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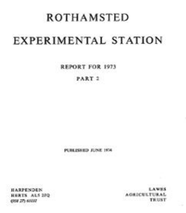
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The Woburn Organic Manuring Experiment II. Soil Analyses, 1964-72, With Special Reference to Changes in Carbon and Nitrogen

G. E. G. Mattingly, Margaret Chater and P. R. Poulton

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The Woburn Organic Manuring Experiment

II. Soil Analyses, 1964–72, with Special Reference to Changes in Carbon and Nitrogen

G. E. G. MATTINGLY, MARGARET CHATER and P. R. POULTON

The experiment described in Part I (Mattingly, 1974) occupies most of Series B on Stackyard Field, Woburn, which was cropped from 1930–60 in a six-course rotation of sugar beet, barley, clover, wheat, potatoes, rye (Yates & Patterson, 1958; Rothamsted Experimental Station, 1970). Barley was grown over the whole area in 1961–63 and the land was fallowed in 1964.

Soil samples (0–23 cm) were taken from all plots at the start of the experiment in April 1964, and again in autumn, 1968 and 1971 after the winter wheat and winter rye crops respectively. Samples were also taken to 53 cm in April 1964 and when the first phase of the experiment was completed after the leys had been ploughed up. Blocks I and III were sampled in spring 1972 and Blocks II and IV in spring 1973.

This paper describes changes in the composition of the surface soils, and the sub-soils to 53 cm with special reference to (i) changes in carbon and nitrogen contents, including mineralisable N and (ii) effects of the different amounts and types of organic matter on the distribution, movement and possible fixation, of residues of P, K and Mg fertilisers.

Mechanical analysis and apparent density of soils

Mechanical analysis. The soil is a sandy loam (Cottenham Series) derived from Lower Greensand. The mean mechanical composition is about 80% coarse and fine sand (2000–20 μm), 5·5% silt (20–2 μm) and 10% clay (<2 μm). Appendix Table 1 gives the mechanical analysis of soils from all main plots, which are parallel and run from SW to NE and slope in this direction. The proportions of coarse and fine sand decrease from over 80% on plots at the SW end of the experiment to 75% or less at the NE end. The silt and clay contents show minima, 3·2 and 7·8% respectively, in plot 8 near the junction of Blocks I and II and similar, though larger minimum values, 5·1 and 5·3% and 9·9 and 9·3% respectively, in plots 24 and 25 at the junction of Blocks III and IV. The largest silt and clay contents (7–8% and 12–13%) were in plots 30–32 at the NE corner of the experiment. The initial C and N contents of the soils follow a similar pattern to the % clay, with minima in plot 8. The linear regression

$$\%C = 0{\cdot}32(\pm\ 0{\cdot}058) + 0{\cdot}044(\pm\ 0{\cdot}0056)\ \%\ \text{clay}$$

accounts for 66% of the variance in carbon contents in the 32 plots in 1964.

Apparent density of soils. Crowther (1936) gives the weights/acre for surface soils (0–9 in.) from Stackyard as 1370 tons air-dry soil/acre and 1420 tons air-dry soil/acre for sub-surface soils (9–18 in.). The air-dry soils now contain 0·7–1·2% moisture and these weights, which correspond to apparent densities of 1·51 and 1·56 g air-dry soil/cm^3, have been used by several other workers (Bolton & Penny, 1968; Chater & Gasser, 1970) and are used in this paper for all soils other than those ploughed out from leys. Bulk densities of soils under leys were calculated from the weights of soil removed to measure roots weights of the leys before ploughing (Part I, p. 103). The mean apparent density was 1·38 g air-dry soil/cm^3, corresponding to 1300 tons/acre for surface soils.

The following metric equivalents are used to calculate gains and losses of organic matter (Table 2) and nutrients (Table 4).

Depth of sampling (cm)	Soil weights (tonnes × 10^3/ha): All treatments except leys	Lc and Ln plots
0–22·9	3·44	3·14
0–15·2	2·29	2·09
15·2–22·9	1·15	1·05
22·9–30·5, 30·5–38·1, 38·1–45·7, 45·7–53·3	1·19	1·19

Soil analyses in 1964

Appendix Table 2 gives mean analyses of all surface soils (0–23 cm) sampled in 1964, 1968 and 1971. In 1964, before different organic matter treatments were applied, the soils (averaged over four blocks) contained little organic C and values, measured by the Walkley (1947) method, using 1·3 for the correction factor, were 0·73–0·81%. Nitrogen contents were 0·082–0·091% and the soils contained moderate amounts of $NaHCO_3$-soluble P (24–30 μg P/g) but little exchangeable K (71–79 μg K/g) or Mg (12–20 μg Mg/g). The variations in C, N and total P contents within blocks are given in Appendix Table 1.

Organic C and N. The organic C and N contents of soils from all sections of Stackyard Field have diminished steadily since 1876 when the soils were first analysed. No carbon or nitrogen analyses are available for Series B before 1964 but the mean C contents of soils from the adjacent Series A and C decreased from 1·51 to 0·90% and from 1·32 to 0·70% respectively between 1876 and 1959. The mean annual rate of loss is about 0·007% C, equivalent to 0·42 tonnes/ha of soil organic matter, assuming a conversion factor of 1·724 g organic matter/g C.

pH and exchangeable cations. Unlike other parts of Stackyard, Series B was limed regularly between 1930–60. The mean pH values ranged only from 5·75–6·00 in 0·01*M* $CaCl_2$. The pH, measured in water, was related to values in 0·01*M* $CaCl_2$ by

$$\text{pH (water)} = 0{\cdot}52(\pm 0{\cdot}183) + 0{\cdot}96(\pm 0{\cdot}032)\ \text{pH}(CaCl_2)$$

Exchangeable K. The mean value in 1964 was 75 μg K/g, which is less than Williams (1973) calculated would be present (108 μg K/g) in soils from Stackyard Field when the amounts of K removed by crops were balanced by the amounts applied in K fertilisers. The crops from the six-course rotation (1930–60), which preceded the Woburn Organic Manuring experiment, were not analysed. The evidence here suggests that they removed more than the average amounts of K (52 kg/ha) applied to them each year so that exchangeable K values on Section B on Stackyard Field were less in 1964 than in 1930.

Exchangeable Mg. The mean value (15 μg Mg/g) is typical of other Stackyard soils in the 1960s (Bolton & Penny, 1968; Williams, 1973) and much smaller than in the 1930s (Crowther, 1936). Magnesium deficiency symptoms and yield responses to Mg fertilisers occur at these soil Mg levels (Bolton & Penny, 1968).

Soluble P in the soils. In contrast to exchangeable K and Mg, the soils contained moderate amounts of $NaHCO_3$-soluble P. The mean value (28 μg P/g) exceeds the value for Stackyard (22 μg P/g) quoted by Williams (1973) and which he calculated in the same way as for potassium. The amounts of P added in the six-course rotation (16·5 kg P/ha each year) were, therefore, more on average than the crops removed.

Water-soluble B in the soils. The soils were not analysed for water-soluble B until symptoms of heart-rot were detected in sugar beet grown in 1969 (*Rothamsted Report for 1970*, Part 1, pp. 56–57). The values (0·4–0·6 μg B/g) are within the range where sensitive crops may show visual symptoms of boron deficiency.

Changes in soil analyses, 1964–71

Table 1 briefly describes the eight treatments applied to the main-plots (Part I) and gives changes in all analyses of surface soils (0–23 cm) between 1964–68 and 1964–71. Changes in soil C and N contents are often small and they are difficult to measure reliably over short periods. The changes in Table 1 were calculated from means of 16 sub-plots and

TABLE 1

Soil analyses in 1964 and increases between 1964–68 and 1964–71

(All analyses are on air-dried soils, 0–23 cm)

	pH (in 0·01*M* $CaCl_2$)	% Total C[a]	% Total N	μg/g Organic P	μg/g $NaHCO_3$-soluble P	μg/g Exchangeable cations K	μg/g Exchangeable cations Mg
Mean value in 1964	5·86	0·767	0·085	227	28	75	15
Increases between 1964 and 1968							
PKMg manuring equivalent to straw + supplementary P							
Leys with clover (Lc)	−0·67	0·148	0·006	33	7	39	16
Leys with nitrogen (Ln)	−0·42	0·094	0·004	6	11	46	16
Peat (Pt)	−0·57	0·266[b]	0·002	13	15	18	6
Straw (St)	−0·44	0·044	0·003	18	12	20	9
Green manures (Gm)	−0·58	0·074	0·002	20	12	14	8
Fertilisers only (Fs)	−0·47	−0·026	−0·003	8	13	18	7
PKMg manuring equivalent to farmyard manure							
Fertilisers only (Fd)	−0·39	−0·005	−0·006	7	33	39	16
Farmyard manure (Dg)	−0·32	0·153	0·010	25	28	47	29
Standard error of increase	—	±0·0185	±0·0018	±4·9	±1·6	±3·7	±1·0
Increases between 1964 and 1971							
PKMg manuring equivalent to straw + supplementary P							
Leys with clover (Lc)	−0·01	0·153	0·006	31	14	131	32
Leys with nitrogen (Ln)	0·16	0·107	0·005	25	13	113	27
Peat (Pt)	0·03	0·624[b]	0·015	21	18	84	16
Straw (St)	0·46	0·094	0·004	25	17	84	16
Green manures (Gm)	0·13	0·034	0·002	4	14	62	14
Fertilisers only (Fs)	0·36	−0·065	0·000	6	17	74	16
PKMg manuring equivalent to farmyard manure							
Fertilisers only (Fd)	0·13	−0·048	−0·004	13	36	190	24
Farmyard manure (Dg)	0·46	0·304	0·017	30	32	171	35
Standard error of increase	—	±0·0148	±0·0029	±6·0	±1·5	±10·8	±2·2

(a) Total C = 1·30 × Walkley value; (b) Increase in %C = 1·23 × Walkley value for peat only the standard errors were derived from analyses of variance of these differences and not from the errors of the separate soil analyses given in Appendix Table 2.

Changes in C and N contents of soils. The carbon contents of the soils increased significantly between 1964–68 in all treatments which included organic manures (peat (Pt), straw (St) and farmyard manure (Dg)) green manures (Gm) or leys with clover (Lc) or leys given 'Nitro-Chalk' (Ln). Carbon contents decreased slightly in soils given only fertilisers (Fs and Fd). Between 1968–71 organic C further increased where farmyard manure, peat or straw were applied cumulatively, but not where leys were grown. Carbon decreased slightly in soils where only one green manure crop (in 1971) was grown. The mean loss of soil carbon from plots given only fertilisers was $-0{\cdot}056 \pm 0{\cdot}0181\,\%$ C, corresponding to an annual rate of loss of 0·008% C. This value is very similar to the average loss between 1876 and 1959 from arable soils in experiments on other parts (Series A and C) of Stackyard Field.

The changes in % total C in surface soils from all main-plots between 1964–71 were similar in all four blocks, despite the variations in the mechanical composition of the soils (Appendix Table 1). Covariance analyses confirmed that the changes in carbon contents were unrelated ($-0{\cdot}0033 \pm 0{\cdot}00624$) to % clay and adjusting the changes in %C to allow for variations in clay contents slightly increased the residual variance of the measurements. Within this experiment, therefore, variations in clay contents from 7·8–13·1% did not affect either the loss or accumulation of soil carbon in seven years.

Changes in the N content of the soils closely followed changes in soil carbon but they were more difficult to measure reliably because they were very small; only the increases on plots growing leys or given farmyard manure were significant between 1964–68. At the end of 1971 the N content of soils given farmyard manure or peat had increased by

TABLE 2

Net gains and losses of carbon, nitrogen and organic matter, 1964–71/2

		tonnes/ha			kg/ha	
Treatment	Years	Carbon recovered[a]	Organic matter recovered[a]	Organic matter added[b]	Nitrogen recovered[a]	Nitrogen added[b]
Leys with clover	1964–71	4·81	8·3	9·2	190	150
	1964–72[c]	5·27	9·1	9·0	455	160
Leys with nitrogen	1964–71	3·36	5·8	8·2	160	155
	1964–72[c]	7·15	12·4	10·5	405	185
Peat	1964–71	21·47	37·2	41·8	515	535
Straw	1964–71	3·23	5·6	43·4	140	290
Green manures	1964–71	1·17	2·0	6·1[d]	70	160[d]
Fertilisers only (Fs)	1964–71	−2·24	−3·9	—[e]	0	—[e]
Fertilisers only (Fd)	1964–71	−1·65	−2·9	—[e]	−140	—[e]
Farmyard manure	1964–71	10·46	18·1	36·2	585	1580

(a) Calculated from changes in C and N contents (Table 1), using soil weights of $3{\cdot}14 \times 10^3$ tonnes/ha for leys and $3{\cdot}44 \times 10^3$ tonnes/ha for all other treatments
(b) For amounts added see Part I, Tables 2, 3 and 6. N values rounded to nearest 5 kg N/ha.
(c) Results for Blocks II and IV only.
(d) Amounts of organic matter and nitrogen in Italian ryegrass in 1964 and 1965 were not measured.
(e) Roots and stubble of barley, winter wheat, beans and rye, and potato and sugar beet tops were ploughed in on *all* plots

0·017 and 0·015 ± 0·0029% respectively. The C : N ratio of all soils given organic manures, green manures or growing leys increased between 1964–71 but decreased from 8·9 to 8·3–8·5 on soils without organic manures (Appendix Table 2). Proportionally more C than N was also lost from land fallowed between arable crops on the adjacent green manuring site (Series A) between 1936–66 (Chater & Gasser, 1970), and the C : N ratio decreased from 9·5 to 9·1. The evidence here (Table 1) suggests that the plant residues (roots and stubble of barley, winter wheat and winter rye and potato haulms and sugar beet tops) which were ploughed in between 1966–71 did not provide enough organic matter to balance losses.

Table 2 shows net gains and losses of C, N and organic matter between 1964–71/2 in relation to the amounts added in organic manures. The amounts of soil carbon and nitrogen measured by analysis in 1971 agree well with the amounts present in the leys which were estimated from the weights (Part I, Table 6) ploughed down in 1971/2. Soil analyses made on two blocks (II and IV) in 1972 appeared to overestimate the amounts of nitrogen (but not carbon) which accumulated under the leys. Much of the difference (220 kg N/ha) between N recovered by analysis (405 kg N/ha) and the 185 kg N/ha in the tops and roots of the ley given 'Nitro-Chalk' (Ln) can be explained. 'Nitro-Chalk' (126 kg N/ha) was given on 8 March for the first cut of grass and again on 26 June for a second cut, which was not taken because there was little rain in July–September. Much of the fertiliser nitrogen applied appeared to remain in the surface soil (0–23 cm). It is more difficult, however, to account for the difference (295 kg N/ha) between the N in soils under the clover ley (455 kg N/ha) and the amounts measured in the roots of the clover and grass (160 kg N/ha). In 1972, much mineral N may have accumulated under the clover ley during a long dry summer but was lost when the roots were washed before analysis. These discrepancies, which may also be due to sampling and analytical errors, emphasise the difficulties of measuring unambiguously the amounts of N that accumulate in soil under leys grown for only a few years.

