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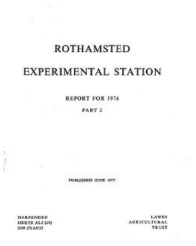

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Soil Organic Matter in the Hoosfield Continuous Barley Experiment

D. S. JENKINSON and A. E. JOHNSTON

Introduction

Apart from Broadbalk, the Hoosfield Continuous Barley experiment, started in 1852, is the longest-running field experiment on cereals in the world. Over the years, fewer changes have been made in this experiment than in any of the other Rothamsted Classical experiments and in consequence Hoosfield is uniquely valuable in providing information on the long-term effects of manuring on organic matter in arable land.

The Hoosfield experiment tests the effects of a wide range of manurial treatments, including farmyard manure (FYM), on the growth of spring barley. The manurial treatments are repeated annually (for details see Warren & Johnston, 1967) and barley has been grown every year except 1912, 1933, 1943 and 1967, when the whole experiment was fallowed to control weeds. In 1968 the experiment was modified by dividing each plot into four sub-plots receiving different amounts of nitrogen; the FYM and PK applications were not changed. Details of the revised experiment are given in the *Numerical Results of the Field Experiments* (1968) and in the *Rothamsted Experimental Station Guide* (1974). Data on yields have been given by Lawes and Gilbert (1873, 1895), by Russell and Watson (1938a, b, 1939) and by Warren and Johnston (1967). Soil analyses have been published by Dyer (1902), Warren (1956) and Warren and Johnston (1967).

The immediate aim of the work in this paper was to measure, as accurately as possible, the changes in soil organic carbon, carbonate carbon, nitrogen and phosphorus that have occurred in selected plots since the experiment was laid down in 1852. This entailed analysing a set of samples collected in 1975, taken by the traditional Rothamsted box procedure to maintain continuity with the earlier samplings. It also entailed re-analysing all the earlier samples that had survived from these plots, to avoid the necessity of comparing analyses done at different times by different analysts, often by different methods. The ultimate aim of this work is to assemble data for use in a later paper, in which different mathematical models for predicting the effects of crop and management on the amount of organic matter in a soil will be tested.

Of the 28 plots in the pre-1968 experiment, seven were selected for the detailed studies described in this paper: the three unmanured plots (1–0, 6–1 and 6–2); the plot that received FYM annually between 1852 and 1871, but has been unmanured since (7–1); the plot receiving FYM annually since 1852 (7–2) and two of the plots receiving inorganic fertilisers (4–0 and 4–A). Details of the pre- and post-1968 manurial treatments are given in Table 1, as are the pre- and post-1968 plot numbers.

During the long history of the experiment the methods of cultivation have changed repeatedly. With a spring-sown cereal, more cultivations were possible than on say Broadbalk, and extra spring seedbed cultivations were often given to control weeds in the days before herbicide sprays were available. The stubble was usually shallow ploughed (10–13 cm) in autumn. Between 1852 and 1915 the plots were again shallow ploughed after fertiliser and FYM had been applied, usually in March. From 1916 to 1967 the FYM was applied between September and January and the plot reploughed; inorganic fertilisers were applied in the spring and worked into the seedbed. Since 1968 the FYM is applied to the stubble before ploughing (as are the P and K fertilisers) and the plots ploughed once only in autumn. Nitrogen is now applied soon after sowing. Tractors

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TABLE 1

Analyses[1] of surface soils collected from Hoosfield at different dates

Plot No.	Manuring	Sampling date	Sampling procedure[2]	Sieve size,[3] mm	Number of samples combined for analysis	% carbonate C	% organic C[4]	% total N	C/N ratio	% total P
1–0	Unmanured	Feb. 1882	Box	6·25	4	0·40	0·91	0·106	8·6	0·0551
1–0	Unmanured	Oct. 1904	Box	?	3	0·29	0·84	0·102	8·2	0·0540
1–0	Unmanured	Oct. 1913	Box	3	4	0·28	0·94	0·109	8·7	0·0551
1–0	Unmanured	Aug. 1946	Spade	2	6	0·22	0·90	0·107	8·4	0·0547
1–0	Unmanured	May 1966	Corer(X+Y)[11]	2	–	0·16	0·93	0·101	9·1	0·0540
111–114[5]	Unmanured	Sep. 1975	Box	6·25	4	0·11	0·91 (0·87)	0·101	9·0	0·0571
6–1	Unmanured	Oct. 1913	Box	3	2	0·05	1·05	0·118	8·9	0·0601
611–614[5]	Unmanured	Sep. 1975	Box	6·25	4	0·01	1·12 (1·05)	0·110	10·2	0·0633
6–2	Unmanured[6]	Oct. 1913	Box	3	4	0·06	1·10	0·119	9·3	0·0615
621–624[5]	Unmanured[6]	Sep. 1975	Box	6·25	4	<0·01	1·21 (1·12)	0·107	11·3	0·0634
7–1	FYM residues[7]	Feb. 1882	Box	6·25	3	0·19	1·96	0·201	9·7	0·0749
7–1	FYM residues[7]	Oct. 1913	Box	3	3	0·12	1·68	0·171	9·8	0·0686
7–1	FYM residues[7]	Aug. 1946	Spade	2	6	0·03	1·51	0·156	9·7	0·0690
7–1	FYM residues[7]	May 1966	Corer(X+Y)[11]	2	–	0·02	1·65	0·147	11·2	0·0707
711–714[5]	FYM residues[7]	Sep. 1975	Box	6·25	4	<0·01	1·58 (1·50)	0·141	11·2	0·0647
4–0	PK Na Mg[8]	Feb. 1882	Box	6·25	4	0·19	1·12	0·117	9·5	0·0715
4–0	PK Na Mg[8]	Oct. 1913	Box	3	2	0·09	1·10	0·122	9·1	0·0996
4–0	PK Na Mg[8]	Aug. 1946	Spade	2	6	0·03	1·17	0·125	9·3	0·1059
411–414[5]	PK Na Mg[8]	Sep. 1975	Box	6·25	4	0·01	1·10 (1·07)	0·105	10·4	0·1321
4–A	NPK Na Mg[9]	Mar. 1868	Box	6·25	?	0·18	0·71	0·102	7·0	0·0655
4–A	NPK Na Mg[9]	Feb. 1882	Box	6·25	3	0·11	1·08	0·121	8·9	0·0792
4–A	NPK Na Mg[9]	Feb. 1897	Box	6·25	3	0·03	1·03	0·115	8·9	0·0880
4–A	NPK Na Mg[9]	Oct. 1904	Box	?	3	0·04	1·06	0·121	8·8	0·0910
4–A	NPK Na Mg[9]	Oct. 1913	Box	3	4	0·01	1·09	0·118	9·2	0·0948
4–A	NPK Na Mg[9]	Aug. 1946	Spade	2	6	0·01	1·15	0·118	9·8	0·0972
4–A	NPK Na Mg[9]	May 1966	Corer(X+Y)[11]	2	–	0·02	1·16	0·112	9·9	0·1173
421–424[5]	NPK Na Mg[9]	Sep. 1975	Box	6·25	4	0·01	0·96 (0·94)	0·098	9·9	0·1336
7–2	FYM[10]	Feb. 1882	Box	6·25	3	0·27	2·39	0·237	10·1	0·0912
7–2	FYM[10]	Oct. 1904	Box	?	3	0·19	2·57	0·249	10·3	0·1050
7–2	FYM[10]	Oct. 1913	Box	3	3	0·13	3·01	0·283	10·7	0·1127
7–2	FYM[10]	Aug. 1946	Spade	2	6	0·06	3·07	0·285	10·8	0·1416
7–2	FYM[10]	Oct. 1965	Corer(A)[12]	2	–	0·02	3·31	0·316	10·5	0·1454
7–2	FYM[10]	Oct. 1965	Corer (B)[13]	2	–	0·02	3·36	0·306	11·0	0·1462
7–2	FYM[10]	May 1966	Corer(X+Y)[11]	2	–	0·03	3·06	0·268	11·4	0·1340
721–724[5]	FYM[10]	Sep. 1975	Box	6·25	4	0·01	3·38 (3·26)	0·297	11·4	0·1413
721–724[5]	FYM[10]	Sep. 1975	Box[14]	6·25	4	0·01	2·19	0·205	10·7	0·1195

