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A new, offer versus demand, modelling approach to assess the impact of micro-organisms spatio-temporal population dynamics on soil organic matter decomposition rates

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ABSTRACT

We used the multi-agent MIOR simulator as an exploratory tool to discuss some basic modelling principles as regards soil organic matter (SOM) decomposition processes, which are viewed as the result of interactions between the soil living community (represented by MM micro-organisms entities) and the “dead” organic matter (the SOM resource represented by individualized OM entities). In this paper we formalize the original offer–demand mechanism implemented in MIOR in a way that allows for the comparison of different conceptual points of view as regards the best way to couple biologically based population models (for the decomposer dynamics) and physically based first-order kinetic models (for the decomposed substrate). We show that accounting for explicit interactions leads to the introduction of effective decomposition rates which vary in time as a function of the M/C living (M) versus dead (C) matter carbon content ratio. More generally, by means of numerical experiments, we show that, as soon as we account for temporal or spatial variations of the microbial biomass, it brings into question the classical way to estimate a constant SOM decomposition rate from soil carbon content decay data.

1. Introduction

Getting deeper knowledge on soil organic matter (SOM) decomposition processes and related soil CO_2 efflux is a key issue in many research fields. It is well known that these processes are mediated by soil micro-organisms, which are the SOM consumers, and which release CO_2 through respiration (Six et al., 2004; Cleveland et al., 2007), but most analytical models do not include this component (McGill, 1996; Izaurralde et al., 2006). As regards the modelling of carbon decay in SOM, most of the models are based on the physico-chemical, first-order Michaelis–Menten kinetics, that is on the equation $dC/dt = -kC$, which states that the decrease of a particular carbon pool C is proportional to the size of the pool according to a constant decomposition rate k. The decomposition rates are usually estimated on empirical grounds, from field or laboratory dedicated experiments, and they vary depending on the types of carbon pools. Microbial C is sometimes included in the models as one more SOM pool, more resistant to decomposition.

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Fang et al. (2005) explain why we should try to include microbes more explicitly in models, as an actual decomposer compartment, whose function is totally different from that of a mere substrate of decomposition: because microbial community action is so far only indirectly included in the way the constant decomposition rates are parameterized, the current models are "independent of temporal and spatial variations in the soil microbial community" and will give biased estimates as regards long term evolution (Panikov, 1999). These authors state that, using a simple linear assumption to link SOM decomposition rate and microbial pool size, the predictions for net change in the contribution of soils to atmospheric C over the 21st Century are modified "up to 30%". It is not so clear whether microbes acts as "enzymes" in the chemical reactions driving the decay of SOM carbon, or if we can consider them as the actual SOM decomposers, whose activity totally explains carbon mineralization and CO_2 emissions (Van de Werf and Verstaete, 1987) due to their respiration. What is acknowledged almost everywhere is that, without any microbial life in the soil, SOM would not decompose at all (Gignoux et al., 2001; Fontaine and Barot, 2005; Fang et al., 2005).

Models have been developed by ecologists as regards the evolution of microbial populations in general (e.g. Kreft et al., 1998) and a few of them in soils (Sung et al., 2006; Ginovart et al., 2005; Cleveland et al., 2007; Polhert et al., 2007); they focus on the dynamics of the microbial populations which use carbon (released by the organic matter decomposition) as the main substrate for their maintenance and growth, and represent many other important aspects of what can be described as a highly complex microscopic ecosystem (Young and Crawford, 2004). In these models, the growth of the consumers is a function of the resource availability, but there is usually no retroaction from the consumer abundance on the resource decomposition rate, except in Ginovart et al. (2005) who introduced an enzymatic effect, by adding to the reference constant decomposition rate a supplementary term function of the microbial biomass.

Recent attempts have been made explicitly to couple population dynamics with the physically based approach (Fontaine and Barot, 2005; Gignoux et al., 2001; Neill and Gignoux, 2006; Masse et al., 2007), trying to introduce the microbial SOM "living component" as an explicit actor in the consumption of the dead organic matter resources by microbial populations. It appears that present models are still in infancy and this paper is a contribution to the research field through the analysis of simulations as experiments (Peck, 2004).

We will use here the multi-agent simulator MIOR (Masse et al., 2007) to analyse different points of view on how to model interactions between organic matter decay and microbial communities dynamics. In Section 2 below, we will recall how MIOR has been designed to enable individual-based modelling of soil ecosystems of increasing heterogeneity and complexity, how it enables the simulation of several types of OM (dead SOM pools) and MM (living micro-organismal patches) as individualized entities interacting in a virtual space, and present the simplified conditions that we apply in the present work. Then, in Section 3, we will formalize the simulator principles to focus on its carbon offer/demand mechanism, which provides a unified framework to represent various modelling assumptions about the dynamics of C (the total dead SOM carbon content) and M (the carbon content of the living community). This will lead to a discussion of two recently published mathematical models (Fontaine and Barot, 2005; Gignoux et al., 2001) and a comparison with the computer-based approach implemented in MIOR. Finally in Section 4 we will depict some numerical experiments, which bring into question the classical way to estimate a constant SOM decomposition rate from soil carbon content decay data in presence of temporal or spatial variations of the microbial biomass. Throughout the paper, we present in a first stage some exploratory numerical experiments, then in a second stage we propose interpretations of the results based on simple case studies and associated mathematical calculations.

2. MIOR, a distributed, multi-agent simulator to simulate offer/demand interactions between individualized entities

2.1. A multi-agent, individual-based modelling approach

We refer to Masse et al. (2007) for a description of the first use of the simulator MIOR, where detailed simulations were carried out using an individual-based approach and a large and heterogeneous set of interacting entities. MIOR was built using a computer science, multi-agent based approach. It actually enables the construction of a virtual space where any type of computer entity or agent can be created and assigned individual rules as regards its own behaviour and its interaction with other agents in its environment (Bousquet and Le Page, 2004). Such an approach is supported by the belief that representing the real world as an assemblage of a (usually big) number of individual interacting entities will lead to better understanding of causal mechanisms in complex systems. This is achieved by observing the collective, macroscopic, simulated phenomena emerging from the behavioural rules which are assigned to each entity/individual/agent at the microscopic level according to various assumptions and scenarios.

In the present application, we will use MIOR to assess a simplified simulation of SOM decomposition and compare the results to those of existing mathematical models. We will drop here many of the possibilities of the multi-agent approach, which may hide the consequences of the basic modelling assumptions. The simulator generates a cubic soil sample in 3D, where pools of dead soil organic matter and patches of microbial colonies are represented, respectively, by so-called organic matter (OM) and meta-micro-organisms (MM) agents, at a given scale known as "level of granularity" in computer science. In Fig. 1a, a screen copy of the simulator interface exhibits an example involving many entities, generated according to two types of OM agents, three types of MM agents, plus a third class of agents, the so-called N (nitrogen) agents representing mineral nitrogen availability.

In the following study, we simplify even further and neglect as well the effects of nitrogen and oxygen availability on micro-organisms' life (considering only the non-N-limited, non-O_2-limited case), as well as roots, water, or any other type of agents and interactions. We consider the simplest version of the MIOR model, involving only one generic type of OM and