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Coupling Scales in process-based soil organic carbon modelling including dynamic aggregation

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EGU 17.4.2024, SSS5.2: Carbon sequestration in soils

Sharing is encouraged

Motivation

- Soils harbor twice as much carbon as the atmosphere
  ⇒ high public relevance to **quantify the fate of organic matter (OM) and carbon in soils**
- **Soil structure** is directly **related to particulate organic matter (POM) dynamics**: the break-up of **soil aggregates** and their formation influences the persistence of organic carbon (OC) in soils

The dilemma: microscale processes drive questions of global relevance

⇒ process-based mechanistic, temporally and spatially explicit model describing the interaction of

- dynamic (re-)arrangement of soil aggregates
- turnover of OM by microbes
- simultaneous soil surface interactions

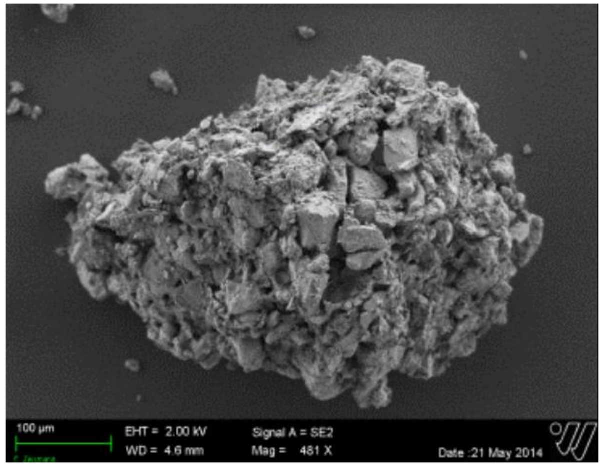

Figure: Picture by courtesy of DFG RU 2179 „MAD Soil - Microaggregates: Formation and turnover of the structural building blocks of soils“.

Why use pore scale models?
We want to think **BIG!**

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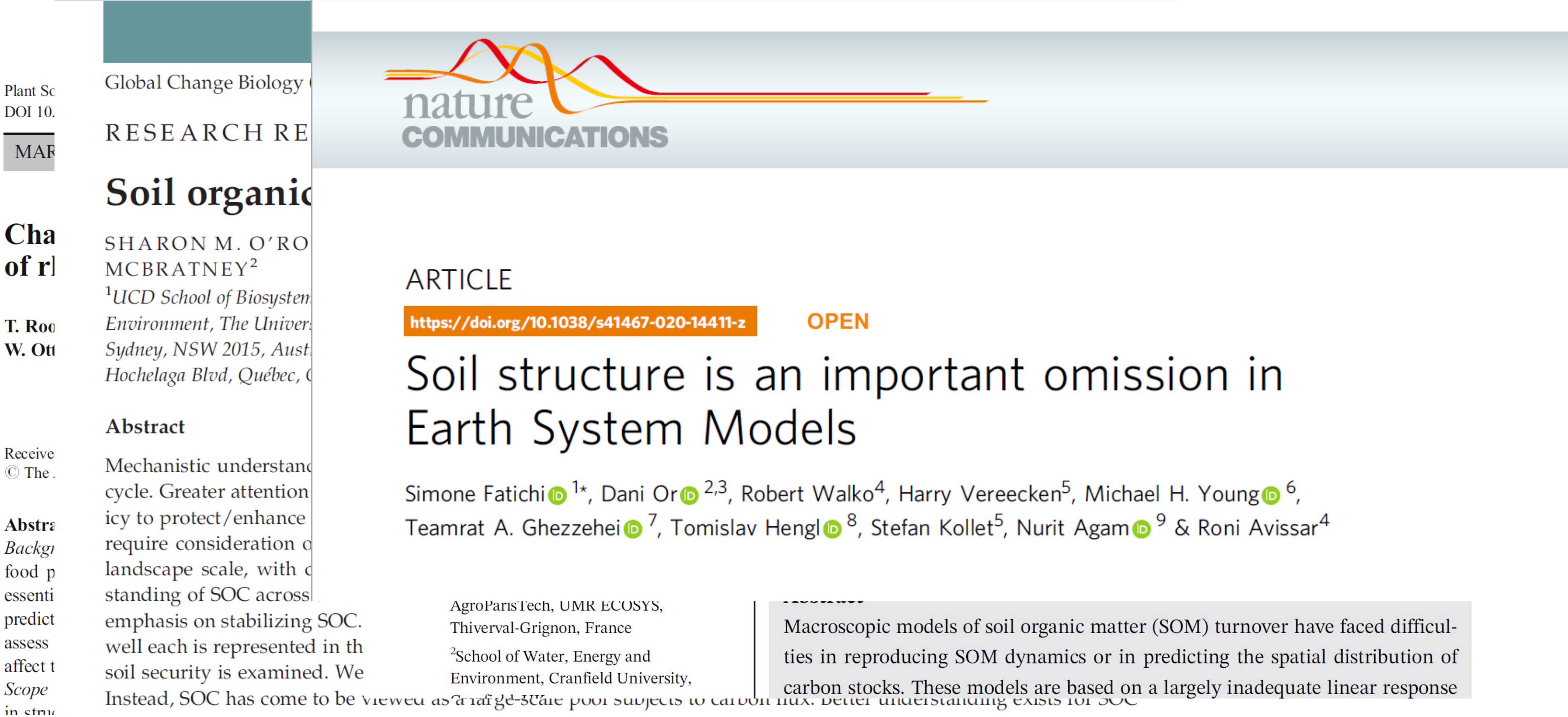

