



Short communication

A continual model of soil organic matter transformations based on a scale of transformation rate

Sergey I. Bartsev^{a,b}, Aleksei A. Pochekutov^{a,*}^a Institute of Biophysics SB RAS, Krasnoyarsk, Russia^b Institute of Fundamental Biology and Biotechnology of Siberian Federal University, Krasnoyarsk, Russia

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ABSTRACT

The study proposes a model of transformation and decomposition of soil organic matter, based on using the rate of matter transformation as a continual scale of its transformation degree. The model is represented by one partial derivative differential equation that has an analytical solution. This model has only two adjustable parameters, while the number of experimentally determined parameters depends on how detailed the description of the plant litter is supposed to be. The model has been tested, and model parameters have been evaluated by comparing model predictions with the literature data on the stock of soil organic matter in different types of ecosystems.

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1. Introduction

Transformation of soil organic matter (SOM) is a complicated multistage process. General trend of this process is a conversion of the readily transformed matter into more recalcitrant compounds (humification). Simultaneously, part of SOM being decomposed to simple inorganic compounds and leaves the soil (mineralization). Exact formulas of most of the compounds, the number of stages of SOM transformation, and exact transformation rate coefficients are unknown (Orlov, 1992).

The most frequently used mathematical models of SOM transformation are those based on kinetic equations (Manzoni et al., 2009; Manzoni and Porporato, 2009). In the majority of these models, SOM is divided into several compartments, whose decomposition rates differ by approximately a factor of 10. The compartmental approach, however, has the following limitations: the random division into compartments and the complexity involved in determining the parameters of the models consisting of a large number of equations (Ågren and Bosatta, 1998).

Another approach to the mathematical description of SOM transformation processes is continual description, which shows more clearly the multistage nature of SOM transformation and its numerous stages. This approach describes transformation as

movement of the matter along a scale representing the degrees of stability of the matter toward transformation. A simple version of the continual description of organic matter transformation was proposed by Carpenter (1981) to describe decomposition of detritus in aquatic ecosystems. The author used the continuum of an abstract value, decomposability, as the scale.

The continual method of describing SOM transformation was developed by Ågren and Bosatta (1998) and Bosatta and Ågren (2003). The authors proposed a scale of substrate quality, which expressed the accessibility of the matter to SOM-transforming soil bacteria, and, based on this scale, derived a general integro-differential equation expressed in partial derivatives. That equation was used as a basis to construct a family of models that described temporal dynamics of SOM distribution along that scale. In these models, SOM transformation is described explicitly, as a result of activities of the soil decomposer community. That description entailed a considerable increase in the complexity of the model equations and the use of a large number of unknown or difficult to determine parameters and functions.

Sierra et al. (2011) proposed a normalized decomposability rank scale, which basically corresponds to the quality scale. Mathematical description of SOM transformation as a Markov process (Sierra et al., 2011) actually changes the continual model into a discrete one, with a great number of compartments.

Forney and Rothman (2012) proposed a continual scale of decay rate constant. However they used this scale for modelling of plant litter decomposition but not of humification.

* Corresponding author. Tel.: +7 3912494328.

E-mail addresses: bartsev@yandex.ru (S.I. Bartsev), a-a-po@mail.ru (A.A. Pochekutov).

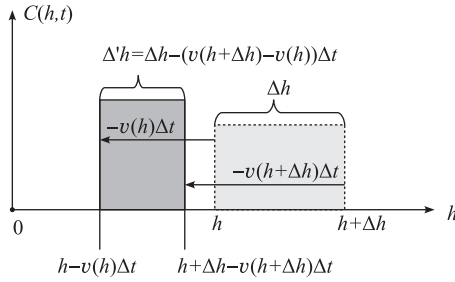


Fig. 1. SOM transformations as a motion along a scale of the humification rate. Right rectangle denotes an amount of SOM with the humification rate h in a range $(h, h + \Delta h)$ at time t . Left rectangle denotes this amount of SOM at time $t + \Delta t$. Note that the range of h becomes shorter and SOM concentration increases with time.

The use of SOM humification rate as a scale of organic matter humification degree, which we previously proposed (Bartsev and Pochekutov, 2013), gives a simple continual model of SOM transformation with a small number of parameters. Testing of the first version of this model showed that plant litter input should be described in a different way, and, thus, another version of the model equation was constructed, as reported in this study.

2. A continual equation of SOM transformation

The proposed model describes the process of SOM transformation as dynamics of distribution of organic matter amounts $C(h, t)$ according to the rates of their humification, h , at time point t . That is, the amount of SOM whose humification rate at time point t ranges between h and $h + dh$ is equal to $C(h, t) \cdot dh$. In this model, value h is regarded as the only indication of the degree of SOM humification, which decreases as the process of humification develops. This leftward shift along the h scale corresponds to the transformation of the matter into more stable forms.

