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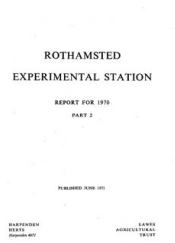

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The Accumulation of Organic Matter in Soil Left Uncultivated

D. S. JENKINSON

Introduction

In the early 1880s, Sir John Lawes allowed two areas of arable land at Rothamsted to revert to wilderness. The site on Geescroft field has been undisturbed ever since and is now an oak-dominated wood. Part of the other site, on Broadbalk field, has also been undisturbed and is now mixed woodland; another part of this site has been stubbed regularly, so that trees did not establish themselves, and is now dominated by a mixed herbaceous vegetation. The botanical changes in these wildernesses have been described at intervals (Lawes, 1895; Hall, 1905; Brenchley & Adam, 1915; Thurston, 1958; Witts, 1965).

Lawes (1895) forecast that the wilderness soils would gain nitrogen, a forecast confirmed by Hall (1905), who sampled both wildernesses in 1904. Soil samples taken from Broadbalk and Geescroft fields during the early 1880s, when the future wilderness sites were still under cultivation, have been preserved, together with those taken in 1904 by Hall. Further samples were taken in 1964 and 1965 and the complete set provides a unique chronosequence of soils for measuring the net rate at which organic matter accumulates in uncultivated land.

Experimental sites, sampling procedure and analytical methods

History of the wildernesses

Broadbalk. The wilderness is on land that had long been in cultivation, possibly since Roman times: the foundations of a Roman temple lie less than 150 m away. A map of 1623 shows that the field now called Broadbalk was then arable. Sometime during the 18th or early 19th century the whole field was chalked, from pits (dell holes) dug down to the underlying chalk, although there are no dell holes in that part of the field now occupied by the wilderness. The site of the wilderness is west of the Permanent Wheat Experiment and carried wheat from 1843 till 1882, like the rest of the field, but was always unmanured (Garner, 1965). The whole field, present wilderness included, was tile drained in 1849. The wilderness site was last cultivated during the autumn of 1881 and the wheat crop sown that autumn was never harvested. Since about 1900, trees and shrubs have been removed by regular stubbing from one part of the wilderness and the stubbings carted off. The present wooded part has been untouched since 1881, save for the felling of some trees along the eastern edge in 1959. In both parts of Broadbalk wilderness, reversion is assumed to have begun in 1883, when the first self-sown crop came up.

Geescroft. Like Broadbalk, this site had long been in cultivation, and is also shown on the 1623 map as arable land. The whole field was tile drained in 1849. The present wilderness was part of an experimental field growing beans from 1847 till 1878, with frequent breaks towards the end because of crop failures. After bare fallowing for four years, clover was grown from 1883 to 1885, and the 'wilderness-to-be' fenced off and left to

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itself in January 1886. It was last cultivated during the spring of 1883. Reversion to wilderness is assumed to start with the clover crop, in 1883.

Soils. Geescroft and Broadbalk wildernesses are 1·3 km apart, on the same gently undulating plateau at an elevation of about 130 m. Both are on very slight slopes and both are on the same soils series (Batcombe). The Batcombe series is classified as a leached brown soil (*sol lessivé*) with a loamy surface layer overlying Clay-with-flints (Avery, 1964). Drainage is somewhat impeded by the clay substratum, as evidenced by varicoloured mottling, black manganiferous deposits, and grey coated cleavage faces at depths below 45–60 cm. Both sites are now classified as moderately well drained. Soil profiles from Geescroft wilderness and from both parts of the Broadbalk wilderness are described in the Appendix. Table 1 shows the mechanical composition of the soils. Mechanical analyses were done on composite soil samples made, for each soil layer, by combining equal weights of fine soil (0·635 cm sieve) from each of the four holes dug per site. The mechanical composition of the stubbed site on Broadbalk is almost identical with that of Geescroft all the way down the profile. Although the 0–22·9 cm layer in both the wooded and stubbed sites in Broadbalk is similar, there is appreciably less clay and more silt in both the 22·9–45·7 and 45·7–68·6 cm layers of the wooded site. This is consistent with the greater thickness of the stony loam layer (see Appendix) in some of the sampling holes of the wooded section. The mechanical analyses of all three profiles are consistent with the suggestion (Avery 1964) that the surface horizon of the Batcombe series contain loessial material. The origin and development of the soil on Broadbalk was discussed in Part 2 of the *Rothamsted Report for 1968*.

Earthworms are very active in both parts of Broadbalk wilderness: both are mull sites and there is no carry-over of leaf litter from year to year. In Geescroft earthworm activity is less and some irregular areas are now covered with a thin moder layer, up to 1 cm thick. In December 1965 eight equispaced quadrats were sited along the 1965 (No P) soil sampling line (see 'Location of Sampling Sites' below): in four the 1965 leaf fall lay directly on the mineral soil, in the others the 1965 fall lay on partly decomposed leaf litter from previous years. Geescroft is in transition from mull to moder: as the pH continues to fall (see Table 3), earthworms will probably disappear from those parts of the site they still occupy and the whole area then go over to moder.

Soil sampling. So that samples taken at different times should be directly comparable, the sampling procedure used in 1881 and 1883 (described in detail by Lawes and Gilbert, 1882) was followed in 1964 and 1965. Briefly, after removal of plants and surface litter, a strong steel box 6 inches (15·2 cm) square and 9 inches (22·9 cm) deep was driven into the ground until the top was level with the soil. The soil and stones in the box were then removed, giving the 0–9 inch sample, the surroundings dug away till level with the bottom of the box, the box again driven down 9 inches and the 9–18 inch sample taken out. Further depths were sampled similarly.

The samples were air dried (25–35°C), and the weights of air-dried fine soil, i.e. soil passing a 0·25 inch (0·635 cm) sieve, stones retained by the sieve, and roots retained by the sieve recorded. From these weights, corrected to an oven-dry basis (24 hours at 100°C), the weights of fine oven-dry soil, stones and roots per hectare were calculated, knowing the area of the sampling box. Samples were stored, air-dry, in sealed bottles. The root weights are subject to large experimental error and will not be considered further: to assess these accurately it would have been necessary to sample much larger volumes of soil, especially in the wooded sites.

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TABLE 1

Mechanical composition of Broadbalk and Geescroft soils

Site	Sampling date	Land use	Sampling depth, cm	As percentage oven-dry fine soil passing 0·635 cm sieve				
				Gravel 6·35–2 mm	Coarse sand 2–0·2 mm	Fine sand 0·2–0·02 mm	Silt 0·02–0·002 mm	Clay <0·002 mm
Broadbalk field	November 1964	Stubbed	0–22·9	4	5	41	22	24
			22·9–45·7	3	4	29	16	45
			45·7–68·6	2	3	26	10	57
Broadbalk field	November 1964	Wooded	0–22·9	3	5	42	22	23
			22·9–45·7	2	5	39	21	30
			45·7–68·6	1	3	28	14	50
Geescroft field	April 1965	Wooded	0–22·9	4	5	44	23	21
			22·9–45·7	3	4	32	17	43
			45·7–68·6	2	4	29	9	55

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The 1904 samples were taken and stored in the same way except that a 0·3 cm sieve was used and a known weight of chalk was picked out of the 0–9 inch Broadbalk samples before sieving. Table 3 gives, for each site and depth, the factors used to convert analyses done on the 0·3 cm soil to a 0·635 cm basis. These factors were obtained by measuring the amount of stones passing a 0·635 cm sieve but retained by a 0·3 cm sieve in the 1964 and 1965 samples and assuming that this weight of stones had been excluded from the corresponding 1904 samples.

Sampling was usually done along a straight line laid across the site to be sampled, and the holes dug at equal intervals along this line. The number of samples taken, i.e. holes dug per site at each sampling, is given in Table 3. For analysis, soil was ground to pass a 30 mesh sieve.

Location of sampling sites

Broadbalk. No soil samples taken before 1895 from what is now the wilderness have survived, so that those taken in 1881 from the unmanured plot (plot 3) of the adjacent Permanent Wheat Experiment had to be used to represent the initial condition of the wilderness. Plot 3 runs up to the edge of the stubbed part of the present wilderness. For comparison, samples from the plot given sulphate of ammonia alone (plot 10) were also analysed. The initial weights of soil and stones per hectare were taken as those found for the Permanent Wheat Experiment in 1881, and are the means for all plots except those given organic manures (see Table 3). Samples of top-soil were taken from the wilderness in 1895. As the corresponding records of the weights of soil, stones, etc., could not be found, this sampling will not be considered further, other than to record the analyses done on a combined sample of the soil (Table 3). Two sampling holes were dug in 1904, one in the present stubbed section of the wilderness, and one on the edge of the present wooded part. In 1964 the stubbed and wooded parts were sampled separately: see Fig. 1 for sampling positions.

Geescroft. Because Geescroft wilderness is on the old experimental plots, it was possible to sample areas which had received fertiliser phosphorus in the past and other areas that had not. The 1883 (No P) samples were taken from plots 3 and 4 of the Continuous Beans Experiment: both plots received sodium nitrate alone. The 1883 (P) samples were from plots 6 and 7 (both receiving nitrogen and phosphorus) of the old beans experiment. Unfortunately the 9–18 inch (22·9–45·7 cm) sample from plots 6 and 7 has not survived and so a sample from this depth of plot 8, receiving nitrogen, phosphorus and potassium, was substituted. The only surviving figures for the weight of fine soil per hectare in 1883 came from plots on either side of the contemporary sampling lines: see Table 3. The precise position of the 1904 sampling holes is not known, but from the total phosphorus content of the sample, it must have come from the site of plots that had once received phosphorus (total phosphorus in the top 22·9 cm of plots 3 and 4 was 0·054%, in plots 6 and 7, 0·080% and in the 1904 samples 0·073%; Table 3). The 1964 and 1965 (No P) samples were taken on a line close to the division between plots 3 and 4; the 1964 (P) samples on a parallel line 12 m away, close to the old division between plots 6 and 7 (see Fig. 1).