Most of the C and N applied in peat still remained in the soil in 1971. Very little carbon (about 13%) but much more nitrogen (48%) remained from six cumulative dressings of straw. Some of the N given as 'Nitro-Chalk' was probably immobilised by straw between 1965–71 and retained by the soil as organic N. About 30–40% of the C and N remained in 1971 from the green manures; proportionally more C was recovered in 1968 (Table 1) than in 1971, because only one crop of red clover was grown between 1969–71. About 50% of the C and 37% of the N applied as farmyard manure remained in the soil in 1971. Percentage recoveries of C and N from peat, straw, green manures and farmyard manure in 1968 and 1971 are summarised in Table 3.

TABLE 3

Percentage recoveries of carbon and nitrogen from cumulative dressings of peat, straw and farmyard manure and from green manures (grown in 1965, 1966, 1968, 1971)

	% recovered			
	Carbon		Nitrogen	
Organic manures	after 3 years	after 6 years	after 3 years	after 6 years
Peat	79	89	—[a]	97
Straw	12	13	76	48
Green manures	94	33	55	43
Farmyard manure	50	50	42	37

(a) Value unreliable

TABLE 4

Recovery of P, K and Mg by soil analysis (0–53 cm), 1964–72/3

Depth (cm)	Clover ley		Grass ley		Peat		Straw		Green manures		Fertilisers (Fs)		Fertilisers (Fd)		Farmyard manure	
	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
Phosphorus (0·5*M* $NaHCO_3$-soluble P)																
0 –15·2	11·3	3·4	39·5	12·0	38·5	11·7	41·3	12·7	44·5	13·6	42·6	12·9	80·5	12·3	75·9	11·7
15·2–22·9	25·1	7·6	28·1	8·5	37·5	11·4	33·3	10·2	35·9	11·0	38·8	11·8	53·5	8·2	61·2	9·4
22·9–30·5	16·4	5·0	18·8	5·7	32·5	9·9	17·0	5·2	21·3	6·5	25·9	7·9	40·2	6·2	43·6	6·7
30·5–38·1	4·8	1·5	3·0	0·9	5·2	1·6	−1·9	−0·6	−0·5	−0·2	0·0	0·0	13·6	2·1	5·1	0·8
38·1–45·7	4·9	1·5	2·9	0·9	2·9	0·9	2·1	0·6	2·1	0·6	2·1	0·6	6·7	1·0	4·3	0·7
45·7–53·3	4·8	1·5	3·6	1·1	3·3	1·0	2·5	0·8	2·9	0·9	2·4	0·7	6·7	1·0	4·0	0·6
Total recovered	67·3	20·4	95·9	29·1	119·9	36·4	94·3	29·0	106·2	32·5	111·8	34·0	201·2	30·9	194·1	29·9
Total applied[a]	330	100	329	100	329	100	325	100	327	100	329	100	652	100	650	100
Potassium (NH_4-acetate exchangeable)																
0 –15·2	264	29	452	50	181	20	204	23	193	21	172	19	381	17	358	16
15·2–22·9	171	19	215	24	136	15	159	18	158	17	140	15	234	10	234	10
22·9–30·5	169	19	193	21	161	18	133	15	150	16	156	17	254	11	284	13
30·5–38·1	61	7	37	4	82	9	63	7	73	8	68	7	202	9	229	10
38·1–45·7	23	3	13	1	52	6	38	4	48	5	42	5	161	7	193	9
45·7–53·3	18	2	5	—	30	3	20	2	26	3	17	2	108	5	133	6
Total recovered	706	78	915	101	642	70	617	69	648	71	595	65	1340	60	1431	64
Total applied[a]	906	100	904	100	912	100	898	100	910	100	911	100	2236	100	2236	100
Magnesium (NH_4-acetate exchangeable)																
0 –15·2	48·4	49	71·1	70	43·3	43	40·1	41	32·8	33	40·4	39	58·7	22	71·3	27
15·2–22·9	33·2	34	29·6	29	17·0	17	20·3	21	17·9	18	16·3	16	30·1	11	39·5	15
22·9–30·5	27·1	27	28·1	28	15·0	15	18·0	18	19·1	19	18·7	18	30·2	11	39·4	15
30·5–38·1	8·1	8	6·5	6	11·2	11	12·6	13	15·1	15	14·4	14	29·4	11	29·0	11
38·1–45·7	1·9	2	0·0	0	8·1	8	8·1	8	8·9	9	9·9	10	28·3	10	21·4	8
45·7–53·3	1·1	1	−3·3	−3	5·1	5	3·8	4	4·5	5	4·9	5	21·6	8	12·2	5
Total recovered	119·8	121	132·0	129	99·7	100	102·9	105	98·3	100	104·6	101	198·3	73	212·8	80
Total applied[a]	99	100	102	100	100	100	98	100	98	100	104	100	272	100	267	100

(a) Net gains by soil before potatoes were planted in 1971 (Blocks I and III) and 1972 (Blocks II and IV); Means of all blocks. The amounts of P (100 kg/ha) and K (200 kg/ha) applied in autumn 1971 and 1972 for potatoes are included

Changes in organic P contents of soils. Organic P in soils increased significantly between 1964–68 where organic or green manures were applied or a clover ley was grown (Table 1). Between 1968–71 organic P increased slightly in soils given peat, straw or farmyard manure but much more under the ley given 'Nitro-Chalk'. The plots growing green manures lost organic P between 1968–71 (a result parallel to changes in organic C) because only one green manure crop (red clover) was grown. Organic P contents did not change significantly between 1964–71 in plots without organic manures (Fs and Fd) despite net gains of 220 and 550 kg P/ha respectively from superphosphate. Other evidence (Oniani, Chater & Mattingly, 1973) shows that much more superphosphate (up to 3000 kg P/ha), applied over many years, did not alter the organic P contents of arable soils at Rothamsted. The increases in organic P, as percentages of the net gains in P applied during seven years, were 43% (Lc), 35% (Ln), 33% (Pt), 40% (St) and 19% (Dg). The increase in organic P in soils given peat, which was apparently inert, is surprisingly large and may be misleading, because the ignition method of analysis appears to overestimate organic P in soils containing much carbon (Oniani, Chater & Mattingly, 1973).

Changes in pH and exchangeable cations. Some exchangeable K and Mg (and some soluble P) moved below the plough layer and analyses of surface soils (Table 1 and Appendix Table 2) do not show the changes in the nutrient status of the soils between 1964–71 adequately. Most of these changes are discussed in relation to soils sampled to 53 cm (Table 4 and Figs 1–3).

The mean pH of the soils decreased between 1964–68 by about 0·5 units. The site was limed with ground limestone (4·8 tonnes/ha) in February 1969, before the sugar beet crop, and the pH in 1971 was, on average, 0·2 units higher than in 1964.

