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Changes in the Nutrient Reserves of the Rothamsted and Woburn Reference Experiment Soils

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This paper summarises the analyses of soils and crops from the Rothamsted Reference experiment for 1956–70 and the Woburn Reference experiment for 1960–69. Changes in nutrients in the soils are related to the fertilisers and manures applied and to nutrients removed by crops and comparisons between the two experiments are discussed.

The Rothamsted experiment in microplots (each 7 ft × 8 ft), 0·00128 acre (0·00052 ha) was started on clay loam over Clay-with-flints (Batcombe Series) on Great Field IV in 1956. It was sited on very old permanent grassland from which the turf was removed before ploughing. Treatments applied to plots of the original permanent grass started a year later. Details of the site, the experimental design, and the yields of crops grown during 1956–60 were published by Widdowson, Penny and Cooke (1963) and for the period 1961–65 by Widdowson and Penny (1968). Nutrient uptakes by the crops were reported by Williams, Cooke and Widdowson (1963) for the first rotation of arable crops (1956–60), by Widdowson and Penny (1968) for the period 1961–65, and by Widdowson and Penny (1973) for the last rotation.

The Woburn experiment in microplots (each 7 ft × 9 ft), 0·00145 acre (0·00059 ha) was started in 1960 in Stackyard Field (Series C) on a sandy silty loam overlying Lower Greensand (Cottenham Series); the site had grown arable crops for many years. Details of the site, experimental design, and crop yields during 1960–64 were published by Widdowson and Penny (1967a); the nutrients removed were reported by Widdowson, Penny and Williams (1967b). Yields and nutrient uptakes during the second rotation (1964–69) were reported by Widdowson and Penny (1972) when both yields and nutrient uptakes for the first two rotations were compared.

Chemical analyses of the soils. The methods used to analyse the soils from both experiments are listed in the Appendix.

The Rothamsted experiment

The compositions of the soils from the arable section of the Rothamsted Reference experiment are in Table 1, those for the permanent grass in Table 2. Table 3 summarises (as means of the blocks of the experiment) the results of the first soil sampling and indicates that, apart from the larger exchangeable K in block B and the smaller exchangeable Mg in the permanent grass (block F), the site was relatively uniform in nutrients. The hand cultivations given in this experiment did not, in the first year, penetrate a flinty pan which occurred about 15 cm deep. When the second soil samples were taken in 1960 this pan had been broken, consequently analyses, especially those for total P, were affected by dilution of the topsoil by the lower subsoil layer which contained less total P. The soil was initially acid (pH 5·7, Table 3); soils of the arable section received 30 cwt/acre of hydrated lime in 1956. They were re-limed in 1965 and again in 1966 using equivalent lime as calcium carbonate. The permanent grass was limed for the first time in 1965 after soil sampling, using the same rate as for the arable plots.

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TABLE 1 *Compositions of soils of Rothamsted Reference Plots (arable rotation) 1956–70*

(Values are averages for five plots)

		Treatment											
		O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
pH (in water)	1956	5·6	5·9	5·7	5·6	5·8	5·6	5·8	5·7	5·6	5·8	5·7	5·6
	1961	6·4	6·7	6·6	6·5	6·6	6·6	6·4	6·5	6·6	6·6	6·5	6·5
	1965	6·2	6·4	6·4	6·4	6·3	6·4	6·1	6·2	6·2	6·4	6·2	6·4
	1970	6·8	6·9	7·0	7·0	6·9	6·9	6·6	6·8	6·8	7·0	6·9	6·9
Organic carbon % (Walkley–Black values, uncorrected)	1956	2·52	2·46	2·52	2·46	2·30	2·34	2·52	2·52	2·21	2·29	2·29	2·38
	1961	1·70	1·79	1·66	1·79	1·78	1·61	1·93	1·71	1·77	2·00	1·96	2·02
	1965	1·76	1·79	1·82	1·78	1·74	1·81	1·85	1·90	1·90	2·24	2·31	2·35
	1970	1·56	1·60	1·60	1·64	1·59	1·68	1·69	1·80	1·77	2·14	2·30	2·32
Total N %	1956	0·28	0·26	0·27	0·28	0·26	0·27	0·26	0·28	0·27	0·25	0·27	0·26
	1961	0·20	0·21	0·20	0·21	0·20	0·21	0·18	0·21	0·20	0·20	0·23	0·20
	1965	0·19	0·18	0·20	0·21	0·20	0·21	0·21	0·21	0·20	0·24	0·25	0·22
	1970	0·22	0·23	0·23	0·23	0·23	0·23	0·23	0·25	0·25	0·28	0·29	0·30
Total P %	1956	0·078	0·077	0·076	0·082	0·079	0·078	0·078	0·080	0·080	0·080	0·082	0·078
	1961	0·071	0·069	0·075	0·076	0·069	0·069	0·075	0·074	0·073	0·078	0·079	0·078
	1965	0·074	0·077	0·092	0·090	0·073	0·077	0·083	0·083	0·083	0·082	0·096	0·089
	1970	0·071	0·070	0·087	0·088	0·071	0·070	0·085	0·086	0·084	0·080	0·099	0·096
P soluble in 0·5*M* $NaHCO_3$, ppm	1956	11·4	11·0	10·8	11·2	10·2	10·8	10·8	10·8	10·0	10·0	11·4	11·0
	1961	6·8	7·3	11·7	12·1	6·5	6·6	11·2	10·6	10·2	8·8	15·8	12·6
	1965	5·8	6·1	19·4	18·3	6·1	7·2	16·6	13·2	13·7	10·2	22·9	22·2
	1970	5·0	6·1	20·5	22·5	4·8	5·1	16·3	16·8	15·8	12·7	30·1	27·6
P in equilibrium in 0·01*M* $CaCl_2$ solution, μM/litre	1956	2·0	1·7	1·9	1·9	1·7	1·7	1·9	1·9	1·7	1·5	2·0	1·8
	1961	0·5	0·5	0·8	0·9	0·5	0·5	1·0	0·8	0·8	0·9	1·5	1·2
	1965	0·6	1·2	2·1	1·6	9·8	1·1	1·6	1·3	1·3	1·3	2·6	3·0
	1970	0·4	0·4	1·6	1·4	0·9	0·5	1·5	1·4	1·2	1·2	3·9	3·5
Ca exchangeable, ppm	1956	2136	2401	2133	2325	2261	2184	2381	2308	2261	2216	2164	2140
	1961	2829	3190	3086	3154	2889	2966	2891	3090	3880	3138	3972	3062
	1965	3243	3519	3387	3367	3126	3263	3078	3784	3539	3467	3326	3519
	1970	3213	3438	3516	3577	2861	3087	2933	3387	3459	3487	3381	3439
K soluble in 0·01*M* $CaCl_2$ solution, ppm	1956	3·6	3·6	3·5	3·7	3·4	3·5	3·5	3·6	3·8	3·5	3·8	3·6
	1961	2·6	2·3	2·4	2·4	4·3	3·8	3·6	3·2	3·2	6·5	8·6	7·3
	1965	2·6	2·8	2·6	2·5	9·8	10·1	7·0	4·7	5·1	8·9	15·8	14·4
	1970	1·6	1·7	1·6	1·2	21·5	20·2	18·3	13·4	17·5	15·2	37·3	35·4
K exchangeable, ppm	1956	83	57	59	63	65	52	67	59	69	61	70	72
	1961	63	58	57	57	88	82	75	64	76	111	141	121
	1965	52	64	61	50	144	172	122	92	77	133	282	273
	1970	63	66	68	65	318	317	286	231	232	266	543	483
Mg exchangeable, ppm	1956	137	140	140	141	135	130	138	147	136	151	132	137
	1961	105	104	103	102	101	94	97	95	98	121	107	104
	1965	93	88	84	81	77	72	69	64	62	114	89	85
	1970	94	86	87	84	76	67	70	69	71	126	96	92