Stand measurements. All tree stems with diameters exceeding 2·5 cm at a height of 1·3 m were counted and their girths measured on the central parts of both wildernesses in June 1969. In Broadbalk the area thus sampled (533 m²) was the whole site less the outer 5 m. In Geescroft the area sampled (4040 m²) was on plots 3–10 of the old beans

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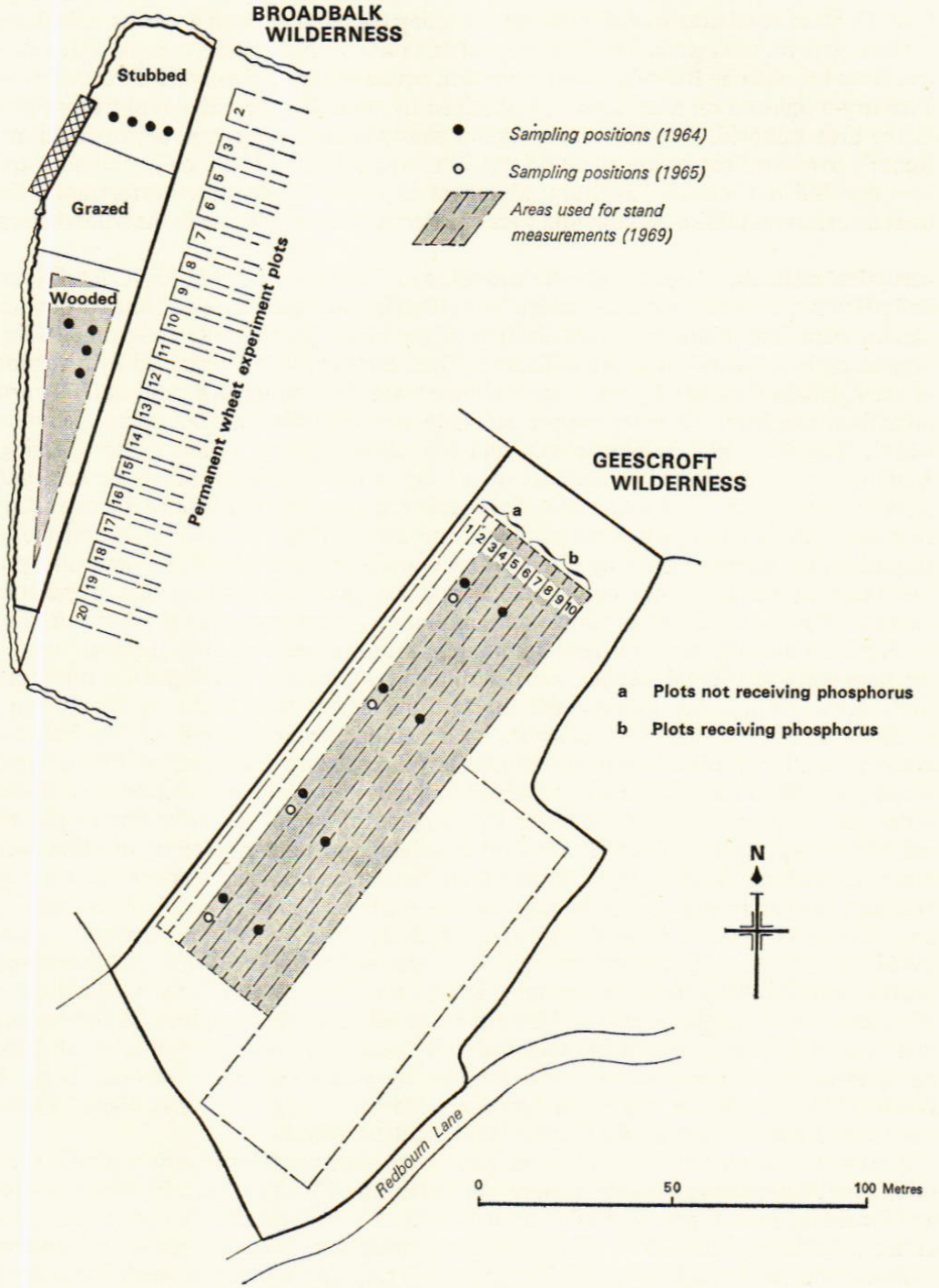

FIG. 1. Broadbalk and Geescroft wildernesses.

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experiment: all parts of the measured area were at least 8 m from the wilderness edge (Fig. 1). Stem basal area was obtained by summing the basal areas of the trees, calculated for each tree from its girth. Tree dry-weight (trunk and branches) was calculated for each tree from the girth by Bunce's (1968) regression equation for all sites and all tree varieties. Tree dry-weight on an area basis was obtained by summing the individual tree weights in the area sampled. The dry-weight figures thus obtained are rough approximations: Bunce's combined regression equation was obtained with ash, birch, oak, sycamore and lime and did not include hawthorn, abundant in both wildernesses. Furthermore, the trees he used to establish his equation were smaller than some of those in the wildernesses.

Analytical methods. Loss on ignition was estimated by igniting soil at 550°C for 1 hour. Soil pH was measured on a suspension of soil (10 g) in water (20 ml). Total and carbonate-carbon were determined by a modification of the Shaw procedure (Jenkinson, 1965b); organic carbon was taken as the difference. Total nitrogen was determined by a version of the Kjeldahl method; 2 g soil were moistened with 5 ml water, 2 g catalyst (100 parts potassium sulphate, 10 parts copper sulphate pentahydrate and 0·5 parts selenium) added, then 6 ml 98% sulphuric acid and the whole digested 2 hours after clearing. Ammonia was determined in aliquots of the digest by distillation into boric acid and titration with 0·005 N sulphuric acid. Inorganic nitrogen was determined by extracting 10 g soil with 50 ml N potassium sulphate, and determining ammonium and nitrate in aliquots of the filtered extract by d'Arifat and Warren's method (1964). Organic nitrogen was taken as the difference between total and inorganic nitrogen so that it includes nitrogen present in the soil as 'fixed' ammonium, i.e. ammonium nitrogen not extracted by N potassium sulphate: for fixed ammonium measurements on soils from Broadbalk see Bremner, 1959. Total sulphur was determined by a method developed for this work (Jenkinson, 1968b): the results were in close agreement with those by Bloomfield's method for total soil sulphur (1962) when both methods were compared on soils from the wildernesses. Inorganic sulphur was estimated by a procedure developed by Williams and Steinbergs (1962) for soluble and adsorbed sulphate: 10 g soil was shaken with 40 ml water and 1 g of calcium carbonate for 16 hours and the sulphate in the filtered extract reduced to hydrogen sulphide. The hydrogen sulphide was determined by titration with mercuric acetate (Archer, 1956) rather than by the colorimetric procedure used by Williams and Steinbergs. Organic sulphur was taken as total soil sulphur less soluble and adsorbed sulphate. Total phosphorus was determined by sodium carbonate fusion (Mattingly, 1970). Organic phosphorus was determined by Williams, Williams and Scott's method (1960), in which 2 g soil is ignited for 1 hour at 550°C, then extracted for 16 hours with 2N sulphuric acid and the difference between the phosphorus in this extract and that in a similar extract of unignited soil taken as organic phosphorus. Organic phosphorus was determined in some samples by another ignition method (Legg & Black, 1955) and by an extraction procedure (Mehta, Legg, Goring & Black, 1954). Mechanical analysis was by the international pipette method.

Nitrogen and carbon mineralisation rates were measured by incubating soil. Air-dried soil (50 g) passing a 0·635 cm sieve was wetted to 60% of its water holding capacity and incubated in a stoppered bottle for 10 days at 25°C in the dark. The bottle also contained a beaker holding 20 ml of N potassium hydroxide. Even though the incubation bottles contained enough oxygen (230 mg) for soil respiration over the whole incubation period, the bottles were aerated after six days. The amount of carbon dioxide absorbed in the alkali was calculated from the volume of standard hydrochloric acid required to bring the pH from 8·30 to 3·70, less that required by the blank. Nitrogen mineralisation

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was measured by determining nitrate and ammonium nitrogen in N potassium sulphate extracts of soil before and after incubation.

All analyses were done in duplicate and the analysis was repeated when discrepancies between duplicate results exceeded those usual with the measurement.

Sampling errors. Most analyses were done on bulked samples, made, for each soil layer, by combining equal weights of 30 mesh soil from each of the holes dug in a given site. To check the validity of this procedure, and also to estimate the significance of differences between sites, soil samples from each depth of the four holes dug per site in 1964 and 1965 were analysed separately, in duplicate, for total nitrogen. Total nitrogen was chosen as giving, in a single determination, a good measure of the organic matter in a soil.

Errors from sample bulking. Table 2 shows the nitrogen in oven-dry fine soil as found on the bulked sample (column C) and as the mean of four separate determinations on the individual samples (column B). Agreement was close: percentage nitrogen as found by the two procedures never differed by more than 0·005. Table 2 also shows

TABLE 2

Nitrogen in wilderness soils

Site	Sampling date	Sampling depth, cm	Oven-dry fine soil Mkg ha^{-1}	% N in oven-dry fine soil		N in oven-dry fine soil, kg ha^{-1}	
			A	B	C	D	E
Broadbalk wilderness, stubbed part	November 1964	0–22·9	2·32	0·266	0·261	6170	6060
		22·9–45·7	2·71	0·100	0·098	2700	2660
		45·7–68·6	3·09	0·074	0·075	2270	2320
Broadbalk wilderness, wooded part	November 1964	0–22·9	2·29	0·252	0·255	5750	5840
		22·9–45·7	2·71	0·099	0·099	2680	2670
		45·7–68·6	3·01	0·080	0·079	2400	2370
Geescroft wilderness, wooded	April 1965	0–22·9	2·19	0·166	0·168	3630	3670
		22·9–45·7	2·94	0·092	0·093	2720	2730
		45·7–68·6	3·12	0·067	0·072	2090	2230
L.S.D. ($P = 0·05$) between sites (9 D.F.)			0·22	0·015	—	490	—
L.S.D. ($P = 0·05$) between depths (18 D.F.)			0·17	0·012	—	400	—

A. Means of four measurements per site.
B. Samples from each hole analysed separately in duplicate: figures in this column are means of four such measurements per site.
C. Means of duplicate analyses on composite sample from all four holes.
D. Weights of nitrogen per hectare calculated individually for each hole from measurements made on that hole alone: figures in this column are means of four such measurements per site.
E. Mean weight of fine soil per hectare × per cent nitrogen in composite sample ÷ 100.

