12	5·40	5·91	5·41	6·86
3	None	1·39	1·03	1·80	0·95	1·90
5	PKMg(Na)	1·47	1·27	2·48	1·06	2·30
6	N_1PKMg(Na)	2·76	2·71	3·89	2·69	4·44
7	N_2PKMg(Na)	3·90	4·10	4·51	4·29	5·25
8	N_3PKMg(Na)	4·51	4·79	4·71	5·08	5·66
9	N_4PKMg(Na)	4·88	4·81	4·25	5·13	5·42
10	N_2	2·36	2·26	2·53	2·48	2·99
11	N_2P	2·64	2·40	2·68	3·01	3·37
12	N_2PNa	3·30	3·13	3·22	3·56	4·05
13	N_2PK	4·09	4·55	4·08	3·95	5·00
14	N_2PK′Mg	3·92	3·94	4·16	3·93	4·90
15	N_3PKMg(Na)	4·24	4·53	4·30	4·75	4·87
16	N_2PKMg(Na)	3·71	4·11	4·46	3·90	4·80
17	$N_2\frac{1}{2}$[PKMg(Na)]	3·29	4·07	4·55	3·90	4·94
18	$N_2\frac{1}{2}$[PKMg(Na)]	3·42	4·22	4·69	4·11	5·08
19	Castor meal	2·93	3·14	3·93	3·20	4·10
20	N_2KMg(Na)	2·47	*	*	*	*
Mean (excluding plots 1, 20)		3·66	3·70	4·03	3·78	4·62
		Standard errors				
(a)		0·344	0·389	0·398	0·353	0·443
(b)		0·281	0·339	0·352	0·290	0·372

(a) Of mean per plot, based on pooled mean squares for all plots.
(b) Of mean yield of all plots except 1, 20.

Fig. 2, where it can be seen that the curve fitted least well to the wheat after beans; a more sharply curved function would have been better. This discrepancy appears to be largely due to unusually poor yields at the higher rates of applied N in 1973.

Maximum yields given later in this paper are calculated from the curves fitted as above.

Seasonal variation

Figure 3 shows the yields of three plots of section 1 (wheat each season since 1966) together with maximum potential soil moisture deficits estimated by W. Day (Physics Department). With FYM or N_3PKMg(Na) yields were least in the years 1975 and 1976 when soil moisture deficits were greatest; 1976 was a memorably dry summer, hotter than average after anthesis. Yields of unmanured wheat varied less than those of well manured crops but followed a generally similar pattern. Yields of wheat grain on other sections and of beans showed similar variation. Yields of wheat straw were more erratic; yields of well manured potatoes showed seasonal variation similar to those of well manured wheat except that in 1975, when planting was exceptionally late, yields were less than in 1976.

Positional variation

Between plots. Table 5 presents the mean differences between pairs of plots treated alike in 1970–78. (Their treatments before 1968 differed, but appreciable residual effects seem unlikely.) None of the mean differences was large in relation to seasonal variation. The difference 7 *minus* 16 was positive in all types of wheat crop and in potatoes, but negative

TABLE 4

Broadbalk 1970–78: selected treatment differences and their standard errors for yields of wheat grain and straw, potatoes and bean grain, t ha⁻¹

Plots	Treatment difference	Wheat grain					Potato tubers	Bean grain	Wheat straw				
		WC(1)	WC(9)	W1F	W2F	W1Be			WC(1)	WC(9)	W1F	W2F	W1Be
21–22	(FYM+N₂)–(FYM)	−0·10	−0·48	−0·48	+0·05	−0·48	+ 4·8	−0·19	+0·76	+0·70	+0·53	+1·23	+0·44
	SE	0·391	0·306	0·295	0·423	0·298	1·50	0·177	0·455	0·261	0·319	0·441	0·389
9– 8	(N₄M)–(N₃M)*	+0·36	−0·03	−0·17	+0·11	−0·14	+ 3·1	−0·02	+0·37	+0·02	−0·46	+0·05	−0·23
	SE	0·101	0·216	0·225	0·169	0·079	1·42	0·160	0·127	0·176	0·228	0·165	0·229
22– 9	(FYM)–(N₄M)*	+0·36	+0·33	+1·40	−0·05	+0·95	− 2·8	+0·06	+1·24	+0·59	+1·65	+0·28	+1·44
	SE	0·321	0·309	0·092	0·341	0·281	2·40	0·225	0·365	0·300	0·317	0·342	0·508
11–10	(N₂P)–(N₂)	−0·02	+0·05	−0·16	+1·09	+0·28	− 1·6	−0·72	+0·28	+0·15	+0·15	+0·53	+0·38
	SE	0·298	0·312	0·303	0·300	0·112	0·42	0·190	0·216	0·276	0·264	0·177	0·143
13–11	(N₂PK)–(N₂P)	+1·50	+1·98	+1·14	+0·66	+0·85	+14·6	+1·73	+1·45	+2·15	+1·41	+0·94	+1·63
	SE	0·208	0·328	0·197	0·176	0·205	2·51	0·320	0·269	0·407	0·351	0·198	0·245
7–17/18	(N₂M)–(N₂½M)*	+0·19	+0·15	−0·18	+0·15	−0·15	+ 3·9	−0·03	+0·55	−0·05	−0·11	+0·28	+0·24
	SE	0·104	0·136	0·203	0·081	0·104	1·80	0·198	0·271	0·162	0·212	0·160	0·171

* M denotes PKMg(Na).

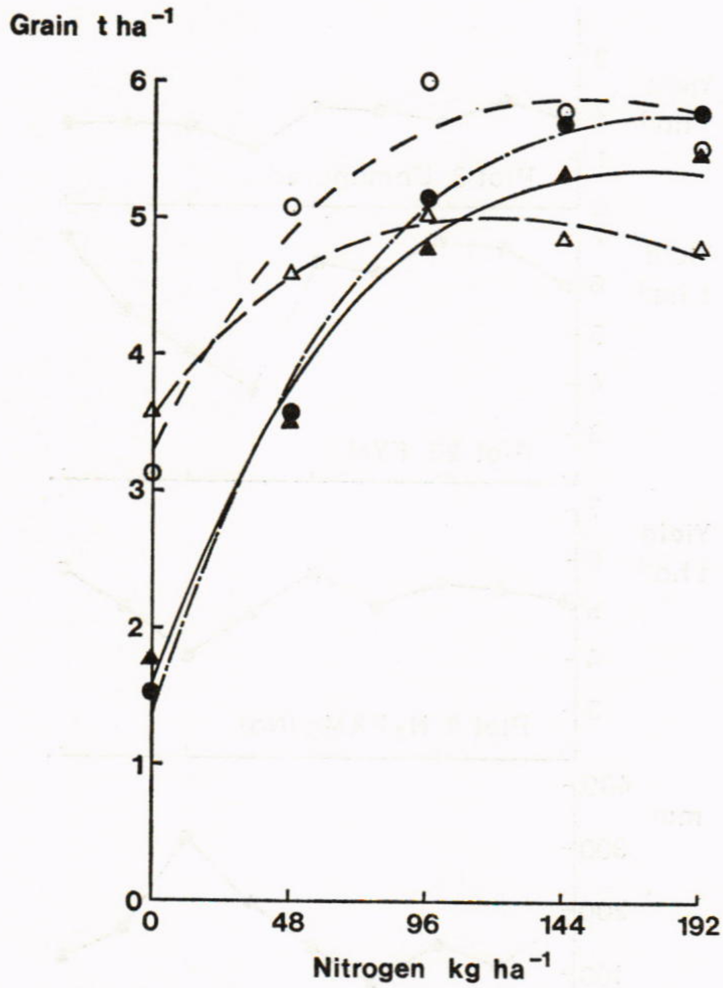

FIG. 2. Broadbalk, 1970–78. Relationship between nitrogen applied and mean yield of wheat grain grown in four rotations with fitted curves. Continuous wheat, ▲; Wheat after beans, ○; First wheat after fallow, △; Second wheat after fallow, ●.

TABLE 5

Broadbalk 1970–78: mean differences between yields, with standard errors in parentheses, of similarly treated plots; wheat grain, potatoes and bean grain, t ha⁻¹

		Plots		
		7 *minus* 16	8 *minus* 15	17 *minus* 18
Wheat	WC(1)	+0·03 (0·071)	−0·29 (0·146)	−0·10 (0·066)
	WC(9)	+0·15 (0·154)	+0·27 (0·234)	−0·39 (0·113)
	W1F	+0·17 (0·187)	+0·20 (0·246)	+0·06 (0·094)
	W2F	+0·24 (0·117)	−0·07 (0·140)	0·00 (0·077)
	W1Be	+0·06 (0·094)	−0·26 (0·160)	+0·05 (0·029)
	Mean	+0·13	−0·03	−0·08
Potatoes		+1·3 (1·78)	+1·6 (1·48)	−0·5 (0·56)
Beans		−0·03 (0·160)	+0·13 (0·149)	−0·09 (0·074)

in beans. The other differences showed positive and negative values in roughly equal numbers. There is no clear evidence that yield varies because of changes in environment across the field.

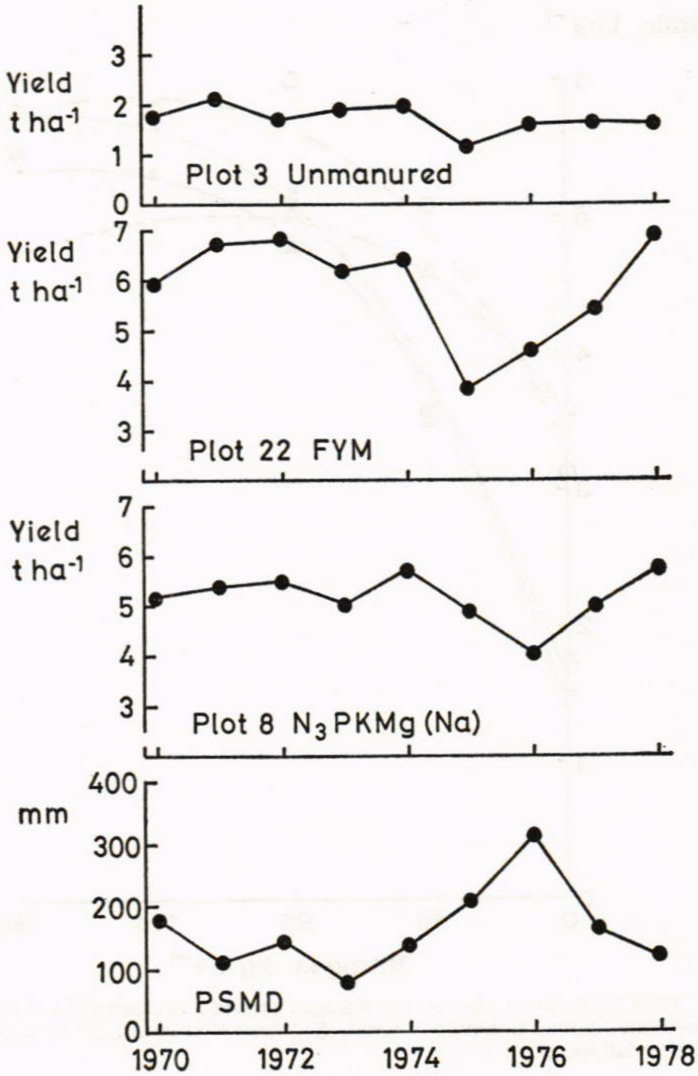

FIG. 3. Broadbalk: Yields of grain at 85% dry matter from selected plots on Section 1 and maximum potential soil moisture deficit (PSMD).

Between sections. In the 9 years 1970–78 each of the rotations completed three cycles, each crop being grown three times in each of the allotted sections. Table 6 shows the mean yields of crops grown on all plots (except 1 and 20) in each phase of the 3-year rotation, with standard errors based on variation between years within phases (6 d.f.). In each type of wheat crop mean yields in the second year of the cycle exceeded those of the first year; for continuous wheat on sections 1 and 9, and for the second crop after fallow, those of the third year were intermediate whereas in the first crop after fallow, and in wheat after potatoes, beans, mean yields in the third year exceeded those of the second year. It appears that variations of yield were more closely associated with differences between seasons than with differences between sections. This is confirmed by the mean squares for variation between cycles; the pooled mean square within the three types of crop that occupied three sections each in rotation (first and second after fallow,

TABLE 6

Broadbalk 1970–78: mean yields of wheat grain, potatoes and bean grain grown in different years of the 3-year cycle, t ha^{-1}

		Year of cycle			
Years		First 1970, 73, 76	Second 1971, 74, 77	Third 1972, 75, 78	SE
Wheat	WC(1)	3·98	4·61	4·47	0·357
	WC(9)	3·85	4·50	4·26	0·577
	W1F	4·51	4·76	4·88	0·634
	(Section)	(5)	(3)	(6)	
	W2F	4·24	5·02	4·86	0·266
	(Section)	(6)	(5)	(3)	
	W1Be	4·75	5·60	6·13	0·299
	(Section)	(7)	(4)	(2)	
	Mean	4·27	4·90	4·92	
Potatoes		27·9	29·0	20·4	5·01
	(Section)	(2)	(7)	(4)	
Beans		1·77	2·74	2·53	0·630
	(Section)	(4)	(2)	(7)	

and after beans) was 0·6879 t^2 ha^{-2}, not significantly greater than that for the two crops grown continuously on sections 1 and 9 (0·3277 t^2 ha^{-2}).

Yields of beans show a pattern very similar to those of wheat yields; yields of potatoes, by contrast, were least in the third year of the cycle, and about equal in years 1 and 2.

