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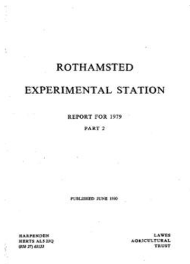

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Changes in Organic Phosphorus Contents of Soils from Long-continued Experiments at Rothamsted and Saxmundham

MARGARET CHATER and G. E. G. MATTINGLY

Abstract

The mean annual rates of loss or accumulation of organic P under contrasting systems of manuring and cropping are discussed in relation to changes in the ratio of carbon, nitrogen and organic P (ΔC:ΔN:Δorg.P) in soils over periods of 10–45 years.

In several experiments, the changes over many years in carbon, nitrogen and organic P contents of arable soils were too small to use quantitatively. Where changes were measurable, mean annual rates of mineralisation of organic P in the soils ranged from 0·5–8·5 kg P ha^{-1} $year^{-1}$ and were least (0·5–1·4 kg P ha^{-1} $year^{-1}$) on old arable soils which had received no organic manures and greatest (7·6–8·5 kg P ha^{-1} $year^{-1}$) on soils ploughed out of permanent pasture or containing residues from recent large amounts (100 t ha^{-1}) of farmyard manure. The greatest rates of mineralisation represent about one-half of the P removed each year by average crops (4·5–5·0 t ha^{-1}) of cereals.

Variations in the ratio ΔN:Δorg.P were much wider than those for ΔC:ΔN. At Rothamsted (Batcombe series) the ratios ΔC:ΔN:Δorg.P did not vary greatly in different experiments. At Saxmundham (Beccles series), the ratios ΔN:Δorg.P varied from 10:0·17 on plots in continuous arable cropping to 10:1·64 on plots given much farmyard manure. These ratios do not provide any reliable guide to amounts of organic P that mineralise, relative to losses of carbon or nitrogen, in arable soils from different soil series with varying histories of management and manuring.

Introduction

Few measurements of the organic P contents of soils have been made at Rothamsted and none at Saxmundham Experimental Station. Dean (1938), in a classic paper on the fractionation of soil phosphorus, estimated 'organic alkali-soluble P' contents of soils taken from the Continuous Wheat plots on Broadbalk, Rothamsted, in 1893 and 1936 and from the Continuous Barley experiment on Stackyard, Woburn, in 1888 and 1927. This P fraction increased on Broadbalk from 100 mg P kg^{-1} soil in 1893 to 250 mg P kg^{-1} soil in 1936 on plots given farmyard manure (FYM) each year. Corresponding values for soils from the Continuous Barley experiment at Woburn were 220 mg P kg^{-1} soil in 1888 and 310 mg P kg^{-1} soil in 1927. In a review on the estimation of organic P in soils, Barrow (1961) suggested that these and other earlier attempts (Ghani, 1943) to measure organic P were, perhaps, partially invalidated by hydrolysis of organic P during extraction with hot 0·25N-NaOH. This seems likely, because Dean's (1938) results showed that organic alkali-soluble P also increased by 125 mg P kg^{-1} soil between 1893 and 1936 at Rothamsted and by 85 mg P kg^{-1} soil between 1888 and 1927 at Woburn on plots given inorganic PKNaMg fertilisers together with N as ammonium sulphate. These apparent increases in organic P, which were *not* accompanied by significant increases in organic C, can probably be attributed to acidification of the soils by ammonium sulphate (Johnston,

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TABLE 1

Experiments sampled and summary of treatments,

Experiment and year in which soils were sampled	Plot number, treatments and manuring
Agdell Rotation, Rothamsted: Sampled 1913, 1953, 1958, 1969, 1975	1 and 2 NPKNaMg (fallow and clover) 3 and 4 PKNaMg (fallow and clover) 5 and 6 None (fallow and clover) 1848–1951: Manures applied in 4 years 48 kg N as ammonium sulphate 112 kg N as rape cake 32–42 kg P as superphosphate 130–220 kg K as potassium sulphate (+22 kg Na and 18 kg Mg) 1952–58 No P or K fertilisers 1959–75 Test dressings of P and K fertilisers on microplots
Exhaustion Land Experiment, Hoosfield, Rothamsted: Sampled 1903, 1958, 1974	1 and 2 None 3 and 4 FYM 5 and 6 N only 7, 8, 9 and 10 NP or NPK 1856–1901: Manures applied 96 kg N each year as ammonium sulphate or sodium nitrate 1410 kg P in *total* 5000 kg K in *total* 35 t FYM each year (1876–1901 only) 1902–40: No fertilisers or FYM 1941–75: 63 or 88 kg N each year
Residual Phosphate Rotation, Rothamsted: Sampled: 1961, 1967, 1975–76	Arable (Sawyers I) and old grassland sites (Great Field IV) 11, 15, 25 No phosphate 45, 53, 61 76, 91, 103 4, 16, 32 Superphosphate each year 38, 54, 67 78, 87, 99 2, 23, 26 Superphosphate in 1959, 1966 and 1972 47, 49, 66 79, 86, 104 1960–72: Superphosphate applied 27·5 kg P each year 165 kg P in 1959 and 1966 1973–78: Superphosphate applied 25 kg P each year 150 kg P in 1972
Rotation II, Saxmundham: Sampled 1964, 1968, 1973–74, 1977–78	1 None 2 FYM 4 FYM and superphosphate 8 FYM and superphosphate until 1952 1899–1964: Manures applied in 4 years 29 kg N as sodium nitrate 60 kg P as superphosphate 25 t FYM 1965–68: 100 t FYM (plot 4 only) 1969–78: Superphosphate every 2 years 27·5, 55 and 82·5 kg P on microplots

1969; Johnston & Chater, 1975) and an increase in soluble inorganic P, some of which was measured in the alkali-soluble fractions.

Oniani, Chater and Mattingly (1973), using more recent methods to measure organic P (Mehta, Legg, Goring & Black, 1954; Saunders & Williams, 1955) found much smaller increases (18–44 mg P kg^{-1} soil) in organic P in soils from Barnfield, Rothamsted, which had received the same dressings of FYM each year (35 t ha^{-1}) since 1856 as Broadbalk.