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[1] All analyses were done in 1975 and are given on an oven-dry (24 h at 105 °C) basis

[2] Using a 6 × 6 × 9 inch sampling box or a 2 cm diam. corer. All samples were taken to a depth of 23 cm unless otherwise specified. The box samples were normally taken on the centre line of the plot; three of the spade samples were taken on the centre line of the north half of the plot (split longitudinally) and three from the centre line of the south half; core samples were taken from the central area alone

[3] Analyses done on soil passing specified mesh

[4] Figures in parentheses give organic carbon as determined by wet combustion (Shaw, 1959)

[5] In 1968 the old plots were subdivided into four sections, receiving 0, 48, 96 and 144 kg N ha^{-1} annually as 'Nitro-Chalk', on a rotating basis

[6] Receiving ashes 1852–1932, none since

[7] Receiving 35 t farmyard manure ha^{-1} annually between 1852 and 1871, none since

[8] Receiving 33 kg P, 90 kg K, 15 kg Na, 11 kg Mg ha^{-1}, annually since 1852

[9] Receiving 33 kg P, 90 kg K, 15 kg Na, 11 kg Mg ha^{-1}, annually since 1852. N (48 kg ha^{-1}) applied annually as ammonium sulphate between 1852 and 1967

[10] Receiving 35 t farmyard manure (containing 3·0 t C and about 225 kg N) ha^{-1}, annually since 1852

[11] From the 0–15 cm depth of the split plots (X and Y) on which two different barley varieties were tested

[12] Composite sample of many cores

[13] From the 0–23 cm horizon of the relatively small number of cores taken to a depth of 46 cm

[14] From the 23–25 cm depth

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replaced horses in 1921 but for many years thereafter ploughing remained shallow, probably to a depth not greater than 15 cm. Of recent years ploughing has been deeper and the plough depth is now about 22 cm. Considerable movement of soil across plot boundaries took place as a result of the intensive cultivations and ploughings given to this particular experiment in the 1920s (Warren & Johnston, 1967). To minimise errors caused by soil movement the 1975 samples were taken from the centre line of the pre-1968 plots.

Materials and methods

Analytical methods. Total N was determined by the Kjeldahl method (Bremner, 1965); total C gravimetrically by dry combustion (Kalembasa & Jenkinson, 1973); carbonate C gravimetrically (Kalembasa & Jenkinson, 1973); organic C was obtained by difference. The total C contents of a few samples were also determined by wet combusion (Shaw, 1959). Total P was determined by sodium carbonate fusion (Mattingly, 1970). Soils were ground to pass a 30-mesh sieve prior to analysis. The results are means of triplicate determinations of C and duplicate determinations of N and P.

Soil sampling. Sampling in 1975 was done by the traditional procedure as described by Dyer (1902). Four samples were taken per plot, one from the centre of each of the four sub-plots into which the main plots had been divided in 1968.

Stored samples. The 1882, 1904, 1913 and 1946 samples had been stored in corked bottles and the 1966 samples in cardboard boxes. It is likely that little change occurred in the C and N content of these particular samples during storage. Thus Dyer (1902) gave the organic C contents of samples taken in 1882 from plots 7–1, 7–2 and 4–A as 2·03, 2·49 and 1·08% respectively: on re-analysis many years later we obtained values of 1·96, 2·39 and 1·08 (Table 1). Our N values are about 10% greater than those given by Dyer, which were determined about 1882 by the soda-lime method, known to give lower recoveries of soil N than the Kjeldahl method first used on soils at Rothamsted in the late 1880s or early 1890s. Our values for the N contents of the 1913 and 1946 samples are consistently about 4% greater than those given by Warren (1956); part of this discrepancy arises because our figures are given on an oven-dry basis, whereas Warren's results were given on an air-dry basis.

Some samples did probably undergo changes in storage. By 1865, Lawes and Gilbert had finalised their procedure for taking soil samples but it was not until 1877, when Warington demonstrated that nitrification occurred during the storage of moist soil, that the importance of dry storage was fully realised. Before that, bulk samples of Rothamsted soil were sometimes bottled and stored moist. The abnormally low C/N ratio of the single 1868 sample (Table 1; plot 4–A) strongly suggests that it had been stored moist for many years before being dried. The results of the 1868 sampling will not therefore be considered further.

Results and discussion

Organic carbon, carbonate carbon and total nitrogen in the soils. The values are given in Table 1. Of the data in this table, the results for the 1882, 1913, 1946 and 1975 samplings are the most consistent with each other in regard to sampling procedure, so that most of the subsequent discussion is concerned with these samplings alone.

Soil bulk density. For each plot (except that receiving farmyard manure) the bulk density of the soil to a depth of 23 cm was almost the same in 1882 and 1975 (Table 2).

