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THE TURNOVER OF SOIL ORGANIC MATTER IN SOME OF THE ROTHAMSTED CLASSICAL EXPERIMENTS

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ABSTRACT

Data are assembled from the Rothamsted classical field experiments on the effects of long-continued cropping and manuring on the amount of organic matter in soil, on the age of this soil organic matter, on the amount of microbial biomass in the soil, and on the rate at which plant residues decompose in these soils. These data were then fitted to a model in which soil organic matter was separated into five compartments: decomposable plant material (DPM, half-life 0.165 years); resistant plant material (RPM, 2.31 years); soil biomass (BIO, 1.69 years); physically stabilized organic matter (POM, 49.5 years) and chemically stabilized organic matter (COM, 1980 years). For unitary input of plant material (1 t fresh plant C ha^{-1} year^{-1}) under steady-state conditions, after 10,000 years, the model predicts that the soil will contain 0.01 t C in DPM, 0.47 t in RPM, 0.28 t in BIO, 11.3 t in POM, and 12.2 t in COM. The predicted radiocarbon age is 1240 years (equivalent age). The fit between predicted and measured data is sufficiently good to suggest that the model is a useful representation of the turnover of organic matter in cropped soils.

INTRODUCTION

The annual input of organic carbon into soil carrying cereals is of the order of 1-2 t ha^{-1}, with grassland receiving perhaps twice as much. In the long run, all this organic matter is decomposed, no fraction being completely resistant to decay. This process, in which losses and gains proceed simultaneously, is described as turnover and may be defined as the flux of organic C through a given volume of soil. Turnover time is then the amount of C in a soil system when equilibrium has been reached, divided by the annual input of C into that system.

The Rothamsted classical field experiments, in which crops are grown, usually in monoculture, year after year on the same soils with the same manuring, provide unique material for turnover studies. Soil analyses go back 100 years and, in some of the experiments, cropping and manuring have been virtually continuous for even longer.

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This paper is an attempt to construct a model that collates the data assembled over the years on the turnover of organic matter in soils from some of the Rothamsted classical experiments. Although the paper is exclusively concerned with Rothamsted soils and Rothamsted experiments, our aim is to use the Rothamsted data to develop an approach that will have application to other soils and environments.

THE DATA

The data used in this paper come from five main sources: (a) from long-term changes in the amounts of organic matter in soils from certain of the classical experiments, giving information over the 10–100 year time scale; (b) from incubation experiments on the decomposition of ^{14}C-labelled plant material in soils, giving information over the 1–10 year period; (c) from radiocarbon dating, over the thousand year period; (d) from the effect of thermonuclear radiocarbon on radiocarbon age (the 'bomb effect'), giving information on the annual input of organic matter, and finally (e) some new and rather fragmentary data on the amounts of biomass in soils from the classical experiments.

(a) Changes in the amount of organic matter in soils of the classical experiments

The Hoosfield Continuous Barley Experiment, started in 1852, tests the effects of a wide range of manurial treatments including farmyard manure (FYM) on the growth of spring barley. The manurial treatments are repeated annually and barley has been grown every year, with the exception of 4 years when the whole field was fallowed to control weeds. Figure 1 shows the changes that have occurred in the C contents of the soil in three of the plots. The plot receiving FYM has gained C steadily and has still not reached equilibrium after 120 years. The organic content of the unmanured plot has remained unchanged over the last 100 years (incidentally at a level not significantly different from that in the plot receiving complete inorganic fertilizers annually). The plot that received FYM annually over the 20 years 1852–1871 (but nothing since) still contains more organic C and N than the plot that has been unmanured throughout, even though more than 100 years have elapsed since the last application of FYM.

