How does soil spatial heterogeneity affect decomposition kinetics?

Arjun Chakrawal[1,2], Anke Herrmann[3], Johannes Koestel[3], Jerker Jarsjö[1,2], Naoise Nunan[4], Thomas Kätterer[5], and Stefano Manzoni[1,2]

[1]Department of Physical Geography, Stockholm University, Sweden; [2]Bolin Centre for Climate Research, Stockholm University, Sweden; [3]Department of Soil & Environment, SLU, Uppsala, Sweden; [4]Institute of Ecology and Environmental Sciences, Sorbonne Universités, Paris, France;[5]Department of Ecology, SLU, Uppsala, Sweden

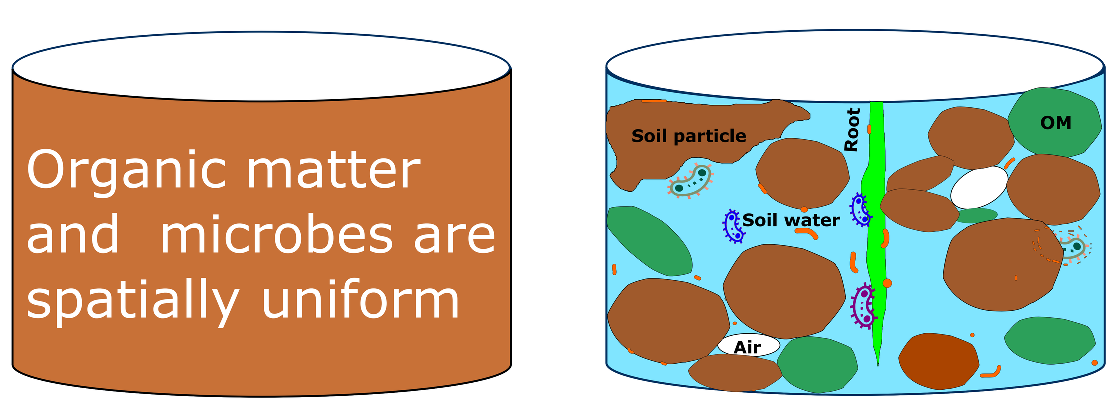
Stockholms universitet

Motivation

The distribution of organic substrates and microorganisms in soils is spatially heterogeneous at the micro-scale. Most soil carbon cycling models do not account for this micro-scale heterogeneity, which may affect predictions of carbon (C) fluxes and stocks. To meet this need, we use scale transition theory to analytically link micro- and macro-scale dynamics in a two dimensional spatially heterogeneous medium.

Introduction

In this study, we develop a general theoretical approach to link micro and macro scales in SOM decomposition model using **Scale Transition Theory**. With this approach, we demonstrate the effect of heterogeneity and nonlinearity at the micro-scale on macroscopic decomposition rates. The micro-scale heterogeneity is identified as the non-uniform spatial distribution of substrate C (C_s) and microbial C (C_b) and homogeneous system has same amount of C_s and C_b homogeneously distributed (Fig.1).



Homogenous Heterogeneous

Figure: Homogeneous and heterogeneous conceptualization of spatial distribution of soil organic matter (SOM).

Objectives

1. To develop an analytical upscaling solution for a two pool C model
2. To quantify the impact of different spatial structures of substrate C_s, microbial biomass C_b on the C dynamics

