



Short communication

Quantitative description of vertical organic matter distribution in real soil profiles by means a simple continuous model

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ABSTRACT

Previously we have proposed a continuous model of soil organic matter (SOM) transformation which was based on describing only the most general notions of this process – a gradual increase in SOM stability toward transformation, occurring concurrently with partial decomposition of SOM. The model provided qualitative description of vertical SOM distributions in different soils. In the present study this model has been modified to make the description more realistic. The study demonstrates quantitative correspondence between the calculated and averaged observed vertical distributions of SOM for different biomes.

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1. Introduction

In a previous study, we proposed a simple continuous model of SOM transformation and decomposition (Bartsev and Pochekutov, 2015). That model was based on the most general notions of these processes: a gradual increase in the stability of SOM toward transformation, which occurs simultaneously with decomposition of some part of SOM. The continuous scale of stability of the matter used in the basic model was the rate of further transformation of SOM into more stable forms. Then, we proposed a modified model, which established a one-to-one correspondence between the stationary SOM distributions along the transformation rate and along the depth in soil profile. For that model, we demonstrated qualitative correspondence of the patterns of SOM vertical distribution curves to those for various types of real soils (Bartsev and Pochekutov, 2016).

Although derivation of model equations in the previous papers (Bartsev and Pochekutov, 2015, 2016) was described in terms of the classical theory of humification (Essington, 2004), the model can be used within the framework of both this theory and any other SOM transformation concepts that suggest a gradual increase in SOM stability toward transformation and decomposition. These are the concepts suggesting, e.g., an increase in SOM stability caused by an

increase in its inaccessibility and protection against decomposers (von Lützow et al., 2006) or even by an increase in the proportion of stable compounds in the plant litter due to more rapid mineralization of readily mineralized substances (Berg and McClaugherty, 2008). The reason why this model is so universal is that it has been constructed using a very simple approach, which involves a phenomenological representation of the most general notions about the nature and direction of SOM transformation process, providing no details or internal mechanisms of these processes, which would connect the model to certain theoretical notions of organic matter transformation in soil.

2. The model equations and their new modification

2.1. The transformation equations

The basic equation of the model (Bartsev and Pochekutov, 2015):

$$\frac{\partial C(h, t)}{\partial t} - \frac{\partial}{\partial h} (h^2 C(h, t)) = -k(h)C(h, t) + D(h, t) \quad (1)$$

describes SOM transformation as movement of the matter along a continuous scale representing the degrees of stability of the matter toward further transformation (including decomposition). The rate of SOM transformation into a more stable form is used as this scale, h . In terms of the classical theory of humification, h means the rate of humification of the matter. $C(h, t)$ is SOM distribution along scale h , changing over time; $k(h)$ is coefficient of mineralization rate, assigned in the existing versions of the model from the

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empirical function $k(h) = bh^p$, where b and p are adjustable parameters (interpreted elsewhere (Bartsev and Pochekutov, 2016)). Plant litter is described by its input rate $D(h, t)$, which is defined in the model from an approximate equation

$$D(h) = \sum_i D_{0i} \delta(h - h_{0i}), \quad (2)$$

where δ is the Dirac delta function, and index i numbers plant litter components characterized by their annual average amount D_{0i} and initial transformation rate h_{0i} .

When plant litter input is defined by (2), Eq. (1) can be written for $C_i(h, t)$ – the distribution of transformation products of each litter component. Then, the distribution of the total SOM is expressed as $C(h, t) = \sum_i C_i(h, t)$.

In the stationary case, solution of Eq. (1) written for $C_i(h, t)$ has the following form:

$$\bar{C}_i(h) = \frac{D_{0i}}{h^2} \exp\left(\frac{b}{p-1}(h^{p-1} - h_{0i}^{p-1})\right) (1 - \theta(h - h_{0i})), \quad (3)$$

where θ is the Heaviside step function.

In this study, in order to bring the model concepts closer to the notions of the nature of soil processes, we propose a modified model, which assumes that not all matter in the soil simultaneously undergoes transformation.

In any stage of transformation of the matter, only some part of this matter undergoes transformation at any given time. If reactions of both decomposition and transition to a more stable form are described by the laws of chemical kinetics, at any moment there is a part of the matter that has entered into the reaction and a part of the matter that has not. Then, Eq. (1) only describes the dynamics of the part of the matter that undergoes transformation at a given time. Moreover, for reasons described in a review by von Lützow et al. (2006) some of the SOM may become inaccessible to the effects of biological or chemical factors causing transformation of the matter.

Without going into great detail, we can describe the total result of the operation of these mechanisms in a generalized way as follows. The part of the SOM that is undergoing transformation at a given time will be called active SOM, and its distribution will be denoted by $c(h, t)$. The other part of the SOM, which is not undergoing transformation at the same time, will be called inactive SOM, and its distribution will be denoted by $s(h, t)$. The distribution of the total SOM will be expressed as $C(h, t) = c(h, t) + s(h, t)$. Assuming that the rate of transition of the matter from the active state to the inactive one can be expressed as $\beta(h)c(h, t)$ and the rate of transition of the matter from the inactive state to the active one as $\alpha(h)s(h, t)$, we obtain a system of equations describing the total SOM dynamics in both forms:

$$\frac{\partial c(h, t)}{\partial t} - \frac{\partial}{\partial h} (h^2 c(h, t)) = -bh^p c(h, t) + D(h, t) - \beta(h)c(h, t) + \alpha(h)s(h, t); \quad (4)$$

$$\frac{\partial s(h, t)}{\partial t} = \beta(h)c(h, t) - \alpha(h)s(h, t). \quad (5)$$

In the stationary case, $\beta(h)\bar{c}(h) = \alpha(h)\bar{s}(h)$, and (4) will assume the form that fully coincides with the stationary form of Eq. (1), and, hence, the solution of this equation will have the form of (3). Then, the total stationary distribution of SOM will be

$$\bar{C}(h) = \left(1 + \frac{\beta(h)}{\alpha(h)}\right) \bar{c}(h). \quad (6)$$

Let us assume that $\beta(h)$ and $\alpha(h)$ can be approximated by the simplest linear functions, $\beta(h) = qh$, $\alpha(h) = rh$, where q and r are

positive constants. Then, the distribution of the products of transformation of the i th litter component will take the following form:

$$\bar{C}_i(h) = \left(1 + \frac{q}{r}\right) \frac{D_{0i}}{h^2} \exp\left(\frac{b}{p-1}(h^{p-1} - h_{0i}^{p-1})\right) (1 - \theta(h - h_{0i})). \quad (7)$$

In this modification of the model, only one new parameter, q/r , is introduced into the equations. This parameter denotes how many times the amount of inactive SOM is different from the amount of active SOM.

2.2. The vertical transport equations

In order to establish one-to-one correspondence between the stationary SOM distributions along the transformation rate h and along the depth z in soil profile, one should assign $w(h) \equiv dz/dt$. The equation of relation between scales h and z that we derived previously (Bartsev and Pochekutov, 2016, Eq. (9)), in the general case for the arbitrary $w(h)$ form, will be written as

$$\frac{dh}{dz} = -\frac{h^2}{w(h)}. \quad (8)$$

The stationary distribution of SOM along the scale z , $\bar{C}(z)$, will be related to the stationary distribution of SOM along the scale h , $\bar{C}(h)$, by the equation

$$\bar{C}(z) = J \cdot \bar{C}(h(z)), \quad (9)$$

where $J \equiv -dh/dz$ is transition Jacobian from scale h to scale z (Bartsev and Pochekutov, 2016).

While previously (Bartsev and Pochekutov, 2016) we assumed $w(h) = ah$, we now assume

$$w(h) = ah + A, \quad (10)$$

where a and A are nonnegative constants. Thus, for any substance, its vertical transport velocity, w , consists of two components: one component is determined by the stability of the substance and the other is the same for all substances in the soil. This also brings model concepts closer to processes in real soils. Summand A is added to take into account possible vertical transport factors that affect particles of the matter irrespective of its degree of transformation, such as transport of particles with the liquid when large amounts of water percolate through the soil.

By solving the differential Eq. (8) taking into account (10) and initial condition $h(z=0) = h_{0i}$, we obtain a new expression of the relation between scales z and h :

$$z = a \log\left(\frac{h_{0i}}{h}\right) + A \left(\frac{1}{h} - \frac{1}{h_{0i}}\right). \quad (11)$$

The function $h(z)$ necessary for further computations can only be obtained from this by numerically solving the transcendental Eq. (11) relative to h . For each plant litter component that differs from other components in the h_{0i} value, function $h(z)$ must be calculated individually, using this very value of h_{0i} .

As follows from (8) and (10), Jacobian J in Eq. (9) assumes the form $(h^2(z))/(ah(z) + A)$. Then Eq. (9), taking into account (7) for products of transformation of the i th component of plant litter will be written as

$$\bar{C}_i(z) = \frac{(1 + \frac{q}{r})D_{0i}}{ah(z) + A} \exp\left(\frac{b}{p-1}(h^{p-1}(z) - h_{0i}^{p-1})\right) \theta(z). \quad (12)$$

Eq. (12) holds for products of transformation of plant litter components falling onto soil surface such as aboveground parts of plants. To make an accurate description of the root litter, one should take into account that roots and, hence, root litter are distributed over depth along the soil profile. To take into account the depth-distributed input of the root litter, one must know its distribution function, $\mathcal{D}_R(z, h)$. In the simple case, if all root litter is

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