

Inert Organic Matter (IOM) in the Rothamsted Soil-Carbon Turnover Model: Analytical Solutions

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Abstract: In the Rothamsted soil-carbon turnover model, the inert organic matter (IOM) pool represents a soil carbon (C) pool of great age and is used to reconcile the annual inputs of C with the measured quantity of organic matter and radiocarbon (^{14}C) in the soil. Thermonuclear 'bomb' ^{14}C data are used indirectly in the model to estimate the size of the IOM pool by a numerically iterative process. In this paper, analytical solutions of the Rothamsted soil-carbon turnover model are derived that allow the expression of IOM and annual inputs in terms of total C and ^{14}C data. The analytical solution simplifies the calculation of IOM, and more importantly, allows the interpretation of the IOM pool in relation to the model assumptions.

Keywords: Rothamsted soil-carbon turnover models; Inert Organic Matter; ^{14}C ; Thermonuclear 'bomb' ^{14}C

1. INTRODUCTION

The Rothamsted soil-carbon turnover model has been used widely to simulate changes in soil organic matter on a variety of soil types and land-uses [Coleman et al., 1997] including arable, grassland and forestry. It has been used to estimate ecosystem net primary productivity [Jenkinson et al., 1992] and CO_2 fluxes at regional [Parshotam et al., 1995], national [Tate et al., 1996] and global scales [Jenkinson et al., 1991]. The model has provided useful insights into the processes for stabilising organic matter.

In the Rothamsted model, the concept of the inert organic matter (IOM) fraction is introduced to enable the model to fit pre-bomb (<1960s) ^{14}C data, and to deal with the much greater soil (and soil biomass) ^{14}C ages than would be expected from calculations based on rates of SOM accumulation and plant residue inputs [Jenkinson, 1990]. As such, the need to postulate an IOM compartment is one of the least satisfactory features of the current model [Jenkinson et al., 1987]. Marked variations in the size of the IOM pool in soils, between and within sites [e.g. Tate et al., 1995], are a major source of error in calculating carbon inputs to soil. In studying the effect of climate and land-use change on soil C turnover, the size of the IOM fraction has been arbitrarily defined [e.g. Jenkinson et al., 1991; Tate et al., 1996; Parshotam et al., 1995], equated to zero [e.g. Post et al., 1995], or excluded (e.g. Wang and Polglase, 1995). At present, no method

exists to assess whether model estimates for IOM are even realistic.

The Rothamsted SOM model is perhaps the only SOM model in current use that estimates the size of inert organic matter carbon (IOM-C) from bomb ^{14}C in topsoil and a knowledge of soil organic matter turnover and may therefore also be considered to be an IOM-C model. Although not essential for the use of the Rothamsted model, measurements of 'bomb' ^{14}C in soil profiles can be used to estimate the IOM fraction indirectly by using an iterative process [Jenkinson et al., 1992], which can be tedious. Statistical relationships based on modelling paired bomb ^{14}C measurements have been developed to estimate IOM-C [Falloon et al., 1998]. These have been based on numerous computer runs that match modelled plant input rates and IOM to measured total C and $\Delta^{14}\text{C}$.

In this work, IOM-C and plant inputs are expressed exactly in terms of total soil organic carbon and bomb ^{14}C , for a given site. The formulation of the part of the model used to calculate IOM-C is currently unpublished.

2. MODEL ASSUMPTIONS

The current model assumes five major pools (see Figure 1): decomposable plant material (DPM); resistant plant material (RPM); microbial biomass (BIO); humified organic matter (HUM); and inert organic matter (IOM). Apart from the IOM