TABLE 7

Broadbalk 1970–78: mean yields of wheat grain and straw on sections 0 and 8, t ha^{-1}

	Years	Section 0 1970–78		Section 8 1970, 1971, 1974–78	
Plot	Treatment	Grain	Straw	Grain	Straw
1	FYM+N_2PK	*	*	*	*
21	FYM+N_2	4·59	5·90	4·20	6·06
22	FYM	5·56	5·74	4·22	5·82
3	None	1·81	1·47	2·03	1·65
5	PKMg(Na)	2·21	1·66	2·70	3·10
6	N_1PKMg(Na)	3·82	3·06	2·59	3·41
7	N_2PKMg(Na)	5·06	4·30	3·39	4·77
8	N_3PKMg(Na)	4·99	4·41	4·09	5·33
9	N_4PKMg(Na)	4·96	4·64	4·33	5·87
10	N_2	2·68	2·19	3·06	3·30
11	N_2P	3·48	2·80	2·40	3·46
12	N_2PNa	4·58	3·68	2·85	3·67
13	N_2PK	4·81	4·04	3·12	4·88
14	N_2PK′Mg	4·79	4·22	3·52	4·37
15	N_3PKMg(Na)	5·00	4·46	3·95	5·31
16	N_2PKMg(Na)	4·51	3·93	3·16	4·92
17	$N_{2\frac{1}{2}}$[PKMg(Na)]	4·68	3·56	3·34	5·20
18	$N_{2\frac{1}{2}}$[PKMg(Na)]	4·48	3·47	3·37	5·46
19	Castor meal	4·21	3·10	3·16	3·76
20	N_2KMg(Na)	3·51	2·61	*	*
Mean (excluding plot 20)		4·23	3·70	3·30	4·49
Plots	Treatment difference				
21–22	(FYM+N_2)–(FYM)	−0·97	+0·16	−0·02	+0·24
9–8	(N_4M)–(N_3M)	−0·03	+0·22	+0·23	+0·53
22–9	(FYM)–(N_4M)	+0·59	+1·10	−0·11	−0·04
11–10	(N_2P)–(N_2)	+0·79	+0·61	−0·65	+0·17
13–11	(N_2PK)–(N_2P)	+1·33	+1·24	+0·72	+1·42
7–17/18	(N_2M)–($N_{2\frac{1}{2}}$M)	+0·48	+0·78	+0·03	−0·56

Average dates of planting were 11 April, 13 April and 2 May for the first, second and third years respectively and later planting may well account for poor yields in the third year.

In general, results in 1970–78 confirm the conclusion of Russell & Watson (1940) that differences in yield due to position in the field, though real, are unlikely to affect estimates of treatment-effects seriously.

Section 0 and Section 8. In 1925 a 5-year cycle of fallow followed by four wheat crops was introduced to control weeds on the five sections I to V then existing. This pattern was broken first in 1956 on section I and then in 1963 on section V when on two of the half-sections, labelled 0 and 9 in 1968, wheat was grown in place of fallow. Thus wheat has been grown continuously on section 0 since 1952 and section 9 since 1959. Chemical weedkillers were used on section 0 from 1957. Section 8, the other half of section V, was fallowed in cycle in 1953 and 1958; it has never received chemical weedkiller. Since 1958 it has been fallowed in 1972 only, when weed growth made this essential. Yields on section 8 in 1973 (first crop after fallow) are omitted from Table 7, which shows mean yields of grain and straw on plots on sections 0 and 8. Yields recorded on section 0 may be expected to be more variable than on the adjacent section 1, previously the other half of section I, partly because section 0 is substantially shorter than other sections, partly because section 0 adjoins Broadbalk Wilderness. Opposite plots 1 to 8 is low vegetation but opposite the remainder are trees about 20 m tall. These cause differential shading and leaf-fall on the plots of wheat. Section 0 yielded less than section 1 on all plots except those with incomplete manuring which limited yield. Yields on section 8 were at least 1 t ha^{-1} less than on section 9 except on plots 3 and 5 where yields were larger on section 8 than on section 9. These latter plots receive no N and, on plot 5 especially, leguminous weeds thrive and contribute some N to the soil on section 8.

Effect of cropping and manurial treatments on yields of crops

Wheat grain. Yields of wheat grain on section 1 and 9, last fallowed in 1966 and 1958 respectively, were on average similar (Table 2). The slight superiority of section 1 arose mainly from plots with poor yields (3, 10, 11) in both sections. Yields of the first and second crops after fallow, both on average greater than those of continuous wheat by about 0·3 t ha^{-1}, were, also on average, equal but there were substantial differences on individual plots. Without applied N (plots 3, 5) the first crop yielded double the second, presumably because of the N accumulated in the soil during the fallow year being available to an autumn-sown crop, whereas on plots given fertilizer N at 96 kg ha^{-1} or more the second crop outyielded the first. Wheat after the two-year break (potatoes, beans) yielded on average about 0·8 t ha^{-1} more than the crops after fallow and about 1·2 t ha^{-1} more than continuous wheat.

Many of the differences shown in Table 4 are small and non-significant in relation to annual variation but a few are worthy of note. In the first crop after fallow, FYM alone (plot 22) yielded 1·40 t ha^{-1} more than N_4PMg(Na) (plot 9) with standard error 0·092. In wheat after beans the mean difference was 0·95 t ha^{-1} but with much greater seasonal variation, s.e. 0·281. Comparing plots 11 and 10, P as superphosphate, in the absence of K, had small effects, except in the second crop after fallow (+1·09 t ha^{-1}, s.e. 0·300) and in wheat after beans (+0·28 t ha^{-1}, s.e. 0·112). In plots 13 and 11, K as potassium sulphate (in the presence of P) gave mean increases ranging from 0·66 t ha^{-1}, s.e. 0·176 to 1·98 t ha^{-1}, s.e. 0·328. P and K at half rate (plots 17, 18) gave average yields similar to P and K at full rate with the same rate of fertilizer N (plots 7, 16).

Plot 12, N_2PNa, which continued to receive Na in amounts chemically equivalent to the amount of K applied on plot 13, continued to yield more than plot 11, N_2P, but less than plot 13, N_2PK. This benefit may be ascribed to the release of soil K by replacement with Na because the difference in the K uptake by the crops on plots 12 and 11 are larger than the differences in Na uptake. This benefit from Na on wheat and the direct effect of K can be compared for wheat, potatoes and beans (t ha^{-1}):

	N_2P	N_2PNa	N_2PK
Wheat (grain)	3·90	4·58	5·12
Potatoes (total)	8·4	11·9	23·0
Beans (grain)	0·80	0·80	2·53

For wheat, enough K was released to increase yield half way to that given by K fertilizer but for potatoes, although yield was increased by 41% compared to that given by N_2P, the effect of fresh K was very much larger. Although beans are obviously very K-responsive on this soil, the fact that the N_2P and N_2PNa treatments gave only the same yield suggests that any benefit from K released may have been masked by a harmful effect of Na on the beans.

Standard errors for each of the wheat crops considered were greater on plots with greater yields; this is reflected in the relative uniformity of the coefficients of variation. Section 9, however, showed greater seasonal variation than section 1. Section 9 is on the shallow slope at the Eastern end of the field, section 1 on the plateau at the Western end. It is not known if the different topography is responsible for the greater seasonal variation on section 9. There was also greater seasonal variation in the first crop after fallow than in the second after fallow, or wheat after beans, perhaps because of variable damage by wheat bulb fly. There is no clear evidence that seasonal variation was greater for the crops that occupied three different sections in successive years than for those that occupied fixed positions in the field.

Potatoes. The potato haulm was usually burnt off, and the potatoes lifted, earlier than usual for potato crops on Rothamsted Farm because of the need to apply fertilizers, plough and drill the next season's wheat crops. In consequence yields are not as large as those in some other experiments. The greatest average yield of total tubers (42·1 t ha^{-1}) came from FYM+N_2 (plot 21) but $N_4PKMg(Na)$ (plot 9) gave only 2 t ha^{-1} less (Table 2). FYM alone gave 4·8 t ha^{-1} less than FYM with N at 96 kg ha^{-1}. N_2 only (plot 10) yielded less than the unmanured plot and N_2P (plot 11) less still: this can be ascribed to the greater depletion of soil K by the larger yields of wheat carted off plots 10 and 11 between 1852 and 1967. The addition of K (plot 13) more than doubled the yield with N_2 or N_2P and the further addition of Mg (plot 7) further increased yields from 23·0 to 32·1 t ha^{-1}. The apparent test of Mg in the presence of NPK on plots 14, 13 is not valid because dressings of K were not given to plot 14 until 1968 and then only at 90 kg ha^{-1} which is far too small a dressing for potatoes on a K-deficient soil. Full rate PKMg yielded nearly 4 t ha^{-1} more than corresponding plots with half-rate PKMg.

Standard errors of potato yields, like those of wheat yields, were greater on the better-yielding plots; the coefficient of variation of mean yield was substantially larger than that of any of the wheat crops.

In all years the proportion of tubers retained on a 3·81 cm ($1\frac{1}{2}$ in.) square mesh riddle was determined and some results for selected treatments are in Table 8. Pentland Crown grown in 1977–78 had a larger proportion of ware than King Edward grown in 1970–75. Percentage ware was increased only a little by increasing dressings of fertilizer N and there was little difference between complete fertilizers and FYM. Fertilizers, other than N, at the half rate, plots 17, 18, gave yields significantly less than those given by the full rate, plot 7, (Table 4) but percentage ware was not affected (Table 8). Without fertilizers,

TABLE 8

Broadbalk potatoes 1970–78: Percentage ware using 3·81 cm riddle

Plot	Treatment	King Edward 1970–72	King Edward 1973–75	Pentland Crown 1976–78
3	None	73	78	93
7	$N_2PKMg(Na)$	82	85	94
8	$N_3PKMg(Na)$	86	86	96
9	$N_4PKMg(Na)$	91	89	96
22	FYM	89	86	96
21	FYM+N_2	89	89	95
17	$N_2\frac{1}{2}[PKMg(Na)]$	88	89	95
18	$N_2\frac{1}{2}[PKMg(Na)]$	89	89	95
10	N_2	71	77	90
11	N_2P	35	60	73
12	N_2PNa	56	67	77
13	N_2PK	77	88	89
14	$N_2PK'Mg$	77	84	93

or with N only, yields were much less than with full manuring but percentage ware of King Edward was decreased only slightly whilst that of Pentland Crown was not affected. Percentage ware was little affected by the omission of Mg, plot 13 *v* plot 7, or by the recent addition of K, plot 14 *v* plot 13, although yields on plots 13 and 14 were much less than on plot 7. However, percentage ware was much less on plots 11 and 12, N_2P and N_2PNa respectively, than with any other manurial treatment.

Beans. Yields of beans averaged little more than half those of continuous wheat (Table 2). Even on plots given either FYM or PKMg, where beans yielded a little better in proportion to wheat than on other plots, mean yields were less than 3 t ha^{-1}. Like potatoes, beans yielded less on plots 10 and 11 (N_2, N_2P) than on plot 3 (no fertilizer) probably because beans, like potatoes, are responsive to K. Yield was substantially increased by K-fertilizer; much more in proportion to yield than for wheat. Half-rate PKMg gave yields about equal to those with full-rate PKMg. The yield from plot 19 (castor meal) was poor. The seasonal variation of yields of beans was generally greater than that of wheat even in terms of yield per unit area but especially so relative to mean yield; the coefficient of variation of the mean yield of all plots was two to four times those of the various wheat crops and substantially larger than that of potatoes.

Comparison between yields with FYM and with fertilizers

The maximum yields obtained with fertilizer have been estimated from the fitted curves shown in Fig. 2. Wheat on plot 22 (FYM only since 1844) gave more grain than the estimated maximum yield, except in the second crop after fallow (Table 9). In the sections 1 and 9, that had been under wheat for many years the difference was about 0·5 t ha^{-1}, and where wheat followed beans the difference was about 0·6 t ha^{-1}; for the first crop

TABLE 9

Broadbalk 1970–78: comparison between yields of wheat grain given by FYM, FYM+ nitrogen and estimated maximum yields from fertilizers, t ha^{-1}

Crop	WC(1)	WC(9)	W1F	W2F	W1Be
(a) FYM+N_2	5·75	5·34	5·70	5·78	5·99
(b) FYM	5·85	5·82	6·18	5·72	6·47
(c) Estimated maximum with fertilizers only	5·36	5·36	5·00	5·74	5·87
(b) *minus* (c)	0·49	0·46	1·18	−0·02	0·60

after fallow the difference was about 1·2 t ha^{-1}. This crop may have benefited from the nitrogen mineralized during the fallow from the dressing of FYM given in the fallow year. The second crop after fallow yielded almost the same with fertilizers as with FYM and only in this cropping sequence did FYM plus N_2 give more grain than FYM alone.

The modified and new plots with treatments FYM + N_2 and FYM + N_2PK. Plots 22 and 21 have received FYM at 35 t ha^{-1} annually since 1844 and 1885 respectively and the total N content of the soils, 0·25 and 0·22 % N respectively, are not dissimilar now; there is however, much more N in these soils than in those which have received fertilizers only (about 0·11 % N). Since 1968 an extra 96 kg ha^{-1} fertilizer N has been tested on plot 21. The extra N decreased wheat grain yields in 1970–72 and 1973–75, by, on average, 0·7 t ha^{-1} but had no effect in 1976–78. Potato yields were consistently increased by the extra N but the effect on bean yields was variable (Table 10). Plot 1 was formed in 1968 from non-experimental sideland which had received no FYM and probably little fertilizer except N

TABLE 10

Broadbalk 1970–78: mean yields on plots 1, 21 and 22, t ha^{-1}

	Plot			Differences	
	1	21	22	21 *minus* 22	1 *minus* 22
Treatment 1968–78	FYM + N_2PK	FYM + N_2	FYM		
FYM since	1968	1885	1844		
Fertilizers since	1968	1968			
(a) Wheat after beans, grain					
1970–72	6·08	5·83	6·92	−1·09	−0·84
1973–75	6·05	6·25	6·60	−0·35	−0·55
1976–78	5·88	5·90	5·88	+0·02	+0·00
(b) Potatoes, total tubers					
1970–72	33·7	46·7	40·1	+6·6	−6·4
1973–75	36·4	44·0	39·3	+4·7	−2·9
1976–78	28·1	35·6	32·3	+3·3	−4·2
(c) Beans, grain					
1970–72	2·16	2·51	2·53	−0·02	−0·37
1973–75	2·75	3·29	3·23	+0·06	−0·48
1976–78	2·25	2·58	3·18	−0·60	−0·93

for many years. It was given FYM plus N_2PK (all at the standard rates used elsewhere on Broadbalk) because this combination of manures had been found to give the maximum yield of root crops when tested on Barnfield. Table 10 indicates that yields of wheat on the new plot were less in 1970–72 and 1973–75 than those on the adjacent plot 22 given FYM for 130 or more years, but from 1976 there was no difference. Yields of both potatoes and beans on plot 1 were less than those on either plot 21 or 22 throughout the period, presumably because the soil contained too little P and K for potatoes and too little K for beans.

Comparisons with earlier periods

Yields of wheat grain in 1970–78 were substantially greater than those in 1852–61 and in 1902–11 (see Table 11 of which part 1 is a revised version of a table given by Johnston & Mattingly, 1976). Yields with neither FYM nor N fertilizer were about 50 % greater than in the earlier periods. With PKMg(Na) and N differences were larger, both absolutely and proportionally; with N at 96 or 144 kg ha^{-1} the 1970–78 yields were about double the early ones and with FYM they were more than double. Yields of total produce (part 2 of the table) had not changed greatly between 1852–61 and 1902–11; on poorer-yielding plots they decreased a little but on plots with FYM or N_3PKMg(Na) they increased.