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RESEARCH RE

Soil organic

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Abstract

Mechanistic understand
cycle. Greater attention
icy to protect/enhance
require consideration o
landscape scale, with c
standing of SOC across
emphasis on stabilizing SOC.
well each is represented in th
soil security is examined. We
Instead, SOC has come to be viewed as a large-scale pool subjects to carbon flux. Better understanding exists for SOC

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nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-14411-z OPEN

Soil structure is an important omission in Earth System Models

Simone Fatichi[1*], Dani Or[2,3], Robert Walko[4], Harry Vereecken[5], Michael H. Young[6], Teamrat A. Ghezzehei[7], Tomislav Hengl[8], Stefan Kollet[5], Nurit Agam[9] & Roni Avissar[4]

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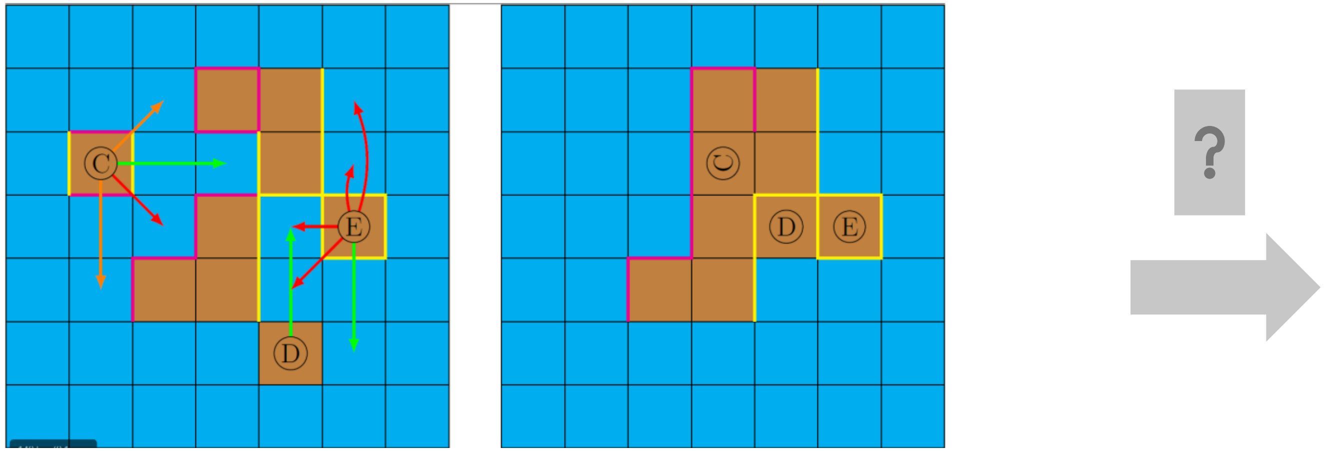
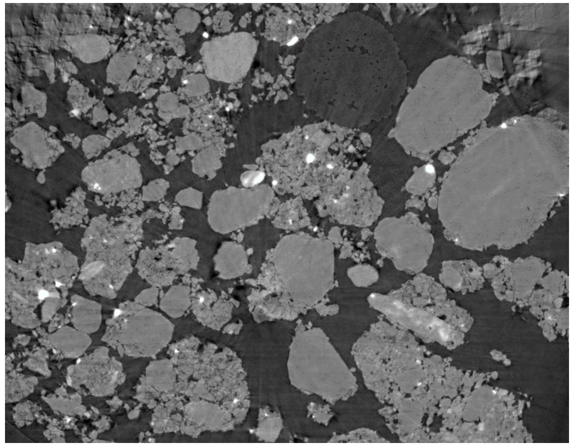
Macroscopic models of soil organic matter (SOM) turnover have faced difficulties in reproducing SOM dynamics or in predicting the spatial distribution of carbon stocks. These models are based on a largely inadequate linear response