fraction, each fraction is homogeneous and decomposes exponentially. The IOM fraction is not subject to biological transformation and is therefore constant. Addition of plant carbon from plant residues is represented by the DPM and RPM fractions; the quality or decomposability of these additions is given by a DPM : RPM ratio. Organic carbon inputs are assumed to enter the DPM and the RPM pool, which decomposes to form CO₂, microbial biomass and humified organic matter. When substrate C is metabolised by the biomass, a fraction α is incorporated into the microbial biomass compartment, a fraction β enters the humus compartment, and the rest is liberated as CO₂. The current model is a modification of an earlier version [Jenkinson and Rayner, 1977] in which the 'chemically stabilised organic matter' (COM) fraction is replaced by the small, 'inert organic matter' (IOM) fraction that is given an arbitrary age of 50 000 years, i.e. both its ¹⁴C content and decay rate constant were effectively set to zero. This inert fraction is assumed to be uniformly distributed throughout the soil profile as proposed by O'Brien and Stout [1978], and to have been present in the soil before modern soil-forming processes began 10 000 years ago [Hart, 1984].

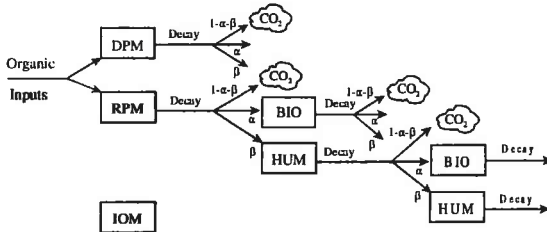


Figure 1. The Rothamsted soil-carbon turnover model.

3. MODEL EQUATIONS

The current model [Jenkinson et al., 1987], is formulated as a system of discrete sums of exponentials. In this form, new organic matter is assumed to enter the soil as discrete pulses P_{dpm} and P_{rpm} at the beginning of a sampling time interval, and all processes are discontinuous. A balance of exponential terms is performed for each compartment in discrete time intervals, and this results in a system of difference equations with matrix coefficients given by sums of exponentials. Transition matrices convert the quantity of organic matter in each compartment at the beginning of a time interval to the end of this time interval. The model equations are given by:

$$\begin{pmatrix} DPM[(n+1)T] \\ RPM[(n+1)T] \\ BIO[(n+1)T] \\ HUM[(n+1)T] \end{pmatrix} = \mathfrak{S} \begin{pmatrix} DPM[nT] \\ RPM[nT] \\ BIO[nT] \\ HUM[nT] \end{pmatrix} + \begin{pmatrix} P_{dpm}[nT] \\ P_{rpm}[nT] \\ 0 \\ 0 \end{pmatrix} \quad (1)$$

with the initial conditions

$$\begin{pmatrix} DPM[0] \\ RPM[0] \\ BIO[0] \\ HUM[0] \end{pmatrix} = \begin{pmatrix} DPM_0 \\ RPM_0 \\ BIO_0 \\ HUM_0 \end{pmatrix}, \quad (2)$$

where n is a positive integer and T is the sampling time interval. \mathfrak{S} is the decomposition transition matrix, which may be expressed as $\mathfrak{S} = \Lambda + (I_4 - \Lambda)e^{Dt}$, where I_4 is the 4x4 identity matrix, $D = \text{diag}(-k_{dpm}, -k_{rpm}, -k_{bio}, -k_{hum})$,

$$\Lambda = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \alpha & \alpha & \alpha & \alpha \\ \beta & \beta & \beta & \beta \end{pmatrix}, \quad (3)$$

and k_{dpm} , k_{rpm} , k_{bio} and k_{hum} are exponential-decay rate constants for DPM, RPM, BIO and HUM, respectively. The fractions α and β are empirically determined functions of clay percent. The model time step, T is monthly. In the current model, rate constants are multiplied by rate-modifying factors, which are empirically determined functions of temperature, moisture, evaporation and a plant retention factor if growing plants are present. Steady-state solutions are found by arbitrarily computing for 10 000 years [Jenkinson, 1990].