TABLE 2

Compositions of soils of Rothamsted Reference Plots (permanent grass) 1957–70

(Values are for individual plots)

		Treatment											
		O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
pH (in water)	1957	5·9	6·1	5·5	5·6	5·8	5·9	5·9	5·5	5·7	5·5	5·6	6·0
	1961	5·4	5·3	5·1	5·4	5·2	5·6	5·3	5·4	5·5	5·5	5·5	5·5
	1965	5·4	5·4	5·1	5·5	5·1	5·4	5·1	5·2	5·7	5·4	5·8	5·8
	1970	6·0	6·4	5·9	6·3	5·9	6·6	5·8	6·3	6·8	6·4	7·0	7·0
Organic carbon % (Walkley–Black values, uncorrected)	1957	2·66	2·42	2·24	2·36	2·48	2·60	2·48	2·24	2·12	2·36	2·42	2·36
	1961	1·85	1·79	2·00	2·06	2·00	1·94	2·15	1·88	1·94	2·03	2·53	2·12
	1965	2·32	2·70	2·15	2·28	2·48	2·75	2·63	2·42	2·78	2·92	3·53	3·24
	1970	2·15	2·44	2·10	2·57	2·31	2·45	2·30	2·80	2·53	2·89	3·86	3·61
Total N %	1957	0·28	0·24	0·23	0·22	0·24	0·27	0·26	0·23	0·22	0·24	0·23	0·24
	1961	0·23	0·18	0·23	0·21	0·23	0·24	0·23	0·19	0·25	0·21	0·26	0·26
	1965	0·25	0·26	0·23	0·26	0·24	0·29	0·27	0·26	0·28	0·32	0·35	0·35
	1970	0·25	0·30	0·23	0·30	0·25	0·28	0·27	0·29	0·29	0·37	0·45	0·43
Total P %	1957	0·078	0·081	0·080	0·074	0·075	0·078	0·084	0·079	0·076	0·080	0·079	0·075
	1961	0·071	0·066	0·071	0·071	0·069	0·080	0·082	0·069	0·073	0·075	0·082	0·075
	1965	0·077	0·068	0·082	0·082	0·072	0·075	0·098	0·079	0·074	0·082	0·104	0·104
	1970	0·069	0·064	0·092	0·075	0·068	0·072	0·106	0·082	0·075	0·089	0·120	0·105
P soluble in 0·5M $NaHCO_3$, ppm	1957	13·6	10·8	9·6	5·6	9·6	11·4	14·2	9·6	7·4	4·6	6·2	8·0
	1961	9·6	8·6	13·2	10·8	9·6	9·2	16·0	9·6	10·2	11·4	15·4	16·0
	1965	13·2	9·2	30·8	16·0	15·4	11·4	45·6	16·0	15·4	20·6	34·2	34·2
	1970	8·6	5·0	26·6	15·0	8·6	5·0	36·8	14·0	10·8	18·0	49·0	46·0
P in quilibrium in 0·01M $CaCl_2$ solution, μM/litre	1957	4·3	1·5	1·4	1·7	1·9	3·2	3·4	1·5	1·5	1·6	2·0	1·8
	1961	1·7	1·0	1·6	1·4	1·5	2·0	2·6	1·7	2·6	2·2	3·9	4·5
	1965	2·6	1·7	5·4	2·2	1·5	2·1	9·8	2·5	3·6	7·0	13·7	13·5
	1970	2·3	1·9	6·9	4·8	1·7	1·8	10·6	5·0	2·7	9·7	21·0	18·1
Ca exchangeable, ppm	1957	2445	2285	1824	1984	2144	2285	2445	1824	1824	1824	1944	2285
	1961	1663	1503	1343	1824	1443	1984	1663	1663	1904	1663	1824	1824
	1965	1603	1764	1283	2084	1042	1824	1283	1764	2224	1924	2886	2645
	1970	2224	3026	2305	3287	1703	3006	2064	3046	3627	2926	4088	3627
K soluble in 0·01M $CaCl_2$ solution, ppm	1957	3·1	2·6	2·9	3·1	2·4	2·9	3·1	2·7	2·3	3·0	3·5	2·5
	1961	3·2	3·0	3·7	3·2	4·8	3·2	4·1	3·7	3·0	11·8	14·4	12·0
	1965	5·1	4·4	5·5	4·3	43·0	15·5	30·5	13·0	6·3	23·0	53·0	42·0
	1970	2·3	1·9	6·9	4·8	1·7	1·8	10·6	5·0	2·7	9·7	21·0	18·1
K exchangeable, ppm	1957	55	45	50	43	48	50	53	53	65	45	63	58
	1961	78	55	45	78	93	65	68	55	65	143	145	140
	1965	55	75	83	93	418	220	393	193	120	303	618	518
	1970	67	59	74	74	516	149	387	129	82	411	856	716
Mg exchangeable, ppm	1957	99	66	79	88	74	84	111	71	84	62	99	89
	1961	78	61	68	92	80	75	84	68	56	114	142	92
	1965	78	40	46	47	53	60	56	43	41	154	173	105
	1970	56	27	45	26	43	38	39	29	24	172	153	123