(column E) the weight of nitrogen in a given layer calculated from the weight of fine soil per hectare (mean of results from four holes) and the nitrogen content of the bulked sample. The weights of nitrogen per hectare given in column D are the means of four independent measurements, one from each hole, calculated from measurements made and analyses done on soil from that hole alone. The differences between columns D and E are small relative to the total amount of nitrogen in the soils, so that the errors introduced by sample bulking are relatively unimportant.

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Significance of differences between sites. Table 2 shows that the weights of fine soil per hectare in the top layer (0–22·9 cm) of Geescroft wilderness, the stubbed part of Broadbalk and the wooded part of Broadbalk do not differ significantly ($P = 0{\cdot}05$). In all three sites there was significantly less fine soil in the top than in the second layer, and significantly less in the second than in the third. The top layer of Geescroft contains significantly less nitrogen per hectare than the equivalent layer in either part of Broadbalk wilderness. There is less nitrogen in the top layer of the wooded part of Broadbalk than in the stubbed part, but the difference does not quite reach significance (Table 2, column D). The amounts of nitrogen in the second and third layers do not differ significantly between sites.

The accuracy of the sampling in 1881, 1883 and 1904 cannot now be assessed. Probably the sampling error was less in 1881 and 1883 than in 1964 and 1965 because more samples

TABLE 3

Sampling and analysis of soils

Site	Sampling date	Land use	Sampling depth,[1] cm	Oven-dry fine soil[2] Mkg ha^{-1}	Oven-dry stones Mkg ha^{-1}	Oven-dry roots Mkg ha^{-1}	Equivalent soil depths at different sampling dates,[3] cm
Broadbalk field	October 1881	Arable	0–22·9	2·87[9]	0·61[9]	—	22·9
			22·9–45·7	3·04[9]	0·38[9]	—	45·7
			45·7–68·6	3·10[9]	0·22[9]	—	68·6
,,	,, October 1881	Arable	0–22·9	2·87[9]	0·61[9]	—	22·9
			22·9–45·7	3·04[9]	0·38[9]	—	45·7
			45·7–68·6	3·10[9]	0·22[9]	—	68·6
,,	,, October 1895	Scrub	0–22·9	—	—	—	—
,,	,, March 1904	Scrub	0–22·9	2·77[12,22]	0·51[12,21]	—	24·0
			22·9–45·7	3·01[12,22]	0·04[12,21]	—	47·4
			45·7–68·6	3·05[13,22]	0·03[12,21]	—	71·0
,,	,, November 1964	Stubbed	0–22·9	2·32[11]	0·50[11]	0·006[11]	28·8
			22·9–45·7	2·71[11]	0·50[11]	0[11]	53·5
			45·7–68·6	3·09[11]	0·12[11]	0[11]	76·5
	,, November 1964	Wooded	0–22·9	2·29[11]	0·42[11]	0·022[11]	29·0
			22·9–45·7	2·71[11]	0·32[11]	0·014[11]	53·6
			45·7–68·6	3·01[11]	0·17[11]	0·005[11]	76·6
Geescroft field	April 1883	Arable (No P)	0–22·9	2·73[10]	—	—	22·9
			22·9–45·7	3·01[10,23]	—	—	45·7
			45·7–68·6	3·10[10,24]	—	—	68·6
	,, April 1883	Arable (P)	0–22·9	2·73[10]	—	—	22·9
			22·9–45·7	3·01[10,23]	—	—	45·7
			45·7–68·6	3·10[10,24]	—	—	68·6
,,	,, April 1904	Scrub	0–22·9	2·71[12,22]	0·64[12,21]	—	23·1
			22·9–45·7	3·03[12,22]	0·35[12,21]	—	45·7
			45·7–68·6	3·13[13,22]	0·03[12,21]	—	68·1
,,	,, April 1965	Wooded (No P)	0–22·9	2·19[11]	0·70[11]	0·007[11]	27·8
			22·9–45·7	2·94[11]	0·43[11]	0·003[11]	50·8
			45·7–68·6	3·12[11]	0·16[11]	0·002[11]	73·9
,,	,, November 1964	Wooded (No P)	0–22·9	2·25[11]	0·73[11]	0·009[11]	—
,,	,, November 1964	Wooded (P)	0–22·9	2·28[11]	0·76[11]	0·008[11]	—

[1] Sampling depths 0–9 inches, 9–18 inches and 18–27 inches in all cases.
[2] One Mkg ha^{-1} = 892 200 lb per acre.
[3] Depth to which soil must be sampled to contain the same weight of ignited fine soil per hectare as in the 0–22·9, 0–45·7 and 0–68·6 cm layers of Broadbalk in 1881 or of Geescroft in 1883.
[4] All from Broadbalk plot 3 (continuous wheat: unmanured).
[5] Six from Broadbalk plot 10A: six from 10B (both under continuous wheat and receiving N fertiliser alone).
[6] Two from Geescroft plot 3: two from plot 4 (both under continuous beans and receiving N fertiliser alone).
[7] Two from Geescroft plot 6: two from plot 7 (both under continuous beans and receiving N and P fertilisers).
[8] All from Geescroft plot 8 (continuous beans, receiving N, P, K, Na and Mg fertilisers).
[9] Mean of 108 measurements (six on each plot of the experiment, plots 2 and 19 excluded).
[10] Mean of 12 measurements (two on each of plots 1, 2, 9 and 10; four on plot 8).
[11] Mean of four measurements.
[12] Mean of two measurements.
[13] One measurement.
[14] Corrected for chalk removed from sample prior to sieving (0·53 g per 100 g oven-dry 0·635 cm sieve fine soil).
[15] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 2·64 g stones retained by a 0·3 cm sieve, plus 0·53 g chalk removed prior to sieving.

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were taken per site and the sites were then probably more uniform. Sampling errors were probably greater in 1904 than in preceding or subsequent samplings.

Results

Soil expansion during reversion to wilderness. Table 3 gives the weights of fine soil, stones and roots per hectare for the different sites and sampling dates. The soil has expanded: for example in 1881, the top layer (0–22·9 cm) of Broadbalk contained 2·75 million kg of ignited fine soil per hectare, whereas in 1964 the corresponding value for the stubbed section of the wilderness was only 2·15 million kg. For this example, the equivalent depth is defined as the depth to which the soil should have been sampled in 1964 to contain the same weight of ignited fine soil per hectare as when sampled to

TABLE 3 (*continued*)

Number of samples combined for analysis	Soil pH	As percentage oven-dry fine soil passing 0·635 cm sieve								
		Loss on ignition	Organic C	Carbonate C	Organic N	Inorganic N	Organic S	Inorganic S	Organic P	Inorganic P
6[4]	8·1	4·19	0·92	0·52	0·102	0·0024	0·0166	0·0015	0·0252	0·0408
6[4]	7·7	4·98	0·59	0·01	0·077	0·0010	0·0107	0·0017	0·0244	0·0255
6[4]	7·4	5·36	0·46	0	0·066	0·0004	0·0063	0·0013	0·0205	0·0216
12[5]	7·9	4·12	1·04	0·41	0·113	0·0022	0·0181	0·0020	0·0264	0·0378
12[5]	7·7	4·90	0·59	0·01	0·079	0·0013	0·0107	0·0021	0·0252	0·0270
12[5]	7·6	6·16	0·49	0·01	0·065	0·0008	0·0085	0·0017	0·0223	0·0257
7[25]	7·9	5·68	1·43	0·56	0·143	0·0026	0·0216	0·0014	0·0276	0·0385
2[15]	8·0	5·31[14]	1·34	0·46[14]	0·142	0·0006	0·0197	0·0015	0·0291	0·0351
2[16]	7·6	6·33	0·66	0·01	0·097	0·0012	0·0132	0·0017	0·0280	0·0305
2[17]	7·4	6·83	0·52	0·01	0·080	0·0010	0·0073	0·0013	0·0261	0·0284
4	7·8	7·48	2·79	0·29	0·260	0·0010	0·0397	0·0022	0·0420	0·0354
4	7·9	6·15	0·81	0·04	0·098	0·0001	0·0142	0·0015	0·0311	0·0273
4	7·7	6·71	0·55	0·01	0·075	0·0004	0·0091	0·0017	0·0287	0·0247
4	7·9	7·19	2·70	0·39	0·254	0·0009	0·0396	0·0021	0·0410	0·0416
4	8·0	4·67	0·85	0·16	0·098	0·0004	0·0162	0·0020	0·0309	0·0308
4	7·8	5·78	0·61	0·01	0·078	0·0004	0·0132	0·0020	0·0300	0·0303
4[6]	7·1	4·06	1·04	0	0·115	0·0025	0·0147	0·0012	0·0250	0·0292
4[6]	7·1	5·37	0·58	0	0·083	0·0008	0·0098	0·0011	0·0248	0·0272
4[6]	7·1	5·82	0·49	0	0·070	0·0011	0·0075	0·0011	0·0212	0·0268
4[7]	7·0	4·27	1·10	0	0·117	0·0024	0·0151	0·0014	0·0254	0·0547
4[8]	7·1	5·33	0·56	0	0·079	0·0015	0·0090	0·0014	0·0234	9·0224
4[7]	7·1	6·02	0·47	0	0·066	0·0007	0·0078	0·0013	0·0222	0·0217
2[18]	6·1	4·58	1·37	0	0·131	0·0023	0·0190	0·0015	0·0286	0·0445
2[19]	6·9	4·40	0·58	0	0·082	0·0010	0·0103	0·0012	0·0248	0·0283
2[20]	7·1	5·34	0·42	0	0·069	0·0004	0·0078	0·0011	0·0198	0·0266
4	4·5	5·93	1·98	0	0·166	0·0022	0·0267	0·0059	0·0327	0·0234
4	5·5	6·32	0·76	0	0·092	0·0008	0·0172	0·0062	0·0249	0·0256
4	6·2	6·52	0·49	0	0·071	0·0007	0·0117	0·0065	0·0204	0·0287
4	4·6	5·31	1·85	0	0·159	0·0017	0·0246	0·0050	0·0321	0·0236
4	4·7	5·21	1·82	0	0·156	0·0018	0·0236	0·0044	0·0344	0·0433

