RothC-26.3 - A Model for the turnover of carbon in soil

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Introduction

Rothc-26.3 is a model of the turnover of organic carbon in non-waterlogged soils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total organic carbon (t C ha^{-1}), microbial biomass carbon (t C ha^{-1}) and $\Delta^{14}C$ (from which the radiocarbon age of the soil can be calculated) on a years-to-centuries timescale (Jenkinson, 1990; Jenkinson and Coleman, 1994; Jenkinson *et al.*, 1987; Jenkinson *et al.*, 1991; Jenkinson *et al.*, 1992). It needs few inputs and those it needs are easily obtainable. It is an extension of the earlier model described by Jenkinson and Rayner (1977), and by Hart (1984). Needless to say, it has many ideas in common with other contemporary turnover models, notably CENTURY (Parton *et al.*, 1988) and Van Veen and Paul's model (Van Veen and Paul, 1981).

Data requirements

The only data required to run the model are:-

1) Monthly rainfall (mm).
2) Monthly open pan evaporation (mm).
3) Average monthly air temperature (°C).
4) Clay content of the top soil (as a percentage).
5) An estimate of the decomposability of the incoming plant material - the DPM/RPM ratio.

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6) Soil cover - Is the soil bare or vegetated in a particular month ?.

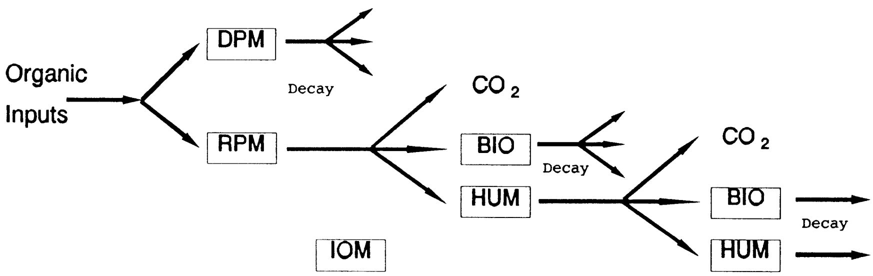
7) Monthly input of plant residues (t C ha^{-1}).
As the below-ground part of this input is rarely known, the model is most often run 'in reverse' generating monthly (or more often yearly) inputs from known soil, site and weather data.

8) Monthly input of farmyard manure (FYM, in t C ha^{-1}), if any.

Model Structure

Soil organic carbon is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The priming action is taken to be zero and the proportion of an input of organic matter that is decomposed in a given time is taken to be independent of the amount added. The IOM compartment is resistant to decomposition. The structure of the model is shown in Figure 1.

Figure 1 - Structure of the Rothamsted Carbon Model



RPM : Resistant Plant Material

DPM : Decomposable Plant Material

BIO : Microbial Biomass

HUM : Humified OM

IOM : Inert Organic Matter

Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For example, for most agricultural and improved grassland, we use a DPM/RPM ratio of 1.44, i.e. 59% of the plant material is DPM and 41% is RPM. For a deciduous or tropical woodland a DPM/RPM ratio of 0.25 is used, so 20% is DPM and 80% is RPM. All incoming plant material passes through these two compartments once, but only once.

Both DPM and RPM decompose to form CO_2 (lost from the system), BIO and HUM. The proportion that goes to CO_2 and to BIO + HUM is determined by the clay content of the soil - see below. The BIO + HUM is then split into 46% BIO and 54% HUM, a partition established by tuning the model to data from some of the Rothamsted long-term field experiments (Jenkinson, 1990). BIO and HUM both decompose to form more CO_2, BIO and HUM.

FYM is assumed to be more decomposed than normal plant material. It is split in the following way : DPM 49%, RPM 49% and HUM 2%.

Decomposition of an active compartment

If an active compartment contains Y t C ha^{-1}, this declines to Y e^{-abckt} t C ha^{-1} at the end of the month.

where a is the rate modifying factor for temperature

b is the rate modifying factor for moisture

c is the plant retainment rate modifying factor

k is the decomposition rate constant for that compartment

t is 1 / 12, since k is based on a yearly decomposition rate.

So Y (1 - e^{-abckt}) is the amount of the material in a compartment that decomposes in a particular month.

Decomposition rate constants

The decomposition rate constants (k), in $years^{-1}$, for each compartment are set at: -

DPM, 10.0; RPM, 0.3; BIO, 0.66; HUM, 0.02. These values were originally set by tuning the model to data from some of the long-term field experiments at Rothamsted (Jenkinson *et al.*, 1987; Jenkinson *et al.*, 1992) : they are not normally altered when using the model.

Calculation of the rate modifying factors

Temperature : the rate modifying factor (a) for temperature is given by: -

$$a = \frac{47.9}{1 + e^{\left(\frac{106}{tm + 18.3}\right)}}$$

where tm is the average monthly air temperature (°C). Air temperature is used rather than soil temperature because it is more often obtainable.

