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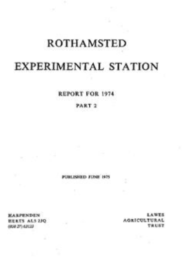

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G. E. G. Mattingly, Margaret Chater and A. E. Johnston

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Experiments made on Stackyard Field, Woburn, 1876–1974

III. Effects of NPK Fertilisers and Farmyard Manure on Soil Carbon, Nitrogen and Organic Phosphorus

G. E. G. MATTINGLY, MARGARET CHATER and A. E. JOHNSTON

Introduction

The publication by the Agricultural Advisory Council (1970) of their report on *Modern Farming and the Soil* focused attention on the losses of organic matter from light soils. The authors implied, rather than stated explicitly, that the decline in soil organic matter could be attributed to the increase in the number of cereal crops grown in recent years and to 'modern' methods of arable farming. No evidence was given, however, which clearly established that the rates of loss of soil organic matter have been greater in recent years than 50 or more years ago.

The experiments started on Stackyard Field at Woburn in 1876, and continued until the present day, provide unique data for assessing both the rates of loss of organic matter from soil cropped in traditional four-course rotations and from soils in continuous cereal cropping. Russell and Voelcker (1936) published the results from the first 50 years of the experiments on Stackyard and Crowther (1936) discussed critically some of the changes in soil organic matter in many of the soils. This paper describes:

(i) the changes in carbon and nitrogen contents of soils from the Continuous Wheat and Barley experiments from 1876–1972,
(ii) the changes in organic phosphorus in these soils from 1888–1959, and
(iii) compares losses of soil carbon and nitrogen from soils growing continuous cereals (often fallowed) with losses from soils in the same field cropped in rotations.

Experiments started since 1936 on Stackyard Field (and summarised in Part I of this series of papers) have investigated the possibility of lessening losses of soil organic matter from Woburn soils by growing green manures or leys or by applying organic manures; some are still in progress or have recently been extensively modified. Detailed discussions of these alternative systems of maintaining or increasing soil organic matter at Woburn are deferred until results from all relevant recent experiments have been summarised and published.

Changes in the carbon and nitrogen contents of soils from the Continuous Wheat and Barley experiments

The analytical methods used to measure soil carbon and nitrogen are given in the Appendix. Appendix Tables 1 and 2 give the C, N, total P and organic P contents and the C/N and C/organic P ratios of soils (0–23 cm) from all 13 main plots from the Continuous Wheat and Barley experiments in 1888, 1927, 1932 and 1959. The carbon and nitrogen analyses in 1888, 1927 and 1932 for whole plots were calculated from the means of sub-plot analyses given by Crowther (1936). Values in 1959 were calculated from the means of quarter-plot analyses for carbon; nitrogen analyses were done on bulked samples from quarter plots. All sub-plots (see Part I) were sampled and analysed only for

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total carbon in 1959 (0–23 cm, 23–30 cm and 30–45 cm) and in 1965 (0–23 cm); these results are in Appendix Table 3. Plots 1, 2 and 3 from both the wheat and barley experiments were further analysed for carbon and nitrogen in 1967 and 1972 (Table 1).

TABLE 1

Carbon and nitrogen contents, C/N ratios and pH of soils (0–23 cm) from plots 1, 2 and 3 of the Continuous Wheat and Barley experiments, Stackyard, Woburn, 1888–1972

	Plot 1 (unmanured)				Plot 2 (ammonium sulphate)				Plot 3 (sodium nitrate)			
Year	Total C (%)	Total N (%)	C/N	pH in 0·01M-$CaCl_2$	Total C (%)	Total N (%)	C/N	pH in 0·01M-$CaCl_2$	Total C (%)	Total N (%)	C/N	pH in 0·01M-$CaCl_2$
					Continuous wheat							
1888	1·18	0·126	9·4	5·0	1·26	0·131	9·6	4·6	1·25	0·126	9·9	5·3
1927	1·03	0·105	9·8	4·6	0·96	0·099	9·7	4·0	1·00	0·099	10·1	4·9
1932	0·97	0·106	9·2	4·5	0·91	0·097	9·4	4·0	0·94	0·097	9·7	4·7
1959	0·89	0·105	8·5	4·5	0·63	0·078	8·1	4·5	0·77	0·092	8·4	4·6
1965	0·89	0·096	9·3	5·5	0·61	0·071	8·6	5·8	0·76	0·080	9·5	5·7
1967	0·85	0·100	8·5	5·9	0·69	0·080	8·6	6·2	0·77	0·090	8·6	6·1
1972	0·75	0·085	8·8	6·4	0·60	0·070	8·6	6·4	0·68	0·076	9·0	6·4
					Continuous barley							
1888	1·26	0·144	8·8	4·9	1·34	0·143	9·4	4·7	1·33	0·143	9·3	5·1
1927	0·96	0·094	10·2	4·4	0·96	0·101	9·5	4·3	1·02	0·105	9·7	5·1
1932	0·93	0·095	9·8	4·4	0·94	0·097	9·7	4·3	0·95	0·099	9·6	5·0
1959	0·65	0·080	8·1	4·6	0·53	0·070	7·6	4·7	0·71	0·088	8·1	4·9
1965	0·73	0·083	8·8	5·8	0·60	0·075	8·0	6·0	0·68	0·080	8·5	6·0
1967	0·64	0·070	9·1	6·0	0·63	0·070	9·0	6·2	0·70	0·090	7·8	6·3
1972	0·64	0·070	9·1	6·8	0·56	0·063	8·9	6·8	0·65	0·073	8·9	6·8

Crowther (1936) noted that the carbon contents (and C/N ratios) of several plots in the Continuous Wheat experiment (especially plots 7 and 8), which are in the southern corner of the field, close to the boundary fences and an old access gate, were anomalously high due to the presence of coal and charcoal in the soils. He commented 'All experiments with unreplicated plots, and especially those with systematic arrangements, are subject to irregularities of unknown magnitude. Conclusions from the Woburn soil analyses can be drawn with confidence only when a number of similarly treated plots show similar effects or when the trends over a series of repeated samplings are clear'. In his discussion of the results of these experiments up to 1932 he emphasised that 'the results of all relevant plots and samplings are averaged whenever possible' and we have adopted this procedure to follow further changes in the analyses of these soils between 1932 and 1972.

Fig. 1 shows, as means of both the Continuous Wheat and Barley experiments, the changes in %C, %N, C/N ratios and C/organic P ratios and the total and organic P contents of some soils between 1876–1959 (1965 for soil carbon). During the first phase of the experiments the mean carbon and nitrogen contents of soils from plots 1–9 decreased steadily from 1·34% C and 0·135% N in 1888 to 1·06% C and 0·103% N in 1927. Variations in the carbon contents of soils at the start of the experiment (especially the high values on plots 4, 7 and 8 from the Continuous Wheat experiment referred to above) make it difficult to assess, in any one year, the effects of the main fertiliser treatments (other than FYM) on the carbon content of the soil. The poor crops of barley, particularly on plots 2, 5 and 8 which went acid early in this century, must have returned little organic matter to the soil as crop residues. There is no evidence from either experiment that the soil organic carbon declined less rapidly on well-manured plots (5, 6, 8 and 9) than on unmanured plots (1 and 7) or plots given only nitrogen fertilisers (2 and 3).