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cropping and manuring per hectare

Cropping	Notes and references to yields, treatments and soil analyses
1848–1951 Clover rotation: swedes or turnips, barley, clover or beans, winter wheat. Fallow rotation: swedes or turnips, barley, fallow, winter wheat 1952–57 Barley, spring wheat, beans and potatoes 1958–70 One-half of experiment in grass leys and one-half in arable crops for 3 years and then fallowed 1970–75 Potatoes, barley and sugar beet grown on both halves of the experiment	Between 1848 and 1903 the experiment compared the effects on soil fertility of feeding *vs*. carting and removing the swedes from plots Warren (1958) Johnston and Penny (1972) Mattingly and Johnston (1976)
1856–75 Winter wheat	Warren and Johnston (1960)
1876–1901 Potatoes	Johnston and Poulton (1977)
1902–75 Cereals, mainly barley	
1960–65 Potatoes, barley, swedes 1966 Fallow 1967–73 Potatoes, barley, swedes 1974–76 Winter wheat following barley	Analyses in Table 6 and Appendix Table 3 are means of samples from six plots from Sawyers and three plots, analysed in duplicate, from Great Field Mattingly (1968; 1970b)
1899–1964 Wheat, swedes or mangolds, barley, beans or clover 1965–68 Barley, potatoes, turnips and sugar beet 1969–74 Potatoes, barley, sugar beet, barley 1975–78 Barley	Soil samples were taken from whole plots in the rotation in 1964 and 1968. Soil samples from microplots were bulked over whole plots before analysis in 1973–74 and 1977–78 Boyd and Trist (1966) Mattingly, Johnston and Chater (1970) For details of design and manuring 1969–74 see Mattingly and Johnston (1976)

Furthermore, the amounts of inositol penta- and hexaphosphates, estimated by chromatography (Anderson, 1964), were only very slightly greater (4 mg P kg^{-1} soil) in soils given FYM than in soils given inorganic fertilisers. This work also did not confirm the large increases in organic P that Dean (1938) recorded on plots given *inorganic* fertilisers for many years. The only other measurements of changes in organic P in Rothamsted soils were reported by Jenkinson (1971) who studied the accumulation of

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organic matter in two areas of arable land which had reverted to wilderness (i.e. mature trees and shrubs) since the early 1880s. He compared five widely used methods for estimating organic P and commented on the poor agreement between them, especially when used for subsoils.

The purpose of the work described here was to measure changes in total organic P in soils from long-continued field experiments at both Rothamsted and Saxmundham Experimental Stations in order to compare rates of loss or accumulation of organic P under contrasting cropping systems. Results given here refer only to *net* changes over many years and some changes are small and difficult to measure reliably. The precision of the results has been increased (i) by duplicate or triplicate estimations on each sample, (ii) by averaging results by the ignition method (Saunders & Williams, 1955) and by extraction (Mehta, Legg, Goring & Black, 1954), and (iii) by averaging results from several similarly treated plots in the experiments, a method used successfully to measure small changes in the organic P contents of soils from the continuous wheat and barley experiments at Woburn (Mattingly, Chater & Johnston, 1975). In all experiments described here the changes in organic P resulting from cropping or manuring were related to corresponding changes in soil carbon and nitrogen, with particular reference to changes in the ratios of carbon, nitrogen and organic P, i.e. $\Delta C:\Delta N:\Delta$ org.P.

Experiments and soils sampled

Soils used in the experiments were samples, mostly sieved <2 mm, which had been stored air-dry in sealed containers since they were taken. The significance of possible changes on prolonged storage of the samples is briefly discussed later in this paper (p. 49).

Table 1 summarises the experiments from which soil samples were taken and gives brief details of treatments and references to published work on them.

The Agdell Rotation experiment, Rothamsted

This experiment, started by Lawes and Gilbert in 1848, compared two crop rotations and three manurial treatments (Table 2). There were six main plots, three for each of the rotations. One was the traditional Norfolk four-course rotation with swedes, barley, clover or beans and winter wheat (the clover rotation); in the other, a fallow replaced the legume crop (the fallow rotation). The experiment also compared, between 1848 and 1903, the effects on crop yield and soil fertility of allowing sheep either (a) to eat the root crop on the land, or (b) carting the roots before they were eaten. Detailed accounts of this experiment have been given by Warren (1958) and Johnston and Penny (1972). The original treatments were discontinued in 1951. The experiment was subsequently extensively modified to test, on microplots, the value of the residues of P and K fertilisers built up in the soil between 1848 and 1951 (Johnston & Penny, 1972). The early results and subsequent modifications up to 1974 were summarised by Mattingly and Johnston (1976). Appendix Table 1 gives analyses of soil samples taken in 1913, 1953, 1958, 1969 and 1975.

Comparison of 'fed' and 'carted' sub-plots. Samples were taken in 1913 and 1953 from sub-plots of the test of carting *v.* feeding swedes by sheep (Table 2); the mean carbon and organic P contents of 'carted' and 'fed' treatments were virtually identical, both in 1913, 10 years after the treatments ceased and in 1953. Total soil P was slightly greater, by 14 and 9 mg P kg^{-1} in 1913 and 1953 respectively, on sub-plots on which sheep were fed. Warren (1958) showed that feeding rather than carting swedes slightly increased the soluble P and exchangeable K in these soils in 1913 but the effect was negligible by 1953.

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TABLE 2

Effects of feeding or carting roots (1848–1903) on the total carbon, phosphorus and organic phosphorus in soils (0–23 cm) from the Agdell Rotation, Rothamsted

		Rotation with fallow			Rotation with clover			
Year	Treatment	None	PK	NPK	None	PK	NPK	Mean
				Carbon, %				
1913	Carted	1·00	1·00	1·11	1·22	1·18	1·28	1·13
	Fed	0·94	1·12	1·09	1·09	1·29	1·31	1·14
1953	Carted	1·03	1·01	1·00	1·34	1·21	1·25	1·14
	Fed	1·02	1·00	0·99	1·24	1·28	1·29	1·14
				Total phosphorus, mg P kg^{-1} soil				
1913	Carted	540	614	732	540	570	670	611
	Fed	548	682	732	496	610	682	625
1953	Carted	568	674	754	516	652	772	656
	Fed	572	740	748	544	688	700	665
				Organic phosphorus,* mg P kg^{-1} soil				
1913	Carted	175	160	187	184	171	213	182
	Fed	168	172	189	155	194	212	182
1953	Carted	180	176	206	199	186	242	198
	Fed	171	187	200	166	211	232	194

* Means of values by extraction and ignition methods

Comparison of rotations with fallow or with clover, 1848–1951. Table 3 gives carbon, nitrogen, total P and organic P contents of those soils which were in arable cropping from 1913 to 1975. Between 1958 and 1970 one-half of each plot tested the values of residues of P and K fertilisers for arable crops and one-half was sown to a succession of grass leys (Johnston & Penny, 1972). During these tests, much P was applied as superphosphate between 1958 and 1970 and mean total P contents of the soils increased from 656 mg P kg^{-1} soil in 1958 to 847 mg P kg^{-1} soil in 1975. (Results from plots sown to grass are discussed in the next section of the paper.)

Mean amounts of carbon, nitrogen, organic P and total P in the soils changed very little between 1913 and 1958. At all three samplings total carbon, nitrogen and organic P contents were greater on plots which had been in the clover rotation, but total P was smaller by 30 mg P kg^{-1} soil or, assuming a weight of soil to plough depth of 2630 t ha^{-1} (Johnston & Penny, 1972), by about 80 kg P ha^{-1}. Johnston and Penny (1972) estimated from crop analyses (their Table 1) that the clover rotation had, by 1951, removed more P (about 130 kg P ha^{-1}) than the fallow rotation, which is in reasonable agreement with the measured changes in total soil P.