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TABLE 2

Soil weights in the 1882, 1913 and 1975 samplings

Plot No.[1]	Weight of stones > 6·25 mm to a depth of 23 cm, Mkg ha^{-1}			Weight of dry fine soil < 6·25 mm to a depth of 23 cm, Mkg ha^{-1}			Bulk density of whole soil, kg m^{-3}		
	1882	1913[2]	1975	1882	1913[2]	1975	1882	1913	1975
1–0	0·57	0·54	0·60	2·96	3·16	2·86	1540	1620	1510
6–1	—	0·80	0·87	—	2·83	2·62	—	1590	1520
6–2	—	0·81	0·96	—	2·87	2·56	—	1610	1540
7–1	0·70	0·79	0·91	2·79	2·70	2·58	1520	1520	1520
4–0	0·83	0·76	0·93	2·67	2·90	2·51	1530	1600	1500
4–A	0·86	0·72	0·94	2·59	2·97	2·61	1510	1610	1550
7–2	0·82	0·58	0·67	2·34	2·43	2·29	1380	1310	1290

[1] For plot numbers since 1968 see Table 1

[2] The 1913 samples were put through a 3 mm sieve: the values in the table have been corrected to a 6·25 mm basis by assuming that 1 kg dry fine soil < 6·25 mm contains 20 g stones > 3 mm and < 6·25 mm.

In most plots the bulk density to sampling depth was greater in 1913 than in 1882 or 1975, which suggests that sampling was too deep in 1913 or that the soil was more compacted. For this reason the 1913 soil weights have not been used in calculating the amounts of C and N per hectare (except with plot 7–2). Two other points emerge from Table 2; the soil on the FYM plot (7–2) shows a continued decline in bulk density over the period 1882–1975, as would be expected in a plot accumulating organic matter. The soil on plot 1–0 (unmanured) at the north-east corner of the experimental site has the same overall bulk density as similarly treated soils on the other side of the experimental site but differs from them in that the weight of fine soil per hectare to a depth of 23 cm is greater and the weight of stones correspondingly less.

Changes in carbonate carbon. Hoosfield was chalked at an unknown date long before the start of the experiment in 1852. The chalking must have been uneven; the unmanured plot on the north-east edge of the experiment (1–0) contained 0·28% CO_3-C in 1913, much more than in the two unmanured plots at the other side of the experiment, 6–1 and 6–2, which contained 0·05 and 0·06% CO_3-C respectively.

All the plots considered in Table 1 lost CO_3-C during the experiment. Plot 1–0 (which is still calcareous) showed a mean loss of 91 kg CO_3-C ha^{-1} year^{-1} over the period 1882–1975, similar to the loss on the unmanured plot of Broadbalk, found by Bolton (1972) to be 80 kg CO_3-C ha^{-1} year^{-1} over the period 1865–1966.

By 1913, the carbonate reserves had been exhausted in plot 4–A and by 1975 they were exhausted in six of the seven plots listed in Table 1. The rates of loss remained roughly linear in all plots until the CO_3-C content had fallen below 0·03%; the rate was of course greater in plot 4–A, which received ammonium sulphate, than in any of the other plots. Once the chalk was gone, plot 4–A became acid. Russell and Watson (1938b) gave the pH of the topsoil as 5·6 in 1932; in 1946 the pH of the 0–23 cm horizon was 5·8 and in 1954 it had fallen to 4·8 in the 0–15 cm layer at the centre of the plot (Warren & Johnston, 1967). In winter 1954–55 a heavy dressing of chalk was given and a regular programme of liming started. By 1965 the 0–23 cm layer of soil on plot 4–A had a pH of 6·7.

It is unlikely that the development of soil acidity on plot 4–A during the first half of this century had an appreciable effect on the organic content of the soil; the organic C and N contents changed little between 1882 and 1966 (Table 1), a period spanning both the development and the suppression of acidity.

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Changes in total phosphorus. Table 1 shows that there was no measurable change in the P content of soil from plot 1–0 (unmanured) over the period 1882–1975, despite the removal of a small amount of P in the harvested crop each year. Warren and Johnston (1967) gave 2·9 kg P ha^{-1} $year^{-1}$ as the offtake by Plumage Archer over the period 1964–66. Plots 4–0 and 4–A, both receiving 33 kg P ha^{-1} $year^{-1}$, accumulated P steadily; a linear regression fitted to the data in Table 1 gave the annual gain in plot 4–0 over the period 1882–1975 as 16 kg P ha^{-1} $year^{-1}$; the corresponding gain in plot 4–A over the period 1868–1975 was 14 kg ha^{-1} $year^{-1}$. Over the period 1882–1975 there was a slow loss of P from plot 7–1 of 2 kg ha^{-1} $year^{-1}$. Between 1882 and 1946 the plot receiving FYM (7–2) gained P steadily but of late years the rate has declined. The explanation is unknown; possibly P is now accumulating at greater depths in the profile. In 1975 the 23–25 cm layer of this plot contained almost as much P as the 0–23 cm layer (Table 1).

Calculation of the amounts of carbon and nitrogen held in the topsoil

Correction for changes in bulk density. Corrections were unnecessary in all plots except 7–2; the amounts of C and N per hectare given in Table 3 were calculated by simply multiplying the percentage content of an element (from Table 1, adjusted, if

TABLE 3

Changes in the amounts of organic carbon and nitrogen in Hoosfield topsoil[1]

Plot No.	Manuring	Year	Adopted soil weight, Mkg ha^{-1}	Total N in topsoil[2] t ha^{-1}	Organic C in topsoil[2] t ha^{-1}
1–0	Unmanured	1852	2·91[3]	(3·41)	(30·7)
		1882	2·91	3·09	26·5
		1913[7]	2·91	3·11	26·8
		1946[8]	2·91	3·03	25·3
		1975	2·91	2·94	26·5
7–1	Farmyard manure 1852–71, unmanured since	1852	2·62[4]	(3·41)	(30·7)
		1872	—	(5·33)	(52·5)
		1882	2·62	5·27	51·4
		1913[7]	2·62	4·40	43·2
		1946[8]	2·62	3·98	38·8
		1975	2·62	3·69	41·4
4–0	PK Na Mg	1852	2·62[4]	(3·41)	(30·7)
		1882	2·62	3·07	29·3
		1913[7]	2·62	3·12	28·3
		1946[8]	2·62	3·20	29·9
		1975	2·62	2·75	28·8
4–A	NPK Na Mg	1852	2·62[4]	(3·41)	(30·7)
		1882	2·62	3·17	28·3
		1913[7]	2·62	3·04	27·8
		1946[8]	2·62	3·01	29·3
		1975	2·62	2·57	25·2
7–2	Farmyard manure	1852	2·62[4]	(3·41)	(30·7)
		1882	2·34	5·95[6]	59·9[6]
		1913[7]	2·43	7·11[6]	75·5[6]
		1946[8]	2·35[5]	7·14[6]	76·3[6]
		1975	2·29	7·68[6]	86·8[6]

