Geophysical Research Abstracts
Vol. 21, EGU2019-15340, 2019
EGU General Assembly 2019

How does soil spatial heterogeneity affect decomposition kinetics?

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The location of organic matter and microorganisms is spatially heterogeneous in undisturbed soils. For example, organic matter can occur in patches, creating hot-spots at the soil pore-scale where microbial activity is higher in comparison with regions poor in organic matter. How these pore-scale heterogeneities affect the average dynamics of organic matter and microorganisms remains a challenging question. Because most soil carbon cycling models do not consider soil spatial heterogeneity, addressing this question is important and could help improving predictions of carbon stocks in Earth system models.

Here, we study the dynamics of the macro-scale decomposition rate ($\overline{D}$) function of the degree of spatial heterogeneity of the substrates, i.e. organic matter, and microorganisms at the pore-scale. We consider a coupled substrate-microbial biomass model valid at the micro-scale, and numerically simulate organic matter dynamics at each cell of a 2D domain characterized by a heterogeneous distribution of substrate and microorganisms. A spatial averaging scheme is subsequently applied to evaluate the mean behavior of this spatially-explicit system. To interpret the macro-scale behavior, we propose an analytical scale transition approach based on a second order spatial moment approximation (SMA) for $\overline{D}$ that accounts for the micro-scale heterogeneities. The mean behaviors of the numerical spatially-explicit model and of the analytical SMA are compared to the prediction of a spatially-homogeneous version of the model to test the performance of the scale transition approach to capture the dynamics of organic matter at the macro-scale.

Our results show that the second order spatial moments of organic matter and microbes (including spatial variances and covariances) have dynamics of their own. The micro-scale heterogeneity increases or decreases $\overline{D}$ depending upon the sign of these second order spatial moments. This behavior appears only when the micro-scale decomposition formulations are nonlinear. Because the second order moments accounting for spatial heterogeneities introduce additional carbon fluxes in the spatially-averaged equations, the predictions of the spatially homogeneous model are not able to capture the mean behavior of the heterogeneous system. Thus, this study highlights the inadequacy of applying the micro-scale decomposition formulations at larger scales without accounting for second order moments, and proposes that scale transition using SMA could offer insights into how to capture macro-scale dynamics in large-scale Earth system models.