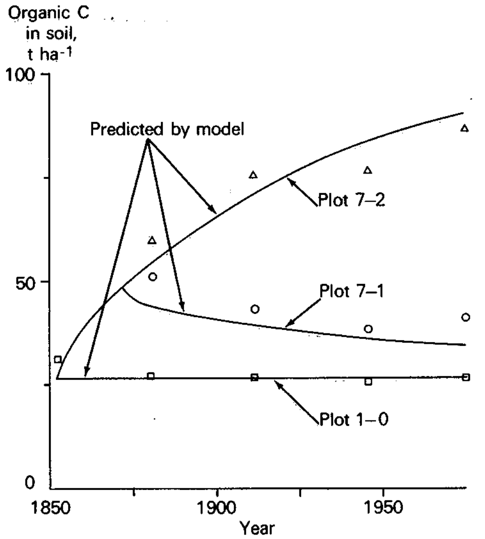

FIG. 1. Organic C in the top 23 cm of a Rothamsted soil under continuous barley (Hoosfield; see Jenkinson and Johnston 1977). The results are adjusted for changes in soil bulk density. Plot 1-0 is unmanured; plot 7-2 receives 35 t FYM ha^{-1} annually (containing 3.0 t C and 0.225 t N); plot 7-1 received 35 t FYM annually between 1852 and 1871 and nothing since. Experimental results are shown by △, ○, or □; the continuous lines are as predicted by the model.

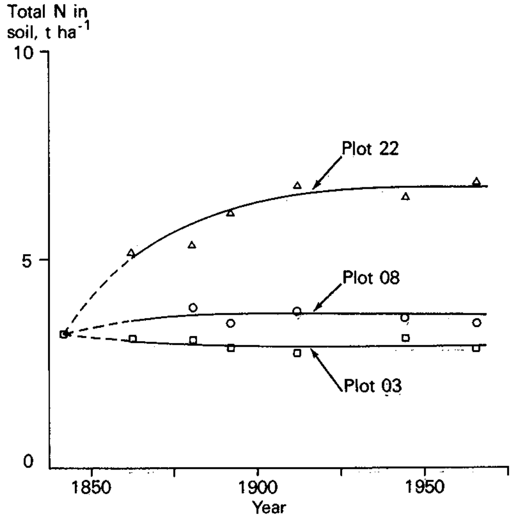

FIG. 2. Total N in the top 23 cm of a Rothamsted soil under continuous wheat (Broadbalk; see Jenkinson 1977a). Calculated from Johnston (1969; Table 5.10) allowing for changes in soil bulk density. Plot 22 receives 35 t FYM ha^{-1} annually; plot 03 is unmanured; plot 08 receives 144 kg N, 35 kg P, and 90 kg K ha^{-1} annually.

Similar data are available for the Broadbalk Continuous Wheat Experiment, started in 1843, which has carried winter wheat on at least part of the field every year since then. Figure 2 shows the changes that have occurred in the total N content of topsoil from three of the plots—that receiving FYM annually, one of those receiving NPK annually, and the unmanured plot. With minor exceptions, the results are similar to those from the Hoosfield Continuous Barley Experiment. In Broadbalk, the plot receiving inorganic fertilizers accumulated a little more soil organic matter than the unmanured plot, in contrast to Hoosfield, where there was no such difference. Recently the rate of accumulation of organic matter by the FYM plot has been greater in Hoosfield than in Broadbalk, probably because Broadbalk has been more frequently fallowed than Hoosfield.

The Rothamsted Drain Gauges, located on the same soil series as Broadbalk and Hoosfield, are 4 m^2 monoliths of undisturbed soil, constructed in 1870 on land that had previously

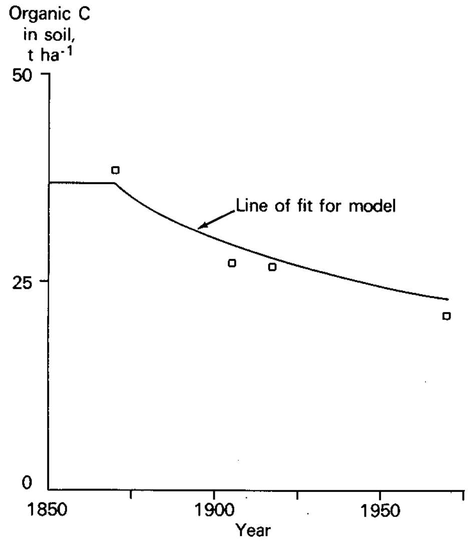

FIG. 3. Organic C in the top 23 cm of a Rothamsted soil kept bare since 1870. (Drain Gauges.)