The idea for the pore scale…

Can we use cellular automata to study the interaction of soil structures, organic matter and biofilms?



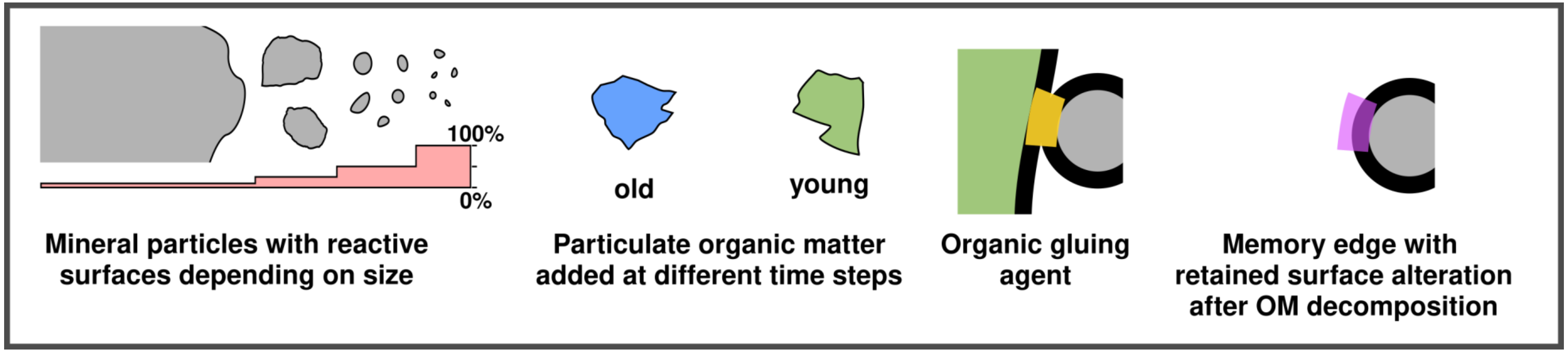


- complexity of soils vs. simplicity of models
- in contrast to lab scenarios: easy variation of a manifold of conditions and isolation of mechanisms / effects possible
- direct access to all parameters of resulting structures - at every time step
- can the reduced perspective help understanding reality?

> The numerical output of a particular calculation is not much help [...]; one needs to know how the various features of the problem interact to produce the outcome
>
> Fowkes & Mahony (1994): An Introduction to Mathematical Modelling

