

What determines the temperature response of soil organic matter decomposition?

Göran I. Ågren*, J.Å. Martin Wetterstedt

Department of Ecology, Swedish University of Agricultural Sciences, P.O. Box 7072, Sweden

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Abstract

The temperature dependence of litter and soil organic matter (SOM) mineralisation is important because it determines how strong the feedback from the expected warmer climate may be on the atmospheric CO₂ concentration. We have used a simple, analytical model to investigate how three different mechanism (i) the rate at which decomposers take up substrate at their surface; (ii) the rate by which substrate diffuses up to the surface of the decomposer; and (iii) the rate at which substrate is made available in the environment interact to determine the temperature response. The mechanisms are characterised by activation energies; two for the uptake rate (i) and one for each of the other two (ii, iii). The model shows that the temperature dependence is the result of the number of processes that effectively contributes to the rate of mineralisation; this result should also be valid if other processes are included. Depending upon the relative magnitude of the four activation energies, the temperature response is mainly determined by one or two of the mechanisms. In a transition zone, where all activation energies are similar and the number of contributing processes changes, there can be either a sharp increase or a sharp decrease in the temperature response when activation energies change.

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1. Introduction

The temperature dependence of litter and soil organic matter (SOM) mineralisation is important because it determines how strong the feedback from the expected warmer climate may be on the atmospheric CO₂ concentration. At the same time, it is scientifically a controversial issue with no consensus (Davidson and Janssens, 2006; Kirschbaum, 2006). The temperature dependence is commonly described by a Q_{10} function but there are no biological reasons for choosing such a function rather than other functions with similar shapes. When empirical data are analysed in terms of Q_{10} functions, the Q_{10} value is not stable but decreases with temperature, which indicates that other functions should rather be chosen. One of the reasons for the difficulty in identifying the temperature response is

that several mechanisms are involved, each with its own specific temperature response. For example, Thornley and Cannell (2001) showed that a temperature dependent adsorption reaction that stabilises organic matter can even increase soil carbon stores if temperature increases and Davidson et al. (2006) argued that the temperature dependences of the maximum enzyme activity and the affinity constant may cancel each other and result in weak temperature responses.

We will in this paper analyse the consequences of combining three different mechanisms that contribute to the temperature dependence of SOM mineralisation.

2. Theory

The use of organic matter by decomposers is determined by at least three independent mechanisms: (i) the rate at which decomposers take up substrate at their surface (μ); (ii) the rate by which substrate diffuses to the surface of the

*Corresponding author. Tel.: +46 18 672449; fax: +46 18 673430.

E-mail address: Goran.Agren@ekol.slu.se (G.I. Ågren).

decomposer (D); and (iii) the rate at which substrate is made available in the environment (S). All these three processes depend on temperature.

We will analyse the problem by looking at the diffusion of a substrate from an external surface to the surface of the decomposer. At the external surface we assume that the substrate is in equilibrium with a huge reservoir such that the substrate concentration at the external surface is constant and equal to S . The equilibrium between the reservoir and the concentration is, however, temperature dependent. At the surface of the decomposer, the rate of substrate assimilation is described by a Michaelis–Menten equation with temperature dependent maximal rate μ and half-saturation constant K . Let the concentration at a point \vec{r} in the space between the external surface and the decomposer be $c(\vec{r})$. If the temperature dependent, but otherwise constant, diffusion coefficient is D , the general problem we have to solve is

$$\begin{aligned} \frac{\partial c(\vec{r})}{\partial t} &= D\nabla^2 c(\vec{r}), \\ c(a) &= S, \\ F = D\hat{r} \cdot \nabla c(b) &= \frac{\mu c(b)}{K + c(b)}, \end{aligned} \quad (1)$$

where $c(a)$ and $c(b)$ are the substrate concentrations on the external surface and the decomposer surface, respectively, \hat{r} is a normal to the decomposer surface, and F the rate of assimilation of substrate. A summary of symbols used is given in Table 1.