All analyses on samples taken in 1953 and 1958 agreed well, which suggests that the methods used for soil sampling and analysis were reliable. Agreement between carbon, nitrogen and total P analyses on samples taken in 1969 and 1975 was also very close but organic P contents were larger, by 10–20 mg P kg^{-1} soil, in 1975 than in 1969 (Table 3). We use here mean analyses for 1953 and 1958 and for 1969 and 1975 to estimate average changes in organic C, N and P, when all soils were in arable crops, during the period 1956–72, which were:

	Rotation with fallow	Rotation with clover
ΔC (%)	−0·180	−0·310
ΔN (%)	−0·020	−0·032
Δ org.P (%)	−0·00110	−0·00195

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TABLE 3

Effects of rotation (with fallow or with clover) from 1848 to 1951 on total carbon, nitrogen, organic phosphorus and phosphorus contents of arable soils from Agdell, Rothamsted

	Old treatments, 1848–1951							
	Rotation with fallow				Rotation with clover			
	None	PK	NPK	Mean	None	PK	NPK	Mean
				Carbon, %				
1913	0·97	1·06	1·10	1·04	1·16	1·24	1·30	1·23
1953	1·02	1·00	1·00	1·01	1·29	1·24	1·27	1·27
1958	1·03	1·11	1·08	1·07	1·30	1·29	1·24	1·28
1969	0·84	0·86	0·79	0·83	0·95	0·97	0·94	0·95
1975	0·88	0·94	0·84	0·89	0·99	0·97	0·99	0·98
				Nitrogen, %				
1913	0·118	0·122	0·127	0·122	0·141	0·148	0·147	0·145
1953	0·118	0·120	0·114	0·117	0·154	0·153	0·142	0·150
1958	0·120	0·125	0·115	0·120	0·145	0·150	0·137	0·144
1969	0·101	0·099	0·089	0·096	0·114	0·124	0·105	0·114
1975	0·106	0·104	0·092	0·101	0·119	0·119	0·111	0·116
				Organic phosphorus,* mg P kg^{-1} soil				
1913	172	166	188	175	170	182	212	188
1953	175	181	203	186	182	198	237	206
1958	167	184	212	188	175	191	237	201
1969	154	184	175	171	158	172	192	174
1975	196	176	170	181	186	195	202	194
				Total phosphorus, mg P kg^{-1} soil				
1913	544	648	732	641	518	590	676	595
1953	570	707	751	676	535	670	736	647
1958	546	694	753	664	560	639	746	648
1969†	748	844	840	811	756	820	896	824
1975†	796	896	880	857	796	824	888	836

* Means of values by extraction and ignition methods

† The total P content of the soil was increased by superphosphate applied from 1958 onwards (Johnston & Penny, 1972)

The ratios of the changes ΔC:ΔN:Δ org.P are 90:10:0·55 for soils from the fallow rotation and 97:10:0·61 for soils from the clover rotation.

If the weight of the soil to plough depth is 2630 t ha^{-1}, the average annual losses of carbon, nitrogen and organic P between 1956 and 1972 were:

	Rotation with fallow	Rotation with clover
	(kg ha^{-1} year^{-1})	
Carbon	296	510
Nitrogen	33	53
Organic P	1·8	3·2

Comparison of arable and ley plots, 1958–69. The six main-plots of the original experiment were divided in half in 1958; one-half remained in arable cropping, the other was sown to grass. The grass was resown several times so the changes in organic C, N and organic P, given in Table 4, result from a sequence of short leys ploughed up every few years.

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TABLE 4

Effects of cropping with short leys (1958–69) on total carbon, nitrogen and organic phosphorus in soils from Agdell, Rothamsted

	Old treatments, 1848–1951							
	Rotation with fallow				Rotation with clover			
Year	None	PK	NPK	Mean	None	PK	NPK	Mean
	Carbon, %							
1953 and 1958 (mean)	1·02	1·06	1·04	1·04	1·30	1·26	1·26	1·27
1969	1·23	1·20	1·27	1·23	1·40	1·44	1·37	1·40
1975	1·18	1·13	1·11	1·14	1·26	1·30	1·21	1·26
	Nitrogen, %							
1953 and 1958 (mean)	0·119	0·122	0·114	0·118	0·150	0·152	0·140	0·147
1969	0·135	0·130	0·125	0·130	0·154	0·158	0·148	0·153
1975	0·136	0·121	0·118	0·125	0·152	0·149	0·130	0·144
	Organic phosphorus,* mg P kg^{-1} soil							
1953 and 1958 (mean)	171	182	208	187	178	194	237	203
1969	178	203	198	193	185	195	214	198
1975	210	194	194	199	212	200	210	207

* Means of values by extraction and ignition methods

The leys, which are described in detail by Johnston and Penny (1972), were:

1958–59	Italian ryegrass (S22)
1960–63	Cocksfoot (S37)
1964–70*	Timothy (S51)

* Some plots were resown in 1968

We again use mean analyses for 1953 and 1958 and values for 1969 to calculate changes in organic C, N and organic P in soils under these short leys between 1958–69:

	Rotation with fallow	Rotation with clover
ΔC (%)	+0·19	+0·13
ΔN (%)	+0·012	+0·006
Δ org. P (%)	+0·0006	−0·0005

Organic C, N and P increased consistently under grass leys grown on plots from the old rotation with fallow (1848–1951). The ratios of the increases in ΔC:ΔN:Δ org.P from 1958 to 1969 (158:10:0·5) are similar to previously published values for soils under pasture (Barrow, 1961). The results from the old rotation with clover, however, are more varied and reveal no consistent pattern of changes, particularly for organic phosphorus. It is unlikely that these variable results arise from sampling errors on only one-half of the experiment. It is more probable that the changes measured are complex and result from a combination of simultaneous changes in soil organic matter which cannot easily be distinguished. Plots from the old experiment, particularly plots 1 and 2 which were given nitrogen as a mixture of ammonium salts (together with rape cake), were very acid (pH 5·0–5·5) by 1953 (Warren, 1958; Johnston & Penny, 1972) and were limed with 18–20 t $CaCO_3$ ha^{-1} between 1954 and 1967. The consequent increase in soil pH (to 7·0 by 1970) would be expected to increase rates of mineralisation of organic P (Anderson,

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1975; Dalal, 1977). Between 1958 and 1969 some or all of the following changes in organic P could reasonably take place simultaneously:

(i) mineralisation of organic P, particularly from residues which accumulated during the clover rotation before 1951;
(ii) accumulation of organic P under the short-term leys (1958–69); and
(iii) rapid mineralisation of organic P from leys in warm soil in autumn when they were ploughed up before resowing.

In these circumstances it is not surprising that changes in carbon, nitrogen and organic P during the period 1958–69 are difficult to interpret quantitatively and unambiguously.

Hoosfield Exhaustion Land experiment, Rothamsted

This experiment, started in 1856, compared manurial treatments applied to continuous wheat (1856–75) which was followed by continuous potatoes (1876–1901). The experiment has been described in detail by Warren and Johnston (1960) and by Johnston and Poulton (1977). The site of the experiment was cropped with cereals, mainly barley, until 1940 but no fertilisers were applied. Since 1941 nitrogen fertilisers supplying 63–88 kg N ha^{-1} as ammonium sulphate or 'Nitro-Chalk' have been applied on all plots.

Appendix Table 2 gives mean carbon, nitrogen, organic P and total P analyses of soil samples taken in 1903, 1958 and 1974 from (a) four plots which were unmanured from 1856 to 1901, (b) two plots given FYM between 1876 and 1901, and (c) four plots given superphosphate and N, K or NK fertilisers between 1856 and 1901. Analyses for organic and total P are summarised in Table 5.

