RothC - A model for the turnover of carbon in soil

Model Description

Version 2.0.0

(June 2025)

K. Coleman, J. M. Prout & A. E. Milne

Rothamsted Research
Harpenden
Herts
AL5 2JQ

Contact:- **Kevin Coleman, Jonah Prout or Alice Milne**

E-mail:- kevin.coleman@rothamsted.ac.uk

jonah.prout@rothamsted.ac.uk

alice.milne@rothamsted.ac.uk

Contents

Version History

Version 1.0.0 (February 2024)

Release of the standard version of RothC aligning with Jenkinson (1990)

Version 2.0.0 (June 2025)

Maintains functionality of RothC version 1.0.0 but adds options to alter the soil moisture function to better represent semi-arid regions (Farina et al., 2013).

Part 1

1.1 Introduction

RothC is a model for the turnover of organic carbon in non-waterlogged top-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 ha $^{-1}$), microbial biomass carbon (t ha $^{-1}$) and $\delta^{14}C$ (from which the equivalent radiocarbon age of the soil can be calculated) on a years to centuries timescale (Jenkinson, 1990; Jenkinson et al., 1991; Jenkinson & Coleman, 1994; Jenkinson et al., 1992; Jenkinson et al., 1987). 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). A comparative study of C turnover models, including RothC, was published (Smith et al., 1997). RothC is designed to run in two modes: 'forward' in which known inputs are used to calculate changes in soil organic matter and 'inverse', when inputs are calculated from known changes in soil organic matter.

RothC was originally developed and parameterized to model the turnover of organic C in arable top-soils from the Rothamsted Long Term Field Experiments - hence the name. Later, it was extended to model turnover in grassland and in woodland and to operate in different soils and under different climates. It should be used cautiously on subsoils, soils developed on recent volcanic ash (but see Saggar et al., 1996; Shirato et al., 2004; Tate et al., 1994), soils from the tundra and taiga and not at all on soils that are permanently waterlogged. It has also been used to model changes in soil carbon in Pinus radiata on Mediterranean agricultural soils (Romanya et al., 2000), forest and pasture ecosystems of Amazon, Brazil (Cerri et al., 2003), Mediterranean agro-silvo-pastoral systems (Francaviglia et al., 2012).

Farina et al. (2013) modified the soil water dynamics for semi-arid regions (which informed the version 2.0.0 release), and Giongo et al. (2020) created a daily version and modified the soil water dynamics, for Caatinga shrublands, in the semiarid region, North-East Brazil.

1.2 Data requirements

The data required to run the model are:

1) Monthly rainfall (mm).

2) Monthly open pan evaporation (mm).

   Rainfall and open-pan evaporation are used to calculate topsoil moisture deficit (TSMD), as it is easier to do this than obtain monthly measurements of the actual topsoil water deficit. If open-pan evaporation is not available, monthly potential evapotranspiration can be calculated with adequate accuracy from Müller (1982) collection of meteorological data for sites around the world. Sites should be selected from Müller's collection that are as similar climatically as possible to the site under investigation. Column 14 in Müller's Tables is headed 'Mean potential evaporation', but in fact this column gives calculated mean monthly potential evapotranspiration. If Müller's 'Mean potential transpiration' is used, you must remember to convert his values to open-pan evaporation by dividing them by 0.75. This is most important because the model is presently primed to run on open-pan evaporation data, which is then multiplied internally by 0.75 to give evapotranspiration.

   i.e., if Müller's data are used as an input for the model, Open-pan evaporation = 'Mean potential transpiration' / 0.75

3) Average monthly mean air temperature (°C).

Air temperature is used rather than soil temperature because it is more easily obtainable for most sites. For Rothamsted, monthly air temperature satisfactorily represents the monthly mean soil temperature in topsoil, the soil temperature at 20 cm showing a difference of only +1°C of the annual minimum and -1°C of the annual maximum.

4) Clay content of the soil (as a percentage).

Clay content is used to calculate how much plant available water the topsoil can hold; it also affects the way organic matter decomposes.

5) An estimate of the decomposability of the incoming plant material - the DPM/RPM ratio.

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

It is necessary to indicate whether or not the soil is vegetated because decomposition has been found to be 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).

7) Monthly input of plant residues (t C ha^{-1}).

The plant residue input is the amount of carbon that is put into the soil per month (t C ha^{-1}), including carbon released from roots during crop growth. As this input is rarely known, the model is most often run in ‘inverse' mode, generating input from known soil, site and weather data.

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

The amount of FYM (t C ha^{-1}) put on the soil, if any, is inputted separately, because FYM is treated slightly differently from inputs of fresh plant residues.

9) Depth of soil layer sampled (cm)

For the soil moisture function options developed for (Farina et al., 2013) four more variables are required:

10) Silt content of the soil (as a percentage).

11) Bulk density of the soil (g cm^{-3}).

12) Organic carbon content of the soil (as a percentage).

13) minRM_moist

This is the minimum value that the rate modifying factor for soil moisture will take at soil moisture deficit corresponding to -1500 kPa. The standard value is 0.2, and values of 0.15 and 0.1 were tested by Farina et al. (2013).

1.3 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 IOM compartment is resistant to decomposition. The structure of the model is shown in Figure 1.