Table 1
Definition and default values of variables and parameters

| Variable/ parameter | Explanation | Default value |
|------------------------|---|-------------------------|
| a | Distance to external surface | |
| b | Radius of decomposer | |
| A_μ | Activation energy for carbon uptake | 5000 K |
| A_D | Activation energy for diffusion | 5000 K |
| A_K | Activation energy for half-saturation of carbon uptake | 5000 K |
| A_S | Activation energy for carbon release | 5000 K |
| D | Diffusion coefficient | |
| D_0 | Base value for diffusion coefficient | 1/ 273×10^8 |
| F | Carbon flux into decomposer | |
| K | Half-saturation value for carbon uptake | |
| K_0 | Base value for half-saturation value for carbon uptake | 4.71×10^7 |
| L | Distance between decomposer and external surface, $a-b$ | 10 |
| S | Rate of carbon release | |
| S_0 | Base rate for carbon release | 10^8 |
| μ | Rate of carbon uptake | |
| μ_0 | Base rate for carbon uptake | 10^8 |

When not given, the units chosen are arbitrary, but values are chosen to give consistent magnitudes.

The steady state solution to Eq. (1) in planar geometry is

$$\begin{aligned} \frac{d^2 c}{dx^2} &= 0, \\ \frac{dc}{dx} &= k_1, \\ c &= k_1 x + k_2, \end{aligned} \quad (2)$$

where k_1 and k_2 are integration constants, which are determined from the boundary conditions at $x = a$ and $x = b$ ($L = a - b$). With the boundary conditions defined in Eq. (1), we get

$$\begin{aligned} F = Dk_1 &= \frac{1}{2} \left(\mu + D \frac{K + S}{L} \right) \\ &\quad - \sqrt{\frac{1}{4} \left(\mu + D \frac{K + S}{L} \right)^2 - \frac{\mu DS}{L}}. \end{aligned} \quad (3)$$

The special cases when either of μ , D , S or K is small or large are of interest

$$F \approx \begin{cases} \frac{SD}{L}, & \mu \text{ large,} \\ \mu, & S \text{ large,} \\ \frac{\mu S}{K+S}, & D \text{ large,} \\ \frac{\mu S}{K}, & K \text{ large,} \end{cases} \quad F \approx \begin{cases} \mu, & \mu \text{ small,} \\ \frac{\mu DS}{KD + \mu L}, & S \text{ small,} \\ \frac{SD}{L}, & D \text{ small,} \\ \frac{SD}{L}, & K \text{ small.} \end{cases} \quad (4)$$

Eq. (3) is also valid for a cylindrical geometry where the decomposer is a tube with radius a inside a tube of radius b , and for a spherical geometry where the decomposer is a sphere of radius a inside a sphere of radius b if the characteristic distance L is replaced as follows:

$$\begin{aligned} L &\rightarrow b \ln \frac{a}{b} \quad \text{cylindrical geometry,} \\ L &\rightarrow \frac{b}{a}(a - b) \quad \text{spherical geometry.} \end{aligned} \quad (5)$$

We will now assume that the four rate determining parameters vary with temperature T as follows:

$$\begin{aligned} \mu(T) &= \mu_0 e^{-A_\mu/T}, \\ S(T) &= S_0 e^{-A_S/T}, \\ D(T) &= TD_0 e^{-A_D/T}, \\ K(T) &= K_0 e^{-A_K/T}. \end{aligned} \quad (6)$$

The temperature dependence of $D(T)$ is taken from Jost (1960), whereas for the others we have assumed conventional Arrhenius temperature responses. We will for simplicity refer to the A 's as activation energies, rather than a more precise E ($= AR$).

Typical values for D are $10^{-5} \text{ cm}^2 \text{ s}^{-1}$. We estimate L as follows. The length of living fungal hyphae can be 200 km dm^{-3} (Berg and McLaugherty, 2003). This gives an average radius of soil around the hyphae of $4 \times 10^{-6} \text{ dm}$, which should be a typical value for L . Concentrations of dissolved organic carbon ($\sim S$) can be 100 mg(C) L^{-1} (Fröberg, 2004). The flux of carbon to decomposers is of the order of $SD/L = 100 \times 10^{-6} \times 10^{-7} \times 3600 \times 24 / 4 \times 10^{-4} \text{ kg(C) d}^{-1} = 0.2 \times 10^{-2} \text{ kg(C) d}^{-1}$ in 1 dm^3 of soil.

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