TABLE 11

Broadbalk: effects of FYM and fertilizers on yields of winter wheat grown continuously

Treatment†	Period and Variety: 1852–61 Red Rostock	1902–11 Squarehead's Master	1970–78* Cappelle Desprez
	1. Mean yields of grain, t ha^{-1}		
None	1·12	0·80	1·65
FYM	2·41	2·62	5·84
PKMg(Na)	1·29	1·00	1·78
N_1PKMg(Na)	1·91	1·58	3·52
N_2PKMg(Na)	2·42	2·28	4·84
N_3PKMg(Na)	2·52	2·76	5·32
N_4PKMg(Na)	—	—	5·49
	2. Mean yields of grain plus straw at 85% dry matter, t ha^{-1}		
None	3·03	2·01	2·86
FYM	6·67	7·76	11·60
PKMg(Na)	3·43	2·56	3·15
N_1PKMg(Na)	5·21	4·39	6·25
N_2PKMg(Na)	6·99	6·74	8·84
N_3PKMg(Na)	7·59	8·49	9·98
N_4PKMg(Na)	—	—	10·34
	3. Harvest Index‡		
None	0·37	0·40	0·58
FYM	0·36	0·34	0·50
PKMg(Na)	0·38	0·39	0·57
N_1PKMg(Na)	0·37	0·36	0·56
N_2PKMg(Na)	0·35	0·34	0·55
N_3PKMg(Na)	0·33	0·33	0·53
N_4PKMg(Na)	—	—	0·53

* Means of sections 1 and 9.
† Plots 3, 22, 5, 6, 7, 8 and 9 (all periods).
‡ Harvest index calculated as (mean yield of grain)/(mean yield of grain plus straw).

In 1970–78, however, total yields were greater by 1 to 4 t ha^{-1} on well-manured plots (especially with FYM), but little changed on plots receiving neither N nor FYM.

In 1852–61 and 1902–11 responses to N fertilizer were much smaller than in 1970–78. This may be ascribed partly to the changes of variety and partly to better control of weeds and pests but it must be remembered also that in 1852–61 all the N fertilizer, and in 1902–11 part of the N fertilizer (24 kg ha^{-1}) was applied in autumn and probably lost some of its effect in consequence. Harvest index (part 3 of the table), the ratio (mean yield grain)/(mean yield total produce), was markedly greater in 1970–78 than in the earlier periods. Some of the change is probably caused by the change from harvesting by hand or by binder to harvesting by combine (which entails loss of chaff, cavings, etc. retained and weighed in the earlier periods) but undoubtedly much of the change must be ascribed to the shorter straw of Cappelle Desprez. Samples of Red Rostock still preserved show that the crop on well-manured plots stood about 1·8 m tall, nearly double the height of Cappelle Desprez. Harvest index was in all periods greatest on plots not given FYM or N and (except in 1970–78) least with N_3PKMg(Na). In 1970–78 FYM gave the smallest harvest index.

Efficiency of N fertilizer

Responses to the single and double rates of N fertilizer on plots given PKMg(Na) were 31 and 19 kg grain dry matter per kg N applied (Table 12). If the first crop after fallow is excluded, responses to the first 48 kg ha^{-1} N, applied as 'Nitro-Chalk' were, on average, +1·91 t ha^{-1}; this is equivalent to 34 kg grain dry matter per kg N applied, in

TABLE 12

Broadbalk 1970–78: mean responses to 48, 96 kg N ha^{-1} (as 'Nitro-Chalk'), grain at 85% dry matter, t ha^{-1} (and, in brackets, kg grain dry matter per kg N)

Crop	N, kg ha^{-1} 48 *minus* 0	96 *minus* 48
After many wheat crops (mean of sections 1 and 9)	+1·74 (31)	+1·28 (23)
Second crop after fallow	+2·04 (36)	+1·57 (28)
First crop after beans	+1·95 (35)	+0·91 (16)
First crop after fallow	+1·04 (18)	+0·42 (7)
Mean	1·69 (31)	1·05 (19)

close agreement with the value of 35 kg given by Boyd, Yuen & Needham (1976) based on annual experiments on sites in normal farming systems.

It is noted in passing that in the seasons 1979–81, when the variety Flanders has been grown, and fungicides have been applied to control leaf diseases, the mean responses to the first 48 kg ha^{-1} N have been appreciably greater than those in 1970–78, indicating that each kg N has produced more than 40 kg of dry matter in grain.

Fitted response curves

Because the fitted nitrogen response curves were constrained to have the same shape, they may be superimposed by suitable horizontal and vertical shifts as shown in Fig. 4. Interpreting horizontal shifts as differences in available N, and vertical shifts as differences in potential yield, the comparisons with continuous wheat are as follows:

(i) the first wheat after fallow benefited by 53 kg ha^{-1} available N but produced 0·36 t ha^{-1} less yield,
(ii) the second wheat after fallow lost by 9 kg ha^{-1} available N but produced 0·38 t ha^{-1} more yield,
(iii) wheat after beans benefited by 23 kg ha^{-1} available N and produced 0·51 t ha^{-1} more yield.

Plant nutrients in the wheat crops

After the plots were divided into ten sections in 1968 it was decided that it was impracticable to keep samples for chemical analysis from all plots. Hence each year only wheat grain and straw were kept from each continuous wheat plot on section 1, and from plots where wheat followed potatoes and beans. Potato tubers and bean grain and straw samples were also kept.

All samples from 1970–75 have been analysed for N, P, K, Ca, Mg and Na, but from 1976–78 only N has been determined in wheat, potatoes and beans. Here, results are given for each plot averaged over the 6- or 9-year period as appropriate with some data for individual years for selected treatments. Nutrient uptake shown in the tables is the amount removed in the harvested crop, which may not be the maximum amount in the crop before harvest. Mean values in Tables 15–29 exclude plots 1 and 20 because there is no data for both continuous and rotation wheat on both plots. Standard errors for each value in the Tables were calculated as for the yields (see p. 9) but are not given, except for the mean, because they were relatively uniform.

Some treatment effects are given, together with standard errors calculated as for

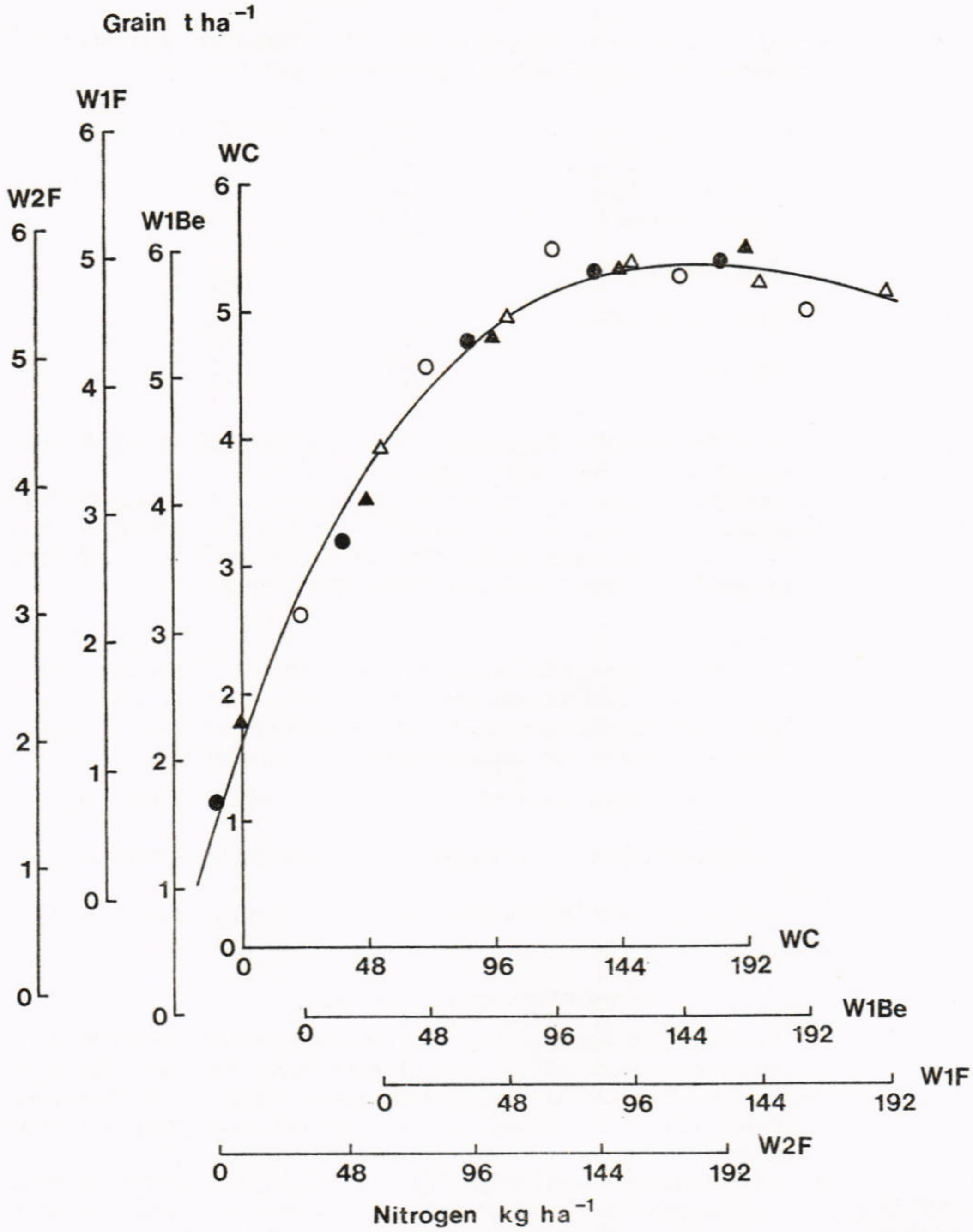

FIG. 4. Broadbalk, 1970–78. Yields and fitted curves in Fig. 2 brought into coincidence with continuous wheat. Continuous wheat, ▲; Wheat after beans, ○; First wheat after fallow, △; Second wheat after fallow, ●.

effects on yield, in Appendix Table 1 for the wheat crops and Appendix Table 2 for potato tubers and bean grain composition. The effects are discussed for each nutrient separately in following sections. However, as stated previously (p. 9), in an experiment with little replication apparent significant differences may not be genuine treatment effects. We have tended to accept as probably real, treatment differences which occur in both continuous and rotational wheat, especially if changes in composition and uptake are both in the same direction. This method of looking at the data could ignore important differences between continuous and rotational wheat. Such differences might arise if rotational wheat had a larger root system and took up extra amounts of nutrient which were not diluted by any extra dry matter produced. Nutrient concentration and uptake often did not increase or decrease together because some factor, e.g. foliar disease, affected yield.

Treatment differences in Appendix Table 1 which use data from plot 11 do not agree with values obtained by using the data in the main tables. This is because the continuous wheat grain sample from plot 11 in 1974 was lost. The values in Appendix Table 1 were calculated using data for the 5 years for which results were available.

Percentage composition and nutrient uptake in crops grown on the replicated plots, 7 and 16, 8 and 15, 17 and 18 were remarkably similar, significant differences occurred in only a very few cases.

Where comparisons with earlier periods are made these data are taken from Johnston (1969). In 1966–67 the cultivar was Squarehead's Master. Yields are now much larger, some comparisons are made in Table 13.

TABLE 13

Yields, t ha^{-1}, of grain and straw of wheat grown continuously on Broadbalk in 1966–67 and 1970–78

		1966–67 Squarehead's Master				1970–78 Cappelle Desprez			
Plot	Treatment	Grain	Straw	Total	Harvest index	Grain	Straw	Total	Harvest index
3	None	1·12	1·39	2·51	0·446	1·72	1·39	3·11	0·554
22	FYM	2·60	3·73	6·33	0·411	5·85	6·12	11·97	0·489
5	PKMg(Na)	1·27	1·59	2·86	0·444	1·67	1·47	3·14	0·531
6	N_1PKMg(Na)	2·12	2·62	4·74	0·447	3·48	2·76	6·24	0·558
7	N_2PKMg(Na)	3·02	4·14	7·16	0·422	4·81	3·90	8·71	0·552
8	N_3PKMg(Na)	3·53	4·49	8·02	0·440	5·13	4·51	9·64	0·532
9	N_4PKMg(Na)	—	—	—	—	5·49	4·88	10·37	0·529
10	N_2	1·44	2·13	3·57	0·403	3·53	2·36	5·89	0·599

Seasonal variation. Johnston (1969) summarized the results of analyses made by Lawes and Gilbert of wheat grain and straw grown on Broadbalk. They had shown that for any one treatment in one year better matured grains contained smaller percentages of nitrogen and total mineral matter because favourable growing conditions enhanced starch accumulation; and also that fully ripened grain had a very uniform mineral composition. In good growing 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 each of the three nutrients was, however, greater in the better seasons. Over 16 consecutive years seasonal differences caused larger variations in the percentage of P and K in the grain and straw from any one treatment, than those between the means of the three contrasted treatments, unmanured, FYM and N_2 only.

Our recent results largely confirm the conclusions above. Minimum, mean and maximum values for N, P, K and Mg percentages in grain and straw (Table 14) are given for the four treatments, none, FYM, N_2 and N_2PKMg(Na). The last was not included by Lawes and Gilbert. Mean concentrations in grain of the four nutrients differ less between treatments than they do between seasons within any one treatment except for the N_2 treatment because this soil now contains so little P that %P and %Mg were appreciably less than in crops which receive P or were unmanured. There were large seasonal and

TABLE 14

*Mean and range of percentage N, P, K and Mg in dry matter of grain and straw of wheat grown continuously and in rotation on Broadbalk, 1970–75**

	Continuous wheat				Wheat in rotation			
	None	FYM	N_2PK Mg(Na)	N_2	None	FYM	N_2PK Mg(Na)	N_2
			Grain %N					
Mean	1·73	2·02	1·84	2·03	1·65	2·09	1·91	2·04
Minimum	1·45	1·67	1·65	1·71	1·37	1·67	1·50	1·63
Maximum	1·96	2·27	2·06	2·32	1·80	2·44	2·32	2·30
			Grain %P					
Mean	0·35	0·38	0·36	0·25	0·36	0·37	0·34	0·26
Minimum	0·31	0·32	0·31	0·18	0·33	0·34	0·32	0·19
Maximum	0·39	0·42	0·39	0·29	0·39	0·43	0·38	0·35
			Grain %K					
Mean	0·47	0·46	0·48	0·44	0·46	0·46	0·45	0·42
Minimum	0·40	0·36	0·39	0·31	0·40	0·37	0·39	0·35
Maximum	0·55	0·50	0·56	0·53	0·49	0·55	0·48	0·49
			Grain %Mg					
Mean	0·10	0·11	0·10	0·08	0·11	0·11	0·10	0·09
Minimum	0·08	0·10	0·09	0·05	0·10	0·10	0·10	0·08
Maximum	0·12	0·12	0·12	0·10	0·13	0·13	0·12	0·11
			Straw %N					
Mean	0·39	0·45	0·46	0·51	0·38	0·55	0·46	0·53
Minimum	0·27	0·31	0·36	0·38	0·27	0·34	0·37	0·38
Maximum	0·45	0·60	0·55	0·68	0·52	0·72	0·53	0·67
			Straw %P					
Mean	0·07	0·11	0·08	0·04	0·07	0·11	0·08	0·05
Minimum	0·06	0·06	0·07	0·03	0·06	0·09	0·06	0·03
Maximum	0·10	0·14	0·09	0·07	0·09	0·16	0·11	0·09
			Straw %K					
Mean	0·69	1·41	1·00	0·48	0·68	1·57	0·98	0·46
Minimum	0·20	0·68	0·74	0·18	0·25	0·83	0·54	0·22
Maximum	0·97	2·02	1·24	0·73	0·90	2·35	1·40	0·75
			Straw %Mg					
Mean	0·05	0·05	0·04	0·05	0·06	0·05	0·05	0·05
Minimum	0·03	0·04	0·04	0·02	0·04	0·04	0·04	0·04
Maximum	0·08	0·06	0·05	0·06	0·08	0·06	0·06	0·07

* %N, 1970–78.

treatment differences in composition of the straw partly because of the accumulation and depletion of nutrients in soil after more than 100 years of different treatments and partly because of leaching from the straw.