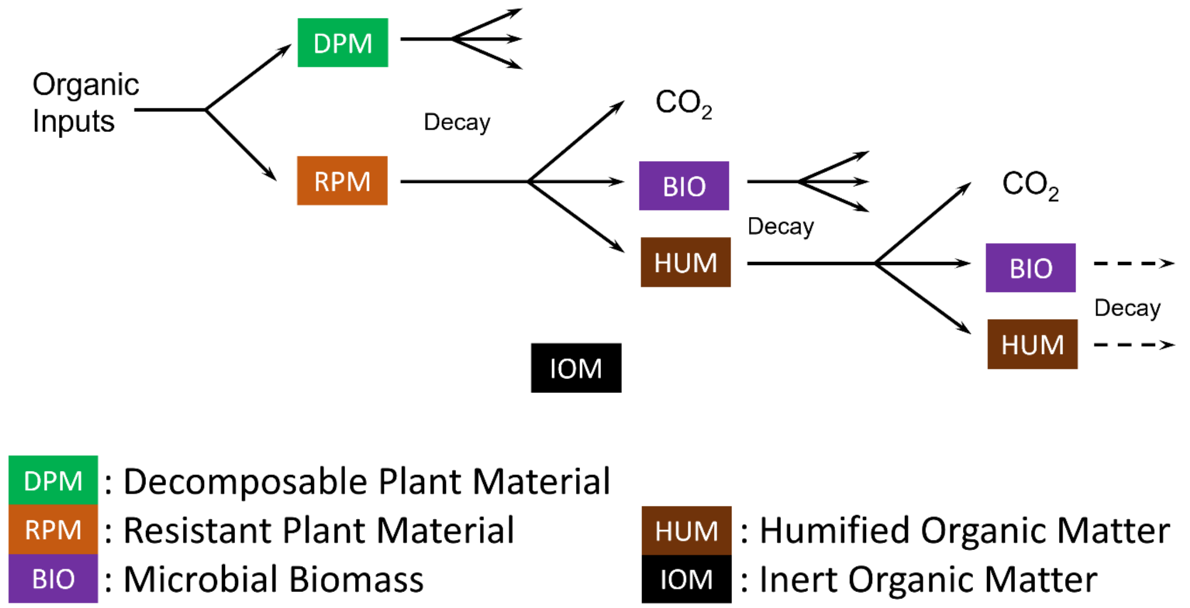

Figure 1 Structure of the Rothamsted Carbon Model.

Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For most agricultural crops 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 unimproved grassland and scrub (including Savanna) a ratio of 0.67 is used. 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, BIO and HUM. The proportion that goes to CO_2 and to BIO + HUM is determined by the clay content of the soil - see section 1.7. The BIO + HUM is then split into 46% BIO and 54% HUM. BIO and HUM both decompose to form more CO_2, BIO and HUM.

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

1.4 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 = RM_Tmp is the rate modifying factor for temperature

b = RM_Moist is the rate modifying factor for moisture

c = RM_Cover is the soil cover 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.

1.5 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., 1992; Jenkinson et al., 1987): they are not normally altered when using the model.

1.6 Calculation of the rate modifying factors

1.6.1 Temperature: the rate modifying factor (RM_Tmp) for temperature is given by:

$$\mathrm{RM\_Tmp} = \frac{47.91}{1 + e^{\frac{106.06}{T+18.27}}} \tag{1}$$

where T is the average monthly air temperature (°C). (Figure 2)

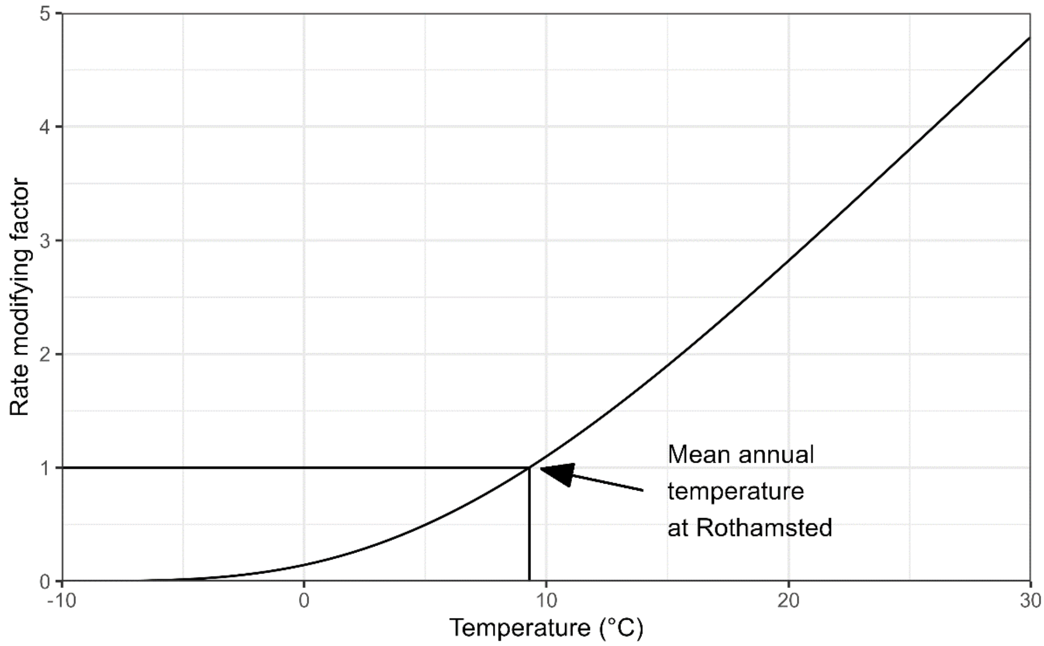

Figure 2 The rate modifying factor for temperature. The mean annual temperature at Rothamsted at the time of development is marked.

1.6.2 Moisture: the topsoil moisture deficit (TSMD) rate modifying factor (RM_Moist) can be calculated as in version 1.0.0 of RothC (described below and Figure 3a (black line)) and for the other options described in (Farina et al., 2013) (Figures 3b to 3d). This is determined by the two variables: opt_RMmoist and opt_SMDbare.

These are both given values of 1 to use the calculations as in version 1.0.0 which are given below (section **1.6.2.1**). See section **1.6.2.2** for the additional options and calculations added in version 2.0.0.

Table 1 Options controlling the moisture rate modifying factor calculation.

Opt_RMmoist	Opt_SMDbare	Effect	Figure 3 panel
1	1	Version 1.0.0	3a

1.6.2.1 Version 1.0.0: the rate modifying factor for soil moisture (RM_moist) is calculated as follows (represented in Figure 3a) (until reference to version 2.0.0):

The maximum TSMD (greatest negative value) for the 0-23 cm layer of a particular soil is first calculated from:

$$Max.TSMD = -(20.0 + 1.3\text{clay} - 1.01\text{clay}^2) \qquad (2)$$

where clay is the texture fraction in percent.

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

For a soil layer of different thickness, the maximum TSMD thus calculated is divided by 23 and multiplied by the actual thickness, in cm.