TABLE 3

Average value of soil properties in blocks of the Rothamsted Reference Plots

	Block*						
	A	B	C	D	E	F	Mean
pH (in water)	5·4	5·7	6·0	5·6	5·8	5·7	5·7
Nitrogen %	0·27	0·25	0·26	0·27	0·28	0·24	0·26
Organic carbon %	2·39	2·25	2·45	2·40	2·50	2·39	2·40
Total P %	0·081	0·075	0·081	0·078	0·080	0·078	0·079
$NaHCO_3$-soluble P, ppm	10·5	11·4	10·4	9·4	12·3	9·2	10·5
Exchangeable Ca, ppm	1790	1950	2620	2250	2600	2090	2220
Exchangeable K, ppm	58	78	60	65	62	52	63
Exchangeable Mg, ppm	135	147	138	135	137	84	129
Exchangeable Na, ppm	38	40	55	54	48	35	45

* Blocks A–E, the arable section in plot order sampled 1956, Block F permanent grass sampled 1957

Composition of the soils

Total nitrogen in the arable soils, initially about 0·25% N, declined steadily during the 15 years on all treatments except those receiving FYM, where small increases occurred. Soils under permanent grass had similar % total N in 1957 to the arable soils; these initial amounts were maintained and in some plots increased by applying fertiliser only. Soil N was increased by the annual dressing of 15 tons/acre FYM given alone, or with NPK fertiliser; gains under grass from FYM were much greater than gains on the arable section which received less manure. After 15 years, total N in soil under grass on FYM-treated plots was 0·45% N—having been nearly doubled.

Organic carbon in the arable soils, initially about 2·4%, diminished in the fertiliser-treated plots and was just maintained when FYM was given. It increased where NPK fertiliser was given to permanent grass and more when FYM was also applied.

Total phosphorus in the soil was related to the balance between P applied by fertilisers and FYM, and that removed by crops; the largest gains were from applying FYM and fertiliser together. (As mentioned above, total P found in surface soil in 1956 was greater than in 1961 because the latter samples contained more subsoil.) Changes between 1961 and 1970 were more closely related to treatments, but were smaller in the arable section than on the permanent grass plots where FYM and NPK fertiliser increased total P by 50%.

Soluble phosphorus. P soluble in 0·5*M* sodium bicarbonate solution was increased where the P applied exceeded that removed by crops. Where poor crops were grown because N and K were not given, soluble P increased two or three times; the gain was only 50% when P and K were both applied, but where N and K fertiliser (but no phosphate) was applied, soluble P decreased by 50%. FYM applied with NPK fertiliser increased bicarbonate-soluble P three times in the arable soils and five to eight times in soils under permanent grass. The amounts of P in equilibrium in 0·01*M* $CaCl_2$ solutions changed similarly to the bicarbonate-soluble P in soils under permanent grass; the relationship between the results for the two methods of extracting soluble P was closer for soils under grass than for the arable rotation.

Exchangeable calcium was increased on the arable section as the result of adequate liming. On the permanent grass it had diminished by 1965. By 1970 both exchangeable calcium and pH were increased in soil of the grass plots by lime applied after sampling the soils in 1965.

Exchangeable potassium was initially small (about 60 ppm) in 1956; amounts increased where K fertiliser was applied, when FYM was also given, increases were still larger. There were seven-fold increases in exchangeable K in soils of the arable section when both FYM and NPK fertilisers were applied; these treatments caused much larger increases in soil under permanent grass.

Potassium soluble in 0·01*M* $CaCl_2$ solution changed similarly to exchangeable K except where both manure and fertiliser were applied, when they were less. On the permanent grass in 1970 it decreased.

Exchangeable magnesium was larger in soils of the arable section than in the permanent grass soils when the experiment started; it decreased with all treatments, except where permanent grass received FYM. This decrease was most where fertilisers supplied the largest amount of N, these treatments nearly halved exchangeable Mg in the arable soils and decreased it even more in the permanent grass soils. Dressings of 4 cwt/acre $MgSO_4$ were given annually after 1968 to the arable treatments after Mg deficiency had been diagnosed in potatoes. Although this increased exchangeable Mg slightly it did not influence yields, Widdowson and Penny (1973).

Exchangeable sodium (Table 3) varied more between the years than between treatments. For example, it was about 45 ppm in the soils in 1956 and 1961, and about 20 ppm in 1965 and 1970.

At Rothamsted the compositions of the soils of the arable rotation are still influenced by the very long period under permanent grass before the experiment began. Even where only NPK fertilisers have been given the soils still have 1·8% C. An interesting comparison is given by permanent grass of similar age on Highfield where 12 years of arable treatments diminished organic carbon from 2·4% to 1·7%. Fallowing that soil for two years after ploughing permanent grass lowered the organic carbon to 1·6% and fallowing for 11 years to 1·2%. The mechanical composition of the Rothamsted soil influences the retention of organic matter. It has about 15% stones, 56% of coarse particles (6 mm–0·02 mm) of which more than half are in the range 0·02–0·05 mm, 25% silt (0·02–0·002 mm), and 19% clay (<0·002 mm). Crops root deeply in this soil and are less

TABLE 4

Estimates of annual changes, caused by treatments, in nutrients in the soils of the arable rotation of Rothamsted Reference Plots 1956–70

Treatment	N (lb/acre)	P (lb/acre)	K (lb/acre)
None	−69	−8	−36
N_1	−19	−8	−41
P	−73	+13	−44
N_1P	−18	+13	−39
K	−88	−10	+59
N_1K	−45	−10	+52
PK	−107	+10	+40
N_1PK	−64	+7	+26
N_2PK	−21	+7	+16
D	+15	+12	+55
DN_1PK	+49	+32	+145
DN_2PK	+92	+31	+130

FIGS. 1–4. Soil analyses and nutrient balances for P and K in the Rothamsted Reference experiment.