The relationship between %N, P and K and yield of grain and straw for the crops grown continuously and in rotation with N_2PKMg(Na) during a number of seasons are shown in Fig. 5. Other than a tendency for %P and %K in straw to increase as straw yield increased there was no clear relationship. The data do not appear to indicate any critical nutrient concentration in the harvested crop below which crop growth was affected. To determine if there are such critical concentrations it would be necessary to study changes in nutrient concentration in the crop during growth.

Nitrogen

Percentage N in grain dry matter and N removed in wheat grain plus straw are in Table 15. Averaged over all treatments %N in grain was 1·92 and 1·94% when wheat was grown

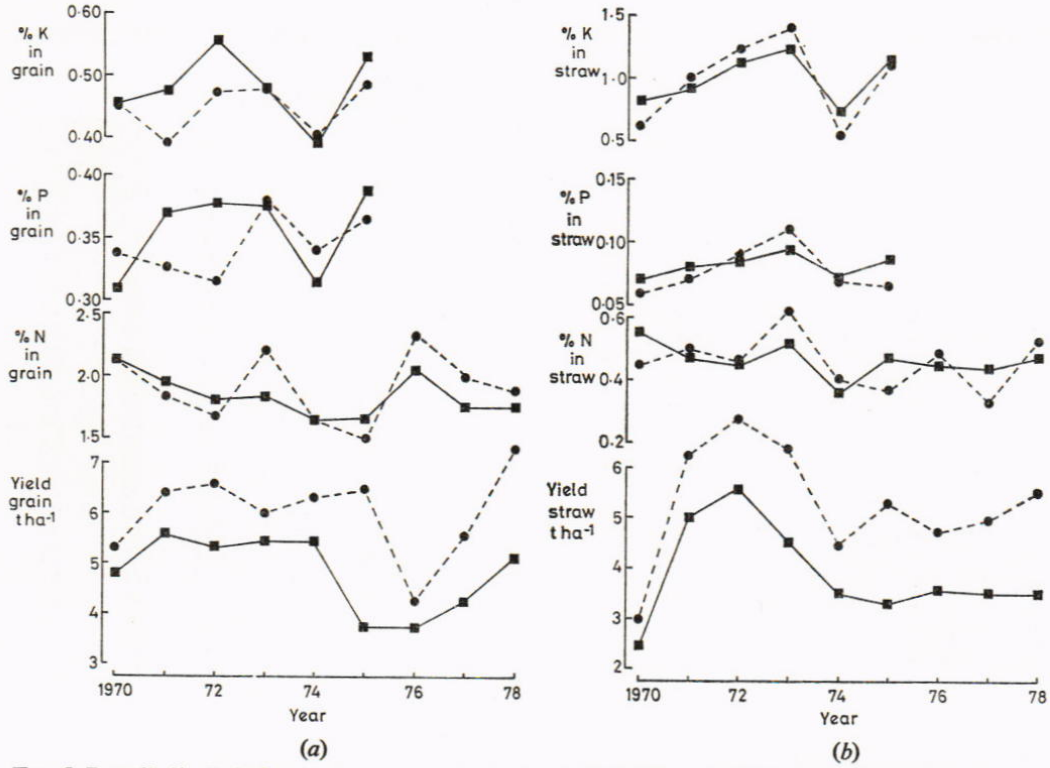

FIG. 5. Broadbalk: Relationship between grain yield and %N, %P and %K in grain dry matter (Fig. 5a) and straw yield and %N, %P and %K in straw dry matter (Fig. 5b). Wheat grown continuously, ■; and in rotation, ●; and given $N_2PKMg(Na)$. Yields and %N 1970–78; %P and %K 1970–75.

continuously and in rotation respectively. For wheat grown continuously %N in grain declined only from 2·01% in 1966–67 to 1·92% in 1970–78 even though yields were 50% larger in 1970–78.

The effect of fertilizer N on %N in grain and N in grain plus straw at harvest are shown in Fig. 6 for wheat grown continuously and in rotation. At each level of applied fertilizer N there was remarkably little difference in %N for the two systems, 0·04% more N when wheat followed beans. The first 48 kg N ha^{-1} had little effect on %N in grain; it declined by 0·02% in continuous wheat and was increased by 0·04% when wheat was grown in rotation. Increasing the N applied from 48 to 144 kg ha^{-1} increased %N in grain almost linearly from 1·68 to 2·14% averaged over the two wheat crops.

The 48 kg ha^{-1} N increment from 144 to 196 ha^{-1} was much less efficient at increasing N% in grain, Fig. 6a. The increase, 0·09 and 0·10% for wheat grown continuously and in rotation respectively, was nevertheless statistically significant (Appendix Table 1). This decline may reflect, like the decrease in yields, the fact that foliar diseases were not adequately controlled in this period or it may be because the linear relationship between %N in grain and applied fertilizer N does not hold for large dressings of N even in healthy crops.

Grain from FYM-treated soils contained a little less N than grain given 144 kg N as fertilizer and significantly less than grain given 192 kg N. Adding 96 kg fertilizer N to FYM-treated soil significantly increased %N in grain by about 0·25%; to 2·28 and 2·39% respectively in wheat grown continuously and in rotation (Appendix Table 1).

The effects of P and K on %N in grain were not significant but there was a significant effect of K on N uptake because grain yield was increased significantly.

TABLE 15

Percentage N and amount of N removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–78

		%N				Uptake kg N ha^{-1}				% of total uptake in grain	
		Grain		Straw		Grain		Grain + straw			
Plot	Treatment	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
1	FYM + N_2PK	—	2·28	—	0·70	—	115	—	155	—	75
21	FYM + N_2	2·27	2·39	0·70	0·80	110	119	152	170	73	71
22	FYM	2·02	2·14	0·45	0·55	101	117	125	151	81	79
3	None	1·73	1·65	0·39	0·38	25	37	30	44	85	86
5	PKMg(Na)	1·68	1·65	0·44	0·41	24	44	30	52	81	85
6	N_1PKMg(Na)	1·66	1·69	0·37	0·36	49	72	57	86	85	84
7	N_2PKMg(Na)	1·84	1·91	0·46	0·46	75	96	90	117	83	83
8	N_3PKMg(Na)	2·11	2·16	0·60	0·65	92	101	115	133	80	77
9	N_4PKMg(Na)	2·20	2·26	0·65	0·76	102	104	130	140	79	75
10	N_2	2·03	2·04	0·51	0·53	60	85	70	98	86	86
11	N_2P	1·99	1·88	0·55	0·49	56	83	69	97	82	86
12	N_2PNa	1·88	1·85	0·45	0·45	72	88	85	103	85	85
13	N_2PK	1·84	1·89	0·41	0·49	78	97	92	118	85	83
14	N_2PK′Mg	1·81	1·85	0·41	0·46	79	99	92	118	85	84
15	N_3PKMg(Na)	2·08	2·09	0·55	0·60	96	104	115	130	83	81
16	N_2PKMg(Na)	1·90	1·87	0·42	0·46	77	94	90	113	85	84
17	$N_2\frac{1}{2}$[PKMg(Na)]	1·86	1·87	0·41	0·46	71	98	83	118	86	84
18	$N_2\frac{1}{2}$[PKMg(Na)]	1·88	1·89	0·41	0·49	74	98	86	119	86	83
19	Castor meal	1·78	1·86	0·44	0·43	61	86	72	102	85	85
20	N_2KMg(Na)	2·05	—	0·51	—	62	—	73	—	86	—
Mean†		1·92	1·94	0·48	0·51	72	90	88	112	83	82
SE of mean		0·071	0·074	0·019	0·040	3·2	3·6	4·3	6·2	1·0	1·5

* Cont.: Wheat grown continuously; Rotn: Wheat grown in rotation.
† Excluding plots 1 and 20.

Currently the normal minimum %N in grain dry matter for British bread is 2·14%N corresponding to 12·2% protein. This N concentration was achieved in Cappelle Desprez on Broadbalk by applying 192 kg N to continuous wheat, or 144 kg N or more to wheat grown in rotation; by growing wheat in rotation on soils given FYM annually for many years; or, for both wheat crops, by applying 96 kg fertilizer N to FYM-treated soils.

Squarehead's Master was grown both continuously and as a first crop after fallow for a number of years prior to 1968. Without fertilizer N, %N in grain in 1966–67 was larger for both crops than it was for Cappelle Desprez during 1970–78 (Fig. 6a) because yields of Squarehead's Master were less. Figure 6a shows that %N in grain was least in continuous wheat but the difference diminished as applied fertilizer N increased because the crop after fallow responded only a little to the larger N dressings, and with the largest application of N yields of both crops were very similar.

The efficiency with which N is used to increase %N in grain can be tested by calculating the amount of N needed to increase the N concentration by 0·1 %N. From Fig. 6a Cappelle Desprez required only 21 kg N for N dressings ranging from 48 to 144 kg N ha^{-1} over which range the %N–fertilizer N rate relationship was linear. This value is very similar to that of 24 kg N over the range 50 to 150 kg N applied to Cappelle Desprez and Maris Huntsman when both were grown continuously on the Chalky Boulder Clay soil at Saxmundham (Widdowson *et al.*, 1980). However both are appreciably less than that of 32 kg N over the range 50 to 175 kg N ha^{-1} reported by Benzian & Lane (1981) from many earlier experiments with different varieties on a wider range of soils.

There are probably several reasons for this difference. On Broadbalk and at Saxmundham cereals had been grown continuously for some years and there was little change in the amounts of soil organic matter. Therefore, there was probably only a small contribution from soil N to N uptake. In many other experiments soil N, mineralized

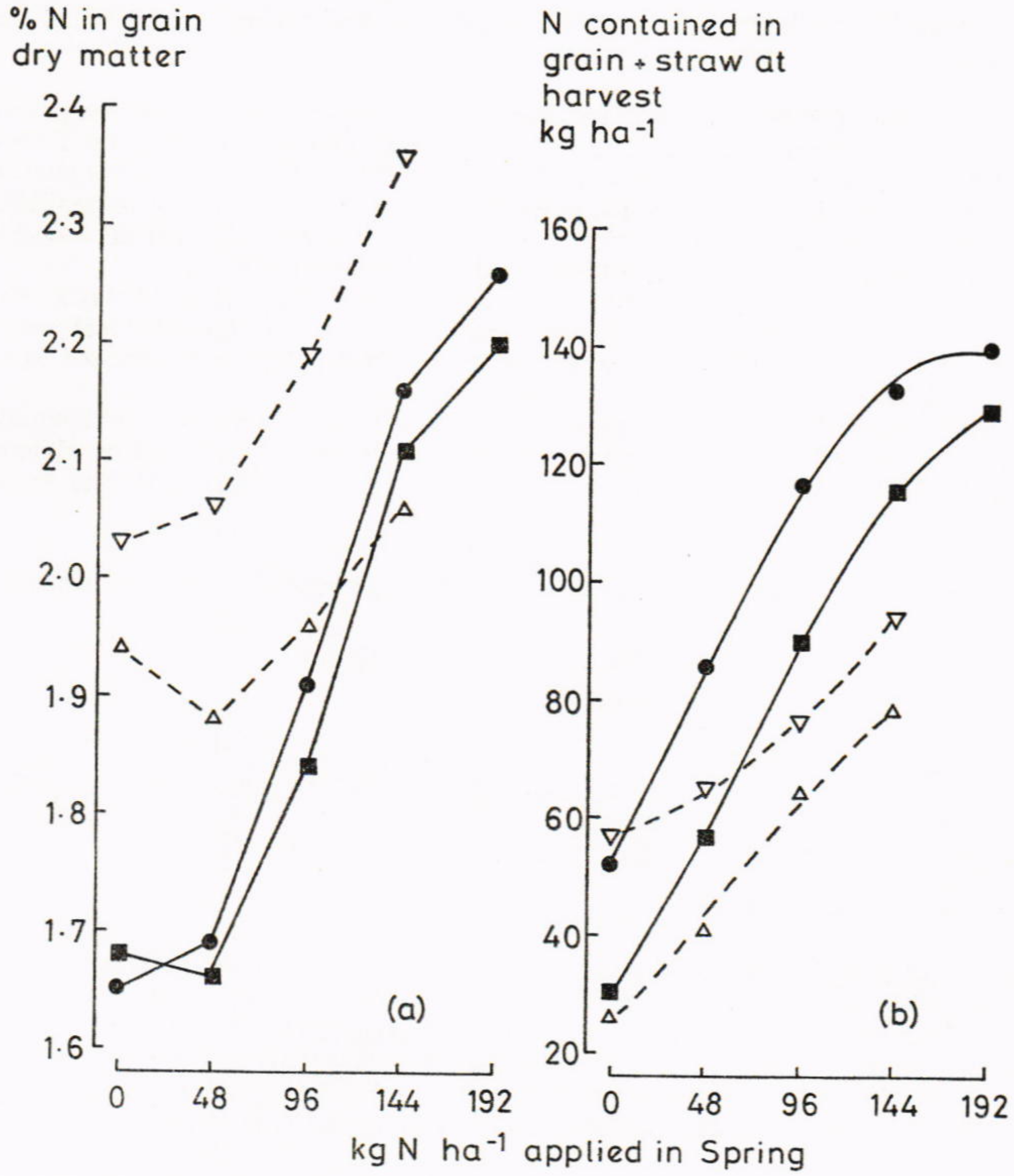

FIG. 6. Broadbalk: Percentage N in grain (Fig. 6a) and N removed in grain plus straw (Fig. 6b). (i) Wheat grown continuously, ■; and in rotation, ● 1970–78; (ii) Wheat grown continuously, △; as a first crop after fallow ▽, 1966–67.

from organic matter or as residues from previous fertilizer dressings, is usually available to an autumn sown crop, probably contributing appreciably to N uptake and the efficiency with which the current N dressing is used. There is also a difference between cultivars; 53 and 48 kg fertilizer N were needed for an increase of 0·1 %N in grain of Squarehead's Master when grown continuously and as a first crop after fallow respectively (Fig. 6a), whilst 21 kg N were needed by Cappelle Desprez when it was given the same amounts of fertilizer N and grown on the same soils.

