

# A multi-layer box model of carbon dynamics in soil

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**Abstract** A multi-layer box model (MLB) for quantification of carbon fluxes between soil and atmosphere has been developed. In the model, soil carbon reservoir is represented by two boxes: fast decomposition box (FDB) and slow decomposition box (SDB), characterised by substantially different turnover time (TT) of carbon compounds. Each box has an internal structure (sub-compartments) accounting for carbon deposited in consecutive time intervals. The rate of decomposition of carbon compounds in each sub-compartment is proportional to the carbon content. With the aid of the MLB model and the  $^{14}\text{C}$  signature of carbon dioxide, the fluxes entering and leaving the boxes, turnover time of carbon in each box, and the ratio of mass of carbon in the slow and fast box ( $M_s/M_f$ ) were calculated. The MLB model yields the turnover time of carbon in the FDB ( $\text{TT}_f$ ) *ca.* 14 for typical investigated soils of temperate climate ecosystems. The calculated contribution of the  $\text{CO}_2$  flux originating from the slow box ( $F_s$ ) to the total  $\text{CO}_2$  flux into the atmosphere ranges from 12% to 22%. These values are in agreement with experimental observations at different locations. Assuming that the input flux of carbon ( $F_{in}$ ) to the soil system is doubled within the period of 100 years, the soil buffering capacity for excess carbon predicted by the MLB model for typical soil parameters may vary in the range between 26% and 52%. The highest values are obtained for soils characterised by long  $\text{TT}_f$  and well developed old carbon pool.

**Key words** box model • soil  $\text{CO}_2$  •  $^{14}\text{C}$  • turnover time (TT) • carbon fluxes

## Introduction

Investigations of the dynamics of carbon cycle, rapidly intensified over the last twenty years, stimulated development of mathematical models used for quantitative description of ecosystems storing carbon. Division of the global carbon pool into compartments, mass of carbon comprised in each compartment and carbon fluxes exchanged between them are the basic parameters used in a class of models called lump-parameter models, which are widely applied in studying dynamics of carbon cycle. Quantitative modelling of natural processes is the most effective way of constructing prognoses of environment response to changing forcing.

Observed increase of the atmospheric  $\text{CO}_2$  concentration is the most prominent example of global scale forcing with potential far-reaching consequences e.g. [10, 11, 13, 17, 20, 22]. Global soil and detritus carbon pool is estimated to be 1580 Pg of carbon (1 Pg =  $10^{15}$  g) and is larger than the combined atmospheric and vegetation carbon reservoir [18]. Thus, the soil carbon reservoir is expected to act as a buffer, moderating anthropogenic increase of atmospheric  $\text{CO}_2$  concentration. However, fluxes of carbon (in the form of carbon dioxide) between soil and continental atmosphere belong still to the most uncertain elements of the global

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carbon cycle. Therefore precise assessment of the carbon tonnage bound in soils as well as decomposed and released back to the atmosphere as CO<sub>2</sub> is crucial for balancing carbon pools.

Early studies of soil carbon dioxide carried out by Haas *et al.* [6] showed a distinct dependence of the <sup>14</sup>C content in soil CO<sub>2</sub> on the depth and season of the year. Diffusion models proposed by Thorstenson *et al.* [19] considered root respiration as the only source of soil CO<sub>2</sub>. In another work [2], seasonal variation of root respiration as well as microbial decomposition were estimated by <sup>14</sup>C measurements in soil CO<sub>2</sub> for different soil types. Dynamics of soil organic carbon in grass and woodland ecosystems was also discussed by O'Brien [15], and Harkness *et al.* [7].

The subsequent studies of carbon circulation within soil itself and between soil and atmosphere [3, 5, 8, 9, 16, 21] confirmed complexity of the decomposition process and documented that its characterisation by a single value of turnover time is not possible. The climatic dependence of carbon turnover time in soil was supported by latitudinal gradient of this parameter found for both hemispheres for low-altitude, not water-stressed locations [1].

### Formulation of the MLB model

Analysis of carbon compounds present in bulk soil points to strong inhomogeneity of both physical and chemical form in which carbon appears. Observed stratification in the depth profile reflects differences in time of deposition as well as degree of decomposition of the primary form. Thus considering soil for modelling purpose as one well mixed box and not distinguishing inner structure is a simplification going too far.