Contact Information
arjun.chakrawal@natgeo.su.se

Theory and methods

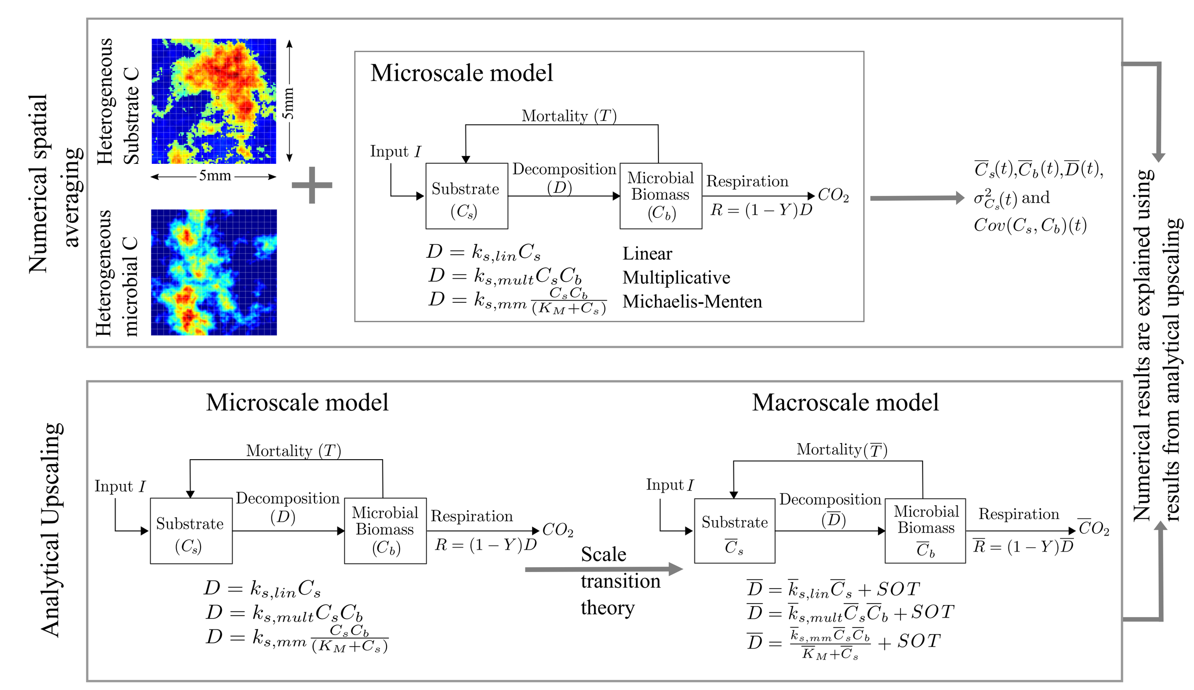


Figure: Schematic of the two upscaling approaches used to study the C dynamics at the macro-scale, (i) Numerical spatial averaging and (ii) Analytical upscaling.

Scale Transition Theory

For a generic decomposition rate at micro-scale D as a function of C_s and C_b, the mean decomposition rate at macro-scale is given by

$$\overline{D}(C_s,C_b) = D(\overline{C}_s,\overline{C}_b) + \frac{1}{2}\frac{\partial^2 D}{\partial C_s^2}\Big|_{\overline{C}_s,\overline{C}_b}\sigma^2_{C_s} + \frac{1}{2}\frac{\partial^2 D}{\partial C_b^2}\Big|_{\overline{C}_s,\overline{C}_b}\sigma^2_{C_b} + \frac{\partial^2 D}{\partial C_s \partial C_b}\Big|_{\overline{C}_s,\overline{C}_b}\overline{C_s'C_b'}$$

Mean Decomposition rate = Mean-field approximation + Second order terms

For the multiplicative model, the rate of decomposition at the micro-scale is, $D = k_{s,mult}C_sC_b$,

$$\overline{D} = k_{s,mult}\overline{C}_s\overline{C}_b + k_{s,mult}\overline{C_s'C_b'}$$

Scenarios

Multiplicative Kinetics

Biophysical heterogeneity

Scenario1: Initial C_s and C_b are distributed around the steady state of the micro-scale

Scenario2: Initial C_s and C_b are distributed around values larger than the steady state of the micro-scale

