Soil Biology & Biochemistry 42 (2010) 72–82

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

# Temperature sensitivity of organic matter decomposition in two boreal forest soil profiles

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ARTICLE INFO

*Article history:*
Received 17 June 2009
Received in revised form
14 September 2009
Accepted 1 October 2009
Available online 23 October 2009

*Keywords:*
Temperature sensitivity
Soil organic matter
Decomposition
Incubation
Substrate availability
$Q_{10}$

ABSTRACT

Controversial conclusions from different studies suggest that the decomposition of old soil organic matter (SOM) is either more, less, or equally temperature sensitive compared to the younger SOM. Based on chemical kinetic theory, the decomposition of more recalcitrant materials should be more temperature sensitive, unless environmental factors limit decomposition. Here, we show results for boreal upland forest soils supporting this hypothesis. We detected differences in the temperature sensitivity 1) between soil layers varying in their decomposition stage and SOM quality, and 2) inside the layers during a 495 day laboratory incubation. Temperature sensitivity increased with increasing soil depth and decreasing SOM quality. In the organic layers, temperature sensitivity of decomposition increased during the early part of a 495 day laboratory incubation, after respiration rate and SOM quality had notably decreased. This indicates that decomposition of recalcitrant compounds was more temperature sensitive than that of the labile ones. Our results imply that $Q_{10}$ values for total heterotrophic soil respiration determined from short-term laboratory incubations can either underestimate or overestimate the temperature sensitivity of SOM decomposition, depending on soil layer, initial labile carbon content and temperature range used for the measurements. Using $Q_{10}$ values that ignore these factors in global climate models provides erroneous estimates on the effects of climate change on soil carbon storage.


## 1. Introduction

The feedbacks between soil carbon (C) and climate change cause remarkable uncertainty in the current global climate change predictions (Cox et al., 2000). Soil carbon models are based on the assumption that all soil C reacts similarly to climate warming (Cox et al., 2000; Jones et al., 2005). However, according to chemical kinetic theory, decomposition of recalcitrant, slowly decomposing substrates has higher activation energy, and thus higher temperature sensitivity (Bosatta and Ågren, 1999; Davidson and Janssens, 2006). Studies on decomposing leaf litter (Fierer et al., 2005) and organic soils have supported this theory (Mikan et al., 2002; Biasi et al., 2005), but results from mineral soils are controversial (e.g. Giardina and Ryan, 2000; Liski et al., 1999; Fang et al., 2005; Fierer et al., 2003; Knorr et al., 2005; Leifeld and Fuhrer, 2005; Reichstein et al., 2005; Hartley and Ineson, 2008; Conant et al., 2008a, b). One reason for this controversy, according to Davidson and Janssens (2006), is that the observed apparent temperature sensitivity in conditions where environmental constraints limit decomposition, may be lower or higher than the intrinsic temperature sensitivity determined by the kinetic properties of the substrates. In the mineral soils, association of SOM with minerals and low substrate availability are likely to obscure the effect of organic matter quality (Davidson and Janssens, 2006). More evidence on the temperature sensitivity of decomposition of different soil organic matter (SOM) fractions is needed for the development of more reliable models.

Few studies have paid attention to the mechanisms controlling temperature sensitivity of SOM decomposition in different soil layers during long-term laboratory incubation until now (Dalias et al., 2001; Fierer et al., 2003; Reichstein et al., 2005; Fang et al., 2005). Studies of this kind are needed, because $CO_2$ production in short-term laboratory incubations, and conventional field-measurements combining the $CO_2$ produced in the whole soil profile, is dominated by the most labile C fractions, and does not give information about the temperature sensitivity of the more recalcitrant fractions. In podzolic forest soils, the organic matter of different soil layers represents, on average, different decomposition stages, because there is very little vertical mixing of litter materials by soil organisms (Scheu and Parkinson, 1995). Because of this lack of biogenic vertical mixing, and despite the eluviation of dissolved

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doi:10.1016/j.soilbio.2009.10.002

organic carbon (DOC) downwards in the soil profile leading to formation of Bs horizons, the mean residence times of carbon in distinct soil layers of a podzol increase with soil depth. Overlying the mineral horizons there is an organic horizon, where association with minerals is not limiting decomposition.

Our objective was to study the temperature sensitivity of different SOM fractions by comparing the temperature sensitivities of the different soil layers of boreal forest soils, and changes in temperature sensitivity within each layer during a long-term laboratory incubation. We assumed that at the beginning of the incubation, the organic layers are in a relatively early stage of decomposition, and labile substrate availability is not limiting decomposition. Association with minerals is not limiting decomposition either. Therefore, we hypothesize that, in the organic layers at the beginning of the incubation, the temperature sensitivity of soil respiration reflects the intrinsic temperature sensitivity of the compounds decomposed, and thus increases with substrate recalcitrance and incubation time. However, as the studied soils are disconnected from the plants and roots when the laboratory incubation begins, the amount of labile substrates originated from the root-exudates starts to decrease. Thus, when the incubation proceeds, the availability of labile substrates becomes an environmental constraint limiting decomposition (Davidson and Janssens, 2006), because most soil microbes are available C limited (Kaye and Hart, 1997). We hypothesize that later during the incubation in the organic layers, while the SOM quality continues to decrease, the apparent $Q_{10}$ will not increase any longer, and may start to decline instead. During this late phase of decomposition, the temperature sensitivity is limited by the availability of labile C substrates, as they are needed to provide energy for the decomposition of the more complex substrates (e.g. co-metabolism of lignin) (Kirk et al., 1976). We hypothesize that the mineral soil layers will be in this kind of late stage of decomposition already at the beginning of the incubation and have higher intrinsic temperature sensitivity of decomposition due to low SOM quality. Substrate availability exerts a stronger control on decomposition compared to the organic layers, which may cause higher fluctuation to the apparent temperature sensitivity during the incubation (Larionova et al., 2007).