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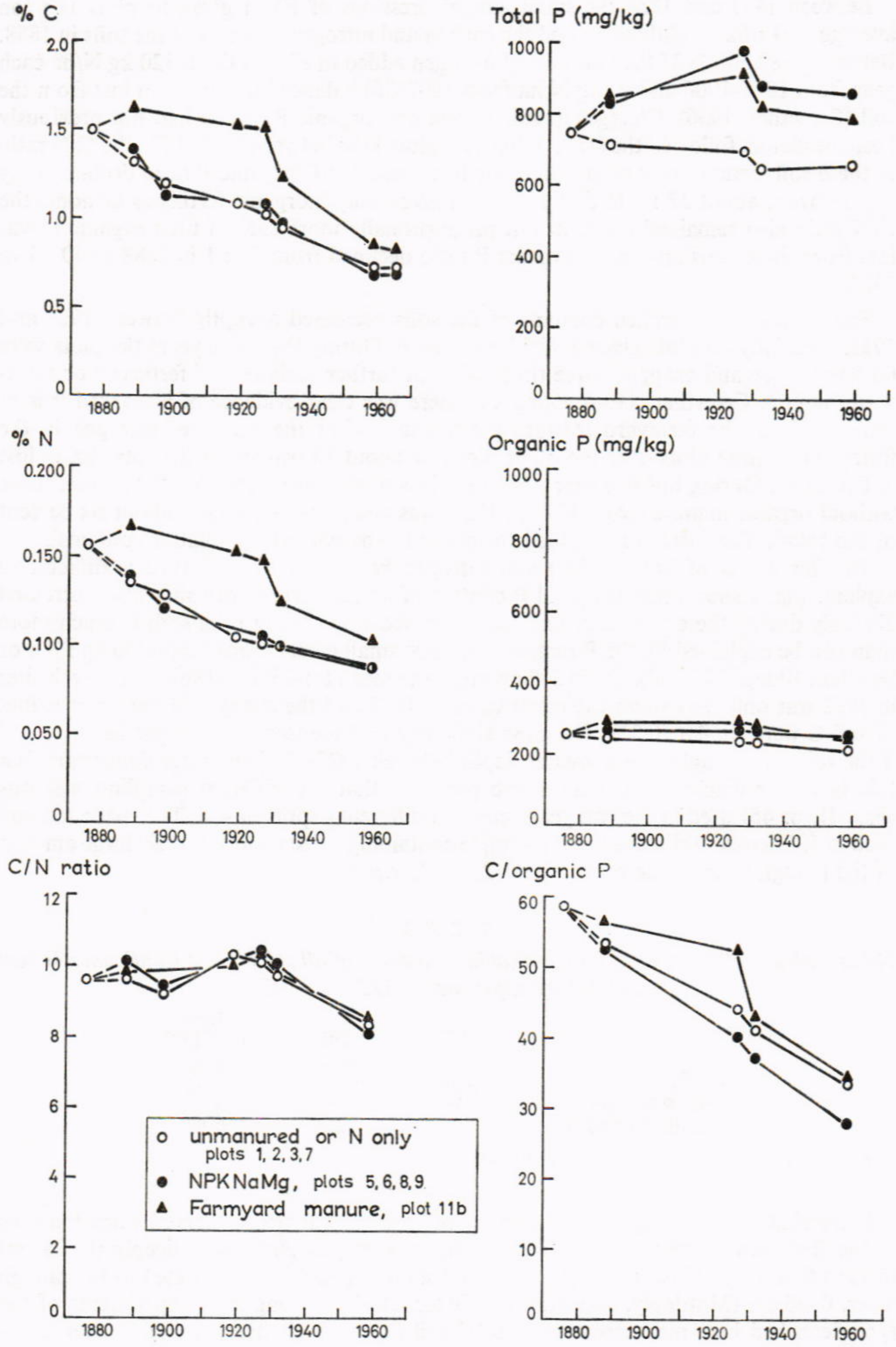

FIG. 1. Changes in the %C, %N, organic P, total P and the C/N and C/organic P ratios of some soils from the Continuous Wheat and Barley experiments, Stackyard, Woburn, 1876–1959 (1965 for carbon).

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Between 1877 and 1888 the small annual dressings of FYM given to plots 11b (on average 19·7 t/ha) slightly increased the carbon and nitrogen contents of the soils in 1888. Between 1888 and 1927 the amounts of nitrogen added in FYM (about 120 kg N/ha each year from 1877–1906 and 90 kg N/ha from 1907–26) balanced the nitrogen lost from the soil (Crowther, 1936). Changes in soil carbon and organic P, which had not previously been measured, followed the same pattern on plots 11b; between 1888–1927 the C/N ratio in these soils remained constant at about 10 : 1 and the C/organic P ratio declined only slightly from about 57 : 1 to 53 : 1. In soils given only inorganic fertilisers or none, the C/N ratio also remained constant but proportionally more carbon than organic P was lost from these soils and the C/organic P ratio declined from 55 : 1 in 1888 to 40 : 1 in 1927.

The carbon and nitrogen contents of the soils decreased abruptly between 1927 and 1932, especially on plots given FYM before 1926. During these five years the plots were fallowed twice and cropped three times without further additions of fertilisers or farmyard manure. Crowther (1936) stated '. . . there was clear evidence of a marked loss of nitrogen from the farmyard manure plots, one half of the excess of nitrogen in the farmyard manure plots over the other plots, or about 16 percent of the total being lost in five years. During this five year period the loss of nitrogen from plots 1 to 9 (i.e. those without organic manures from 1876 to 1927) was comparatively slight (about six percent of the total). The losses thus tended to follow the actual organic matter contents'.

This large loss of both carbon and nitrogen between 1927 and 1932 is difficult to explain. Fig. 1 shows that the total P content of all soils from both sites also decreased abruptly during these five years and the mean decrease (75 mg P/kg soil) is much more than can be explained by the P removed in three small cereal crops (about 30 kg P/ha or less than 10 mg P/kg soil). Table 2 shows that the mean total P in all soils from both sites in 1932 was only 0·91 times the mean value in 1927 and the changes in the mean values of soil C were similar (0·92). The close similarity of these two ratios might be explained if the soil was ploughed to a greater depth between 1927–32 than in previous years, but this is very unlikely. It is much more probable that the different sampling methods (Part II, p. 45) used in the two years sampled different depths of soil. The spade method used in 1927 could well have given a sample containing a disproportionately large amount of the plough layer in the composite 0–23 cm horizon.