Next, the accumulated TSMD for the specified layer of soil is calculated from the first month when 0.75*(open pan evaporation) exceeds rainfall until it reaches the max. TSMD, where it stays until the rainfall starts to exceed 0.75*(open pan evaporation) and the soil wets up again. If open pan evaporation is not known, potential evapotranspiration from Müller (1982) can be used by selecting sites from his compilation that are as similar climatically to the sampling site as possible. Note that the model is presently primed to run on open-pan evaporation data, which is multiplied internally by 0.75 to give evapotranspiration. Data from Müller’s tables should therefore be divided by 0.75 before entering: this is **most** important.

Bare soil moisture deficit (BareSMD)

The maximum TSMD obtained above is that under actively growing vegetation.

If the soil is bare during a particular month, this maximum is divided by 1.8 is give BareSMD, to allow for the reduced evaporation from a bare soil. When the soil is bare it is not allowed to dry out further than BareSMD, unless the accumulated TSMD is already less than BareSMD in which case it cannot dry out any further.

An example of this calculation for Rothamsted is shown below.

Table 2 Accumulated Topsoil Moisture Deficit (Acc. TSMD) for Rothamsted soil

	Rainfall	Open pan evaporation	0.75*E	R - 0.75*E	Acc. TSMD
	(mm water)				
Jan	74	8	6.00	68.00	0.00
Feb	59	10	7.50	51.50	0.00
Mar	62	27	20.25	41.75	0.00
Apr	51	49	36.75	14.25	0.00
May	52	83	62.25	-10.25	-10.25*
Jun	57	99	74.25	-17.25	-27.50
Jul	34	103	77.25	-43.25	-44.94**
Aug	55	91	68.25	-13.25	-44.94
Sep	58	69	51.75	6.25	-38.69
Oct	56	34	25.50	30.50	-8.19
Nov	75	16	12.00	63.00	0.00
Dec	71	8	6.00	65.00	0.00

*First month when 0.75 (evaporation) is greater than the rainfall

**Max. TSMD

Note that the calculation in the above table starts from the 1st of January, when the soil is assumed to be at field capacity. For situations where this is not so, the weather data input should be displaced by a whole number of months, so that the soil is at field capacity at the start of the model run. Thus, in the Southern Hemisphere, the weather data file should start in July when the soil is wet, so that July will appear as January in the output.

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

$$\text{if acc. TSMD} > 0.444 \text{ max. TSMD then } \mathrm{RM_{moist}} = 1.0 \tag{3}$$

Otherwise,

$$\mathrm{RM\_Moist} = 0.2 + (1.0 - 0.2)\frac{(\text{max. TSMD} - \text{acc. TSMD})}{(\text{max. TSMD} - 0.444 \text{ max. TSMD})} \tag{4}$$

This is shown in black in Figure 3a.

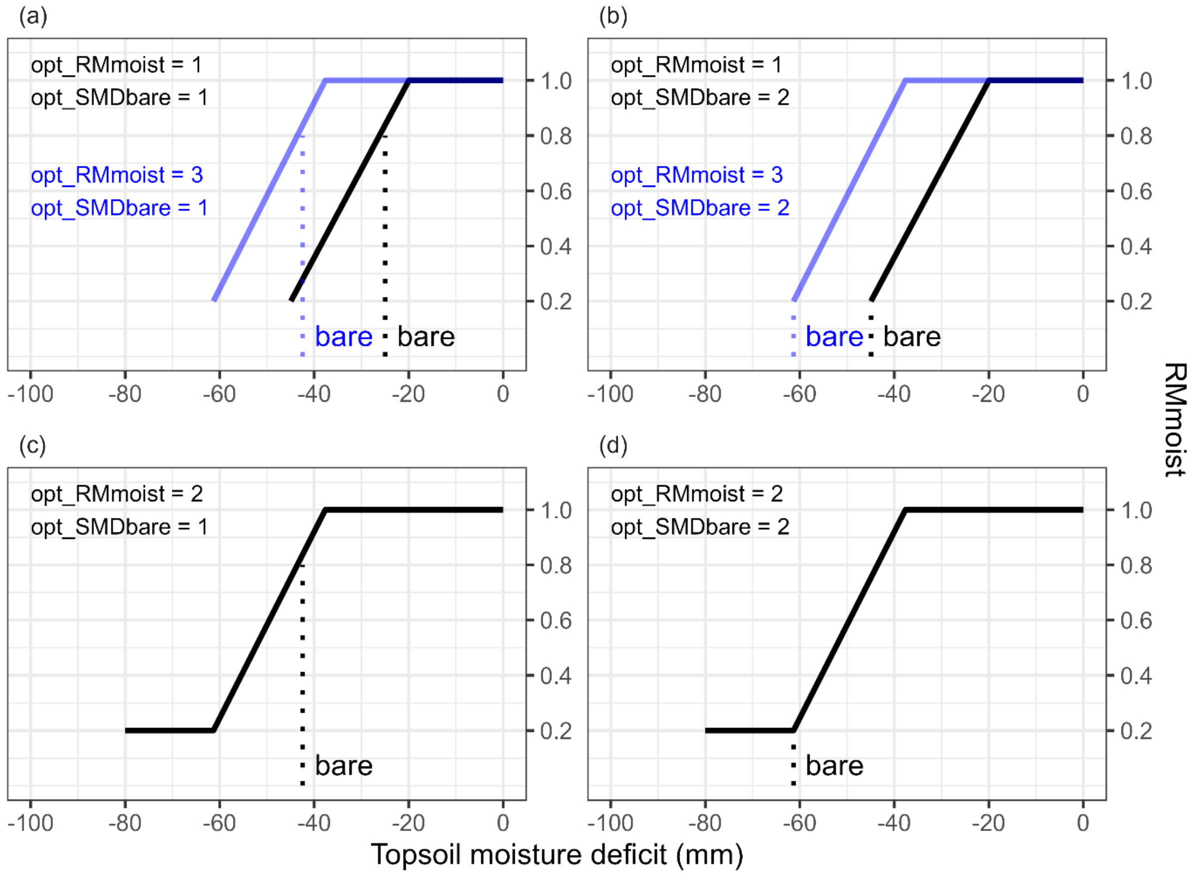

Figure 3 The rate modifying factor for moisture. Each panel shows the result of the annotated combination of opt_RMmoist and opt_SMDbare. The soil properties used for the calculation were: clay = 23.4%, depth = 23 cm ((a) and (b), black lines), and silt = 58.6%, bulk density = 1.27 g cm^{-3}, organic carbon = 0.94 ((a) and (b), blue lines, (c) and (d)).