In accordance with the model, any SOM is continuously transformed, causing its h to decrease, at a velocity $dh/dt = -v(h)$. The form of function $v(h)$ will be considered below. Simultaneously, a part of the matter is mineralized, and leaves the soil at the rate equal to $k(h)C(h, t)$. The $k(h)$ is mineralization rate coefficient determined by h .

The amount of the matter with the humification rate h in a certain range of values $(h, h + \Delta h)$ at a certain time point, t , is equal to $C(h, t)\Delta h$.

In time Δt , part of this matter will undergo humification and shift leftward along the h scale, while the other part will leave soil as a result of mineralization. Thus, in accordance with the law of conservation of matter, the amount of SOM at time t in range Δh will be equal to the sum of organics that has moved from range Δh to range $\Delta' h$ (Fig. 1) and the organics that has left soil as a result of mineralization:

$$C(h, t)\Delta h = C(h - v(h)\Delta t, t + \Delta t)\Delta' h + k(h)C(h, t)\Delta h\Delta t. \quad (1)$$

By expanding $C(h - v(h)\Delta t, t + \Delta t)$ and $v(h + \Delta h)$ into a Taylor series at point (h, t) and ignoring minor terms of expansion, we obtain the equation of SOM transformation and decomposition:

$$\frac{\partial C(h, t)}{\partial t} - \frac{\partial}{\partial h}(v(h) \cdot C(h, t)) = -k(h)C(h, t). \quad (2)$$

We obtained a typical transport equation. However an explicit derivation of this equation illustrates a phenomenon of increase of SOM concentration per unit of the scale h in the course of humification process. This is an effect of the righter is situated the matter on the scale h , the greater is the velocity of its motion to the left along the scale. It results in permanent shortening of h -distance between the matters situated in different points of the scale, i.e. in the increase of the concentration, what is illustrated in Fig. 1.

While in our previous study (Bartsev and Pochekutov, 2013) the supply of plant litter to soil was described by assigning boundary conditions, in this model, we use a more accurate description of plant litter supply. In this case, the supply of the new matter to soil is taken into account by adding another summand $D(h, t)$ (a distribution of litter supply rate over the scale h) to Eq. (2):

$$\frac{\partial C(h, t)}{\partial t} - \frac{\partial}{\partial h}(v(h) \cdot C(h, t)) = -k(h)C(h, t) + D(h, t). \quad (3)$$

Fundamental point of model inference is a choice of function $v(h)$ which is the velocity of the motion of the matter along the scale of humification rates. It seems reasonable to suppose the rate of transformation is proportional to a variable which is a measure of matter decomposability (Carpenter, 1981). In our case this measure is the rate of humification h . Thus, $-v(h) = dh/dt = -r \cdot h$. But the proportionality coefficient r should be equal to h too, since it is a coefficient of the rate of the reaction that causes further movement of the matter along this scale. Thus, h is both the changing value and the coefficient of the rate of change of the same value. So,

$$v(h) \equiv -\frac{dh}{dt} = h \cdot h = h^2. \quad (4)$$

Thus, the general equation of the model of SOM transformation is as follows:

$$\frac{\partial C(h, t)}{\partial t} - \frac{\partial}{\partial h}(h^2 \cdot C(h, t)) = -k(h)C(h, t) + D(h, t). \quad (5)$$

3. Steady state solution

First, we should make sure that the proposed equations have a solution that corresponds to the soil parameters actually observed in nature. To do this, steady state distribution of SOM is calculated and total steady state amounts of SOM is compared with the available experimental data for different ecosystems.

Mean annual distribution of the plant litter may be written as:

$$D(h) = \sum_i D_{0i} \delta(h - h_{0i}), \quad (6)$$

where δ is Dirac delta function, index i numbers litter components, D_{0i} is mean annual input and h_{0i} is initial humification rate of i th litter component.

We specify the mineralization rate as the following simple function:

$$k(h) = b \cdot h^p, \quad (7)$$

where b and p are constants different for different ecosystems.

Inserting (6) and (7) in (3) and considering $\partial C(h, t)/\partial t = 0$, we obtain an equation of steady state SOM distribution which has the following solution:

$$\bar{C}(h) = \frac{1}{h^2} \exp\left(\frac{bh^{p-1}}{p-1}\right) \sum_i \left(A_i - D_{0i} \theta(h - h_{0i}) \exp\left(-\frac{bh_{0i}^{p-1}}{p-1}\right) \right), \quad (8)$$

where θ is the Heaviside step function. From the condition that no transformation products of the i th litter component can be found to the right of h_{0i} along the h scale, constant A_i is determined as $A_i = D_{0i} \exp(-bh_{0i}^{p-1}/(p-1))$. According to (7), h_{0i} can be calculated from initial decomposition rates of plant litter k_{0i} as $h_{0i} = (k_{0i}/b)^{1/p}$. The estimate of the steady state SOM stock is $\bar{S} = \int_0^{h_{0m}} \bar{C}(h) dh$, where h_{0m} is the maximal value among h_{0i} .

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