Exchangeable K in the surface soils increased in all treatments between 1964–68 (Table 1), the increases being more on plots growing leys than on the corresponding plots under arable crops, although balancing K dressings were given (Part I) to compensate for differential removals. The larger amounts of K given as farmyard manure or equivalent fertilisers (Fd) increased the exchangeable K in the surface soils only slightly more (by 20–30 μg K/g) than the smaller (Fs) dressings. Much of the extra K must have leached below 23 cm during this period or been 'fixed'. Exchangeable K in the surface soil increased more between 1968–71 than between 1964–68, partly because more K was applied (Part I, Appendix Table 1).

Changes in exchangeable Mg followed a similar pattern to those for exchangeable K, more accumulating in surface soils under leys than under arable cropping and more where farmyard manure or equivalent fertilisers were applied. By 1971 exchangeable K and Mg in the surface soils ranged from 141–267 μg K/g and 30–49 μg Mg/g (Appendix Table 2). The values for Mg are adequate for most crops on this soil (Bolton & Penny, 1968). Exchangeable K in surface soils, from plots given only the smaller amounts of fertiliser, may be insufficient for maximum yields of some crops (e.g. potatoes, sugar beet) grown in the testing phase of the experiment (1972–75) unless large amounts of potassium fertilisers are used.

Figs 1 and 2 show the vertical distribution of exchangeable K and Mg in the soils before the experiment started in spring 1964 and before potatoes, the first test crop, were planted in spring 1972 and 1973. Potassium fertiliser (200 kg K/ha) was broadcast in the autumns of 1971 and 1972 before ploughing. The distribution in the following springs, shown in these Figures, is therefore the result of the movement and 'fixation' of K, applied between 1964 and 1971/2, together with the effects of ploughing down a large single dressing of potassium fertiliser in 1972/3. Table 4 gives the distribution and percentage recovery of the residues of P, K and Mg applied as fertilisers, and gained by the soils, between 1964–72/3.

Between 65–70% of the total K gained by plots given peat, straw, green manures or fertilisers only (Fs) was recovered as exchangeable K in the top 53 cm of soil so about 250–300 kg K/ha was lost by 'fixation' or leaching. There are no obvious differences in the distribution of exchangeable K in the presence and absence of organic matter (Fig. 1). About the same proportion (60–64%) of K gained from farmyard manure, or from

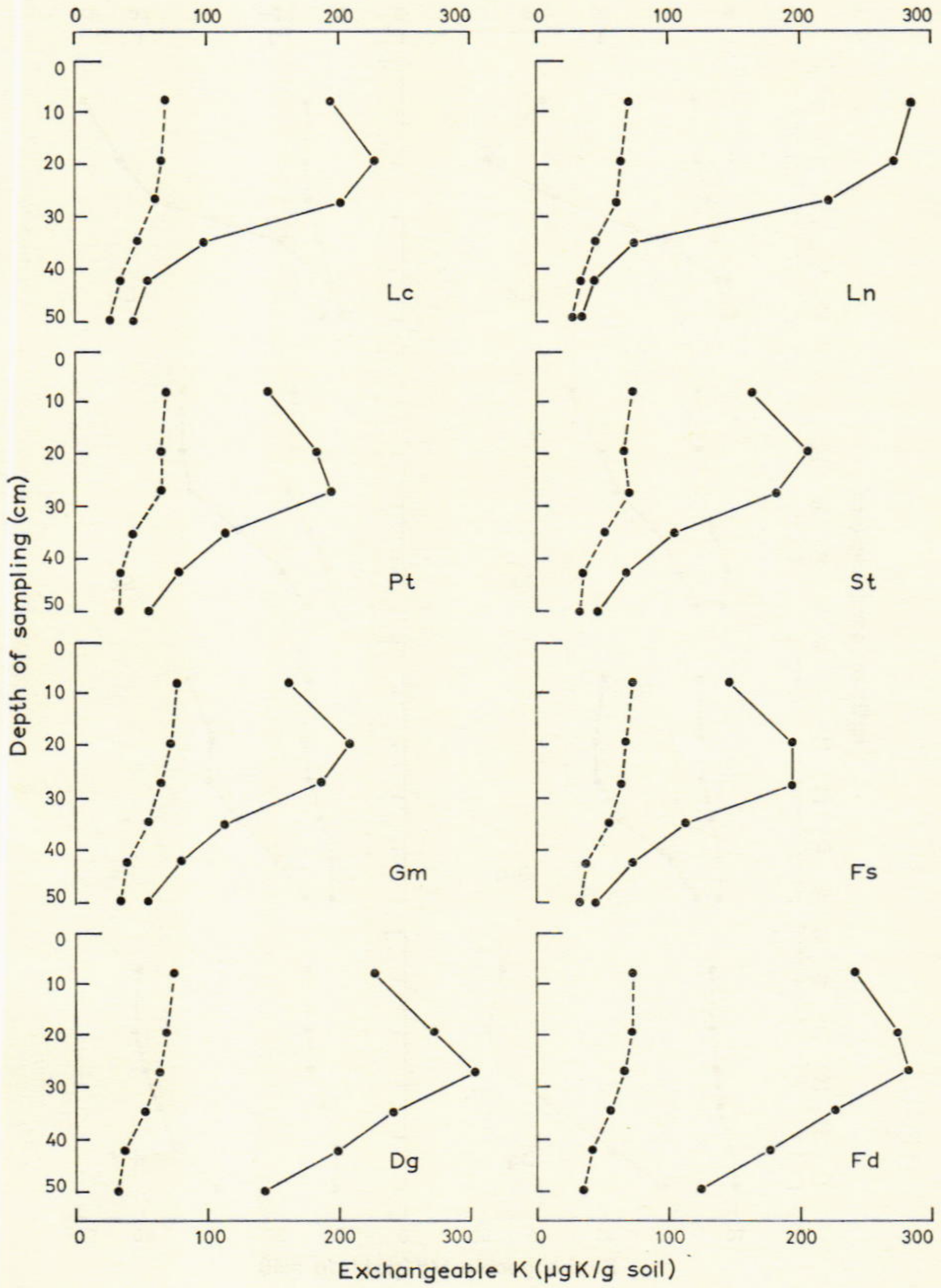

FIG. 1. Distribution of exchangeable K in soils sampled to 53 cm in 1964 (●---●---●) and in 1972/3 ●—●—●).

equivalent amounts of fertiliser (Fd), was present as exchangeable K. About 800 kg K/ha were not recovered and the distribution in Fig. 1 suggests that some had leached below 53 cm. All the K gained by the all-grass ley (Ln) and 78% of that gained by the clover ley (Lc) was recovered as exchangeable K.