1.6.2.2 Version 2.0.0: In general, the options for the rate modifying factor for soil moisture (RM_moist) follow the same approach in terms of the accumulated topsoil moisture deficit (below table and Figure 3). However, using values of 2 or 3 for opt_RMmoist will use Mualem-van Genuchten equations from (Wösten et al., 1999) based on (van Genuchten et al., 1980) for determining the maximum topsoil moisture deficit and the other soil water parameters involved.

Table 3 Options controlling the moisture rate modifying factor calculation.

Opt_RMmoist	Opt_SMDbare	Effect	Figure 3 panel
1	1	Calculated as in version 1.0.0.	3a (black)
1	2	Moves the bare-soil moisture modification to the moisture deficit corresponding to – 1500 kPa.	3b (black)
2	1	Calculates the topsoil moisture deficit at the corresponding matric potentials using Maulem-van Genuchten equations.	3c
2	2	The same moisture deficit profile as in Figure 3c but moves the bare-soil moisture modification to the moisture deficit corresponding to – 1500 kPa.	3d
3	1	The same form as Version 1.0.0 but parameters calculated using Maulem-van Genucthen equations.	3a (blue)
3	2	The same as 3a previous but moves the bare-soil moisture modification to the moisture deficit corresponding to – 1500 kPa.	3b (blue)

When opt_RMmoist = 2 or 3, the topsoil moisture deficits associated with different matric potentials are calculated using Maulem-van Genuchten equations (van Genuchten, 1980; Wösten et al., 1999):

$$\text{Organic matter in \% (OM)} = 1.72(\text{organic carbon in \%})$$

$$\alpha = \exp(-14.96 + 0.03135 * \text{clay} + 0.0351 * \text{silt} + 0.646 * \text{OM} + 15.29 * \rho - 0.192 * \text{topsoil} - 4.671 * \rho^2 - 0.000781 * \text{clay}^2 - 0.00687 * \text{OM}^2 + 0.0449 * \text{OM}^{-1} + 0.0663 * \ln(\text{silt}) + 0.1482 * \ln(\text{OM}) - 0.04546 * \rho * \text{silt} - 0.4852 * \rho * \text{OM} + 0.00673 * \text{clay} * \text{topsoil}) \quad (5)$$

$$\theta_S = (0.7919 + 0.001691 * \text{clay} - 0.29619 * \rho - 0.000001491 * \text{silt}^2 + 0.0000821 * \text{OM}^2 + 0.02427 * \text{clay}^{-1} + 0.0113 * \text{silt}^{-1} + 0.01472 * \ln(\text{silt}) - 0.0000733 * \text{OM} * \text{clay} - 0.000619 * \rho * \text{clay} - 0.001183 * \rho * \text{OM} - 0.0001664 * \text{silt} * \text{topsoil} \quad (6)$$

$$\theta_R = 0.01 \quad (7)$$

$$n = \exp(-25.23 - 0.02195 * \text{clay} + 0.0074 * \text{silt} - 0.194 * \text{OM} + 45.5 * \rho - 7.24 * \rho^2 + 0.0003658 * \text{clay}^2 + 0.002885 * \text{OM}^2 - 12.81 * \rho^{-1} - 0.1524 * \text{silt}^{-1} - 0.01958 * \text{OM}^{-1} - 0.2876 * \ln(\text{silt}) - 0.0709 * \ln(\text{OM}) - 44.6 * \ln(\rho) - 0.02264 * \rho * \text{clay} + 0.0896 * \rho * \text{OM} + 0.00718 * \text{clay} * \text{topsoil}) + 1 \quad (8)$$

$$m = 1 - \frac{1}{n} \quad (9)$$

$$\text{WC}_i = \theta_\text{R} + \frac{\theta_S - \theta_\text{R}}{(1 + (\alpha\ \text{mbar})^n)^m} \quad (10)$$

$$TSMD_i = 10\left(\text{WC}_i - \text{WC}_{fc}\right)\text{depth} \quad (11)$$

Where,

Clay and silt are the soil texture fractions in %

ρ is the bulk density (g cm^{-3})

topsoil is a qualitative variable having the value of 1

WC_i is the water content at *i* mbar.

mbar is the matric potential (cm), which is 50 at field capacity, 1000 at 1 bar, 15000 at 15bar or wilting point, and 1000000 at 1000 bar.

WC_{fc} is the water content at field capacity.

$TSMD_i$ is the topsoil moisture deficit (mm) and calculated for -1 bar, -15 bar, or -1000 bar (the latter for opt_RMmoist = 2).

Using 3 for the value of Opt_RmMoist is not included in (Farina et al., 2013) however allows for the application of the Mualem-van Genuchten equations without the extension of the topsoil moisture deficit.

An additional variable which can be specified in the input file for the model is minRM_moist, the minimum value for RM_moist, set to 0.2 in version 1.0.0 but tested with values of 0.15 and 0.1 in (Farina et al., 2013).

Bare soil moisture deficit (BareSMD)

The difference between opt_SMDbare = 1 and 2 is that when set to 2, the bare soil moisture deficit (bareSMD) is set to the topsoil moisture deficit corresponding to -1500 kPa (which is the same as the maximum topsoil deficit in version 1.0.0) (Figures 3b and 3d).

