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Methods for estimating temperature sensitivity of soil organic matter based on incubation data: A comparative evaluation

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ABSTRACT

Although the temperature sensitivity (Q_{10}) of soil organic matter (SOM) decomposition has been widely studied, the estimate substantially depends on the methods used with specific assumptions. Here we compared several commonly used methods (i.e., one-pool (1P) model, two-discrete-pool (2P) model, three-discrete-pool (3P) model, and time-for-substrate (T4S) Q_{10} method) plus a new and more process-oriented approach for estimating Q_{10} of SOM decomposition from laboratory incubation data to evaluate the influences of the different methods and assumptions on Q_{10} estimation. The process-oriented approach is a three-transfer-pool (3PX) model that resembles the decomposition sub-model commonly used in Earth system models. The temperature sensitivity and other parameters in the models were estimated from the cumulative CO_2 emission using the Bayesian Markov Chain Monte Carlo (MCMC) technique. The estimated Q_{10}s generally increased with the soil recalcitrance, but decreased with the incubation temperature increase. Our results indicated that the 1P model did not adequately simulate the dynamics of SOM decomposition and thus was not adequate for the Q_{10} estimation. All the multi-pool models fitted the soil incubation data well. The Akaike information criterion (*AIC*) analysis suggested that the 2P model is the most parsimonious. As the incubation progressed, Q_{10} estimated by the 3PX model was smaller than those by the 2P and 3P models because the continuous C transfers from the slow and passive pools to the active pool were included in the 3PX model. Although the T4S method could estimate the Q_{10} of labile carbon appropriately, our analyses showed that it overestimated that of recalcitrant SOM. The similar structure of 3PX model with the decomposition sub-model of Earth system models provides a possible approach, via the data assimilation techniques, to incorporate results from numerous incubation experiments into Earth system models.

1. Introduction

Soil organic matter (SOM) is the largest carbon (C) pool in terrestrial ecosystems (Schlesinger, 1995). As a biochemical process, the decomposition of SOM is sensitive to increased temperature (Luo et al., 2001; Fang et al., 2005; Davidson and Janssens, 2006), and consequently has critical impacts on global C cycle and climate change (Cox et al., 2000; Schlesinger and Andrews, 2000). However, SOM consists of many components with different kinetic properties (Davidson and Janssens, 2006), leading to large uncertainty in predicted soil C storage under future climate change (Friedlingstein et al., 2006). Therefore, there is an increasing concern on how temperature sensitivity (expressed as Q_{10}, which measures the change in decay rates for a 10 K warming) depends on the SOM compounds and C qualities (Fang et al., 2005; Conant et al., 2008; Xu et al., 2012). However, the Q_{10} estimation substantially relies on the methods used, which usually have their respective assumptions, leading to contradictory conclusions (Liski et al., 1999; Fang et al., 2005; Rey and Jarvis, 2006; Conant et al., 2008). To better understand the warming impacts on SOM decomposition, it is important to evaluate these methods and the underlying assumptions.

The direct calculation at specific incubation time has been used to estimate the Q_{10} of SOM decomposition based on incubation data

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using an equation $\left(\frac{R_2}{R_1}\right)^{\frac{10}{T_2-T_1}}$, where T_1 and T_2 are the incubation temperatures, and R_1 and R_2 are the CO_2 emission rates at T_1 and T_2, respectively (Rey and Jarvis, 2006). The estimate is usually an apparent Q_{10} and likely underestimates the temperature sensitivity after the initial incubation stage because greater decomposition results in less substrate at high than low temperatures at the same point of incubation time. To resolve this issue, a method that estimates the apparent Q_{10} by comparing the times for respiring a given amount of C at different temperatures (called the time-for-substrate Q_{10}) has been developed (Rey and Jarvis, 2006; Conant et al., 2008). One important assumption of this method is that a given amount of respired CO_2 is from similar fractions of SOM when the substrates are at the same level at different temperatures (Conant et al., 2008).

In addition, first-order kinetic models have also been used to estimate the Q_{10} (Kätterer et al., 1998; Rey and Jarvis, 2006). In these models, the soil is usually treated as one or several discrete fractions (or pools) based on the turnover times (Kätterer et al., 1998; Rey and Jarvis, 2006). Through these models, the intrinsic Q_{10} (defined as the temperature sensitivity of individual C pools with similar turnover time) for each pool can be derived (Rey and Jarvis, 2006). Generally, the multi-pool models fit the incubation data very well (Kätterer et al., 1998; Rey and Jarvis, 2006). However, these models do not include C transfers across pools which occur in natural ecosystems (Rovira and Vallejo, 2002; Cheng et al., 2007). On the other hand, although three conceptual pools with C transfers among them have been widely used to describe SOM dynamics in Earth system models (Parton et al., 1987; Jenkinson, 1990; Luo et al., 2003), the three-transfer-pool model has never been used, to our knowledge, to estimate temperature sensitivity of SOM decomposition from soil incubation data. Moreover, although a large amount of experimental studies have been conducted and have improved our understanding of the temperature sensitivity of SOM decomposition, the Q_{10} is usually set to be one single value (usually around 2) in Earth system models. It is imperative to find ways to use results from numerous incubation experiments to improve these models.