TABLE 2

Mean carbon, nitrogen, total P and organic P contents of all soils[a] from Continuous Wheat and Barley experiments, 1927 and 1932

	1927	1932	Ratio 1932/1927
C (%)	1·088	0·996	0·92
N (%)	0·106	0·101	0·95
Total P (mg/kg)	838	763	0·91
Organic P (mg/kg)	261	252	0·97

(a) Means of plots 1–9, 10a, 10b, 11a and 11b

Somewhat larger changes in soil carbon and total soil P were observed when the soils in the Rotation II experiment at Saxmundham were ploughed more deeply (to 25 cm) in 1964 than in previous years and when soil sampling had been restricted to the plough layer, 0–20 cm (Mattingly, Johnston & Chater, 1970). In long-term experiments of the type described here measurements of total soil P, which changes negligibly over a few years, provide a useful method of detecting spurious changes in carbon and nitrogen contents of soils due to changes in methods of sampling or cultivation.

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Changes in C contents of soils from plots 1, 2 and 3 between 1888–1927 and 1932–72. The most complete set of carbon analyses refer to plots 1, 2 and 3 from both the Continuous Wheat and Barley experiments. Changes in carbon contents in all six plots are summarised in Table 3 for the periods 1888–1927 and 1932–72, covering 39 and 40 years respectively and omitting the abrupt change in soil carbon between 1927 and 1932.

TABLE 3

Changes in carbon content[a] of soils (0–23 cm) from plots 1, 2 and 3 of the Continuous Wheat and Barley experiments, Stackyard, Woburn, 1888–1972

Plot no.	Treatment	Years	Continuous wheat	Continuous barley	Mean
1	Unmanured	1888–1927	−0·15	−0·30	−0·22
		1932–72	−0·22	−0·29	−0·26
2	Ammonium sulphate only	1888–1927	−0·30	−0·38	−0·34
		1932–72	−0·31	−0·38	−0·34
3	Sodium nitrate only	1888–1927	−0·25	−0·31	−0·28
		1932–72	−0·26	−0·30	−0·28

(a) %C in air-dry soil

Table 3 shows that (i) more soil carbon was lost from each plot of the Continuous Barley experiment than from the Continuous Wheat experiment and (ii) losses were larger from plot 2 (ammonium sulphate) in both experiments than from plots 1 or 3 (unmanured and sodium nitrate). The larger losses of carbon from soils growing barley are consistent with the longer period from harvest to drilling with barley than with winter wheat. The larger losses of carbon from the soils in both experiments from plot 2 (ammonium sulphate from 1877–1926) may be because these plots grew very small crops (1888–1927) or were often fallowed (1932–72) before the soil acidity was corrected by the liming programme in the 1950s (Part II). The differences in pH in 1959 between soils from plots 2 and 3 were only small after liming but, during much of the period 1888–1927, soil pH was 0·8–0·9 pH units less on ammonium sulphate plots than on sodium nitrate plots. Whilst most evidence suggests that the rate of decomposition of soil organic matter increases with increasing pH, the larger losses of carbon from the most acid soils in these experiments are tentatively attributed to the long periods of fallowing and to the small amounts of organic matter returned to them. It is, however, possible that the soil clays were modified during the long period during which soils in plot 2 remained acid (pH 4 in 0·01M-$CaCl_2$) and that some organic matter may have formed soluble complexes with exchangeable Al. Analyses of sub-soils, 23–30 cm and 30–45 cm (Appendix Table 3) do not suggest, however, that any more carbon moved into these depths on the plots given ammonium sulphate than on plots given sodium nitrate.

In all comparisons made in Table 3, as much carbon was lost between 1932–72 as between 1888–1927. Losses of carbon from soils due to microbial activity normally follow an exponential curve so that larger losses would be expected in the first than in the second period. The results here, which seem well-established, can reasonably be explained by assuming that the organic matter in the roots and stubble of the larger crops grown between 1877–1906 (see yields in Part I) compensated to some extent for the losses of organic matter by microbial activity. Small crops and long periods of fallow after 1927 (the barley experiment was fallowed in nine of the 32 years between 1927–58) would explain the large losses of carbon from soils between 1932–72.

The organic phosphorus content of the soils

Table 4 gives the total and organic P contents of soils from the Continuous Wheat and Barley experiments between 1888–1959. The organic P values are means of analyses by

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extraction and ignition methods and are rounded to the nearest 5 mg P/kg soil. Total P and organic P values were slightly larger on the wheat than on the barley experiment but, with the exception of plot 11b, the changes in organic P over 71 years were very similar on both sites. Between 1888–1959 organic P decreased on soils given no phosphorus in the wheat and barley experiments by 35 and 25 mg P/kg soil respectively, about 12% of the total organic P present in 1888. These changes are equivalent to a mean annual loss of about 1·5 kg organic P/ha from the top 23 cm of soil.

TABLE 4

Total and organic phosphorus contents of soils from the Continuous Wheat and Barley experiments, Stackyard, Woburn, 1888–1959

			Total P (mg/kg)		Organic P[b] (mg/kg)	
Treatment	Plots	Year	Wheat experiment	Barley experiment	Wheat experiment	Barley experiment
No phosphorus since 1876	1, 2, 3, 7	1888	720	715	265	230
		1927	695	695	250	215
		1959	695	620	230	205
Superphosphate (1877–1926)	5, 6, 8, 9	1888	850	810	280	245
		1927	1020	930	285	255
		1959	895	810	270	240
Farmyard manure, rape cake[a]	10a, 10b, 11a	1888	735	825	260	260
		1927	745	780	280	280
		1959	720	720	250	255
Farmyard manure (1877–1926)	11b	1888	885	820	(315)[c]	260
		1927	930	900	285	290
		1959	785	795	260	245

(a) For details of manuring, see Part I, p. 32
(b) Means of estimations by extraction and ignition
(c) Anomalous value, see text

Organic P values changed very little in both experiments between 1888–1927 on soils given superphosphate. It seems reasonable to attribute the almost constant values of organic P on plots 5, 6, 8 and 9 to the additions of larger amounts of roots and stubble which contained some organic P or which provided sufficient amounts of carbohydrate to immobilise 1–2 kg P/ha each year as organic P. Between 1927–59, when no superphosphate was applied and smaller crops were grown, plots 5, 6, 8 and 9 lost about the same amounts of organic P (15 mg P/kg soil) as plots 1, 2, 3 and 7.

The value (315 mg P/kg) for the organic P content of plot 11b in the wheat experiment in 1888 is clearly anomalous. Several adjacent plots (7, 8, 9 and 11a) also contained large amounts of total carbon and organic P in 1888 and C/N ratios on these plots, which ranged from 9·9 to 11·5, were larger than values on corresponding plots of the barley experiment (Appendix Tables 1 and 2). It is probable, as Crowther (1936) commented, that the soils from these plots initially contained more organic matter (including organic P) than soils from the rest of the experimental area. Organic P increased in plot 11b of the barley experiment by 30 mg P/kg between 1888–1927 and decreased, between 1927–59, when no more farmyard manure was applied, by 25 and 45 mg P/kg on the wheat and barley experiments respectively. The average annual rate of mineralisation of organic P from residues of farmyard manure during this period was about 1 mg P/kg soil, equivalent to 3·5 kg P/ha.

The manuring of plots 10a, 10b and 11a (given in Part I) varied during the period 1876–1926 but all three plots were given some organic manure as farmyard manure or rape cake. The organic P in these soils increased on both sites by 20 mg P/kg soil between 1888–1927 and decreased in the wheat and barley experiments by 30 and 25 mg P/kg respectively between 1927–59. The changes since 1927 are greater than those on plots given superphosphate but slightly smaller than those on plots given farmyard manure.

Recoveries of carbon, nitrogen and organic phosphorus from farmyard manure

Table 5 summarises the amounts of carbon, nitrogen and organic phosphorus, applied in farmyard manure from 1877–1926, which remained in the soils in 1927, 1932 and 1959.

TABLE 5

Recoveries of carbon, nitrogen and organic phosphorus from farmyard manure applied between 1877–1926 in the Continuous Wheat and Barley experiments

	Applied between 1877–1926	Remaining in soils in 1927 0–23 cm	1932 0–23 cm	1959 0–23 cm	1959 23–45 cm
Carbon, t/ha	78·5[a] / 71·5[b]	15·5	8·3	4·8	1·8
Carbon, % remaining	a	19·8	10·6	6·1	2·3
	b	21·7	11·6	6·7	2·5
Nitrogen, t/ha	5·50[c]	1·56	0·85	0·45	n.a.
Nitrogen, % remaining	—	28·4	15·5	8·2	n.a.
Organic P, kg/ha	230[d]	117	131	62	n.a.
Organic P, % remaining	—	51	57	27	n.a.

(a) Assuming 50 dressings of farmyard manure (17·6 t/ha/year) containing 154 kg organic matter/t =89 kg carbon/t (Part 1, p. 34)
(b) Assuming an average C/N ratio of 13 : 1
(c) Total N added = 5500 kg N (Part 1, p. 34)
(d) Assuming one-quarter of total P added as organic P

The data in this table are derived from mean analyses from both the Continuous Wheat and Barley experiments (Appendix Tables 1 and 2); increases in the total carbon, nitrogen and organic phosphorus in each year were calculated from differences between values for plots 11b *minus* mean values for plots 1–9 inclusive. The weight of air-dry soil (0–23 cm) is 3440 t/ha. The total amount of nitrogen applied (5·50 t/ha) is a fairly reliable estimate (Part I, p. 34). The amount of carbon applied in not known but two estimates are used (Part I, p. 34). The amount of organic phosphorus in farmyard manure varies with the source and method of storage; we have used a value of 25% of the total phosphorus applied which is near the average for many samples (Peperzak, Caldwell, Hunziker & Black, 1959).

Proportionally more nitrogen (29%) than carbon (20–22%) remained in the soil in 1927 after farmyard manure had been applied cumulatively for 50 years. Losses in the next five years appeared to be very rapid; nearly one-half of the residues of carbon and nitrogen were lost from the surface soil (0–23 cm) between 1927–32. These losses may be exaggerated by differences in the methods of sampling used in the two years, discussed above, particularly as there were no significant differences between the amounts of organic phosphorus in the soils in 1927 and 1932.

The amounts of carbon, nitrogen and organic phosphorus remaining in the surface soils almost halved between 1932 and 1959. A greater proportion of organic P (27%) applied in farmyard manure remained in the surface soil in 1959 than carbon (7%) or nitrogen (8%). Analyses of sub-soils in 1959 (Appendix Table 3) showed that small

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amounts of carbon moved below 23 cm on plots given farmyard manure; the amounts recovered at these depths (plot 11b *minus* mean of plots 1–9) were about one-third those recovered in the surface soil.

Comparison of soil carbon in the Continuous Wheat and Barley experiments and in the rotation experiments

Table 6 gives the %C in samples of surface soils (0–23 cm) taken from the Continuous Wheat and Barley experiments and from Series A, C and D, described in Part I, between 1876 and 1972. The analyses before 1932 were given by Crowther (1936). The most complete data refer to the nine plots from the Continuous Wheat and Barley experiments, none of which received organic manures and all of which were sampled in 1888, 1927, 1932 and 1959. Less is known about the reliability of the sampling (i.e. the location and number of sampling units) of soils from the early rotation experiments (Series A, C and D) and soils from Series B were not analysed before 1964.

TABLE 6

Carbon contents[a] of soils (0–23 cm) from Continuous Wheat and Barley experiments and from rotation experiments on Stackyard Field, Woburn, 1876–1972

Continuous Wheat and Barley experiments		Rotation experiments					Mean difference between soils in continuous cereals and in rotations
Year	Plot 1–9[b]	Year	Series A	Series C	Series D	Mean of Series A, C and D	
1876	1·49[c]	1876	1·51[c]	1·32[c]	1·59[c]	1·47	+0·02
1888	1·34	1886	1·46	1·36	1·66	1·49	−0·15
1898	1·17[d]	1899	1·31	1·20	1·57	1·36	−0·19
1927	1·06	1920	0·98[e]	—	1·22[e]	1·10	−0·04
1932	0·98	1932	0·97[e]	1·00	1·14	1·04	−0·06
—	—	1936–38	0·86	—	1·02[f]	0·94	—
1959	0·73	1957–60	0·90[e]	0·70	0·91[f]	0·84	−0·11
1972	0·70	1972	0·78	0·68	0·88[f]	0·78	−0·08

(a) %C in air-dry soil. (b) Plots given inorganic fertilisers only. (c) Initial site samples. (d) Only six barley plots and four wheat plots sampled. (e) Values calculated from %N assuming C/N ratio = 10. (f) Plots in continuous arable rotations, without farmyard manure (Johnston, 1973).

Soils from Series C had the least C (1·32%) and soils from Series D the most C (1·59%) in 1876 and these differences persisted until 1972. The amounts of carbon in soils from Series C and D decreased very little between 1876 and 1898 and during this period the soils under rotational cropping lost only 0·11% C (mean of Series A, C and D). These losses were about one-third of the soil carbon lost from soils from the Continuous Wheat and Barley experiments during this period. Rotational cropping continued on Series C and D until 1937; in the years between 1898 and 1932, the mean carbon content of these soils decreased more (by 0·32% C) under rotational cropping than on plots growing cereals (0·19% C). In 1932, soils under rotational cropping contained 1·07% C (mean of Series C and D), whilst those under continuous cereals contained slightly less, 0·98% C.