When the Maulem-van Genuchten equations are used (opt_RMmoist = 2 or 3) and opt_SMDbare = 1, the calculation of the bare soil parameter is changed to:

$$TSMD_{bare} = TSMD_{-1500kPa} - \left(\frac{0.6388}{0.8}\right)(TSMD_{-1500kPa} - TSMD_{-100kPa}) \qquad (12)$$

1.6.3 Soil cover factor: The soil cover factor (RM_cover) slows decomposition if growing plants are present. In earlier version of the model this factor is called the 'retainment factor'

If soil is vegetated: RM_cover = 0.6

If soil is bare: RM_cover = 1.0

1.7 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:

$$x = 1.67(1.85 + 1.60\exp(-0.0786clay) \qquad (13)$$

where *x* is the ratio of CO_2 to (BIO+HUM) which are resolved in the following equations:

$$\mathrm{CO_2\ evolved} = \frac{x}{x+1} \qquad (14)$$

$$\mathrm{BIO\ allocation} = 0.46\left(\frac{1}{x+1}\right) \qquad (15)$$

$$\mathrm{HUM\ allocation} = 0.54\left(\frac{1}{x+1}\right) \qquad (16)$$

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.

Note that the above equation relating the CO_2 / (BIO+HUM) ratio to %clay is not the same as that given by Jenkinson et al. (1987) or Jenkinson (1990) which used cation exchange capacity. The equation was recalculated using clay content from the same dataset.

Figure 4 shows how the % clay content of the soil affects the soil texture factor, i.e. the CO_2 / (BIO+HUM) ratio.

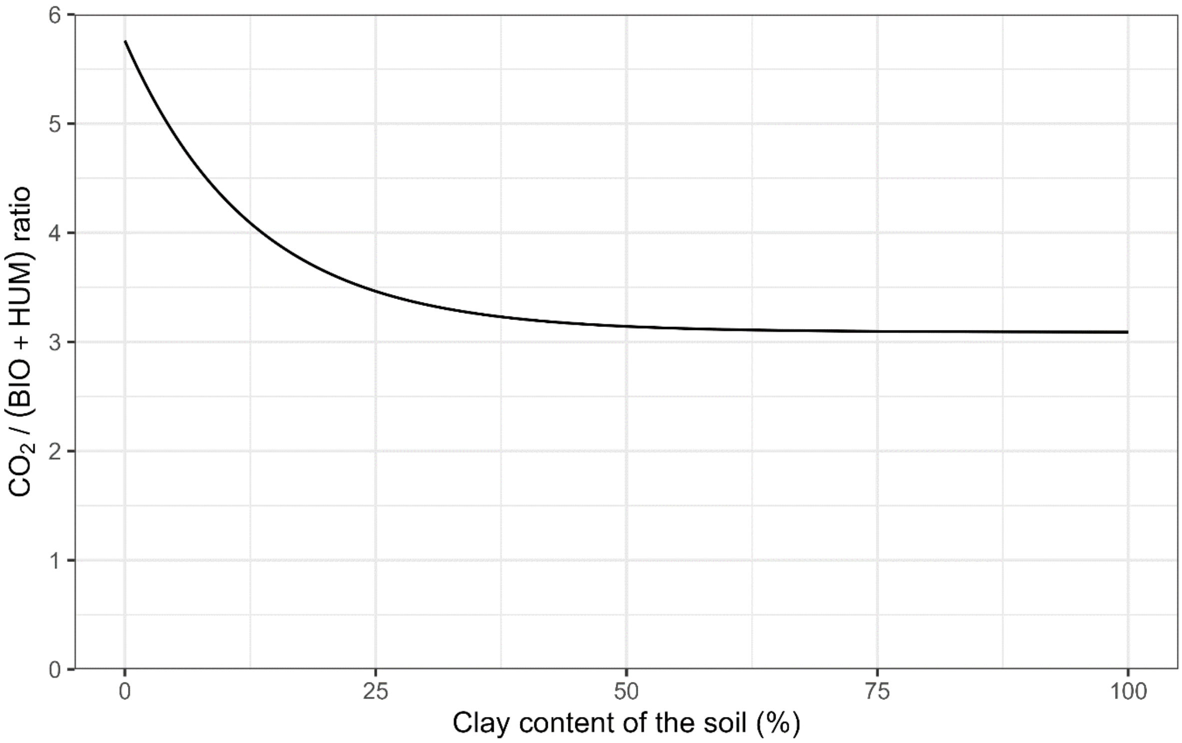

Figure 4 The effect of clay on the ratio of CO_2 released to (BIO+HUM) formed.

1.8 Calculation of the equivalent 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).

So,

$$\delta^{14}\mathrm{C} = 10(\%\mathrm{Modern}) - 1000 \tag{17}$$

The standard is defined as 0.95 of the ^{14}C activity of the NBS standard oxalic acid.

Equivalent radiocarbon age is related to δ14C in the model by the following equation:

δ14 C = 1000 exp(-equivalent radiocarbon age / 8035) - 1000

$$\delta^{14}\mathrm{C} = 1000 \exp\left(-\text{equivalent radiocarbon age}/8035\right) - 1000 \qquad (18)$$

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

Equivalent radiocarbon age is defined as the radiocarbon age of a homogeneous sample having the same radiocarbon content as the measured (non-homogeneous) sample. Before 1860, the model assumes that the radiocarbon age of the plant material entering the soil each year is zero, i.e. 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 - shown graphically in Figure 5.