The same method of matrix calculation is used when calculating ¹⁴C activities and, hence, ¹⁴C ages and $\Delta^{14}C$. Amounts of radioactivity in the compartments are represented in a vector where monthly radioactivity transition matrices carry out the same transfers of C from compartment to compartment as for the decomposition transition matrix, but also allow for the loss of radioactivity during a time period. This monthly radioactivity transition matrix is given by

$$\mathfrak{S}_a = \mathfrak{S} e^{-\frac{\ln 2}{12\tau_a}}, \quad (4)$$

where $\tau_a=5600$ years is an approximation to the conventional half life of ¹⁴C. New plant inputs into the system have a specific activity that corresponds to the atmospheric specific activity in that year. Each 'cohort' of plant material entering the soil

maintains its specific activity as it decomposes, i.e., there is no isotopic discrimination. Nor is there any isotopic exchange between cohorts entering the soil at different times. Before 1860, the model assumes that the ^{14}C age of the plant material entering the soil each year is zero, i.e. its $\Delta^{14}\text{C}$ value is zero and it is 100% modern. After 1860, the ^{14}C content of the incoming plant carbon (expressed as % modern (pM)) in a particular year is given from data on the ^{14}C content of atmospheric CO_2 from literature with either bomb or Seuss effects (i.e. ^{14}C dilution by fossil fuel). Plant inputs are multiplied by a 'radioactive scaling factor', s . This scaling factor is the ^{14}C activity of the input for a particular year, expressed as either pM/100 or $(\Delta^{14}\text{C} + 1000)/1000$, so that the value for 1859 is 1. The ^{14}C activity vector is therefore given by

$$\begin{pmatrix} \text{DPM}_a[(n+1)T] \\ \text{RPM}_a[(n+1)T] \\ \text{BIO}_a[(n+1)T] \\ \text{HUM}_a[(n+1)T] \end{pmatrix} = \mathfrak{S}_a \begin{pmatrix} \text{DPM}_a[nT] \\ \text{RPM}_a[nT] \\ \text{BIO}_a[nT] \\ \text{HUM}_a[nT] \end{pmatrix} + s[nT] \begin{pmatrix} P_{\text{dpm}}[nT] \\ P_{\text{rpm}}[nT] \\ 0 \\ 0 \end{pmatrix} \quad (5)$$

with the initial conditions

$$\begin{pmatrix} \text{DPM}_a[0] \\ \text{RPM}_a[0] \\ \text{BIO}_a[0] \\ \text{HUM}_a[0] \end{pmatrix} = \begin{pmatrix} \text{DPM}_{a0} \\ \text{RPM}_{a0} \\ \text{BIO}_{a0} \\ \text{HUM}_{a0} \end{pmatrix} \quad (6)$$

For convenience, \mathbf{C} and \mathbf{a} are denoted as the soil carbon content and ^{14}C activity vectors, respectively. These vectors have the components C_i and a_i for $i=1, 2, \dots, 4$, so that C_{DPM} or C_1 , for example, denotes carbon content in the DPM compartment. C_{IOM} , C_5 or simply IOM shall denote IOM-C. At any time, a comparison of the mass vector in Equation (1) with the corresponding radioactivity vector in Equation (5) gives the following mean ^{14}C age for each compartment [Hart, 1984]

$$t_i = \frac{1}{\lambda} \ln\left(\frac{C_i}{a_i}\right), \quad (7)$$

where C_i is the total amount of organic C in compartment, i (t ha^{-1} down to 23 cm); a_i is the total ^{14}C activity of organic C in the compartment, i ; t_i is the ^{14}C age of the compartment, i (in years), and λ is given by $(\ln 2)/\tau_a$. The average ^{14}C age t_{av} for all pools is given by Hart [1984]:

$$t_{\text{av}} = \frac{1}{\lambda} \ln\left(\frac{C_{\text{TOT}}}{a_{\text{TOT}}}\right) \quad (8)$$

where

$$C_{\text{TOT}} = \sum_i C_i \quad (9)$$

is the total soil C in all compartments and

$$a_{\text{TOT}} = \sum_i a_i \quad (10)$$

is the total sum of ^{14}C activity in all compartments. A mean value of $\Delta^{14}\text{C}_i$ for each compartment is obtained at any time from the mean $\Delta^{14}\text{C}$ age, t_i , using

$$\Delta^{14}\text{C}_i = (e^{-\lambda t_i} - 1) \times 1000 \text{‰}, \quad (11)$$

so that the average $\Delta^{14}\text{C}_{\text{av}}$ for all compartments is related to the ^{14}C age in the model by the following:

$$\Delta^{14}\text{C}_{\text{av}} = (e^{-\lambda t_{\text{av}}} - 1) \times 1000 \text{‰}. \quad (12)$$