The MLB model proposes boxes that are composed of layers. Each layer represents carbon deposited in well defined period of time e.g. within one year and can be identified in the depth profile of soil. Carbon introduced into the layer in the year of formation (first layer) has isotopic composition specific for this year and there is no mass exchange between layers i.e. each layer is closed with respect to input of new carbon. Number of layers comprised in a box can be arbitrarily fixed, however in calculations presented below, it is large or tends to infinity. Inner structure of the box allows following the "history" of each layer and, if necessary, to treat separately output flux coming from the particular layer or to form clusters of layers having the same parameters.

In the discussed multi-layer box model (MLB), input flux of carbon to the soil pool is represented by organic matter in vast majority consisting of plant debris ( $F_{in}$ ), and CO<sub>2</sub> coming from root respiration ( $F_r$ ). The output flux is composed of CO<sub>2</sub> leaving soil surface,  $F_{out}$ , and CO<sub>2</sub> that forms carbonates/bicarbonates,  $F_{cw}$ , feeding underground water reservoirs (Fig. 1). The soil carbon pool is divided into two pools: i) fast decomposition box (FDB), and ii) slow decomposition box (SDB). The general criterion of this division is the time of conversion of a given mass of organic matter present in soil into CO<sub>2</sub> that is then removed from the box (fluxes:  $F_s$ ,  $F_f$ , Fig. 1).

Flux of carbon dioxide finally going out of the system ( $F_{out}$ ) is a mixture of three components associated with fast ( $F_f$ ) and slow ( $F_s$ ) compartments, and with root respiration ( $F_r$ ) of the plant cover. Both slow and fast box in the MBL model have a layered structure of layers (sub-boxes) containing carbon introduced into the system within a certain period of time, e.g. one year ( $\Delta t = 1$  y). Carbon dioxide originating from root respiration forms a separate box, RRB, (Fig. 1) representing contemporary, fast circulating carbon in the gaseous form (CO<sub>2</sub> of the current year). Thus, the surface plants are controlling entirely dynamics of this component which depends on seasonal vegetation activity.

In the MBL model, the carbon compounds comprised in both boxes undergo decomposition with the rate proportional to the total mass of carbon in each box (and layer). For each layer one can write the equation (Eq. (1)) that has the same form for both slow and fast box. Compounds of Eq. (1) for the FDB, and SDB are distinguished by subscripts "f", and "s", respectively:

$$(1) \quad \frac{d}{dt} M_{f,s}^i = -\beta_{f,s} \cdot M_{f,s}^i$$

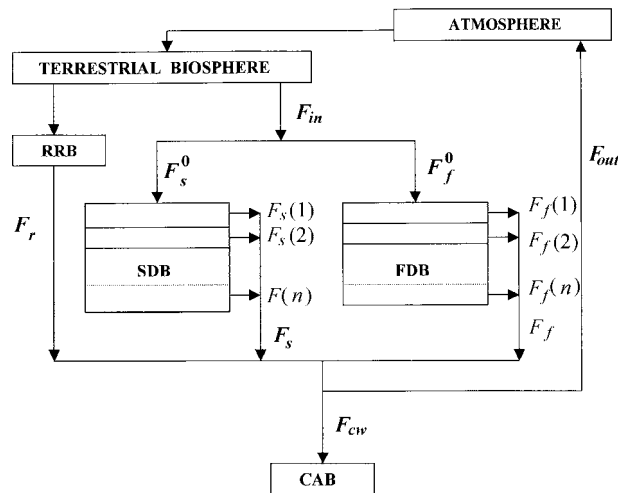
where:  $M_{f,s}^i$  – mass of carbon comprised in layer "i" of the FDB, and SDB (kg · m<sup>-2</sup>);  $\beta_{f,s}$  – decomposition constants for the FDB and SDB, respectively (y<sup>-1</sup>).

Thus, the output flux from the layer "i" of the FDB and SDB is

$$(2) \quad F_{f,s}^i = -\beta_{f,s} \cdot M_{f,s}^i$$

where:  $F_{f,s}^i$  – carbon output flux from the layer "i" of the FDB and SDB, respectively (kg · m<sup>-2</sup> · y<sup>-1</sup>).

