Organic Substances in Soil and Water: Natural Constituents and Their Influences on Contaminant Behaviour

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Significance of Organic Matter in Agricultural Soils

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1 Introduction

In his report[1] entitled 'Organic Chemistry in its Application to Agriculture and Physiology' presented in 1840 to the British Association for the Advancement of Science, Liebig discussed the view then held by vegetable physiologists that humus, produced by the decomposition of vegetable matter, was the principle nutriment of plants being directly extracted by plant roots from the soil. Although Liebig successfully demolished this hypothesis, he nevertheless proposed an important role for humus. 'Humus does not nourish plants by being taken up and assimilated in its unaltered state, but by presenting a slow and lasting source of carbonic acid which is absorbed by the roots and is the principal nutriment of young plants at a time when, being destitute of leaves, they are unable to extract food from the atmosphere'. Later he noted, 'Its (humus) quantity heightens the fertility of a soil . . .'. Liebig was aware that the breakdown of organic matter produced carbon dioxide and he later proposed that carbonic acid was responsible for releasing elements like potassium and magnesium from soil minerals.

The concept that the fertility of a soil depended on its humus content was soon disproved by the results of field experiments on crop nutrition started by Lawes and Gilbert in 1843 at Rothamsted. They showed that nutrients like nitrogen, phosphorus, and potassium were taken up by roots from soil, and that adding organic matter to soil to produce carbon dioxide had no benefit. As early as 1845, it had been demonstrated that it was more important to have within soil a supply of 'available and assimilable nitrogen' to increase yields of winter wheat and turnips.[2] Subsequently Lawes and Gilbert often commented that although their experimental soils often contained 4000 kg ha^{-1} total nitrogen (in organic matter) it was in a form which did not benefit crop growth because when up to 100 kg ha^{-1}

nitrogen was given as a water soluble ammonium or nitrate salt there was a very large increase in yield. However, 130 years later, Russell noted that there has always been a lingering concern about the relationship between the fertility of a soil and the quantity of humus, that complex of organic compounds found mainly in the surface soil. The paper from which this comment was taken[3] was probably, in part, a considered response to the Strutt Report on 'Modern Farming and the Soil'.[4] This report was commissioned following two very poor harvests in consecutive years, 1968 and 1969. The enquiry was an official response to vigorously expressed, but poorly identified, concerns that modern farming, principally the intensification of arable cropping, mainly in the eastern counties, was having adverse effects on soil fertility. Soil humus content was one factor considered and the report suggested that humus levels should not be allowed to fall below about 3%.

In his paper[3] Russell went on to point out that the problem facing agricultural researchers was to define the role of humus in soil fertility, the time scales and husbandry practices which affect humus content, and the separation and quantification of the various factors which could contribute to any overall humus effect. However, as often happens in many branches of science, it is essential to define the problem to encourage research. This has been so with the agronomic effects of humus; until there were measurable effects on yield few researchers were interested in quantifying the various components which contribute to the overall effect. In temperate climates soil organic matter levels change only slowly and it may take many years to get soils with appreciably different levels of humus in an experiment where its effects can be estimated with accuracy. In such experiments it is also essential to ensure that no other factor like soil acidity or phosphorus (P) and potassium (K) status will limit growth. In tropical climates soil organic matter levels change much more rapidly but humus effects may be masked by chronic water shortage and organic additions to soil may be better left as surface mulches to minimize the risk of soil erosion.

This paper considers some aspects of the significance of humus in the productivity of temperate soils using data from the Rothamsted and Woburn Experimental Stations. Rothamsted dates its foundation as 1843, most of the soils are silty clay loams, 25–30% clay, and average annual rainfall is about 700 mm. Woburn was started in 1876 by the Royal Agricultural Society of England; it has been managed by Rothamsted since 1926. The soils at Woburn are mainly sandy loams, about 10% clay, and average annual rainfall is 650 mm. On both farms there are experiments with contrasted treatments which have affected the humus content of the soil. Equally important is the existence of a unique archive of crop and soil samples which have been taken throughout the history of these experiments. This archive allows estimates of many organic and inorganic constituents to be made now so that changes in concentration over time can be studied.

2 Effect of Soil Organic Matter on Crop Yield

All the early experiments at Rothamsted compared yields given by plots treated with either inorganic fertilizers or farmyard manure (FYM). Yields of winter wheat, spring barley, and mangolds were as large on plots given small quantities of readily available plant nutrients in fertilizers as on plots with much larger amounts of FYM (Table 1). The similarity of the yields of these three crops, together with those of sugar beet, on the two differently treated soils continued into the 1960s and 1970s, even though there was by this time about 2.5 times as much humus in FYM- as in fertilizer-treated soils. The difference in soil organic matter had arisen because of the long continued annual applications of FYM.

