



Linking short-term soil carbon and nitrogen dynamics: Environmental and stoichiometric controls on fresh organic matter decomposition in agroecosystems

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ABSTRACT

We developed a continuous, nonlinear model (FLOG-CN) linking carbon mineralization and nitrogen mineralization–immobilization with respect to time that successfully reproduced the complex CO₂–C and SMN dynamics for a collection of 70 paired C and N soil datasets. Application of the model to diverse C and N datasets showed that incorporating latency into the model of C mineralization, and using C to drive N dynamics, allows heterogeneous data from many different soil amendments to be described by the same model. We successfully modeled complex CO₂–C and SMN dynamics of widely different shapes and from a variety of soil amendments containing plant and animal residues. The re-interpretation of these datasets with the FLOG-CN models improved the quantitative analysis of C and N dynamics, yielding new insights into how amendment characteristics and experimental conditions influence the timing and quantity of C and N mineralized. Model parameters were responsive to varying soil characteristics (pH, C, N, C:N), amendment N:C, amendment rate, incubation temperature, and N additions. Stepwise regression was used to predict model parameters using metadata available for 56 of these datasets. Significant relationships were developed to estimate model parameters independently using measured system properties or other model parameters that could be independently estimated. Estimates of C and N dynamics both fell along a 1:1 line indicating that the model parameters could be adequately described by the measured properties, but the available metadata was not able to describe C dynamics with high precision. Nitrogen mineralization–immobilization was strongly related to amendment N:C, and switched between the two processes at an amendment N:C between 0.077 and 0.085 (C:N between 11.7 and 12.9). We believe that the modeling approach described here will allow quantitative and objective comparisons of diverse C and N datasets that have been hindered by subjective descriptions of the past.

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1. Introduction

Global soil biogeochemical cycles (C, N, P, S) are intricately linked with aboveground terrestrial productivity and atmospheric gas concentrations (Fontaine et al., 2007; Wardle et al., 2004). Agricultural practices in particular, representing approximately 38% of the Earth's land area (FAO STAT, 2013), with respect to soil management have led to significant soil organic matter losses and subsequent land degradation (Koch et al., 2013). Soil conservation practices have promoted additions of agricultural residues in soil to maintain primary productivity in these systems through improved soil structure and building of soil organic matter pools (Lal, 2004). The rates of soil carbon and nitrogen turnover from organic matter additions are intimately linked to substrate quality and quantity, as well as to abiotic factors such as climate and soil type (Voroney et al., 1989).

Several studies have reported C losses in excess of 85% from field soils receiving amendments, e.g. plant residues, with the majority being lost within the first year (Jenkinson and Rayner, 1977; Voroney et al., 1989). High variability in the composition of organic amendments limits current quantitative models to making generalized predictions of decomposition (Gras et al., 2011; Morvan and Nicolardot, 2009).

Current approaches for determination of organic matter decomposition dynamics, specifically for carbon and nitrogen, are typically based around environment-controlled soil incubation studies. Carbon and nitrogen dynamics are clearly linked through the chemical composition and stoichiometry of biomolecules. The aerobic dynamics of carbon mineralization (CO₂ evolution) are typically less complex than for soil mineral nitrogen, which has a number of interrelated intermediate forms. Carbon mineralization from soils is often described using first-order kinetic models, similar to those used to fit nitrogen mineralization data. When first-order models are unable to adequately describe empirical data, modifications including the first order plus linear or double

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first order models have been used (Bernal and Kirchmann, 1992; Murwira et al., 1990; Voroney et al., 1989). Inclusion of two exponential equations to represent ‘fast’ and ‘slow’ pools has been used to provide limits on mineralization based on substrate quantity or quality (Gordillo and Cabrera, 1997). However, there is an implied assumption that the fastest mineralization rate for ‘recalcitrant’ organic matter is at $t = 0$, which is not the case for polymerized substrates that are utilized microbially later in time (Cayuela et al., 2009). An alternative model for C mineralization proposed by Gillis and Price (2011) uses a first order exponential plus logistic function (FLOG) which allows for a delay between peak mineralization rates of the two pools. The logistic function limits the quantity of potentially mineralizable substrate by assuming that the mineralization rate from the logistic pool is proportional to both the fraction of substrate remaining (representing resource depletion) but also to the amount of substrate C mineralized to $\text{CO}_2\text{-C}$. This assumes a process of either microbial growth or increased metabolic activity as the more complex substrates are degraded.

Modeling the dynamics of soil mineral nitrogen (SMN), on the other hand, is complicated by the rapid transformations into different soluble ion forms (Nannipieri and Paul, 2009; Schimel and Bennett, 2004), which has been viewed as a substrate-specific phenomenon (Jensen, 1929; Jensen et al., 2005; Morvan et al., 2006; Peters and Jensen, 2011; Trinsoutrot et al., 2000). Jensen (1929) noted that “the proportion between the supplies of energy material and nitrogenous food” determines whether mineralization or immobilization of SMN will occur. Modeling soil responses with traditional zero- or first-order kinetic equations generates unrealistic parameters, and parameter estimates can be dependent on the initial values during nonlinear regression. Challenges continue to exist in relating the model parameters to measurable soil and substrate characteristics (Morvan and Nicolardot, 2009). Moreover, the variability associated with SMN dynamics along the continuum of mineralization to immobilization often precludes the use of first-order kinetic equations for many datasets. Schimel and Bennett (2004) propose a modified soil nitrogen cycle paradigm emerging from empirical observations, where plants and microbes compete for mineral N, as well as organic monomers containing N. Nitrogen mineralization is dependent on extracellular depolymerizing enzymes producing monomers from complex polymerized organic forms (Schimel and Bennett, 2004). Competition from plants is excluded in aerobic soil incubation studies and competition for SMN is assumed to be solely microbial, assuming gaseous N losses are minimal. In previous work, we postulated that the timing of the delayed logistic pool from the FLOG model of carbon mineralization is related to SMN availability (Gillis and Price, 2011), since depolymerization by exoenzymes is thought to be a rate-limiting step in the soil microbial decomposition of both C and N (Fontaine et al., 2003; Schimel and Bennett, 2004).