[16] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 2·24 g stones retained by a 0·3 cm sieve.
[17] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 1·43 g stones retained by a 0·3 cm sieve.
[18] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 2·53 g stones retained by a 0·3 cm sieve.
[19] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 1·39 g stones retained by a 0·3 cm sieve.
[20] Analytical results converted to 0·635 cm sieve basis by assuming that 100 g oven-dry fine soil (0·635 cm sieve) contains 1·20 g stones retained by a 0·3 cm sieve.
[21] Stones passing 0·635 cm sieve but retained by 0·3 cm sieve deducted.
[22] Stones passing 0·635 cm sieve but retained by 0·3 cm sieve added.
[23] Assuming 96·2% oven-dry fine soil in air-dried fine soil
[24] Assuming 94·7% oven-dry fine soil in air-dried fine soil
} See Hall (1917), Chapter III, Table 12.
[25] Samples taken with a sampling box 12 inches square by 9 inches deep: Samples labelled 'Broadbalk Upper Butts'.

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22·9 cm in 1881. Equivalent depths were obtained graphically by plotting the weights of ignited fine soil per hectare in the 0–22·9, 0–45·7 and 0–68·6 cm layers against depth for each sampling date and then reading off the required figures, by extrapolation where necessary. Table 3 gives, for the different sampling dates, the equivalent depths for the 22·9, 45·7 and 68·6 cm sampling depths in 1881 (Broadbalk) or in 1883 (Geescroft).

For the top layer of Broadbalk, the equivalent depths were 22·9 cm (1881) and 28·8 cm (1964: stubbed); for all three layers, 68·6 cm (1881) and 76·5 cm (1964: stubbed). Thus most of the expansion occurred in the top layer. Soil expansion was less in Geescroft than in either part of Broadbalk wilderness.

These calculations of soil expansion assume that nothing leaving a residue on ignition has been added or lost from the various soil layers during the development of the wilderness. This assumption is probably not far wrong. The removal of calcium carbonate by leaching is almost certainly the biggest single loss: if all the chalk in the top 68·6 cm of Broadbalk in 1881 had been leached out by 1964, the equivalent sampling depth given in Table 3 (76·5 cm, stubbed section) would have been too large by only 0·6 cm.

A better basis for these calculations would probably have been the weights of ignited fine soil *plus* stones per hectare. However, because the weight of stones per hectare for Geescroft in 1883 is not known, it was decided to make all calculations on the basis of ignited fine soil alone. The errors thus introduced are small. Broadbalk contained 9·77 million kg ignited fine soil plus stones per hectare in the top 68·6 cm in 1881: to obtain this weight of ignited fine soil plus stones in 1964 it would have been necessary to sample the stubbed section to a depth of 76·8 cm, compared to a depth of 76·5 cm calculated on the basis of ignited fine soil alone.

Calculation of the net accumulation of soil constituents allowing for soil expansion. Because the soil has expanded, the layers sampled and analysed in 1964 do not correspond exactly to those sampled in 1881. Allowance must therefore be made for soil expansion in calculating the net accumulation of a constituent on an area basis for a given layer. This was done, graphically, for each soil constituent, by plotting the amounts in the 0–22·9, 0–45·7 and 0–68·6 cm layers against depth for each sampling date. Using the 'equivalent depths' given in Table 3, the amount of the soil constituent per hectare in a given soil layer at a given sampling was then read off. Table 4 gives the amounts of carbon (organic), nitrogen (organic), sulphur (total and organic) and phosphorus (total and organic) in equivalent layers of the two wildernesses at different sampling dates. These corrections for soil expansion are substantial: for example the top layer (0–22·9 cm) of Broadbalk wilderness (stubbed) *as sampled* in 1964 contained 3100 kg per hectare more organic nitrogen in 1964 than in 1881, whereas *when allowance is made for soil expansion*, the top 22·9 cm of soil in 1881 gained 3900 kg per hectare by 1964.

Table 5 shows the gains in organic carbon, organic nitrogen, organic sulphur and organic phosphorus in the top layer (0–22·9 cm) during reversion to wilderness. A similar table can be constructed for the whole profile from the results in Table 4. However, the errors in gains thus calculated for the whole profile are much greater than in the gains for the top layer: extrapolation to a depth greater than that sampled is necessary to correct for soil expansion in the whole profile, the lower layers are more heterogeneous than the top layer, and the whole-profile gains (especially of sulphur and phosphorus) are much smaller relative to the amounts originally present than are the gains in the top layer.

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TABLE 4

Carbon, nitrogen, sulphur, and phosphorus in equivalent soil layers

Site	Sampling date	Land use	Soil layer,[a] cm	Soil constituent,[b] kg ha^{-1}					
				Organic C	Organic N	Total S	Organic S	Total P	Organic P
Broadbalk field	October 1881	Arable[e]	0–22·9[e]	26 300	2930	520	480	1890	720
			0–68·6[f]	58 000	7300	1130	1000	4710	2100
	October 1881	Arable[d]	0–22·9[e]	29 700	3240	580	520	1840	760
			0–68·6[f]	63 000	7600	1280	1110	4910	2210
	March 1904	Scrub	0–24·0[e]	38 600	4110	620	570	1860	850
			0–71·0[f]	73 000	9600	1320	1190	5360	2520
	November 1964	Stubbed	0–28·8[e]	71 800	6860	1100	1040	2230	1200
			0–76·5[f]	109 000	11 800	1840	1670	5650	3020
	November 1964	Wooded	0–29·0[e]	69 400	6600	1110	1040	2380	1170
			0–76·6[f]	110 000	11 600	2060	1880	6000	2990
Geescroft field	April 1883	Arable (No P)	0–22·9[g]	28 400	3150	430	400	1480	680
			0–68·6[h]	61 000	7800	1030	930	4540	2080
	April 1883	Arable (P)	0–22·9[g]	30 000	3210	450	410	2190	690
			0–68·6[h]	61 000	7600	1050	930	4930	2080
	April 1904	Scrub (P)	0–23·1[g]	37 400	3610	560	520	2020	780
			0–68·1[h]	68 000	8100	1180	1070	5010	2130
	April 1965	Wooded (No P)	0–27·8[g]	49 300	4240	860	700	1550	870
			0–73·9[h]	84 000	9000	2100	1530	4610	2210

[a] Equivalent layers (see Table 3) have same suffix, i.e. [e], [f], [g], or [h].
[b] 1 kg ha^{-1} = 0·8922 lb per acre.
[c] Plot 3; see Table 3.
[d] Plot 10; see Table 3.

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TABLE 5

Organic carbon, nitrogen, sulphur and phosphorus gained by the top 22·9 cm (9 inches) of soil during reversion to wilderness

		Broadbalk stubbed	Broadbalk wooded	Geescroft wooded
Gained by soil since 1883,[a,b] kg ha^{-1}	Organic C	45500	43100	20900
	Organic N	3930	3670	1090
	Organic S	560	560	300
	Organic P	480	450	190
Mean annual gain, kg ha^{-1} year^{-1}	Organic C	560	530	250
	Organic N	49	45	13
	Organic S	6·9	6·9	3·7
	Organic P	5·9	5·6	2·3
Initial soil ratios[b]	C/N	9·0	9·0	9·0
	S/N	0·16	0·16	0·13
	P/N	0·25	0·25	0·22
Ratios in gain	C/N	11·6	11·7	19·2
	S/N	0·14	0·15	0·28
	P/N	0·12	0·12	0·17

[a] All gains calculated on an equivalent depth basis.
[b] For Broadbalk the initial status is taken to be that of Broadbalk plot 3, as sampled in 1881: for Geescroft that of Geescroft plots 3 + 4, as sampled in 1883.

Changes in the wildernesses over the experimental period

pH. The calcium carbonate reserves of the Broadbalk wilderness site ensured that changes in pH between 1881 and 1964 were trivial. In contrast, Geescroft had no carbonate reserves, and the pH of the top layer (0–22·9 cm) fell from 7·1 in 1883 to 6·1 in 1904 and to 4·5 in 1965 (Table 3). Acidity increased less in the lower soil horizons.

Organic carbon. The wooded and stubbed parts of Broadbalk have accumulated almost exactly the same amounts of organic carbon during 81 years: more than 80% of the gain occurred in the top layer. The annual accumulation rate in Geescroft was only about half the rate in Broadbalk: again the accumulation was mainly in the top layer. Both wildernesses gained organic carbon slightly faster before than after 1904.

Organic nitrogen. As with carbon, the wooded and stubbed parts of Broadbalk have accumulated almost the same amount of organic nitrogen in 81 years, most of the accumulation also being in the top layer. The 1904 samples from the 45·7–68·6 cm layer contained more nitrogen than either of the corresponding 1964 samples (Table 3). Hall found the total nitrogen content of the 1904 sample to be 0·0839% (Hall, 1905); my result for the same sample was 0·0823% so that nitrogen gain during storage can be discounted. Organic carbon behaved differently: being less in the 1904 sample than in the 1964 samples, as would be expected. Because of this peculiarity in the nitrogen content of the 45·7–68·6 cm layer, and to a lesser extent, the 22·9–45·7 cm layer, the 1904 results for these layers have not been used in calculating annual accumulation rates etc.