On the sandy loam at Woburn beneficial effects from extra soil organic matter were suspected in the Market Garden experiment in the early 1960s.[5] This led to a number of experiments testing organic matter, see for example Mattingly *et al.*[6] Results from one experiment in the 1970s showed that potatoes and spring barley benefited from extra humus but not winter wheat and winter barley (Table 2). This difference suggested that whilst deep rooted, autumn sown crops could make better use of subsoil water, spring sown, shallow rooted crops might be more responsive to differences in soil organic matter. The benefit could be through better soil structure and/or a small increase in the soil's water holding capacity. Although the latter might not amount to more than a few days water use by the crop this could be sufficient to delay the onset of severe water stress before the next rainfall. Another very important result in Table 2 is that for both potatoes and spring barley extra fertilizer nitrogen did not substitute for less soil organic matter. For both crops the final increment of nitrogen tested did not give an increase in yield on a low organic matter

Table 1 *Yields,* t ha^{-1}, *of winter wheat and spring barley grain, at 85% dry matter, and roots of mangolds and sugar beet at Rothamsted*

Experiment	*Crop*	*Period*	*Yield with FYM*	*Yield with NPK fertilizers**
Broadbalk	Winter wheat	1852–61	2.41	2.52
		1902–11	2.62	2.76
		1970–75	5.80	5.47
Hoosfield	Spring barley	1856–61	2.85	2.91
		1902–11	2.96	2.52
		1964–67	4.60	3.36
		1964–67	5.00	5.00†
Barnfield	Mangolds	1876–94	42.2	46.0
	Mangolds	1941–59	22.3	36.2
	Sugar beet	1946–59	15.6	20.1

*FYM, 35 t ha^{-1}; N to winter wheat, 144 kg ha^{-1}; to spring barley, 48 kg ha^{-1}; (except †, 96 kg ha^{-1}); mangolds and sugar beet, 96 kg ha^{-1}.

Table 2 *Yields of potatoes, winter wheat, and winter and spring barley at Woburn 1973–80*

% C in soil	Fertilizer N applied* 0	1	2	3	Average April–July rainfall and deviation from long-term average†
Potatoes, tubers, t ha^{-1}, *1973 and 1975*					
0.76	25.7	35.6	41.7	43.2	
2.03	27.1	40.6	50.7	59.0	266(−14)
Spring barley, grain, t ha^{-1}, *1978*					
0.76	2.19	5.00	6.73	7.05	
1.95	2.58	5.12	6.85	7.81	222(+20)
Winter wheat, grain, t ha^{-1}, *1979*					
0.76	3.54	7.32	8.05	7.82	
1.95	4.81	7.21	8.09	8.08	247(+45)
Winter barley, grain, t ha^{-1}, *1980*					
0.76	3.05	6.01	7.32	7.83	
1.95	3.57	5.92	7.00	7.98	258(+56)

* N0, N1, N2, N3: 0, 100, 200, 300 kg N ha^{-1} for potatoes; 0, 50, 100, 150 kg N ha^{-1} for cereals.
† April–August rainfall for potatoes.

soil. Much of this nitrogen could have been left in soil as nitrate in autumn and hence prone to loss by leaching. Further examples of the benefits of extra humus on the sandy loam at Woburn have been given elsewhere.[7]

On the silty clay loam at Rothamsted it took somewhat longer to demonstrate beneficial effects of extra humus. In the early 1970s yields from the two ley-arable experiments showed no beneficial effect from extra organic matter accumulated during a three-year period of grass, grass-clover, or lucerne leys. Very similar yields of winter wheat, potatoes, and spring barley were obtained after the leys and in an all-arable rotation, provided the correct amount of fertilizer nitrogen was used. But, the optimum nitrogen application was always less after a ley than in an all-arable rotation, because of the nitrogen released as the organic matter from the ley decomposed. Yields of potatoes were generally larger, however, in the experiment on soils with 3.6% organic matter than in the experiment on soil with 2.7% organic matter. This effect of extra humus on yields of potatoes was shown more convincingly, together with a similar benefit for sugar beet but not cereals, in another experiment at Rothamsted in 1968–73 (Table 3). Although the largest amount of fertilizer nitrogen tested on each crop was much larger than that in general use at that time, yields of potatoes and sugar beet on soils with less organic matter did not equal those on soils with more. In very recent years following the introduction of cultivars of wheat and barley with a high yield potential, best yields of both on Broadbalk and Hoosfield, respectively, are on soils annually treated with FYM and given extra fertilizer nitrogen (Table 4).