Percentage N in straw ranged from 0·4 to 0·8%, about a quarter to a third of that in grain. Straw %N like that of grain, increased with increasing N application, 192 kg N gave a significantly larger %N in straw than 144 kg N, and adding N to FYM did the same.

The amount of N in the harvested crop varied from 30 kg ha^{-1} when wheat was grown continuously without fertilizer N to 170 kg in wheat grown in rotation on FYM-treated soils given an additional 96 kg fertilizer N. On average, 82 and 83% of the total N in the crop was in the grain when grown in rotation and continuously respectively. For continuous wheat this proportion was a little larger than the 80% in the 1966–67 crops reflecting the change in harvest index (Table 13) in favour of grain.

The crop grown in rotation contained, on average, an extra 24 kg N ha^{-1} but it cannot be assumed that all this N came from the beans. The extra N in the rotational wheat declined from 29 to 10 kg N ha^{-1} when the fertilizer N dressings were increased from 48 to 192 kg ha^{-1}.

The effects of N and PKMg on the N in grain plus straw of wheat grown continuously have changed little during the experiment. When no N was applied, with or without PKMg(Na) the N content has remained about 30 kg N ha^{-1} (Table 16). The crops

TABLE 16

Annual uptake of nitrogen, kg ha^{-1}, by grain plus straw of winter wheat grown continuously on Broadbalk

Means for 1852–61, 1966–67 and 1970–78

	Uptake kg N ha^{-1}								
	Without N			With N*			With N *minus* without N		
	1852–61	1966–67	1970–78	1852–61	1966–67	1970–78	1852–61	1966–67	1970–78
PKMg(Na)									
Without	26	25	30	43	32	70	17	7	40
With	32	26	30	64	64	90	32	38	60

* N applied annually 96 kg ha^{-1}.

given N_2PKMg(Na) and N_2 only contained 90 and 70 kg N ha^{-1} respectively in 1970–78, compared to 64 and 32 kg N in 1966–67. The increases are because of the extra grain yield. With N_2 only the N content in 1966–67 (32 kg) had declined compared to that in 1852–61 (43 kg) and this decline was ascribed to diminishing yields as P and K in the soil decreased. However the trend to lower yields has been reversed, Cappelle Desprez seemingly being less sensitive to the declining soil P and K levels in plot 10 (N_2 only) than Squarehead's Master.

The recovery of fertilizer N by crops currently attracts much interest. Apparent % recoveries can be calculated as:

$$\frac{\text{Uptake by crop given N } \textit{minus} \text{ uptake by crop without N}}{\text{N applied}} \times 100$$

For our data the uptake on plot 5 was taken as standard. Johnston (1969) showed that the apparent % recoveries of fertilizer N by wheat grown continuously changed little between 1852–71 and 1966–67 ranging between 32 and 39%. The smallness of this range is perhaps surprising because during 1852–71 all the N, as ammonium salts, was applied in autumn, whilst for the 1966–67 crops only 24 kg N was applied in autumn with the remainder given in spring. Crops grown in 1970–78 apparently recovered 46 to 71% of the applied N (Table 17) and there was little difference in the % recovery between wheat

TABLE 17

Apparent % recovery of added fertilizer N by winter wheat† grown continuously or in rotation on Broadbalk*

		Apparent % recovery using plot 5 as standard			Apparent % recovery of each additional 48 kg N increment		
Plot	N applied kg ha⁻¹	1966–67 Cont.	1970–78 Cont.	1970–78 Rotn	1966–67 Cont.	1970–78 Cont.	1970–78 Rotn
6	48	32	56	71	32	56	71
7	96	39	63	68	47	69	65
8	144	36	59	56	29	52	33
9	192	—	52	46	—	31	15
Mean		36	58	60	36	52	46

* In 1966–67 N applied as ammonium sulphate; 24 kg N in autumn on each plot remainder in spring. In 1970–78 all N in spring as 'Nitro-Chalk'.
† 1966–67 Squarehead's Master, 1970–78 Cappelle Desprez.

grown continuously or in rotation at each level of N. The larger apparent recoveries obtained now, compared to the earlier periods, are probably because of the current larger grain yields; although part of the reason could be that all the N on these plots has been applied in spring since 1968. However, even if all the autumn applied N in 1966–67 had been lost the apparent recoveries of the spring applied part of the 96 and 144 kg N ha^{-1} dressings were much less than the present apparent recoveries by Cappelle Desprez.

This method of assessing the uptake of fertilizer N is not necessarily the best because it assumes that the same amount of soil N is taken up by crops with and without applied N. It is hoped that current studies using ^{15}N will give much more accurate information on the recovery of fertilizer N. Preliminary results are given by Jenkinson *et al.*, 1981.

Another technique calculates the apparent recovery of each additional N increment (Table 17) and this method shows clearly the poor apparent recovery of the larger N dressings.

Both methods of calculation show similar patterns of N recovery by continuous wheat in 1966–67 and 1970–78. Apparent recovery of the 48 kg N dressing was less than that of the 96 kg N dressing, but this was not so when wheat was grown in rotation. A possible explanation (Jenkinson, private communication) could be that enough tillers did not develop, or did not survive, when wheat was grown continuously with only 48 kg N for the crop to make full use of the N. The extra N from the beans or a better root system of wheat after a break crop appears to correct this. Apparent recovery of the 144 and 192 kg N dressing is much less than that of the 96 kg N because the larger dressings did not increase yield proportionally.

Phosphorus

Percentage P in dry matter of grain was similar in all treatments given fertilizer P at about 0·34%; %P in straw was a fifth to a quarter of this (Table 18). Grain grown on soil given no P for more than 120 years now contains significantly less P than when grown on soil given NPK fertilizers, whilst both grain and straw grown on FYM-treated soil contained more P than when grown with fertilizers only. Where the half-rate of P and K fertilizers were applied (plots 17 and 18) %P in grain was less than with the full rate but the difference was significant only for continuous wheat. Increasing amounts of fertilizer N had no consistent effect on %P in grain.

Percentage P in grain changed very little between 1862–71 and 1966–67, even though much P had accumulated in the soils to which P was applied, but it was about a fifth less during 1970–75 (Table 19). This decrease occurred when soil P was still accumulating

TABLE 18

Percentage P and amount of P removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–75

		%P				Uptake kg P ha⁻¹				% of total uptake in grain	
		Grain		Straw		Grain		Grain+straw			
Plot	Treatment	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
1	FYM+N_2PK	—	0·34	—	0·09	—	17·4	—	23·0	—	77
21	FYM+N_2	0·37	0·37	0·10	0·12	18·8	18·7	24·8	26·9	77	72
22	FYM	0·38	0·37	0·11	0·11	19·1	21·2	25·3	28·8	77	76
3	None	0·35	0·36	0·07	0·07	5·3	8·1	6·2	9·3	86	87
5	PKMg(Na)	0·36	0·37	0·11	0·11	5·4	10·0	6·8	12·3	79	82
6	N_1PKMg(Na)	0·37	0·35	0·08	0·07	11·8	16·1	13·7	18·9	86	85
7	N_2PKMg(Na)	0·36	0·34	0·08	0·08	15·2	18·1	18·1	21·7	85	84
8	N_3PKMg(Na)	0·33	0·36	0·07	0·10	14·5	17·4	17·6	22·8	83	77
9	N_4PKMg(Na)	0·34	0·33	0·07	0·10	16·4	15·6	19·7	20·5	84	77
10	N_2	0·25	0·26	0·04	0·04	8·1	12·0	9·0	13·3	91	91
11	N_2P	0·36	0·33	0·08	0·07	11·1	15·9	13·1	18·0	85	89
12	N_2PNa	0·35	0·33	0·07	0·07	14·6	17·3	16·8	20·0	87	87
13	N_2PK	0·34	0·35	0·06	0·07	15·2	18·7	17·3	21·8	88	86
14	N_2PK′Mg	0·34	0·36	0·06	0·07	15·5	20·2	17·6	23·4	88	86
15	N_3PKMg(Na)	0·33	0·35	0·07	0·09	16·0	17·8	18·4	21·8	87	83
16	N_2PKMg(Na)	0·34	0·34	0·06	0·06	14·6	17·7	16·6	20·6	88	87
17	$N_2\frac{1}{2}$[PKMg(Na)]	0·33	0·33	0·06	0·06	13·1	18·0	14·7	20·6	89	88
18	$N_2\frac{1}{2}$[PKMg(Na)]	0·33	0·34	0·05	0·06	13·7	18·0	15·2	20·9	90	86
19	Castor meal	0·34	0·34	0·07	0·07	11·9	15·9	13·8	18·5	87	87
20	N_2KMg(Na)	0·24	—	0·03	—	7·6	—	8·3	—	92	—
Mean†		0·34	0·34	0·07	0·08	13·4	16·5	15·9	20·0	86	84
SE of mean		0·010	0·012	0·006	0·009	0·78	0·65	1·19	1·27	1·7	2·3

* Cont.: Wheat grown continuously; Rotn: Wheat grown in rotation.
† Excluding plots 1 and 20.

TABLE 19

Comparison of percentage P in grain and straw of, and total P uptake in, winter wheat grown continuously on Broadbalk in three periods

Means for 1862–71, 1966–67 and 1970–75

		%P in dry matter of						Total P in crop kg ha⁻¹		
		Grain			Straw					
Plot	Treatment	1862–71	1966–67	1970–75	1862–71	1966–67	1970–75	1862–71	1966–67	1970–75
22	FYM	0·44	0·44	0·38	0·10	0·10	0·11	13·3	12·8	25·3
3	None	0·44	0·41	0·35	0·09	0·06	0·07	4·7	4·5	6·2
5	PKMg(Na)	0·45	0·43	0·36	0·12	0·08	0·11	6·1	5·7	6·8
10	N_2	0·34	0·34	0·25	0·07	0·04	0·04	6·8	4·8	9·0
7	N_2PKMg(Na)	0·41	0·41	0·36	0·07	0·06	0·08	11·4	12·8	18·1

and when yields were much greater (Table 14). It is unlikely therefore that the larger concentrations of P in the grain in the earlier periods were critical levels.

Total P in the harvested crop was on average 15·9 kg ha⁻¹ in continuous wheat and 20 kg in rotational wheat; mainly because of the difference in yield than because of larger concentrations of P in grain or straw (Table 18). On average between 84 and 86% of the total offtake was in the grain. The P removed in wheat grown continuously changed little in the three periods 1862–71, 1966–67, 1970–75 where N or P or both limited growth. Where yields were increased by full manuring P offtake was increased to about 25 kg P ha⁻¹ with FYM and 19 kg with NPK fertilizers. However these removals were only about 60 and 50% of the P applied in FYM and superphosphate respectively. Larger offtakes in wheat grown in rotation, about 24 and 29 kg P ha^{-1} on fertilizer and FYM-treated soils respectively, were still only about two-thirds of the P applied each year.

Potassium

Percentage K in dry matter. On average, %K in grain differed little between wheat grown continuously and in rotation (Table 20). Grain %K was not significantly affected

TABLE 20

Percentage K and amount of K removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–75

		%K				Uptake kg K ha^{-1}				% of total uptake in grain	
		Grain		Straw		Grain		Grain+straw			
Plot	Treatment	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
1	FYM+N_2PK	—	0·44	—	1·31	—	22	—	104	—	28
21	FYM+N_2	0·48	0·48	1·73	1·92	24	24	133	159	22	19
22	FYM	0·46	0·46	1·41	1·57	23	26	107	134	26	25
3	None	0·47	0·46	0·68	0·68	7	10	15	22	49	50
5	PKMg(Na)	0·48	0·47	0·92	0·93	7	13	20	32	40	43
6	N_1PKMg(Na)	0·50	0·45	0·82	0·78	16	21	37	53	47	42
7	N_2PKMg(Na)	0·48	0·45	1·00	0·98	20	23	56	71	38	37
8	N_3PKMg(Na)	0·46	0·47	1·06	1·18	21	23	66	88	36	31
9	N_4PKMg(Na)	0·47	0·44	1·16	1·38	23	21	77	93	34	28
10	N_2	0·43	0·42	0·48	0·46	14	19	25	32	60	62
11	N_2P	0·49	0·45	0·31	0·51	15	21	25	38	66	62
12	N_2PNa	0·48	0·44	0·40	0·42	20	23	33	40	65	61
13	N_2PK	0·47	0·45	0·85	1·01	21	24	51	73	44	37
14	N_2PK′Mg	0·48	0·48	0·55	0·63	22	27	40	56	57	51
15	N_3PKMg(Na)	0·46	0·45	1·15	1·25	22	23	66	81	37	34
16	N_2PKMg(Na)	0·49	0·45	0·84	0·88	21	23	48	63	46	40
17	$N_2\frac{1}{2}$[PKMg(Na)]	0·47	0·45	0·80	0·86	19	25	40	64	50	41
18	$N_2\frac{1}{2}$[PKMg(Na)]	0·47	0·44	0·82	0·79	20	24	44	62	48	43
19	Castor meal	0·47	0·44	0·76	0·58	16	21	36	43	50	52
20	N_2KMg(Na)	0·43	—	0·87	—	13	—	33	—	45	—
Mean†		0·47	0·45	0·88	0·93	18	22	51	67	45	42
SE of mean		0·020	0·018	0·124	0·134	1·2	1·2	8·1	11·0	4·6	5·0

* Cont.: Wheat grown continuously; Rotn: Wheat grown in rotation.
† Excluding plots 1 and 20.

even where K had not been given for more than 120 years but it was affected by the long continued omission of P (Appendix Table 1). There was no significant effect from increased amounts of applied N and, unlike %P in grain, %K was not affected by FYM. There has been only a small decline in %K in grain from earlier periods to the present, 0·50 to 0·48 %K in dry matter, probably because of increased grain yields.