The annual accumulation rate in the top layer of the stubbed site during the first 21 years was 56 kg organic nitrogen per hectare per year, slightly greater than during the succeeding 60 years (46 kg per hectare per year). Over the whole period the stubbed part of Broadbalk gained 49 kg per hectare per year in the top layer and 55 kg per hectare per year in the whole profile. The corresponding figures for the wooded part are 45 and 53 kg per hectare per year. Geescroft accumulated much less nitrogen: little more than

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quarter of that gained by Broadbalk. Here the annual accumulation of organic nitrogen in the top layer was 13 kg per hectare per year; in the whole profile, 15 kg per hectare per year.

Relative to their organic nitrogen contents, the inorganic nitrogen contents of all the soils are small (see Table 3), so that gains in organic nitrogen can be taken as gains in total nitrogen without introducing errors of more than 1–2%.

Sulphur. The top layers of the wooded and stubbed section of Broadbalk wilderness gained about the same amount of organic sulphur in 81 years. However, the two lower layers of the wooded part contained 840 kg organic sulphur per hectare in 1964, compared with 640 kg in the corresponding layers of the stubbed part. No completely satisfactory explanation of this difference between sites can be given. It is unlikely to be due to analytical error: the total sulphur contents of the 1964 Broadbalk samples were determined by X-ray fluorescence spectrometry and the values obtained were all within 10 ppm of those given in Table 3 (Brown & Kanaris-Sotiriou, personal communication). If subsoil heterogeneity is the explanation, then the additional organic sulphur might be expected to be accompanied by additional organic carbon. The 22·9–45·7 and 45·7–68·6 cm layers of the wooded part do contain more carbon than the corresponding layers in the stubbed part, but the differences are less than those for organic sulphur (Table 3).

Calcareous soils can contain water-insoluble sulphate associated with the calcium carbonate (Williams, Williams & Scott, 1960). Such sulphur would be reported as 'organic' in Tables 3, 4 and 5. However, it is improbable that the Broadbalk soils contain much such 'organic' sulphur because the chalk in them contains little sulphur. Chalk hand-picked from the top layer (0–22·9 cm) of the stubbed section of Broadbalk wilderness contained only 190 ppm total sulphur.

The mean annual gain for the top layer of Geescroft was 3·7 kg organic sulphur per hectare per year, roughly half the corresponding gain for Broadbalk (6·9 kg organic sulphur per hectare per year). Inorganic sulphur behaved differently: the mean annual gain for the top layer of Geescroft was 1·6 kg inorganic sulphur per hectare per year, but in Broadbalk the gain was negligible (0·2 kg inorganic sulphur per hectare per year).

Phosphorus. The total phosphorus content of the whole profile of Broadbalk was 4710 kg per hectare in 1881, 5360 kg per hectare in 1904, 5650 kg per hectare in the stubbed part of the wilderness in 1964 and 6000 kg per hectare in the wooded part in 1964, all on an equivalent depth basis. This gain may not be real, because the 1881 samples from plot 3, taken to represent the status of the soil before the wilderness was allowed to develop, may have contained less phosphorus than the actual wilderness site, especially that part of it now wooded. It is also possible that phosphorus could have been brought up from below 68·6 cm by deep rooting plants, although this is unlikely as the gain in phosphorus between 1881 and 1964 is much less in the top layer (0–22·9 cm) than in the 22·9–68·6 cm layer (Table 4). Phosphorus brought up from the deep subsoil would almost certainly accumulate mainly in the top layer, the layer that receives most of the incoming plant debris. Chance contamination by phosphorus-containing materials cannot be completely excluded as the site is so near the present farm buildings, but is unlikely in a carefully preserved experimental area.

In Geescroft, the initial samples came from the area that is now wooded, and the total phosphorus content of the 1965 samples corresponds closely with that of the 1883 (No P) samples (Table 4). In 1964, parts of the wilderness that had once received superphosphate

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TABLE 6

Organic phosphorus in soil, as determined by different methods

	Soil	Broadbalk plot 3, sampled 1881 0–22·9 cm	Broadbalk plot 3, sampled 1881 45·7–68·6 cm	Broadbalk stubbed, sampled 1964 0–22·9 cm	Broadbalk stubbed, sampled 1964 45·7–68·6 cm	Geescroft wooded, sampled 1965 0–22·9 cm	Geescroft wooded, sampled 1965 45·7–68·6 cm
		ppm P in oven-dry soil					
Total		660	421	774	534	561	491
Method A	Extracted from untreated soil	188	79	195	59	126	65
	Extracted from ignited soil	440	284	615	346	452	268
	Organic	252	205	420	287	326	203
Method B	Extracted from untreated soil	207	84				
	Extracted from ignited soil	442	286				
	Organic	235	202				
Method C	Extracted from untreated soil	305	239	326	287	250	253
	Extracted from ignited soil	482	312	591	369	455	322
	Organic	177	73	265	82	205	69
Method D	Extracted from untreated soil	305	239				
	Extracted from ignited soil	486	319				
	Organic	181	80				
Method E	Total P extracted	473	316	590	379	460	341
	Inorganic P extracted	327	278	391	372	301	310
	Organic	146	38	199	7	159	31

Method A—Extract 2 g soil 16 hours with 100 ml 2N H_2SO_4. Ignite at 550°C for 1 hour.
Method B—Extract 0·5 g soil 16 hours with 100 ml N H_2SO_4. Ignite at 550°C for 0·5 hours.
Method C—Extract soil with concentrated HCl. Ignite at 240°C for 1 hour.
Method D—Ignite at 550°C for 1 hour. Otherwise as C.
Method E—Extract soil with concentrated HCl, then with 0·5N NaOH.

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and parts that had not were sampled separately. Table 3 shows that the additional phosphorus made no difference to the amounts or organic carbon, nitrogen or sulphur accumulating in the top 22·9 cm of soil.

The division of soil phosphorus into organic and inorganic parts in Tables 3 and 4 is suspect. The organic phosphorus values in these Tables were measured by Williams, Williams and Scott's (1960) method, hereafter called method A. Organic phosphorus measurements by method A were compared with those by four other methods on six of the soils appearing in Table 3. Table 6 shows that there is poor agreement between the different methods, especially when applied to subsoils. Method A, in which organic phosphorus is taken as the difference between the phosphorus soluble in cold 2N sulphuric acid before and after ignition, always gave the largest value. Method B is a slight modification of method A, using N sulphuric acid as extractant: it gives substantially the same results as method A. In method C, organic phosphorus is taken as the difference between the phosphorus soluble in hot concentrated hydrochloric acid before and after ignition. Slightly more phosphorus is dissolved after ignition than in method A, but as much more inorganic phosphorus is dissolved from the unignited soil, method C gives considerably smaller values for organic phosphorus than method A. The differences between the amounts of phosphorus extracted by hot concentrated hydrochloric acid and cold 2N sulphuric acid from the unignited soils are 131 and 228 ppm for the 1964 Broadbalk topsoil and subsoil respectively; as the subsoil contains much less organic matter, these differences are unlikely to represent organic phosphorus hydrolysed by hot hydrochloric acid but not by cold dilute 2N sulphuric acid. A more plausible explanation of the discrepancy between methods A and B is that a fraction of originally insoluble *inorganic* phosphorus is rendered soluble in cold 2N sulphuric acid by ignition, whereas this fraction is soluble in hot concentrated hydrochloric acid whether or not the soil has been ignited: with method A this fraction would be reported as organic phosphorus. Method D is the same as method C except that the soil is ignited at 550°C instead of at 240°C: the two methods give almost the same results. In method E the soil is extracted with hot concentrated hydrochloric acid, followed by cold and hot 0·5N sodium hydroxide: the difference between total and inorganic phosphorus in the combined extracts is called organic phosphorus. Values obtained by this method were smaller and more variable than by the other four methods. The total amount of phosphorus extracted did not differ greatly from that extracted from ignited soil by hot concentrated hydrochloric acid (method C), suggesting that extraction was complete, and that this method gives low values for organic phosphorus because organic phosphorus is hydrolysed during extraction.

Methods A, C and E all show that organic phosphorus in the top 22·9 cm of the Broadbalk soil increased as the stubbed site reverted to wilderness. In 81 years the amounts of organic carbon, nitrogen and sulphur in the top layer of soil from this site all more than doubled, whereas the increase in organic phosphorus by method A was 67%, by method C, 50% and by method E, 36%. Thus, despite the discrepancies, all three methods indicate that the gain of organic phosphorus, relative to the initial content, is much less than that of organic nitrogen, organic carbon or organic sulphur (Table 3). Little else can be said about the organic phosphorus results in Tables 3, 4, 5 and 6 until more is known about the measurement of organic phosphorus in soil.

Mineralisation of nitrogen and carbon by soils from the wildernesses. Table 7 shows that the C/N ratio of the organic matter mineralising in Geescroft lies between the corresponding ratios for the wooded and stubbed parts of Broadbalk. Ammonium is nitrified almost

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TABLE 7

Mineralisation of carbon and nitrogen by soils from the wildernesses

Soil[a]	Broadbalk stubbed, sampled 1964	Broadbalk wooded, sampled 1964	Geescroft wooded, sampled 1964	Geescroft wooded, sampled 1965
ppm NO_3-N initially in soil	1	3	12	13
ppm NH_4-N initially in soil	8	8	7	7
ppm NO_3-N in soil after incubation	71	83	13	15
ppm NH_4-N in soil after incubation	4	4	28	32
ppm N mineralized during incubation	66	76	22	27
ppm CO_2-C mineralised during incubation	650	490	190	210
C mineralised during incubation / N mineralised during incubation	9·9	6·5	8·6	7·8
organic C initially in soil / organic N initially in soil	10·7	10·6	11·6	11·9

[a] 0–22·9 cm sample (see Table 3) in all cases.