The soils on Series B were cropped in a six-course rotation (sugar beet, barley, clover, wheat, potatoes and rye) from 1930–60 and with barley from 1961–63. Although no analyses are available for 1930, the data in Table 6 suggest that the mean soil carbon content would have been near 1·0% C. The mean value in 1964 was 0·76% C (Mattingly, Chater & Poulton, 1974). This evidence, although partly circumstantial, also suggests that losses of soil organic carbon between 1930 and the early 1960s were no larger under

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poor cereal crops (frequently fallowed because barley failed on some plots due to soil acidity) than in a six-course rotation in which good crops were grown and the land was limed regularly (Yates & Patterson, 1958).

The results summarised in Table 6 show that differences (about 0·15–0·2% C) had developed between the carbon contents of the soils under rotational cropping and under continuous cereals on Stackyard by about 1900. During the last 70 years, however, the rate of loss of soil organic matter from soils from the rotation experiments has increased slightly and differences between carbon contents of soils under rotational cropping and under cereals ranged only from 0·04–0·11% C between 1927 and 1972. The results given here (Table 6) do not, therefore, support the view that losses of organic matter from soils on Stackyard Field in recent years have been significantly greater in experiments growing continuous cereals (wheat or barley) than in experiments cropped with three, four- or six-course rotations.

Comparison of Continuous Wheat and Barley experiments with Broadbalk, Rothamsted

Fig. 2 shows changes in the nitrogen content of some soils from the Continuous Wheat and Barley experiments on Stackyard Field (1876–1972) and compares them with changes in

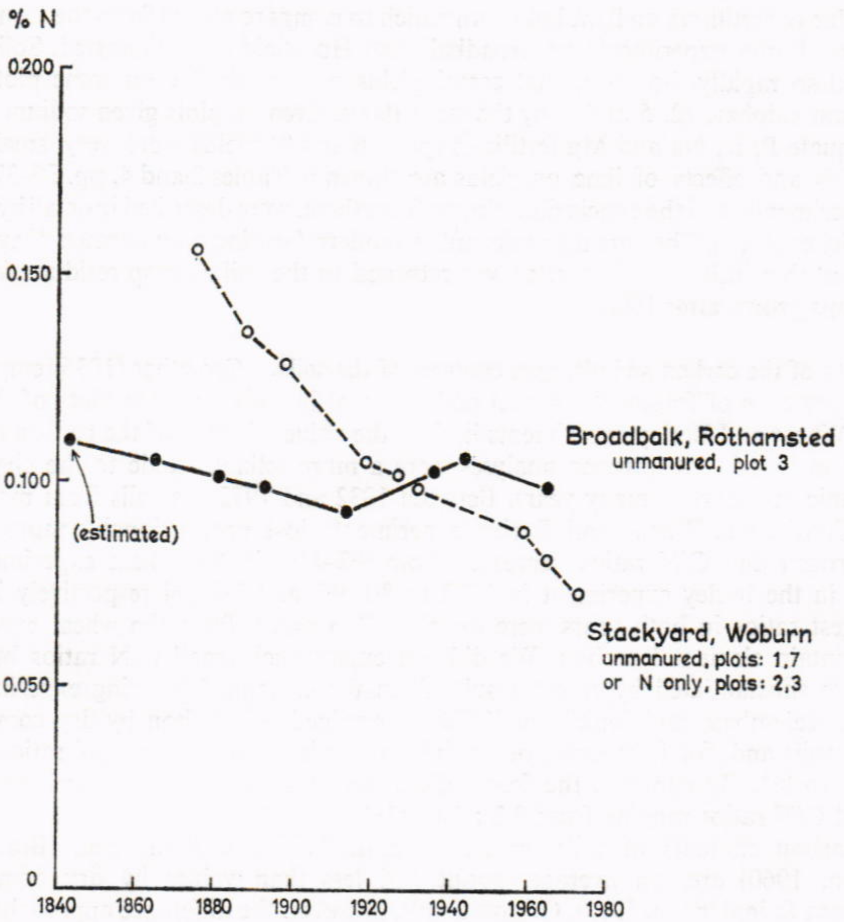

FIG. 2. Changes in nitrogen contents of soils from the Continuous Wheat and Barley experiments, Stackyard, Woburn, and from the Continuous Wheat experiment on Broadbalk, Rothamsted.

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the nitrogen content of soils from the Continuous Wheat on Broadbalk, Rothamsted (Johnston, 1969.) The two lines are strikingly different. The nitrogen content of the Woburn soils has approximately halved in 100 years whereas, in the Rothamsted soil, it has remained almost constant. The nitrogen content of the Woburn soils, when the experiment began in 1876, was about 0·156% N; it has since decreased and shows no signs of reaching an equilibrium value.

We do not know why the soils initially had so different an organic matter content. Broadbalk had probably been farmed in a four-course rotation of arable crops for many years. Stackyard Field received much farmyard manure before 1876 and the soil contained residues of old grass. By about 1930 both soils had the same %N (0·10). Where no more organic manures have been applied, the Woburn soils have since lost a further one-quarter of their soil nitrogen whereas the Rothamsted soils have lost none.

Discussion and conclusions

The early experiments. Stackyard Field is a unique light land site in England because experiments on both rotational cropping and continuous cereal growing have been in progress since 1876 and the soils have been sampled frequently for almost 100 years. The Continuous Wheat and Barley experiments were started partly to provide evidence of the value of fertilisers on light land with which to compare results from the Continuous Wheat and Barley experiments on Broadbalk and Hoosfield at Rothamsted. Soil acidity developed so rapidly, however, that cereal yields were negligible on some plots given ammonium sulphate (2, 5 and 8) by the early 1900s. Even on plots given sodium nitrate, and adequate P, K, Na and Mg fertilisers (plots 6 and 9) yields were very small (1·5 t ha). Yields and effects of lime on yields are shown in Tables 3 and 4, pp. 36–37. These early experiments, and the conclusions drawn from them, were described in detail by Russell and Voelcker (1936). They are now relevant to modern farming only because they clearly established that little organic matter was returned to the soil as crop residues from the small crops grown after 1900.

Variability of the carbon and nitrogen contents of the soils. Crowther (1936) emphasised that the presence of fragments of coal and charcoal in soils on some plots of the Continuous Wheat and Barley experiments limited the value of some of the carbon analyses and he concluded that nitrogen analyses were a more reliable guide to the changes in soil organic matter over many years. Between 1932 and 1972 the soils from most plots of the Continuous Wheat and Barley experiments lost proportionally more carbon than nitrogen and C/N ratios decreased from 9·2–11·4 in the wheat experiment and 9·5–10·0 in the barley experiment in 1932 to 8·1–9·7 and 7·3–8·4 respectively in 1959. The largest ratios in both years were on plots 7, 8 and 9 from the wheat experiment which contain elemental carbon. We did not expect such small C/N ratios but these results are substantiated by recent results from the Organic Manuring experiment on Series B. Kalembasa and Jenkinson (1973) determined soil carbon by dry combustion on these soils and, for four soils not receiving organic manures, the C/N ratios ranged from 8·8 to 9·1. By contrast, the four soils under leys, or given farmyard manure or peat, had C/N ratios ranging from 9·2 : 1 to 11·4 : 1.