The age of the IOM compartment was set to 50 000 years ~ 9 half lives, i.e. both its ^{14}C and decay rate constant were effectively set to zero. This implies that it contains virtually no ^{14}C (i.e. $\Delta^{14}\text{C} = -998.02 \text{‰}$) and is of a geological rather than a pedological age [Coleman and Jenkinson, 1995].

Inputs to the model are meteorological data (temperature ($^{\circ}\text{C}$), rainfall (mm), evaporation (mm)), soil clay percent, plant residue inputs, DPM:RPM ratio (which depends on the vegetation type), FYM (farm yard manure), if any, and a soil cover factor. The initial soil state and ^{14}C age of a compartment are required, and initial ^{14}C activities are calculated from Equation (7). These initial conditions are arbitrarily defined for long-term runs (10 000 years). Inputs (e.g. from cropping and harvesting practices) may often vary throughout the year. It is assumed that this method of adding inputs makes little difference to the calculated equilibrium value for total organic C or to ^{14}C age, and only if the model is used to predict annual changes in fractions with short turnover times (such as the BIO and the DPM compartments) will the temporal distribution of inputs appreciably affect the results [Coleman and Jenkinson, 1995].

To illustrate the use of the model, suppose that data from a long-term field trial are to be modelled. The

data available are total soil C, ^{14}C age of the soil organic matter when the experiment was first started, and data of short-term management treatments that follow, such as measured inputs from FYM and plant residues. It is first necessary to run the model to produce a starting soil organic C content the same as that originally present in the soil. This is done by assuming that the total soil organic C has reached equilibrium in this year and by running the model iteratively with different annual inputs of plant C and IOM until the value of this measured total C and $\Delta^{14}\text{C}$ is reached. From measurements of ^{14}C , the IOM content of the soil and the annual inputs of plant C may be iteratively adjusted to give both the correct organic C content and the correct ^{14}C age for a particular sampling date. The equilibrium solution is used as an initial condition for short-term runs. Several shorter term runs may follow where inputs could vary from changes in land management practices (e.g. by continuous cropping for many years). The estimated IOM is assumed to be a constant throughout these runs. IOM may be estimated from ^{14}C data at any point in time and not necessarily at the same time that the initial total soil carbon was sampled.

4. RESULTS AND DISCUSSION

An analytical solution is obtained for IOM and plant input I , in terms of measured total carbon, \hat{C}_{TOT} at steady state and measured ^{14}C enrichment, $\Delta^{14}\text{C}_{av}$.

The model equations (1) and (5) may be expressed in the form:

$$\mathbf{C}[(n+1)T] = \mathfrak{S}\mathbf{C}[nT] + \mathbf{u}, \quad \mathbf{C}(0) = \mathbf{C}_0 \quad (13)$$

$$\mathbf{a}[(n+1)T] = \mathfrak{S}_a\mathbf{a}[nT] + s[nT]\mathbf{u}, \quad \mathbf{a}(0) = \mathbf{a}_0 \quad (14)$$

The radioactivity vector \mathbf{a} and the carbon content vector \mathbf{C} are uncoupled and have the similar source term \mathbf{u} . The transition matrices \mathfrak{S} and \mathfrak{S}_a , are related to each other by the difference of a constant matrix. The plant input vector \mathbf{u} is given by

$$\mathbf{u} = \mathbf{w}I \quad (15)$$

where, I is the annual rate of organic inputs and

$$\mathbf{w} = \begin{pmatrix} \kappa \\ 1 - \kappa \\ 0 \\ 0 \end{pmatrix}, \quad (16)$$

where κ is the fraction of plant input, I , which is DPM (so that $1 - \kappa$ will be the remaining fraction that is RPM). The scalar $s[nT]$ is the plant input radioactive scaling factor. Equation (13) has the exact solution:

$$\mathbf{C}[(n+1)T] = \mathfrak{S}^n\mathbf{C}_0 + (I_4 - \mathfrak{S}^n)(I_4 - \mathfrak{S})^{-1}\mathbf{u} \quad (17)$$

and the steady state solution

$$\hat{\mathbf{C}} = (I_4 - \mathfrak{S})^{-1}\mathbf{u} \quad (18)$$

If it is assumed that the radioactivity vector, \mathbf{a} , is at steady state, $\hat{\mathbf{a}}$, by the year $n_0=1850$ and radioactive scaling factors begin from the year 1851, (where the averaging period for s is $T=1$ year), let $\mathbf{a}_0 = \hat{\mathbf{a}}$, so that

$$\mathbf{a}[(n+1)T] = [\mathfrak{S}_a^{n-n_0}(I_4 - \mathfrak{S}_a)^{-1} + \sum_{j=n_0}^{n-1} \mathfrak{S}_a^j s[(n+1)T]\mathbf{u}] \quad (19)$$

for n years from $n_0=1850$. For convenience, define $\hat{\mathbf{C}} = \mathbf{P}\mathbf{u}$ and $\mathbf{a}[(n+1)T] = \mathbf{Q}\mathbf{u}$, where $\mathbf{P} = (I_4 - \mathfrak{S})^{-1}$ and \mathbf{Q} is a matrix given by the expression in square brackets in the right hand side of Equation (19). The matrix \mathbf{P} is a constant matrix and the matrix \mathbf{Q} is a function of the time interval nT and the scaling factors from n_0 to nT . An expression for $\Delta^{14}\text{C}_i$ may be obtained from Equations (7) and (11) during time interval $(n+1)T$:

$$\Delta^{14}\text{C}_i[(n+1)T] = \left(\frac{a_i[(n+1)T]}{C_i[(n+1)T]} - 1 \right) \times 1000\text{‰} \quad (20)$$

A similar expression may be obtained for $\Delta^{14}\text{C}_{av}$ from a_{TOT} and \hat{C}_{TOT} and used to derive an expression for IOM and plant inputs, I during any given time interval nT , in terms of total carbon at steady state, \hat{C}_{TOT} and average ^{14}C enrichment, $\Delta^{14}\text{C}_{av}$, by noting that

$$\hat{C}_{TOT} = \sum_{i=1}^4 \hat{C}_i + IOM, \quad (21)$$

and

$$a_{TOT} = \sum_{i=1}^4 a_i + a_{IOM} \quad (22)$$

where

$$a_{IOM} = \left(1 + \frac{\Delta^{14}\text{C}_{IOM}}{1000} \right) IOM. \quad (23)$$

This is done as follows:

$$\frac{\Delta^{14}C_{av}}{1000} = \frac{\sum_{i=1}^4 a_i + a_{IOM} - \hat{C}_{TOT}}{\sum_{i=1}^4 C_i + IOM} \quad (24)$$

so that

$$\frac{\Delta^{14}C_{av}(\sum_{i=1}^4 \hat{C}_i + IOM)}{1000} = \sum_{i=1}^4 a_i + (1 + \frac{\Delta^{14}C_{IOM}}{1000})IOM - \hat{C}_{TOT} \quad (25)$$

and

$$\frac{\Delta^{14}C_{av}}{1000} \sum_{i=1}^4 \hat{C}_i - \sum_{i=1}^4 a_i + (\frac{\Delta^{14}C_{av} - \Delta^{14}C_{IOM}}{1000} - 1)IOM = -\hat{C}_{TOT} \quad (26)$$

Define **S** to be the 1 by 4 unit matrix used as a matrix column summation operator so that from equation (26)

$$S[\frac{\Delta^{14}C_{av}}{1000}(I_4 - S)^{-1} - (I_4 - S_a)^{-1}]u + \frac{1}{1000}(\Delta^{14}C_{av} - \Delta^{14}C_{IOM} - 1000)IOM = -\hat{C}_{TOT} \quad (27)$$

from which follows

$$(\frac{\Delta^{14}C_{av}}{1000} + 1)\hat{C}_{TOT} = SQwI + (1 + \frac{\Delta^{14}C_{IOM}}{1000})IOM \quad (28)$$