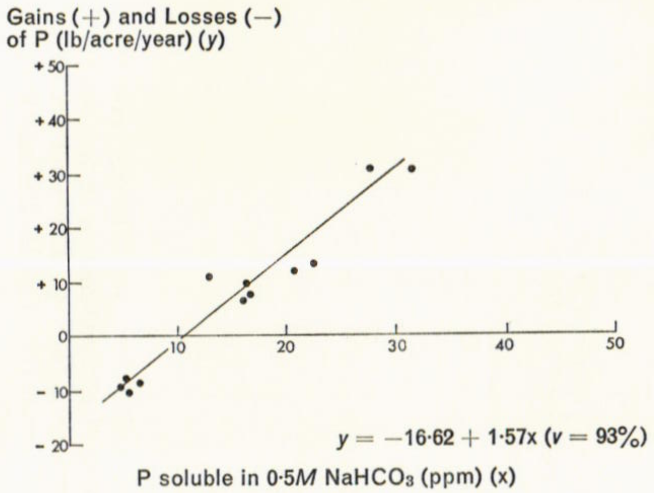


FIG. 1. Arable rotation (1956–70).

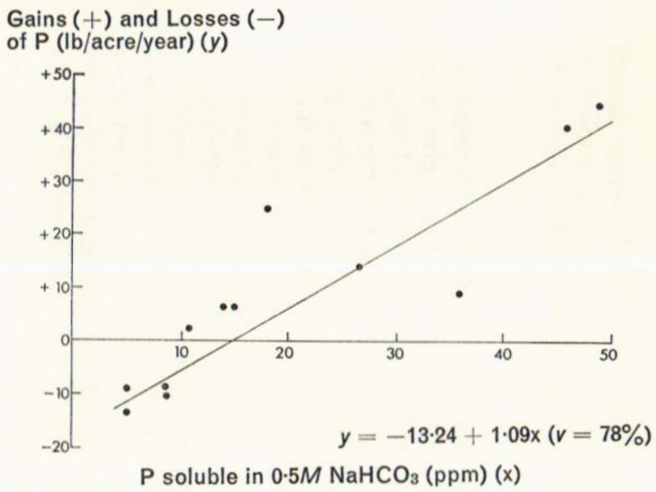


FIG. 3. Permanent grass (1957–70).

Relationships between losses and gains of phosphorus and soil P, soluble in sodium bicarbonate solution.

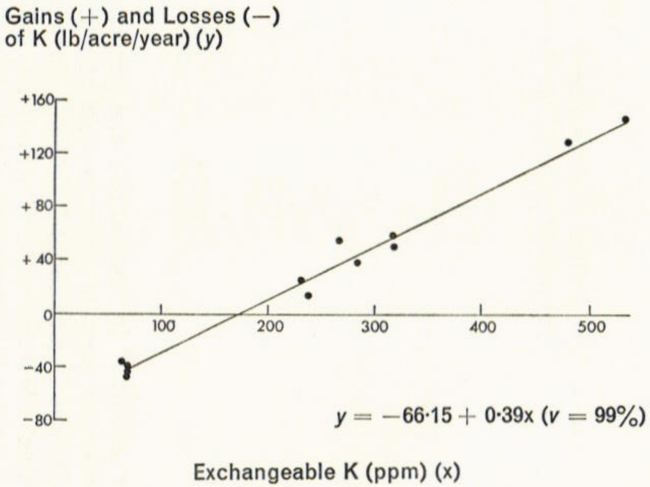


FIG. 2. Arable rotation (1956–70).

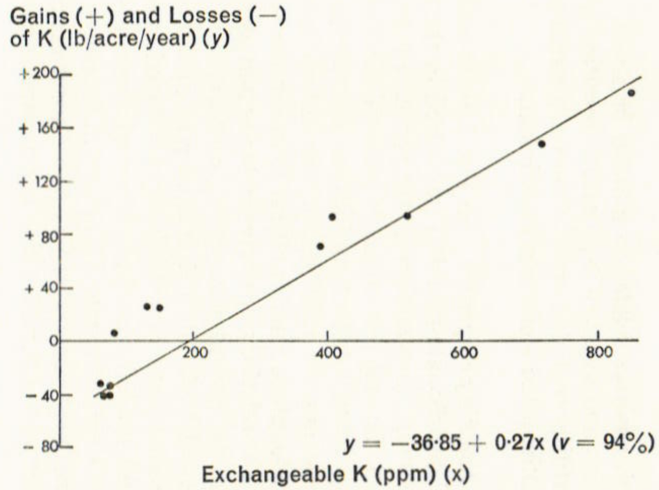


FIG. 4. Permanent grass (1957–70).

Relationships between losses and gains of potassium and exchangeable K.

(V = *percentage of variance associated with linear regression.*)

affected by moisture stress in dry seasons or by leaching of nitrate N in wet years than at Woburn.

Soil analyses related to nutrient balances. Table 4 gives the estimated average annual gains and losses of N, P and K resulting from the balance between amounts applied by fertiliser or FYM and the amounts removed in crops grown on the arable section of the Rothamsted Reference experiment.

Soluble phosphorus. In Fig. 1 these amounts are related to the mean concentrations of bicarbonate-soluble P measured in the soils in 1970; Table 5 and Fig. 3 give corresponding information for the permanent grass. When losses balance gains, Fig. 1 suggests that the soil has about 11 ppm of bicarbonate-soluble P under the arable treatments; Fig. 3 suggests that equilibrium is at about 15 ppm of soluble P for the permanent grass soils, but the relationship was not so satisfactory for the permanent grass as for the arable plots. Similar effects found in the Woburn experiment are discussed below.

The relationships between losses and gains of bicarbonate-soluble P for both the arable and permanent grass were closer where P was supplied by fertilisers than when it came from FYM. The PK treated plot in the permanent grass section of the experiment is anomalous; this soil initially contained more bicarbonate-soluble P and $CaCl_2$-soluble P than soil of the other plots and these amounts increased more rapidly than on other fertiliser treatments. This plot is at the end of a block only 5 yards from the stump of a large tree felled years ago. Soil phosphorus concentration may have been affected by leaf fall over a long period which has enhanced its extractability by these two reagents.