The carbon contents of soils, measured using boiling chromic acid (Bremner & Jenkinson, 1960) are, on average, about 5% less than values by dry combustion (Kalembasa & Jenkinson, 1973). On some soils, however, the difference approaches 10%; soils taken in 1972 from plot 1 from both the wheat and barley experiments, and analysed by dry combustion by D. S. Jenkinson, gave 0·82% C (wheat experiment) and 0·70% C

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(barley experiment) which are 8% and 10% respectively greater than the values given in Table 1 (see following section on soil erosion).

Sampling errors have not been measured reliably in these experiments. When many plots are sampled in different years, values can correlate very closely; carbon analyses made on all 26 plots of both the Continuous Wheat and Barley experiments sampled in 1959 and 1965 (Appendix Table 3) are very closely related ($r^2 = 0{\cdot}94$). However, the agreement between analyses made on samples from a single plot taken in successive years is often much poorer. Jenkinson (1972) used a soil sample taken in 1971 from plot 1 of the Continuous Barley experiment to estimate the equivalent age of the soil carbon. His value for the total soil C in 1971 was 0·77% C, which was 10% greater than the value (0·70%) in the sample taken in 1972; the soil contained 0·070% N in both samples.

Soil erosion. The ground on which this experiment is sited slopes away from the main road (see plan on p. 30); plots 1, 2 and 3 of both experiments are at the bottom of the slope. In the early 1950s observations made during heavy rain showed that there was much surface-water run-off. During the last five years gulleys, up to 15 cm deep, have been made after heavy rain, particularly on plots 1 and 2 of the barley experiment, and so much clay and silt has been removed from the surface of the soil that a bleached sand layer has appeared on parts of the plots. We cannot estimate the amount of soil which may have been removed by water erosion during the course of the experiment and, as yet, no measurements have been made to assess variations in the carbon and nitrogen contents of the soils caused by erosion. The sharp decrease, between 1959 and 1972, in the nitrogen content of plots 1, 2 and 3 from both experiments (Fig. 2) may be due to the differential movement of soil by water erosion. Differences between carbon contents of soils from plot 1 (barley experiment, taken in 1971 and 1972), which were discussed above, may have the same cause.

Soil organic phosphorus. Both Dean (1938) and Ghani (1943) showed that much organic P had accumulated by 1927 in the soils of the Continuous Wheat and Barley experiments on plots given farmyard manure from 1877–1926. Their methods of analysis appeared somewhat to overestimate the amounts present (70 mg P/kg) which were comparable to, or greater than, the total amounts of organic P applied in farmyard manure. The analyses given in Appendix Tables 1 and 2, and summarised in Table 4, showed similar changes on both sites. The average amounts of organic P mineralised each year from 1932–59 were equivalent to 1·5–3·5 kg P/ha and the larger amount is sufficient to supply about one-third of the phosphorus removed by the small cereal crops grown.

Effects of inorganic fertilisers on soil organic matter. Analyses of soils from the Continuous Wheat experiment on Broadbalk, Rothamsted, showed that, on the unmanured plots, the soil nitrogen content has remained almost constant (0·10% N) since 1843 (Fig. 2). The larger crops grown with full NPKNaMg fertilisers appeared to leave larger crop residues which increased the soil nitrogen content by about 20% (Johnston, 1969). There is no evidence for a similar effect in the Continuous Wheat and Barley experiments on Stackyard Field. Neither the carbon nor the nitrogen contents of soils were significantly larger in soils given full NPKNaMg manuring than in soils which were given only nitrogen fertilisers or which were unmanured (Fig. 1). Recent results from analyses of the carbon contents of soils from the Ley–Arable experiment (Johnston, 1973) and the Organic Manuring experiment (Mattingly, Chater & Poulton, 1974) adequately confirm that crop residues alone, even from large cereal crops, do not provide enough organic matter to maintain, and certainly do not increase, the organic matter content of light soils at Woburn.

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Summary

1. This paper describes changes, from 1888–1959, in the C, N and organic P in surface soils (0–23 cm) taken from the Continuous Wheat and Barley experiments on Stackyard Field, Woburn, and subsequent changes, from 1959–72, in soil C and N in some of the soils. Changes in soil C in soils cropped continuously with wheat or barley, or occasionally fallowed, from 1876–1972 are compared with changes in other soils on Stackyard Field cropped in rotations.

2. Soil carbon and nitrogen decreased from 1·49% C and 0·156% N in 1876 to about 0·82% C and 0·094% N in the Continuous Wheat experiment and to about 0·64% C and 0·084% N in the Continuous Barley experiment in 1959 on plots given inorganic fertilisers or none. Inorganic fertilisers (NPKNaMg), applied from 1877–1926 did not increase the carbon and nitrogen contents of the soils more than no fertilisers or nitrogen only, probably because crop yields were small and the extra amounts of organic matter returned to the soil as roots and stubble were negligible. (The larger wheat crops grown with NPKNaMg fertilisers in the Continuous Wheat experiment on Broadbalk, Rothamsted, increased soil organic matter and soil nitrogen by about 20% more than the unmanured soils.) Farmyard manure (about 17·6 t/ha each year from 1877–1926) increased soil carbon and nitrogen in the surface soils by about 0·14% C and 0·013% N in 1959 and these residues are equivalent to about 7% and 8% respectively of the amounts of carbon and nitrogen applied in the manure. A further 2–3% of the carbon applied was recovered in the sub-soil (23–45 cm) in 1959.

3. Methods of sampling soils changed between 1927 and 1932. The soils sampled in 1932 contained 0·91 times as much total P as soils sampled in 1927, probably because the 1927 sample contained a disproportionately large amount of surface soil. This change in the sampling method resulted in a large apparent loss of carbon and nitrogen from plot 11b (farmyard manure) in 1932.

4. Organic P decreased between 1888–1959 on soils given no phosphorus fertilisers by about 30 mg P/kg soil and these soils lost, in 71 years, about 12% of the total organic P they contained in 1888. Organic P remained almost constant from 1888–1927 in soils given superphosphate but decreased by about 15 mg P/kg soil between 1927–59 when no superphosphate was applied. Organic P in the soils increased by about 30 mg P/kg between 1888–1927 on plots given farmyard manure and decreased by about 35 mg P/kg soil between 1927–59 when no more farmyard manure was applied. About 27% of the organic phosphorus applied in farmyard manure between 1877–1926 remained in the surface soil (0–23 cm) in 1959. The amounts of organic P mineralised each year in these soils ranged from 1·5–3·5 kg P/ha.