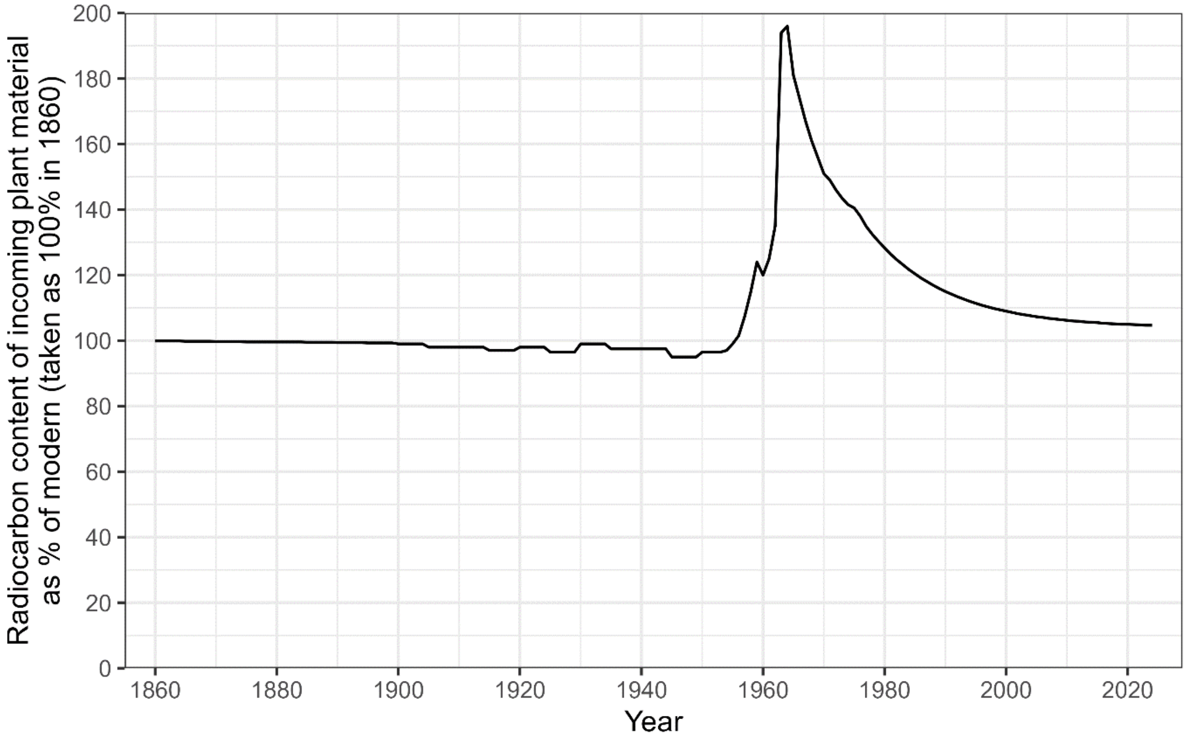

Figure 5 Postulated radiocarbon content of incoming plant material 1860–2024.

This input table was constructed from data on the radiocarbon content of atmospheric CO_2: for the 1860 - 1949 period from Baxter and Walton (1971), for 1950 - 1984 from Harkness et al. (1986) and for 1987 - 1993 from Levin et al. (1997). 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.

If no radiocarbon measurements are available, IOM is set using the equation below (Falloon et al., 1998):

$$\mathrm{IOM} = 0.049(\mathrm{TOC})^{1.139} \tag{19}$$

Where, IOM is Inert organic matter, t C ha^{-1} and TOC is Total organic carbon, t C ha^{-1}

This is a very rough approximation for surface soils alone.

1.9 Definitions of abbreviations used

a	:	Rate modifying factor for temperature (RM_Tmp)
b	:	Rate modifying factor for moisture (RM_Moist)
BIO	:	Microbial biomass
c	:	Rate modifying factor for soil cover (RM_Cover)
DPM	:	Decomposable plant material
FYM	:	Farmyard manure
HUM	:	Humified organic matter
IOM	:	Inert organic matter
k	:	Decomposition rate constant
RPM	:	Resistant plant material
SMD	:	Soil moisture deficit
t	:	time
T	:	Temperature
TSMD	:	Topsoil moisture deficit
TOC	:	Total organic carbon (t C ha^{-1})

Part 2

2.1 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 (Macdonald et al., 2018). 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 2.7 t C ha^{-1} in IOM, as calculated from the equation of Falloon et al. (1998). Soil organic C is assumed to have been at equilibrium in 1852. The modelled plant input needed to obtain 33.8 t C ha^{-1} in the soil is then 1.70 t C ha^{-1} y^{-1}. This input is distributed as follows: 0.212 t C ha^{-1} $month^{-1}$ from January to July and in December, with no inputs in the other four months. This distribution is no more than a guess for the mixed arable cropping that prevailed on Hoosfield before the experiment commenced in 1852. 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. A soil cover factor of 1 was used in the months with plant inputs, zero in the other four months.

Once the starting C content has been established, land management files are created for each of the three treatments modelled in Figure 6; these are plot 7-2 (farmyard manure annually), plot 7-1 (farmyard manure annually 1852-1871, nothing thereafter) and a mean of plots 6-1 and 6-2 (both unmanured).

For the unmanured treatment, the annual input of plant residues was calculated to be 1.60 t C ha^{-1} y^{-1} (distributed with 0.16 t C ha^{-1} in April, 0.32 in May, 0.48 in June and 0.64 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 0 was used in all twelve months.

For the treatment receiving farmyard manure annually (plot 7-2), the annual input of plant residues from the barley was calculated to be 2.80 t C ha^{-1} y^{-1} (0.28 t C ha^{-1} in April, 0.56 in May, 0.84 in June and 1.12 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 $ha^{-1}y^{-1}$) was applied in February each year from 1852-1911 and from 1913-1930. 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 $ha^{-1}y^{-1}$) every February from 1852 to 1871 and nothing thereafter (plot 7-1). From 1852 to 1876, plant residue input was set at 2.80 t C ha^{-1} y^{-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 1.60 t C ha^{-1} y^{-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 6 shows the modelled data for total soil organic C in the three treatments, together with the measured data. The modelled results for the treatment receiving FYM for only 20 years are considerably lower than the measurements; agreement is closer with the other two treatments.