Generally,  $\beta_f$  and  $\beta_s$  can be functions of time enabling individual computation for each layer. This is much



**Fig. 1.** Schematic illustration of the MLB model, and fluxes of CO<sub>2</sub> circulating within soil. SDB – slow decomposition box; FDB – fast decomposition box; RRB – root respiration box; CAB – box of inorganic carbon (carbonates/bicarbonates). Subscripts "f", and "s" refer to fluxes generated in FDB, and SDB, respectively. Variable "i" indicates layer of the box, the greater value the older layer.

more complicated when a one-box model is applied. In the presented below description, “ $\beta$ ” is assumed as constant, i.e. has the same value for each new formed layer and is not changing with time ( $\beta_{f,s}^i(t) = \beta_{f,s}$ ). In case when input and output fluxes are equal ( $F_f^0 = F_r, F_s^0 = F_s$ ), the FDB and SDB is in steady state, i.e. the total mass of carbon comprised in a given box is conserved ( $M_{f,s}(t) = M_{f,s}$ ). However, new layers are being formed one above another and at the same time the old ones reduce their carbon content due to decay of organic matter. Mass balance equation formulated for carbon fluxes circulating between soil and atmosphere (Fig. 1) one can write:

$$(3) \quad \frac{dM_f}{dt} + \frac{dM_s}{dt} = F_r + F_{in} - F_{out} - F_{cw}$$

and for steady state conditions equation has the form:

$$(3') \quad \frac{dM_f}{dt} + \frac{dM_s}{dt} = F_r + F_{in} - F_{out} - F_{cw} = 0$$

where:

$$(3'') \quad M_{f,s} = \sum_{i=0}^N M_{f,s}^i; \quad F_{f,s} = \sum_{i=0}^N F_{f,s}^i;$$

$$F_f + F_s + F_r = F_{cw} + F_{out}.$$

In general, each component in Eqs. (3), (3') and (3'') may vary with time.

At the surface, we observe a mixture of carbon (CO<sub>2</sub>) originating from different layers belonging to the both boxes. The output flux from the single layer “ $i$ ” at time “ $t$ ” is:

$$(4) \quad F_{f,s}^i(t) = F_{f,s}^0(t - \Delta t \cdot i) \cdot (1 - \exp(-\beta_{f,s} \cdot \Delta t)) \cdot \exp(-\beta_{f,s} \cdot \Delta t \cdot i)$$

where:  $F_{f,s}^0(t - \Delta t \cdot i)$  – input flux of carbon to the FDB and SDB, respectively, at time “ $t - \Delta t \cdot i$ ”, (kg·m<sup>-2</sup>·y<sup>-1</sup>);  $\Delta t$  – time interval between the formation of consecutive layers; if expressed in years then  $\Delta t = 1$ .

Consequently, the product “ $\Delta t \cdot i$ ” in the exponent is replaced by consecutive natural numbers simplifying the formula. The carbon output flux  $F_f(t)$  and  $F_s(t)$  from the fast and slow box, respectively, is a sum of partial fluxes generated by consecutive layers in time interval  $\Delta t$ :

$$(4') \quad F_{f,s}^i(t) = (1 - \exp(-\beta_{f,s} \cdot \Delta t)) \cdot \sum_{i=0}^N F_{f,s}^0(t - \Delta t \cdot i) \cdot \exp(-\beta_{f,s} \cdot \Delta t \cdot i).$$

Finally, the total CO<sub>2</sub> flux at the soil-atmosphere interface is composed of carbon representing the spectrum of ages spanning over hundreds and thousands of years, for the FDB and SDB reservoir, respectively.

Using Eq. (4'), one can show that the boxes are in steady state, i.e. the input and output fluxes are equal

( $F_{f,s} = F_{f,s}^0 = \text{const}$ ) if the input flux to the box is constant ( $F_{f,s}^0(t) = F_{f,s}^0$ ) for the time long enough with respect to the  $\beta_{f,s}$  value and when the summation extends over sufficiently large number of layers ( $N \rightarrow \infty$ ). The equality of fluxes ( $F_s = F_s^0$  and  $F_f = F_f^0$ ) is equivalent to conservation of the total mass of carbon in the FDB and SDB reservoir, respectively. In the case when  $F_{f,s}^0(t)$  is a function of time, the box acts as a sink or a source of carbon.