Straw %K was much smaller in 1966–67 than in 1852–1921 (Table 21) and this decline was attributed in part to the change in method of harvesting; combining as opposed to

TABLE 21

Comparison of percentage K in straw of winter wheat grown continuously on Broadbalk in three periods

Means for 1852–1921, 1966–67 and 1970–75

	Plot								
Period	22	3	5	7	10	11	12	13	14
	%K in dry matter								
1852–1921	1·18	0·82	1·04	1·12	0·63	0·51	0·68	1·10	0·70
1966–67	0·78	0·39	0·51	0·58	0·29	0·27	0·28	0·63	0·26
1970–75	1·41	0·68	0·92	1·00	0·48	0·31	0·40	0·85	0·55

cutting, stooking and carting for later threshing. However, in 1970–75 %K in straw was larger than in 1966–67 where K was applied (plots 22, 5, 7, 13) and was almost as large as in the earliest period. Figure 5 shows that there were larger seasonal variations in %K in straw than in grain. These may arise, in part, because of leaching by rain. The lower %K in straw in 1966–67 cannot be attributed entirely to the extra rainfall (53 mm in June, July and August) in 1966.

TABLE 22

Effect of applied fertilizer N on %K in straw dry matter, Broadbalk, 1970–75

Plot number	5	6	7	8	9
N applied, kg ha^{-1}	0	48	96	144	192
%K in straw					
Continuous wheat	0·92	0·82	1·00	1·06	1·16
Rotational wheat	0·93	0·78	0·98	1·18	1·38

Rather more interesting is the effect of increasing N dressings on %K in straw (Table 22). The smallest N dressing decreased %K in straw compared to that grown without N and then as more N was applied %K increased. With increasing N dressings the extra nitrate ions taken up require increasing amounts of cations, of which K is likely to be most readily available in soil.

Percentage K in straw, unlike %K in grain, was very small on plots without added K. With N_2PNa, %K was a little larger than with N_2P, possibly because, as explained previously (Johnston, 1969), the 55 kg Na ha^{-1} dressing released some soil K which was taken up by the plant. Plot 14, now $N_2PK'Mg$, did not receive K before 1968 and straw grown on this soil, which was for long depleted of K, contained only 0·55 %K compared with 0·85% in straw from the adjacent plot 13 which has been enriched with K during many years.

Total K in harvested crop on average varied from 51 to 67 kg K ha^{-1} in grain plus straw of continuous and rotational wheat and of this total 45 to 42% was in the grain (Table 20). On plots receiving fertilizer K, 90 kg ha^{-1}, only the rotational wheat given most N removed more K than was applied. However, if wheat yields increase further, then the amount of K removed in grain plus straw could exceed the K applied and it will be necessary to consider adjusting the size of the dressing; this is discussed further on p. 36. The FYM dressings supplied 325 kg K ha^{-1} during 1970–75 and the maximum offtake from FYM-treated soils of 160 kg ha^{-1} was only half this amount. The amount of K in the FYM dressing is unlikely to change appreciably in the immediate future but if offtakes did ever consistently exceed the amount applied then a supplementary dressing of fertilizer K would have to be applied.

Calcium

Percentage Ca in dry matter. Calcium is not tested on Broadbalk. In the early 1950s soil acidity, which had developed in some plots where ammonium sulphate had been applied for many years, was corrected using ground chalk. Further dressings of chalk were applied between 1954 and 1967 to plots receiving ammonium sulphate and rape cake. Since 1968 all N has been given as 'Nitro-Chalk' and since autumn 1975 all plots have received chalk dressings of about 2·9 t ha^{-1} every third year to maintain a pH of about 7.

Grain %Ca was the same, 0·05%, for crops grown continuously and in rotation, and the concentration in straw was 6 or 7 times as large (Table 23).

In the absence of K but in the presence of N, application of P increased growth and %Ca in grain increased, Ca, in part, presumably replacing K whilst when K was added %Ca was significantly decreased (Appendix Table 1).

TABLE 23

Percentage Ca and amount of Ca removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–75

		%Ca				Uptake kg Ca ha^{-1}				% of total uptake in grain	
		Grain		Straw		Grain		Grain+straw			
Plot	Treatment	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
1	FYM+N_2PK	—	0·05	—	0·35	—	2·4	—	22	—	12
21	FYM+N_2	0·05	0·05	0·33	0·35	2·5	2·6	22	25	12	11
22	FYM	0·04	0·04	0·26	0·28	2·1	2·4	17	20	13	13
3	None	0·05	0·05	0·35	0·38	0·8	1·1	5	7	17	17
5	PKMg(Na)	0·05	0·05	0·44	0·41	0·7	1·2	7	9	12	16
6	N_1PKMg(Na)	0·04	0·04	0·25	0·25	1·4	1·9	7	12	19	17
7	N_2PKMg(Na)	0·04	0·04	0·29	0·28	1·8	2·2	12	15	16	16
8	N_3PKMg(Na)	0·05	0·05	0·33	0·34	2·0	2·4	15	20	15	13
9	N_4PKMg(Na)	0·05	0·05	0·34	0·38	2·3	2·4	17	21	14	13
10	N_2	0·05	0·05	0·39	0·38	1·7	2·4	10	13	18	20
11	N_2P	0·07	0·06	0·41	0·37	2·1	3·0	13	14	19	23
12	N_2PNa	0·06	0·06	0·40	0·39	2·4	3·0	14	18	18	18
13	N_2PK	0·04	0·04	0·28	0·30	1·9	2·4	11	16	17	16
14	N_2PK′Mg	0·05	0·05	0·30	0·34	2·1	2·6	12	17	18	15
15	N_3PKMg(Na)	0·05	0·05	0·31	0·34	2·2	2·4	13	17	17	15
16	N_2PKMg(Na)	0·04	0·04	0·26	0·28	1·7	2·2	9	14	18	16
17	$N_2\frac{1}{2}$[PKMg(Na)]	0·04	0·04	0·29	0·29	1·7	2·3	9	15	19	16
18	$N_2\frac{1}{2}$[PKMg(Na)]	0·04	0·04	0·28	0·34	1·8	2·2	9	17	19	14
19	Castor meal	0·05	0·05	0·36	0·32	1·6	2·2	11	14	16	17
20	N_2KMg(Na)	0·04	—	0·29	—	1·3	—	8	—	18	—
Mean†		0·05	0·05	0·33	0·34	1·8	2·3	12	16	17	16
SE of mean		0·001	0·001	0·021	0·028	0·10	0·07	1·1	1·5	1·5	1·7

* Cont.: Wheat grown continuously; Rotn: Wheat grown in rotation.
† Excluding plots 1 and 20.

Total Ca in the harvested crop is small, 5 to 25 kg Ca ha^{-1}, and is largely related to yield, the concentration in the crop being very consistent. On average only 16 to 17% of the total Ca uptake is in the grain. Calcium offtakes, which had remained remarkably constant up to 1967 (Johnston, 1969, Table 4.13), were a little larger in 1970–75 for continuous wheat, mainly because yields have increased.

Magnesium

Percentage Mg in dry matter was, on average, about 0·10% in grain and about half this in straw (Table 24). Crops grown on FYM-treated soil contained rather more magnesium than those given fertilizers, plot 22 minus 9, (Appendix Table 1), even though Mg, as magnesium sulphate, was applied at a rate larger than the annual offtake of Mg. As with Ca, percentage Mg was larger in the crop given N_2P than in that given N_2.

Total Mg in the harvested crop was on average 5·5 and 7·2 kg Mg ha^{-1} for continuous and rotational wheat and about 70% of the total removed was in the grain (Table 24). The range in magnesium offtakes was from 2·2 kg ha^{-1} by continuous wheat on unmanured soil to 9·5 kg ha^{-1} by rotational wheat on FYM-treated soil. The offtakes by continuous wheat are a little larger than those recorded for earlier periods (Johnston, 1969, Table 4.13) because yields are now larger.

Sodium

Sodium concentrations in both grain and straw varied so little between treatments that only the mean values are given (Table 25).

Grain contained only about 0·006 %Na in dry matter and straw twice as much. Even giving Na but no K had little effect on %Na. Sodium offtakes were very small, at most

TABLE 24

Percentage Mg and amount of Mg removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–75

		%Mg				Uptake kg Mg ha^{-1}				% of total uptake in grain	
		Grain		Straw		Grain		Grain+straw			
Plot	Treatment	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
1	FYM+N_2PK	—	0·10	—	0·05	—	5·2	—	8·2	—	64
21	FYM+N_2	0·11	0·11	0·05	0·05	5·8	5·4	8·8	9·0	66	61
22	FYM	0·11	0·11	0·05	0·05	5·7	6·4	8·5	9·5	68	68
3	None	0·10	0·11	0·05	0·06	1·6	2·5	2·2	3·6	72	71
5	PKMg(Na)	0·11	0·12	0·06	0·08	1·7	3·2	2·5	4·8	68	67
6	N_1PKMg(Na)	0·11	0·11	0·05	0·05	3·4	5·1	4·6	7·1	76	71
7	N_2PKMg(Na)	0·10	0·10	0·04	0·05	4·4	5·5	5·9	7·8	74	71
8	N_3PKMg(Na)	0·10	0·11	0·04	0·05	4·3	5·3	6·1	7·8	72	67
9	N_4PKMg(Na)	0·10	0·10	0·05	0·05	4·8	4·7	6·8	7·2	71	66
10	N_2	0·07	0·09	0·05	0·05	2·2	4·0	3·3	5·5	67	73
11	N_2P	0·10	0·10	0·05	0·05	3·3	4·8	4·8	6·4	71	76
12	N_2PNa	0·10	0·10	0·05	0·06	4·1	5·1	5·6	7·3	74	71
13	N_2PK	0·09	0·10	0·03	0·04	4·0	5·5	5·2	7·3	77	76
14	N_2PK′Mg	0·10	0·12	0·06	0·07	4·7	6·5	6·6	9·5	72	69
15	N_3PKMg(Na)	0·10	0·11	0·04	0·05	4·7	5·4	6·2	7·6	76	72
16	N_2PKMg(Na)	0·10	0·11	0·05	0·05	4·3	5·5	5·7	7·6	76	73
17	$N_2\frac{1}{2}$[PKMg(Na)]	0·10	0·09	0·05	0·05	3·9	5·0	5·2	7·1	75	70
18	$N_2\frac{1}{2}$[PKMg(Na)]	0·10	0·10	0·05	0·05	4·1	5·6	5·5	8·0	76	70
19	Castor meal	0·10	0·11	0·06	0·06	3·7	5·1	5·2	7·3	71	70
20	N_2KMg(Na)	0·08	—	0·05	—	2·6	—	3·6	—	73	—
Mean†		0·10	0·11	0·05	0·06	3·9	5·0	5·5	7·2	72	70
SE of mean		0·004	0·003	0·003	0·003	0·24	0·06	0·42	0·32	2·2	2·5

* Cont.: Wheat grown continuously; Rotn: Wheat grown in rotation.
† Excluding plots 1 and 20.

TABLE 25

Percentage Na and amount of Na removed in winter wheat, cv. Cappelle Desprez grown on Broadbalk, 1970–75

	%Na				Uptake kg Na ha^{-1}				% of total uptake in grain	
	Grain		Straw		Grain		Grain+straw			
	Cont.*	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn	Cont.	Rotn
Mean of all plots	0·006	0·006	0·010	0·027	0·23	0·29	0·6	1·1	44	35
SE of mean	0·0004	0·0004	0·0004	0·0167	0·024	0·021	0·04	0·36	3·7	5·0

* Cont.: Wheat grown continuously; Rotn: wheat grown in rotation.

1·5 kg ha^{-1} of which about 40% was in the grain. They have changed little during the course of the experiment.

Plant nutrients in potato tubers

Data are given only for the composition in dry matter of, and total uptake by, potato tubers at harvest (Table 26). Potatoes were lifted earlier than normal farm practice (p. 17) which may possibly have affected composition and offtakes.

Differences in both composition and uptake for all nutrients between duplicate plots: 7 and 16, 8 and 15, 17 and 18 were small and not significant. Some treatment differences and their standard errors are in Appendix Table 2.

Nitrogen

Percentage N in tuber dry matter ranged from 0·96 to 1·87%. With increasing amounts of fertilizer N, %N increased from 0·96 to 1·50%. Potatoes on FYM-treated

TABLE 26

*Mean percentage and amount of N, P, K, Ca and Mg in potato tubers at harvest, Broadbalk 1970–75**

		% in dry matter					Uptake kg ha^{-1}				
Plot	Treatment	N	P	K	Ca	Mg	N	P	K	Ca	Mg
1	FYM+N_2PK	1·41	0·19	2·59	0·04	0·09	96	15·1	196	3·0	6·8
21	FYM+N_2	1·56	0·21	2·79	0·04	0·10	132	20·4	266	3·9	9·1
22	FYM	1·25	0·23	2·72	0·04	0·09	98	20·6	241	3·1	8·0
3	None	1·09	0·19	1·71	0·03	0·07	28	5·2	47	0·9	1·9
5	PKMg(Na)	0·96	0·27	2·63	0·03	0·08	32	9·6	95	1·2	3·1
6	N_1PKMg(Na)	1·09	0·24	2·57	0·03	0·09	55	14·6	154	2·0	5·3
7	N_2PKMg(Na)	1·26	0·22	2·51	0·03	0·09	86	17·7	198	2·6	7·2
8	N_3PKMg(Na)	1·43	0·20	2·49	0·04	0·09	112	18·6	221	3·2	8·3
9	N_4PKMg(Na)	1·50	0·19	2·51	0·04	0·10	126	17·5	226	3·9	8·8
10	N_2	1·64	0·17	1·25	0·03	0·05	39	4·3	31	0·8	1·3
11	N_2P	1·87	0·25	1·20	0·04	0·05	36	4·9	23	0·7	1·0
12	N_2PNa	1·76	0·24	1·18	0·04	0·05	51	7·4	38	1·2	1·7
13	N_2PK	1·44	0·23	2·64	0·04	0·08	68	12·8	144	2·1	4·6
14	N_2PK′Mg	1·34	0·21	1·54	0·03	0·07	78	12·9	94	2·0	4·4
15	N_3PKMg(Na)	1·40	0·20	2·60	0·04	0·09	103	17·0	211	2·9	7·5
16	N_2PKMg(Na)	1·23	0·20	2·49	0·03	0·09	83	15·9	190	2·6	7·0
17	$N_{2\frac{1}{2}}$[PKMg(Na)]	1·25	0·19	2·36	0·03	0·09	77	14·0	166	2·5	6·3
18	$N_{2\frac{1}{2}}$[PKMg(Na)]	1·27	0·20	2·35	0·04	0·09	80	14·0	166	2·7	6·4
19	Castor meal	1·24	0·22	1·63	0·03	0·07	59	11·2	84	1·7	3·7
Mean of all		1·37	0·21	2·20	0·04	0·08	76	13·4	147	2·3	5·4
SE of mean		0·070	0·006	0·061	0·001	0·003	6·5	2·20	20·3	0·38	0·78

* %N and amount of N, 1970–78.

soil contained only 1·25 %N, almost identical to that in the crop given N_2PKMg(Na) and significantly less than in the crop given most fertilizer N. Adding N to FYM significantly increased %N in dry matter. Treatments N_2 only and N_2P yielded 9·9 and 8·4 t ha^{-1} respectively, presumably because soil K had been depleted where P had been given to the wheat crop. The %N in the smaller crop was significantly greater than in the larger, but this difference in composition was not reflected in N offtakes which were almost identical with these two treatments. Giving K as well as N_2P significantly increased yield and decreased %N in dry matter.

