Comparison of a novel model to three conventional models describing carbon mineralization from soil amended with organic residues

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ABSTRACT

The decomposition of organic soil amendments is a dynamic process that is not fully understood at present. Carbon mineralization by soil microorganisms has been modeled to derive useful theoretical parameters regarding the decomposition process. This paper compares a new model describing carbon mineralization from amended soil to three others commonly used in the literature. Carbon dioxide evolution from soil amended with five rates of an alkaline-stabilized biosolid (0, 2.08, 4.16, 8.32, and 12.48 mg/g d.w.) was monitored using alkali traps sampled on days 0, 3, 6, 9, 12, 15, 22, 29, 45, 55, 71, 88, 103 and 121. The new model, a first order exponential plus logistic function (FLOG), is based on the recognition of different competitive strategies (the $r–K$ continuum) in the soil environment. The FLOG model performs better than the first order and first order plus linear models for all amendment rates except the control. A double first order model produced a lower mean square error for all treatments but had non-normal residuals in one case. The FLOG model performs comparably well against other common models, and can generate curves ranging from almost exponential in appearance to curves containing inflection points, a feature not possible in combined exponential and/or linear models. Further investigation into the biological significance of the new parameters may be beneficial in describing the decomposition process, such as linking the timing of the delayed pool to changes in soil enzyme activities, shifts in microbial community composition, or aspects of the nitrogen cycle for example.

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1. Introduction

Organic soil amendments such as manure, compost, and biosolids are important sources of fertility in agriculture and have the added benefit of increasing soil organic carbon pools (Lal, 2004). The land application of municipal organic residuals is a common method of recycling nutrients, especially in places such as the Halifax Regional Municipality, Nova Scotia, Canada where landfilling and incineration of organic residuals are banned. Soil microbial biomass is mostly responsible for the cycling of carbon, nitrogen, phosphorus, sulfur, and other nutrients in soil as they decompose organic material (Van Veen et al., 1985). Labile compounds are generally limited in soil (Morita, 1988), but organic amendments provide a diverse array of consumable substrates for soil microorganisms. The more labile components such as simple sugars and amino acids are consumed quickly (hours–weeks), while more stable components, such as structural polymers, can persist for years (Lorenz et al., 2007). The soil ecosystem is highly complex, and our understanding of the decomposition behavior of organic materials is still incomplete. Highly variable soil conditions, biotic and abiotic factors, as well as

the nature of the organic amendment can alter decomposition dynamics in soil. There is a need to further understand this process for different types of organic waste residuals being directed to soil under varying environmental conditions if we are to predict any potential impacts of our soil management practices. Moreover, there is a need to interpret any results in the context of an ecological system, i.e. the interaction between organisms in response to a disturbance in their environment (Wardle and Giller, 1996; Prosser et al., 2007; Andrén et al., 2008).

Chemical composition of the organic inputs and make-up of the microbial communities in the soil are important, interrelated factors affecting the dynamics of carbon mineralization from amended soils. The active soil microbial community at a given site is governed in part by land use, which influences the nature of plant-derived carbon inputs and SOM quality (Waldrop and Firestone, 2004). Lauber et al. (2008) found that land use alone as a predictor of microbial community composition is not sufficient, especially if soil properties and nutrient status vary significantly within that site. The addition of organic residuals to soil can alter the composition of the soil microbial community and consequently cause a shift in decomposition dynamics (Waldrop and Firestone, 2004). As early as the 1920s, it was observed that adding different forms of nitrogen to soil resulted in different organisms appearing in the soil cultures compared to unamended soil (Winogradsky, 1928). This observation gave rise to

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the recognition of different competitive strategies in the soil environment. More recently, Abaye and Brookes (2006) compared three soils under different land use management strategies, each amended with three different organic inputs. Their results indicate that the active microbial population can determine initial carbon mineralization dynamics in the short term, but as the composition of the soil microbial biomass shifts over time, in response to substrate addition, the substrate quality of the organic amendment can dominate mineralization dynamics.

Sewage biosolids are produced from the solid residuals of municipal wastewater treatment. Some biosolids may undergo a biological digestion process at the treatment plant to decrease the labile carbon content prior to land application. Biosolids can receive further treatment such as composting, thermal drying, or alkaline stabilization to meet regulatory requirements prior to land applica-tion. Differences in the treatment processes affect the quality of the carbon substrate for soil microorganisms. Bernal et al. (1998a) incubated solids from different stages of sewage treatment in soil and found a decrease in CO_2 evolution with biological digestion and composting compared to undigested solids. Similarly, Fernández et al. (2007) found that thermally-dried sewage biosolids are significantly more active than composted biosolids, based on the amount of CO_2 evolved from the amended soil. Alkaline-stabilized biosolids, such as N-Viro Soil, are produced by adding quicklime (CaO), cement kiln dust, or other alkaline materials that undergo an exothermic reaction with water. Supplemental heating is sometimes used to achieve higher temperatures. This raises the pH and temperature in order to inhibit microbial activity and kill pathogens (Logan and Harrison, 1995). Consequently in many areas, these biosolids are used as a soil liming agent but little research on the decomposition dynamics of these alkaline-stabilized biosolids has been conducted.