The generally accepted measure for the rate of conversion of organic carbon to carbon dioxide is turnover time (TT) defined as the ratio of carbon mass comprised in the box to the exchange flux. The definition of TT holds for the steady-state situation, i.e. when mass of carbon comprised in the box is constant in time and input and output fluxes are equal. TT can be also calculated as time necessary for decomposition of carbon mass comprised in the box. The meaning of TT is limited to stationary conditions in the box and can be expressed by the following formula for FDB and SDB (subscripts “ $f$ ” and “ $s$ ”, respectively):

$$(5) \quad \text{TT}_{f,s} = \frac{M_{f,s}}{F_{f,s}}$$

where:  $M_{f,s}$  stands for the sum of carbon in consecutive layers of the boxes

$$(5') \quad M_{f,s} = \sum_{i=0}^{\infty} F_{f,s}^0 \cdot \Delta t \cdot \exp(-\beta_{f,s} \cdot \Delta t \cdot i)$$

$$= \frac{F_{f,s}^0 \cdot \Delta t}{1 - \exp(-\beta_{f,s} \cdot \Delta t)}.$$

The product  $F_{f,s}^0 \cdot \Delta t$  represents the mass of carbon deposited in a given layer and since  $F_{f,s}^0 = F_{f,s}$

$$(5'') \quad \text{TT}_{f,s} = \frac{\Delta t}{1 - \exp(-\beta_{f,s} \cdot \Delta t)}.$$

Putting  $\Delta t = 1$  year, and expressing  $\beta_{f,s}$  also in years, Eq. (5'') gets a simpler form (TT<sub>f,s</sub> is in years):

$$(5''') \quad \text{TT}_{f,s} = \text{TT}_{f,s}^* = \frac{1}{1 - \exp(-\beta_{f,s})}.$$

Eq. (5''') also defines the apparent turnover time, TT<sub>f,s</sub><sup>\*</sup>, used when the conditions are not steady state (TT<sub>f,s</sub><sup>\*</sup> is expressed in years). For small values of  $\beta_{f,s}$  one can use with the sufficient accuracy:

$$(5''''') \quad \text{TT}_{f,s} = \text{TT}_{f,s}^* = \frac{1}{\beta_{f,s}}.$$

It is worth noticing that the decomposition constant,  $\beta_{f,s}$ , is not limited to steady state conditions in contrary to turnover time, TT<sub>f,s</sub>, and characterises the dynamics of a given box also in case when it behaves as a sink or a source.

Each of the two boxes representing part of the soil carbon reservoir (Fig. 1) contains a certain mass of carbon characterised by  $TT_f$  and  $TT_s$ . Taking advantage of the definition of turnover time, one can derive the ratio of the output fluxes from each layer as follows:

$$(6) \quad \frac{F_f(i)}{F_s(i)} = \frac{M_f(i)}{M_s(i)} \cdot \frac{TT_s}{TT_f}.$$

After summation over all layers:

$$(7) \quad \frac{F_f}{F_s} = \frac{M_f}{M_s} \cdot \frac{TT_s}{TT_f}.$$

Knowledge of numerical value of any of two ratios in Eq. (7) enables calculation of the third one. Usually  $F_f/F_s$  and  $TT_s/TT_f$  are measured/assessed experimentally, and  $M_f/M_s$  is calculated.

Part of  $CO_2$  generated in the soil is dissolved in infiltrating water and forms the pool of total dissolved inorganic carbon (mostly carbonates and bicarbonates). This carbon sink constitutes a separate carbon flux,  $F_{cw}$ , (Fig. 1) which enters the box of dissolved carbonates, CAB, leaving reservoir of the soil organic carbon. A backward flux from the CAB to the soil  $CO_2$  is considered negligible.

Root respiration, especially active during vegetation period, is strongly related to plant cover and generates additional  $CO_2$  flux,  $F_r$ , that supplies surface soil layers with additional  $CO_2$ . This  $CO_2$ , marked in Fig. 1 as a separate box, RRB, represents atmospheric carbon relevant to the current vegetation period (delay between assimilation and root respiration can be neglected).