TABLE 8

Stand measurements in Geescroft and Broadbalk wildernesses

Species	No. stems per ha[a]	Stem basal area,[b] $m^2\ ha^{-1}$	Dry weight $kg\ ha^{-1}$
GEESCROFT			
Hawthorn (*Craetagus monogyna*)	300	3·6	14500
Oak (*Quercus robur*)	167	16·5	105100
Elm (*Ulmus* spp.)	155	2·0	8400
Ash (*Fraxinus excelsior*)	140	8·5	46700
Elder (*Sambucus nigra*)	118	0·4	1100
Maple (*Acer campestre*)	29	0·4	1500
Sycamore (*Acer pseudoplatanus*)	2	0·3	1600
Hazel (*Corylus avellana*)	2	0·02	50
Silver birch (*Betula pendula*)	2	0·2	1400
All species	915	31·9	180000
BROADBALK			
Hawthorn (*Craetagus monogyna*)	1801	22·0	88600
Sycamore (*Acer pseudoplatanus*)	394	9·1	50300
Hazel (*Corylus avellana*)	281	1·9	6100
Ash (*Fraxinus excelsior*)	206	17·4	104100
Maple (*Acer campestre*)	38	3·6	21500
Elder (*Sambucus nigra*)	19	0·04	110
Oak (*Quercus robur*)	19	0·8	3600
All species	2758	54·8	274000

[a] With stem diameter >2·5 cm at a height of 1·3 m.
[b] At a height of 1·3 m.

completely in the Broadbalk soils during incubation; in the Geescroft soils little, if any, nitrification occurs during incubation, although the soil initially contained some nitrate. This is almost certainly because the pH of the Geescroft soils is near the lower limit for nitrification (Weber & Gainey, 1962).

Stand measurements on the trees in Broadbalk and Geescroft wildernesses. Table 8 gives the number of tree stems, stem basal area and calculated dry-weight of trunks and canopy for the wildernesses, all per hectare. All three values are greater on Broadbalk

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than on Geescroft, suggesting that annual production is greater in Broadbalk, although differences in the botanical colonisation sequence (Hall, 1905; Brenchley & Adam, 1915; Thurston, 1958) could also contribute to the present difference in tree dry-weight between the two sites.

Discussion

Accumulation of organic carbon by the wilderness soils. Organic matter accumulates in soil at a rate depending on the annual input of plant material and on the rate at which this plant material decomposes. Thus the smaller rate of accumulation in Geescroft could be caused by a smaller annual input or a greater annual loss than in Broadbalk, or by a combination of both. Stem basal area and calculated dry weight of trunks and canopy (Table 8) are both greater on the wooded part of Broadbalk than on Geescroft and there can be little doubt that more organic matter enters the soil each year in Broadbalk than in Geescroft. There is much more under-story vegetation on Broadbalk than on Geescroft, further increasing the productivity difference between the sites.

First consider factors that could cause the production of plant material (and hence the amount of organic matter entering the soil) to be less on Geescroft than on Broadbalk. External climatic factors such as sunlight, rainfall, and temperature cannot be involved as these are substantially the same for two adjacent sites of similar topography and altitude. Although stand measurements were done on the central parts of the wildernesses to minimise edge effects, the wooded part of Broadbalk is so much smaller (0·13 ha) than the wooded part of Geescroft (1·3 ha) that some of the productivity difference between the sites (Table 8) may result from the greater importance of edge effects on Broadbalk. For example, more light probably reaches the centre of the wilderness from the edge in Broadbalk than in Geescroft.

Brenchley and Adam (1915) considered that the botanical differences between the two sites indicated Geescroft to be the wetter, and forecast that Geescroft was too wet to revert to woodland. The appearance of the profiles shows that drainage is, or has been, more impeded on Geescroft than on Broadbalk (Appendix). However, this drainage difference cannot be great because the mechanical composition of the two sites is almost identical, both are tile-drained, and both have slight slopes. Drainage has not been sufficiently impaired on Geescroft to prevent reversion to woodland. Differences in drainage and structure between Geescroft and Broadbalk did not restrict plant production on Geescroft in the pre-wilderness period; plot 7 on Broadbalk (receiving nitrogen, phosphorus, potassium and magnesium) produced 2100 kg of wheat per hectare per annum over the period 1869–73, whereas plot 14 on Geescroft, given the same manurial treatment, gave 2400 kg oats per hectare, both good yields by the standards of that time. It is most improbable that the drainage of the two sites differs enough to account for the difference in productivity.

Differences in pH are unlikely to have influenced plant production directly, at least over the first few decades. By 1904 the pH of the Geescroft topsoil had only fallen to 6·1, yet the accumulation of organic carbon was markedly less than on Broadbalk.

Differences in productivity caused by potassium and phosphorus can be excluded. Both sites contain about the same amount of exchangeable potassium: the top layer of the 1904 Geescroft soil contained 116 ppm exchangeable potassium and the corresponding Broadbalk sample 117 ppm. Were plant production limited by phosphorus deficiency in Geescroft, then the part that used to receive phosphate should have produced more plant material than the part that had never received any. This difference

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should then have been reflected in the amount of organic matter entering the soil and hence on the amount of organic carbon accumulated by the soil. No such difference was found, so that Geescroft is not a site of the type discussed by Walker and Adams (1958), where organic production is limited by soil phosphorus.

The most probable reason for Geescroft producing less organic matter than Broadbalk is that less nitrogen is available for plant growth. Soil from Broadbalk now mineralises more than twice as much nitrogen as soil from Geescroft (Table 7). This difference has developed because the capacity of the two sites to accumulate nitrogen differs: see next section.

The other factor influencing the accumulation of organic matter in a soil is the rate at which the incoming organic matter decomposes. As the pH difference between Geescroft and Broadbalk widened, the rates of decomposition on the two sites may also have diverged. Experiments on the decomposition of carbon-14 labelled ryegrass in Rothamsted soils, of similar clay content but different pH, showed that, although decomposition was slower in acid soils at first (Jenkinson, 1965a), by the end of five years the difference between acid and calcareous soils had almost disappeared (Jenkinson, 1968a). Kononova (1966; p. 252) suggested that humic materials are more stable under calcareous than under non-calcareous conditions. If this is so, the decomposition curves for the carbon-14 experiments will cross over and less labelled carbon will remain in acid soils, after (say) 100 years, than in the corresponding calcareous ones. Broadbalk would then accumulate soil organic matter faster than Geescroft because it receives more plant material each year *and* because organic matter is more stable under calcareous conditions. The relative importance of these two mechanisms cannot be assessed from the data in this paper.

Accumulation of nitrogen by the wildernesses

Site accumulation. The total site gain by the wooded parts of Broadbalk and Geescroft exceeds the soil gain by the amount of nitrogen in the standing vegetation. This was not measured but its order of magnitude can be established from Ovington's (1962) figures for the dry-weights and nitrogen contents of broad-leaved deciduous English forests. The mean nitrogen content of the above-ground part of the trees from nine different sites was 0·386%. Applying this figure to the tree weights for Broadbalk and Geescroft wildernesses (Table 8), the trunks and canopy on Broadbalk contained 1100 kg nitrogen per hectare, those on Geescroft 700 kg nitrogen per hectare. The nitrogen in the over-wintering vegetation on the stubbed part of Broadbalk is negligible, compared with the amount in the soil. Neglecting the understory nitrogen and the nitrogen in large roots, and taking the gain in soil organic nitrogen as the gain in total soil nitrogen, the total site gain for the wooded part of Broadbalk wilderness is then 65 kg per hectare per year (12 kg in the standing vegetation, plus 53 kg in the soil to a depth of 68·6 cm), comparable with recent results for woodlands from different parts of the world (Ovington, 1962; Richards, 1964; Moore, 1966). The stubbed part of Broadbalk gained a little less nitrogen (55 kg per hectare per annum) and Geescroft much less, 23 kg (8 kg in the standing vegetation plus 15 kg in the soil). Although these estimates of vegetation nitrogen are rough, most of the site gain is in the soil, so that errors of even 50% in the vegetation nitrogen estimate will not greatly influence the total site gain.

Sources of the nitrogen accumulating in the wildernesses

Rainfall. Over the period 1889–1903 the mean annual amount of mineral nitrogen carried down in the rain at Rothamsted was 4·4 kg per hectare, of which 1·3 kg per hectare

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was nitrate nitrogen, and 3·1 kg per hectare was ammonium nitrogen (Hall, 1917; Chapter II, Table 7). Over the period January 1960–December 1964 the corresponding total was 5·4 kg per hectare, of which 2·4 kg was nitrate nitrogen and 3·0 kg was ammonium nitrogen. These values, together with all the other values in this paper for the chemical composition of rain and air over the period January 1960–December 1964, are means of monthly samples analysed by the Government Chemist under the direction of the Meteorological Office: for the procedure used see Stevenson (1968).

'Dry' sorption of ammonia. The mean annual ammonia content of the air at Rothamsted over the period January 1960–December 1964 was 4·8 μg per m^3. Eriksson (1968), reviving earlier theories, suggested that the soil: plant system absorbs part of this atmospheric ammonia, and he constructed a map from the ammonia concentrations over Western Europe during 1958 in which the dry deposition of ammonia at Rothamsted was calculated to be 13 kg nitrogen per hectare per year.

The construction of the new farm buildings with their attendant manure heaps, cattle stalls etc., within 200 m of the Broadbalk wilderness will have provided a new source of ammonia (see Hutchinson & Viets, 1969). Some ammonia may reach the wilderness directly from the farm buildings but the amount is unlikely to be large because if it were, the crop on the adjacent unmanured plot 3 of the Permanent Wheat Experiment should also gain nitrogen by the same process. Johnston (1969a) showed that the wheat on plot 3 took up about the same amount of nitrogen annually in 1966–67 as in 1852–61, long before the new buildings were erected.

Organic nitrogen in dust, rain, bird droppings etc. Allen, Carlisle, White and Evans (1968) found, for four sites in England, that between 2·8 and 5·4 kg organic nitrogen per hectare per year was collected in their rain gauges, the largest amounts coming from the sites nearest heavy industry. Organic nitrogen in their rain gauges was from 28 to 50% of the inorganic nitrogen. These results make it improbable that more than 2 or 3 kg organic nitrogen per hectare per year are added to the soil at Rothamsted from this source. From analyses done almost 100 years ago, Miller (1905) put the Rothamsted figure at 1·5 kg per hectare per year. Birds will concentrate nitrogen in the wilderness by collecting food from the surrounding cultivated areas and defecating in the wooded parts of the wilderness. Although this may be important near roosting and nesting areas (Weir, 1969), it is unlikely to be important over whole sites: in any case the soil under the wooded part of Broadbalk, home to vast numbers of sparrows, contains no more nitrogen than the soil of the stubbed part.