Magnesium gained by plots given peat, straw, green manures or fertilisers (Fs) between

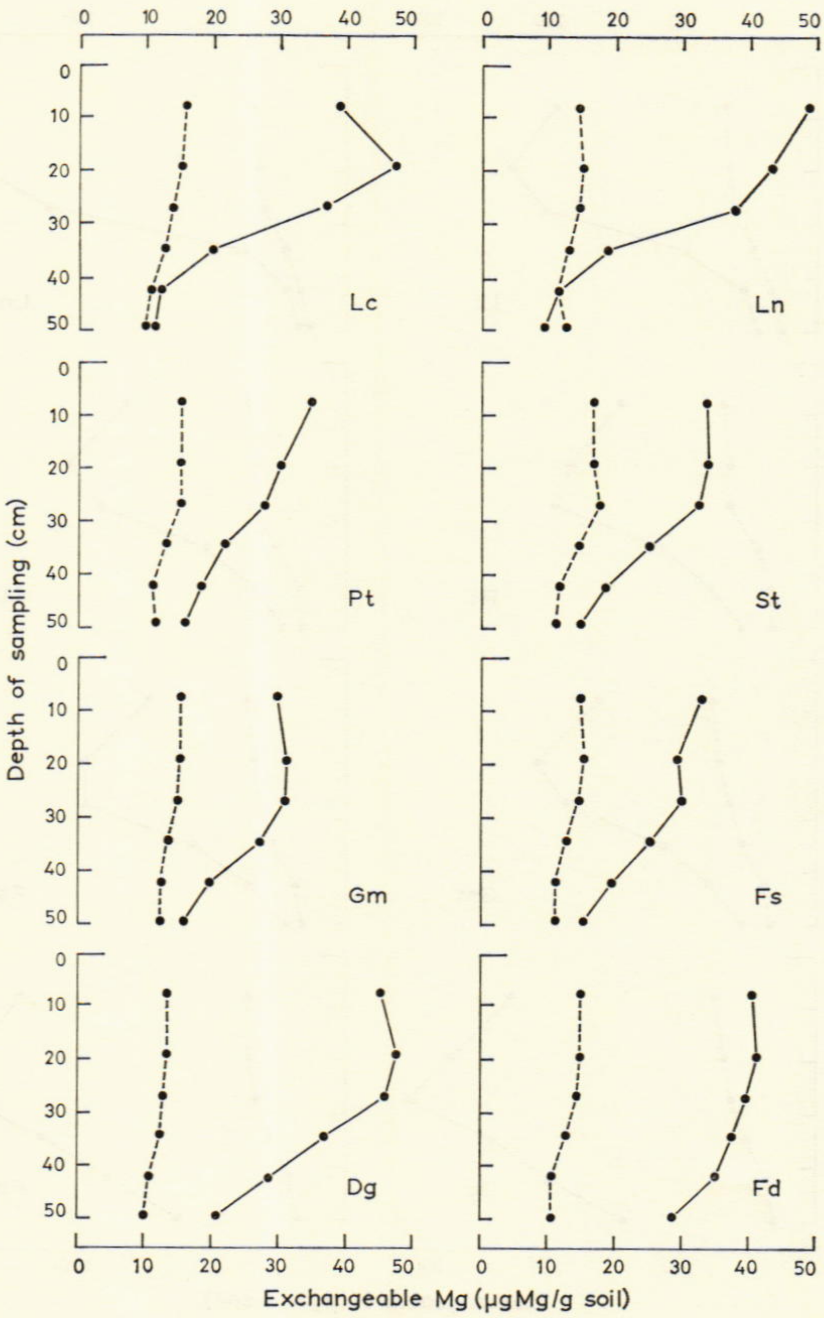

FIG. 2. Distribution of exchangeable Mg in soils sampled to 53 cm in 1964 (●---●---●) and in 1972/3 (●—●—●).

1964–72 remained mostly within the top 53 cm of soil and its vertical distribution was independent of the amounts of organic matter which accumulated in the soils. Less Mg (73–80%) gained from farmyard manure, or from equivalent fertilisers (Fd) was recovered (Table 4) and slightly more remained in the top 30 cm of soils given farmyard manure than in soils given fertilisers. In contrast to the results with soils from the arable crop

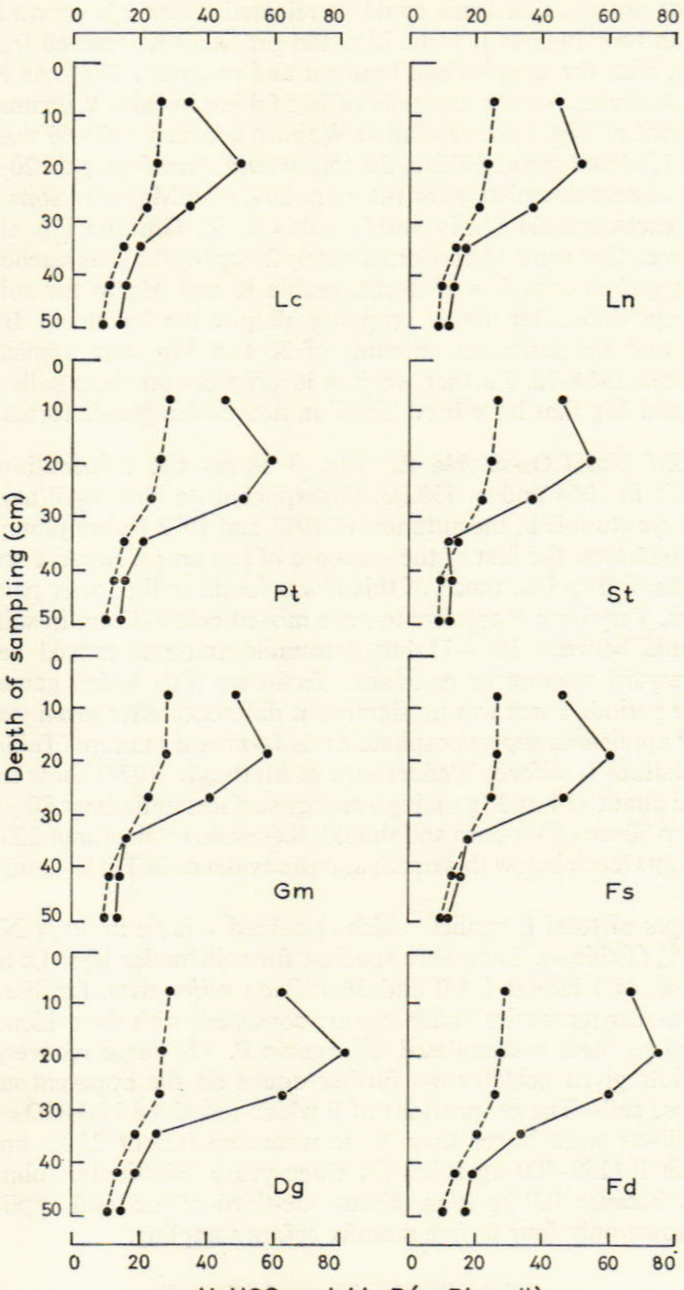

FIG. 3. Distribution of 0·5*M* sodium bicarbonate-soluble P in soils sampled to 53 cm in 1964 (●---●---●) and in 1972/3 (●—●—●).

sequence, 20–30% *more* Mg was recovered as exchangeable Mg under leys than was gained from fertilisers applied between 1964–71 (Table 4). This discrepancy could arise (i) from experimental errors, (ii) from the release of non-exchangeable Mg from the soil, (iii) from underestimating the amounts of Mg removed in cut grass or (iv) from Mg present in rain. Bolton and Penny (1968) found little non-exchangeable Mg was released from Woburn soil during exhaustive cropping with ryegrass in the glasshouse though it is possible, but not proven, that some could be released under leys grown for seven years. These results can be explained if some Mg, and probably K, leached from grass left on the plots to dry, after the samples had been cut and removed. They can be more reasonably explained, however, by the amounts of Mg falling in rain. Williams (1973) showed the annual amount of Mg in the rainfall at Woburn between 1960–69 was 2·5 kg Mg/ha. Between spring 1964 and spring 1972/3, the soils would, therefore, gain 20–22·5 kg Mg/ha, which accounts almost completely for the extra 20–30 kg Mg/ha in soils under leys. The distribution of exchangeable Mg in arable soils (Pt, St, Gm and Fs), shown in Fig. 2, suggests, moreover, that some Mg (approximately 20 kg Mg/ha) has leached below 53 cm.