#### $^{14}C$ in soil carbon modelled by the MLB model

Considering  $^{14}C$  as a natural tracer present in atmospheric  $CO_2$  and, in consequence, in any "fresh" organic matter deposited in the soil, one can calculate specific radiocarbon activity,  $^{14}A(t)$ , appearing in the output  $CO_2$  flux from the slow and fast box. Taking into account the layered structure of the two boxes, the partial output fluxes from consecutive layers (Eq. (4)), and decay of  $^{14}C$  since the time of deposition, the specific  $^{14}C$  activity in the total  $CO_2$  output flux,  $A_{f,s}(t)$ , is calculated as a weighted mean of fluxes from consecutive layers summed over all layers:

$$(8) \quad A_{f,s}(t) = \frac{\sum_{i=0}^N F_{f,s}^0(t - \Delta t \cdot i) \cdot A^0(t - \Delta t \cdot i) \cdot \exp(-\Delta t \cdot i \cdot (\beta_{f,s} + \lambda))}{\sum_{i=0}^N F_{f,s}^0(t - \Delta t \cdot i) \cdot \exp(-\Delta t \cdot i \cdot \beta_{f,s})}$$

where:  $\lambda$  – decay constant of  $^{14}C$ ;  $A^0(t - \Delta t \cdot i)$  –  $^{14}C$  specific activity in carbon deposited at time  $(t - \Delta t \cdot i)$ ; if:  $F_{f,s}^0(t - \Delta t \cdot i) = F_{f,s}^0 = \text{const}$ ,  $\Delta t = 1$ , and  $N \rightarrow \infty$ , Eq. (8) becomes simpler:

$$(9) \quad A_{f,s}(t) = \left(1 - \exp(-\beta_{f,s})\right) \cdot \sum_{i=1}^{\infty} A^0(t - i) \cdot \exp(-i \cdot (\beta_{f,s} + \lambda)).$$

This equation is valid for slow and fast decomposition box, assuming the same structure of the boxes and the same isotopic composition of the input flux. The calculated  $A_{f,s}(t)$  values as a function of time, represent temporal distribution of  $^{14}CO_2$  in the output flux of the FDB and SDB box, respectively. Practical advantage of the layer structure of the box is demonstrated in Eqs. (8) and (9), when isotopic composition of the output flux is to be computed at varying  $^{14}C$  activity in the input flux usually performed in numeric form. Time interval in which  $A_{f,s}(t)$  is defined depends on radiocarbon input function  $A^0(t - \Delta t \cdot i)$ . This function should cover a period of time long enough with respect to the exponent component in summation (Eq. (9)) dependent on the  $\beta_{f,s}$  value. In practice, the  $A^0(t - \Delta t \cdot i)$  function is taken as the  $^{14}C$  activity of atmospheric  $CO_2$  relevant to the location of investigated soil. Usually, the numerical values of this function are partly compiled from experimental data and partly obtained by extrapolation/interpolation of  $^{14}C$  records known for other regions.

The  $CO_2$  flux leaving the soil surface contains component of root respiration,  $F_r$ , (Fig. 1) influencing shallow soil layers and depending on the type of surface vegetation and season of the year. The  $^{14}C$  content of the root respiration flux is the same as in the surrounding atmosphere, since the delay between assimilated and respired  $CO_2$  is negligibly small with respect to the decay of  $^{14}C$ .

Flux of  $CO_2$  that enters the inorganic carbon pool,  $F_{cw}$ , (Fig. 1) does not participate in the  $CO_2$  flux entering the atmosphere. This is, however, the main channel of supply carbon to groundwater systems. Estimation of this flux enables closing of the balance equation (Eq. (3)).

The total  $CO_2$  flux leaving the soil surface ( $F_{out}$ ) is a mixture of three components:  $F_f$ ,  $F_s$ , and  $F_r$ :

$$(10) \quad F_{out}(t) = F_f(t) + F_s(t) + F_r(t)$$

with relative contributions labelled as  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$ :

$$(11) \quad \alpha_1(t) = \frac{F_f(t)}{F_{out}(t)}, \quad \alpha_2(t) = \frac{F_s(t)}{F_{out}(t)}, \quad \alpha_3(t) = \frac{F_r(t)}{F_{out}(t)}.$$

The  $^{14}C$  signature of each flux component may be different depending on the soil system parameters ( $F_f$ ,  $F_s$ ), and the local atmospheric  $^{14}C$  level ( $F_r$ ). The MBL model run with a chosen set of parameters and appropriate input functions ( $F_{f,s}^0(t - \Delta t \cdot i)$  and  $A^0(t - \Delta t \cdot i)$ ) delivers time record of  $^{14}C$  specific activity in the total soil  $CO_2$  flux entering the atmosphere ( $A_m(t)$ ).