Concepts

Schematic overview



Mineral particles with reactive surfaces depending on size

Particulate organic matter added at different time steps

Organic gluing agent

Memory edge with retained surface alteration after OM decomposition

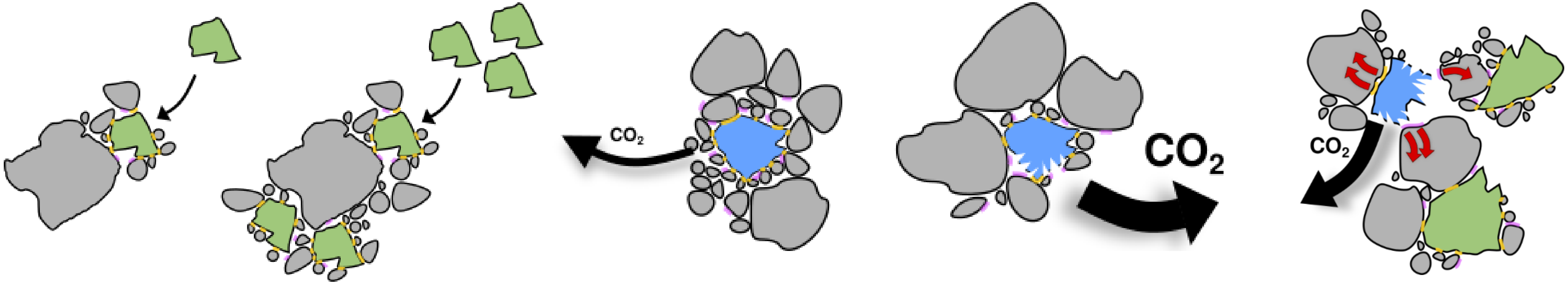


Figure: Schematic overview of model components, processes and resulting observations.

Drivers: **POM input** **POM decomposition rate** **Soil texture** **Surface sites with different reactivity**

Processes and Mechanisms

Realized in a Cellular Automaton Setting

- Size-dependent movement of water-stable particles (Brownian motion, Stokes-Einstein relation)
- Attraction by electric forces
- Attraction of reactive surface contacts (organo-mineral etc..)
- Biomass growth (Michaelis-Menten Kinetics with organic carbon and oxygen, nitrogen…)
- Evolution of gluing agents
- Bio-perturbation, tillage, drying-wetting: random brake-up
- Cellular Root growth
- Root Exudation and spreading

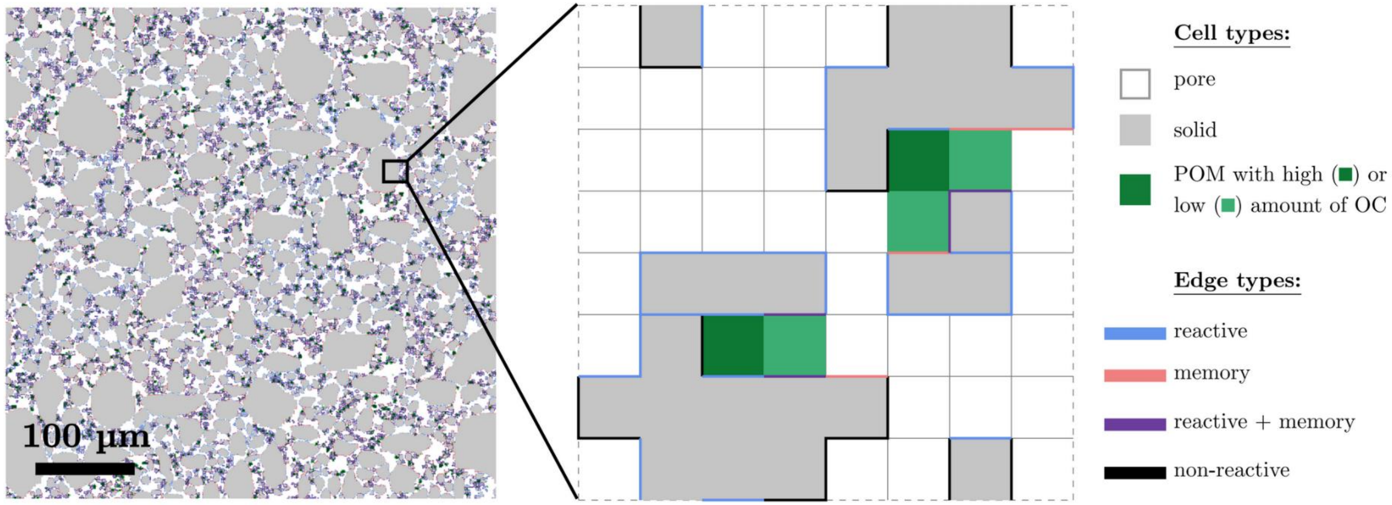
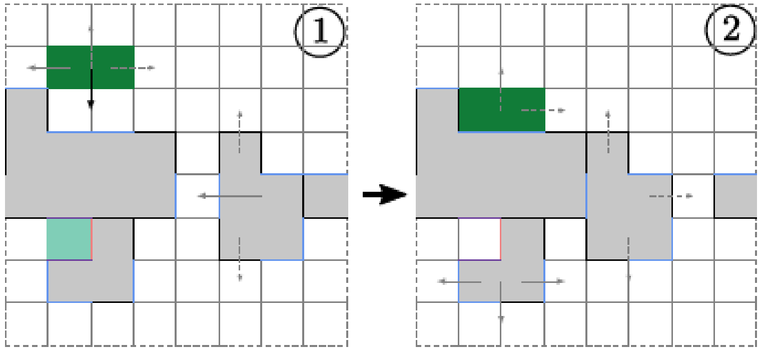


Figure 1: Schematic representation (*right*) of the computational domain (*left*) with pixels of type solid (■), pore (☐) or POM with different amounts of OC (high (🟩) or low (🟩)) and edges of type reactive (|), non-reactive (|), memory (|) or both reactive and memory (|).



Disentangling the interplay of soil organic carbon storage and structure dynamics

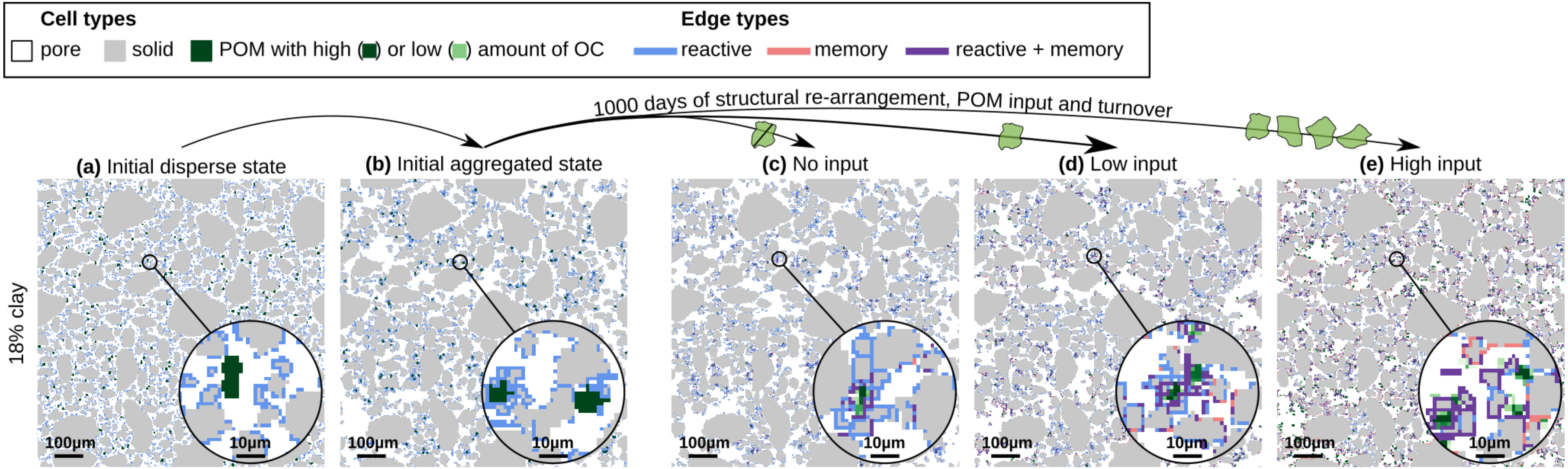


Figure: Conceptual overview over modelled scenarios and exemplary states (i.e. one repetition each) for different steps of the model, soil texture with 18% clay content and varying input scenarios: Random initial disperse state with shapes from dynamic image analysis (a), aggregated initial state after application of CAM (b), final state after no input (c), low input (d) and high input (e) scenario.

Zech et al. (2022), Global Change Biology.

Results

POM dynamics

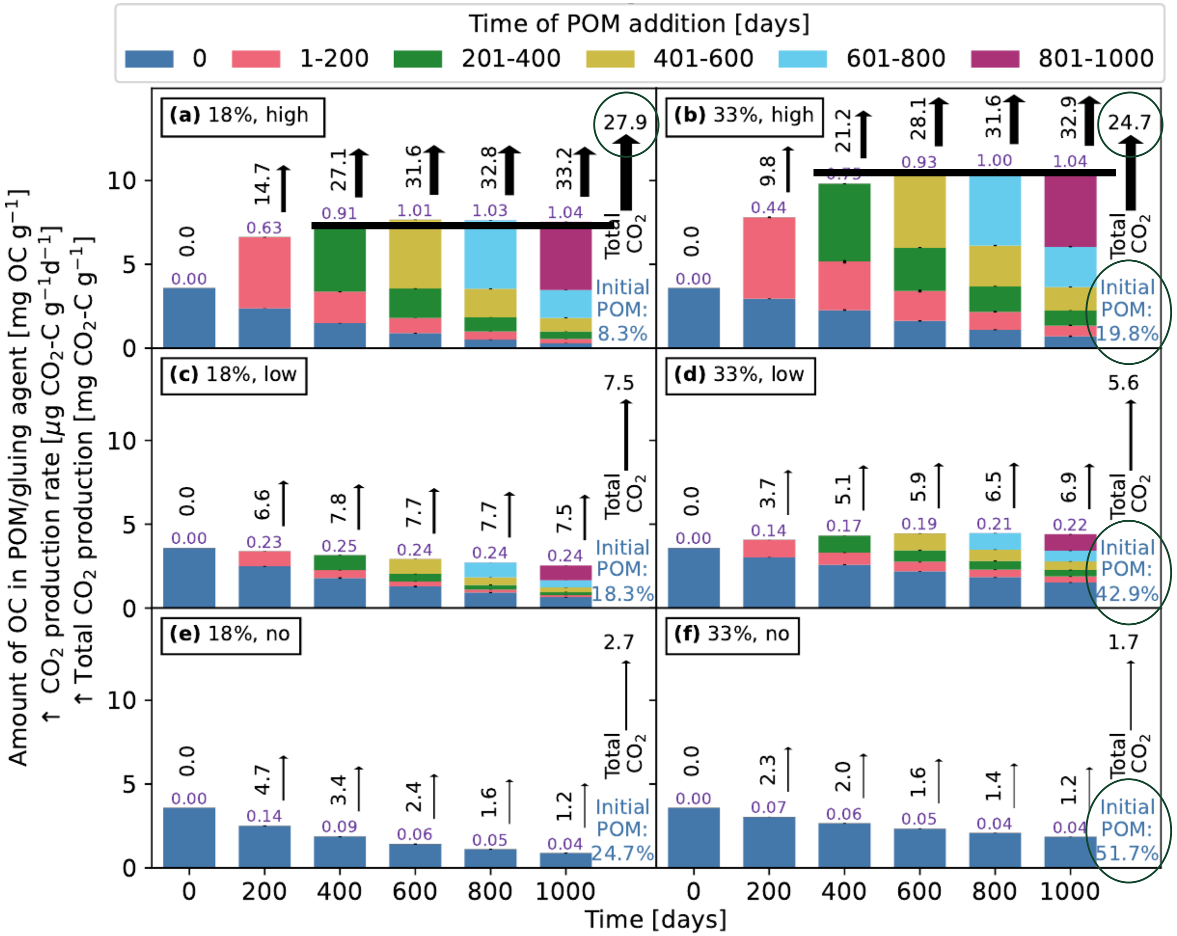


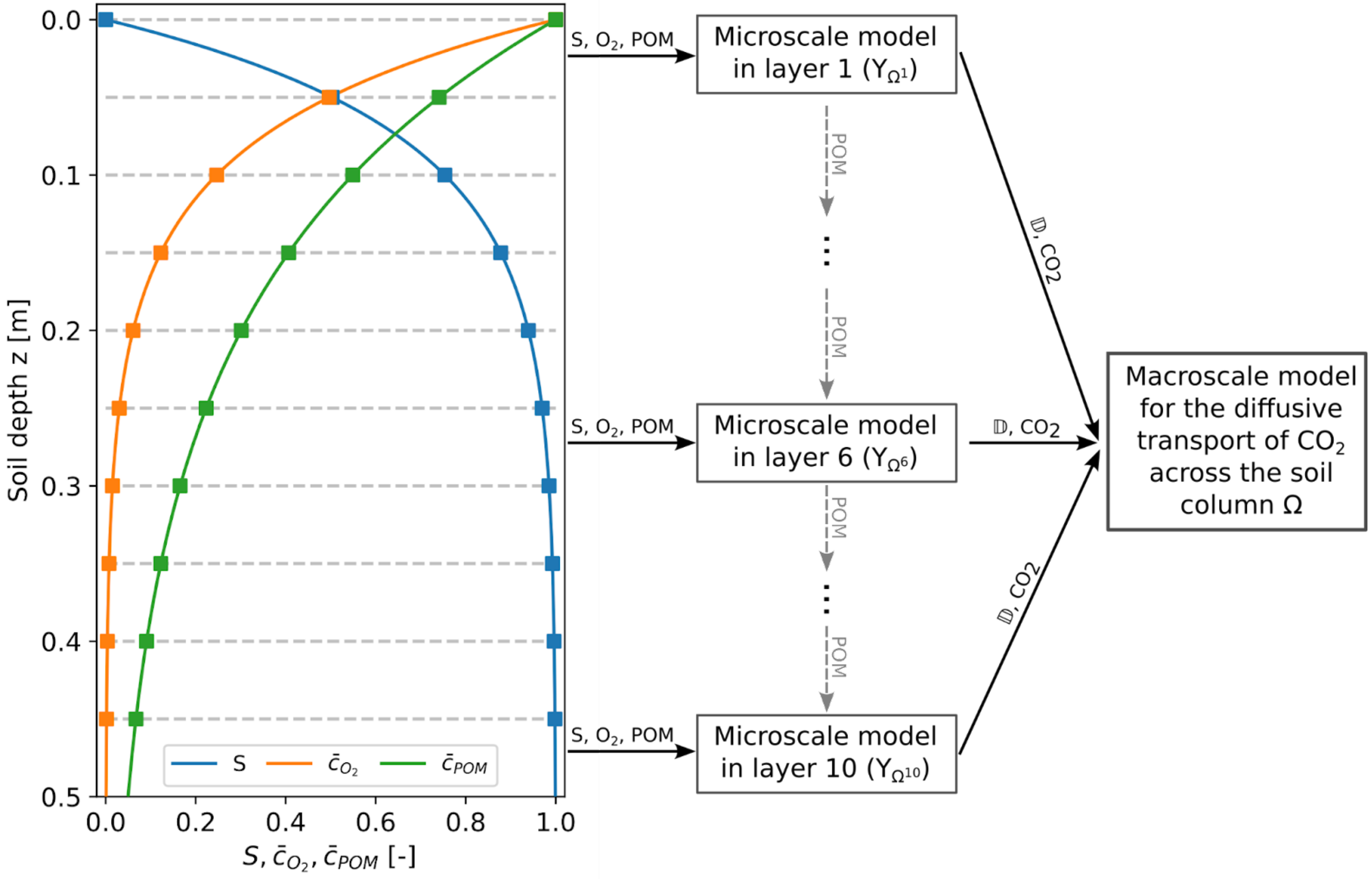
Figure: Amount of OC in different fractions of POM by age and gluing agent, CO$_2$ production rate, total CO$_2$ production and remaining share of initial POM in different input scenarios and for both soil textures and different input scenarios with low decomposition rate.

- Stationary states for POM concentrations through balance of POM input and degradation, even in high input setting
- **Effect of soil structure**: Higher clay content leads to higher POM content and lower total CO$_2$
- **Effect of structural re-arrangement**: Increased POM input leads to higher decomposition of initial, occluded POM => **structural priming effect**

Zech et al. (2022), Global Change Biology.

Coupling the scales

Combine micro- and macroscales problems

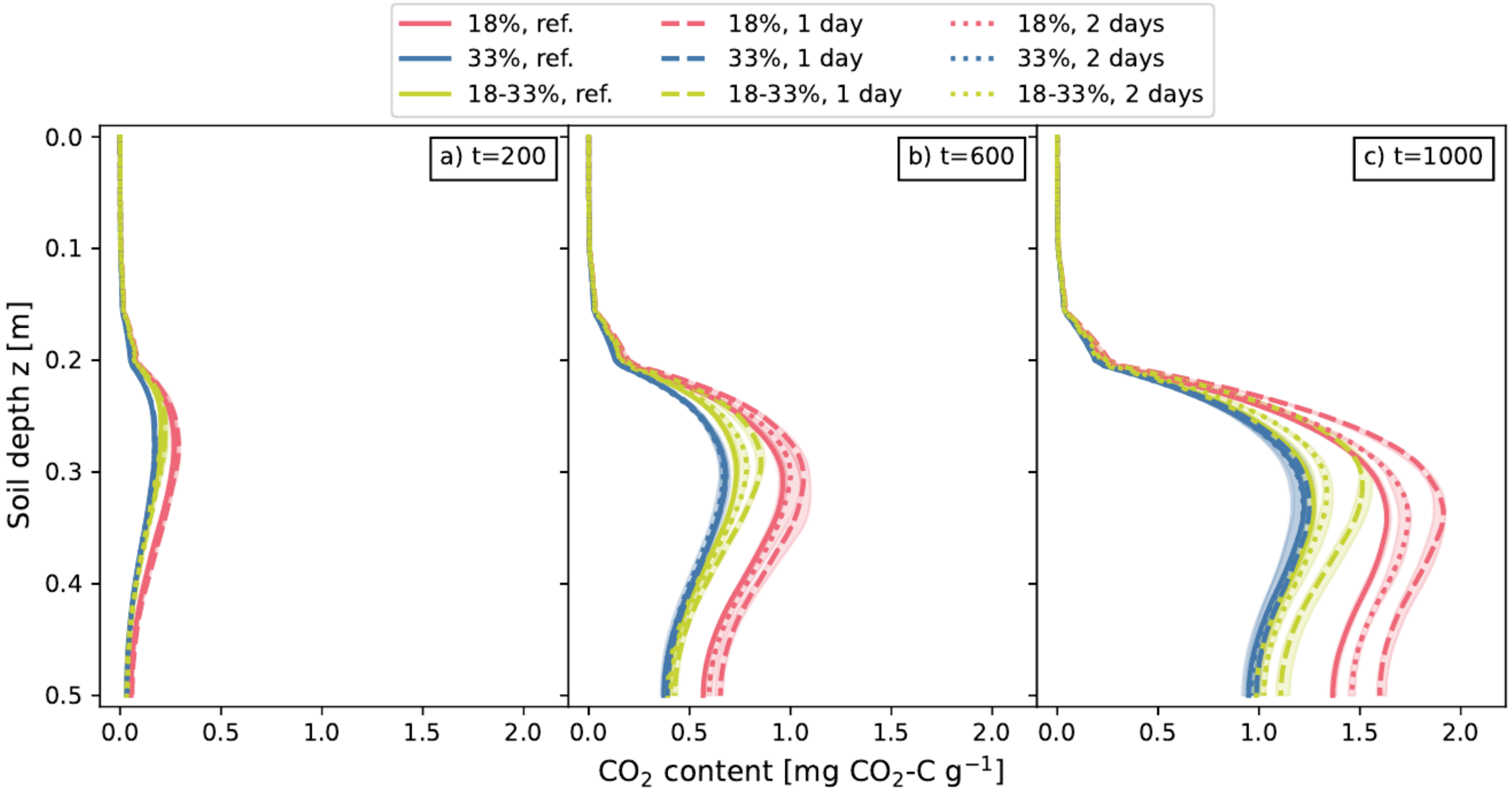


a) Macroscopic environmental conditions b) Microscale model c) Macroscale model

- CO_2 transport across soil profile (macrosale) is informed by a pore-scale (microscale) model for C turnover
- The macroscopic environmental conditions water **saturation**, **POM** content, and **oxygen** concentration influence the microscale problem

Zech et al. (2024), J. Plant Nutr. Soil Sci.

Coupling scales in process-based soil organic carbon modeling including dynamic aggregation



Macroscopic profile of remaining CO2 content after 200 (a), 600 (b) and 1000 (c) days. Median of 10 repetitions with error band representing lower and upper quartile.

Zech et al. (2024), J. Plant Nutr. Soil Sci.

- The coupled simulations of macroscopic transport and pore scale carbon and aggregate turnover reveal **the complex, nonlinear interplay** of the underlying processes.
- Limitations by diffusive transport, oxygen availability, texture dependent occlusion and turnover of OM drive CO$_2$ production and carbon storage.

Conclusion

Image and process-based micro-macro models for carbon turnover allow the

- **Discrimination**
  Study the detailed processes acting at the pore scale – and decide *then* if or when which lumped parameter (function)s are reasonable
- **Variation**
  Ability to simulate and evaluate scenarios systematically
- **Access**
  Visualisation, access to parameters and temporal evolutions not assessible in wet lab
- **Scaling**
  Bridge the scales on the basis of large data sets and mathematical techniques
- **Reduction**
  Investigate „What if…?“ *under the given configuration*

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Thank you for your attention!

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