The amounts and distribution of exchangeable K and Mg in the soils were slightly different after leys than after arable cropping, despite the balancing dressings (Part I) which ensured that the same net amounts of K and Mg were applied to both crop sequences between 1964–72. Further work is in progress on these soils to estimate the amounts of K and Mg that have been 'fixed' in non-exchangeable forms.

Changes in 0·5*M* $NaHCO_3$-soluble P. Fig. 3 shows the distribution of $NaHCO_3$-soluble P in soils in 1964 and in 1972/3. Superphosphate (100 kg P/ha) was broadcast on the leys and rye stubble in the autumns of 1971 and 1972 before ploughing to provide adequate P for potatoes, the first of the sequence of test crops. Because soil samples were taken in the following spring, much of this P was found in the lower part (15–29 cm) of the plough layer. Very little P appears to have moved below 30 cm in soils where 220 kg P/ha accumulated between 1964–71 but detectable amounts moved below 30 cm on plots given farmyard manure or equivalent fertilisers (Fd) which gained 550 kg P/ha during the same period. There was no significant difference after seven years between the movement of P applied as superphosphate or as farmyard manure (Table 4).

Recent calculations (Holford, Wedderburn & Mattingly, 1974) show that surface soils at Woburn hold about 114 μg P/g on high-energy surfaces and about 80 μg P/g much less strongly. The top 30 cm of Woburn soil should, therefore, retain about 520 kg P/ha before detectable amounts leach below this depth and the evidence in Table 4 and Fig. 3 supports this prediction.

The percentages of total P applied which remained soluble in 0·5*M* $NaHCO_3$ ranged from 20·4–36·4% (Table 4). They were smallest for soils under leys (Lc and Ln) and on plots given straw, and largest (34·0 and 36·4%) on plots given fertilisers only (Fs) or peat (Pt). The smaller recoveries under leys are consistent with the evidence that 30–40% of the P applied to them accumulated as organic P. The large recovery of $NaHCO_3$-soluble P on plots given peat throws further doubt on the apparent accumulation of organic P in these soils. The proportions of P which remained $NaHCO_3$-soluble in plots given only fertilisers were larger than those measured (about 25%) on Saxmundham soils given much P (250–500 kg P/ha) for three years (Mattingly, Johnston & Chater 1970), probably because 100 kg P/ha (about one-third of the total applied to Fs plots) was ploughed down only four to five months before sampling.

Mineralisable nitrogen in the soils

Surface soil samples, taken in autumn 1968 and 1971, were used in incubation tests to measure mineralisable N. Inorganic N ($NH_4 + NO_3$) was measured in the soils before incubation in 1971 but not in 1968. Soils were incubated for three or eight weeks without or with $CaCO_3$ (0·2%), which brought the soils above pH 7. (This amount of $CaCO_3$ is approximately equivalent to a field dressing of 7 tonnes/ha.) Appendix Table 3 gives the NO_3-N and inorganic N contents of the soils and Table 5 the increases in mineralisable N, calculated as kg N/ha.

TABLE 5

Increases[a] in total soil N and mineralisable-N from residues of leys, peat, straw, green manures and farmyard manure in 1968 and 1971

		Increases (kg N/ha) in						
			Mineralisable N					Mean, as % increase in total soil N
			Unlimed		Limed			
Treatment	Year	Total soil N[b]	3 weeks	8 weeks	3 weeks	8 weeks	Mean	
Leys with clover	1968	190	36	40	41	48	41	22
	1971	190	49	48	28	38	41	22
Leys with nitrogen	1968	125	1	17	18	17	13	10
	1971	160	20	33	20	34	27	17
Peat	1968	—[c]	5	1	5	2	3	—
	1971	515	3	10	3	15	8	2
Straw	1968	—[c]	31	28	21	26	26	—
	1971	140	37	44	52	44	44	31
Green manures	1968	—[c]	9	27	22	33	23	—
	1971	70	13	30	23	27	23	33
Farmyard manure	1968	345	12	22	29	25	22	6
	1971	585	37	61	45	70	53	9

(a) Relative to plots given only fertilisers
(b) From Tables 1 and 2
(c) Increases not reliable

Mean increases in mineralisable N (Table 5) were 21 and 30 kg N/ha on unlimed soils, after three and eight weeks respectively and 26 and 32 kg N/ha on the limed soils. The averages of all four values, expressed as a percentage of the increase in total N in soils, ranged from 2 to 33% (Table 5). Nitrogen residues from peat were inert. About one-third of the residues, accumulated between 1965–71 from straw and green manures, mineralised readily. The absolute amounts of nitrogen that mineralised from residues of farmyard manure were 22 kg N/ha in 1968 samples and 53 kg N/ha in 1971 samples, about 6 and 9% respectively of the total N accumulated in the soils. More N mineralised in both years after the clover ley than after the ley given 'Nitro-Chalk', even though much N (126 kg N/ha per cut) was given to the N-treated ley in 1970–71 to avoid the risk of ploughing in an N-deficient sward. About twice as much N mineralised in 1971 as in 1968 from soils under the ley given 'Nitro-Chalk'. These results indicate the extra amounts of nitrogen which are potentially available in these soils after six to seven years under regimes which conserve or increase soil organic matter. They also confirm that nitrogen added as peat (over 500 kg N/ha) is largely inert, whereas about 10% of the residues from farmyard manure (585 kg N/ha) mineralises readily.

Conclusions and summary

1. This paper describes changes in the C, N and organic P in surface soils (0–23 cm) and in $NaHCO_3$-soluble P and exchangeable cations in soils, sampled to 53 cm, from an experiment on Stackyard Field, Woburn. The soils were cropped from 1965–71, (a) without organic manures, at two levels of PKMg manuring, (b) with additions of peat,

straw, green manures or farmyard manure, or (c) maintained under a grass–clover ley (without fertiliser N) or a grass ley given 'Nitro-Chalk'.

2. The amounts of organic matter that accumulated under the leys ranged from 8–10 tonnes/ha and contained 160–180 kg N/ha. About 90% of the organic matter added as peat, and all the N, remained in the soil in 1971; less than 2% of the N mineralised in incubation tests. About 13% of the organic matter added as straw, but nearly one-half of the N, was recovered in the soil in 1971. Between 30–40% of the organic matter and N from four green manure crops remained in the soil. About 30% of the N residues from straw and green manures mineralised rapidly on incubation. One-half of the organic matter and over one-third of the N from farmyard manure remained in the soil in 1971. Mineralisable N in soils containing residues of FYM more than doubled between 1968–71 and exceeded 50 kg N/ha.

3. Organic P accumulated in soils under leys and in soils given straw or FYM. Its apparent increase in soils given peat, which was otherwise inert, may be an artefact of the ignition method of analysis. Organic P did not change significantly in seven years in soils growing green manures or given only fertilisers.

4. Exchangeable K in surface soils increased from 75 to 152 μg K/g on arable soils and to 196 μg K/g under leys on plots which gained 680 kg K/ha, and to 256 μg K/g on plots which gained 2000 kg K/ha either from FYM or K fertiliser given between 1964–71. Only 60–70% of the K gained in the arable crop sequence was present as exchangeable K (to 53 cm); 250 and 800 kg K/ha had been 'fixed' or had leached below this depth from the small and large dressings respectively. More K (80–100% of the net gain by the soils) remained in the top 53 cm of soils under leys.