TABLE 5

Organic P and total P contents of soils from Hoosfield Exhaustion Land, Rothamsted, 1856–1974

Plot	Treatment 1856–1901	Year	Organic P* (mg P kg^{-1} soil)	Total P† (mg P kg^{-1} soil)	Organic P as % total P
Site sample	—	1856	194	528	37
1, 2, 5, 6	Unmanured	1903	173	530	33
		1958	185	532	35
		1974	191	478	40
3, 4	FYM (1876–1901)	1903	198	862	23
		1958	202	698	29
		1974	199	630	32
7, 8, 9, 10	NPK and PK fertilisers	1903‡	172	886	19
		1958	186	693	27
		1974	193	606	32

* Mean of ignition and extraction methods
† From Johnston and Poulton (1977)
‡ Plots 9 and 10 only in 1903

Organic P decreased between 1856 and 1903 by 21–22 mg P kg^{-1} soil both on the unmanured plots and on plots given NPK or PK fertilisers (Table 5). The changes in the ratio $\Delta C:\Delta N:\Delta$ org.P during this period were closely similar for the two sets of plots, 78:10:0·58 and 87:10:0·58 respectively, despite the large increase in total soil P resulting from the application of superphosphate. The organic P contents of plots 1, 2, 5 and 6 and plots 7–10, sampled in 1958 and 1974, were also closely similar. There is no evidence from this experiment that large amounts of inorganic P applied as superphosphate between 1856 and 1901 (about 1400 kg P ha^{-1}) had any measurable effect on the organic P content of the soil.

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The total amount of P applied between 1876 and 1901 in 26 annual dressings of FYM, each of 35 t ha^{-1}, was estimated (Johnston & Poulton, 1977) to be 1025 t ha^{-1}. Assuming 25% of this P was present in organic combination (Peperzak, Caldwell, Hunziker & Black, 1959) and that the weight of air-dry soil, to 23 cm, is 3030 t ha^{-1} (Johnston & Poulton, 1977), the increase in organic P from FYM, if none was mineralised, should be about 85 mg P kg^{-1} soil. The differences between the organic P contents of unmanured plots and those given FYM (Table 5) were:

Increase in organic P on FYM-treated plots	1903	1958	1974
mg P kg^{-1} soil	25	17	8
% of P applied	29	20	9

The amounts of organic P (25 mg P kg^{-1} soil) remaining in 1903 from FYM applied between 1876 and 1901 are comparable with those previously measured on an old arable field (Barnfield, Rothamsted) which grew root crops for many years (Oniani, Chater & Mattingly, 1973). They are much less, however, than the increases in organic alkali-soluble P (100–250 mg P kg^{-1} soil) due to FYM which were measured by Dean (1938) on the continuous wheat plots on Broadbalk. By 1974, the organic P content of plots 3 and 4 had decreased by a further 17 mg P kg^{-1} soil, and represented less than 10% of the organic P added between 1876 and 1901. For comparison, the percentage of organic P remaining in the sandy loam soil at Woburn from 50 applications of FYM, applied between 1877 and 1926, was about 50% in 1927 and 27% 32 years later (Mattingly, Chater & Johnston, 1975).

Between 1903 and 1974 the organic P (Table 5) and the carbon and nitrogen contents (Appendix Table 2) *increased* slightly on all plots except those given FYM. It is therefore impossible to use these analyses with any confidence to calculate long-term changes due to manuring or cropping. Reasons for these small increases over a period of 70 years are not known. Johnston and Poulton (1977) commented that their analyses also showed that 'soils without P additions apparently lost little P before 1958 although some P was obviously removed by the crops'. They suggested the discrepancy may be due to sampling and analytical errors and to the movement of soil across plot boundaries. It is also possible, though this cannot be established unequivocally, that the samples taken in 1903 may have lost small amounts of carbon, nitrogen and organic P by mineralisation on prolonged storage. Jenkinson and Johnston (1977) discuss examples of such changes in soils from the Continuous Barley experiment on Hoosfield. Another possibility is that the larger barley crops grown in recent years have left larger root residues in the soil than formerly and that these immobilised some inorganic P in an organic form, particularly on soils which, by 1974, contained only 2–12 mg P kg^{-1} soil of $NaHCO_3$-soluble P (Johnston & Poulton, 1977).

Organic P, as a percentage of total P in these soils, increased in all treatments between 1903 and 1974 (Table 5) and was slightly greater in 1903 and 1958 on plots 3 and 4, which were given FYM before 1901, than on plots 7–10, which were given superphosphate; both groups of soils contained almost the same amounts of total P.

Residual Phosphate Rotation experiments, Rothamsted

These experiments started in 1960 on two sites with contrasting histories of previous management. One experiment was sited on a field which had been in arable cropping for many years (Sawyers I), the other was on land ploughed out from permanent grassland in 1956 (Great Field IV). The purpose and design of the experiments has been described

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elsewhere (Mattingly, 1968, 1970b). The crops grown in rotation on both sites were potatoes, swedes and barley, which was followed, in the experiment on Sawyers, by winter wheat grown continuously from 1974 to 1977, 1975 to 1978 and 1976 to 1979 on the three series respectively. (Barley was followed by a grass–clover ley on Great Field from 1974 onwards but no samples from the ley treatments were analysed.)

Soil samples (0–23 cm), taken from three of the 12 treatments were analysed for total carbon, nitrogen, phosphorus and organic P. The treatments compared here were (i) no phosphate fertilisers since 1960 or earlier, (ii) P applied annually as superphosphate, (iii) P applied in single large dressings in 1959, 1966 and 1972. Analyses for total C, N, P and organic P are given in Appendix Table 3 and are summarised in Table 6.

Organic P decreased by 6–24 mg P kg^{-1} soil between 1961 and 1976 on the old arable soil and by 31–40 mg P kg^{-1} soil between 1961 and 1975 on the old grassland soil (Table 6). Averaging the three treatments sampled, the mean decreases in carbon, nitrogen and organic P were 0·19%, 0·022% and 15 mg P kg^{-1} on the arable soil, and 0·71%, 0·065% and

TABLE 6

Total carbon, nitrogen and organic phosphorus contents of soils from the Residual Phosphate Rotation, Rothamsted, 1961–75/6

	Arable soil (Sawyers)				Old grassland soil (Great Field)			
Year	No phosphate	P applied annually	P applied 6-yearly	Mean	No phosphate	P applied annually	P applied 6-yearly	Mean
				Carbon (%)				
1961	1·52	1·50	1·50	1·51	2·53	2·47	2·56	2·52
1967	1·38	1·38	1·34	1·37	2·19	2·07	2·10	2·12
1975/6	1·31	1·34	1·30	1·32	1·79	1·80	1·85	1·81
				Nitrogen (%)				
1961	0·159	0·156	0·154	0·156	0·260	0·253	0·260	0·258
1967	0·148	0·146	0·144	0·146	0·228	0·220	0·222	0·223
1975/6	0·136	0·134	0·132	0·134	0·195	0·189	0·196	0·193
				Organic phosphorus* (mg P kg^{-1} soil)				
1961	230	214	229	224	306	301	310	306
1967	213	213	218	215	289	280	282	284
1975/6	206	208	212	209	266	270	276	271

* Means of values by extraction and ignition methods

35 mg P kg^{-1} on the old grassland soil. The ratios of the changes $\Delta C:\Delta N:\Delta$ org.P were 86:10:0·68 and 109:10:0·53 respectively. The old grassland site clearly lost proportionally more carbon than nitrogen or organic P. Carbon, nitrogen and organic P were mineralised in the old arable soil in almost the same proportions as on the Agdell Rotation and on Hoosfield Exhaustion Land. Superphosphate applied either annually or 6-yearly increased the total P in the soils by about 100 mg P kg^{-1} by 1975–76 (Appendix Table 3) but did not significantly affect losses of carbon, nitrogen and organic P from the soils (Table 6).