Also note that

$$\hat{C}_{TOT} = \sum_{i=1}^4 C_i + IOM = SPwI + IOM \quad (29)$$

This results in the following linear system of equations

$$\begin{pmatrix} 1 \\ 1 \end{pmatrix} \hat{C}_{TOT} = \begin{pmatrix} \frac{1}{1 + \Delta^{14}C_{av}/1000} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} SQw & 1 + \frac{\Delta^{14}C_{IOM}}{1000} \\ SPw & 1 \end{pmatrix} \begin{pmatrix} I \\ IOM \end{pmatrix} \quad (30)$$

and by matrix inversion

$$\begin{pmatrix} I \\ IOM \end{pmatrix} = \begin{pmatrix} SQw & 1 + \frac{\Delta^{14}C_{IOM}}{1000} \\ SPw & 1 \end{pmatrix}^{-1} \begin{pmatrix} \frac{1}{1 + \Delta^{14}C_{av}/1000} & 0 \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \hat{C}_{TOT} \quad (31)$$

Similar results may be obtained for the current model with monthly time interval steps, yearly periodic pulse inputs and exponential decay rate constants, and similar results may also be obtained for the continuous form of the Rothamsted soil-carbon turnover model given by Parshotam [1996].

The analytical solution simplifies the calculation of IOM and, more importantly, allows the interpretation of the IOM pool in relation to the model assumptions. It may be shown from the analytical solution (Equation 31) that IOM and plant inputs, *I*, are given as proportions of (i.e. correlated to) total C with coefficients of proportionality given by environmental factors and ¹⁴C enrichment. Also, IOM and plant inputs *I* are not constant and are a *direct* function of environmental conditions (given by matrices **P** and **Q**), ¹⁴C_{av} and bomb data, with time. If the ¹⁴C content of IOM were set to zero, *a*_{IOM} ≈ 0, so that

$$\begin{pmatrix} I \\ IOM \end{pmatrix} = \begin{pmatrix} SQw & 1 \\ SPw & 1 \end{pmatrix}^{-1} \begin{pmatrix} \frac{1}{1 + \Delta^{14}C_{av}/1000} & 0 \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \hat{C}_{TOT} \\ = \frac{(1 + \Delta^{14}C_{av}/1000)}{S(Q - P)w} \begin{pmatrix} 1 & -1 \\ -SPw & SQw \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & \frac{1}{1 + \Delta^{14}C_{av}/1000} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \hat{C}_{TOT} \\ = \frac{(1 + \Delta^{14}C_{av}/1000)}{S(Q - P)w} \begin{pmatrix} 1 - \frac{1}{1 + \Delta^{14}C_{av}/1000} \\ -SPw + SQw \frac{1}{1 + \Delta^{14}C_{av}/1000} \end{pmatrix} \hat{C}_{TOT} \quad (32)$$

This equation provides a simple way to calculate IOM and plant inputs *I* exactly from the model, and does away with the regression equation given by Falloon *et al.* [1998], which relates conceptual "pool" estimates (e.g. IOM) against measured data (e.g. total C), rather than finding relationships of measured data against measured data. Another advantage with equation (32) is that one can easily test by sensitivity analysis, the 'unrealistic' assumption of a 50 000y residence time for IOM, an assumption in the model of a fraction which is beyond the "detection" limit of 36 000 years.

5. CONCLUSIONS

In this paper, analytical solutions of the Rothamsted soil-carbon turnover model are derived that allow the expression of IOM and annual inputs in terms of total C and ¹⁴C data. The analytical solution simplifies the calculation of IOM, and, more importantly, allows the interpretation of the IOM pool in relation to the model assumptions.

The whole 'concept' of inert organic matter is the subject of future work and will be examined in a further paper (in this issue).

6. ACKNOWLEDGMENTS

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