5. Exchangeable Mg in surface soils increased from 15 to 32 μg Mg/g on arable soils and to 46 μg Mg/g under leys on plots which gained 90 kg Mg/ha and to 40–50 μg Mg/g on plots which gained 260 kg Mg/ha either from FYM or from Mg fertilisers. All Mg accumulated from the smaller dressings in the arable crop sequence was recovered as exchangeable Mg (to 53 cm). About 50–70 kg Mg/ha from the larger dressings had leached below 53 cm or was 'fixed' by the soil. More Mg (20–30 kg Mg/ha) was present as exchangeable Mg under leys, mostly in the top 30 cm of soil, than was gained by manuring. The amounts of Mg added in rain (20–22 kg Mg/ha) between 1964–72/3 account for the extra Mg in soils under leys and show that about 20 kg Mg/ha leached below 53 cm in arable soils.

6. $NaHCO_3$-soluble P in surface soils increased from 28 to 43 μg P/g on plots which gained 220 kg P/ha and to 65 μg P/g on plots which gained 550 kg P/ha between 1964–71. Little P moved below 30 cm when the smaller amount was applied but soil below 30 cm was slightly enriched with soluble P from the larger dressings.

7. Organic matter, accumulated in soils between 1965–71 had little effect on the amounts or vertical distribution of exchangeable K or Mg, or $0{\cdot}5M$ $NaHCO_3$-soluble P, in soils sampled to a depth of 53 cm. More exchangeable K and Mg, and slightly less $NaHCO_3$-soluble P, accumulated in the top 30 cm under leys than in soils in the arable crop sequence. In the second phase of this experiment (1972–76) the effects of different types and amounts of organic matter accumulated from 1965–71 will, therefore, be evaluated on soils in which both the amounts and distribution of P, K and Mg are similar but not identical.

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APPENDIX

Total nitrogen by Kjeldahl digestion using a Cu–Se catalyst. NH_3 in the digests was estimated by distillation.

Total carbon was measured on soil ground <0·5 mm by the method described by Walkley (1947); no phosphoric acid was added before titrating and *n*-phenylanthranilic acid was used as the indicator.

Surface soils taken from all plots in 1971 were also analysed by the Tinsley (1950) method described by Bremner and Jenkinson (1960). The ratio of Tinsley C/Walkley C ranged from 1·28–1·35 ± 0·026 for all soils other than those given peat, for which the ratio was 1·23. The correction factors used were 1·30 for all treatments except peat.

Total P was estimated, after fusion with sodium carbonate (Mattingly, 1970), on the 'Technicon AutoAnalyzer' using the method described by Salt (1968).

Organic P was measured by an ignition method described by Saunders and Williams (1955). Soil (2 g < 60 mesh) was ignited at 500–550°C for 2 hours and extracted with 0·2*N* H_2SO_4 (100 ml) for 2 hours at room temperature. Organic P was estimated from the difference between 0·2*N* H_2SO_4-soluble P extracted from ignited and air-dry soil.

Sodium bicarbonate-soluble P was measured, after extraction with 0·5*M* $NaHCO_3$ (Olsen *et al.*, 1954), on the 'Technicon AutoAnalyzer' (Salt, 1968).

Water-soluble boron. Ten grammes air-dry soil (<2 mm) were refluxed with 20 ml of boron-free water for 15 minutes in silica flasks. Boron was estimated colorimetrically with 1,1′-dianthrimide (Gorfinkiel & Pollard, 1952).

Exchangeable cations were leached from soils (<2 mm) with *N* ammonium acetate (Metson, 1956). Aliquots were evaporated to dryness, the residue oxidised with 0·5 ml conc. HNO_3 and dissolved in 10 ml 0·2*N* HCl. Na, K and Ca were measured by emission and Mg by atomic absorption spectrophotometry.

Mineralisable nitrogen. Fifty grammes soil (<2 mm), air-dried and stored for 18–20 weeks, were incubated at 25°C at one-half of their water-holding capacity, measured in the laboratory. After three or eight weeks, the soils were extracted for 2 hours with 100 ml *N* K_2SO_4, adjusted to pH 1. NH_4-N and NO_3-N were determined in the extracts by steam distillation (Bremner & Keeney, 1965); NO_3-N was reduced with Devarda's alloy (<300 mesh). Phosphate in the extracts did not interfere with NO_3-N estimations.

APPENDIX TABLE 1

Mechanical analyses[a] of surface soils (0–23 cm) in 1964, total C, N and P contents and increases in C contents, 1964–71

			Mechanical analysis, % oven-dry soil						% air-dry soil			
Block	Plot No.	Treatment	Coarse sand 2000–200 μm	Fine sand 200–20 μm	Silt 20–2 μm	Clay <2 μm	Loss on solution	Air-dry moisture	Total C	Total N	Total P	Increase in total C (1964–71)
I	1	Lc	48·0	31·2	5·5	10·7	2·5	1·0	0·833	0·091	0·083	0·217
	2	Ln	62·2	17·7	5·6	9·8	2·5	0·9	0·823	0·094	0·081	0·126
	3	St	45·7	36·4	4·0	9·8	2·3	0·8	0·753	0·086	0·077	0·092
	4	Gm	57·8	25·1	4·8	10·0	2·1	0·9	0·734	0·085	0·080	0·029
	5	Dg	65·0	17·6	4·9	9·5	2·2	0·8	0·726	0·084	0·075	0·278
	6	Fd	47·4	37·2	4·8	8·8	2·1	0·8	0·698	0·080	0·077	−0·079
	7	Pt	62·7	21·9	3·6	8·3	2·0	0·7	0·675	0·075	0·073	0·633
	8	Fs	50·2	35·5	3·2	7·8	1·7	0·7	0·566	0·066	0·065	−0·021
	Mean		54·9	27·8	4·5	9·3	2·2	0·8	0·726	0·083	0·076	0·159
II	9	Fd	55·1	29·6	3·8	8·6	2·1	0·8	0·671	0·079	0·075	−0·075
	10	Gm	66·4	18·9	3·6	8·4	2·0	0·8	0·668	0·073	0·070	0·036
	11	Dg	55·9	29·7	4·0	7·8	1·9	0·7	0·645	0·072	0·071	0·320
	12	Pt	65·3	18·5	4·8	9·2	2·2	0·8	0·755	0·082	0·074	0·656
	13	Lc	53·1	28·5	5·8	11·0	2·5	0·9	0·760	0·082	0·072	0·118
	14	Fs	52·4	29·9	5·4	10·2	2·3	1·0	0·788	0·086	0·076	−0·035
	15	St	39·9	39·0	7·0	11·1	2·5	1·0	0·858	0·092	0·070	0·053
	16	Ln	34·8	42·1	7·8	11·9	3·0	1·1	0·862	0·095	0·072	0·108
	Mean		52·9	29·5	5·3	9 8	2·3	0·9	0·751	0·083	0·072	0·148
III	17	St	53·1	27·3	6·0	11·1	2·8	1·0	0·851	0·090	0·084	0·135
	18	Fs	62·0	19·4	5·7	10·2	2·4	1·1	0·835	0·092	0·081	−0·058
	19	Gm	60·6	19·8	6·6	10·4	2·4	0·9	0·801	0·090	0·081	0·048
	20	Ln	59·3	20·7	5·6	10·1	2·6	0·9	0·811	0·090	0·079	0·074
	21	Pt	55·2	24·3	6·9	10·0	2·7	0·9	0·788	0·086	0·074	0·592
	22	Fd	42·8	36·7	6·4	10·1	2·7	1·0	0·783	0·085	0·076	−0·052
	23	Dg	55·6	24·8	5·4	10·2	2·3	1·0	0·771	0·078	0·076	0·278
	24	Lc	49·2	32·1	5·1	9·9	2·2	0·8	0·655	0·076	0·076	0·151
	Mean		54·7	25·6	6·0	10·2	2·5	0·9	0·787	0·086	0·078	0·146
IV	25	Ln	44·1	37·4	5·3	9·3	2·4	0·8	0·758	0·083	0·073	0·121
	26	Dg	42·5	38·0	5·6	11·1	2·4	1·0	0·777	0·088	0·074	0·342
	27	Pt	45·6	31·4	7·0	11·2	2·5	1·1	0·753	0·088	0·069	0·613
	28	Fs	56·3	21·2	7·0	11·1	2·2	1·1	0·827	0·093	0·070	−0·077
	29	Lc	55·3	22·0	6·7	11·9	2·7	1·0	0·812	0·090	0·073	0·126
	30	Fd	56·0	21·4	7·4	12·4	2·5	1·2	0·822	0·088	0·071	−0·053
	31	St	41·8	34·2	7·6	13·1	2·9	1·2	0·853	0·090	0·069	0·091
	32	Gm	39·1	34·4	8·2	12·8	3·0	1·2	0·846	0·092	0·070	0·020
	Mean		47·6	30·0	6·8	11·6	2·6	1·1	0·806	0·089	0·071	0·148