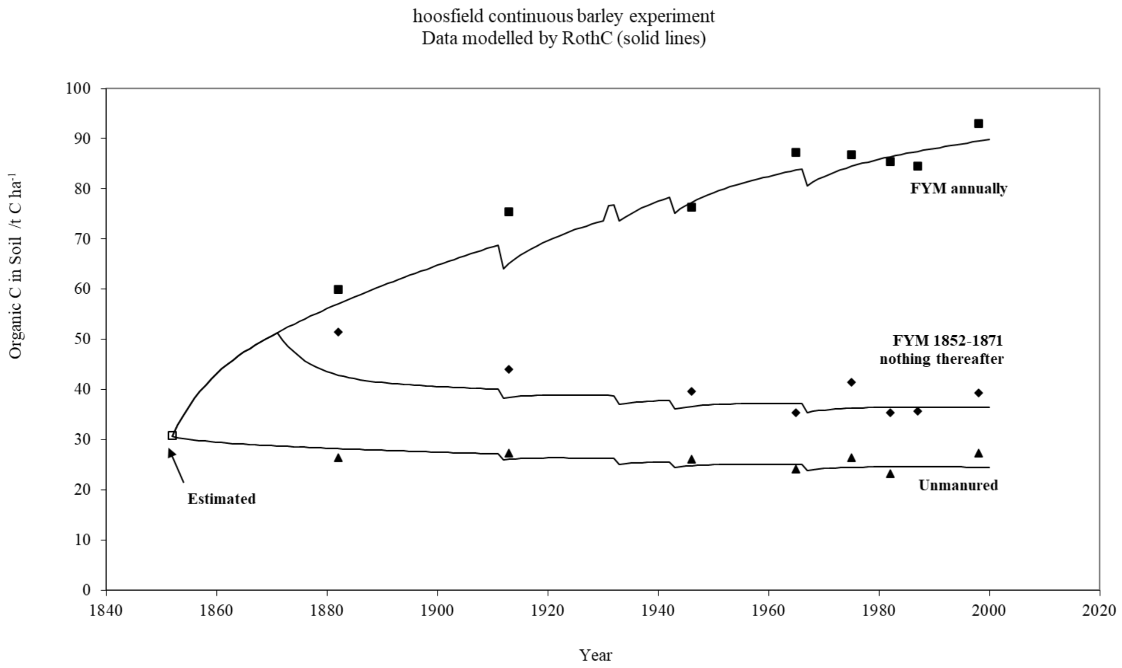

Figure 6 Hoosfield continuous barley experiment. Points are sampled carbon stocks and lines are the results modelled using RothC.

2.2 How the model calculates the carbon content of the soil and its equivalent radiocarbon age

To see how carbon content, equivalent age and Δ ^{14}C values are calculated, we will examine the first month (January 1852) of the simulation for the unmanured plot on the Hoosfield spring barley experiment (Figure 6). First consider the position at the end of this preliminary run to equilibrium on 31st December 1851, after the model had run for 10,000 years using the Rothamsted weather file, the Hoosfield Land Management file (with an annual input of 1.70 t C ha^{-1} year^{-1}), a DPM/RPM ratio of 1.44 and an IOM of 2.7 t C ha^{-1}. On 31st December 1851 the state of the model is:

	Carbon (t C ha^{-1})	Equivalent Radiocarbon age (years)	Δ ^{14}C
DPM	0.1533	0.10	-0.01
RPM	4.4852	6.70	-0.83
BIO	0.6671	21.69	-2.69
HUM	25.8576	116.88	-14.44
IOM	2.7000	50000.00	-998.02
Total	33.8632	764.37	-90.75

Now consider the state on the 31st January 1852 for the unmanured plot, which does not receive any input of plant C or FYM in January. The temperature, moisture and soil cover during January give a combined rate modifying factor, *abc*, of 0.3561. Using the rate constants given in Section 1.5, the C content of the different compartments are changed as follows.

DPM becomes 0.1533 * exp[- 10 * 0.3561 / 12] = 0.1140

RPM becomes 4.4852 * exp[- 0.3 * 0.3561 / 12] = 4.4455

BIO becomes 0.6671 * exp[- 0.66 * 0.3561 / 12] = 0.6542

HUM becomes 25.8576 * exp[- 0.02 * 0.3561 / 12] = 25.8423

The difference between one month and the next for the C content of each compartment is:

DPM 0.0393

RPM 0.0397

BIO 0.0129

HUM 0.0153

These differences represent the material that decomposes during the month in each compartment. This material is split (see Section 1.7) between (BIO+HUM) and CO_2 in the following way:

(3.51 / 4.51) * (difference) is CO_2-C

(1 / 4.51) * (difference) is (BIO+HUM)

The (BIO+HUM) thus formed is split as 46% BIO and 54% HUM

This is shown in the following table:

	Diff	BIO	HUM	CO_2-C
DPM	0.0393	0.0039	0.0047	0.0307
RPM	0.0397	0.0041	0.0048	0.0308
BIO	0.0129	0.0013	0.0015	0.0100
HUM	0.0153	0.0016	0.0018	0.0119

The carbon content of each compartment is now made up in the following way

DPM = 0.1140 = 0.1140

RPM = 4.4455 = 4.4455

BIO = 0.6542 + 0.0039 + 0.0041 + 0.0013 + 0.0016 = 0.6651

HUM = 25.8423 + 0.0047 + 0.0048 + 0.0015 + 0.0018 = 25.8551

The model calculates the age of each compartment from a matrix which starts with the age of that compartment on 31 December 1851 and adjusts it for changes occurring during January 1852. For the DPM and RPM compartments, which in this particular example receive no fresh inputs of plant material in January, the age on 31 December is increased by one month to give the age on 31 January. For the BIO and HUM compartments, the incoming material added at the end of the month comes tagged with the age of the compartment from which it came. The age of the whole compartment is than obtained by weighting the age of its components by their carbon content. The resulting values for equivalent radiocarbon age and $\Delta^{14}C$ are then:

	Equivalent Radiocarbon age (years)	$\Delta^{14}C$
DPM	0.19	-0.02
RPM	6.78	-0.84
BIO	21.78	-2.70
HUM	116.91	-14.45

A similar procedure is followed if there is an input of fresh plant residue during a particular month. This input is given the appropriate radiocarbon scaling factor for the year in which it occurs and distributed between DPM and RPM in the specified proportions at the end of the month in question.

For the unmanured plot in the Hoosfield experiment the calculated radiocarbon age of the whole soil organic C is 987 years in 1950 and 70 years in 1970, the decline being due to radiocarbon from thermonuclear testing. 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 content for a particular sampling date.

References

Baxter, M. S., & Walton, A. (1971). Fluctuations of atmospheric carbon-14 concentrations during past century. *Proceedings of the Royal Society of London Series a-Mathematical and Physical Sciences*, *321*(1544), 105–127. https://doi.org/10.1098/rspa.1971.0016

Cerri, C. E. P., Coleman, K., Jenkinson, D. S., Bernoux, M., Victoria, R., & Cerri, C. C. (2003). Modeling soil carbon from forest and pasture ecosystems of Amazon, Brazil. *Soil Science Society of America Journal*, *67*(6), 1879–1887.