Table 3 *Yields of potatoes and sugar beet, spring barley, and spring wheat in 1968–73 on soils treated with fertilizers or FYM since 1846*

Crop	Manuring	Fertilizer N applied* 0	1	2	3
Potatoes	FYM	24.2	38.4	44.0	44.0
	PK	11.6	21.5	29.9	36.2
Sugar beet	FYM	27.4	43.5	48.6	49.6
	PK	15.8	27.0	39.0	45.6
Spring barley	FYM	4.18	5.40	5.16	5.08
	PK	1.85	3.74	4.83	4.92
Spring wheat	FYM	2.44	3.73	3.92	3.79
	PK	1.46	2.97	3.53	4.12

*N0, N1, N2, N3: 0, 72, 144, 216 kg N ha^{-1} for potatoes and sugar beet; 0, 48, 96, 144 kg N ha^{-1} for spring barley and spring wheat.

Table 4 *Largest annual yields of winter wheat and spring barley,* t ha^{-1}, *given by fertilizers and farmyard manure, Rothamsted*

Experiment and period	Crop	Treatment NPK*	FYM	FYM + N†
Broadbalk 1985–90	Winter wheat grown: continuously	6.69	6.17	7.92
	in rotation	8.61	7.89	9.36
Hoosfield 1988–91	Spring barley grown: continuously	5.21	5.50	6.06

* Soils with FYM treatment contain about 2.5 times as much organic matter as those given fertilizers.
† N 96 kg ha^{-1} as fertilizer.

3 Amounts of Organic Matter in Soil

The amount of humus in soil depends on (i) the amount of added organic material and its rate of decomposition; (ii) the rate of decomposition of existing humus; (iii) soil texture; (iv) climate. Soil humus usually has a carbon:nitrogen (C:N) ratio of about 10:1 despite the wide range of C:N ratios of added organic material which can be within the range 100:1 (straw) to 30:1 (leguminous crop residues). Both factors (i) and (ii) above are affected by the farming system practised, but for any one farming system on a given soil type, soil humus tends towards an equilibrium value. For example this is about 1.7% and 5.0% organic matter in permanent arable and grassland soils, respectively, at Rothamsted.

The quantity of organic matter added to soil at any one time is rarely more than a very small fraction of the humus in soil. Any addition is a welcome source of food for the ever hungry soil microbial population, the carbon content of which rarely exceeds about 5% of the total organic carbon in soil. Provided soil moisture and temperature are above the critical values below which microbial activity ceases, the microbial biomass rapidly attacks added organic material of plant or animal origin. For example, added cereal straw loses about 40% of its dry weight in 40 days after incorporation in autumn. Some residues with a narrower C:N ratio may almost totally disappear in this period. This rapid rate of decay may have implications for the quantity of low molecular weight organic molecules in the soil solution. Concentrations of these molecules may also be affected by microbial activity in the rhizosphere and by root exudates.

The concept that humus is a comparatively uniform end-product of microbial activity is well shown in Figure 1. In the Market Garden experiment at Woburn, FYM, FYM compost, sewage sludge, and sludge compost were each added to soil at 37.5 and 75 t ha^{-1} of fresh material each year for between 20 and 25 years during the period 1942–67 (for details see reference 5). These additions resulted in different amounts of humus in the eight differently treated soils. But once the applications ceased the rate of humus decay for each treatment fitted a single decay curve.[8] Presumably soluble organic molecules produced by the decay of humus could have very similar properties independent of the form in which organic matter was originally added to soil.