$$(12) \quad A_m(t) = \alpha_1(t) \cdot A_f(t) + \alpha_2(t) \cdot A_s(t) + \alpha_3(t) \cdot A_r(t).$$

Generally, the mixing ratios defined above (Eq. (12)) can vary with time and is difficult to find functional dependence with acceptable accuracy. In case of multi-

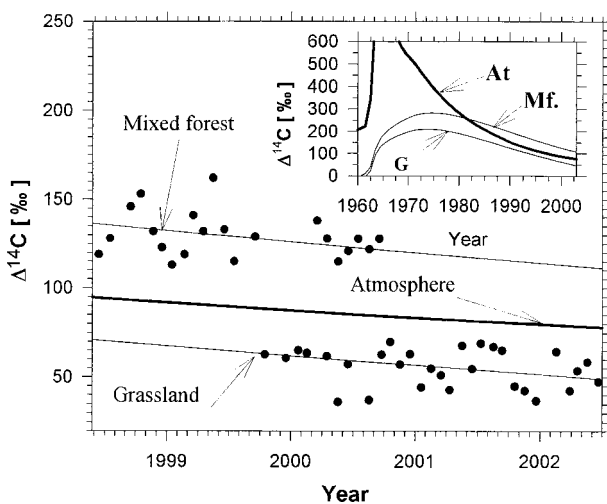
year records of yearly mean values one puts:  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  as constants for the entire length of the record. Seasonal fluctuations of mixing ratios modulating the long-term trend can be estimated considering local climatic parameters and, if necessary, regarded in the model.

The  $A_m(t)$  function derived in this way represents a real record of  $^{14}\text{C}$  in the soil derived  $\text{CO}_2$ . The MLB model run for particular input functions i.e. flux of  $\text{CO}_2$  and  $^{14}\text{C}$  specific activity produces  $A_m(t)$  functions which are then fitted to the experimental data, with different values of fitting parameters.

### Carbon dynamics in the MLB model

The fast and slow decomposition boxes in the MLB model comprise a certain mass of carbon, which under steady state conditions, remains constant and can be calculated, e.g. with the use of Eq. (7). Both the record  $^{14}\text{C}$  content in the input fluxes and time record of the  $^{14}\text{CO}_2$  respired by soil reservoir are necessary for the experimental assessment of turnover times of carbon in fast and slow box, as well as the relation between carbon fluxes from these boxes.

The discussed MLB model was run for  $^{14}\text{CO}_2$  experimental data collected in southern Poland. Input functions used for calculations were constructed on the ground of Schauinsland [14] (Fig. 2, insert) and Kraków [12] data in numeric form, while the output curves fitted records of  $^{14}\text{C}$  activity in  $\text{CO}_2$  respired by soil representing two different ecosystems: i) grassland, and ii) mixed forest [4]. Each of the collected samples integrated the signal over time interval of ca. 1 month, while the total record covered time period of at least 1 year. Curves fitted to experimental data collected at these two sampling points (Fig. 2) yield turnover time ( $\text{TT}_f$ ) of 14 years in both cases, and the ratio of masses in the slow and fast box ( $M_s/M_f$ ) 40, and 22, respectively.



**Fig. 2.**  $\Delta^{14}\text{C}$  records in  $\text{CO}_2$  respired by soil sampled at the soil surface in southern Poland (mixed forest – Mf. and grassland – G. [4]). Thin lines represent model calculations for the soil  $^{14}\text{CO}_2$  while solid line shows the reference level of  $\Delta^{14}\text{C}$  in atmospheric  $\text{CO}_2$  (At) for Schauinsland [14]. In the insert the same lines are extended back to 1960.