Falloon, P., Smith, P., Coleman, K., & Marshall, S. (1998). Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. *Soil Biology & Biochemistry*, *30*(8-9), 1207–1211.

Farina, R., Coleman, K., & Whitmore, A. P. (2013). Modification of the RothC model for simulations of soil organic C dynamics in dryland regions. *Geoderma*, *200-201*, 18–30. https://doi.org/10.1016/j.geoderma.2013.01.021

Francaviglia, R., Coleman, K., Whitmore, A. P., Doro, L., Urracci, G., Rubino, M., & Ledda, L. (2012). Changes in soil organic carbon and climate change - Application of the RothC model in agro-silvo-pastoral Mediterranean systems. *Agricultural Systems*, *112*, 48–54. https://doi.org/10.1016/j.agsy.2012.07.001

Giongo, V., Coleman, K., Santana, M. D., Salviano, A. M., Olszveski, N., Silva, D. J., Cunha, T. J. F., Parente, A., Whitmore, A. P., & Richter, G. M. (2020). Optimizing multifunctional agroecosystems in irrigated dryland agriculture to restore soil carbon - Experiments and modelling. *Science of the Total Environment*, *725*, Article 138072. https://doi.org/10.1016/j.scitotenv.2020.138072

Harkness, D. D., Harrison, A. F., & Bacon, P. J. (1986). The temporal distribution of bomb carbon-14 in a forest soil. *Radiocarbon*, *28*(2A), 328–337. https://doi.org/10.1017/s0033822200007426

Hart, P. B. S. (1984). *Effects of soil type and past cropping on the nitrogen supplying ability of arable soils* University of Reading, UK].

Jenkinson, D. S. (1990). The Turnover of Organic-Carbon and Nitrogen in Soil. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, *329*(1255), 361–368.

Jenkinson, D. S., Adams, D. E., & Wild, A. (1991). Model Estimates of Co2 Emissions from Soil in Response to Global Warming. *Nature*, *351*(6324), 304–306.

Jenkinson, D. S., & Coleman, K. (1994). Calculating the Annual Input of Organic-Matter to Soil from Measurements of Total Organic-Carbon and Radiocarbon. *European*

Journal of Soil Science, *45*(2), 167–174.
Jenkinson, D. S., Harkness, D. D., Vance, E. D., Adams, D. E., & Harrison, A. F. (1992). Calculating Net Primary Production and Annual Input of Organic-Matter to Soil from the Amount and Radiocarbon Content of Soil Organic-Matter. *Soil Biology & Biochemistry*, *24*(4), 295–308.
Jenkinson, D. S., Hart, P. B. S., Rayner, J. H., & Parry, L. C. (1987). Modelling the turnover of organic matter in long-term experiments at Rothamsted. *INTECOL Bulletin*, *15*, 1–8.
Jenkinson, D. S., & Rayner, J. H. (1977). Turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science*, *123*(5), 298–305.
Levin, I., Kromer, B., Schoch-Fischer, H., Levin, I., Bruns, M., Munnich, M., Berdau, D., Vogel, J. C., & Munnich, K. O. (1997). *Delta 14 CO2 records from two sites in Central Europe. CDIAC, ESS-DIVE repository* (https://doi.org/doi:10.3334/CDIAC/ATG.027
Macdonald, A., Poulton, P., Clark, I., Scott, T., Glendining, M., Perryman, S., Storkey, J., Bell, J., Shield, I., McMillan, V., & Hawkins, J. (2018). *Guide to the Classical and Other Long-term experiments, Datasets and Sample Archive. Rothamsted Research*.
Müller, M. J. (1982). *Selected climatic data for a global set of standard stations for vegetation science*. Dr. W. Junk, Publishers. The Hague. https://doi.org/https://doi.org/10.1007/978-94-009-8040-2
Romanya, J., Cortina, J., Falloon, P., Coleman, K., & Smith, P. (2000). Modelling changes in soil organic matter after planting fast-growing Pinus radiata on Mediterranean agricultural soils [Article]. *European Journal of Soil Science*, *51*(4), 627–641.
Saggar, S., Parshotam, A., Sparling, G. P., Feltham, C. W., & Hart, P. B. S. (1996). C-14-labelled ryegrass turnover and residence times in soils varying in clay content and mineralogy [Article]. *Soil Biology & Biochemistry*, *28*(12), 1677–1686.
Shirato, Y., Hakamata, T., & Taniyama, I. (2004). Modified Rothamsted carbon model for andosols and its validation: Changing humus decomposition rate constant with pyrophosphate-extractable Al. *Soil Science and Plant Nutrition*, *50*(1), 149–158.
Smith, P., Smith, J. U., Powlson, D. S., McGill, W. B., Arah, J. R. M., Chertov, O. G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D. S., Jensen, L. S., Kelly, R. H., Klein-Gunnewiek, H., Komarov, A. S., Li, C., Molina, J. A. E., Mueller, T., Parton, W. J., Thornley, J. H. M., & Whitmore, A. P. (1997). A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma*, *81*(1-2), 153–225.
Sommers, L. E., Gilmour, C. M., Wildung, R. E., & Beck, S. M. (1981). The Effect of Water Potential on Decomposition Processes in Soils. In *Water Potential Relations in Soil Microbiology* (pp. 97–117). https://doi.org/https://doi.org/10.2136/sssaspecpub9.c3
Sparling, G. P., Cheshire, M. V., & Mundie, C. M. (1982). Effect of barley plants on the decomposition of c14-labeled soil organic-matter. *Journal of Soil Science*, *33*(1), 89–100.
Tate, K. R., Giltrap, D. J., Parshotam, A., Hewitt, A. E., Ross, D. J., Kenny, G. J., & Warrick, R. A. (1994, Oct 10–14). Impacts of climate change on soils and land systems in New Zealand. Wellington, New Zealand.

van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/https://doi.org/10.2136/sssaj1980.03615995004400050002x

Wösten, J. H. M., Lilly, A., Nemes, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma*, *90*(3), 169–185. https://doi.org/https://doi.org/10.1016/S0016-7061(98)00132-3