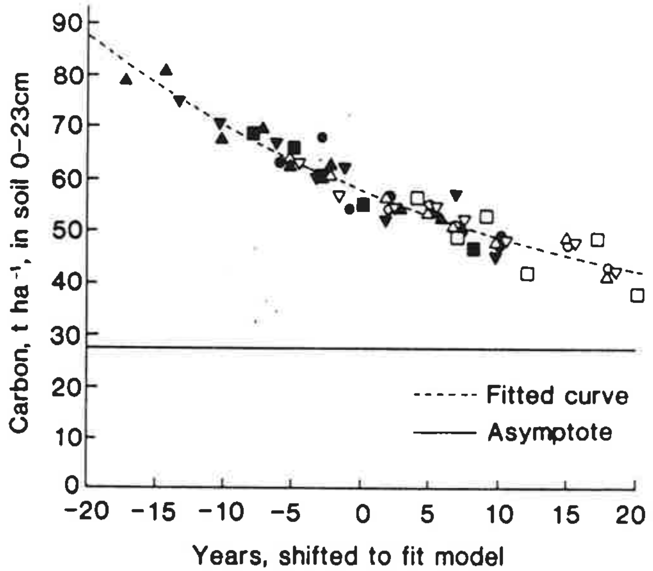

Figure 1 *Decline in soil carbon, t ha^{-1}, in a sandy loam, Market Garden experiment, Woburn. All treatments shifted horizontally to test whether they fitted a single decay curve. FYM, single □, double ■; sewage sludge, single △, double ▲; FYM compost, single ○, double ●; sludge compost, single ▽, double ▼*

The slow rate of change of humus in temperate soils, together with the effect of soil texture is well shown in Figure 2. On the silty clay loam at Rothamsted humus levels in soils which have been unmanured or given inorganic fertilizers since 1852 have remained essentially constant during the last 100 years. Soils given fertilizers contained about 10% more organic matter because they grew bigger crops and larger organic residues were returned to the soil each year. Soil given 35 t ha^{-1} FYM each year has still not reached its equilibrium humus content although the annual rate of gain is now very small. In 1876 the soils of Stackyard Field at Woburn had been in arable cropping for some years but nevertheless contained more humus than similarly cropped soils at Rothamsted. This was probably because the Woburn soils had a long period in grassland before the 1830s.[9] However, since 1876 the Woburn soils, which have had similar cropping and manuring to the soils on Hoosfield, have gradually lost humus and they now contain less than the Rothamsted soils do.

The magnitude of the changes in humus with changes in cropping have been discussed in detail elsewhere.[7] In one example a grassland soil with about 5.2% organic matter was ploughed. After about 20 years, 30% of the humus had been lost where a six course rotation (three cereals, two root crops, and a one year ley) was followed. Where more root crops were grown, four in six years, about 40% of the humus was lost, presumably because there was more soil cultivation for weed control and less root residues were returned. Where the soils were kept without crop and without weeds, nearly 50% of the humus had gone in the same period.

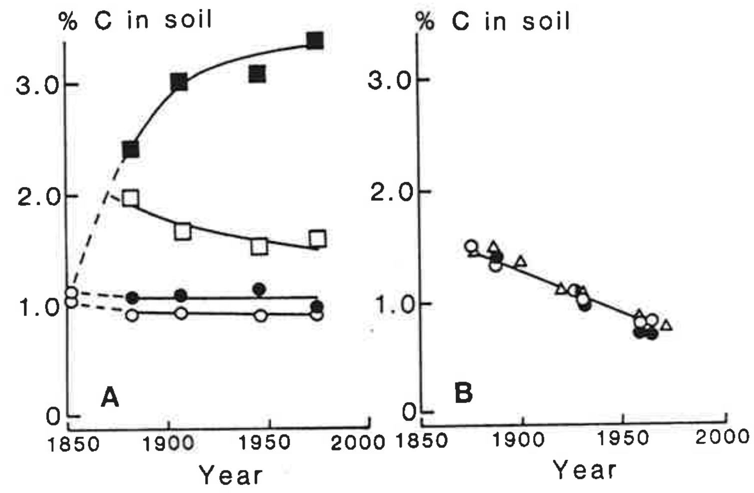

Figure 2 *Percentage carbon in soil. A. Hoosfield, Rothamsted, barley each year and treatments continuous since 1852. ○, unmanured; ●, NPK fertilizers; □, FYM 1852–71 none since; ■ FYM, 35 t ha^{-1}. B. At Woburn arable crops each year; cereals, ○, unmanured; ● NPK fertilizers; △, manured four-course rotation*

In the ley–arable experiments at Rothamsted, a sequence of three years of leys and three arable crops was compared with a six year, all-arable rotation. After 27 years the grass and grass–clover leys had done little to increase total humus content compared to that in the all-arable rotation whilst lucerne had no effect at all (Table 5). However, as already mentioned, the leys especially the lucerne, did leave a readily mineralized organic residue, probably too small to determine accurately, which did affect the response of the following arable crops to fertilizer nitrogen. On a soil initially with about 5% organic matter, continuous arable cropping caused the humus content to fall and the short leys did little to prevent the decline. On soils with little humus at the start, the short leys did little to increase humus content; it was only under permanent grass that soil organic matter content increased.[10]