Nitrogen offtakes in the harvested crop ranged from 28 kg to 132 kg ha^{-1}. The crop given PKMg(Na) but no N contained 32 kg N, very similar to the amount in wheat grain plus straw from the same plot. Increasing the fertilizer N from 48 to 192 kg ha^{-1} increased N in the crop from 55 to 126 kg ha^{-1}, but the apparent percentage recoveries of the four amounts of fertilizer N were only 48, 56, 56 and 49%, using plot 5 as standard. These apparent recoveries are a little less than those by wheat (Table 17). Most N, 132 kg ha^{-1}, was removed in the crop given FYM plus N_2 which also yielded most.

In the Rothamsted Reference experiment (Widdowson *et al.*, 1980) which is sited about 1 km from Broadbalk and on very similar soil, potatoes tended to be harvested later and yielded more than on Broadbalk. With similar treatments %N in tubers were larger, but offtakes of N were smaller on Broadbalk than on the Reference experiment. There were similar differences on %P and %K which suggests that earlier harvesting on Broadbalk did not adversely affect %N, P and K in the tubers.

Phosphorus

Percentage P in tuber dry matter ranged from 0·17 to 0·27%. It was least in crops grown on soils given N_2 but no other fertilizer during 130 years. Wheat always yielded more on the N only plot than on the unmanured plot and the extra P and K removed from the N_2 plot has so depleted soil P and K that potatoes, which are very responsive to P and K, yielded a little less with N_2 only, than when unmanured. Unmanured potatoes contained 0·19 %P in dry matter, those given N_2 0·17 %P. In the presence of P and K increasing amounts of fertilizer N consistently decreased %P in dry matter.

P offtakes in the harvested crop ranged from 4·3 to 18·6 kg P ha^{-1} where fertilizers were applied. These amounts were similar to those in wheat grown continuously and a little less than wheat grown in rotation. Like the wheat, the potatoes are removing at most only about half of the P applied as superphosphate. Offtakes in potatoes for FYM-treated soils were a little larger than from fertilizer-treated soils but were much less than the total P applied in each annual dressing of FYM.

Response to P. In 1966 bicarbonate soluble P in soils given N_2PKMg(Na) annually and the same amount of P and K in alternate years was about 88 and 48 mg kg^{-1} respectively. Since 1968 rather than applying P and K in alternate years, half the P and K dressing is applied each year. Potato yields with the half-rate P and K were 3·9 t ha^{-1} less than with the full rate, a difference which just reached significance. Both %P, 0·20% and 0·22% and P offtakes, 14·0 and 17·7 kg P ha^{-1}, with half and full rate P and K respectively were also significantly different.

Potassium

Percentage K in tuber dry matter ranged from 1·18 to 2·79%. The larger concentrations were in crops treated with FYM or FYM + N_2, 2·72 and 2·79% respectively, and these values were significantly larger than those in crops grown on fertilizer-treated soils. The lowest concentrations, 1·18 and 1·20% were in crops grown on soils long treated with N_2PNa and N_2P respectively. Obviously K offtakes in wheat over many years have depleted soil K reserves. As with P, %K in tubers grown on soils with the half-rate of P and K was significantly less than in tubers given the standard K dressing. Increasing the amount of applied fertilizer N had little effect on %K in tuber dry matter, the range being only 2·49 to 2·57%.

Potassium offtake in the harvested tubers and K balance. Offtakes ranged from 23 to 266 kg K ha^{-1}. The smallest amounts were in crops given no K, and the largest, over 220 kg, removed from fertilizer-treated soils were well in excess of the 90 kg ha^{-1} applied each year. During the period when potatoes, beans and wheat were grown in rotation 400 kg K ha^{-1} was taken off during the three years whilst only 270 kg was applied. In 1966 these soils contained reasonable reserves of exchangeable K, about 300 mg K kg^{-1}, but it is not certain how long these reserves will continue to support good yields. Subsequently, the rotation has been changed to fallow, potatoes and wheat, because stem eelworm severely decreased bean yields. Although manures, other than N, are now applied to fallowed soils and average K offtakes are likely to decrease, to about 320 kg ha^{-1} per rotation whilst wheat yields do not exceed 6 t ha^{-1}, there will still be a negative K balance which will increase if wheat yields improve. If the exchangeable K content of the soil is not to be depleted the standard K dressing will have to be increased or extra K given to the potatoes. The only other alternative would be to seek a break crop other than potatoes.

Similar problems are unlikely to occur on FYM-treated soils whilst FYM continues to supply the current large amount of K. The three-crop rotation removed about 520 kg K ha^{-1} whilst without beans and with wheat yields of about 6 t ha^{-1} the offtake is likely to be about 430 kg. However, 975 kg K ha^{-1} are applied in 3 years by the 35 t ha^{-1} FYM dressing.

Calcium

Calcium in dry matter was small, both in concentration and amount, percentages were 0·03–0·04% and offtakes ranged from 0·7 to 3·9 kg ha^{-1}.

Magnesium

Percentage Mg in tuber dry matter ranged from 0·05 to 0·10% and uptakes from 1·0 to 9·1 kg ha^{-1}; there was little difference between the largest offtakes from soils treated with fertilizer and FYM. On fertilizer-treated soils (except plot 14) 35 kg Mg ha^{-1} was applied every third year as kieserite, so the annual offtake was about three quarters of the mean annual dressing. Much more Mg, about 25 kg ha^{-1}, was applied in FYM every year and more than half remains in the soil as a residue.

Magnesium deficiency symptoms were occasionally seen in potato tops in June or July on plots which received no magnesium. When mean yields with N_2PK, and $N_2PKMg(Na)$, are compared (Table 27) there is a response to Mg of 8 or 9 t ha^{-1} for each period considered between 1968 and 1981. Averaged over the 6 years 1970–75 %Mg in dry matter was 0·083% for tubers given N_2PK and 0·089% and 0·090% in tubers given $N_2PKMg(Na)$ (plots 7 and 16 respectively). Average yields with FYM and FYM+N_2, were 36 and 42 t ha^{-1} respectively, about 4 and 10 t ha^{-1} more than with

TABLE 27

Potato yields on selected plots on Broadbalk in five periods between 1968 and 1981

Plot	Treatment	1968–69	1970–72	1973–75	1976–78	1979–81	Mean
		Yield tubers* t ha^{-1}					
7	$N_2PKMg(Na)$	33·9	32·1	36·9	27·4	30·3	32·0
13	N_2PK	24·3	22·5	27·4	19·1	21·9	22·9
14	$N_2PK'Mg$	20·1	22·1	26·6	24·4	27·4	24·4
16	$N_2PKMg(Na)$	31·6	32·2	32·9	27·2	28·7	30·5
22	FYM	36·6	40·1	39·3	32·3	32·8	36·2
21	FYM+N_2	43·8	46·7	44·0	35·6	39·8	41·9

* 1968–69, Majestic; 1970–75, King Edward; 1976–81, Pentland Crown.

$N_2PKMg(Na)$ but %Mg was 0·089 and 0·095, much the same as in tubers given $N_2PKMg(Na)$. So the effect of the Mg added in FYM was to increase yield rather than %Mg in dry matter (Table 28).

TABLE 28

Yields of, and %K and %Mg in, potato tubers grown on selected plots on Broadbalk, 1970–75 and exchangeable K and Mg in soil in 1966

Plot	Treatment	Yield tubers t ha^{-1}	% in dry matter: K	% in dry matter: Mg	Ratio %K:%Mg	Exchangeable cations, mg kg^{-1}: K	Exchangeable cations, mg kg^{-1}: Mg*	Ratio K:Mg
7	$N_2PKMg(Na)$	32	2·51	0·089	28·2	341	54	6·3
16	$N_2PKMg(Na)$	31	2·49	0·090	27·7	319	—	—
13	N_2PK	23	2·64	0·083	31·8	322	31	10·4
14	$N_2PK'Mg$	24	1·54	0·070	22·0	89	133	0·7
22	FYM	36	2·72	0·089	30·6	655	105	6·2
21	FYM+N_2	42	2·79	0·095	29·4	—	—	—

* Bolton, 1972.

Magnesium and potassium concentrations in tubers. Besides the comparison of yields with N_2PK and $N_2PKMg(Na)$, plots 13 and 7 respectively, discussed above, the effect of Mg can apparently be measured by comparing yields on plots 13 and 14. However, the latter comparison is not valid because plot 14 has received K, 90 kg ha^{-1}, only since 1968. Before 1968 plots 11, 12, 13 and 14 received N_2P, N_2PNa, N_2PK, N_2PMg respectively and the amounts of K, Na and Mg applied on the three plots were chemically equivalent. Wheat yields with N_2PNa and N_2PMg were always larger than those with N_2P, but less than those with N_2PK. Various suggestions, summarized by Johnston (1969), have been made to explain these effects. The most likely is that Na and Mg released soil K which was taken up by the plant. The amounts of K released, judged by the effects on yield, were less in the 1960s than previously, and in 1968 it was decided to apply K to the soil previously treated with N_2PMg only (plot 14).

Wheat yields responded immediately to the addition of K and have shown some benefit, compared to yields with N_2PK, from the Mg (Table 2). Potato yields were however similar, on average, with N_2PK and $N_2PK'Mg$ and were less than on soil for long given K (plot 7). Thus the large annual Mg dressing, 30 kg ha^{-1}, appeared to have no benefit. Looked at in more detail however (Table 27) yields where K was newly applied in 1968–69 (plot 14) were much less than with N_2PK (plot 13) because K was acutely deficient. Between 1970 and 1975 yields were similar on the two plots and during 1976–81 have been better with $N_2PK'Mg$ than with N_2PK but were still not as large as where K and Mg had been applied for many years (plot 7). Of considerable interest is the fact that very similar average yields with N_2PK and $N_2PK'Mg$ in 1970–75 were achieved with %Mg of 0·089 and 0·070% and %K of 2·64 and 1·54% respectively (Table 28). The much smaller %K with $N_2PK'Mg$ was to be expected, the smaller %Mg, less than on any other plot, was unexpected in view of the large Mg dressing given to that plot.

This suggests that the uptake of K and Mg may be related in some way. For 5 of the 6 plots (plot 14 excluded) yields ranged from 23 to 42 t ha^{-1} and the average ratio %K: %Mg was 29:1, range 28:1 to 32:1. On soil newly treated with K the ratio was 22:1, well outside the range; although in relation to K proportionally more Mg was taken up, the lack of K has restricted both %K and %Mg in tuber dry matter.

With $N_2PKMg(Na)$ and FYM yields were 32 and 36 t ha^{-1}, a difference of 4 t ha^{-1}. However both the ratio of %K to %Mg in the tuber dry matter and the ratio of exchangeable K to Mg in soil were very similar for both crops and soils respectively from the fertilizer and FYM-treated plots. Although yields with N_2PK were less than with $N_2PKMg(Na)$, presumably because Mg was limiting, the ratio %K to %Mg was very similar for the crops from these two treatments, and the exchangeable K to Mg ratios, 10·4 and 6·3 were not dissimilar. Where K has only been given since 1968 (plot 14) both yield and the ratio of %K to %Mg were very different from those where K has been given for many years (plot 7) and the ratio of exchangeable K to Mg in this soil was very much smaller, 0·7:1.

Plant nutrients in beans

Detailed data are given for composition and content in harvested bean grain only, both averaged over the 6 years 1970–75 (Table 29). Offtakes of N, P, K, Ca and Mg in bean grain were 79, 85, 45, 10 and 60% respectively of the total offtake in grain plus straw. Thus, most of the N and P but less than half the K were in the grain; these proportions are very similar to those for wheat. Detailed discussion of the data may be of doubtful value because yields were affected by stem eelworm.

Nitrogen

Percentage N in grain dry matter ranged from 4·37 to 5·17%. The larger values were in crops grown on soils without K fertilizer where lack of K restricted yields. On plots 5

TABLE 29

*Mean percentage and amount of P, K, Ca and Mg in bean grain at harvest, Broadbalk, 1970–75**

		% in dry matter					Uptake kg ha^{-1}				
Plot	Treatment	N	P	K	Ca	Mg	N	P	K	Ca	Mg
1	FYM+N_2PK	4·49	0·58	1·28	0·12	0·12	90	12·4	27	2·3	2·6
21	FYM+N_2	4·72	0·62	1·35	0·11	0·12	112	15·6	34	2·5	3·1
22	FYM	4·63	0·60	1·34	0·10	0·12	118	15·2	33	2·4	3·0
3	None	5·03	0·46	1·12	0·12	0·11	79	7·4	18	1·9	1·8
5	PKMg(Na)	4·64	0·56	1·29	0·12	0·12	111	12·6	29	2·5	2·8
6	N_1PKMg(Na)	4·37	0·59	1·32	0·10	0·12	102	13·4	29	2·3	2·8
7	N_2PKMg(Na)	4·40	0·61	1·33	0·10	0·13	103	13·9	30	2·3	2·9
8	N_3PKMg(Na)	4·50	0·62	1·34	0·11	0·13	115	15·6	33	2·6	3·2
9	N_4PKMg(Na)	4·60	0·63	1·34	0·12	0·13	116	16·3	34	2·7	3·3
10	N_2	5·11	0·41	1·00	0·13	0·11	67	6·0	15	1·7	1·6
11	N_2P	5·16	0·58	1·05	0·16	0·12	35	4·6	8	1·2	1·0
12	N_2PNa	5·17	0·62	1·03	0·13	0·13	36	5·1	9	1·0	1·0
13	N_2PK	4·49	0·61	1·31	0·12	0·12	99	13·1	27	2·6	2·6
14	N_2PK′Mg	4·79	0·60	1·22	0·12	0·13	98	12·4	25	2·4	2·6
15	N_3PKMg(Na)	4·38	0·60	1·33	0·11	0·12	107	14·1	30	2·3	2·8
16	N_2PKMg(Na)	4·67	0·62	1·35	0·11	0·13	109	15·4	33	2·4	3·0
17	$N_{2\frac{1}{2}}$[PKMg(Na)]	4·71	0·61	1·34	0·11	0·12	109	15·2	33	2·5	3·0
18	$N_{2\frac{1}{2}}$[PKMg(Na)]	4·59	0·61	1·32	0·10	0·12	111	15·9	34	2·5	3·2
19	Castor meal	4·78	0·58	1·22	0·12	0·12	73	9·9	21	1·8	2·0
Mean of all		4·17	0·58	1·26	0·12	0·12	94	12·3	27	2·2	2·5
SE of mean		0·117	0·024	0·030	0·016	0·002	15·2	2·45	4·9	0·39	0·47

* %N and N amount 1970–78.

to 9 with increasing amounts of fertilizer N the first N increment decreased %N in grain which then increased with each additional increment. Bean grain therefore responded to fertilizer N as wheat grain did. Offtakes of N in grain ranged from 35 to 118 kg ha^{-1}; the smallest amounts were on soils given N_2P and N_2PNa. With PKMg(Na) both wheat and potatoes contained only about 30 kg N ha^{-1} at harvest but the beans responded well to the P and K and contained 137 kg N ha^{-1}, in grain and straw. The extra N compared to that in wheat came presumably from symbiotic fixation.