Contribution of the flux from slow decomposition box ( $F_s$ ) varies from 12% for mixed wood to 21% for grassland. These values indicate a remarkable contribution of the old component in case of the grassland and the presented above estimates of  $M_s/M_f$  confirms that the “slow” box (SDB) can comprise to ca. forty times more carbon than the fast one, and constitutes major pool of carbon present in soil. On the other hand, the SDB contributes in a relatively small percentage to the final flux of  $\text{CO}_2$  respired by soil. However, the slow decomposition box (SDB) also comprises a certain  $^{14}\text{C}$  activity, the  $\text{TT}_s$  value cannot be calculated in the way used for FDB because changes of  $^{14}\text{C}$  activity in the decomposed  $^{14}\text{CO}_2$  are not detectable. In this situation,  $\text{TT}_s$  can be assessed by measurement of  $^{14}\text{C}$  age of the soil organic matter at the depth corresponding to the SDB. Assuming the radiocarbon age represents average age of the SDB, one can use the following equation:

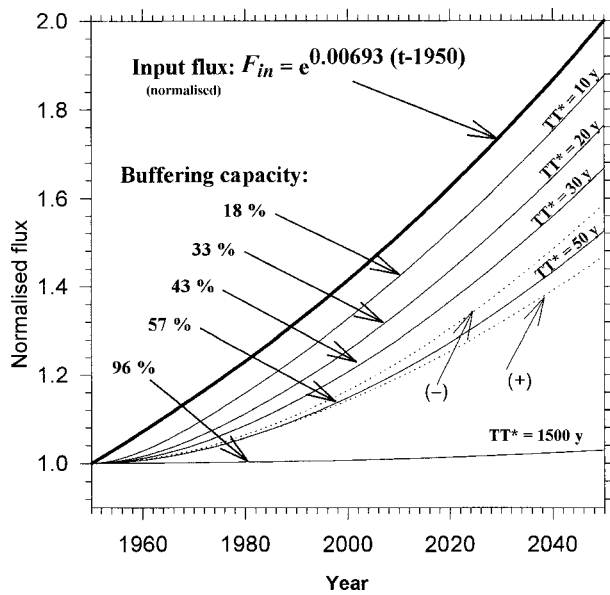
$$(13) \quad \text{TT}_s = \frac{\exp(-\lambda) - \exp(\lambda \cdot t)}{\exp(-\lambda) - 1}$$

where:  $t$  – average  $^{14}\text{C}$  age (y);  $\lambda$  – decay constant of  $^{14}\text{C}$  ( $\text{y}^{-1}$ );  $\text{TT}_s$  is expressed in years.

### Simulated response of the soil to increasing input carbon flux

Exchange of carbon between atmosphere and soil in steady state conditions analysed by the MLB model or other similar models delivers estimates of the soil parameters which can be verified by observation data. In addition, accumulation in the soil of excess carbon present in atmosphere can be also analysed using the MLB model. Let us consider a scenario in which in the course of 100 years (e.g. from 1950 to 2050) the flux of organic carbon entering the soil reservoir is exponentially increasing to doubled value (Fig. 3). The expected response of the soil reservoir to continuously changing input carbon flux should be the increased output flux. Relation between these two fluxes is controlled by the decomposition constant,  $\beta$ , which characterises dynamics of the soil reservoir. Apparent turnover time,  $\text{TT}_{f,s}^*$ , introduced for the case of not steady state conditions when the definition of  $\text{TT}_{f,s}$  (Eq. (5)) does not apply, is defined by Eq. (5’). Because the apparent turnover time,  $\text{TT}_{f,s}^*$ , in further discussion refers to one box only not distinguishing between FDB and SDB, the subscript “f” or “s” is abandoned. The  $\text{TT}^*$  has meaning only in relation to the  $\beta$  value which is constant in contrary to input and output fluxes and carbon mass comprised in the box. Normalised fluxes of carbon are plotted in Fig. 3 as functions of time, for different  $\text{TT}^*$  values (10–1500 y). They reveal a similar shape in response to forcing, but their slopes become lower with increasing  $\text{TT}^*$  values.

The output flux, what one could expect, is sensitive to dynamic changes of  $\text{TT}^*$  i.e. when  $\text{TT}^*$  (and  $\beta$ ) varies in time. As an example demonstrating magnitude of this effect, the output flux was calculated for case when  $\text{TT}^* = 50$  y increases or decreases by 0.2% per year of