Symbiotic fixation. Legumes once occurred on both parts of Broadbalk wilderness (Brenchley & Adam, 1915), but are now confined to the stubbed part, where *Lathyrus pratensis* is the only legume present (Thurston, personal communication). By 1913 legumes had disappeared from all but the margin of the wooded part (Brenchley & Adam, 1915). Geescroft grew a good crop of red clover in 1883, 1884 and 1885: Gilbert (1890) estimated, from soil and crop analyses, that roughly 170 kg nitrogen per hectare was fixed per year over this period, of which the soil gained about 60 kg per year. However, the clover soon died out in Geescroft and thereafter legumes comprised a very small part of the vegetation (Hall, 1905), although found in the botanical surveys of 1895, 1898, 1903 and 1913. None were present when the site was examined in 1957 (Thurston, personal communication). The reason for the early disappearance of legumes in Geescroft is unknown; even as late as 1913 the site contained open areas where they might have

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been expected. It follows that legumes have played a negligible role in fixing nitrogen in the wooded parts of both wildernesses, except possibly during the early years of Broadbalk.

No known nodulating non-legume able to fix nitrogen, for example alder (*Alnus incana*), has ever been recorded in either Broadbalk or Geescroft wilderness. Moore (1966) reviewed work suggesting that the roots of some non-nodulating plants can form associations with microorganisms that fix nitrogen. More evidence is needed before ascribing a significant role to such associations in the Rothamsted wildernesses.

Non-symbiotic fixation. Ashby (1907) found that soil from Broadbalk wilderness fixed more than twice as much nitrogen as soil from Geescroft wilderness when incubated with mannitol: *Azotobacter chroococcum* were 'abundant' in the Broadbalk samples but the Geescroft soil contained none. Ziemiecka (1932) found more *Azotobacter* in the stubbed than in the wooded sections of Broadbalk wilderness, but even the former contained far fewer than plot 3. In 1960 Burlingham (see Meiklejohn, 1969) failed to find *Azotobacter* in the stubbed part of Broadbalk wilderness. This evidence strongly suggests that *Azotobacter* now play a negligible role in the accumulation of nitrogen in the soils of these wildernesses.

Broadbalk soil contains *Clostridium pasteurianum* cells in larger numbers than *Azotobacter* (Meiklejohn, 1956). Soil from plot 3 incubated with straw under semi-anaerobic conditions fixed nitrogen vigorously (Barrow & Jenkinson, 1962) and it may be that anaerobes are the active fixing agents in Broadbalk wilderness. Some of the nitrogen accumulated by Geescroft may also have been fixed anaerobically, especially during the early years when the soil was less acid and organic matter accumulated faster.

Algae are sometimes plentiful enough in Broadbalk wheat field to form a crust on the surface soil (Bristol Roach, 1927). Dart and Roughley (personal communication) found that crusts from Broadbalk actively reduce acetylene to ethylene and so presumably fix nitrogen. Whether or not enough light reaches the soil surface in the wildernesses for significant fixation by blue-green algae is not known.

Nitrogen balance. The accumulation of nitrogen by a site depends on the annual input *and* on the extent to which the soil: plant system can retain nitrogen. Inorganic nitrogen alone cannot cause accumulation of organic matter: in 1966 the mean nitrogen content of the top 23 cm of plot 10 of the Permanent Wheat Experiment was 0·106%, little more than that of plot 3, although by then plot 10 had received 12 000 kg nitrogen per hectare as sulphate of ammonia during the 123 years of the experiment (Johnston, 1969b). When an old arable site reverts to wilderness, the amount of organic matter entering the soil each year increases, so that there is more substrate for heterotrophic nitrogen-fixation and also more plant carbon to stabilise nitrogen. In the Broadbalk wilderness the C/N ratio of the soil organic matter has changed little, suggesting that the ability of decomposing plant carbon to retain nitrogen has altered little during the development of these wildernesses. By contrast, in Geescroft the C/N ratio has steadily increased since the start (Table 5). This has not been caused by the lack of mineral nitrogen for microbial attack on accumulating plant residues of wide C/N ratio; the C/N ratio of the organic matter *mineralized* in Geescroft is not very different from the ratio of that mineralized by either the wooded or stubbed part of Broadbalk (Table 7).

Thus, although biological fixation of nitrogen is almost certainly less in Geescroft than in Broadbalk, this is not the only difference between the sites: the process by which decomposing plant carbon stabilises nitrogen in a residue with a C/N ratio of about 10 in calcareous Broadbalk is less effective in acid Geescroft.

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The large nitrogen gains in both parts of Broadbalk wilderness cannot be satisfactorily explained at present. Similar gains in wooded and stubbed parts point to mechanisms that are independent of vegetation type. The relatively small gain in Geescroft suggests that little of the nitrogen gained by the Broadbalk wildernesses can have come from rain, dust or atmospheric ammonia, which would have supplied equal amounts of nitrogen to all the sites. Most of the nitrogen fixed by the Broadbalk wildernesses must have been fixed biologically, but not, in the wooded part at least, by free-living azotobacter, by algae, or in symbiosis with legumes.

Accumulation of sulphur by the wildernesses. Sulphate sulphur accumulates in Geescroft but not in Broadbalk, presumably because positive sites, able to retain anions, developed in Geescroft as the pH fell.

There was more than enough sulphur in precipitation alone to account for all the sulphur gained by the wilderness soils. Miller (1905) found that Rothamsted rain deposited 7·8 kg of sulphur per hectare per year over the period 1881–87. Recent measurements are even larger: between January 1960 and December 1964 (inclusive) the rain deposited an average of 12·5 kg sulphur per hectare per year. Soils and plants can gain sulphur by direct absorption of atmospheric sulphur dioxide (Johansson, 1959; Spedding, 1969) and the amounts of sulphur entering the soil by this process probably greatly exceed the amounts carried down in the rain. Eriksson (1968) calculated that the 'dry' deposition of sulphur at Rothamsted was six times that carried down in precipitation in 1958. Thus sulphur accumulation in the wilderness soils has been limited not by supply but by the sulphur-retaining power of the soil.

Summary

The accumulation of soil organic carbon, nitrogen, sulphur and phosphorus was measured in three sites that had not been cultivated since 1883. The sites had previously been arable for centuries, and are located on the same soil series within 1·3 km of each other. Two had once been chalked and are still calcareous; in the third the pH, 7·1 in 1883, had fallen to 4·5 in 1965. The non-calcareous site, and one of the calcareous sites, have been undisturbed and are now deciduous woodland. Tree seedlings are regularly removed from the other calcareous site by stubbing.

Despite completely different vegetation, the soils of the calcareous stubbed and wooded sites have gained similar amounts of organic carbon, nitrogen, sulphur and phosphorus. In contrast, organic carbon, nitrogen, sulphur and phosphorus have all accumulated more slowly in the soil of the non-calcareous wooded site than in the soil of the calcareous wooded site. The wooded non-calcareous site gained 23 kg nitrogen per hectare per year over a period of 82 years (15 kg in the soil to a depth of 68·6 cm, plus an estimated 8 kg in the trees). The stubbed site gained 55 kg nitrogen per hectare per year over a period of 81 years (all in the soil), and the wooded calcareous site 65 kg over a period of 81 years (53 in the soil plus an estimated 12 kg in the trees). These differences between the sites are attributed to the increasing acidity of the non-calcareous soil. Little of the nitrogen gained by the two wooded sites can have been fixed in symbiosis with legumes, as legumes have long been absent from both.

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APPENDIX

Profile Descriptions of Wilderness Soils

B. W. AVERY and D. W. KING

The descriptions of colour, texture, structure and consistence are in accordance with the U.S.D.A. Soil Survey Manual, 1951. Horizon designations are after Avery (1964).

Geescroft wilderness (wooded)

L	2–0 cm	Litter layer (mainly current leaf fall).
A	0–4 cm	Very dark greyish brown (10 YR 3/2) slightly stony loam or silt loam; brown when crushed; stones mainly small angular flints and flint pebbles; moderate fine sub-angular blocky and granular structure; friable, soft; irregular penetration of organic matter with corresponding variations in colour and structure; worm casts present; abundant fine woody roots; sharp irregular boundary.
Eb	4–28 cm	Brown (10 YR 4/4–5/4) stony loam with common darker coloured channel fillings and ped coatings, especially in the upper part; few, fine, faint, paler coloured and ochreous mottles locally; stones as above; weak medium to coarse blocky structure; friable to firm; slightly hard; common fine manganiferous concretions; common fine woody roots; narrow boundary.
B1t	28–46 cm	Brown (7·5 YR 4/4–5/6) slightly stony clay with common faint to distinct paler brown and red mottles; stones as above, but generally larger; moderate medium to coarse blocky structure; very firm; very hard; few infilled worm channels; common woody roots; merging boundary.
B2t(g)	46–60+ cm	Strong brown (7·5 YR 5/6) slightly stony clay with common, increasingly distinct, pale brown and red mottles; moderate coarse blocky structure, with smooth shiny cleavage faces; very firm; very hard; fewer roots and channels.

Broadbalk wilderness (wooded)

A	0–10 cm	Very dark greyish brown (10 YR 3/2) stony loam with moderately developed fine sub-angular blocky and granular structure, the latter best expressed in the first 2 cm; stones comprise small sub-angular flints and a few rounded flint pebbles; slightly plastic; non-sticky; friable; abundant fine fibrous and common small woody roots; earthworms throughout profile; slightly calcareous; merging boundary.