(a) Mechanical analyses were done by E. Bird, using the International pipette method. Organic matter was removed with H_2O_2 and the soils dispersed with NaOH

APPENDIX TABLE 2

Chemical analyses[a] of air-dry soils in 1964, 1968 and 1971

Treat-ment	Year	Total C[b] (%)	Total N (%)	C/N	pH[d] in 0·01*M* $CaCl_2$	Total P (µg/g)	Organic P (µg/g)	$NaHCO_3$-P (µg/g)	Exchangeable cations (µg/g) K	Na	Ca	Mg	Water-soluble B (µg/g)
Lc		0·77	0·085	9·0	5·92	761	221	28·0	73	10	1370	15	0·49
Ln		0·82	0·091	9·0	5·95	763	238	25·8	75	11	1420	16	0·50
Pt		0·74	0·083	8·9	5·75	724	218	28·4	72	9	1260	15	0·62
St	1964	0·82	0·090	9·1	5·89	752	237	25·9	77	9	1470	17	0·54
Gm		0·77	0·085	9·0	5·90	751	242	28·7	80	11	1360	16	0·49
Fs		0·75	0·084	8·9	5·76	731	229	27·5	74	11	1270	15	0·49
Fd		0·74	0·083	8·9	6·00	746	213	30·1	77	10	1340	15	0·54
Dg		0·73	0·080	9·1	5·94	740	218	30·7	75	12	1310	14	0·56
Mean		0·77	0·085	9·0	5·89	746	227	28·1	75	10	1350	15	0·53
Lc		0·91	0·091	10·0	5·25	—	254	35·0	112	10	1100	31	0·38
Ln		0·91	0·095	9·6	5·53	—	244	36·9	122	10	1230	32	0·41
Pt		0·96[c]	0·084	11·4	5·18	—	231	43·0	90	10	1060	21	0·44
St	1968	0·87	0·093	9·4	5·45	—	255	37·5	96	9	1300	26	0·39
Gm		0·83	0·087	9·5	5·32	—	262	40·4	94	12	1130	24	0·36
Fs		0·73	0·081	9·0	5·29	—	237	40·7	91	8	1100	22	0·38
Fd		0·74	0·078	9·5	5·42	—	220	62·7	115	8	1070	32	0·34
Dg		0·88	0·090	9·8	5·62	—	243	58·8	122	14	1170	43	0·42
Mean		0·85	0·087	9·8	5·38	—	243	44·4	105	10	1145	29	0·39
Lc		0·92	0·091	10·1	5·91	798	252	41·5	204	7	1320	48	0·45
Ln		0·92	0·096	9·6	6·11	801	263	38·5	188	9	1430	43	0·35
Pt		1·33[c]	0·098	13·6	5·78	774	238	46·7	157	5	1430	31	0·50
St	1971	0·92	0·093	9·9	6·35	785	263	43·1	161	6	1590	34	0·30
Gm		0·79	0·087	9·1	6·03	812	246	42·7	141	6	1380	30	0·34
Fs		0·70	0·084	8·3	6·12	779	235	44·2	148	6	1300	31	0·35
Fd		0·68	0·080	8·5	6·13	789	226	66·2	267	5	1200	40	0·32
Dg		1·04	0·097	10·7	6·41	843	248	62·8	246	8	1520	49	0·40
Mean		0·91	0·091	10·0	6·10	798	246	48·2	189	6·5	1395	38	0·38

(a) All analyses, except total P and water-soluble B, are means of 16 sub-plots; total P and water-soluble B are means of four main plots.
(b) Total C = 1·30 × Walkley value
(c) Total C = 1·23 × Walkley value
(d) pH in water = 0·52 + 0·96 pH (in 0·01*M* $CaCl_2$)

APPENDIX TABLE 3

Nitrate-N and total mineral-N in surface soils (1968 and 1971) incubated for three and eight weeks

(All results in μg N/g air-dried soil)

pH	Time of incubation (weeks)	Clover ley		Grass ley		Peat		Straw		Green manures		Fertilisers (Fs)		Fertilisers (Fd)		Farmyard manure	
		NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N	NO_3^- N	NH_4^+ + NO_3^- N
Samples taken in autumn, 1968																	
Unlimed (pH 5·41)	3	23·9	30·2	18·8	18·8	19·6	20·1	23·2	27·5	20·7	21·2	16·0	18·6	16·8	18·2	19·8	21·6
	8	33·6	34·3	26·2	26·8	21·8	21·8	29·6	29·6	29·4	29·4	21·5	21·5	21·7	21·7	28·1	28·1
Limed (pH 7·07)	3	32·2	33·0	24·5	25·6	19·5	21·4	21·3	26·0	22·4	26·4	19·2	20·0	21·1	22·0	26·6	30·3
	8	39·2	43·0	31·2	33·0	27·0	28·3	34·1	35·2	37·3	37·3	27·1	27·6	27·7	29·2	35·4	36·6
Samples taken in autumn, 1971																	
Unlimed (pH 6·20)	0[a]	1·4	5·1	2·3	5·5	2·9	6·2	3·4	7·0	3·2	6·5	2·8	5·2	2·8	4·8	5·4	9·4
	3	37·4	37·8	27·8	28·4	22·3	23·0	32·6	32·8	25·2	26·0	21·2	22·1	23·0	24·6	34·6	35·3
	8	44·4	45·4	39·0	40·4	31·3	33·0	41·4	42·8	37·3	38·6	29·6	30·0	28·9	29·8	45·2	47·4
Limed (pH 7·15)	3	33·8	35·1	30·6	32·7	26·0	27·1	39·4	41·4	31·0	33·1	24·3	26·3	24·1	25·9	36·1	39·0
	8	43·4	45·8	42·8	44·6	36·2	38·2	43·7	46·6	40·4	41·7	32·9	33·8	31·1	33·1	51·0	53·5

(a) Measured on air-dried soils stored 19 weeks before incubation