[1] 0–23 cm, except for results with superscript[6]
[2] Values in parentheses are estimates
[3] Mean of 1882 and 1975 results for plot 1–0
[4] Mean of all 1882 and 1975 results, excluding plots 7–2 and 1–0
[5] Mean of 1882, 1913 and 1975 results
[6] In layer that contains the same weight of inorganic soil as the 0–23 cm layer in 1852: see text
[7] Analyses on the 1913 samples (Table 1) corrected to a 6·25 mm basis by assuming that 1 kg dry fine soil < 6·25 mm contains 20 g stones > 3 mm and < 6·25 mm
[8] Analyses on the 1946 samples (Table 1) corrected to a 6·25 mm basis by assuming that 1 kg dry fine soil < 6·25 mm contains 25 g stones > 2 mm and < 6·25 mm

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necessary, to a 6·25 mm sieve basis) by the appropriate adopted weight of fine soil per hectare (as given in Table 3), as the bulk density changed little between 1882 and 1975. Plot 1–0 contained less N on a percentage basis than either of the other two unmanured plots (6–1 and 6–2; Table 1) which are at the other side of the experimental area. However, when calculated on a per hectare basis this difference almost disappeared because plot 1–0 contains a little more fine soil per hectare than either 6–1 or 6–2 (Table 2). Only the values for plot 1–0 are given in Table 3.

In plot 7–2 (FYM) the soil bulk density decreased during the experiment so that the top 23 cm of soil in 1852 occupied a greater depth in 1975. To correct for soil expansion in this plot, the 23–25 cm layer was separately sampled and analysed in 1975. In 1852 the adopted value for the weight of fine soil to a depth of 23 cm was 2·62 Mkg ha^{-1} (Table 3), containing 2·56 Mkg *inorganic* fine soil ha^{-1} (assuming that the soil contained 1·17% C in 1852 and that soil organic matter contains 55% C, see next section). In 1975 the corresponding weight of inorganic fine soil to a depth of 23 cm was 2·15 Mkg ha^{-1}, so that an additional 0·41 Mkg ha^{-1} was required to give the same weight of inorganic fine soil in 1852 and 1975. The amounts of C and N in this quantity of soil were calculated from the data given in Table 1 for the 23–25 cm layer and added to those in the 0–23 cm layer as sampled. Comparable data for correcting the 1913 and 1946 samplings for soil expansion are not available and the corrections for these samplings were obtained by interpolation.

The amount of organic matter in the soil when the experiment started. A major problem in constructing Table 3 was to obtain a reasonable estimate of the amount of organic matter in the soil in 1852, 30 years before the first soil samples were taken. This was estimated in two independent ways: (i) from the decline in grain yields on the unmanured plot in the early years of the experiment and (ii) from the rate at which soil C accumulated in a comparable plot on Broadbalk that also received FYM annually, but in which the starting point was known.

Yields of grain on the three unmanured plots declined rapidly during the first 20 years of the experiment but then remained roughly constant for the next 100. Thus plot 1–0 produced 11·7 t *more* grain per hectare during the 30-year period 1852–81 than in the 30 years 1882–1911; the corresponding figure for plot 6–1 was 13·1 and for plot 6–2, 10·8 t ha^{-1} (Warren & Johnston, 1967). In the unmanured plots, grain made up 45% of the total dry above-ground produce (grain, straw and chaff) over the first 60 years of the experiment (Russell & Watson, 1938a), so that the extra total produce in the first 30 years amounted to 26·4 t ha^{-1} (mean of plots 1–0, 6–1 and 6–2). From Russell and Watson's statement that each kg of N assimilated by barley roots produces about 80–85 kg of above-ground dry matter, about 320 kg of N would have been needed to produce this *extra* 26·4 t of dry matter. In the unmanured plots this N presumably came from the soil organic matter, as it is unlikely that the 'background' supply of N from rain, biological fixation, etc., changed much over the first 60 years of the experiment. Thus, if the unmanured plot 1–0 contained 3·09 t total N ha^{-1} in 1882 (Table 3) it should have contained 3·41 t ha^{-1} in 1852.

Starting in 1885, a previously unmanured plot (2A, now plot 21) on Broadbalk was given an annual dressing of 35 t FYM ha^{-1} (the same application as on the Hoosfield FYM plot, situated about 200 m away). The unmanured soil on Broadbalk (plot 3, now 03) contained 2·99 t N ha^{-1} in 1881 in the top 23 cm of soil (Jenkinson, 1971) and this can reasonably be taken as the starting value for plot 2A in 1885. Twenty-nine years later, the top layer of plot 2A contained 5·46 t N ha^{-1} (calculated from data given by Warren, 1956, after allowing for changes in bulk density), which is equivalent to a mean accumulation rate of 85·2 kg N ha^{-1} year^{-1}. On Hoosfield, the FYM-treated soil (plot 7–2) contained 5·95 t N ha^{-1} in 1882 (Table 3); had it accumulated N at the same rate as plot