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Eb	10–30 cm	Brown (10 YR 4/3) stony loam with moderately developed fine to medium sub-angular blocky structure and with inclusions of very dark greyish brown (10 YR 3/2) more granular material from the surface horizon; stones as above, together with a few very small chalk fragments; non-sticky; slightly plastic; friable; common fine fibrous roots and occasional larger woody roots; very slightly calcareous; narrow irregular boundary.
Eb/Bt	30–40 cm	Brown (7·5 YR 4/4) stony loam to clay loam; stones as above, up to medium in size; moderately developed medium to fine blocky structure; slightly sticky; slightly plastic; friable; few fine fibrous roots; very slightly calcareous; merging boundary.
Bt(g)	40–60+ cm	Reddish brown (5 YR 4/5) stony clay with common, faint, fine, paler brown and reddish mottling; stones as above; moderately developed coarse to medium blocky structure; sticky, plastic; firm; a few fine fibrous roots. (Note that the depth to this horizon varied from 30–75 cm in different holes.)

Broadbalk wilderness (stubbed)

A	0–15 cm	Dark greyish brown (10 YR 3/2–4/2) stony loam with a moderately developed fine sub-angular blocky to granular structure; stones mainly small sub-angular flints with a few rounded pebbles and small chalk fragments; non-sticky; slightly plastic; friable; abundant fine fibrous roots; earthworms throughout profile; slightly calcareous; narrow irregular boundary.
Eb	15–25 cm	Brown (10 YR 4/4) stony loam with a moderately developed fine sub-angular blocky structure; stones as above though more abundant; slightly sticky; slightly plastic; friable; fine fibrous roots common; calcareous; merging boundary.
B1t(g)	25–50 cm	Brown (7·5 YR 4/5) stony clay with common, fine, faint, strong brown and light brown mottling; stones as above; moderate medium blocky structure; sticky, plastic; firm; few infillings from horizons above; few manganiferous specklings; merging boundary.
B2t(g)	50–75+ cm	Strong brown (7·5 YR 5/6) stony clay with distinct, common, fine red (2·5 YR 4/6) and brown (7·5 YR 5/4) mottling, the latter particularly associated with ped faces; stones as above; moderate coarse blocky structure breaking to fine sub-angular blocky; sticky; plastic; firm; few fine fibrous roots; some manganiferous speckling.

References

Allen, S. E., Carlisle, A., White, E. J. & Evans, C. C. (1968) The plant nutrient content of rainwater. *J. Ecol.* **56**, 497–504.

Archer, E. E. (1956) The determination of small amounts of sulphate by reduction to hydrogen sulphide and titration with mercuric or cadmium salts with dithizone as indicator. *Analyst, Lond.* **81**, 181–182.

d'Arifat, J. M. & Warren, R. G. (1964) Reducing nitrate by a zinc–ferrous sulphate mixture. *Rep. Rothamsted exp. Stn for 1963*, 63.

Ashby, S. F. (1907) Some observations on the assimilation of atmospheric nitrogen by a free living soil organism. *J. agric. Sci., Camb.* **2**, 35–51.

https://doi.org/10.23637/ERADOC-1-5

AVERY, B. W. (1964) The soils and land use of the district around Aylesbury and Hemel Hempstead. *Mem. Soil Surv. Gt Br.*, 216 pp.

BARROW, N. J. & JENKINSON, D. S. (1962) The effect of water-logging on fixation of nitrogen by soil incubated with straw. *Pl. Soil* **16**, 258–262.

BLOOMFIELD, C. (1962) A colorimetric method for determining total sulphur in soils. *Analyst, Lond.* **87**, 586–589.

BREMNER, J. M. (1959) Determination of fixed ammonium in soil. *J. agric. Sci., Camb.* **52**, 147–160.

BRENCHLEY, W. E. & ADAM, H. (1915) Recolonisation of cultivated land allowed to revert to natural conditions. *J. Ecol.* **3**, 193–210.

BRISTOL ROACH, B. M. (1927) On the algae of some normal English soils. *J. agric. Sci., Camb.* **17**, 563–588.

BUNCE, R. G. H. (1968) Biomass and production of trees in a mixed deciduous woodland. I. *J. Ecol.* **56**, 759–775.

ERIKSSON, E. (1968) Air and precipitation as sources of nutrients. In: *Handbuch der Pflanzenernährung und Düngung*, Ed. Linser, H. & Scharrer, K. Berlin: Springer-Verlag. Vol. II, Pt 1, 774–792.

GARNER, H. V. (1965) Broadbalk Wilderness—history. *Rep. Rothamsted exp. Stn for 1964*, 218–219.

GILBERT, J. H. (1890) Results of experiments at Rothamsted, on the growth of leguminous crops for many years in succession on the same land. *Agric. Stud. Gaz., Cirenc.* **4**, parts V and VI. (*Rothamsted Mem. agric. Sci.* **6**, No. 15, 60 pp.).

HALL, A. D. (1905) On the accumulation of fertility by land allowed to run wild. *J. agric. Sci., Camb.* **1**, 241–249.

HALL, A. D. (1917) *The book of the Rothamsted Experiments.* 2nd ed. London: John Murray. 332 pp.

HUTCHINSON, G. L. & VIETS, F. G. (1969) Nitrogen enrichment of surface water by adsorption of ammonia volatilized from cattle feedlots. *Science*, **166**, 514–515.

JENKINSON, D. S. (1965a) Decomposition of labelled plant material in soil. In: *Experimental Pedology*, Ed. Hallsworth, E. G. & Crawford, D. V. London: Butterworths. 199–207.

JENKINSON, D. S. (1965b) Studies on the decomposition of plant material in soil. I. *J. Soil Sci.* **16**, 104–115.

JENKINSON, D. S. (1968a) Decomposition of plant material in the field. *Rep. Rothamsted exp. Stn for 1967*, 76.

JENKINSON, D. S. (1968b) A titrimetric method for determining total sulphur in mineral soil. *Analyst, Lond.* **93**, 535–539.

JOHANSSON, O. (1959) On sulphur problems in Swedish agriculture. *K. LantbrHogsk. Annlr* **25**, 57–169.

JOHNSTON, A. E. (1969a) The plant nutrients in crops grown on Broadbalk. *Rep. Rothamsted exp. Stn for 1968*, Part 2, 50–62.

JOHNSTON, A. E. (1969b) Plant nutrients in Broadbalk soils. *Rep. Rothamsted exp. Stn for 1968*, Part 2, 93–115.

KONONOVA, M. M. (1966) *Soil organic matter.* 2nd English ed. Oxford: Pergamon, 544 pp.

LAWES, J. B. (1895) Upon some properties of soils which have grown a cereal crop and a leguminous crop for many years in succession. *Agric. Stud. Gaz., Cirenc.* **7** (New ser.), 65–72.

LAWES, J. B. & GILBERT, J. H. (1882) Determination of nitrogen in the soils of some of the experimental fields at Rothamsted and the bearing of the results on the question of the sources of the nitrogen of our crops. *Rothamsted Mem. agric. Sci.* **5**, No. 19, 60 pp.

LEGG, J. O. & BLACK, C. A. (1955) Determination of organic phosphorus in soils. II. *Proc. Soil Sci. Soc. Am.* **19**, 139–143.

MATTINGLY, G. E. G. (1970) Total phosphorus contents of soils by perchloric acid digestion and sodium carbonate fusion. *J. agric. Sci., Camb.* **74**, 79–82.

MEHTA, N. C., LEGG, J. O., GORING, C. A. I. & BLACK, C. A. (1954) Determination of organic phosphorus in soils. I. *Proc. Soil Sci. Soc. Am.* **18**, 443–449.

MEIKLEJOHN, J. (1956) Preliminary notes on numbers of nitrogen fixers on Broadbalk field. *Proc. 6th int. Cong. Soil Sci., Paris, C*, 243–248.

MEIKLEJOHN, J. (1969) Microbiology of Broadbalk soils. *Rep. Rothamsted exp. Stn for 1968*, Part 2, 175–179.

MILLER, N. H. J. (1905) The amounts of nitrogen as ammonia and as nitric acid, and of chlorine in the rainwater collected at Rothamsted. *J. agric. Sci., Camb.* **1**, 280–303.

MOORE, A. W. (1966) Non-symbiotic nitrogen fixation in soil and soil–plant systems. *Soils Fertil., Harpenden* **29**, 113–128.

OVINGTON, J. D. (1962) Quantitative ecology and the woodland ecosystem concept. *Adv. ecol. Res.* **1**, 103–192.

RICHARDS, B. N. (1964) Fixation of atmospheric nitrogen in coniferous forests. *Aust. For.* **28**, 68–74.

SPEDDING, D. J. (1969) Uptake of sulphur dioxide by barley leaves at low sulphur dioxide concentrations. *Nature, Lond.* **224**, 1229–1231.

STEVENSON, C. M. (1968) An analysis of the chemical composition of rain-water and air over the British Isles and Eire for the years 1959–1964. *Q. Jl R. met. Soc.* **94**, 56–70.

THURSTON, J. M. (1958) Geescroft wilderness. *Rep. Rothamsted exp. Stn for 1957*, 94.

WALKER, T. W. & ADAMS, A. F. R. (1958) Studies on soil organic matter. I. *Soil Sci.* **85**, 307–318.

https://doi.org/10.23637/ERADOC-1-5

WEBER, D. F. & GAINEY, P. L. (1962) Relative sensitivity of nitrifying organisms to hydrogen ions in soils and in solutions. *Soil Sci.* **94**, 138–145.
WEIR, J. S. (1969) Importation of nutrients into woodlands by rooks. *Nature, Lond.* **221**, 487–488.
WILLIAMS, C. H. & STEINBERGS, A. (1962) The evaluation of plant available sulphur in soils. I. *Pl. Soil* **17**, 279–294.
WILLIAMS, C. H., WILLIAMS, E. G. & SCOTT, N. M. (1960) Carbon, nitrogen, sulphur, and phosphorus in some Scottish soils. *J. Soil Sci.* **11**, 334–346.
WITTS, K. J. (1965) Flora (of Broadbalk wilderness). *Rep. Rothamsted exp. Stn for 1964*, 219–222.
ZIEMIECKA, J. (1932) The azotobacter test of soil fertility applied to the classical fields at Rothamsted. *J. agric. Sci., Camb.* **22**, 797–810.

https://doi.org/10.23637/ERADOC-1-5