5. Sections of Stackyard Field (Series C and D) were cropped in a four-course rotation from 1877–1936. Soil carbon decreased less in these soils (−0·11% C) than in the Continuous Wheat and Barley experiments (−0·32% C) between 1876–98 but more (−0·32% C) than in the continuous cereal experiments (−0·19% C) between 1898–1932. Between 1876–1972, the carbon content of soils from the Continuous Wheat and Barley experiments decreased by about 0·8% C and soils from the rotation experiments by about 0·7% C so that long periods of rotational cropping have only lessened losses of soil carbon from the Woburn soils by about 0·1% C in a century.

6. Water erosion during the past 20 years has probably increased losses of soil carbon and nitrogen which are still decreasing on all plots of the Classical Wheat and Barley experiments. Erosion was particularly serious on plots 1 and 2 of the Continuous Barley experiment in 1971 and led to the formation of a bleached layer of sand on the surface soil.

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APPENDIX

Total carbon was measured by the Bangor wet digestion method on soil samples (<100 mesh) taken in 1888, 1927 and 1932. Full details of this method and modifications made to it, are described by Walkley (1935) who standardised the wet digestion method against analyses by the Dennstedt dry combustion method. Analyses in Appendix Tables 1 and 2 are means of analyses of sub-plots by wet digestion (corrected to dry combustion) which were given by Crowther (1936). Soils taken in 1959 and later were analysed by the Tinsley (1950) method described by Bremner and Jenkinson (1960); this method was recently used to measure changes in carbon contents of soils from the Woburn Ley–Arable experiment on Stackyard Field (Johnston, 1973).

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Total nitrogen was measured on all soils by Kjeldahl digestion. The values for samples taken in 1888, 1927 and 1932 are means of sub-plot analyses given by Crowther (1936). Soils taken in 1959 and later were digested with H_2SO_4 and a Cu–Se catalyst. NH_3 in the digests was estimated by distillation and titration.

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

Organic phosphorus was estimated both by the extraction method (A) described by Mehta, Legg, Goring and Black (1954) and by the ignition method (B) of Saunders and Williams (1955). In method A 0·5 g soil (<60 mesh) was first extracted with 5 ml HCl (s.g. 1·18) for 10 minutes at 70°C; a further 5 ml of HCl was added and the suspension allowed to stand for 1 h at room temperature. After centrifuging, the soil was further extracted with 15 ml 0·5N-NaOH at room temperature for 1 h and with 30 ml 0·5N-NaOH at 90°C for 8 h. All extracts were combined, diluted with water to 200 ml in a volumetric flask and kept in a refrigerator to minimise hydrolysis. Organic P was estimated from the difference between total P in an aliquot, measured after oxidation with $HClO_4$ and inorganic P measured on another aliquot. In method B, 2 g soil (<60 mesh) was ignited at 500–550°C for 2 h and extracted with 0·2N-H_2SO_4 (100 ml) for 2 h at room temperature. Organic P was estimated from the difference between 0·2N-H_2SO_4 soluble P extracted from ignited and unignited soil.

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APPENDIX TABLE 1

Chemical analyses[a] of soils (0–23 cm) from the Continuous Wheat experiments, Stackyard, Woburn, 1876–1959

Year	Plot no.	Total C (%)	Total N (%)	C/N	Total P (mg/kg)	Organic P (mg/kg) Ignition	Organic P (mg/kg) Extraction	C/organic P Ignition	C/organic P Extraction
1876	Site sample	1·49	0·156	9·6	748	306	203	48·7	73·4
1888	1	1·18	0·126	9·4	676	253	236	46·6	50·0
	2	1·26	0·131	9·6	688	281	266	44·8	47·4
	3	1·25	0·126	9·9	668	264	210	47·3	59·5
	4	1·25	0·127	9·8	790	290	248	43·1	50·4
	5	1·28	0·130	9·8	840	318	252	40·3	50·8
	6	1·29	0·129	10·0	808	319	226	40·4	57·1
	7	1·70	0·150	11·3	852	355	244	47·9	69·7
	8	1·68	0·146	11·5	928	364	264	46·2	63·6
	9	1·50	0·136	11·0	828	296	228	51·7	65·8
	10a	1·27	0·130	9·8	728	279	208	45·5	61·0
	10b	1·38	0·143	9·7	740	300	222	46·0	62·2
	11a	1·40	0·139	10·1	744	302	258	46·4	54·3
	11b	1·69	0·171	9·9	884	346	286	48·8	59·1
1927	1	1·03	0·105	9·8	646	262	224	39·3	46·0
	2	0·96	0·099	9·7	632	265	206	36·2	46·6
	3	1·00	0·099	10·1	652	249	202	40·2	49·5
	4	1·31	0·117	11·2	1060	280	256	46·8	51·2
	5	1·08	0·100	10·8	1032	312	234	34·6	66·2
	6	1·07	0·104	10·3	960	314	226	34·1	47·3
	7	1·43	0·113	12·7	848	334	270	42·8	53·0
	8	1·36	0·110	12·4	1140	364	288	37·4	47·2
	9	1·16	0·104	11·2	952	310	236	37·4	49·2
	10a	0·99	0·095	10·4	772	294	244	33·7	40·6
	10b	1·06	0·106	10·0	752	311	282	34·1	37·6
	11a	0·99	0·101	9·8	716	309	246	32·0	40·2
	11b	1·52	0·145	10·5	932	314	254	48·4	59·8
1932	1	0·97	0·106	9·2	640	269	224	36·1	43·3
	2	0·91	0·097	9·4	628	248	216	36·7	42·1
	3	0·94	0·097	9·7	604	255	192	36·9	49·0
	4	1·18	0·112	10·5	940	275	212	42·9	55·7
	5	0·965	0·1005	9·6	900	298	204	32·4	47·3
	6	0·94	0·096	9·8	852	284	220	33·1	42·7
	7	1·22	0·107	11·4	796	320	266	38·1	45·9
	8	1·14	0·100	11·4	1036	347	270	32·9	42·2
	9	1·08	0·103	10·5	902	306	244	35·3	44·3
	10a	0·95	0·096	9·9	752	285	210	33·3	45·2
	10b	0·93	0·101	9·2	724	299	248	31·1	37·5
	11a	1·10	0·106	10·4	716	305	230	36·1	47·8
	11b	1·22	0·124	9·8	812	332	232	36·7	52·6
1959	1	0·89	0·105	8·5	660	264	174	33·7	51·2
	2	0·63	0·078	8·1	636	245	180	25·7	35·0
	3	0·77	0·092	8·4	620	245	178	31·4	43·3
	4	0·97	0·109	8·9	888	314	214	30·9	45·3
	5	0·66	0·081	8·1	884	309	220	21·4	30·0
	6	0·77	0·090	8·6	820	300	222	25·7	34·7
	7	1·03	0·106	9·7	856	315	238	32·7	43·3
	8	0·80	0·087	9·2	958	332	222	24·1	36·0
	9	0·90	0·101	8·9	920	309	246	29·1	36·6
	10a	0·70	0·088	8·0	688	268	194	26·1	36·1
	10b	0·75	0·087	8·6	728	285	218	26·3	34·4
	11a	0·83	0·095	8·7	740	275	248	30·2	33·5
	11b	0·93	0·106	8·8	784	288	236	32·3	39·4

(a) Carbon and nitrogen analyses in 1888, 1927 and 1932 are calculated from means of sub-plot analyses given by Crowther (1936).