4 Humus and Nitrate Leaching

One of the major concerns in the agriculture/environment debate of the late 1970s and 1980s has been the amount and source of nitrate in potable waters. Many people have considered that there was a simple direct relationship between the increasing use of nitrogen fertilizers, especially on arable crops, throughout this period and the increasing levels of nitrate observed in some water sources. Research, using a range of arable crops and ^{15}N-labelled inorganic nitrogen fertilizers, showed that, provided the amounts of fertilizer were adjusted to meet expected crop requirements and that the application was timed to satisfy crop demand for nitrogen, then very little ^{15}N-labelled nitrate remained in soil after harvest. Thus the use of inorganic nitrogen fertilizer with best farm practice had little direct effect on nitrate leaching. However, about 20–30% of the spring applied nitrogen was still in the soil but in organic combination and, especially after cereal crops, little of this new organic matter was mineralized rapidly.

Table 5 *Effect of three-year leys on % C in air dry soil, 0–23 cm*. Ley–arable experiments, Rothamsted, mean 1972 and 1975†*

	Continuous arable	*Three years arable preceded by three years of:*		
		Lucerne	*Grass clover*	*Grass with N*
Old grassland soil				
% C in soil	2.01	2.00	2.27	2.24
increase due to ley		−0.01	+0.26	+0.23
Old arable soil				
% C in soil	1.57	1.57	1.81	1.77
increase due to ley		0	+0.24	+0.20

* Soil sampled in autumn of third year of the ley before ploughing.
† 24th and 27th year after the start of the experiment.

Nitrate that appeared in soil after harvest came from the mineralization of humus.

Thus the problem of nitrate leaching is related to the mineralization of humus in autumn when crop demand is small. In largely arable cropping systems the long continued use of nitrogen fertilizers does increase soil organic matter a little (see, *e.g.* Figure 2) relative to the amounts in unmanured soils. Mineralization of this extra organic matter will give some additional nitrate. However, per unit area of land, the amount is likely to be small relative to the quantity of nitrate released following the ploughing of leys and the incorporation of leguminous crop residues.

5 Effects of Humus on the Movement of Organic Chemicals

A well documented effect of soil organic matter is on the mobility of some organic molecules added to soil to control weeds or pests. Here it is essential to differentiate between the effects of elemental carbon and humus. Elemental carbon, often found in soil as coal or charcoal, has also been added to soil in recent times as a result of straw burning. Usually this carbon is very finely divided and is considered to have good sorbance properties. Elemental carbon is determined when soils are analysed by dry combustion and any such carbon multiplied by the conventional factor 1.72, will be reported as organic matter. The decreased efficacy of some soil applied organic chemicals has been related to the presence of elemental carbon. Carbon in humus is still in organic combination and will have very different properties to elemental carbon.

Table 6 shows yields of field beans (*Vicia faba*) grown in an experiment where plots had been treated with inorganic fertilizers or FYM, which had resulted in soils with different humus contents, but there had never been any straw burning. Simazine was used to control weeds but, on soils low in organic matter, the simazine was not retained in the top soil. It moved downwards, as shown by bioassay in the glasshouse, and adversely affected germination, growth, and final grain yield.

Table 6 *Effect of simazine on yield* ($t\,ha^{-1}$) *of field beans* (Vicia faba) *at three levels of soil organic matter*

% Organic matter	*Simazine added* ($kg\,ha^{-1}$)	
	0	0.94
1.2	2.5	1.6
2.0	2.6	2.4
3.5	3.1	2.9

6 Effect of Humus on Metal Content of Soils and Crops

Joint research by Lancaster University and Rothamsted on cadmium in crops and soils of the Rothamsted Classical experiments has been summarized recently.[11] On soils which have received no agricultural amendments, aerial deposition of cadmium has increased the level of soil cadmium over time (Table 7). Soils with $pH_{(water)}$ above 6.5 and low in organic matter (Broadbalk, Hoosfield, Barnfield) have apparently retained none of the cadmium added in superphosphate, made from rock phosphate, since 1889. Before 1889 the superphosphate was made from bone dust which would have contained little or no cadmium. In contrast acid soils with more organic matter (Park Grass) have retained additional cadmium. Much of the extra cadmium in the soils richer in organic matter has accumulated in the near surface layers (Table 8).

Cadmium concentrations in herbage from Park Grass ranged between 102 and 152 μg Cd kg^{-1} between 1861 and 1920, increased sharply to about 250 $\mu g\,kg^{-1}$ by the 1940s, and have remained consistently above 200 $\mu g\,kg^{-1}$ since then. On the unmanured plot which has been limed (given $CaCO_3$) once every four years since 1903, soil pH is now higher

Table 7 *Changes in soil cadmium on untreated plots and those given superphosphate in Rothamsted long-term experiments*

Experiment	*Period*	*Approximate average yearly increase*			
		Soils without P		*Soils with P*	
		($\mu g\,kg^{-1}$)	($g\,ha^{-1}$)	($\mu g\,kg^{-1}$)	($g\,ha^{-1}$)
Broadbalk	1881–1983	1.0	2.9	0.9	2.6
Hoosfield	1882–1982	1.5	3.9	1.6	4.1
Barnfield	1870–1983	0.9	2.3	1.2	3.1
Mean		1.1	3.0	1.2	3.3
Park Grass	1876–1976	1.1	2.9	2.7	7.2

Table 8 *Cadmium* ($mg\,kg^{-1}$) *in soil from different depths, Park Grass, Rothamsted*

Soil layer (cm)	*– P**	*+ P*	*Increase due to superphosphate*
0–7.5	0.21	0.40	0.19
7.5–15.0	0.15	0.28	0.13
15.0–22.5	0.12	0.18	0.06
22.5–30.0	0.08	0.12	0.04
30.0–37.5	0.04	0.08	0.04
37.5–45.0	0.02	0.03	0.01

*–P, +P without and with superphosphate.

(pH 6.4) than on the unlimed plot (pH 5.2), and herbage cadmium concentrations have increased only a little. This suggests that some of the cadmium could have been on the 'outside' of the herbage directly from aerial deposition whilst some was on the 'inside' from root uptake. On the limed soils, any effect of decreasing acidity on lowering cadmium uptake by roots was offset by increased aerial deposition so that concentrations changed little over time. On acid soils root uptake may have been enhanced which, together with increased aerial deposition, caused concentrations to increase. Cereal grain cadmium concentrations were little affected by increased cadmium concentrations in surface soil.[11]

Figure 3 shows the concentration of herbage lead since the late 1950s in another experiment. Lead concentrations have declined throughout the period and were related to a decline in aerial lead. In this experiment herbage grown on soils with and without FYM was analysed. The FYM caused a small increase in soil organic matter (from 5.0% to 6.4%) but this had no effect on herbage lead. This suggests that much of the lead was from aerial deposition on to the outside of the plant. Soil lead burden has increased where 35 t ha^{-1} FYM has been applied each year in the Classical experiments[12] but the amounts were small. Probably much of the animals dietary intake of lead was excreted firmly complexed with the organic fraction and then retained in soil.

This evidence for cadmium and lead suggests that organic matter can play a role in retaining both metals in surface soil. It also suggests that root uptake of both metals will depend on their speciation in soil and for cadmium, uptake can be manipulated by altering soil pH even in the presence of organic matter.

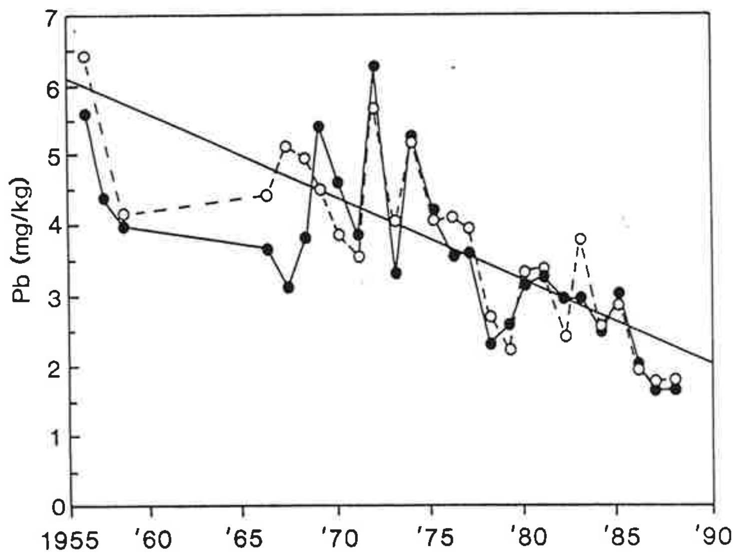

Figure 3 *Lead concentrations in herbage at Rothamsted for the years 1956–1988. Soils given, ●, NPK fertilizers; ○, FYM*