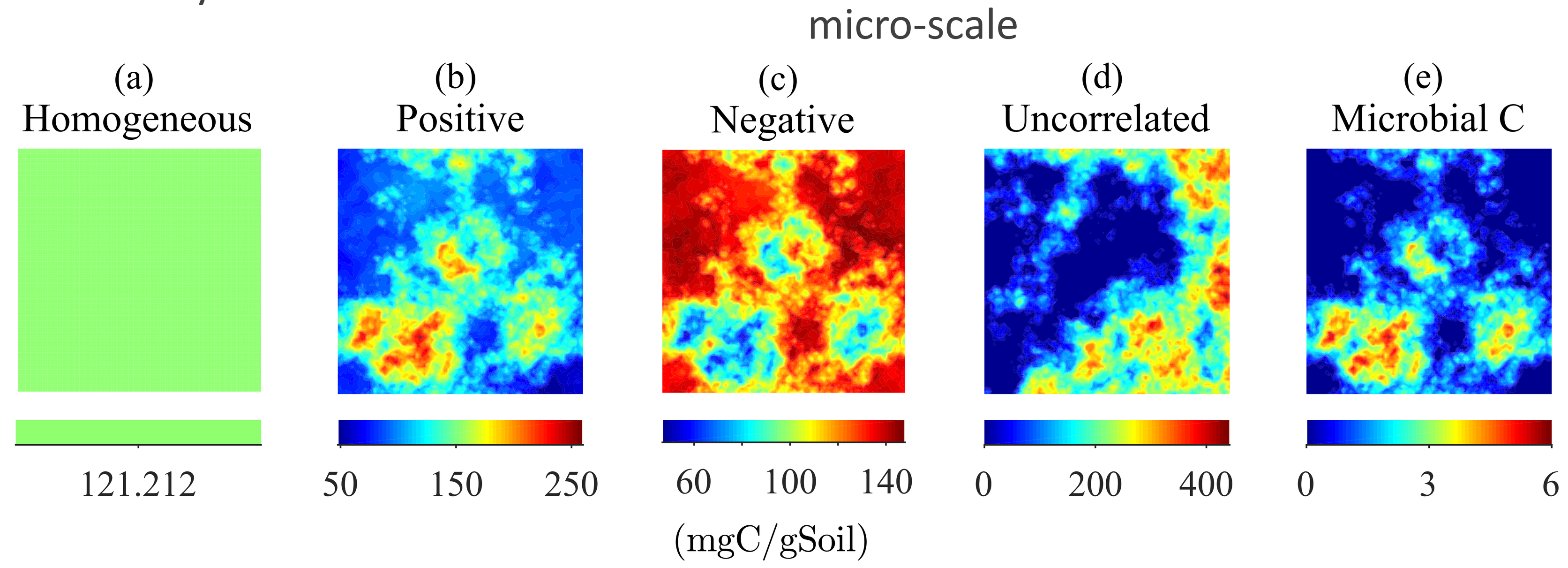
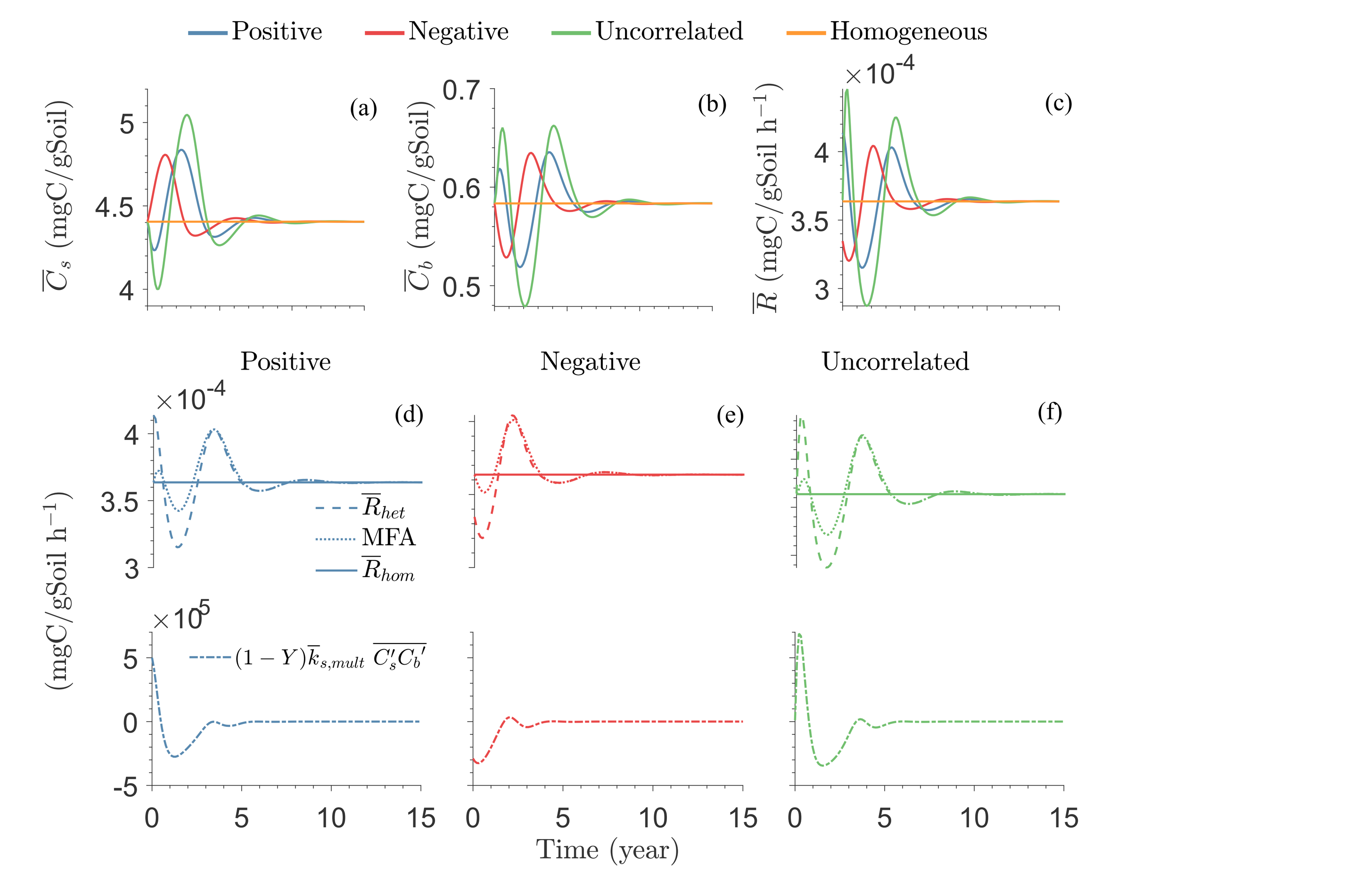