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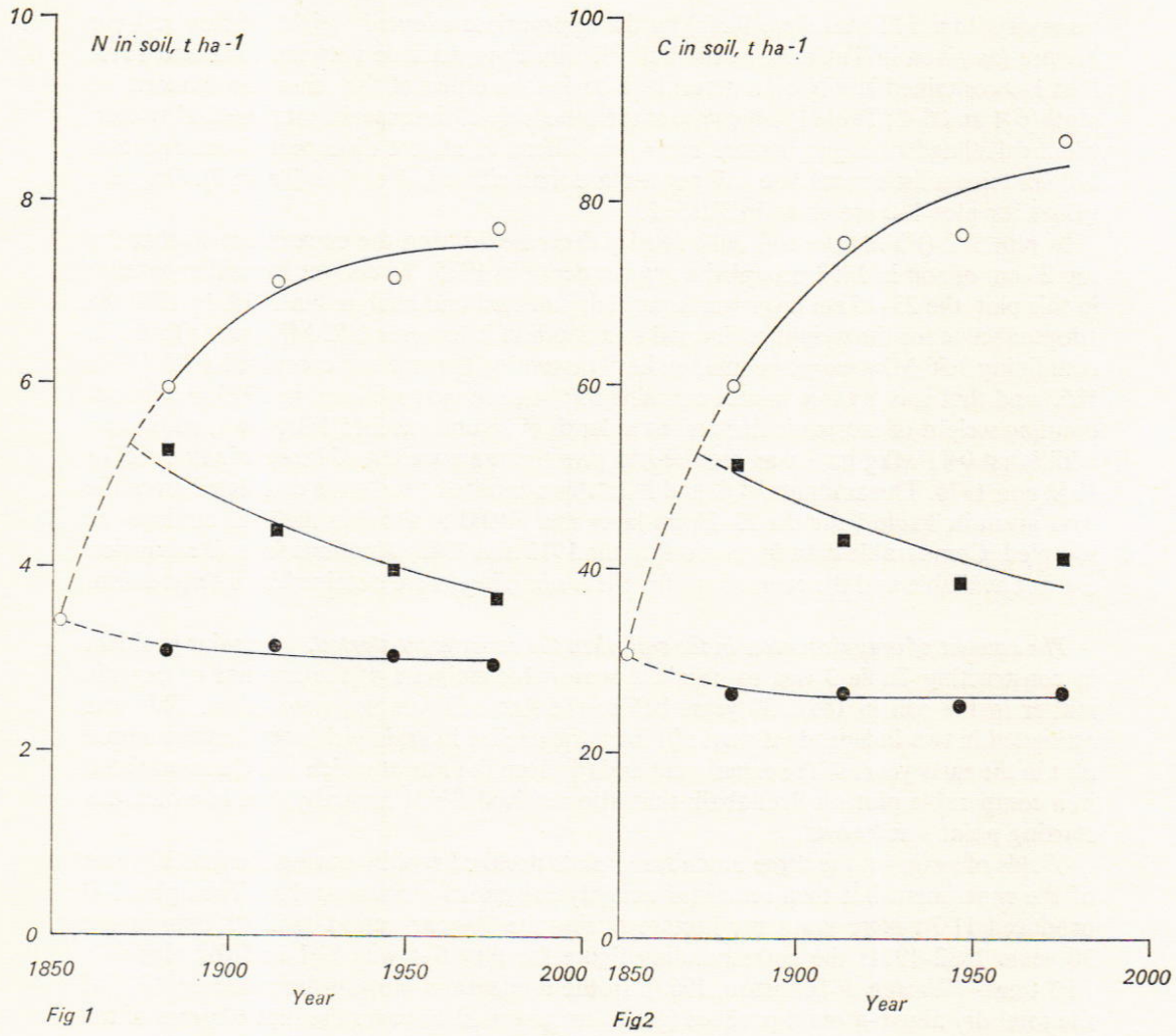

FIG. 1. Nitrogen in the topsoil of three plots on the Hoosfield Continuous Barley experiment; the unmanured plot (1–0), the plot receiving FYM annually (7–2) and the plot (7–1) that received FYM annually between 1852 and 1871 and has been unmanured since. An N test was superimposed on all three plots, starting in 1968; for details see Table 1. All measurements on a 0–23 cm basis; the results for plot 7–2 corrected (see text) to allow for the decrease in bulk density that occurred as organic matter accumulated.

FIG. 2. Organic C in the topsoil of plots 1–0, 7–2 and 7–1, otherwise as Fig. 1.

2A on Broadbalk it would have contained 3·40 t in 1852. Thus, the two totally different calculations both suggest that the initial N content of the top 23 cm of soil on the field was about 3·4 t ha^{-1}. On this basis, the fine soil of plot 1–0 would have contained 0·117% N in 1852; that of the other plots, 0·130%. The C contents of the soils in 1852 (Table 3) were derived from the calculated N contents by assuming a C/N ratio of 9 (Table 1).

The effects of manuring on the amount of organic matter in soil. The FYM plot has gained organic matter steadily throughout the experiment and still has not reached equilibrium (Tables 1 and 3, Figs. 1 and 2). The manure that was added every year between 1852 and 1975 (except 1912 and 1944) contained 27·2 t N ha^{-1} but only a small

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part of this remained in the topsoil, which showed a net gain of 4·27 t ha^{-1} up to 1975. Early work gave offtakes of about 56 kg N ha^{-1} $year^{-1}$ in the straw plus grain and these remained fairly steady until the 1914–31 period, when they declined to about 30 kg (Russell & Watson, 1938a). More recently, larger offtakes have been measured; in the mid-1960s 77 kg N ha^{-1} was removed in the straw and grain on this plot (Warren & Johnston, 1967; mean for Maris Badger and Plumage Archer in 1964 and 1966). Taking a mean of 56 kg N ha^{-1} $year^{-1}$ for the whole period, about 25% of the N in the FYM was removed in the crop, 15% remained in the topsoil and the remaining 60% is unaccounted for, the loss presumably being shared between volatilisation of NH_3, denitrification and leaching of NO_3^-.

The C and N contents of the unmanured plot have remained almost unchanged since the first thorough sampling in 1882, with annual losses balanced by annual gains (Table 3). Similarly, the C and N contents of the soil on the NPK plot (4–A) and on the PK plot (4–0) changed little over the course of the experiment, with the exception of the 1975 sampling. A possible explanation of the low values for plots 4–A and 4–0 in 1975 is that sometime between 1946 and 1975 these plots were ploughed to a depth greater than 23 cm, so that the sampling layer (0–23 cm) was diluted by subsoil poor in organic matter. The values for the total P content of the samples taken in 1975 (Table 1) from these two plots do not, however, support this explanation. Dilution with subsoil, had it occurred, would have depressed the rate at which P accumulated in the topsoil; this did not happen.

An important feature of the results is that the better crops grown on plots receiving inorganic fertilisers have had little effect on the organic content of the soil. Thus, over the period 1852–1962, the NPK plot (4–A) gave a mean yield of 2·46 t grain ha^{-1} and 2·80 t straw ha^{-1}; the PK plot (4–0) 1·32 t of grain and 1·46 t of straw and the unmanured plot 0·88 t of grain and 0·99 t of straw (Warren & Johnston, 1967). Yet by 1946, plot 4–A contained 29·3 t organic C ha^{-1} in the topsoil, plot 4–0, 29·9 t and plot 1–0, 25·3 t, differences that were small and quite possibly the result of long-lasting soil differences that existed before the experiment was started. The 1965 sampling gave a similar result; Warren and Johnston (1967) found that the unmanured plots 1–0, 6–1 and 6–2 contained, respectively, 0·101, 0·111 and 0·109% N in the topsoil, compared with values of 0·110 and 0·100% for plots 4–0 and 4–A.

The amount of organic matter in a soil depends on the annual input of organic material and on the rate at which this material decays in the soil. Two factors will tend to make the ratio (annual input of organic matter to the soil in plot 4–A/(annual input of organic matter to the soil in plot 1–0) closer to unity than the ratio (harvested grain plus straw from plot 4–A)/(harvested grain plus straw from plot 1–0). Root production is increased much less than above-ground production by fertiliser N (Welbank, Gibb, Taylor & Williams, 1974). Crop height is increased by fertiliser N, so that differences in stubble production (cut to the same height whatever the fertiliser treatment) will be less than the measured difference in straw yield. Both factors will tend to minimise the difference between the annual return of organic material in the two plots and thus, ultimately, in the amounts of soil organic matter they contain.

The rate of decay of the plant material entering the soil in plot 4–A may also be greater than that of the material entering plot 1–0, although on present knowledge the difference is unlikely to be great. Although inorganic N speeds the early stages of decomposition of N–poor crop residues, it has little influence on the amount of organic matter remaining once the initial rapid phase of attack is over (Allison, 1973).

The finding that plots growing very different amounts of barley as a result of differences in inorganic manuring contained much the same amount of soil organic matter when sampled in 1966 is the justification for the sampling procedure used in 1975, in which soil was bulked from each of the four sub-plots into which the old plots had been

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divided in 1968. Thus, the 1975 sample from plot 1–0 was a composite of four sub-samples taken from sections that had received different amounts of inorganic N: sub-plot 111 (see Table 1) had received 144 kg N ha^{-1} $year^{-1}$ between 1968 and 1973 and 96 kg N ha^{-1} $year^{-1}$ since 1974; sub-plot 112, 48 kg between 1968 and 1973 and 0 kg since 1974; sub-plot 113, 0 kg between 1968 and 1973 and 144 kg since 1974, and sub-plot 114, 96 kg between 1968 and 1973 and 48 kg since 1974.

The turnover of nitrogen in Hoosfield soil. The turnover of organic N in soil is conventionally assumed to follow the simple exponential model

$$\frac{dN}{dt} = A - rN \qquad (1)$$

where A is the annual addition, N the total nitrogen content of the soil and r the fraction of this N decomposing each year (see Jenkinson, 1966, for a discussion of the validity of this model). The solution of this differential equation is

$$N = N_E + (N_0 - N_E)\, e^{-rt} \qquad (2)$$

where N_E is the total N content of the soil when equilibrium has been reached and N_0 the initial N content of the soil.

Fig. 1 shows equation (2) fitted to the results in Table 3; Table 4 the curve parameters. For plots 7–2 and 1–0 the curves were set to pass through the estimated 1852 values (N_0). For plot 7–1 the curve was set to pass through the calculated value in 1872 (5·33; obtained from the fitted curve for plot 7–2); a point set at 2·99 for the year 2852 is also included, assuming that the N content of plot 7–1 will eventually fall to that predicted for plot 1–0.

There is close agreement between the known input of N in plot 7–2 (242 kg N ha^{-1} $year^{-1}$) and the input calculated from equation (2) (238 kg N ha^{-1} $year^{-1}$). The known input is made up of 225 kg N in the FYM, 2 kg in seed, 5 kg in rain, plus a hypothetical value for dry fixation of atmospheric ammonia, set at 10 kg. There will also be a contribution from non-symbiotic fixation, but this is likely to be small in a plot that receives so much N in manure.

The calculated annual input in plot 7–1 is 34 kg N ha^{-1} $year^{-1}$. If the annual input from rain, seed and dry fixation of ammonia is the same as in plot 7–2 (17 kg ha^{-1} $year^{-1}$), this result suggests that half the N input in the (now) unmanured crop of plot 7–1 comes from biological fixation.

The turnover of carbon in Hoosfield soil. Similar equations to (2) were fitted to the C data in Table 3; the results are shown graphically on Fig. 2. Table 4 gives the values of r, etc., for the fitted curves.

In contrast to N, the calculated annual input of C is much less than the actual input. Thus the calculated input in plot 7–2 is 2·1 t ha^{-1} $year^{-1}$, less than that in the FYM alone (3·0 t ha^{-1} $year^{-1}$), without even allowing for the C returned to the soil in roots and stubble. This discrepancy arises because the C/N ratio of the incoming plant debris (and that of the FYM) is greater than that of the soil organic matter. During the early stages of decomposition, C is rapidly mineralised by microbial activity, but because of the microbial need for N during this stage of the process, N is retained in the system.

By assuming that one-third of the incoming plant material is left in a 'humified' condition (Henin & Dupuis, 1945) the annual input in plot 7–1 can be calculated. Taking A as 0·21 (Table 4) the input of root and stubble C in this plot is then 0·63 t ha^{-1} $year^{-1}$. A barley crop grown at Rothamsted in 1972 (receiving 30 kg N ha^{-1}) contained 0·47 t roots ha^{-1} in the 0·25 cm layer when sampled in June (Welbank, personal communication).

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These roots would have contained about 0·2 t C ha^{-1}, suggesting that most of the annual input comes from crowns and stubble rather than roots.

The decomposition coefficient in plot 7–2 is 0·024, three times that in plot 7–1. This shows that the simple exponential model of equation (1), in which all fractions of the organic matter are considered to be equally decomposable, is not valid for Hoosfield. Another indication of this comes from the radiocarbon age of the unmanured plot (03) on Broadbalk, located about 200 m from the corresponding plot in Hoosfield. In 1881 this plot contained 0·94% organic C in the top 23 cm, almost exactly the same as in Hoosfield plot 1–0 (0·91%), sampled one year later. The equivalent radiocarbon age of the Broadbalk soil was 1385 years (Jenkinson, 1969). For simple exponential decay, turnover time = average age (Bartholomew & Kirkham, 1960), so that the radiocarbon age is vastly greater than the turnover times given in Table 4.

TABLE 4

Decomposition coefficients (r), turnover times (t), annual inputs (A) and equilibrium levels for organic carbon and total nitrogen in Hoosfield

	Organic C				Total N			
Plot	*r*, $year^{-1}$	*t*, years	*A*, t ha^{-1} $year^{-1}$	C_E, t ha^{-1}	*r*, $year^{-1}$	*t*, years	*A*, kg ha^{-1} $year^{-1}$	N_E, t ha^{-1}
1–0	0·079±0·059	—	—	26·2	0·037±0·018	—	—	2·99
7–1	0·008±0·002	128	0·21	26·5	0·011±0·001	87	34	2·98
7–2	0·024±0·005	41	2·10	86·7	0·031±0·005	32	238	7·62

The turnover time and annual input of organic C are not given in Table 4 for the unmanured plot (1–0), because both would have to be calculated from a decomposition coefficient whose standard error is comparable with the actual value, and hence meaningless. This is because the curves for plot 1–0 on Fig. 2 show insufficient curvature to establish *r* precisely.

In applying equation (1) to these results, it is assumed that the annual input (A) is constant. This is not so; the yields have not remained constant since 1852, and on four occasions the field was fallowed. Russell (1975) has introduced a more sophisticated equation, in which allowance is made for varying input. However, there seems to be little point in applying his equation to the data in this paper, because even large variations in yield over a period of many years have failed to produce a measurable difference in the amount of organic matter in the soil.

Effects of soil organic matter on crop yield. The plot receiving NPK fertilisers (old plot 4–A, now plots 421–424) now contains 1·7% organic matter in the top 23 cm of soil (assuming soil organic matter contains 55% C), compared with 5·4% in the plot receiving FYM. The present phase of the experiment, started in 1968, tests four nitrogen dressings (0, 48, 96 and 144 kg N ha^{-1}) on each of the old plots. This provides an opportunity to test the effects of two very different amounts of soil organic matter on the yield of barley. The mean yields over the first eight years of the modern experiment are shown in Fig. 3 for plots 1–0, 4–A, 7–1 and 7–2. This figure also shows the standard errors of the means, calculated from the eight individual annual yields.

During this period there was no significant difference between the maximum yield of grain on the plot with 1·7% organic matter (4–A) and that with 5·4% organic matter (7–2), although of course less inorganic N was required to achieve this maximum in the FYM plot. With straw, the maximum yield was not reached even with 144 kg N ha^{-1} and the FYM plot outyielded plot 4–A at all rates of N. Thus the marked differences between

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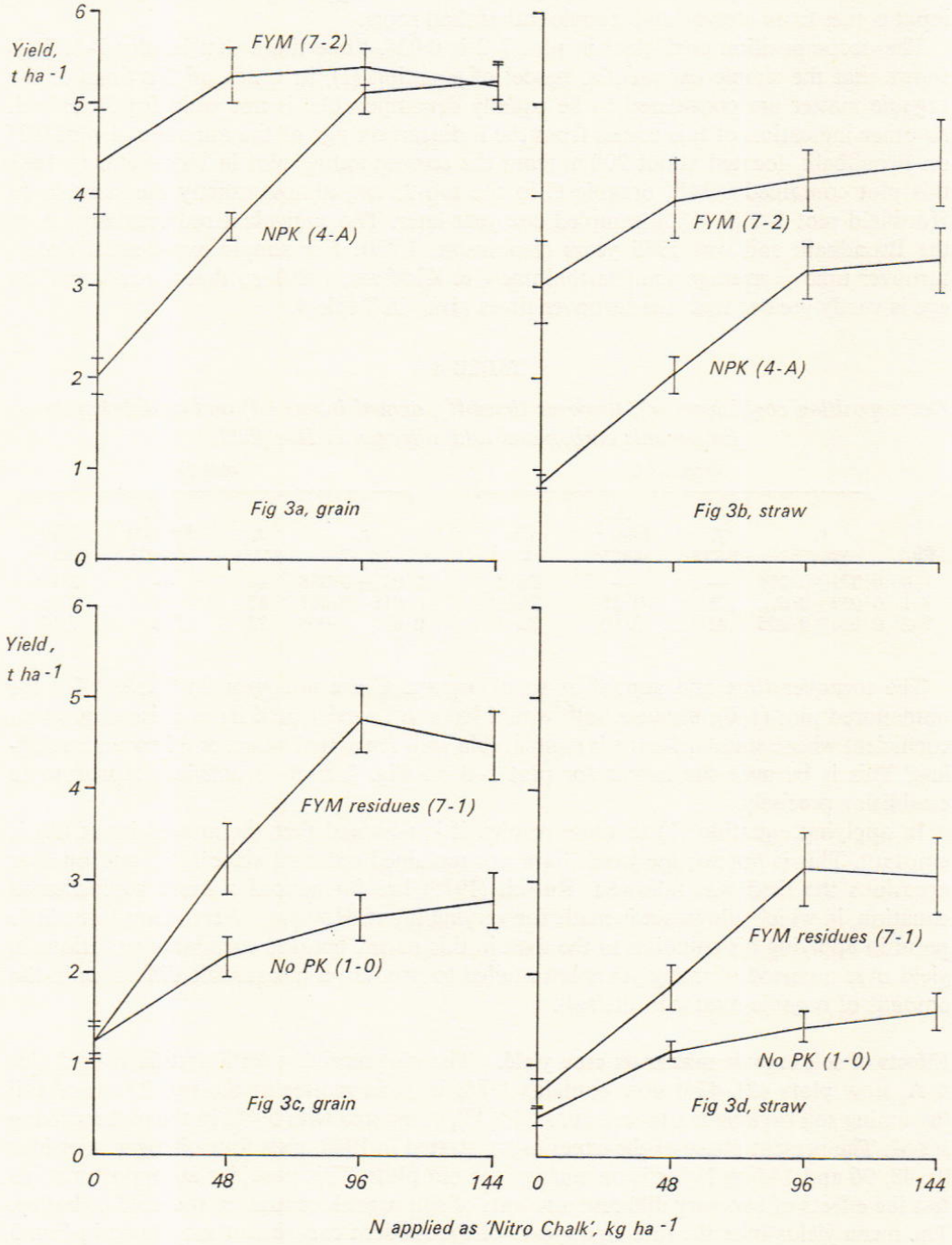

FIG. 3. Response of barley to fertiliser N on selected plots of the Hoosfield Continuous Barley experiment; means for the eight seasons 1968–75. Bars show the standard errors of these means.Figs. 3a and 3b show the response on plot 7–2 (FYM annually 1852–1975; N test superimposed 1968–75) and on plot 4–0 (NPK annually 1852–1967; PK continued and N test superimposed 1968–75). Figs. 3c and 3d show) the response on plot 7–1 (FYM annually 1852–71; unmanured 1872–1967, N test superimposed 1968–75 and on plot 1–0 (unmanured 1852–1967; N test superimposed 1968–75).

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the two soils in bulk density (Table 2) and soil organic matter content have had no effect on the amount of grain produced by the current variety, Julia. Nor do the results support the theory that crop yields vary less from year to year in soil containing much organic matter than in soil containing little. The biggest standard errors were found on the sub-plot of plot 7–2 that received FYM but not inorganic N. The reason for this variation is almost certainly that the FYM is applied in the autumn, so that the soluble N it contains is subject to greater leaching losses in a wet than in a dry winter. An application of 48 kg N ha^{-1} in the spring produced a response in the FYM plot in four years out of the eight: in the other years presumably enough soluble N had survived the winter to give the maximum yield without additional inorganic N.

The 2% or so of organic matter in soil well supplied with P and K on this part of the Rothamsted farm is therefore adequate for the production of barley, provided the correct amounts of inorganic fertiliser are given. With present varieties there is no advantage to be gained by increasing it further.