To test these hypotheses, we incubated soil samples from different layers of boreal forest soils for 495 days in favorable decomposition conditions. We followed changes in SOM quality and microbial community composition during the incubation. In order to study how the temperature sensitivity of soil respiration changes with time i.e. with decreasing SOM quality in each soil layer during the incubation, we followed $CO_2$ production and its temperature sensitivity over this incubation period. To our knowledge, this is the first study where the temperature-dependent $Q_{10}$ curves have been calculated for different layers of boreal forest soil, including both organic and mineral soil layers.

## 2. Material and methods

### 2.1. Study areas and soil sampling

We took soil samples from the organic layers, and from the 0–15 cm and 15–30 cm deep mineral soil layers of two boreal forest sites in autumn 2005. One site was Norway spruce (*Picea abies*) – dominated and the other Scots pine (*Pinus sylvestris*) – dominated. These sites were located at 61°48′N, 24°19′E, 150 m above sea level and had a mean annual temperature of 2.9 °C, and yearly precipitation of 709 mm. Samples of 10 $dm^3$ were taken from each of the three soil layers at both study sites. The organic layer samples were passed through a 4 mm sieve to remove larger roots and mineral soil samples through a 2.8 mm sieve. Soil dry weight was determined by drying a sub sample overnight at 105 °C. The organic matter content was determined as loss in weight on ignition for 4 h at 550 °C.

### 2.2. Laboratory incubation and soil respiration measurements

Soils were incubated for 495 days in the laboratory at 25 °C and 50% air humidity, correcting for moisture loss once a week. Subsamples were taken at three months intervals and $CO_2$ production was measured by incubating the 20 ml organic layer or 60 ml mineral soil layer sub-samples ($n = 3$ for each soil layer) for 24 h in water baths at 5, 12, 19 and 26 °C. $CO_2$ was sampled from the head space of the 120 ml incubation bottles and measured by gas chromatography (Hewlett Packard 6890). These sub-samples were subsequently frozen for later analysis of SOM quality and microbial community composition.

Soil respiration was modeled with a Gaussian model $R(T) = R_0 e^{(aT+bT^2)}$, where $R_0$ is the level of respiration at 0 °C ($a > 0$, $b < 0$) (Tuomi et al., 2008). With a higher value of parameter *a*, the respiration curve is steeper at low temperatures, and with a more negative value of parameter *b* the respiration curve starts to settle and decline earlier. The parameters were fitted using the standard non-linear least squares method. The standard deviations of the respiration measurements at each temperature were used to estimate the corresponding uncertainties. These deviations were used to weight the measurements realistically in the fitting process. The probability distributions of the parameters were sampled using the Markov chain Monte Carlo (McMC) method with Metropolis-Hastings algorithm (Metropolis et al., 1953; Hastings, 1970) to receive reliable error estimates for the parameters. Many studies have shown that $Q_{10}$ is not constant, but temperature-dependent (e.g. Kirschbaum, 1995; Dalias et al., 2001; Biasi et al., 2005; Vanhala et al., 2008). We calculated temperature-dependent $Q_{10}$ curves ($Q_{10} = R(T + 10)/R(T)$) based on the fitted parameters of the Gaussian function.

We used Bayesian model probabilities when calculating whether the temperature dependences were different between different samples. These calculations were repeated for the six measurement times. The Bayesian probabilities were calculated by comparing two models: one with the same parameters *a* and *b* describing the temperature dependence in two datasets (Model 1), and another with parameters $a_1$ and $b_1$ for the first dataset and $a_2$ and $b_2$ for the second (Model 2). The parameter $R_0$ was assumed different for the two sets in both models. We calculated the Bayesian model probabilities for these two models. If these probabilities were significantly higher (>0.95) for the more complicated model, Model 2, we concluded that the temperature dependences differed significantly (with a probability of 95%) between the two datasets.

### 2.3. Characterization of soil organic matter quality during the incubation

In this study we define SOM quality as the degree to which the SOM is resistant to microbial mineralisation (Bosatta and Ågren, 1999; Fierer et al., 2003) and use different indicators for SOM quality. Soil respiration was calculated on organic matter basis (μg $CO_2$ $g^{-1}$ OM $h^{-1}$) and therefore the level of respiration ($R_0$) is itself an index of SOM quality. Cumulative $CO_2$ production in the beginning of laboratory incubation has often been used as a measure of labile C (e.g. Townsend et al., 1997). We calculated the cumulative $CO_2$–C respired during the first 3 months of incubation at 25 °C as a percentage of initial C in each layer in order to compare the decomposability of SOM in different soil layers. The SOM quality in different soil layers was also characterized by the amounts and proportions of different C fractions (see below) with