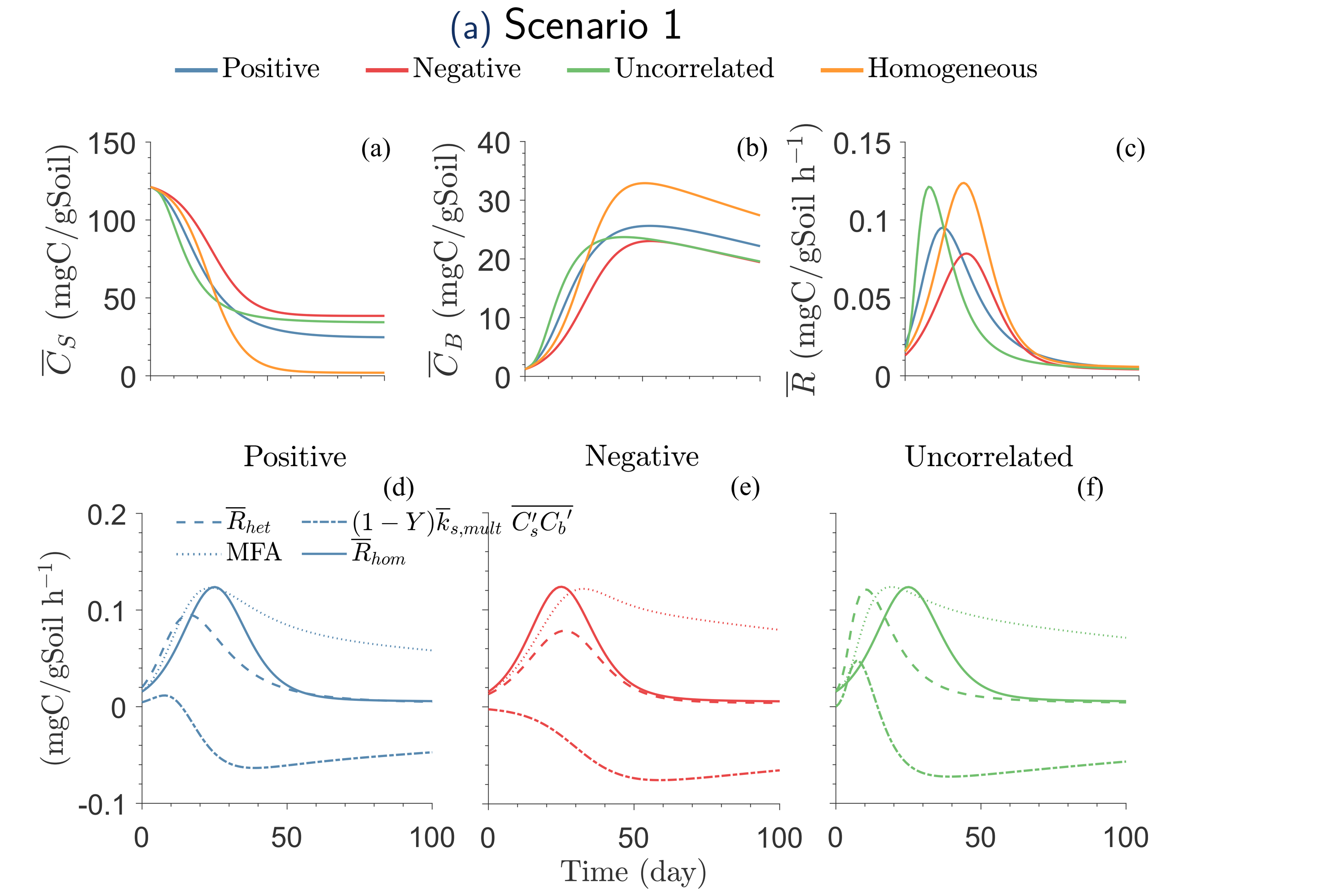