Figure 3 also shows the yields on plot 1–0, which had never received P or K, and on plot 7–1, the plot that received FYM between 1852 and 1871. When no inorganic N was given, the two plots yielded the same amount of grain and almost the same amount of straw, so that the old FYM residues now release little inorganic N for the crop. However, the response to fresh fertiliser N is much greater in 7–1 than in 1–0. For example, the sub-plot on 7–1 receiving 96 kg N ha^{-1} gave 4·76 t grain ha^{-1}, compared with 2·60 t from the corresponding sub-plot on plot 1–0 that received 96 kg N ha^{-1}. This difference cannot be explained by any long-persisting effects the old FYM residues may have had on soil structure; the bulk density is almost the same in both plots. It is, as pointed out by Warren (1956), the result of the P and K in the 20 dressings of FYM that were applied to plot 7–1 between 1852 and 1871. Soil taken from plots 1–0 and 7–1 in 1966 contained respectively, 5 and 12 mg P kg^{-1} soluble in 0·5M $NaHCO_3$. The corresponding amounts of K soluble in 1M ammonium acetate were 87 and 121 K kg^{-1} (Warren & Johnston, 1967). The effects of the FYM on the P and K status of the soil are clearly detectable even after 100 years now that N is given. It is possible that P and K residues still increase yields because uptakes were small during 1872–1967 when no N was given.

Nitrogen in the crops. The uptake of N by barley grain and straw in 1970–72 and 1973–75 is given in Table 5. Unfortunately we do not have a complete set of data for the second period so discussion is largely restricted to the results for 1970–72. In the first period, barley given FYM (plot 7–2) contained 93·0 kg N ha^{-1} when no fertiliser N was given; this N uptake was from the fresh dressing and the residues. There was a wide range of N

TABLE 5

N uptake by barley on Hoosfield, 1970–75

	N application, kg N ha^{-1}							
	0		48		96		144	
Plot	1970–72	1973–75	1970–72	1973–75	1970–72	1973–75	1970–72	1973–75
	kg N ha^{-1} in grain plus straw							
1–0	18·7	—	38·9	—	52·7	—	64·4	—
6–1	16·9	—	45·2	—	55·0	—	81·2	—
6–2	21·8	24·0	57·4	44·1	68·0	60·2	92·0	70·9
7–1	17·8	24·7*	48·8	58·8*	91·1	67·3*	108·7	63·1*
1–A	23·7	17·7	36·8	25·7	46·9	30·7	51·6	38·6
4–0	17·8	—	50·3	—	83·9	—	114·2	—
4–A	31·6	25·4	52·8	53·9	88·9	79·3	111·1	90·7
7–2	93·0	91·2	123·6	113·4	129·3	122·0	146·6	126·7

* 1974–75 only

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uptakes, 16·9 to 31·6 kg N ha^{-1}, on the other plots not receiving fertiliser N. This may be explained by the previous history of these plots, which can be put into three groups. Plots 1–0, 6–1, 6–2 and 4–0 have received no N since 1852 and at harvest the barley contained, on average, 18·8 kg N ha^{-1} (range 16·9 to 21·8). We only have results for plot 6–2 for the second period but for this plot N uptakes in the two periods were much the same, 21·8 and 24·0 kg N ha^{-1} respectively.

Plot 7–1 received 20 dressings of FYM during 1852–71 and none since. During 1970–72 barley on this plot contained 17·7 kg N ha^{-1}, much the same amount as the average for plots 1–0, 6–1, 6–2 and 4–0. In the second period N uptakes on plots 7–1 and 6–2 were almost identical, 24·7 and 24·0 kg N ha^{-1} respectively. This suggests that barley now gets little N from the extra organic matter in this soil. Warren (1956) considered that barley grown on this soil in the 1950s contained an extra 6 kg N ha^{-1} which came from the old FYM residues. The difference between his results and ours got 20 years later suggests that the amount of N now coming from the remaining residues is so small that it cannot be measured in the present experiment.

There are two plots in the third group, 1–A and 4–A. Both soils received 48 kg N ha^{-1} each year from 1852 to 1967; in addition, plot 4–A had PK fertilisers, plot 1–A had none. During 1970–72 barley on plot 1–A contained a little more N than the average of the first group of plots, 23·7 and 18·8 kg N ha^{-1} respectively. In the second period, uptake on plot 1–A was less than on plot 6–2 and 7–1. This variation may be due to chance. Much more N, 31·6 kg ha^{-1}, was removed from plot 4–A in the first period; in the second, uptake was less and only a little more than on plots 6–2 and 7–1. The extra uptake on plot 4–A during the first period may be because this soil contained more readily mineralised organic matter than did the soils of the first group. This additional organic matter could have accumulated from the extra root residues produced by barley given NPK fertilisers for so long. The decline in N uptake, from 31·6 to 25·4 kg N ha^{-1}, between the two periods suggests that this easily mineralised material was soon exhausted.

These results show how difficult it is to get reliable data for amounts of N in crops when none is given.

Recovery of applied N was also affected by previous history. Plots 1–0 and 1–A received no PK fertiliser during 1852–1975 but more P and K was removed from plot 1–A because N was given from 1852 to 1967. The soil of plot 1–A is now so depleted in P and K that barley recovered less of the applied N than it did on plot 1–0. Averaged over all N dressings tested, the recoveries were 23 and 36% on plots 1–A and 1–0 respectively. Recovery of the 96 and 144 kg N ha^{-1} dressing was much larger, often 60% or more, on soils which were enriched with P and K and therefore grew good crops of barley. Although total N uptake was larger on FYM- than on PK-treated soils for each amount of fertiliser N tested, the percentage recovery of fertiliser N was less on the FYM-treated soil.

Summary

The Hoosfield Continuous Barley experiment, running since 1852, provides a unique opportunity to test the long-term influence of manuring on soil organic matter. The C and N contents of the topsoil on the unmanured plot (1–0), the plot receiving P and K (4–0) and the plot receiving N, P and K (4–A) have changed little since 1882 and all three plots contained similar amounts of organic C (26·5, 28·8 and 25·2 t ha^{-1}, respectively) and total N (2·94, 2·75 and 2·57 t ha^{-1}) when sampled in 1975.

The plot receiving FYM (7–2) had trebled its C and N content by 1975 and is still gaining organic matter. The plot receiving FYM between 1852 and 1871, but nothing thereafter (7–1), still contains more organic C (41·4 t ha^{-1}) and total N (3·69 t ha^{-1}) than the plot which has been unmanured since 1852 (1–0).

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The extra organic matter in the FYM plot decreased the bulk density from 1·52 to 1·29 t m^{-3}. Nevertheless the improved structure in the FYM plot did not result in greater yields: when optimal quantities of inorganic N were applied to plots 4–A (N, P and K) and 7–2 (FYM) the grain yields were similar. The FYM applied to plot 7–1 between 1852 and 1871 still had a marked effect on response to N. Without N, plot 7–1 yielded about the same amount of grain as the plot that had been unmanured throughout (1–0), but the response to fertiliser N was much greater in 7–1, presumably because of the residual P and K from the FYM applied long ago.

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