Exchangeable potassium. The relationships between exchangeable K and the mean annual balance between nutrients applied and removed (Tables 4 and 5) was closer than

TABLE 5

Estimates of annual changes, caused by treatments, in nutrients in the soils of the permanent grass of the Rothamsted Reference Plots 1957–70

	lb/acre		
Treatment	N	P	K
None	−71	−10	−42
N_1	−2	−9	−31
P	−63	+14	−35
N_1P	−17	+6	−41
K	−69	−9	+94
N_1K	−27	−13	+23
PK	−86	+9	+71
N_1PK	−21	+6	+26
N_2PK	+20	+2	+6
D	+74	+25	+93
DN_1PK	+126	+44	+185
DN_2PK	+184	+40	+148

for soluble P in both arable and permanent grass soils. There are balances between losses and gains of K in the soils at about 170 ppm of exchangeable K in the arable soils (Fig. 2) and about 200 ppm K under permanent grass (Fig. 4). The result for the arable soils is similar to those found by Williams and Cooke (1971) for the Saxmundham soil and by Johnston (1969) for the Broadbalk experiment.

Nutrients supplied by rainfall at Rothamsted. Rain samples were collected continuously in a polythene gauge 4 ft above the soil in the meteorological enclosure at Rothamsted between 1969 and 1972; 57 batches were analysed without filtering. From the mean concentrations of nutrients in these, and the mean annual rainfall between 1956 and 1970, these estimates of nutrients supplied annually were calculated:

	lb/acre of element
NH_4–N	9·7
NO_3–N	6·5
PO_4–P	0·5
Cl	33
SO_4–S	20
K	3·2
Na	12
Ca	9·7
Mg	2·1

Small amounts of P, K, Ca and Mg were supplied. Amounts of sulphate, chloride and sodium were larger but these ions are removed by leaching. The total nitrogen supplied made an appreciable contribution to those plots not receiving N fertiliser. The rain at Woburn (p. 99), collected during the same period, supplied similar amounts of elements except for sulphate-S of which Rothamsted rain had more. The amounts found in Saxmundham rain (Williams & Cooke, 1971a) were similar to those in Rothamsted and Woburn rain except that at Saxmundham, sodium and chloride were larger as the site is near the sea.

Miller (1905) reported that Rothamsted rain, collected between 1888 and 1901, supplied on average 2·7 lb NH_4–N, 1·1 lb NO_3–N, and 14·9 lb Cl per acre annually. Russell and Richards (1919), for the period 1901 to 1916, found the corresponding amounts of 2·6, 1·5 and 18 lb per acre. The larger amounts in recent rainfall suggest the atmosphere is more polluted.

The Woburn Experiment

Analyses of the soils from the arable rotation of the Woburn Reference experiment are given in Table 6, those for the long ley in Table 7. The compositions of the soils sampled when the experiment began in 1960 are summarised in Table 8 as mean values of the blocks of the experiment; they show that, except for the larger values for exchangeable K in block F (the long ley), the soils were relatively uniform in nutrients. At first the soil was acid (pH 5·8) and all plots were limed with 25 cwt/acre of calcium carbonate when the experiment was started. They were re-limed in 1962. In 1964 the long ley was re-limed but in 1967 only the arable section (Widdowson & Penny, 1972). After magnesium deficiency was diagnosed in the sugar beet in 1968, tests of Mg were applied at first to sugar beet and later to potatoes grown in 1968 and 1969 (Widdowson & Penny, 1967a and 1972).

Composition of the soils

Total nitrogen, initially about 0·1% (Table 8) showed small increases by applying FYM with or without fertiliser, the increases were slightly more in soils under long ley (Tables 6 and 7).

Organic carbon showed similar small changes mainly associated with applying FYM.

Total phosphorus was increased little by the treatments, even on plots receiving FYM.

Soluble phosphorus. Bicarbonate-soluble P was much increased where fertiliser and FYM supplied much more P than crops removed, gains were largest when FYM was

TABLE 6

Compositions of soils of Woburn Reference Plots (arable rotation) 1960–69

(Values are averages of five plots)

		Treatment											
		O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
pH (in water)	1960	6·0	5·7	5·9	5·9	5·9	5·9	5·8	5·8	5·8	5·7	5·9	5·7
	1964	7·7	7·4	7·6	7·3	7·7	7·7	7·7	7·8	7·5	7·5	7·6	7·5
	1969	7·4	7·1	7·4	7·1	7·6	7·5	7·5	7·5	7·1	7·4	7·4	7·2
Organic carbon % (Walkley–Black values, uncorrected)	1960	0·66	0·68	0·67	0·70	0·65	0·67	0·68	0·74	0·66	0·71	0·68	0·68
	1964	0·72	0·72	0·68	0·72	0·69	0·70	0·68	0·71	0·71	0·86	0·86	0·86
	1969	0·64	0·65	0·64	0·64	0·65	0·68	0·63	0·67	0·66	0·88	0·89	0·89
Total N %	1960	0·09	0·09	0·10	0·10	0·10	0·11	0·10	0·10	0·09	0·10	0·09	0·10
	1964	0·09	0·10	0·09	0·09	0·09	0·10	0·09	0·09	0·09	0·11	0·11	0·11
	1969	0·10	0·10	0·10	0·10	0·10	0·10	0·10	0·10	0·10	0·12	0·13	0·13
Total P %	1960	0·071	0·075	0·070	0·074	0·073	0·074	0·073	0·073	0·070	0·075	0·071	0·074
	1964	0·072	0·071	0·074	0·074	0·069	0·072	0·074	0·075	0·075	0·074	0·083	0·075
	1969	0·062	0·063	0·069	0·071	0·063	0·063	0·072	0·072	0·072	0·075	0·082	0·082
P soluble in 0·5*M* $NaHCO_3$, ppm	1960	17·5	19·3	17·5	19·2	18·3	19·8	18·0	18·5	18·1	18·1	18·1	17·8
	1964	15·3	15·6	23·7	23·3	15·3	15·0	22·6	23·3	21·2	21·1	32·7	30·1
	1969	15·6	13·6	33·0	30·2	16·2	13·4	32·9	29·8	26·1	28·8	47·8	42·4
P in equilibrium in 0·01*M* $CaCl_2$ solution, μM/litre	1960	1·7	2·0	1·9	1·9	1·9	2·0	2·0	1·8	1·7	2·0	1·8	1·8
	1964	1·3	1·5	2·8	2·7	1·8	1·4	2·5	2·5	2·3	2·7	4·2	4·2
	1969	1·3	1·2	4·2	4·0	1·2	1·2	4·0	3·8	3·0	3·8	8·2	8·2
Ca exchangeable, ppm	1960	1234	1142	1210	1170	1114	1158	1126	1202	1198	1122	1182	1022
	1964	2164	1940	2148	1856	2048	2160	1940	2297	1944	1944	2124	1976
	1969	1534	1392	1338	1256	1282	1228	1316	1366	1228	1520	1358	1264
K soluble in 0·01*M* $CaCl_2$ solution, ppm	1960	4·0	4·5	4·4	4·3	4·1	4·1	4·3	3·8	3·9	4·1	3·8	4·2
	1964	2·0	2·0	2·8	2·1	8·6	6·1	7·0	4·4	5·5	5·9	11·6	12·9
	1969	1·8	1·8	1·7	1·7	12·9	8·6	13·5	11·4	9·4	9·3	21·8	20·6
K exchangeable, ppm	1960	57	49	65	67	52	67	58	59	56	55	52	48
	1964	25	41	27	24	77	81	84	59	52	48	165	162
	1969	37	38	35	36	180	167	186	131	134	130	311	267
Mg exchangeable, ppm	1960	18	18	18	18	16	17	17	17	18	17	17	15
	1964	13	11	16	12	10	10	10	9	9	30	27	30
	1969	36	26	32	27	27	26	27	28	28	53	44	45