been arable for many years. Since then they have been kept bare by hand weeding and thus provide information on the rate of decay of organic matter in bare uncultivated soil. Figure 3 shows that under these conditions the soil still retained more than half its original C after 100 years.

(b) The decay of plant material in Rothamsted soil

By incorporating ^{14}C-labelled plant material in soil, it is possible to follow the loss of C from a given addition of plant material for many years under field conditions. Figure 4 shows the rate at which uniformly labelled ryegrass decayed in soil taken from various plots on the classical fields. The experiments were done in small outdoor lysimeters set into the soil. About two-thirds of the plant C was lost in the first year but thereafter the rate of loss became less, so that after 10 years about one-eighth still remained in the soil. These experiments showed that a small fraction of the plant-derived C possessed great stability even though the original material, cut just before flowering, was green and succulent. The proportion of the added ryegrass decomposed by a given time was also found to be almost independent of the amount of plant material decomposed.

(c) Radiocarbon dating of soil organic matter

Table 1 shows the equivalent age of the organic matter down the profile on the unmanured plot on Broadbalk. The samples were taken in 1881, almost 40 years after the experiment started, and had been stored air-dry since then in sealed bottles. Despite adequate aeration, a near neutral pH, a moisture regime favouring microbial activity over much of the year, and a mean monthly soil temperature that varies from 3°C in January to 16°C in July, much of the organic matter in this profile is of great age. Similar ages have been measured on old arable soils from other parts of the Rothamsted farm, so that chance contaminants are unlikely to account for this old material. There was too little C present in the 0-23 cm horizon as coal and charcoal (1.4 percent of the total organic C) to have contributed appreciably to the radiocarbon age.

There is evidence that the C in soil can be separated into fractions of very different age. A fraction that it is safe to assume is very young can be separated by Greenland and Ford's (1964) procedure and consists of roots and other discrete pieces of plants. Soil sampled from the

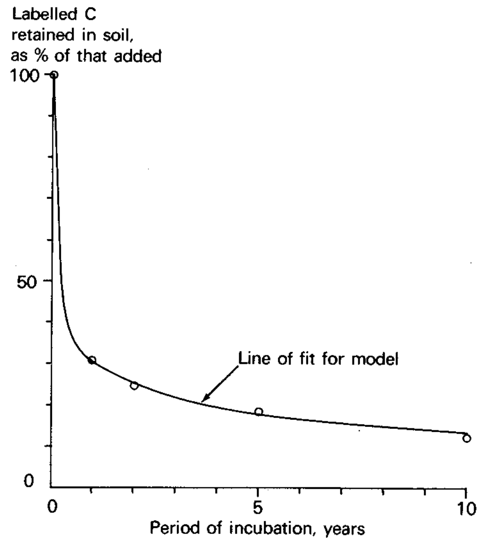

FIG. 4. Decomposition of uniformly labelled ryegrass incubated with soil in the field (Jenkinson 1977b; mean of results from incubation with five different Rothamsted soils).

TABLE 1

*Radiocarbon age of organic matter in soil collected in 1881 from the unmanured plot (03) of Broadbalk**

Sampling depth cm	Organic C %	Equivalent age years†
0–23	0.94	1450
23–46	0.61	2000
46–69	0.47	3700

* From Jenkinson, 1969.

† The equivalent age is defined as the age of a homogeneous sample with the same value of $\delta\,^{14}C$ as that of the (heterogeneous) soil sample analysed.