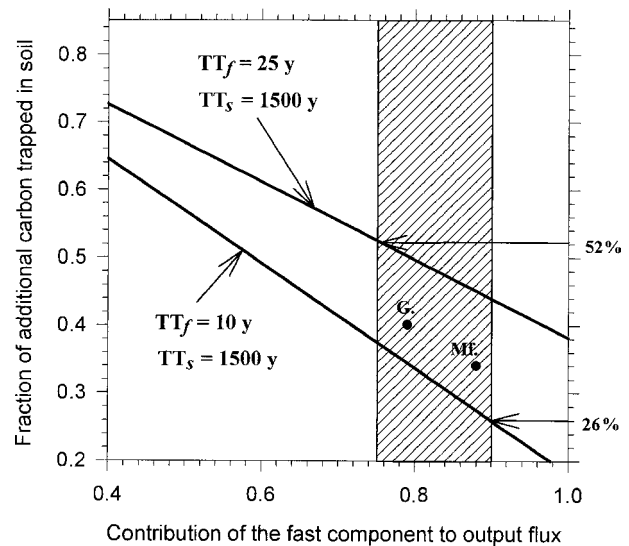
**Fig. 3.** Output fluxes of carbon from the box for different turnover times ( $TT^*$ ) as response to exponentially increasing input flux normalised to 1.0 in 1950 and 2.0 in 2050. Fluxes are expressed as mass of carbon per unit time and unit area. Buffering capacities are calculated as per cent of the excess mass of carbon trapped in the box. Dotted lines represent output flux for  $TT^* = 50$  y in 1950 and then decreasing (-) and increasing (+) by 0.2% of the initial value per year.

the initial value in the discussed period of 100 ( $TT^*(t) = 50(1 \pm (t - 1950) \cdot 0.002)$ ). Result of modelling (Fig. 3) shows that function of the output flux is also of exponential type and quickly approaches the response represented by  $TT^* = 40$  y and 60 y.

The estimated total mass of the “trapped” carbon introduced additionally to the soil reservoir and expressed as percentage of the total excess carbon varies from *ca.* 18% for  $TT^* = 10$  y to 57% for  $TT^* = 50$  y and 96% for  $TT^* = 1500$  y (Fig. 3). These values point to a strong dependence of the soil buffering capacity on the turnover time of carbon.

Considering the model parameters computed for typical soils investigated in temperate climate ecosystems one can accept ranges: of  $TT_f^*$  between *ca.* 10 and 25 years and the contribution of the  $CO_2$  originating from the slow box in the output flux ( $\alpha_2$ ) between 10% and 25% ( $TT_s = 1500$  y). When these values are introduced into the MLB model and assuming scenario in which input carbon flux is doubled within 100 years the mass of excess carbon “trapped” in slow and fast decomposition box can be calculated. With the above-indicated parameters (Fig. 4) the MLB model suggest that the soil is a sink for carbon, trapping from 26% to 52% of the excess carbon introduced in the form of organic matter. Parameters calculated by the MLB model for the investigated mixed forest and grassland ecosystem presented above allow to assess buffering capacity to *ca.* 35% and 40%, respectively (Fig. 4). Buffering capacity is greatest for soil with well developed pool of old carbon.

One box models which assume well mixed content and do not distinguish between carbon introduced in consecutive years show a similar response as the MLB



**Fig. 4.** Buffering capacity of soil represented by two boxes: FDB, and SDB computed for the observed ranges of  $TT_f$  (10–25 y) and contribution of fast component to output flux (75–90%, dashed area),  $TT_s = 1500$  y. Arrows indicate lower and upper limit of the buffering capacity. The modelled soil of mixed forest (Mf.) and grassland (G.) ecosystem is marked by dots in the dashed area.

to exponentially increasing input flux, however in case when one analyses isotopic signature of input flux varying in time assumption of well mixing significantly changes real situation. Serious difficulties arise in solving one box system when residence time should be considered as not constant.

## Conclusions

The discussed MLB model is a useful diagnostic tool for studying carbon dynamics in soil offering a simple way of calculations. The  $^{14}C$  used in the model as tracer of carbon, enables computation of turnover times in slow and fast decomposition compartments of the soil and carbon fluxes from these boxes, thus characterising dynamics of carbon exchange between soil and atmosphere.

The response of the MLB model to time dependent input function for continuously increasing supply of organic matter with the doubling time of 100 years, points to soil as a sink for excess carbon. The soil carbon trapping capacity for the typical soil parameters varies from 26% to 52%.

Better knowledge on soil buffering capacity is crucial for predicting future environmental changes as reaction to constant increase of atmospheric  $CO_2$  concentration and for implementation of sustainable agriculture. The isotopic techniques appeared to be a useful tool providing necessary data for better understanding the dynamics of carbon turnover and carbon storage capacity in soils.

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