TABLE 7

Compositions of soils of Woburn Reference Plots (long ley) 1960–69

(Values are for individual plots)

		Treatment											
		O	N_1	P	N_1P	K	N_1K	PK	N_1PK	N_2PK	D	DN_1PK	DN_2PK
pH (in water)	1960	5·7	5·7	6·3	5·7	5·7	5·6	5·6	5·6	6·9	5·7	5·8	5·7
	1964	7·4	7·3	7·5	7·5	7·5	7·2	7·2	7·0	7·2	7·6	7·5	6·9
	1969	7·1	6·9	7·3	6·8	7·2	7·0	6·9	6·7	6·6	7·2	7·0	6·6
Organic carbon % (Walkley–Black values, uncorrected)	1960	0·65	0·71	0·68	0·71	0·71	0·65	0·68	0·69	0·63	0·68	0·74	0·77
	1964	0·85	0·77	0·80	0·82	0·73	0·79	0·77	0·76	0·79	1·08	1·15	0·97
	1969	0·90	0·74	0·88	0·82	0·90	0·81	0·82	0·91	0·81	1·12	1·38	1·14
Total N %	1960	0·10	0·09	0·09	0·09	0·09	0·08	0·09	0·10	0·10	0·09	0·10	0·09
	1964	0·10	0·09	0·11	0·10	0·10	0·10	0·10	0·10	0·10	0·12	0·13	0·13
	1969	0·12	0·11	0·12	0·11	0·13	0·12	0·12	0·12	0·11	0·15	0·19	0·16
Total P%	1960	0·079	0·078	0·077	0·080	0·081	0·074	0·073	0·078	0·078	0·073	0·082	0·079
	1964	0·070	0·065	0·070	0·070	0·071	0·074	0·085	0·077	0·064	0·075	0·077	0·081
	1969	0·064	0·063	0·082	0·072	0·068	0·065	0·075	0·078	0·073	0·080	0·092	0·081
P soluble in 0·5*M* $NaHCO_3$, ppm	1960	22·8	17·6	19·4	18·2	17·2	19·4	18·2	22·2	17·6	17·6	21·8	20·0
	1964	16·0	11·2	25·2	22·8	12·4	12·4	19·2	16·0	18·4	21·6	33·2	32·0
	1969	16·2	10·2	33·8	25·2	8·0	9·8	24·6	23·0	20·0	26·4	50·4	39·6
P in equilibrium in 0·01*M* $CaCl_2$ solution, μM/litre	1960	2·4	1·5	2·6	2·0	1·8	2·0	2·0	2·1	1·8	2·0	3·0	1·9
	1964	2·1	1·3	4·3	2·4	1·5	1·5	3·4	2·4	2·1	3·2	6·5	6·5
	1969	2·0	1·0	6·6	3·4	0·8	1·1	4·5	3·7	2·0	4·7	15·7	10·2
Ca exchangeable, ppm	1960	1042	942	1202	1022	1042	922	922	942	2305	1022	1142	1082
	1964	2605	2204	2605	2345	2385	2164	1944	1764	2285	2505	2285	1884
	1969	1220	1320	1110	1020	1140	1390	1170	1220	1110	1040	1250	1230
K soluble in 0·01*M* $CaCl_2$ solution, ppm	1960	4·2	4·6	4·0	4·4	4·2	4·4	4·3	4·6	3·8	3·6	4·3	4·0
	1964	2·2	1·8	2·2	1·9	4·9	3·6	5·5	4·4	3·3	12·8	23·3	13·8
	1969	1·8	1·6	1·6	1·6	12·5	6·0	10·0	4·7	2·4	14·0	34·5	20·5
K exchangeable, ppm	1960	94	67	86	55	90	70	110	63	55	86	129	63
	1964	24	12	27	12	51	59	43	47	31	164	262	184
	1969	31	31	35	31	172	82	153	74	47	231	387	258
Mg exchangeable, ppm	1960	18	15	17	16	18	12	13	17	24	17	18	15
	1964	16	10	18	9	7	10	9	7	9	38	40	37
	1969	17	5	16	6	9	4	7	10	9	55	56	40

TABLE 8

Average values of soil properties in blocks of the Woburn Reference Plots

	Block*						
	A	B	C	D	E	F	Mean
pH (in water)	5·6	5·9	5·7	5·9	6·0	5·8	5·8
Nitrogen, %	0·12	0·10	0·09	0·09	0·09	0·09	0·10
Organic carbon, %	0·68	0·69	0·71	0·67	0·66	0·69	0·68
Total P, %	0·073	0·070	0·076	0·071	0·076	0·077	0·074
$NaHCO_3$-soluble P, ppm	19·9	17·4	18·7	17·3	18·3	19·3	18·5
Exchangeable Ca, ppm	890	1240	1130	1410	1120	1130	1150
Exchangeable K, ppm	49	51	62	51	74	81	61
Exchangeable Mg, ppm	14	18	15	20	18	17	17
Exchangeable Na, ppm	46	44	42	45	44	47	45

* Blocks A–E, the arable section in plot order, block F long ley section, sampled 1960

applied, FYM and fertilisers together doubling the original value. P in equilibrium with 0·01*M* $CaCl_2$ solution showed similar trends.