7 Humus and the Movement of Phosphorus

There is concern currently about the sources of phosphorus in inland and coastal waters because of its role in the development of algal blooms when both phosphorus and nitrogen (as nitrate) are above critical thresholds. Much of the nitrate comes from agricultural land, mainly from the mineralization of organic matter. Appreciable amounts of phosphorus can come from point sources (like sewage treatment works) and there is discussion about losses from agricultural land. Studies at Rothamsted on the movement of phosphorus in agricultural soils have been summarized recently.[13]

Table 9 shows the total P content at different depths in soils in one experiment where root crops were grown with NPK fertilizers (33 $kg\,P\,ha^{-1}$) and FYM (35 $t\,ha^{-1}$, containing about 40 $kg\,P\,ha^{-1}$) since 1843. The plough layer is now 23 cm deep and there has been considerable enrichment with phosphorus where both fertilizers and FYM were given. Where superphosphate was applied there was a small increase in the phosphorus concentration in the 23–30 cm layer which could be due to a limited amount of leaching but is more likely to be the result of occasional ploughing just deeper than 23 cm. There has been no phosphorus enrichment of the soil below 30 cm. Where FYM was applied there has been appreciable enrichment of the 23–30 cm and 30–46 cm horizons. These data are summarized and compared with those from other long-term experiments in Table 10. The permanent grassland experiment has not been ploughed for perhaps the last 300 years and unmanured plots and those given superphosphate (33 $kg\,P\,ha^{-1}$) have had the same treatment each year since 1856. In the 0–46 cm layer of the unmanured soil there is the same amount of total P as in the comparable soil of the arable experiment but the distribution is different. Where superphosphate has been applied there has been considerable phosphorus enrichment of both the 23–30 and 30–46 cm layers. When averaged over all treatments for the grassland soil, the increase in total P (670 $mg\,kg^{-1}$) below 23 cm was about 80% of the average increase (820 $mg\,P\,kg^{-1}$) in the top 23 cm.[13] All plots of vegetable crops grown on the sandy loam in the Market Garden experiment at Woburn received superphosphate whilst some were given FYM. Where FYM was given subsoils have been enriched with phosphorus (Table 10).

Table 9 *Total phosphorus,* $mg\,P\,kg^{-1}$, *content of soil in 1958 at various depths where superphosphate and farmyard manure had been applied since 1846, Barnfield, Rothamsted*

Depth (cm)	*Treatment*				
	No P No K	*P No K*	*PK*	*FYM*	*FYM + P*
0–23	770	1350	1295	1376	1971
23–30	464	541	524	649	781
30–46	413	446	448	525	579
46–53	401	396	397	442	411

Each value is the mean of five nitrogen treatments.

Phosphorus enrichment of the subsoils has occurred, therefore, where FYM but not superphosphate was applied to mineral soils growing arable or vegetable crops and where superphosphate was applied to soil rich in organic matter. This suggests that P may be transported as water-soluble, low molecular weight organic phosphorus molecules present in FYM or, in the case of grassland soils, released on the death of roots. When these soils were extracted with different reagents the phosphorus in surface soils from which phosphorus has leached had an enhanced solubility in 0.01 M $CaCl_2$ solution. This solution has a similar ionic strength to that of the soil solution. Any organic phosphorus compounds extracted by this reagent would be readily hydrolysed when the solution was acidified to measure its phosphorus content and would be determined as inorganic phosphorus.

Table 11 shows the total, bicarbonate-soluble and $CaCl_2$-soluble P in control, FYM and superphosphate treated soils in a number of long-term experiments. For the four experiments growing arable crops on mineral soils at Rothamsted the increase in total and bicarbonate soluble P from FYM and superphosphate was essentially the same but the increase in $CaCl_2$-soluble P was between two and five times greater in FYM-treated soils. On Barnfield, where both FYM and superphosphate were applied together, the presence of FYM enhanced the $CaCl_2$-soluble P in the combined treatment more than the sum of the separate effects of FYM and superphosphate. This effect of FYM occurs only when it is added regularly; it had disappeared on the Exhaustion Land by 1974 where the last application of FYM was in 1901 (Table 11) even though the FYM-treated soil still contained about 25% more total organic matter than the fertilizer-treated soil. Table 11 also shows that at Woburn, although sewage sludge-treated soils contained nearly three times as much extra total phosphorus as FYM-treated soils, they had much less extra bicarbonate-soluble P and $CaCl_2$-soluble P. The sewage sludge used between 1942 and 1961 had been anaerobically digested and lagoon dried so it is probable that much soluble P, both inorganic and readily mineralized organic P, had been removed in the treatment works and discharged to the river.

Some of the phosphorus from superphosphate applied to grassland soils has moved down through the soil horizons by leaching. However, in this situation the extra $CaCl_2$-soluble P decreased more rapidly with depth than did bicarbonate-soluble or total P.[13] This suggests that if low molecular weight organic molecules were transported downwards they were rapidly mineralized and the inorganic phosphorus was adsorbed on to sites in the subsoil. Thus organic matter, directly or indirectly appears to play a role in the movement of phosphorus downwards through the profile of agricultural soils.

Table 10 *Total P*, $mg\,kg^{-1}$, *in soil at different depths where superphosphate or farmyard manure were applied to surface soils at* pH 6.5

Soil depth (cm)	*Soil type and P treatment**						
	Silty clay loam					*Sandy loam*	
	Arable crops			*Permanent grassland*		*Vegetable crops*	
	None	*P*	*FYM*	*None*	*P*	*P*	*FYM*
0–23	780	1295	1375	575	1425	1120	1780
23–30	465	525	650	555	785	–	–
30–46	415	450	525	500	600	850	960
Below 46	400	395	440	–	–	790	860

* P superphosphate, FYM farmyard manure.

Table 11 *Total*, $NaHCO_3$*-soluble and* $CaCl_2$*-soluble P in surface soils,* 0–23 cm, *from various long-term experiments at Rothamsted and Woburn*

Experiment and year sampled	*Treatment*	*Total P* ($mg\,kg^{-1}$)*	*P soluble in* 0.5 M $NaHCO_3$ ($mg\,kg^{-1}$)*	*P soluble in* 0.01 M $CaCl_2$ ($g\,mol^{-1} \times 10^6$)*
Barnfield 1958	Control	670	18	0.5
	Superphosphate (P)	1215 (545)	69 (51)	3.0 (2.5)
	FYM	1265 (595)	86 (68)	12.8 (12.3)
	FYM plus P	1875 (1205)	145 (127)	22.3 (21.8)
Broadbalk 1966	Control	580†	8	0.2
	Superphosphate	1080 (500)	81 (73)	6.6 (6.4)
	FYM	1215 (635)	97 (89)	19.5 (19.3)
Hoosfield 1965	Control	630	6	0.3
	Superphosphate	1175 (545)	103 (97)	14.4 (14.1)
	FYM	1340 (710)	102 (96)	25.4 (25.1)
Exhaustion Land 1903	Control	530	8	0.2
	Superphosphate	885 (355)	65 (57)	5.6 (5.4)
	FYM	860 (330)	66 (58)	9.6 (9.4)
1974	Control	480	2	0.1
	Residues of:			
	Superphosphate	595 (115)	10 (8)	0.2 (0.1)
	FYM	630 (150)	12 (10)	0.3 (0.2)
Woburn 1961	Control	1120	94	23
	FYM	1780 (660)	176 (82)	98 (75)
	Sewage sludge	3000 (1880)	151 (57)	43 (20)

* Figures in parenthesis are increases over the control.
† 1944 samples.

8 Conclusions

Soil organic matter or humus plays a crucial role in soil fertility. Humus is the end-product of the microbial decomposition of vegetable or animal organic matter deposited on or in soil. This process is essential for the well-being of soil. It results in a product of relatively uniform C:N ratio which has important physico-chemical properties. The quantity of soil humus depends on the farming system practised, on soil type and climate. For any one husbandry system heavier textured, clayey soils contain more humus than light textured, sandy soils. The humus content for any combination of soil and farming system tends towards an equilibrium value and so there is no universal critical value for humus content. In temperate climates the rate of change is slow and long-term experiments are usually needed to estimate the effects of humus on yields of arable crops. Increased yields on soils with more humus have been measured in recent years especially for spring sown crops with a high yield potential. A number of factors, including better soil structure, water holding capacity and availability of nutrients can contribute to these beneficial effects. Crop quality can be affected through interactions effecting the availability of both nutrients and pollutants.

Besides benefits, there can be problems. When farmed in accordance with good farm practice, mineralization of organic matter is the major source of nitrate at risk to loss by leaching. Humus can retain and affect the availability of some pollutants like cadmium and low molecular weight organic molecules appear to be implicated in the movement of phosphorus downwards through the soil profile. But there is no way in which we could farm without humus.

The many complex interactions between soil and mineral particles, added organic matter, humus, microbial activity, and transport processes are, as yet, not fully understood. But such understanding is crucial in seeking ways to minimize the risk of pollutants moving through soil to water used for human consumption. A knowledge of the role of humus in transport processes is only one part of the story, but a very important one because soil organic matter is crucial to crop production.

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