In this study, we developed a new three-transfer-pool (3PX) model to resemble the model structure of soil carbon dynamics in Earth system models for estimating Q_{10} of SOM decomposition. Then we compared four widely used methods: one-pool (1P) model (Fig. 1a), two-discrete-pool (2P) model (Fig. 1b), three-discrete-pool (3P) model (Fig. 1c), and time-for-substrate (T4S) (Fig. S1) with the 3PX model (Fig. 1d) for Q_{10} estimation using the same data set from a laboratory soil incubation experiment. Parameters of these models were estimated using the Bayesian Markov Chain Monte Carlo (MCMC) technique, which has recently been used to improve parameterization of ecological models (Xu et al., 2006; Gaucherel et al., 2008; Luo et al., 2011; Ahrens et al., 2014). In these models, the intrinsic Q_{10} for each pool was estimated directly through fitting the CO_2 emission data and the apparent Q_{10} was calculated from the estimated intrinsic Q_{10}, pool size and decay rate of each pool. The T4S method estimates temperature sensitivity by comparing the times for decomposing a given amount of C at different temperatures (Fig. S1) (Conant et al., 2008; Xu et al., 2010; Haddix et al., 2011).

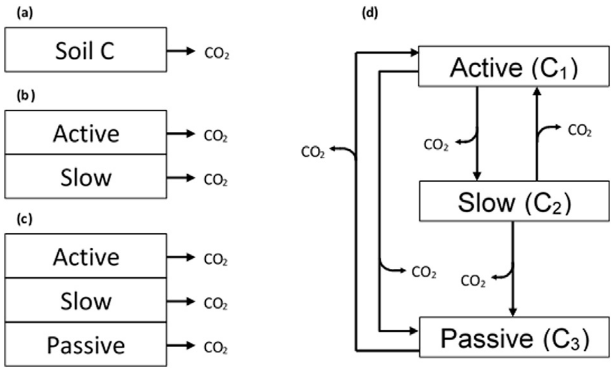

Fig. 1. Model structures of one-pool (a), two-discrete-pool (b), three-discrete-pool (c), and three-transfer-pool (d) models.

2. Materials and methods

2.1. Soil incubation data

The data used here were from a published paper by Haddix et al. (2011). The soil incubation data collected from a native grassland in Indian Head, Saskatchewan, Canada (50.533 °N, 103.517 °W). The mean annual temperature and precipitation are 2 °C and 421 mm, respectively. Information about soil sampling and incubation was described in detail in Haddix et al. (2011). Briefly, samples were collected from three separated locations that were several meters apart (field replicate $n = 3$). Surface litter and aboveground vegetation were cleared away before sampling and soil from 0 to 20 cm was collected. In the laboratory, rocks, surface litter and root materials were removed. The soil was homogenized and passed a 2-mm sieve before incubation. Then the soil samples were incubated at 15, 25, and 35 °C for 588 days (laboratory replicate $n = 4$). CO_2 emission rates were measured daily during the first 2 weeks of incubation, weekly for the next 2 weeks, and every 4 weeks thereafter. Overall, there were 36 sampling times over the 588-day incubation period. Data at all the 15, 25 and 35 °C were used in this study to evaluate various methods as described below.

2.2. Model description

2.2.1. First-order discrete-pool models

Generally, first-order discrete-pool models have similar structure described in Eq. (1) (Stanford and Smith, 1972; Andrén and Paustian, 1987; Kätterer et al., 1998; Rey and Jarvis, 2006; Li et al., 2013; Schädel et al., 2013):

$$C_{cum} = \sum_{i=1}^{n} f_i C_{tot}\left(1 - e^{-k_i t}\right) \tag{1}$$

where C_{cum} is the cumulative CO_2–C emission at time t (mg C g^{-1} soil), C_{tot} is the initial soil C content (mg C g^{-1} soil), f_i and k_i are the initial fraction and decay rate of the ith pool. The sum of f_is is 1. The only difference of these models is the number of pools (Fig. 1a–c). It is generally assumed that the initial fractions of pools are not affected by incubation temperature (Rey and Jarvis, 2006). Hence, we fitted each of the models with the data at all the three temperatures simultaneously using the data assimilation method described below, and the f_is were set to be independent of incubation temperature.

2.2.2. First-order three-transfer-pool (3PX) model

In addition to the discrete-pool models described above, a three-pool model with transfers among soil pools was developed. The basic concept was derived from the CENTURY and TECO model (Parton et al., 1987; Luo et al., 2003). In the model, SOM dynamics are represented by the following first-order differential equation: