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Spatial pattern formation of microbes at the soil microscale affect soil C and N turnover in an individual-based microbial community model

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At the μm-scale, soil is a highly structured and complex environment, both in physical as well as in biological terms, characterized by non-linear interactions between microbes, substrates and minerals. As known from mathematics and theoretical ecology, spatial structure significantly affects the system's behaviour by enabling synergistic dynamics, facilitating diversity, and leading to emergent phenomena such as self-organisation and self-regulation. Such phenomena, however, are rarely considered when investigating mechanisms of microbial soil organic matter turnover. Soil organic matter is the largest terrestrial reservoir for organic carbon (C) and nitrogen (N) and plays a pivotal role in global biogeochemical cycles. Still, the underlying mechanisms of microbial soil organic matter buildup and turnover remain elusive.

We explored mechanisms of microbial soil organic matter turnover using an individual-based, stoichiometrically and spatially explicit computer model, which simulates the microbial de-composer system at the soil microscale (i.e. on a grid of 100 x 100 soil microsites). Soil organic matter dynamics in our model emerge as the result of interactions among individual microbes with certain functional traits (f.e. enzyme production rates, growth rates, cell stoichiometry) at the microscale. By degrading complex substrates, and releasing labile substances microbes in our model continusly shape their environment, which in turn feeds back to spatiotemporal dynamics of the microbial community.

In order to test the effect of microbial functional traits and organic matter input rate on soil organic matter turnover and C and N storage, we ran the model into steady state using continuous inputs of fresh organic material. Surprisingly, certain parameter settings that induce resource limitation of microbes lead to regular spatial pattern formation (f.e. moving spiral waves) of microbes and substrate at the μm-scale at steady-state. The occurrence of these pattern can be explained by the Turing mechanism. These pattern formation had strong consequences for process rates, as well as for C and N storage in the soil at the steady state: Scenarios that exhibited pattern formation were generally associated with higher C storage at steady state compared to those without pattern formation (i.e. at non-limiting conditions for microbes). Moreover, pattern formation lead to a spatial decoupling of C and N turnover processes, and to a spatial decoupling of microbial N mineralization and N immobilization.

Taken together, our theoretical analysis shows that self-organisation may be a feature of the soil decomposer system, with consequences for process rates of microbial C and N turnover. Pattern formation through spatial self-organization, which has been observed on larger spatial scales in other resource-limited communities (e.g., vegetation patterns in arid or wetland eco-systems), may also occur at the soil microscale, leaving its mark on the soil's storage capacity for C and N.