Moisture : Rainfall and open pan evaporation are used to obtain soil moisture deficit (SMD), as it is easier to obtain rainfall and pan evaporation data, from which SMD can be calculated, than monthly measurements of the actual topsoil water deficit. The rate modifying factor (b) for SMD is calculated in the following way:-

The maximum SMD for the 0-23 cm layer of a particular soil is first calculated from

$$\text{Maximum SMD} = -(20.0 + 1.3\ (\%\text{clay}) - 0.01\ (\%\text{clay})^2)$$

So for Rothamsted (%clay = 23.4), the maximum SMD = - 44.94

The maximum SMD thus obtained is that under actively growing vegetation : if the soil is bare during a particular month, this maximum is divided by 1.8, to allow for the reduced evaporation from a bare soil.

Next, the accumulated SMD is calculated from the first month when 0.75 (evaporation) exceeds rainfall until it reaches the max. SMD, where it stays until the rainfall starts to exceed 0.75 (evaporation) and the soil wets up again. The factor 0.75 is conventional for converting open pan evaporation to evapotranspiration from a growing crop.

Finally, the rate modifying factor (b) used each month is calculated from :-

if acc. SMD < 0.444 max. *SMD*,

$$b = 1.0$$

otherwise,

$$b = 0.2 + (1.0 - 0.2) * \frac{(\text{max. } SMD - \text{acc. } SMD)}{(\text{max. } SMD - 0.444 \text{ max. } SMD)}$$

Plant retainment factor : The plant retainment factor (c) slows decomposition if growing plants are present, since decomposition is faster in fallow soil than in cropped soil, even when the cropped soil is not allowed to dry out (Jenkinson *et al.*, 1987; Sommers *et al.*, 1981; Sparling *et al.*, 1982).

If soil is vegetated $c=0.6$

If soil is bare $c=1.0$

Partitioning of carbon between that lost from the soil and that remaining : the CO_2 / (BIO+HUM) ratio

The model adjusts for soil texture by altering the partitioning between CO_2 evolved and (BIO+HUM) formed during decomposition, rather than by using a rate modifying factor, such as that used for temperature. The ratio CO_2 / (BIO + HUM) is calculated from the clay content of the soil using the following equation: -

$$x = 1.67\ (1.85 + 1.60 \exp(-0.0786\ \%\text{clay}))$$

where x is the ratio CO_2 / (BIO+HUM)

Then $x \,/\, (x + 1)$ is evolved as CO_2

and $1 \,/\, (x + 1)$ is formed as BIO + HUM

The scaling factor 1.67 is used to set the CO_2 / (BIO+HUM) ratio in Rothamsted soils (23.4% clay) to 3.51 : the same scaling factor is used for all soils.

Calculation of the radiocarbon age

Radiocarbon measurements are commonly expressed in one of two ways, as % modern, i.e. 100 (specific activity of the sample) / (specific activity of the standard) or as the $\Delta^{14}C$ value, i.e. 1000 (specific activity of the sample - specific activity of the standard) / (specific activity of the standard).

Radiocarbon age is related to $\Delta^{14}C$ in the model by the following equation

$\Delta^{14}C$ = 1000 exp(-radiocarbon age / 8035) - 1000

using the conventional half-life for ^{14}C (5568 years)

Before 1860, the model assumes that the radiocarbon age of the plant material entering the soil each year is zero, ie its $\Delta^{14}C$ value is zero and it is 100 % modern. After 1860 the radiocarbon content of the incoming plant carbon (expressed as % modern) in a particular year is set from an internal table, constructed from data on the radiocarbon content of atmospheric CO_2 : for the 1860 - 1949 period from Baxter & Walton (1971), for 1950 - 1984 from Harkness *et al.*, (1986) and for 1987 - 1993 from Levin *et al.*, (1994). The radiocarbon content of each year's input of plant carbon is taken to be the same as that of atmospheric CO_2 for the same year. The 'radiocarbon activity scaling factor' in the model print-out is the radiocarbon activity of the input for a particular year, expressed as either (%modern) / 100 or ($\Delta^{14}C$ + 1000) / 1000, i.e. taking the value for 1859 as 1.

The age of the IOM fraction is set by default to 50,000 years, implying that it contains virtually no ^{14}C ($\Delta^{14}C$ = -998.0) and that it is of geological age rather than pedological age.

An example of the use of the model

The use of the model will be illustrated using data from one of the Rothamsted long-term field experiments, on the continuous cultivation of spring barley. This experiment was started on Hoosfield in 1852 and was designed to study the effects of fertilizers and FYM on the yield of barley. A detailed account can be found in the booklet *Guide to the classical field experiments* (Rothamsted Experimental Station, 1991). None of the data from this experiment were used in setting the model parameters, so the fit obtained between model and data is an objective test of the model.

In modelling the Hoosfield data, it is first necessary to run the model to produce a starting soil organic C content that is the same as that originally present in the soil (33.8 t C ha^{-1} in 1852, which includes 3.8 t C ha^{-1} in IOM). This is done by assuming that the soil organic C had reached equilibrium in 1852 and running the model iteratively with different annual inputs of plant C from a spring barley crop (DPM/RPM ratio 1.44) until the value of 33.8 t C ha^{-1} is reached (within $\pm$ 0.5 t C ha^{-1}).