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APPENDIX TABLE 2

Chemical analyses[a] of soils (0–23 cm) from the Continuous Barley experiment, Stackyard, Woburn, 1876–1959

Year	Plot no.	Total C (%)	Total N (%)	C/N	Total P (mg/kg)	Organic P (mg/kg) Ignition	Organic P (mg/kg) Extraction	C/organic P Ignition	C/organic P Extraction
1876	Site sample	1·49	0·156	9·6	748	306	203	48·7	73·4
1888	1	1·26	0·144	8·8	716	275	196	45·8	64·3
	2	1·34	0·143	9·4	724	285	200	47·0	67·0
	3	1·33	0·143	9·3	748	288	174	46·2	76·4
	4	1·19	0·122	9·8	776	281	154	42·3	77·3
	5	1·28	0·134	9·6	824	294	174	43·5	73·6
	6	1·34	0·141	9·5	828	288	218	46·5	61·5
	7	1·21	0·126	9·6	676	255	174	47·5	69·5
	8	1·34	0·141	9·5	784	309	208	43·4	64·4
	9	1·42	0·142	10·0	824	296	180	48·0	78·9
	10a	1·33	0·136	9·8	832	304	202	43·8	65·8
	10b	1·39	0·140	9·9	824	300	188	46·3	73·9
	11a	1·74	0·160	10·9	820	325	240	53·5	72·5
	11b	1·57	0·160	9·8	808	314	206	50·0	76·2
1927	1	0·96	0·094	10·2	648	238	172	40·3	55·8
	2	0·96	0·101	9·5	728	268	146	35·8	65·8
	3	1·02	0·105	9·7	708	260	180	39·2	56·7
	4	0·88	0·090	9·8	956	276	216	31·9	40·7
	5	0·96	0·098	9·8	936	291	188	33·0	51·1
	6	1·05	0·109	9·6	928	286	206	36·7	51·0
	7	0·88	0·093	9·5	688	255	212	34·5	41·5
	8	0·96	0·100	9·6	956	285	236	33·7	40·7
	9	1·02	0·108	9·4	908	308	234	33·1	43·6
	10a	0·98	0·101	9·7	840	335	232	29·3	42·2
	10b	1·00	0·106	9·4	776	315	262	31·7	38·2
	11a	1·12	0·115	9·7	728	300	222	37·3	50·4
	11b	1·50	0·151	9·9	900	325	254	46·2	59·0
1932	1	0·93	0·095	9·8	616	238	154	39·1	60·4
	2	0·94	0·097	9·7	652	250	208	37·6	45·2
	3	0·95	0·099	9·6	648	262	202	36·3	47·0
	4	0·85	0·087	9·8	816	255	178	33·3	47·8
	5	0·88	0·091	9·7	816	261	208	33·7	42·3
	6	0·98	0·100	9·8	796	279	228	35·1	43·0
	7	0·86	0·090	9·6	568	235	192	36·6	44·8
	8	0·94	0·096	9·8	824	290	228	32·4	41·2
	9	0·96	0·101	9·5	860	290	252	33·1	38·1
	10a	0·91	0·095	9·6	760	291	234	31·3	38·9
	10b	0·92	0·096	9·6	696	305	224	30·2	41·1
	11a	1·04	0·104	10·0	656	280	200	37·1	52·0
	11b	1·23	0·123	10·0	836	306	268	40·2	45·9
1959	1	0·65	0·080	8·1	620	220	166	29·6	39·2
	2	0·53	0·070	7·6	576	240	148	22·1	35·8
	3	0·71	0·088	8·1	652	238	166	29·8	42·8
	4	0·64	0·077	8·3	788	261	164	24·5	39·0
	5	0·54	0·074	7·3	808	255	156	21·2	34·6
	6	0·68	0·090	7·6	816	282	210	24·1	32·4
	7	0·66	0·088	7·5	632	239	212	27·6	31·1
	8	0·61	0·081	7·5	816	311	202	19·6	30·2
	9	0·72	0·098	7·4	804	286	216	25·2	33·3
	10a	0·67	0·084	8·0	736	285	214	23·5	31·3
	10b	0·69	0·087	7·9	676	285	212	24·2	32·6
	11a	0·81	0·098	8·3	752	309	212	26·2	38·2
	11b	0·81	0·097	8·4	796	288	204	28·1	39·7

(a) Carbon and nitrogen analyses in 1888, 1927 and 1932 are calculated from means of sub-plot analyses given by Crowther (1936)

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APPENDIX TABLE 3

Carbon contents of soils[a] from the Continuous Wheat and Barley experiments, Stackyard, Woburn in 1959 and 1965

Plot no.	Continuous wheat 1959 0–23 cm	Continuous wheat 1959 23–30 cm	Continuous wheat 1959 30–45 cm	Continuous wheat 1965 0–23 cm	Continuous barley 1959 0–23 cm	Continuous barley 1959 23–30 cm	Continuous barley 1959 30–45 cm	Continuous barley 1965 0–23 cm
1	0·89	0·60	0·43	0·89	0·65	0·52	0·43	0·73
2	0·63	0·49	0·42	0·61	0·53	0·47	0·42	0·60
3	0·77	0·50	0·41	0·76	0·71	0·53	0·44	0·68
4	0·97	0·59	0·47	0·99	0·64	0·47	0·36	0·62
5	0·66	0·52	0·46	0·71	0·54	0·46	0·39	0·53
6	0·77	0·58	0·44	0·79	0·68	0·60	0·51	0·70
7	1·03	0·62	0·44	0·99	0·66	0·47	0·40	0·66
8	0·80	0·49	0·44	0·81	0·61	0·53	0·45	0·63
9	0·90	0·58	0·48	0·90	0·72	0·56	0·47	0·72
10a	0·70	0·50	0·40	0·74	0·67	0·55	0·43	0·67
10b	0·75	0·52	0·47	0·76	0·69	0·52	0·42	0·69
11a	0·83	0·52	0·43	0·85	0·81	0·58	0·46	0·80
11b	0·93	0·61	0·48	0·89	0·81	0·60	0·48	0·79
Mean	0·82	0·55	0·44	0·82	0·67	0·53	0·44	0·68

(a) %C in air-dry soil

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