TABLE 2

*Radiocarbon age of fractions of soil organic matter separated by hydrolysis with 6 M HCl under reflux**

	Decalcified soil	Hydro-lysate	Residue from hydrolysis
% total soil organic C in fraction	100	35	35
Equivalent age, years	1450	515	2560

* The soil was from the unmanured plot (03) of Broadbalk, sampled (0–23 cm) in 1881 (Jenkinson 1971).

0-23 cm horizon of the unmanured plot on Broadbalk in 1881 (see Table 1) contained 1.2 percent of its organic C in this form. Part of the same sample fractionated by hydrolysis with 6 M HCl under reflux gave a young hydrolysed fraction and left a residue of 35 percent of the total organic C with an equivalent age of 2560 years (Table 2).

(d) The amount of organic matter entering the soil each year

The radiocarbon ages given in Table 1 were measured in samples collected in 1881 because thermonuclear tests have caused the radiocarbon ages of biologically-active soils to decrease. Figure 5 shows that by 1969 the radiocarbon age of post-bomb samples from the unmanured plot on Broadbalk had fallen to less than half that of the pre-bomb samples—the 'bomb effect.' Thermonuclear explosions release neutrons, which react with nitrogen in the air to produce ^{14}C. This is oxidized to $^{14}CO_2$, which mixes with the naturally produced $^{14}CO_2$ in the atmosphere. It then enters green plants and subsequently soil organic matter.

The 'bomb effect' can be used to calculate the amount of organic matter entering a soil each year. To do this, not only must the pre- and post-bomb ages of the soil C be known, but the soil must have been under steady-state conditions during the period between pre- and post-bomb samplings. Figure 2 shows that there has been little change in the total N content (and hence in the organic C content, which mirrors the total N content closely) of plots 03 and 08 of Broadbalk since 1881. The specific activity of the plant C entering the soil each year must

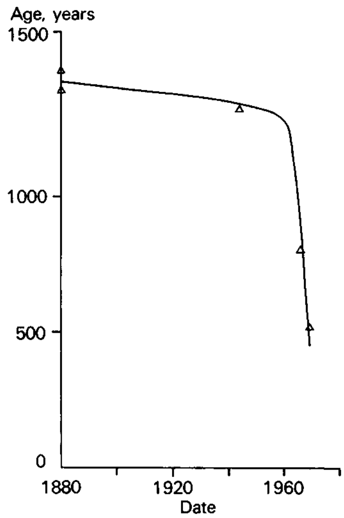

FIG. 5. Equivalent radiocarbon age of soil organic C before and after thermonuclear testing.

TABLE 3

Fresh organic C entering the soil each year in two plots of the Broadbalk continuous wheat experiment

Plot and treatment	Organic C, t ha^{-1}			
	Total to a depth of 23 cm	Entering the top 23 cm of soil each year	Harvested in crop (grain plus straw) each year	Gross turnover time (years)
Unmanured (plot 03)	26	1.2	1.4	22
Inorganic fertilizers (plot 08)	30	1.9	3.2	16

also be known. This can be found (for annual crops) from data on the amount of radiocarbon in the Northern Hemisphere over the past decades (Nydal and Lövseth 1970): the specific activity of the pre-1955 annual input is assumed to be constant. The amount of C remaining in the soil from plant additions made 1, 2, 3, . . . years previously must be known as well. This can be obtained for Rothamsted conditions from the experiments on the decomposition of labelled ryegrass (Fig. 4), assuming that the labelled ryegrass decomposes like the plant material actually entering the soil in the field.

Table 3 shows the results of such calculations for two of the plots on Broadbalk – the unmanured plot (03) and one of the plots (08) receiving inorganic fertilizers. The annual inputs amount to 5 to 6 percent of the total organic C in the soil and the gross turnover times are correspondingly short, 16 years for the plot receiving inorganic fertilizers and 22 years for the unfertilized plot.