Exchangeable calcium was maintained by regular liming, amounts were largest in 1964 after the second dressing of lime.

Exchangeable potassium. Initially the arable soils had about 60 ppm of exchangeable K (Table 8), amounts were increased by dressings of fertiliser-K especially when no N was given, gains were most from 1964 to 1969 when more K was given. On plots receiving fertiliser and FYM, exchangeable K was increased five to six times. The soils of the long ley were initially richer in exchangeable K, increases were related to dressings of fertiliser and FYM, but were smaller and more regular than those on the arable plots because the grass removed more K than the arable crops (Tables 8 and 10). Where grass had the smaller amount of N, the initial exchangeable K in soil was maintained, with the larger dressing it diminished. The concentrations of soil potassium soluble in 0·01*M* $CaCl_2$ solution generally changed in the same way as exchangeable K.

TABLE 9

Estimates of annual changes, caused by treatments, in nutrients in the soils of the arable rotation of Woburn Reference Plots 1960–69

	lb/acre		
Treatment	N	P	K
None	−70	−10	−57
N_1	−30	−12	−67
P	−69	+14	−57
N_1P	−26	+12	−63
K	−83	−11	+62
N_1K	−45	−13	+38
PK	−84	+13	+60
N_1PK	−50	+9	+35
N_2PK	−12	+8	+24
D	+14	+24	+36
DN_1PK	+47	+44	+145
DN_2PK	+75	+42	+114

Exchangeable magnesium was small at first (Table 8), but amounts increased in 1969 on all plots of the arable section because magnesium sulphate was applied to correct Mg deficiency in sugar beet and potatoes (Widdowson & Penny, 1971). Previously exchange-

TABLE 10

Estimates of annual changes, caused by treatments, in nutrients in the soils of the long ley of the Woburn Reference Plots 1960–69

Treatment	lb/acre N	P	K
None	−81	−11	−65
N_1	+37	−15	−69
P	−71	+13	−66
N_1P	+30	+6	−72
K	−108	−13	+40
N_1K	+29	−17	−7
PK	−108	+10	+34
N_1PK	+27	+4	−23
N_2PK	+116	+3	−12
D	+32	+32	+58
DN_1PK	+146	+50	+128
DN_2PK	+237	+46	+83

able Mg had only increased on plots treated with FYM. The long ley received no dressing of Mg; there were continuous decreases in exchangeable Mg in the soils except where 10 tons/acre FYM was given annually. Very small amounts were found in the soils of plots where nitrogen fertiliser was applied to the long ley without FYM.

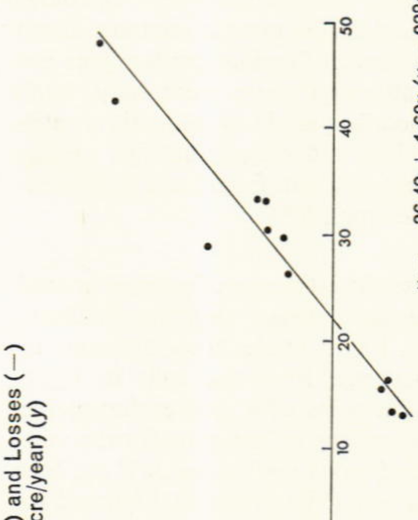
Exchangeable sodium, as in the Rothamsted experiment, varied more between the years than with treatment. Data are not shown in Tables 6 and 7; in 1960 the soils had about 45 ppm exchangeable Na (Table 8), in 1964, 10 ppm, and in 1969 about 20 ppm.

The changes in the nutrients in the Woburn Reference experiment reflect the physical composition of this soil. (It contains little stones or gravel, but has about 85% of coarse particles (6–0·02 mm) of which 60–70% is in the range 0·25–0·1 mm; it contains about 5% of silt (0·02–0·002 mm) and 10% of clay (<0·002 mm).) Organic matter does not accumulate quickly but soluble phosphorus does, although there were only small increases in total P in ten years. The soil has to be limed frequently to maintain a satisfactory pH for the crops grown. Exchangeable potassium and magnesium are rapidly depleted by intensive cropping, the rate of release of these nutrients from the soil minerals is not sufficient to maintain good crops without fertilisers or FYM.

Soil analyses related to nutrient balances. Table 9 shows the estimates of average annual gains or losses of N, P and K resulting from the balance between applying fertilisers or manure and removing nutrients in the arable crops. Fig. 5 relates these amounts to the mean concentrations of bicarbonate-soluble P extracted from the soils in 1969; Fig. 6 shows similar relationships between the losses and gains of K and exchangeable K in the soils. Table 10 and Figs. 7 and 8 give the corresponding information for the long ley. The relationships between bicarbonate-soluble P and gains and losses of P are less satisfactory (Figs. 5 and 7) than those obtained for potassium (Figs. 6 and 8). Figures 5 to 8 suggest that, when nutrients supplied to the soils by fertilisers and manure balance the amounts removed by crops, the soils contain about 20 ppm of bicarbonate-soluble P and about 120 ppm of exchangeable K for both arable treatments and the long ley.

Nutrients supplied by rainfall at Woburn. Rain samples were collected continuously in a polythene gauge 4 ft above the soil in the meteorological enclosure at Woburn between 1968 and 1972; 31 batches were analysed without filtration. From the mean concentra-

FIGS. 5–8. Soil analyses and nutrient balances for P and K in the Woburn Reference experiment.



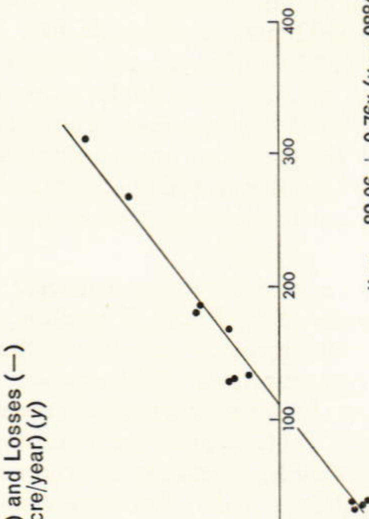
$y = -36{\cdot}42 + 1{\cdot}69x$ ($v = 93\%$)

FIG. 5. Arable rotation (1960–69).