The scientific literature is populated with individual studies on C and N dynamics from the decomposition of organic materials in soil (e.g. Bernal and Kirchmann, 1992; Giacomini et al., 2007; Hadas et al., 1996; Honeycutt et al., 1988; Huang and Chen, 2009; Kirchmann and Lundvall, 1993; Parnaudeau et al., 2004, 2008; Petersen et al., 2005; Pita et al., 2010; Sall et al., 2007; Van Kessel et al., 2000), but efforts to aggregate, analyze, and interpret organic matter decomposition studies in a comprehensive manner are less common (e.g. Nicolardot et al., 2001; Manzoni et al., 2008, 2010; Sinsabaugh et al., 2013). Recent work suggests that there should be underlying patterns in the decomposition behavior of organic matter additions to soil that are conserved across different soil and amendment types, and the patterns should be quantifiable based on differences in the observed C and N dynamics versus measurable properties of the system (Manzoni et al., 2008, 2010; Sinsabaugh et al., 2013). The first objective of this study was to quantify patterns in soil organic matter decomposition dynamics observed across widely varying organic amendment properties, soil types, and environmental conditions. To facilitate direct comparison between all datasets, a secondary objective was to evaluate a model (FLOG-CN) linking short-term changes in carbon mineralization to synchronistic changes in SMN pools using a large and diverse collection of datasets.

2. Materials and methods

2.1. Model development

The compartmental model (FLOG-CN) presented in Fig. 1 describes the decomposition of fresh organic matter inputs to soil by dividing the organic matter into two pools, labile and latent, that are available to microorganisms. Gillis and Price (2011) previously outlined a model for carbon mineralization, FLOG-C, with five parameters that describe $C(t)$, the amount of $\text{CO}_2\text{-C}$ evolved at time t . The equations are as follows:

$$C(t) = C_{labile}(t) + C_{latent}(t) \quad (1)$$

$$\frac{dC_{labile}(t)}{dt} = k_1 \cdot [C_{labile} - C_{labile}(t)] \quad (2)$$

$$C_{labile}(0) = 0$$

$$C_{labile}(t) = C_{labile} \cdot (1 - e^{-k_1 \cdot t}) \quad (3)$$

$$\frac{dC_{latent}(t)}{dt} = \frac{1}{k_3} \cdot C_{latent}(t) \cdot \left[1 - \frac{C_{latent}(t)}{C_{latent}}\right] \quad (4)$$

$$C_{latent}(k_2) = \frac{C_{latent}}{2}$$

$$C_{latent}(t) = \frac{C_{latent}}{1 + e^{-\frac{t-k_2}{k_3}}} \quad (5)$$

Parameters C_{labile} and C_{latent} ($\text{mg C mineralized g}^{-1}$ C added) are the fractions of mineralizable carbon in the labile and latent pools, respectively, which together determine $C(t)$, the cumulative amount of C mineralized. For clarity in our terminology, it is important to note that we use $C_{labile}(t)$, for example, to refer to the variable with respect to time, while C_{labile} is the model parameter which is fitted by nonlinear regression. The dynamics in the labile pool of organic matter are characterized by a first order rate constant k_1 (day^{-1}). The dynamics in the latent pool of organic matter follow a bell curve characterized by parameters k_2 and k_3 . Parameter k_2 (latency, days) is the inflection point in the logistic function and where the maximum mineralization rate of the latent pool occurs, and k_3 (latent period, days) is a scaling factor approximately equal to the time interval between $C_{latent}(t)$ at 50% and 75% maximum heights (Fig. 1). The rate of mineralization from the latent pool of organic matter is controlled by the latent period (k_3 , days) and is comparable to the half-life derived from the first-order rate constant ($\ln[2]/k_1$, days).

The model of $SMN(t)$ is structured the same as $C(t)$, with parameters SMN_{labile} , SMN_{latent} , k_4 , k_5 , and k_6 . The equations are as follows:

$$SMN(t) = SMN_{labile}(t) + SMN_{latent}(t) \quad (6)$$

$$\frac{dSMN_{labile}(t)}{dt} = k_4 \cdot [SMN_{labile} - SMN_{labile}(t)] \quad (7)$$

$$SMN_{labile}(0) = 0$$

$$SMN_{labile}(t) = SMN_{labile} \cdot (1 - e^{-k_4 \cdot t}) \quad (8)$$

$$\frac{dSMN_{latent}(t)}{dt} = \frac{1}{k_6} \cdot SMN_{latent}(t) \cdot \left[1 - \frac{SMN_{latent}(t)}{SMN_{latent}}\right] \quad (9)$$

$$SMN_{latent}(k_5) = \frac{SMN_{latent}}{2}$$

$$SMN_{latent}(t) = \frac{SMN_{latent}}{1 + e^{-\frac{t-k_5}{k_6}}} \quad (10)$$

Parameters SMN_{labile} and SMN_{latent} ($\text{mg SMN mineralized or immobilized g}^{-1}$ C added) are the quantities of mineralizable or

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