(e) The amounts of biomass in soils from the classical experiments

During the development of a method for the measurement of soil biomass, a few values were obtained for the proportion of the total soil organic C in the biomasses of soils from the Rothamsted classical experiments. These are given in Table 4. Information on the amount of biomass formed when a single addition of plant material decomposes in soil can be obtained from earlier work on the decomposition of labelled ryegrass in Broadbalk soils (Table 5).

TABLE 4

*The biomass content of Broadbalk soils**

Plot and treatment	Biomass: Continuous wheat		Biomass: Continuous wheat, then fallow 1 year	
	kg C ha^{-1}	As % total soil organic C	kg C ha^{-1}	As % total soil organic C
Unmanured (plot 03)	530	2.0	440	2.0
Inorganic fertilizers (plot 08)	590	2.0	520	2.0
FYM (plot 22)	1160	1.9	840	1.7

* From Jenkinson and Powlson 1976; measurements made in July.

TABLE 5

*Biomass remaining from a single addition of plant material to soil from Broadbalk**

Period after addition, years	C in biomass, as % plant C originally added
0	0
1	6.3
2	4.0
3	2.8
4	2.3

* From Jenkinson 1966; mean of all experiments, combining all soils and all plant materials and using a k factor of 0.5, not 0.3 as in the original paper.

THE MODEL

The model chosen for this paper attempts to simulate the behaviour of soil organic matter by dividing it into fractions for which, as far as possible, there is evidence that is independent of the data to be fitted. Each of these fractions is then assumed behave as though it contained a single species undergoing biological decomposition by a first-order process. The priming action is assumed to be zero and the proportion of a given addition decomposed after a given time assumed to be independent of the amount added.

The first two of the five fractions needed (called *decomposable plant material* – DPM, and *resistant plant material* – RPM) represent plant C added yearly (in proportion P_D and P_R) from crops or FYM. Incoming plant C passes through these two compartments only once and any added organic C is assumed to belong to one or the other. When any of the five fractions decomposes, it is assumed to decay to the same products; carbon dioxide (lost from the systems), biomass (BIO), and two fractions of slowly decomposable organic matter – physically stabilized organic matter (POM) and chemically stabilized organic matter (COM). For simplicity, a successful biological attack is taken to yield these products in the same proportions (P_B, P_P, P_C) irrespective of which fraction is undergoing attack. If D_0 is the content of DPM in the soil at the beginning of the year (say, just after the annual addition) and D_1 is the content at the end of the year, just before the next addition, then $D_1/D_0 = e^{-k_D} = d$, and similarly for the other compartments. In developing the model it was found convenient to convert the parameters into a transition matrix that converts the soil state (that is, the proportions of the fractions) at the beginning of the year to that at the end. This assumes that decomposition products cannot decay again until the next year. Mean ages for the compartments are also calculated by carrying forward products of proportion and mean ages; similarly for mean radiocarbon ages.

$$T = \begin{bmatrix} d & 0 & P_B(1-d) & P_P(1-d) & P_C(1-d) \\ 0 & r & P_B(1-r) & P_P(1-r) & P_C(1-r) \\ 0 & 0 & b + P_B(1-b) & P_P(1-b) & P_C(1-b) \\ 0 & 0 & P_B(1-p) & p + P_P(1-p) & P_C(1-p) \\ 0 & 0 & P_B(1-c) & P_P(1-c) & c + P_C(1-c) \end{bmatrix}$$

STRUCTURE OF TRANSITION MATRIX

The model was fitted to the 10-year incubation data (Fig. 4) using a maximum-likelihood programme (MLP) developed by Ross (1975) that allows fitting of up to four parameters at a time. The remainder of the data was fitted by trial, by calculating the results of arbitrary changes in the parameters. Steady-state conditions are assumed to have been reached by 10,000 years as the longest half-life used in the model is just under 2,000 years.

The model (Fig. 6) finally adopted has:

Proportion: $P_D = 0.837, P_R = 0.163, P_B = 0.076, P_P = 0.125, P_C = 0.0035$

e^{-k}: $d = 0.015, r = 0.741, b = 0.664, p = 0.986, c = 0.99965$

Rate constant, years^{-1}: $k_D = 4.2, k_R = 0.3, k_B = 0.41, k_P = 0.014, k_C = 0.00035$

Half-life, years: $t_D = 0.165, t_R = 2.31, t_B = 1.69, t_P = 49.5, t_C = 1980.$

For an annual input of 1 t C ha^{-1} year^{-1} into the top 23 cm of soil, the model predicts that, at the end of the 10,000th year, the soil would contain 24.2 t organic C ha^{-1}, of which 0.01 t is in DPM, 0.47 t in RPM, 0.28 t in BIO, 11.3 t in POM, and 12.2 t in COM. The equivalent radiocarbon age of all the organic C in the soil would be 1,240 years (true mean age 1,330 years), of the C in DPM 1 year, of RPM 3.9 years, of BIO 25.9 years, of POM 94.8 years and of COM 2,565 years.

AGREEMENT BETWEEN MODEL AND DATA

Assuming that the unmanured plot on Broadbalk is under steady-state conditions, with an annual input of 1.2 t C ha^{-1} year^{-1} (Table 3), the total amount of C in the top 23 cm of soil is 29 tons, of the same order as that observed (26 tons; Table 3). Agreement is poorer in the plot receiving inorganic fertilizers (input 1.9 ons; Table 3): a predicted value of 46 t, compared to an observed value of 30 t. The model predicts biomass contents of 0.34 and 0.53 t C ha^{-1} for the unmanured and inorganically fertilized plots, respectively, both slightly less than those measured for soil under continuous wheat (Table 4).

The predicted amount of RPM (0.56 t C ha^{-1} for the unmanured plot in Broadbalk) is about twice that measured (0.31 t C ha^{-1}, taking the noncarbonized part of Greenland and Ford's light fraction to be the RPM). However, the input of roots varies throughout the year and in consequence the time of sampling will markedly influence the results obtained for RPM (and likewise the other fractions of short half-life, BIO and DPM). The present model does not take annual fluctuations into account.

The equivalent radiocarbon age of all the organic C in the soil (1,240 years) is of the same order as that observed (1,450 years). This coincidence is hardly surprising as the POM and COM parameters were adjusted to bring this about. The agreement could be made even

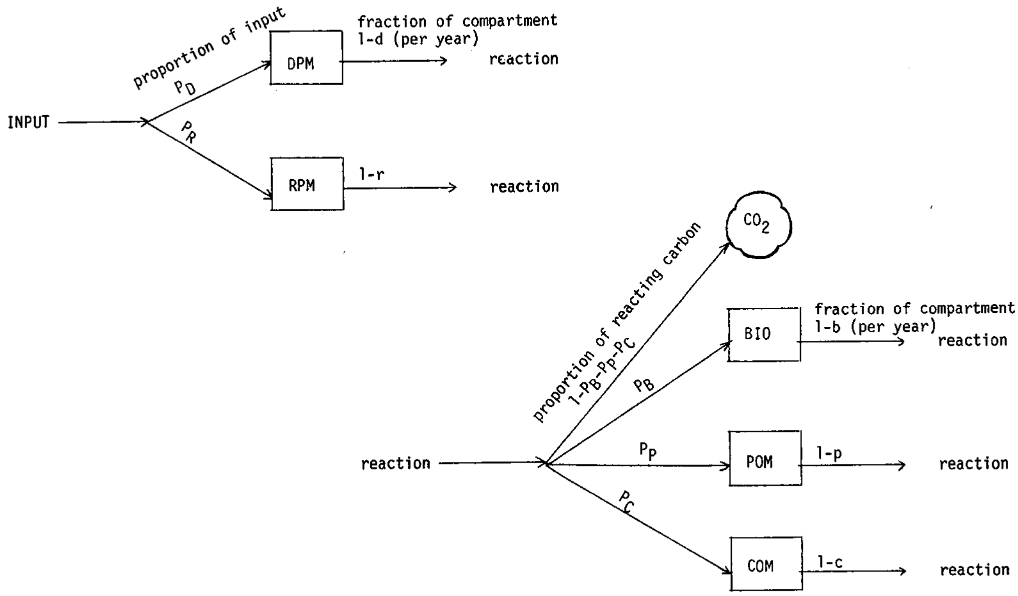

FIG. 6. Flow of C through model from unitary input of plant C into the 0–23 cm layer of soil.

closer by further adjustments, at the cost, however, of a poorer fit to the data in Fig. 3. This does not seem worthwhile, bearing in mind the uncertainties involved in assuming that steady-state conditions hold for fractions of half-life 2,000 years, a span that goes back to the period when the Rothamsted soils are thought to have been first cleared for crops.

The great age predicted for the soil biomass (25.9 years), compared to the half-life (1.69 years) arises because much of the C entering the biomass each year comes from material that has already been in the soil for a long time. The model also predicts a wide range of ages in soil organic matter, ranging from 2,565 years to virtually zero. This prediction is consistent with the age heterogeneity demonstrated in Table 2, although of course fractions separated chemically as in Table 2 cannot be directly equated with fractions of different biological stability such as the POM and COM fractions of the model.

Predictions from the model are shown in Figs. 1, 3, and 4. Only Fig. 1 provides an independent test of the validity of the model, the other two having been used either directly or indirectly to set the model parameters. The model has some rigidity that prevents it passing exactly through the five experimental points in Fig. 4, although it is in another sense overfitted in that the points can be approached more closely than their estimated standard errors. In fitting the drain gauge results (Fig. 3) it was assumed that the soil had attained steady-state conditions in 1870, with an annual input of 1.5 t ha^{-1} year^{-1}, rather more than that for Broadbalk (1.2 t). This assumed input is consistent with the greater C content of the drain gauge soil.

In fitting the Hoosfield data, the unmanured land was assumed to be under steady-state conditions, with an annual input of 1.1 t C ha^{-1} year^{-1}; the plot that had once received FYM to have had an annual input of 1.1 t C ha^{-1} year^{-1} since 1872 and the plot receiving FYM to have an annual input of 7.5 t C ha^{-1} year^{-1} (1.5 t from roots and 6.0 t as the original plant C content of the FYM, assuming that 50 percent of C had been lost by the time the FYM was applied). The fit is good enough (Fig. 1) to suggest that the POM parameters are not grossly in error but the data cover too short a span to provide a critical test for the COM parameters.

By and large, the proposed model is not at serious variance with the experimental data. The major assumption that five factors are sufficient to model the decomposition of plant residues in soil is unlikely to be true, but it seems pointless to postulate a more complex model until we have data that are irreconcilable with the five-factor model. This also holds for the assumption that all fractions decompose alike, giving CO_2, BIO, POM, and COM in the same ratios. Three of the fractions correspond fairly closely with real entities: DPM is the readily decomposable parts of the plant; RPM the resistant lignified plant structures, and BIO the living part of the soil organic matter. In contrast to these three, POM and COM are fractions postulated to explain the data – POM the intermediate 10-100 year data and COM to account for the radiocarbon ages. Organic matter is undoubtably stabilized by physical processes – the protective action of clay is an illustration. The stability of ash-free aqueous dispersions of humic acid to biological attack shows that chemical structure also plays a role in stabilizing soil organic matter. However, the identification of physically stabilized material with the fractions of intermediate stability (POM) is merely a working hypothesis, a hypothesis that moreover is neither proved nor disproved by the concordance observed between data and model in this paper. In all probability there will be a continuum of materials, with physically protected but otherwise decomposable materials at one end and free organic matter that is highly resistant to biological attack at the other.

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