Modeling is a useful tool in decomposition and ecological studies, especially when it is not possible to directly observe or manipulate the microbial populations. In these cases, as long as the system is adequately described, the model provides some predictive capability and allows evaluation of the system function under theoretical scenarios (Gertsev and Gertseva, 2004). Typically, carbon dioxide evolution curves are used to monitor decomposition activity and are a measure of either the net cumulative respiration or respiration rate of the soil microbial biomass under aerobic conditions, and take a variety shapes. Mathematical models containing informative theoretical parameters, such as the quantity of mineralizable carbon and half-life of the material in the exponential model (Table 1), are used to describe CO_2 evolution data but no single model is applicable across all disturbances in soil. For instance, alterations to the first order exponential model have been used to separate the carbon sources into two or more sub-pools representing easily available and more resistant carbon sources within the pool of potentially mineralizable organic carbon (Voroney et al., 1989). However, authors will fit several models and choose the best one based on statistical measures of model adequacy (Bernal et al., 1998b; Berndt, 2008). In cases where the curve has inflection points, exponential and linear models often fail to capture this feature.

The aim of this study was to examine the carbon mineralization dynamics from an alkaline-stabilized biosolid applied at increasing rates to an agricultural field soil. Furthermore, we compared four models describing cumulative CO_2–C evolution from the amended soil using statistical tests of model adequacy. Three of the models have been used previously in the literature and the fourth, a first order exponential plus logistic model (Table 1), is proposed by the current authors as a possible alternative that could be particularly useful in cases where curves have inflection points.

2. Materials and methods

2.1. Sampling and handling

A gleyed and fragic humo-ferric Podzol (Webb et al., 1991) with a crop history of carrots and soybeans was sampled from the Ap horizon, using 30 cm Oakfield soil probes, at the Bio-Environmental Engineering Center in Bible Hill, NS, Canada (45°23′ N, 63°14′ W). Soil was air dried prior to homogenization by 2 mm sieving, re-wetted to 18% GWC and pre-incubated for 10 days prior to biosolids amend-ment. The soil was amended with an alkaline-stabilized biosolid, N-Viro Soil (NVS), which was also homogenized by 2 mm sieving. The NVS was applied wet but at dry weight equivalent rates. The NVS originates from an advanced primary treatment process (settling with chemical flocculation of additional solids), followed by an addition of cement kiln dust and quicklime mixture with supplemental heating. Chemical properties of the agricultural field soil and NVS are listed in Table 2.

2.2. Experimental design

Carbon mineralization from NVS-amended soil was monitored in an aerobic incubation (Hopkins, 2008). Treatments consisted of five amendment rates: 0, 2.08, 4.16, 8.32, and 12.48 mg NVS g^{-1} soil in 1 L glass jars containing 130 g dry weight (d.w.) of soil. A total of 220 jars were included in the study for destructive sampling at eleven pre-determined intervals, on days 0, 3, 6, 9, 12, 15, 22, 29, 55, 88, and 121. Each treatment had four replicates which were incubated at 20 °C in a controlled environment chamber. Evolved CO_2–C was measured titrimetrically during the pre-determined intervals using 25 mL, 1 M NaOH traps, however to prevent anaerobic conditions from forming, additional sampling periods were added on days 45, 71, and 103 (totaling 14 time periods for CO_2–C). Six blank jars were included during each time interval to account for background CO_2–C concen-tration. Traps were manually titrated with standardized 0.5 M HCl using a phenolphthalein end-point indicator. Background soil respi-ration was subtracted from treated soils to examine only evolved CO_2–C resulting from the NVS amendment rates. Soil water content was adjusted periodically by spraying soil with a mist of water until

Table 1
Selected models describing cumulative carbon dioxide evolution from soil over time.

Model	Form	Parameter description (units)
First order exponential (FO)	$C_t = C_0(1 - e^{-k_0 t})$	C_t = cumulative CO_2–C evolved at time t (mg g^{-1})
		C_0 = size of potentially mineralizable carbon pool (mg g^{-1})
		k_0 = first order rate constant (day^{-1})
First order plus linear (FLIN)	$C_t = C_1(1 - e^{-k_1 t}) + k_2 t$	C_1 = size of labile pool (mg g^{-1})
		k_1 = labile pool rate constant (day^{-1})
		k_2 = CO_2–C evolution rate from linear pool (mg g^{-1} day^{-1})
Double first order (DFO)	$C_t = C_1(1 - e^{-k_1 t}) + C_2(1 - e^{-k_3 t})$	C_2 = size of recalcitrant first order pool (mg g^{-1})
		k_3 = recalcitrant pool rate constant (day^{-1})
First order plus logistic (FLOG)	$C_t = C_1(1 - e^{-k_1 t}) + \dfrac{C_3}{1 + e^{-\frac{t - k_4}{k_5}}}$	C_3 = size of delayed logistic pool (mg g^{-1})
		k_4 = location of inflection point (days)
		k_5 = distance from inflection point to ¾ maximum (days)