Assuming the surface soil (0–23 cm) has the same bulk density as the Exhaustion Land site, which is within 300–400 m of the arable site (Sawyers), the average annual losses of carbon, nitrogen and organic P from the two experiments were:

	Old arable soil (1961–76)	Old grassland soil (1961–75)
	(kg ha^{-1} year^{-1})	
Carbon	384	1537
Nitrogen	44	141
Organic P	3·0	7·6

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Rotation II experiment, Saxmundham

This experiment on a Chalky Boulder-clay soil (Beccles Series) started in 1899 and originally consisted of four blocks of plots; each block tested effects of ten manurial treatments on four crops (wheat, roots, barley and a legume) grown in rotation. Results up to 1952 were given by Boyd and Trist (1966). The experiment was modified in 1965 and 16 of the original 40 plots were used to measure the residual value of superphosphate and FYM applied since 1899 (Mattingly, Johnston & Chater, 1970; Mattingly & Johnston, 1976).

Soil samples taken in 1964 (0–20 cm) and in 1968, 1973–74 and 1977–78 (0–25 cm) from four of the treatments were analysed for total carbon, nitrogen, phosphorus and organic P (Appendix Table 4). The site was ploughed to about 25 cm in autumn 1964 after the soil samples were taken. The nutrient contents of the soil to plough depth all decreased and the total carbon, nitrogen and total P contents of the soil were about 90% of those in the plough layer (0–20 cm) in 1964 (Mattingly, Johnston & Chater, 1970). Table 7 summarises analyses for total P and organic P in the soils between 1968 and 1977–78 during which period the experiment had been cropped with potatoes, barley and sugar beet and the depth of ploughing and sampling had remained about 25 cm.

TABLE 7

Total phosphorus and organic P contents of soils from Rotation II Saxmundham, 1968–77/8

Treatment	Manuring 1899–1964	Manuring 1965–68	Year	Total P (mg P kg^{-1} soil)	Organic P* (mg P kg^{-1} soil)	Organic P as % total P
1	Unmanured	NK	1968	402	146	36
			1973–74	405	127	31
			1977–78	416	134	32
2	FYM every 4th year	NK	1968	450	151	34
			1973–74	438	134	31
			1977–78	445	138	31
4	FYM+ superphosphate (P) every 4th year	NK+FYM in 1965 and 1966	1968	644	169	26
			1973–74	581	144	25
			1977–78	586	146	25
8	FYM+ superphosphate (2P) every 4th year until 1952	NK	1968	582	162	28
			1973–74	568	149	26
			1977–78	584	149	26

* Means of values by extraction and ignition method

Organic P decreased by 13–25 mg P kg^{-1} soil between 1968 and 1973–74 but changed negligibly during the following 3–4 years. The largest decrease was on treatment 4 (Table 7) which had received 230 kg P ha^{-1} in two dressings of FYM, each 50 t ha^{-1}, applied in the autumn of 1965 and 1966. Assuming, as previously (p. 49), that about one-quarter of the phosphorus was organically combined, and the weight of soil to plough depth was 3500 t ha^{-1}, the organic P content of the soil should have increased by about 16 mg P kg^{-1} soil. The increases measured from the differences between the organic P contents of plots from treatments 2 and 8 (which had received similar treatments to treatment 4 before 1964) and those measured on treatment 4 were:

Increase in organic P from FYM applied in 1965–66	1968	1973–74	1977–78
mg P kg^{-1}	13	2	2
% total applied	81	12	12

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The differences (2–13 mg P kg^{-1}) are small and subject to considerable error. They suggest, however, that organic P applied in farmyard manure had mineralised almost completely between 1965–66 and 1973–74. Average rates of mineralisation of organic P between 1964 and 1977–78 (Table 8) were about 0·5 kg P ha^{-1} $year^{-1}$ on soil from treatment 1, which had received no organic manures since 1899 and 3·6 kg P ha^{-1} $year^{-1}$ on soils from treatments 2 and 8 which were given small amounts of FYM every fourth year until 1964 (treatment 2) or 1952 (treatment 8). The mean annual rate of mineralisation of organic P between 1968 and 1977–78, from treatment 4, which was given 100 t ha^{-1} of FYM in 1965–66, was over twice as great (8·5 kg P ha^{-1} $year^{-1}$).

Discussion and conclusions

The accurate estimation of total organic P in soils is notoriously difficult (Barrow, 1961; Dormaar, 1964; Oniani, Chater & Mattingly, 1973; Anderson, 1975; Dalal, 1977) and, for this reason, few attempts have been made to measure small changes in organic P resulting from manuring or cropping. The analyses reported here were made on soils taken from experiments in most of which (a) contrasting treatments had been continued for many years, and (b) the interval between samplings was long enough for measurable changes in carbon and nitrogen contents to have occurred. It was, therefore, a reasonable expectation that corresponding changes in organic P would be detectable.

In several experiments (Agdell Rotation, 1913–58; Hoosfield Exhaustion Land, 1903–58) the changes in carbon, nitrogen and organic P content of old arable soils over many years were too small to measure reliably. Moreover, these results agree closely with those from 11 Experimental Stations in the Great Plains region of the United States. Although over a period of 30–48 years, the organic P content of *virgin* soils decreased significantly, it changed very little on cropped and manured soils (Black, 1968).

Table 8 summarises changes in the ratios ΔC:ΔN:Δ org.P during periods when the carbon, nitrogen and organic P contents of soils *all decreased during arable cropping*. With the exception of the values for the Exhaustion Land (1856–1903), the changes recorded all refer to the past 20–50 years. The table also gives average annual rates of mineralisation of organic P, in kg P ha^{-1}, calculated over the period of the measurements. Values for changes in the sandy loam soil at Woburn, derived from previously published data (Mattingly, Chater & Johnston, 1975), are included for comparison with results from Rothamsted and Saxmundham.

The ratios ΔC:ΔN:Δ org.P vary widely and support the conclusion (Black, 1968) that 'The organic phosphorus of soils . . . tends to follow the pattern of accumulation and loss of organic matter as a whole, although there is no evidence for a fixed ratio of gains or losses of organic phosphorus to those of other organic constituents'. Variations in the ratio of ΔN:Δ org.P are much wider than those for ΔC:ΔN. The values in Table 8 range from 78 to 236 for ΔC:ΔN and from 0·17 to 1·64 for ΔN:Δ org.P. The range for *changes* in carbon contents of the soils (relative to N=10) are almost as wide as those quoted by Barrow (1961) for the C:N ratios (71–229) of the soil organic matter whereas the ratios ΔN:Δ org.P are narrower than the N:organic P ratio (0·15–3·05) in the same soils.

Rothamsted soils. The ratios ΔC:ΔN:Δ org.P were not greatly different in the three experiments (Table 8). The largest amounts of carbon, nitrogen and organic P were mineralised from soils from the Residual Phosphate Rotation. The latter were limed every 3 years (*c.* 3 t $CaCO_3$ ha^{-1}) from 1961 to 1976 and the pH increased from about 5·0 to 6·5 (in 0·01M-$CaCl_2$) in 15 years. Liming, which increases the rate of mineralisation of organic P (Barrow, 1961; Anderson, 1975; Dalal, 1977) also accelerates the breakdown of soil organic matter. Net annual rates of mineralisation ranged from 1·4 to 7·6 kg P ha^{-1}

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TABLE 8

Summary of changes in the ratios ΔC:ΔN: Δ organic P on prolonged cropping and net annual rates of mineralisation of organic phosphorus

Experiment and location	Manurial treatments and management	Period over which changes were measured	ΔC:ΔN:Δ org.P	Net rate of mineralisation of organic P* (kg P ha^{-1} year^{-1})
Agdell Rotation, Rothamsted	Rotation with fallow (1848–1951)	1956–72	90:10:0·55	1·8
	Rotation with clover (1848–1951)	1956–72	97:10:0·61	3·2
Exhaustion Land, Rothamsted	Unmanured plots	1856–1903	78:10:0·58	1·4
	Plots given superphosphate	1856–1903	87:10:0·58	1·4
Residual Phosphate Rotation, Rothamsted	Arable soil	1961–76	86:10:0·68	3·0
	Old grassland soil (ploughed up in 1956)	1961–75	109:10:0·53	7·6
Rotation II experiment, Saxmundham	Arable soil, no organics	1964–77/8	117:10:0·17	0·5
	Soils containing residues from FYM (25 t ha^{-1} every 4th year, 1899–1964)	1964–77/8	108:10:0·46	3·6
	Soil containing residues from 100 t ha^{-1} of FYM, 1965–66	1968–77/8	207:10:1·64	8·5
Continuous wheat and Barley experiments, Woburn†	No phosphorus since 1876	1927–59	236:10:1·20	1·6
	Superphosphate (1877–1926)	1927–59	234:10:0·94	1·6
	FYM (1877–1926)	1927–59	138:10:0·75	3·8

* The weights of soil to plough depth used in these calculations are (i) Agdell, 2630 t ha^{-1}; (ii) Exhaustion Land and Residual P rotation, 3030 t ha^{-1}; (iii) Saxmundham, Rotation II, 3500 t ha^{-1}; (iv) Woburn, 3440 t ha^{-1}

† Results calculated from data in Table 4 and Appendix Tables 1 and 2 in *Rothamsted Report for 1974*, Part 2, 61–77

and were smallest on arable soils from the Exhaustion Land and the Agdell Rotation and largest on the soil ploughed out of permanent pasture in the Residual Phosphate Rotation.

Saxmundham soils. Ratios of ΔC:ΔN were wider in soils from Rotation II at Saxmundham than in Rothamsted soils and losses of carbon, relative to nitrogen, were greater. Soils which contained residues from small dressings of FYM (25 t ha^{-1}) every fourth year mineralised about seven times as much organic phosphorus as the control soil (treatment 1) in the rotation. Where FYM (100 t ha^{-1}) was applied in 1965–66 losses of carbon approximately doubled and the net rate of mineralisation of organic P increased from 3·6 to 8·5 kg P ha^{-1}. About 90% of the organic P applied in these large dressings of farmyard manure mineralised during the following 10 years.

Woburn soils. Between 1927 and 1959 these soils lost two to three times as much carbon (relative to losses of N) as the soils from Rothamsted. Stackyard field at Woburn was well-farmed during the last century and, in 1876, contained about 50% more organic matter than arable soils at Rothamsted; over one-half the total soil carbon has been lost from the soil during the past 100 years (Mattingly, Chater & Johnston, 1975). Addition of FYM to these soils between 1876 and 1926 lessened the rate of loss of carbon and nitrogen (Mattingly, Chater & Johnston, 1975) and decreased the ratio ΔC:ΔN on prolonged cropping. The phosphorus applied in FYM between 1877 and 1926 more than doubled the net rate of mineralisation of organic P between 1927 and 1959.

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Conclusions. The results summarised here show how greatly the organic P contents of arable soils at Rothamsted, Saxmundham and Woburn vary with their previous history of cropping and manuring. The net rates of mineralisation range from about 0·5 to 8·5 kg P ha^{-1} year^{-1}. The largest values, on soils containing residues from recent large dressings of farmyard manure, or ploughed out from old grass represent about one-half of the total P removed each year by average crops (4·5–5·0 t ha^{-1}) of cereals.

Summary

1. This paper describes changes in the organic phosphorus contents of soils from long-continued experiments at Rothamsted and Saxmundham Experimental Stations and estimates the mean annual rates of loss or accumulation of organic P under contrasting systems of manuring and cropping. Changes in organic P are discussed in relation to changes in the ratio of carbon, nitrogen and organic P, i.e. $\Delta C:\Delta N:\Delta$ org.P over periods of 10–45 years.

2. In an experiment on arable crops (Agdell Rotation, Rothamsted) the mean carbon and organic P contents of soils sampled in 1913 and 1953 were the same on sub-plots which had compared, from 1848 to 1903, carting *v.* feeding swedes by sheep.

3. The carbon, nitrogen and organic P contents of soils from this experiment in 1913, 1953 and 1958 were consistently greater on plots cropped from 1848 to 1951 in a four-course rotation containing clover (or occasionally beans) than in a rotation where a fallow replaced the legume. Between 1956 and 1972 values of $\Delta C:\Delta N:\Delta$ org.P decreased during arable cropping in the ratios 90:10: 0·55 and 97:10:0·61 in the fallow and clover rotations respectively.

4. Between 1958 and 1970 one-half of the Agdell Rotation was cropped with grass leys and one-half with arable crops for 3 years and then fallowed. Organic carbon, nitrogen and phosphorus increased in the ratio 158:10:0·5 on plots from the old (1848–1951) rotation with fallow when under grass. Results on the old rotation with clover were more variable, probably because the soil pH had increased by 1·0–1·5 units from liming. Increasing soil pH (by liming) increased rates of mineralisation of residues of clover more than of native soil organic matter.

5. In an experiment (Hoosfield Exhaustion Land, Rothamsted) cropped continuously with winter wheat (1856–75) followed by potatoes (1876–1901) organic P decreased between 1856 and 1903 by 21–22 mg P kg^{-1} soil both on the unmanured plots and those given superphosphate (about 1400 kg P ha^{-1}). Plots given FYM from 1876 to 1901 (about 900 t ha^{-1}) contained about 25 mg P kg^{-1} more organic P in 1903 than the unmanured soils or those given superphosphate. The percentage of organic P applied in FYM that remained in the soil decreased from 29% in 1903 to 9% in 1974.

6. In an experiment comparing annual and 6-yearly applications of superphosphate to potatoes, barley and swedes grown in rotation (Residual Phosphate Rotation, Rothamsted) organic P decreased by 6–24 mg P kg^{-1} soil in 15 years on an old arable soil and by 31–40 mg P kg^{-1} soil in 14 years on an old grassland soil. Superphosphate applied either annually or 6-yearly did not significantly affect losses of organic P from either soil. The ratios of changes in $\Delta C:\Delta N:\Delta$ org.P were 86:10:0·68 and 109:10:0·53 on the two soils respectively.

7. In an experiment (Rotation II) on the manuring of wheat, roots, barley and a legume on chalky boulder-clay at Saxmundham, Suffolk, organic P in the soils decreased by

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13–25 mg P kg^{-1} soil between 1968 and 1978. The largest decrease was on plots given FYM (about 100 t ha^{-1} between 1965 and 1966) the organic P in which mineralised almost completely in 8 years.

8. Mean annual rates of mineralisation of organic P in the soils ranged from 0·5 to 8·5 kg P ha^{-1} $year^{-1}$ and were least (0·5–1·8 kg P ha^{-1} $year^{-1}$) on old arable soils which had received no organic manures, intermediate (3·2–3·6 kg P ha^{-1} $year^{-1}$) on soils containing residues from legumes or given FYM once in 4 years and greatest (7·6–8·5 kg P ha^{-1} $year^{-1}$) on soils ploughed out of permanent pasture or containing residues from large amounts (100 t ha^{-1}) of FYM. The greatest rates of mineralisation represent about one-half of the P removed each year by average crops (4·5–5·0 t ha^{-1}) of cereals.

9. The ratios $\Delta C:\Delta N:\Delta$ org.P varied very widely and ratios of $\Delta C:\Delta$ org.P or $\Delta N:\Delta$ org.P do not provide any reliable guide to amounts of organic P that mineralise, relative to losses of carbon or nitrogen, in arable soils with varying histories of management and manuring.

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APPENDIX

Total carbon was measured using the method developed by Tinsley (1950) and described by Bremner and Jenkinson (1960).

Total nitrogen was determined by Kjeldahl digestion. Soils were digested with H_2SO_4 and Cu–Se catalyst and NH_3 in the digests was estimated titrimetrically after distillation.

Total phosphorus was measured after fusion with sodium carbonate (Mattingly, 1970a). Phosphorus in solution was determined on the Technicon AutoAnalyzer using the method described by Salt (1968) for all soils from the Exhaustion Land experiment and for soils sampled in 1964 and 1968 from the Rotation II experiment at Saxmundham. It was estimated manually on all other samples using the method of Fogg and Wilkinson (1958).

Organic phosphorus was estimated both by the extraction method (A) described by Mehta, Legg, Goring and Black (1954) and by the ignition method (B) described by Saunders and Williams (1955). In method A 0·5 g soil (<60 mesh) was first extracted with 5 ml HCl (sp. gr. 1·18) for 10 min at 70°C; a further 5 ml HCl was added and the suspension allowed to stand for 1 h at room temperature. The extracts were centrifuged and further extracted with 15 ml 0·5N-NaOH at room temperature for 1 h and with 30 ml 0·5N-NaOH at 90°C in an oven for 8 h. All extracts were combined, diluted with water in a volumetric

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flask to 200 ml and stored in a refrigerator to minimise hydrolysis. Organic P was estimated from the difference between total P in an aliquot, measured after oxidation with $HClO_4$, and inorganic P measured on another aliquot. In method B, 2 g soil (< 60 mesh) was ignited at 500–550°C for 2 h in a muffle furnace and extracted with 100 ml 0·2N-H_2SO_4 for 2 h at room temperature. Organic P was estimated from the difference between 0·2N-H_2SO_4-soluble P extracted from ignited and unignited soil samples.

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APPENDIX TABLE 1

Total carbon, nitrogen, phosphorus and organic P analyses of soils from the Agdell Rotation, Rothamsted, 1913–75

(All analyses are based on air-dry samples, 0–23 cm)

Plot number	Treatment	Year	Total C (%)	Total N (%)	C/N	Total P (mg P kg^{-1} soil)	Organic P (mg P kg^{-1} soil) Ignition	Organic P (mg P kg^{-1} soil) Extraction	C/Organic P Ignition	C/Organic P Extraction
1	NPKNaMg (Rotation with fallow)	1913	1·10	0·127	8·7	732	208	168	52·9	65·5
		1953	1·00	0·114‡	8·8	751	230	175	43·5	57·1
		1958	1·08	0·115	9·4	753§	242	181	44·6	59·7
		1969*	0·79	0·089	8·9	840	194	156	40·7	50·6
		1969†	1·27	0·125	10·2	972	219	176	58·0	72·2
		1975*	0·84	0·092	9·1	880	195	144	43·1	58·3
		1975†	1·11	0·118	9·4	892	220	168	50·5	66·1
2	NPKNaMg (Rotation with clover)	1913	1·30	0·147	8·8	676	226	199	57·5	65·3
		1953	1·27	0·142‡	8·9	736	267	207	47·6	61·4
		1958	1·24	0·137	9·1	746§	268	206	46·3	60·2
		1969*	0·94	0·105	9·0	896	220	164	42·7	57·3
		1969†	1·37	0·148	9·3	944	244	184	56·1	74·5
		1975*	0·99	0·111	8·9	888	218	186	45·4	53·2
		1975†	1·21	0·130	9·3	880	229	192	52·8	63·0
3	PKNaMg (Rotation with fallow)	1913	1·06	0·122	8·7	648	180	152	58·9	69·7
		1953	1·00	0·120‡	8·3	707	216	146	46·3	68·5
		1958	1·11	0·125	8·9	694§	215	152	51·6	73·0
		1969*	0·86	0·099	8·7	844	204	164	42·2	52·4
		1969†	1·20	0·130	9·2	846	214	192	56·1	62·5
		1975*	0·94	0·104	9·0	896	206	146	45·6	64·4
		1975†	1·13	0·121	9·3	850	224	164	50·4	68·9
4	PKNaMg (Rotation with clover)	1913	1·24	0·148	8·4	590	196	169	63·3	73·4
		1953	1·24	0·153‡	8·1	670	228	168	54·4	73·8
		1958	1·29	0·150	8·6	639§	221	161	58·4	80·1
		1969*	0·97	0·124	7·8	820	198	146	49·0	66·4
		1969†	1·44	0·158	9·1	850	224	166	64·3	86·7
		1975*	0·97	0·119	8·2	824	210	180	46·2	53·9
		1975†	1·30	0·149	8·7	820	229	170	56·8	76·5
5	Unmanured (Rotation with fallow)	1913	0·97	0·118	8·2	544	202	142	48·0	68·3
		1953	1·02	0·118‡	8·6	570	204	146	50·0	69·9
		1958	1·03	0·120	8·6	546§	204	130	50·5	79·2
		1969*	0·84	0·101	8·3	748	192	116	43·8	72·4
		1969†	1·23	0·135	9·1	780	199	158	61·8	77·8
		1975*	0·88	0·106	8·3	796	218	174	40·4	50·6
		1975†	1·18	0·136	8·7	812	228	192	51·8	61·5
6	Unmanured (Rotation with clover)	1913	1·16	0·141	8·2	518	1	154	62·4	75·3
		1953	1·29	0·154‡	8·4	535	206	159	62·6	81·1
		1958	1·30	0·145	9·0	560§	212	138	61·3	94·2
		1969*	0·95	0·114	8·3	756	192	124	49·5	76·6
		1969†	1·40	0·154	9·1	742	202	168	69·3	83·3
		1975*	0·99	0·119	8·3	796	197	174	50·3	56·9
		1975†	1·26	0·152	8·3	746	222	202	56·8	62·4

* Plots in arable cropping, 1958–70
† Plots under grass, 1958–70
‡ The N analyses are derived from weighted mean analyses of samples (0–15 and 15–23 cm) and differ slightly from the 0–15 cm analyses quoted by Warren (1958)
§ Analyses for total P by fusion analysis agree closely with previous analyses by the perchloric acid method (Johnston & Penny, 1972)

APPENDIX TABLE 2

Total carbon, nitrogen, phosphorus and organic P analyses of soils from Hoosfield Exhaustion Land, Rothamsted

(All analyses are based on air-dry samples, 0–23 cm)

Plot	Treatment* 1856–1901	Year	Total C† (%)	Total N† (%)	C/N	Total P† (mg kg^{-1})	Organic P (mg P kg^{-1}) Ignition	Organic P (mg P kg^{-1}) Extraction	C/organic P Ignition	C/organic P Extraction
Site sample	—	1856	1·127	0·132	8·5	528	219	168	51·5	67·1
1, 2, 5, 6	Unmanured	1903	0·848	0·096	8·8	530	196	149	43·3	56·9
		1958	0·973	0·111	8·8	532	212	158	45·9	61·6
		1974	0·881	0·102	8·6	478	212	170	41·6	51·8
3, 4	FYM (1876–1901)	1903	1·447	0·157	9·2	862	222	173	65·2	83·6
		1958	1·172	0·128	9·2	698	226	178	51·9	65·8
		1974	1·103	0·124	8·9	630	232	166	47·5	66·4
7, 8, 9, 10	NPK and PK fertilisers	1903‡	0·795	0·094	8·5	886	187	158	42·5	50·3
		1958	0·964	0·110	8·8	693	214	158	45·0	61·0
		1974	0·881	0·101	8·7	606	218	168	40·4	52·4

* See Johnston and Poulton (1977) for full details of FYM and fertiliser dressings
† From Johnston and Poulton (1977)
‡ Plots 9 and 10 only in 1903

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APPENDIX TABLE 3

Total carbon, nitrogen, phosphorus and organic P analyses of arable and old grassland soils from the Residual Phosphate Rotation, Rothamsted, 1961–75/76

(All analyses are based on air-dry samples, 0–23 cm)

Treatment*	Year	Total C (%)	Total N (%)	C/N	Total P (mg P kg^{-1} soil)	Organic P (mg P kg^{-1} soil) Ignition	Organic P (mg P kg^{-1} soil) Extraction	C/organic P Ignition	C/organic P Extraction
Arable soil (Sawyers I)									
No phosphate	1961	1·52	0·159	9·6	613	251	210	60·6	72·4
	1967	1·38	0·148	9·3	622	240	186	57·5	74·2
	1976	1·31	0·136	9·6	618	222	190	59·0	68·9
Superphosphate (applied annually)	1961	1·50	0·156	9·6	637	240	188	62·5	79·8
	1967	1·38	0·146	9·4	683	246	180	56·1	76·7
	1976	1·34	0·134	10·0	708	234	183	57·3	73·2
Superphosphate (applied in 1959, 1966 and 1972)	1961	1·50	0·154	9·7	673	260	198	57·7	75·8
	1967	1·34	0·144	9·3	683	247	189	54·3	70·9
	1976	1·30	0·132	9·8	691	238	185	54·6	70·3
Old grassland soil (Great Field IV)									
No phosphate	1961	2·53	0·260	9·7	717	325	288	77·8	87·8
	1967	2·19	0·228	9·6	690	306	272	71·6	80·5
	1975	1·79	0·195	9·2	647	275	256	65·1	69·9
Superphosphate (applied annually)	1961	2·47	0·253	9·8	729	316	286	78·2	86·4
	1967	2·07	0·220	9·4	736	301	260	68·8	79·6
	1975	1·80	0·189	9·5	744	293	246	61·4	73·2
Superphosphate (applied in 1959, 1966 and 1972)	1961	2·56	0·260	9·8	772	321	300	79·8	85·3
	1967	2·10	0·222	9·4	765	302	263	69·5	79·8
	1975	1·85	0·196	9·4	749	291	261	63·6	70·9

* Details of the purpose and design of the experiments are given by Mattingly (1968; 1970b)

APPENDIX TABLE 4

Total carbon, nitrogen, phosphorus and organic P analyses of soils from the Rotation II experiment, Saxmundham, 1964–77/78

(All analyses are based on air-dry samples, 0–20 cm in 1964 and 0–25 cm in other years)

Treatment	Manuring* 1899–1964	Manuring* 1965–68	Year	Total C (%)	Total N (%)	C/N	Total P (mg P kg^{-1} soil)	Organic P (mg P kg^{-1} soil) Ignition	Organic P (mg P kg^{-1} soil) Extraction	C/organic P Ignition	C/organic P Extraction
1	Unmanured	NK	1964	1·18	0·127	9·3	434	152	121	77·6	97·5
			1968	1·14	0·118	9·7	402	160	131	71·2	87·0
			1973/4	1·02	0·117	8·7	405	146	108	69·9	94·4
			1977/8	1·04	0·115	9·0	416	155	113	67·1	92·0
2	FYM every 4th year	NK	1964	1·48	0·160	9·2	505	174	137	85·1	108·0
			1968	1·35	0·136	9·9	450	170	132	79·4	102·3
			1973/4	1·15	0·132	8·7	438	155	114	74·2	100·9
			1977/8	1·16	0·127	9·1	445	158	118	73·4	98·3
4	FYM+ superphosphate (P) every 4th year	NK+FYM in 1965 and 1966	1964	1·54	0·152	10·1	683	175	147	88·0	104·8
			1968	1·59	0·156	10·2	644	190	148	83·7	107·4
			1973/4	1·32	0·148	8·9	581	167	122	79·0	108·2
			1977/8	1·30	0·142	9·2	586	170	122	76·5	106·6
8	FYM+ superphosphate (2P) every 4th year until 1952	NK	1964	1·62	0·170	9·5	720	174	144	93·1	112·5
			1968	1·46	0·149	9·8	582	182	142	80·2	102·8
			1973/4	1·31	0·146	9·0	568	170	128	77·1	102·3
			1977/8	1·28	0·142	9·0	584	170	128	75·3	100·0

* Details of the purpose and design of the experiments are given by Mattingly, Johnston and Chater (1970) and Mattingly and Johnston (1976)

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