Phosphorus

Percentage P was quite uniform, 0·56 to 0·63% if plots without added P are excluded. Grain from these two plots, none and N_2 only, contained 0·46 and 0·41 %P respectively, but it is not certain that these are critical concentrations for %P in grain because other plots yielded less whilst having larger %P in grain. The mean value, 0·58 %P in grain dry matter is larger than that in wheat grain, 0·34%, but bean yields were small and in a larger crop the P could well have been diluted to give a lower concentration. The largest amount of P removed, 16·3 kg ha^{-1}, was just less than half the amount applied in superphosphate.

Potassium

Crops grown on soils with a long history of K manuring contained 1·31 to 1·35%K in grain dry matter, almost three times the amount in wheat grain. Where K had not been given for many years the concentration was lower, 1·00 to 1·12%K. Grain removed 30–35 kg K ha^{-1} from fully manured plots whilst the straw removed rather more.

Calcium and Magnesium

The concentrations of both Ca and Mg in grain were about 0·12% on average and were affected little by treatment. Thus %Ca in bean grain was about twice that in wheat grain but both grains contained the same %Mg. Total offtakes in grain plus straw of both Ca and Mg were small, about 22 kg Ca and 4·2 kg Mg on average.

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References

BENZIAN, B. & LANE, P. (1981) Interrelationship between nitrogen concentration in grain, grain yield and added fertiliser nitrogen in wheat experiments of south-east England. *Journal of the Science of Food and Agriculture* **32**, 35–43.

BOLTON, J. (1972) Changes in magnesium and calcium in soils of the Broadbalk Wheat experiment at Rothamsted from 1865 to 1966. *Journal of Agricultural Science, Cambridge*, **79**, 217–223.

BOYD, D. A., YUEN, L. T. K. & NEEDHAM, P. (1976) Nitrogen requirements for cereals. *Journal of Agricultural Science, Cambridge* **87**, 149–162.

JENKINSON, D. S., JOHNSTON, A. E., POWLSON, D. S., PRUDEN, G. & WILLIAMS, A. H. (1981) Recovery of ^{15}N labelled fertilizer by winter wheat on Broadbalk. *Rothamsted Experimental Station, Report for 1980*, Part 1, 247–248.

JOHNSTON, A. E. (1969) The Broadbalk Wheat experiment. The plant nutrients in crops grown on Broadbalk. *Rothamsted Experimental Station, Report for 1968*, Part 2, 50–62.

JOHNSTON, A. E. & MATTINGLY, G. E. G. (1976) Experiments on the continuous growth of arable crops at Rothamsted and Woburn Experimental Stations. The effects of treatments on crop yields and soil analyses and recent modifications in purpose and design. *Annales agronomiques* **27**, 927–956.

ROTHAMSTED (1969) The Broadbalk Wheat Experiment. *Rothamsted Experimental Station, Report for 1968*, Part 2, 215 pp.

ROTHAMSTED EXPERIMENTAL STATION (1978) *Details of the Classical and Long-term experiments, 1968–73*, 77 pp.

RUSSELL, E. J. & WATSON, D. J. (1940) *The Rothamsted field experiments on the growth of wheat.* Technical Communication of the Imperial Bureau of Soil Science, No. 40, 163 pp.

WIDDOWSON, F. V., JOHNSTON, A. E. & PENNY, A. (1980) Multifactorial experimentation on continuous winter wheat grown in sandy clay soil at Saxmundham, Suffolk. *Journal of Agricultural Science, Cambridge* **94**, 155–170.

WIDDOWSON, F. V., PENNY, A. & BIRD, E. (1980) Results from the Rothamsted Reference experiment. II. Yields of the crops and recoveries of N, P and K from manures and soil, 1971–75. *Rothamsted Experimental Station, Report for 1979*, Part 2, 63–76.

APPENDIX TABLE 1
APPENDIX TABLE 2

see pages 42–44

APPENDIX TABLE 1

*Selected treatment differences and their standard errors for nutrient concentrations and amounts in wheat grain and straw, Broadbalk, 1970–75**

Plots / Treatment differences		21–22 (FYM+N_2)–(FYM)		9–8 (N_4M)–(N_3M)†		22–9 (FYM)–(N_4M)		11–10 (N_2P)–(N_2)		13–11 (N_2PK)–(N_2P)		7–17/18 (N_2M)–($N_2\frac{1}{2}$M)	
		Diff.	SE	Diff.	SE	Diff.	SE	Diff.	SE	Diff.	SE	Diff.	SE
Wheat grain, % in dry matter													
N	Cont.	0·25	0·071	0·09	0·043	−0·18	0·071	−0·07	0·050	−0·11	0·085	−0·03	0·060
	Rotn	0·25	0·041	0·10	0·037	−0·12	0·039	−0·16	0·031	0·01	0·046	0·03	0·033
P	Cont.	−0·01	0·013	0·01	0·011	0·04	0·009	0·10	0·008	−0·01	0·014	0·03	0·013
	Rotn	0·00	0·019	−0·03	0·016	0·04	0·016	0·07	0·004	0·01	0·015	0·01	0·008
K	Cont.	0·02	0·023	0·00	0·007	−0·01	0·012	0·03	0·015	−0·01	0·016	0·01	0·013
	Rotn	0·02	0·029	−0·03	0·019	0·02	0·027	0·04	0·007	0·00	0·016	0·00	0·010
Ca	Cont.	0·01	0·001	0·00	0·001	−0·01	0·001	0·01	0·003	−0·03	0·004	0·00	0·002
	Rotn	0·01	0·003	0·00	0·002	−0·01	0·002	0·01	0·002	−0·02	0·002	0·00	0·001
Mg	Cont.	0·001	0·0015	0·002	0·0024	0·012	0·0030	0·029	0·0117	−0·014	0·0052	0·005	0·0037
	Rotn	−0·004	0·0059	−0·009	0·0053	0·011	0·0043	0·013	0·0021	0·000	0·0057	0·007	0·0041
Amount, kg ha^{-1}													
N	Cont.	9·5	8·08	10·5	2·91	−1·4	6·70	−2·6	5·16	21·0	5·00	2·6	2·35
	Rotn	2·2	6·79	2·4	1·41	13·2	7·31	−2·0	2·91	14·2	4·32	−1·3	1·36
P	Cont.	−0·3	1·62	1·9	0·70	2·7	1·68	2·7	0·51	3·7	0·73	1·8	0·44
	Rotn	−2·5	1·51	−1·9	0·50	5·6	1·01	3·9	0·34	2·8	0·70	0·1	0·75
K	Cont.	1·3	1·68	2·0	0·72	0·6	1·78	0·8	0·80	5·2	0·98	1·3	0·68
	Rotn	−2·2	1·76	−2·3	0·62	5·7	1·63	2·6	0·44	2·8	0·99	−0·8	0·87
Ca	Cont.	0·5	0·19	0·2	0·06	−0·2	0·20	0·4	0·10	−0·3	0·10	0·1	0·10
	Rotn	0·2	0·24	0·0	0·11	0·0	0·21	0·6	0·05	−0·6	0·07	0·0	0·06
Mg	Cont.	0·1	0·48	0·5	0·18	0·9	0·50	1·0	0·55	0·7	0·39	0·4	0·16
	Rotn	−0·9	0·42	−0·6	0·16	1·6	0·21	0·8	0·10	0·7	0·32	0·2	0·27

Wheat straw													
% in dry matter													
N	Cont.	0·26	0·039	0·05	0·024	−0·21	0·019	0·05	0·026	−0·14	0·025	0·06	0·019
	Rotn	0·24	0·048	0·11	0·029	−0·21	0·049	−0·04	0·041	0·00	0·034	−0·01	0·030
P	Cont.	−0·01	0·012	0·00	0·003	0·03	0·007	0·04	0·009	−0·02	0·006	0·03	0·002
	Rotn	0·00	0·013	0·00	0·005	0·02	0·005	0·02	0·016	0·00	0·007	0·02	0·004
K	Cont.	0·32	0·088	0·10	0·066	0·25	0·116	−0·17	0·033	0·55	0·077	0·19	0·043
	Rotn	0·35	0·111	0·19	0·070	0·19	0·128	0·05	0·105	0·50	0·108	0·15	0·044
Ca	Cont.	0·07	0·014	0·01	0·012	−0·08	0·024	0·02	0·026	−0·13	0·025	0·01	0·011
	Rotn	0·07	0·015	0·04	0·011	−0·10	0·015	−0·01	0·034	−0·08	0·022	−0·03	0·015
Mg	Cont.	0·000	0·0032	0·000	0·0011	0·005	0·0030	0·005	0·0051	−0·019	0·0060	−0·004	0·0019
	Rotn	0·002	0·0022	0·002	0·0013	−0·001	0·0035	−0·001	0·0040	−0·013	0·0038	−0·001	0·0034
Amount, kg ha^{-1}													
N	Cont.	17·8	3·02	3·9	1·18	−3·6	1·62	2·4	1·13	1·8	1·23	3·6	1·39
	Rotn	16·9	3·62	4·4	1·86	−1·7	2·12	0·8	1·88	6·6	0·70	−0·1	1·98
P	Cont.	−0·1	0·72	0·2	0·20	2·8	0·77	1·0	0·23	0·2	0·22	1·3	0·24
	Rotn	0·6	0·76	−0·4	0·41	2·6	0·88	0·9	0·61	1·0	0·10	0·9	0·27
K	Cont.	24·8	11·76	8·7	3·99	29·7	12·91	−2·5	0·70	21·7	3·87	12·9	2·86
	Rotn	27·7	11·41	6·5	3·63	35·6	16·43	3·0	3·11	32·0	7·82	9·0	3·63
Ca	Cont.	5·1	2·11	1·7	0·97	0·1	1·86	2·0	1·63	−0·7	1·78	2·3	0·48
	Rotn	5·1	1·20	0·6	0·61	−0·3	1·53	0·7	1·48	2·1	0·69	−1·2	0·50
Mg	Cont.	0·2	0·26	0·2	0·11	0·8	0·31	0·3	0·25	−0·2	0·31	0·2	0·12
	Rotn	0·4	0·15	−0·1	0·10	0·7	0·21	0·1	0·20	0·2	0·18	0·0	0·17

* 1970–78 for %N and amounts of N in grain and straw.
† M is used here as an abbreviation for PKMg(Na).

APPENDIX TABLE 2

*Selected treatment differences and their standard errors for nutrient concentrations and amounts in potato tubers and bean grain, Broadbalk, 1970–75**

Plots / Treatment differences	21–22 (FYM+N_2)–(FYM) Diff.	SE	9–8 (N_4M)–(N_3M)† Diff.	SE	22–9 (FYM)(N_4M) Diff.	SE	11–10 (N_2P)–(N_2) Diff.	SE	13–11 (N_2PK)–(N_2P) Diff.	SE	7–17/18 (N_2M)–($N_2\frac{1}{2}$M) Diff.	SE
Potato tubers												
% in dry matter												
N	0·31	0·039	0·07	0·046	−0·25	0·053	0·24	0·054	−0·43	0·093	0·00	0·023
P	−0·02	0·003	−0·01	0·005	0·05	0·009	0·08	0·014	−0·02	0·019	0·03	0·004
K	0·07	0·032	0·02	0·043	0·21	0·038	−0·06	0·041	1·45	0·044	0·15	0·006
Ca	0·00	0·002	0·01	0·002	−0·01	0·002	0·01	0·004	0·00	0·003	0·00	0·002
Mg	0·01	0·001	0·00	0·002	−0·01	0·001	0·00	0·001	0·03	0·005	0·00	0·002
Amount, kg ha^{-1}												
N	33·8	6·64	13·8	4·34	−27·7	9·07	−2·9	1·93	32·1	5·41	7·0	4·08
P	−0·2	0·94	−1·1	1·07	3·1	1·14	0·6	0·33	7·9	1·88	3·7	1·50
K	24·6	11·84	5·1	9·76	14·7	13·12	−8·1	2·15	121·3	21·85	31·8	15·40
Ca	0·8	0·40	0·7	0·17	−0·7	0·32	−0·1	0·05	1·3	0·33	0·1	0·11
Mg	1·1	0·41	0·5	0·23	−0·8	0·41	−0·3	0·07	3·6	0·67	0·8	0·59
Bean grain												
% in dry matter												
N	0·08	0·092	0·10	0·106	0·04	0·073	0·05	0·090	−0·67	0·149	−0·25	0·141
P	0·01	0·010	0·00	0·018	−0·02	0·018	0·17	0·036	0·03	0·023	0·00	0·015
K	0·01	0·021	−0·01	0·024	0·01	0·015	0·05	0·017	0·26	0·038	0·00	0·017
Ca	0·00	0·003	0·00	0·005	−0·01	0·009	0·04	0·031	−0·04	0·034	0·00	0·004
Mg	0·00	0·001	0·00	0·001	−0·01	0·002	0·02	0·004	0·00	0·030	0·00	0·001
Amount kg ha^{-1}												
N	−6·2	6·23	1·0	6·16	2·7	7·63	−31·6	8·83	63·1	12·80	−7·7	9·16
P	0·4	0·78	0·6	0·75	−1·1	1·18	−1·3	0·51	8·5	1·81	−1·6	1·06
K	0·8	1·80	1·1	1·32	−1·4	2·09	−6·7	2·15	19·3	4·08	−3·7	1·92
Ca	0·1	0·11	0·1	0·10	−0·3	0·10	−0·6	0·37	1·4	0·65	−0·3	0·12
Mg	0·1	0·15	0·1	0·12	−0·3	0·18	−0·6	0·21	1·6	0·35	−0·3	0·11

* 1970–78 for %N and amounts of N in tubers and grain.
† M is used here as an abbreviation of PKMg(Na).