It should be noted that the annual input finally chosen (1.63 t C ha^{-1} $year^{-1}$) is distributed between April, May, June and July, with no inputs in other months. This distribution is no more than an educated guess for a particular crop, spring barley, sown in February or March and harvested in early August. It makes little difference to the calculated equilibrium value for total organic C or to radiocarbon age how the annual input is distributed, or even if it is all added in a single pulse. Only if the model is being used to predict annual changes in fractions with short turnover times (notably biomass and DPM) will the input distribution appreciably affect the results.

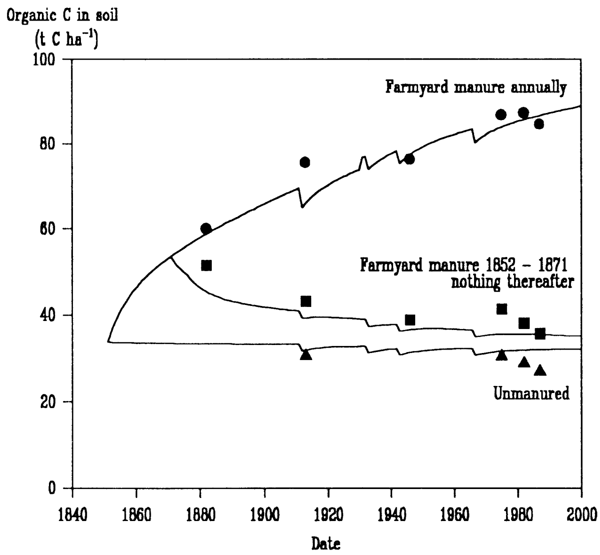
The IOM content of the Hoosfield soil was set at 3.8 t C ha^{-1} throughout the run to establish the equilibrium state. The same value for IOM was used in all the subsequent runs with this soil. This value gives a radiocarbon age of 1055 years for the whole soil organic C in 1852, a little less than the mean (1290 years) for all the pre-1900 Rothamsted topsoils (0 - 23 cm) analysed for radiocarbon (Jenkinson *et al.*, 1992). No measurements of radiocarbon are available from the Hoosfield experiment : had they been, the IOM content of the soil *and* the annual inputs of plant C would have been iteratively adjusted to give both the correct organic C content and the correct radiocarbon age for a particular sampling date.

Once the starting C content has been established, the model was used to predict changes in the organic carbon of three of the plots in the Hoosfield experiment : plot 7-2 (FYM annually), plot 7-1 (FYM annually 1852-1871, nothing thereafter) and a mean of plots 6-1 and 6-2 (both unmanured).

For the unmanured treatment, 1.76 t C ha^{-1} of plant residues was used (distributed, again arbitrarily, with 0.16 t C ha^{-1} in April, 0.16 in May, 0.32 in June and 1.12 in July). A soil cover factor of one was used in April, May, June and July, zero in the other months. These input figures were used from 1852 to 2000, except in the years which were fallow (1912, 1933, 1943 and 1967). For the fallow years the plant input was set at zero (bare cultivated fallow) and a soil cover factor of zero was used in all twelve months.

For the treatment receiving FYM annually (plot 7-2), the annual input of plant residues from the barley was taken to be 2.6 t C ha^{-1} (0.21 t C ha^{-1} in April, 0.37 in May, 0.53 in June and 1.49 in July) Again a soil cover factor of one was used in April, May, June and July, zero in the other months. As with the unmanured treatment, this input was used from 1852 to 2000, except in the four fallow years (1912, 1933, 1943 and 1967). The FYM (containing 3.0 t C ha^{-1}) was applied in February each year from 1852-1911 and from 1913-01930. In 1931 FYM containing 6.0 t C ha^{-1} was applied (3.0 in Feb and 3.0 in Nov). From 1932 to 2000, FYM containing 3.0 t C ha^{-1} was applied in November each year.
The third treatment received FYM (3 t C ha^{-1}) every February from 1852 to 1871 and nothing thereafter (plot 7-1). From 1852 to 1876, plant residues were set at 2.6 t C ha^{-1} (split in the same way as plot 7-2), with the same soil cover factor of one in April, May, June and July, zero in the other months. From 1877 to 2000, plant residues were set at 1.76 t C ha^{-1} (split in the same way as the unmanured plot), with the same soil cover factor, except in the four fallow years of 1912, 1933, 1943 and 1967. Figure 2 shows the results.

Figure 2 – Carbon Changes in the Hoosfield Barley Experiment
Data modelled by RothC-26.3 (Solid lines)



Advantages and Disadvantages of RothC-26.3

RothC-26.3 is solely concerned with soil processes; it does not contain a sub-model for plant production, unlike models such as CENTURY. Its main advantage is that it runs on data that are readily available. As with all such models, it is at its best when operating in situations similar to those for which its was originally parameterised : for RothC-26.3, arable soils in the temperate zone. It should be used with the greatest caution in situations where there are as yet no good long-term measurements of decomposition rates - tundra and taiga soils for example. It deals exclusively with processes in the topsoil, which includes litter, if present.

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