$y = -31{\cdot}19 + 1{\cdot}68x$ ($v = 85\%$)

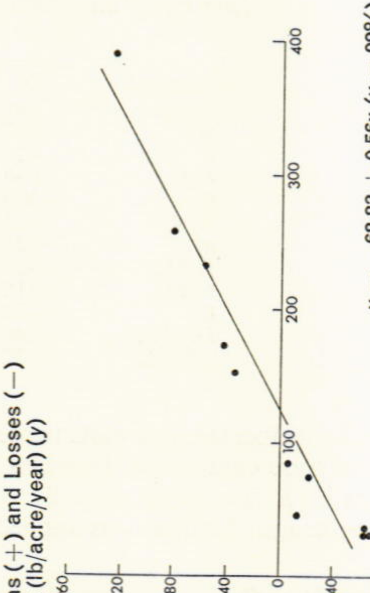
FIG. 7. Long Ley (1960–69).

Relationships between losses and gains of phosphorus and soil P, soluble in sodium bicarbonate solution.



$y = -82{\cdot}06 + 0{\cdot}76x$ ($v = 98\%$)

FIG. 6. Arable rotation (1960–69).



$y = -68{\cdot}83 + 0{\cdot}56x$ ($v = 92\%$)

FIG. 8. Long Ley (1960–69).

Relationships between losses and gains of potassium and exchangeable K.

(V = percentage of variance associated with linear regression.)

tions of the nutrients and the mean annual rainfall at Woburn between 1960 and 1969, these estimates of nutrients supplied annually were calculated:

	lb/acre of element
NH_4–N	7·5
NO_3–N	5·2
PO_4–P	0·2
Cl	28
SO_4–S	16
K	2·3
Na	9
Ca	10
Mg	2·2

Except for the smaller SO_4–S, these amounts are similar to those found in Rothamsted rain (p. 93). The rain supplied less nitrogen at Woburn. Much larger effects of fertiliser nitrogen at Woburn are however because the old arable soil contains smaller stocks of total N than the Rothamsted soil. Because the Woburn soil contains much sand and readily slakes in wet weather, leaching of nitrate is more complete than it is from the stable well-aggregated Rothamsted soil.

Comparison between the results at Rothamsted and Woburn. Differences in rates of loss and gain of nutrients from these two soils, caused by cropping and applying fertilisers and manure are related to differences in the yields of crops grown but also to differences in the soils caused by their mechanical compositions and differing histories. The Rothamsted soil had been in permanent grass for a century or more before the experiment started, the Woburn soil in arable cultivation for as long.

Rothamsted soil retains more carbon from dressings of manure and it is easier to maintain organic carbon content in the Rothamsted clay loam than in the sandy soil at Woburn. Even larger dressings of FYM were applied (1500 tons/acre in 20 years) to the very similar soil of the Woburn Market Garden experiment on Lansome Field; these dressings increased the organic carbon in that soil to 1·26%, which is still only half as much as was in the Rothamsted soil when the arable rotation was started. Soil continuously fallowed for 11 years on Stackyard Field had 0·67% organic carbon—the same as the site on which the Woburn Reference experiment was started. These results suggest that, when the Woburn soil is used for arable cropping, organic matter is decomposed as quickly as it is under a cultivated fallow. Comparative measurements of water-holding capacity using <2 mm soil, done in 1962, indicated that in the permanently cultivated fallow on Stackyard Field at Woburn it was 27%, on the cultivated soil adjacent to the Reference plots in Great Field IV at Rothamsted it was 60% and under the permanent grass of the enclosure it was 68%.

Smaller water-holding capacity of the Woburn soil contributes to the ease with which N is lost in drainage (Williams, 1971), and many field experiments have shown that less of a nitrogen fertiliser dressing is recovered at Woburn than at Rothamsted.

After a few years of intensive cropping with NPK fertilisers in the Woburn experiment, the exchangeable Mg (initially one-seventh of that at Rothamsted, Tables 3 and 8) was more than halved. At Rothamsted, although similar arable cropping halved the exchangeable Mg in the soils, the amount remaining was more than three times that in the Woburn soil when that experiment started. Woburn also has smaller reserves of potassium and Table 10 suggests that K deficiency may limit yields of grass unless much fertiliser is given. Even the large rate of 186 lb/acre given annually since 1963 was insufficient to maintain exchangeable K. The average dressing used at Rothamsted (150 lb/acre K per year) allowed exchangeable K to accumulate. By contrast, it was just as easy to increase bicarbonate-soluble P by fertiliser dressings at Woburn as at Rothamsted (Tables 1 and 6).

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APPENDIX

Methods of analysis used for soils

Total nitrogen by Kjeldahl digestion with Cu and Se catalysts, Bremner (1960).

Organic carbon by Walkley's (1935) method.

Total phosphorus by fusion with sodium carbonate, Mattingly (1970), and measurement by 'Technicon AutoAnalyzer' using the method of Murphy and Riley (1962) with a neutralisation step.

Sodium bicarbonate-soluble P. Extraction with 0·5*M* $NaHCO_3$ using the method of Olsen *et al.* (1954) and measurement with a 'Technicon AutoAnalyzer' using the method of Murphy and Riley (1962) with a neutralisation step.

0·01*M* $CaCl_2$–P. Extraction by Schofield's (1955) method and measurement with a 'Technicon AutoAnalyzer' using the method of Murphy and Riley (1962).

0·01*M* $CaCl_2$–K. Extraction by Schofield's (1955) method and measurement by 'E.E.L.' flame photometer.

Exchangeable calcium, magnesium, potassium and sodium were extracted by *N* ammonium acetate solution (Metson 1956); Ca, K and Na were measured by emission spectrophotometry, Mg by atomic absorption, using a 'Unicam SP 900' spectrophotometer.

Calcium carbonate by the method of Williams (1948).

pH on a 1 : 2·5 soil : water ratio, using a glass electrode.

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