Figure: Two scenarios were implemented based on initial spatial distribution of substrate and microbial C. For each scenario, three different initial distributions of substrate and microbial biomass are considered as representative of micro-scale heterogeneities; i.e., positive, negative and uncorrelated.

Results



(a) Scenario 1



(b) Scenario 2

Figure: Effect of biophysical heterogeneity on the macroscopic decomposition dynamics. In both scenarios, figures show the temporal evolution of (a) mean substrate C ($\bar{C}_s$), (b) mean microbial C ($\bar{C}_b$), (c) mean respiration rate ($\bar{R}$), and (d–f) temporal evolution of mean respiration rate in the heterogeneous system ($\bar{R}_{het}$), which includes the mean-field approximation (MFA) and second order terms (i.e. covariance $\overline{C_s'C_b'}$).

Conclusion

1. The mean-field approximation fails to capture carbon dynamics in a spatially heterogeneous environment.
2. The upscaled governing equations include second order spatial moments; i.e., covariances between substrate and microorganism.
3. Second order terms should be included in a macro-scale carbon model because these moments exhibit a dynamic behavior that alters the mean dynamics of SOM decomposition.

Acknowledgments

This research was supported by the Swedish Research Councils Vetenskapsrådet (grant 2016-04146) and Formas (grant 2015-468).