Physical protection of organic matter: a biophysical approach

Wilfred Otten

Cranfield University
UK

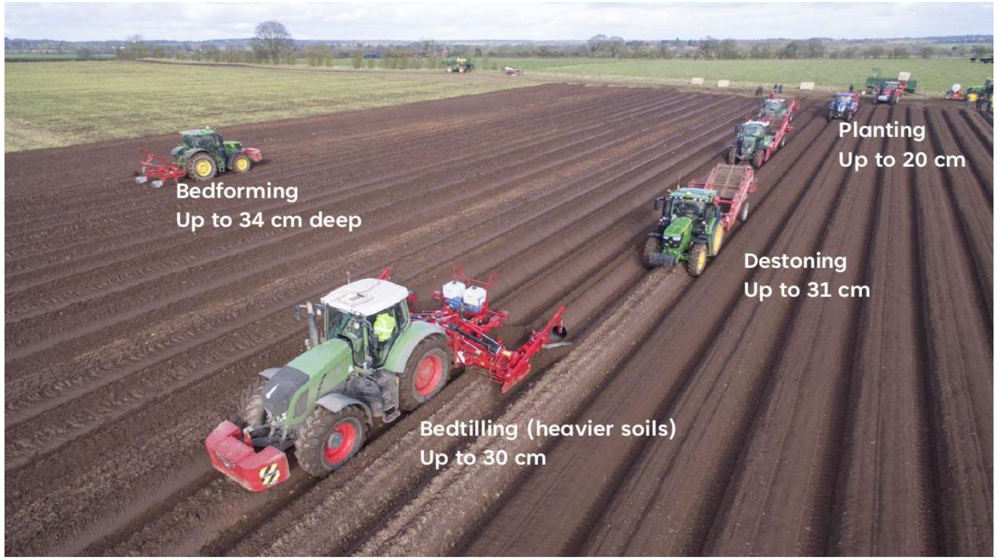
Ruth Falconer, Xavier Portell

SoilCET, Rueil-Malmaison – France, 24-26 January 2024

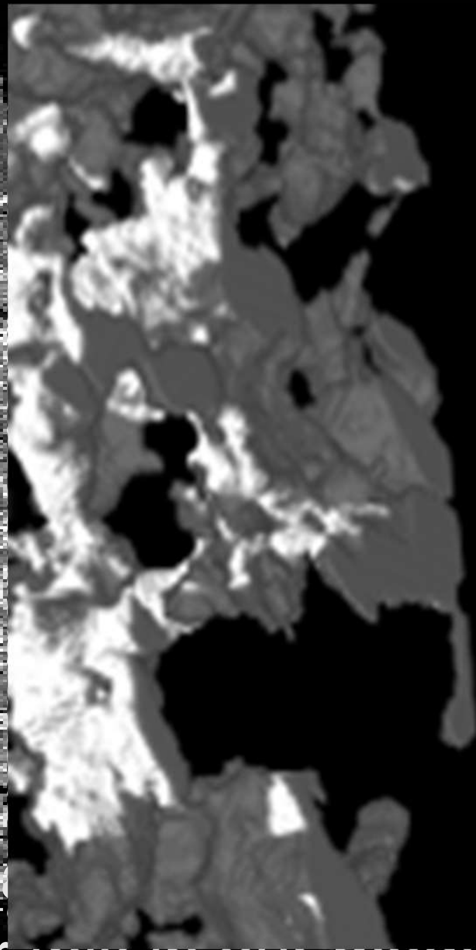
As a business, PepsiCo is deeply committed to developing scientifically validated solutions which will enable us to make progress towards their global goal of spreading regenerative farming practices across 7 million acres by 2030.

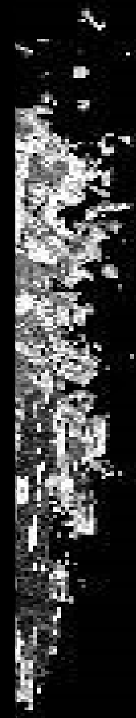
Potato-LITE

low intensity tillage enhancement



PEPSICO McCain GRIMME UKRI Innovate UK





Although soil is unavoidably spati
few attempts to explicitly consider this in our models

Soil Carbon in the Ecological Transition 2024

INRAE

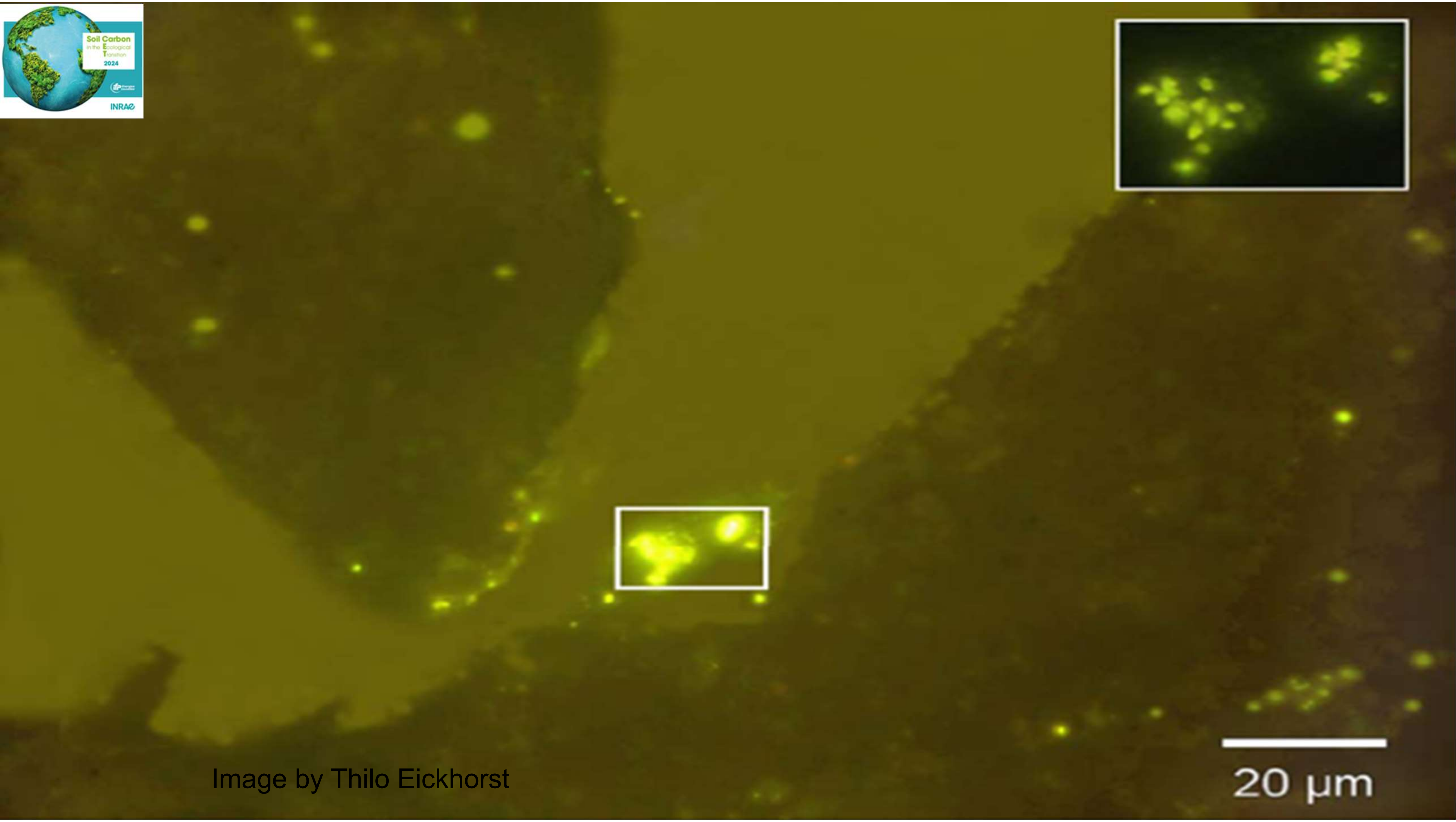
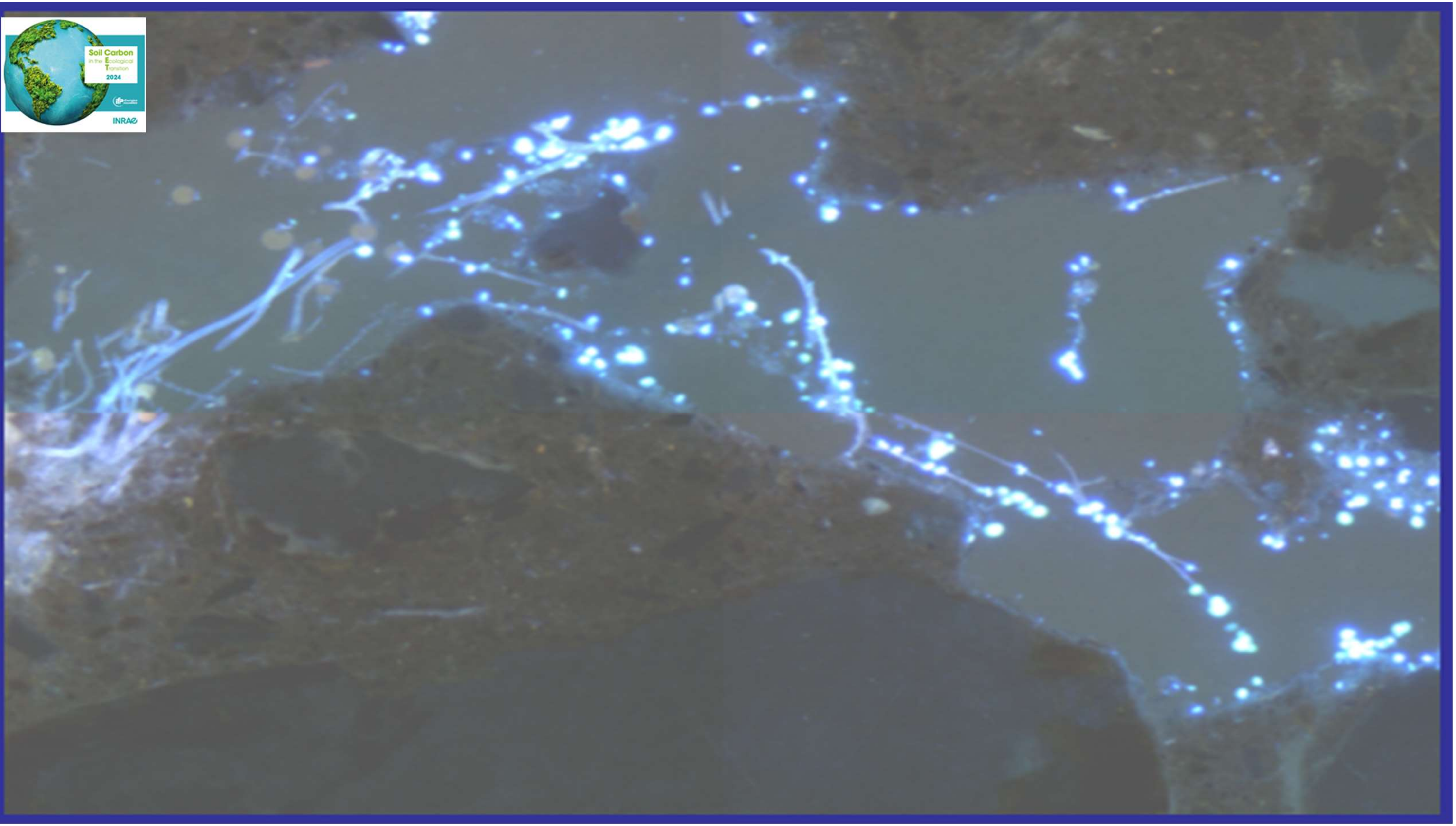


Image by Thilo Eickhorst

Soil Carbon in the Ecological Transition 2024

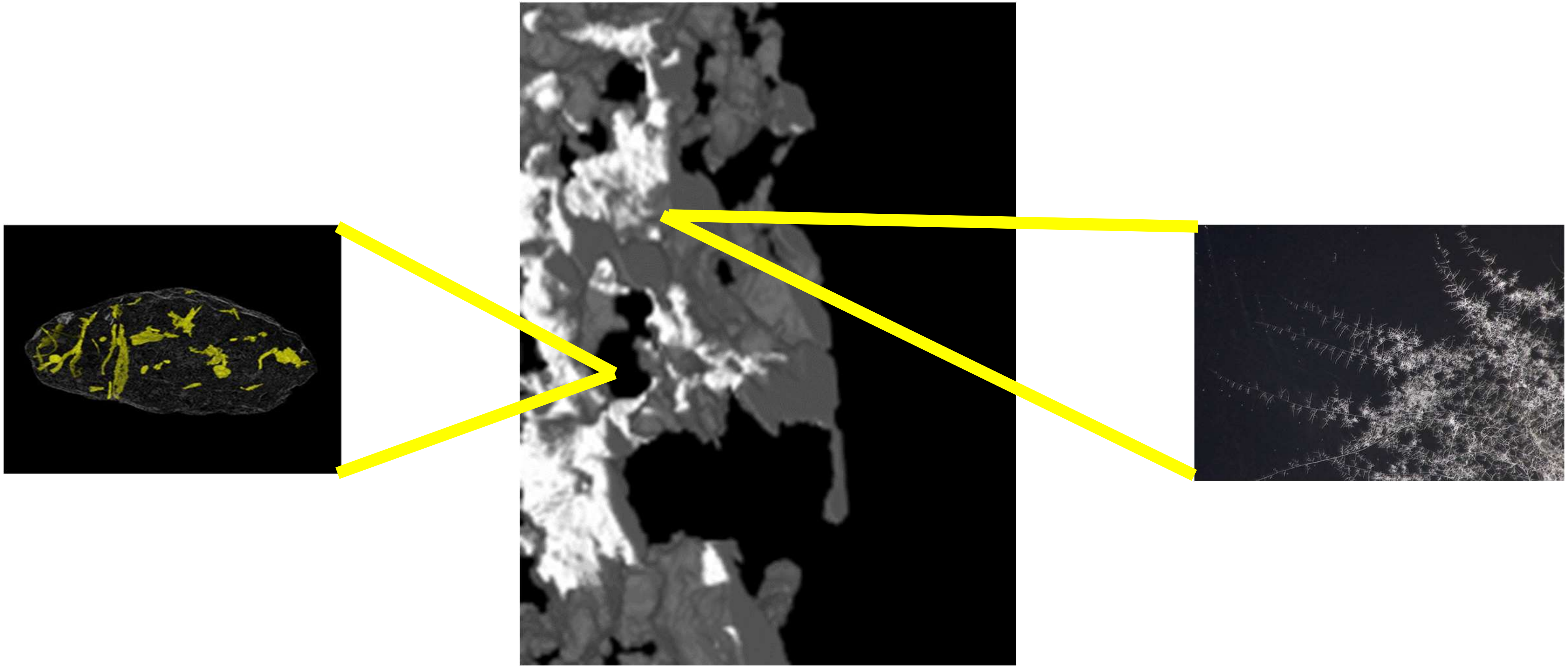
INRAE



Soil Carbon in the Ecological Transition 2024

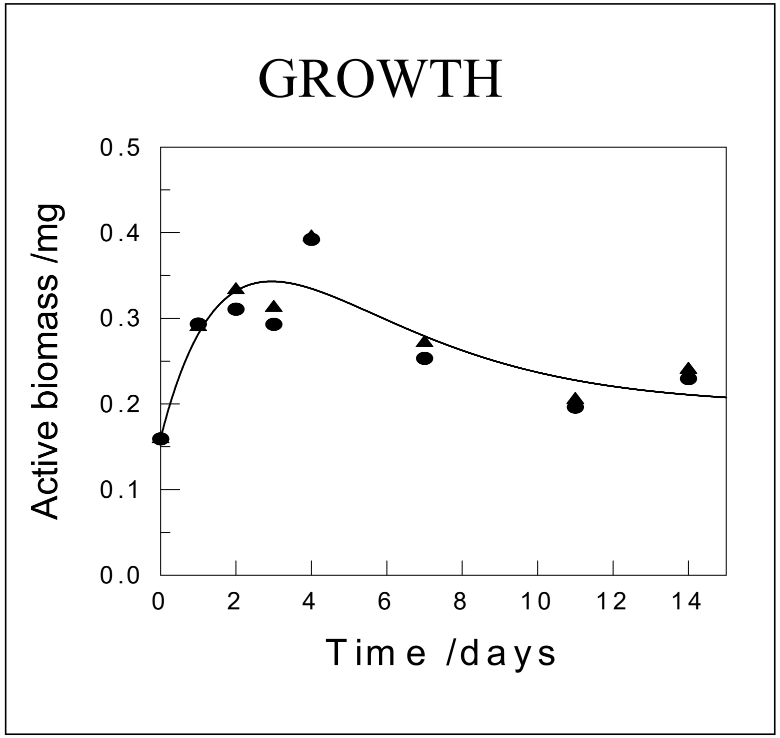
INRAE

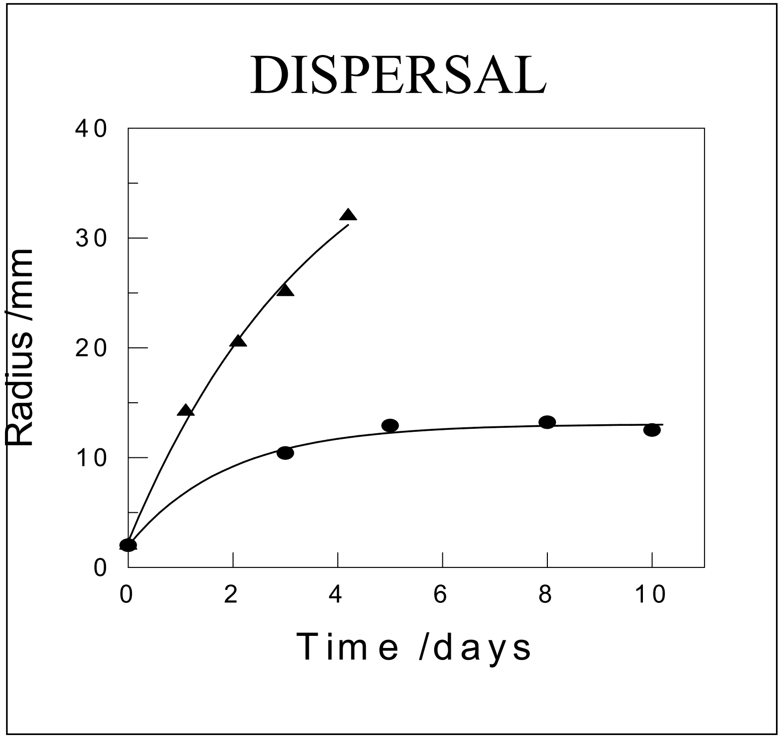
Move towards a more integrated approach for soil physical protection



Empirical observations <➔ biophysical model <➔ increase complexity <➔ explore the unknown

Fungal Growth Dynamics





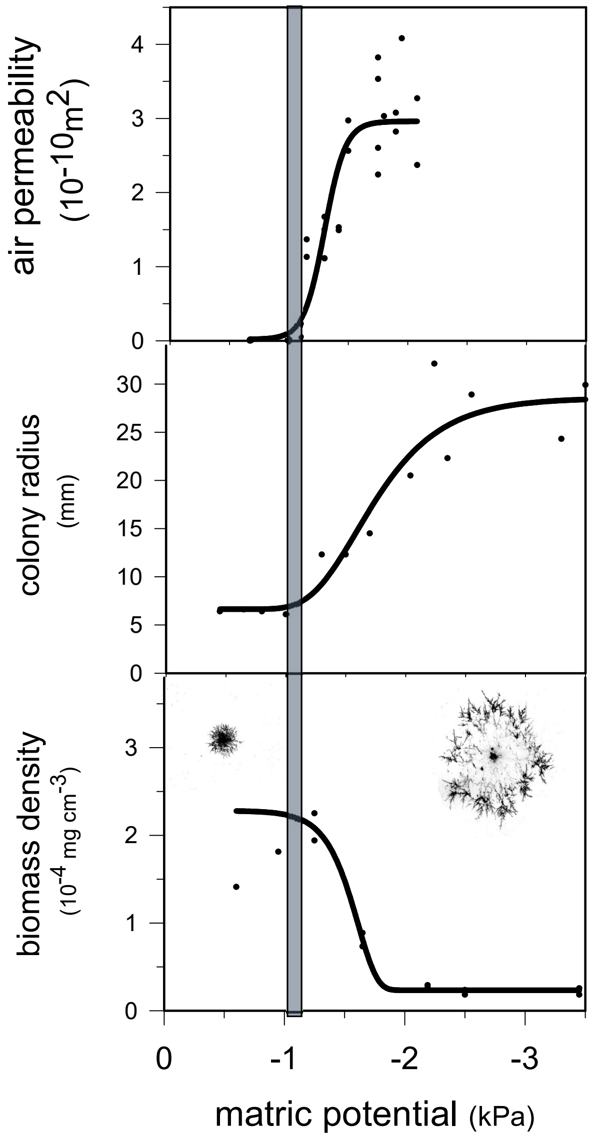
Differential effect of soil physical conditions upon temporal and spatial dynamics

Fungal growth and air-filled pore volume

air-permeability

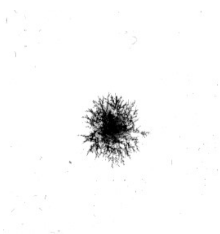
colony radius

colony density



Soil Biol. & Biochem (1999):. 31

Fungal spread is



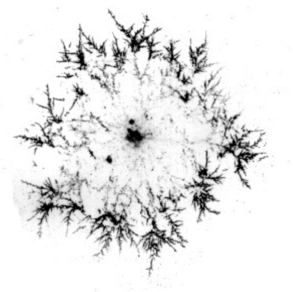
spatially constrained in a

poorly connected air-filled pore volume,

***forming small dense colonies*,**

but

***switches rapidly* in a**

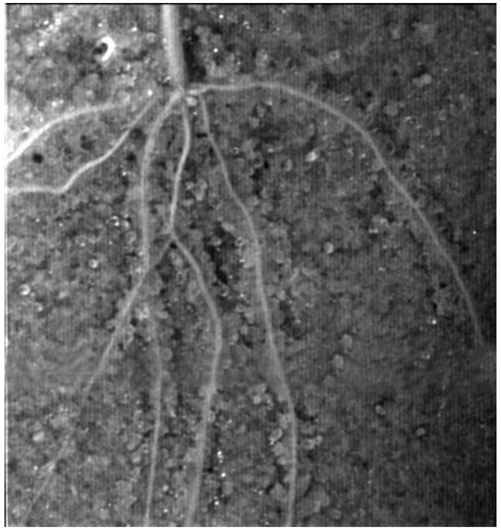


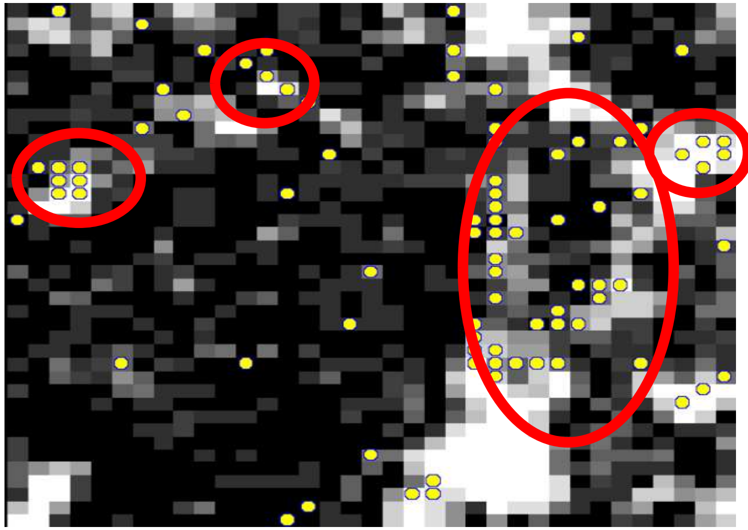
well-connected network to

larger colonies with a lower biomass density

Fungal Growth and Percolation

- Most pathogens spread in environments with hosts in *discontinuous, discrete patches*

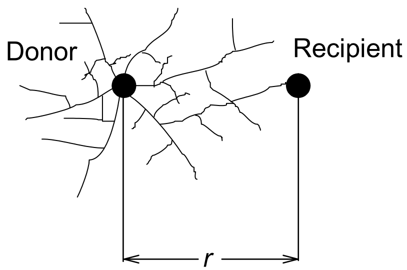




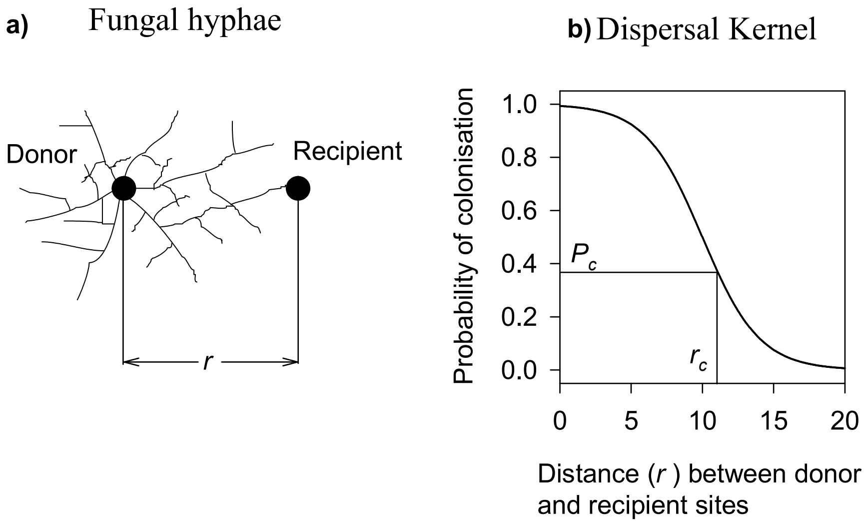
Convenient to visualise spread through a population of discrete sites on a lattice

Fungal Growth and Percolation: the Principle

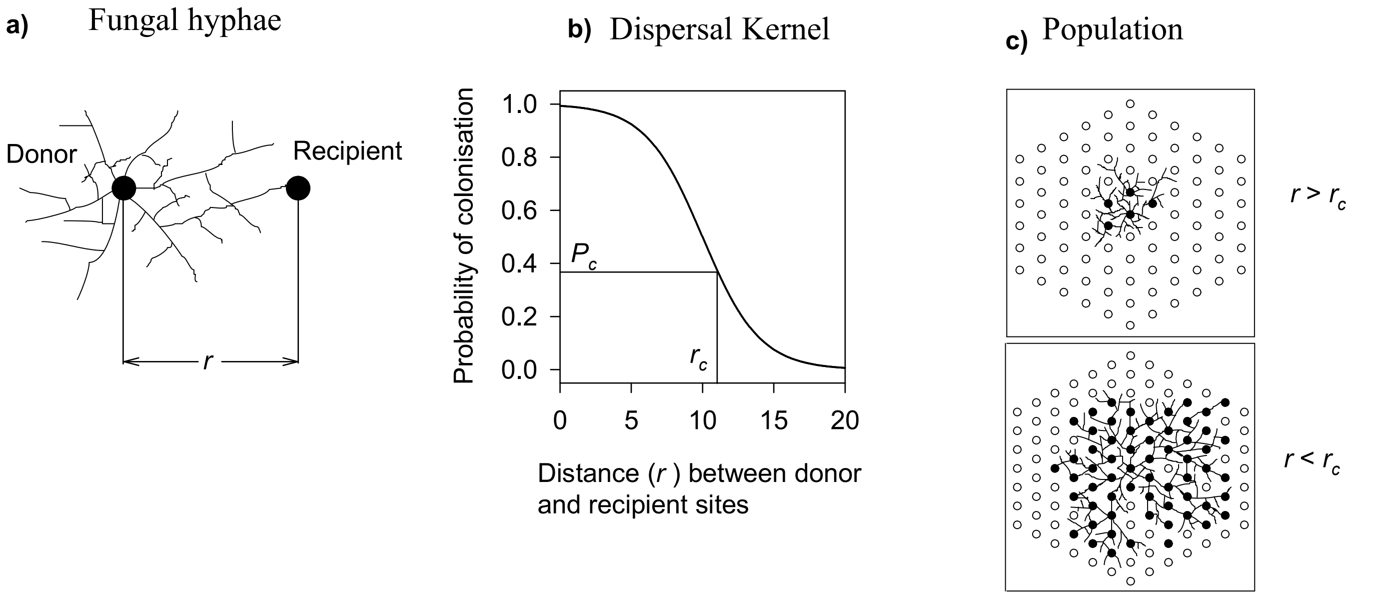
a) Fungal hyphae



Fungal Growth and Percolation: the Principle



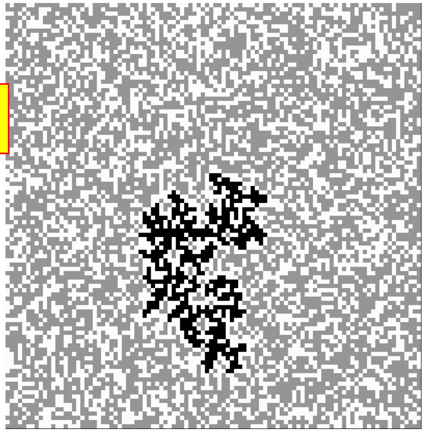
Small differences at local scale induce large effects at macroscale



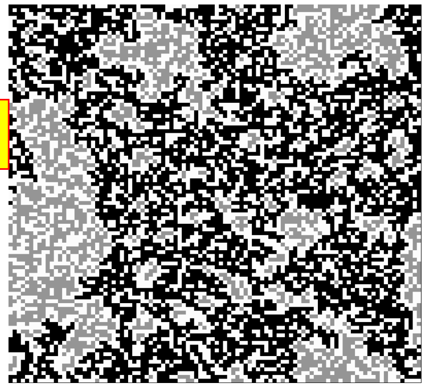
New Phyt. (2000) 146: 535-544

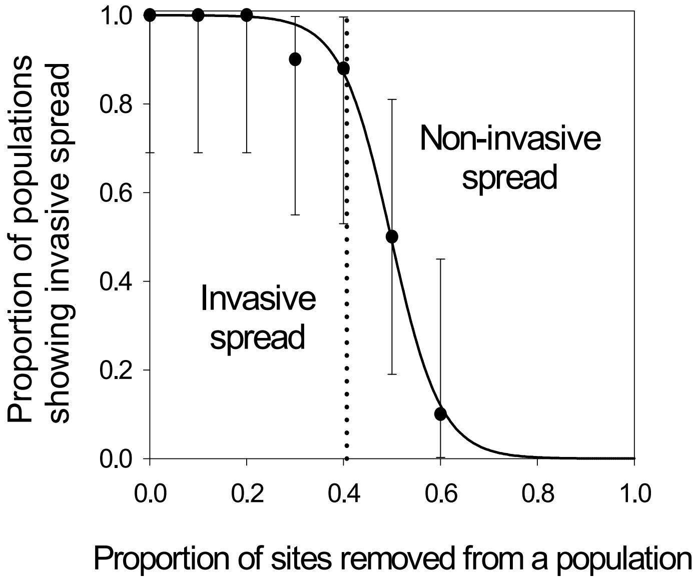
Percolation and Microbial Invasion: Experimental Validation

42%



40%





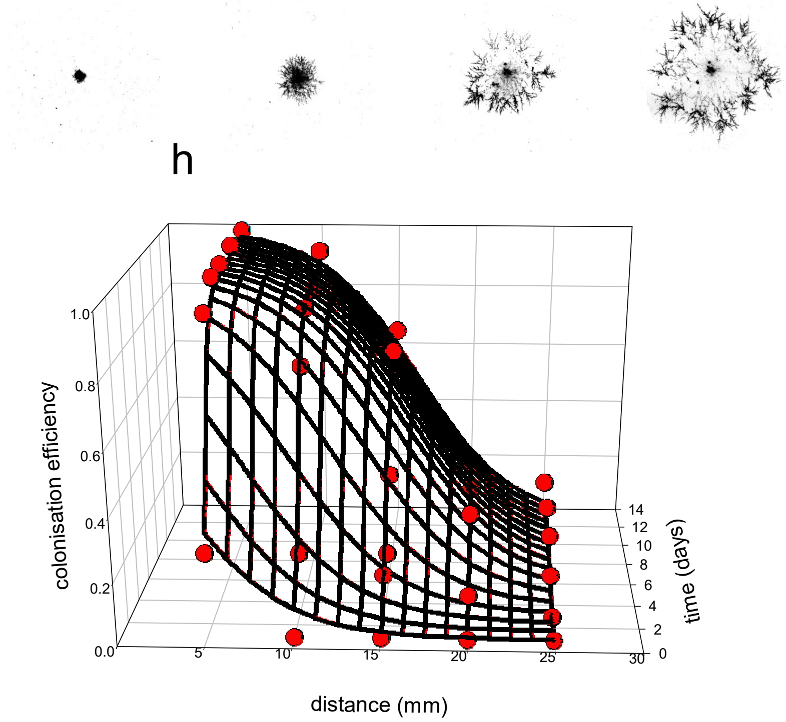
Otten & Gilligan 2006:
Eur J. Soil Sci: 57: 26-37
Otten et al., 2004
New Phyt: 163: 125-132

Extending these concepts to spread through soil

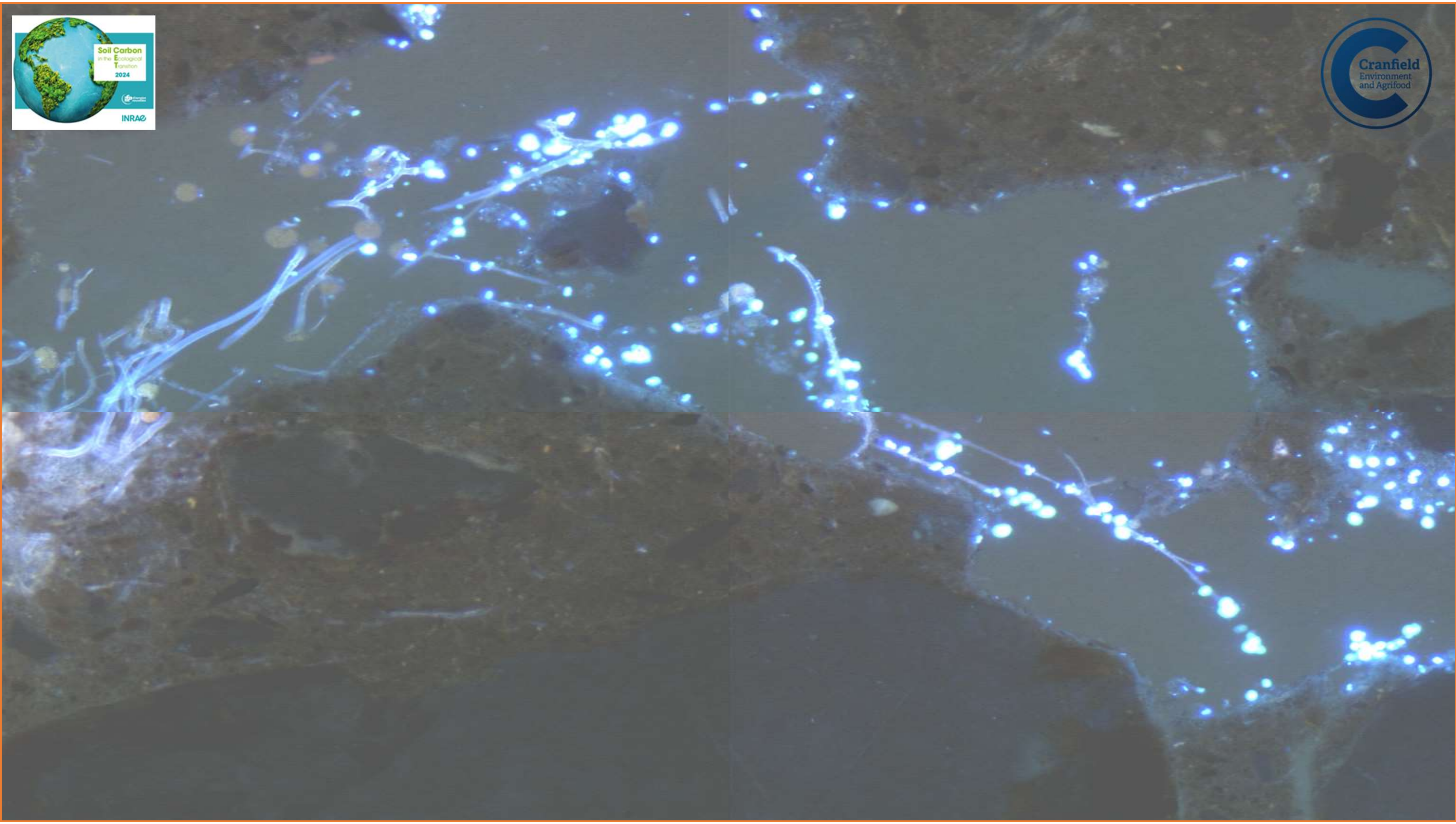
Probabilistic Quantification of Spread in Soil

Efficiency of Colonization

Colonization of POM is summarised by a *dynamic* variable that changes over time towards an *asymptotic* maximum

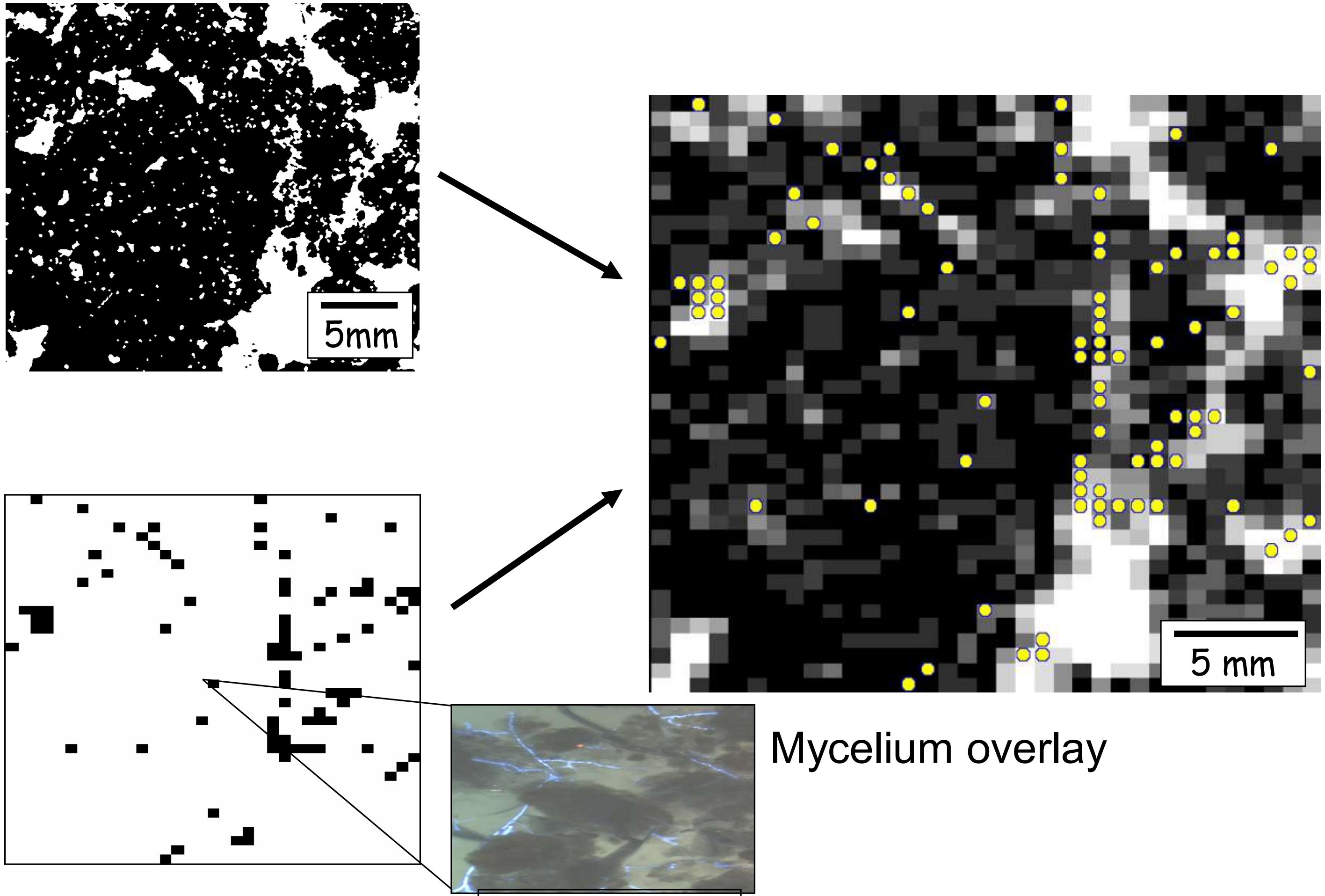


New Phyt. (2001): 151: 459-468


Soil Carbon
in the Ecological
Transition
2024
INRAE
Cranfield
Environment
and Agrifood

Soil heterogeneity and fungal invasion

30 µm thick

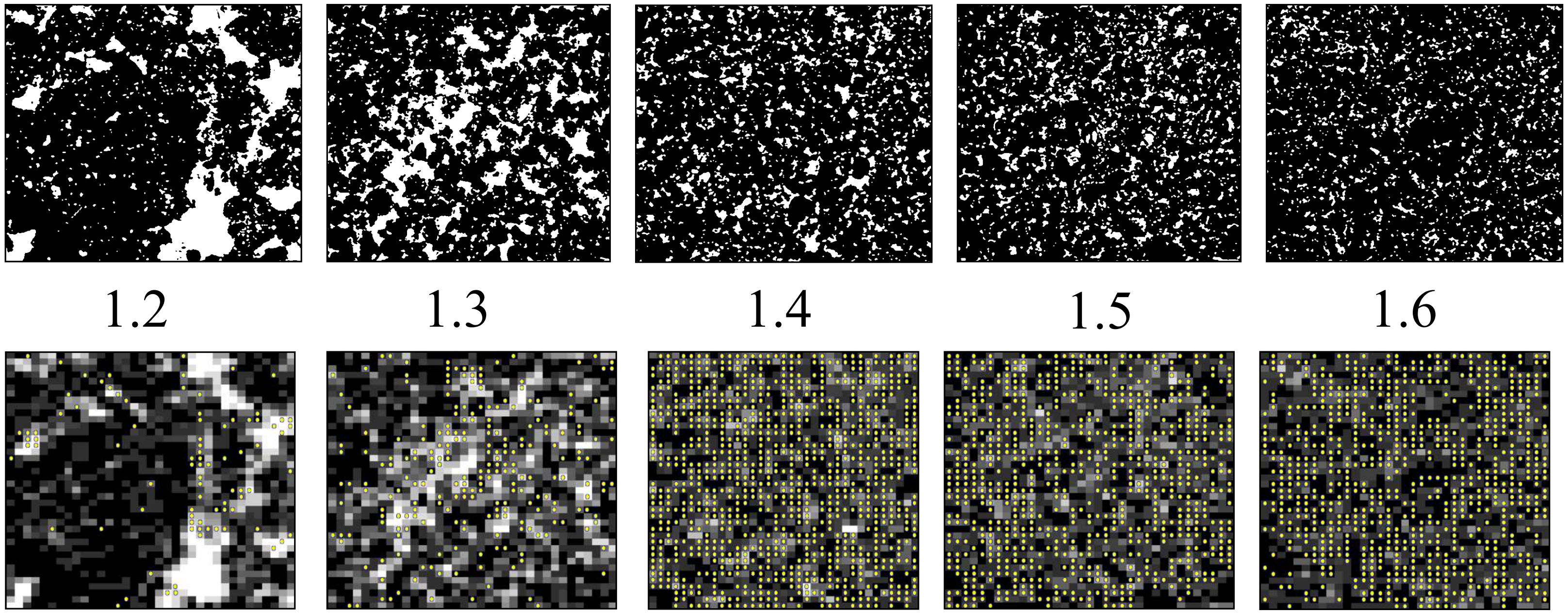


Mycelium overlay

0.7 * 0.5 mm

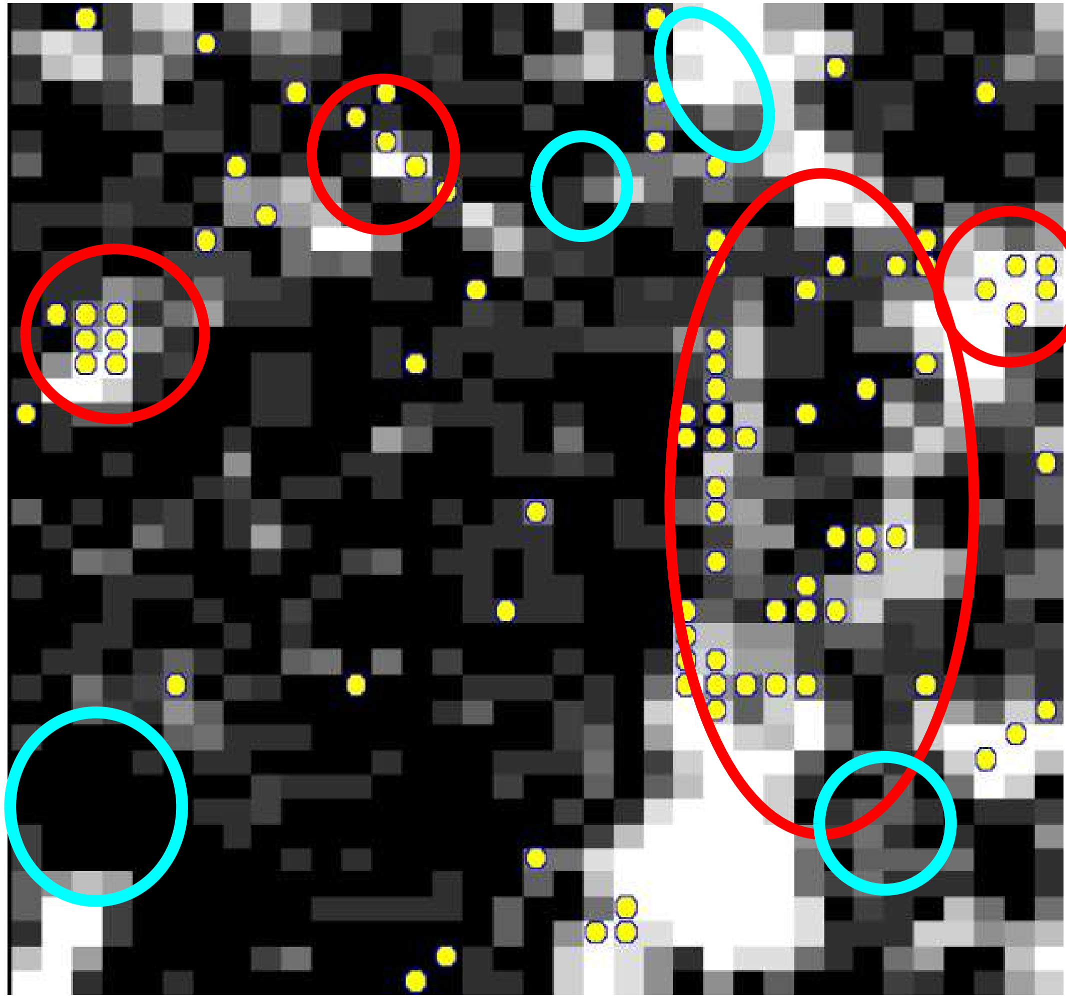
Harris et al.
FEMS ME (2003) 44:45-56

Increasing Bulk-density



Low BD ➔ sparse colonies following preferential pathways.

High BD ➔ dense colonies, entering smaller pore spaces

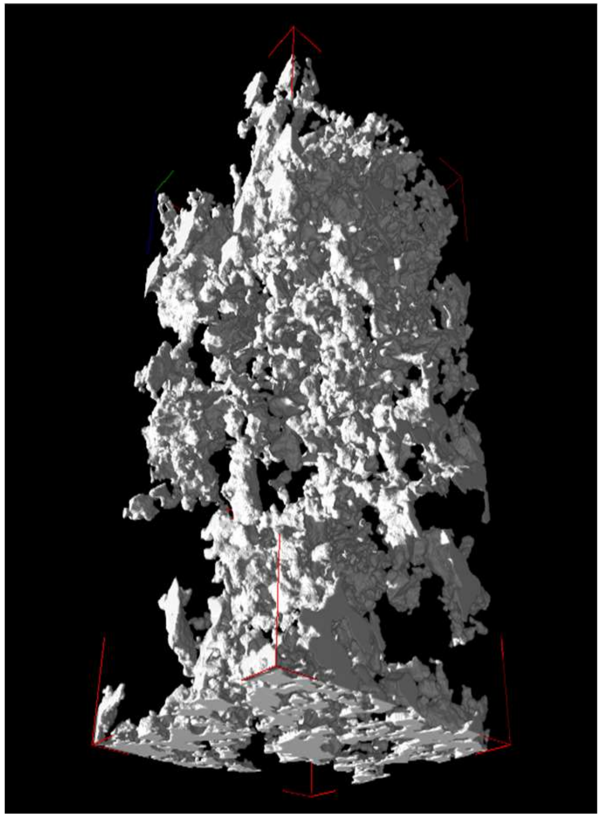


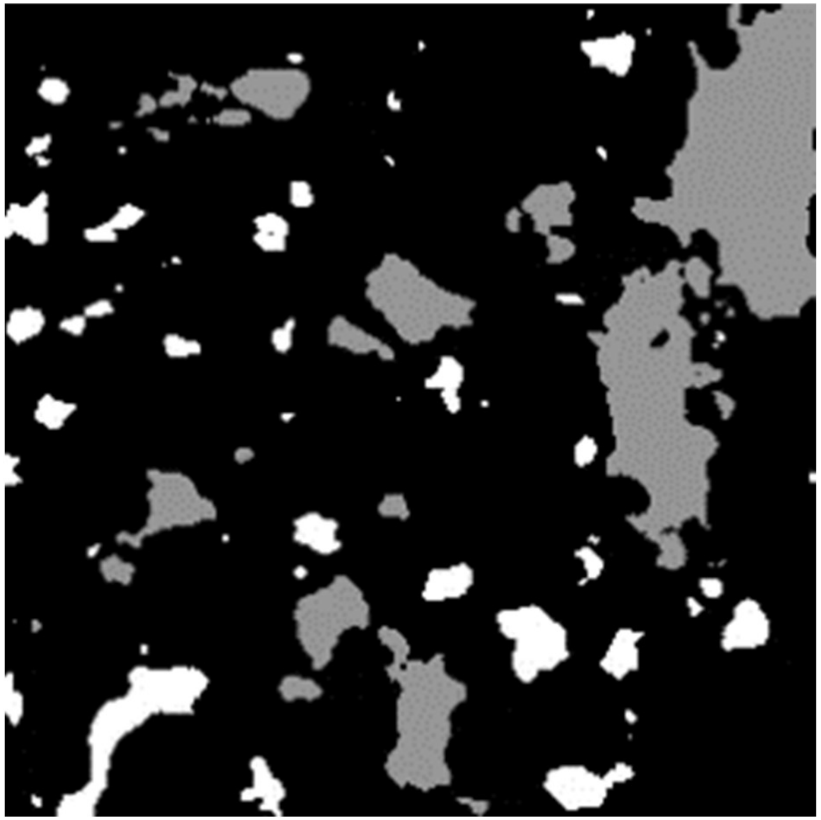
How does mycelium end up in **apparently separated** pore volumes?

Why does mycelium not end up in **closely neighbouring** pore volumes?

Connectivity of pore volumes can only partially be quantified in thin sections

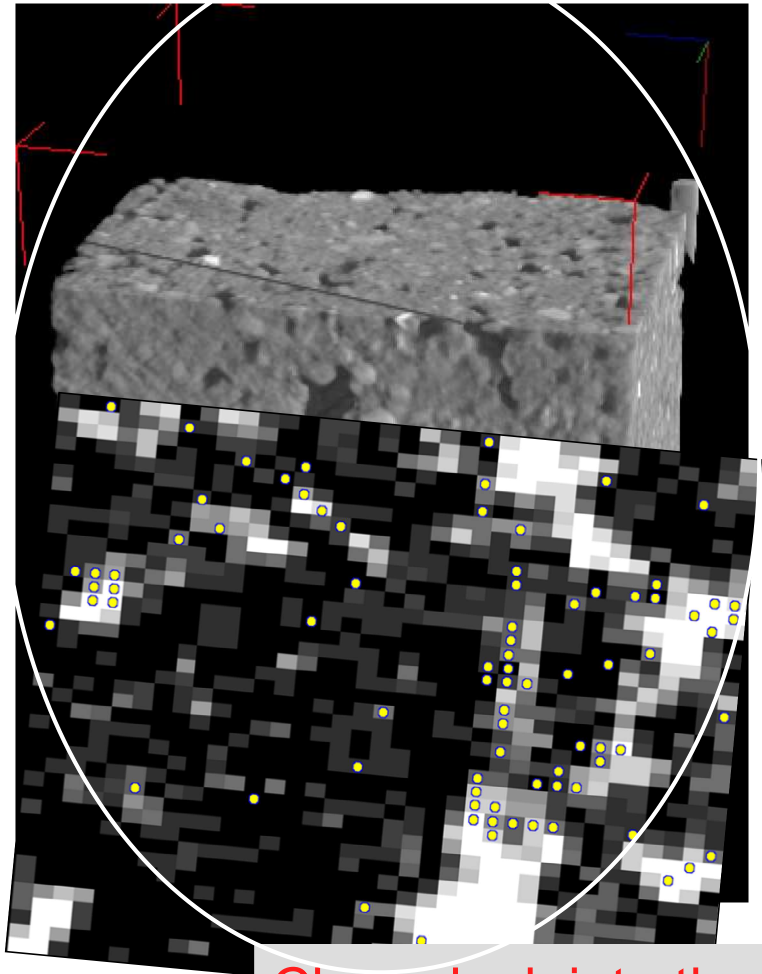
Consequences: Biological Interactions

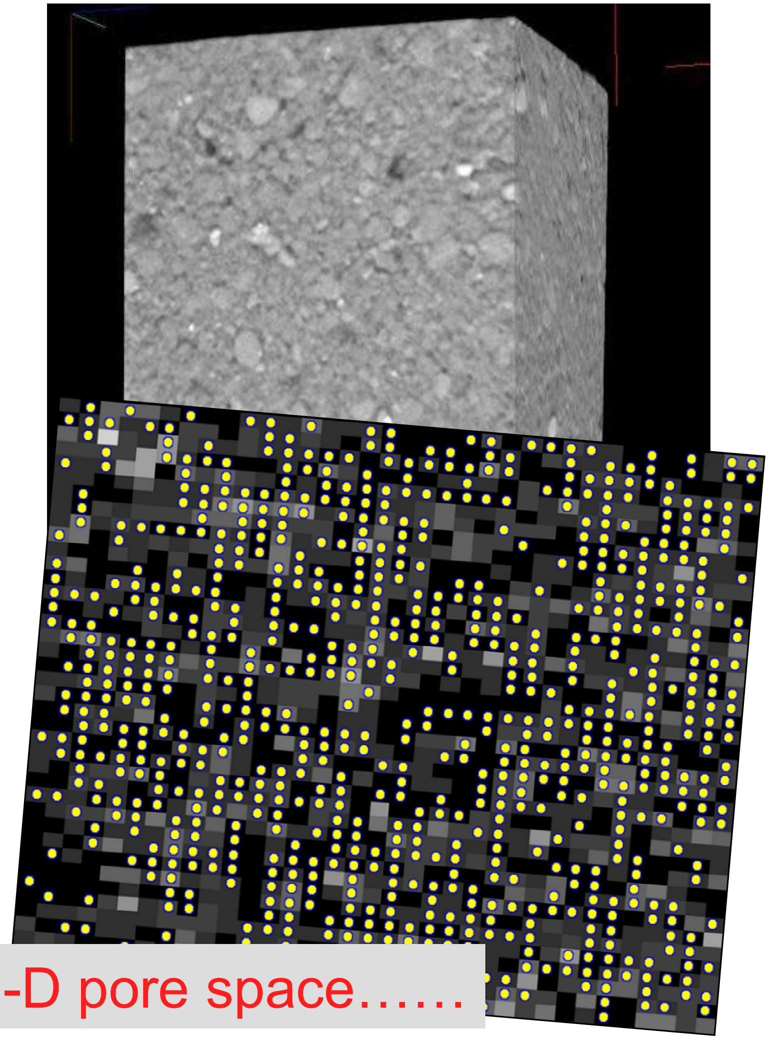




Pore volume exclusion is not just a matter of pore sizes

70 µm





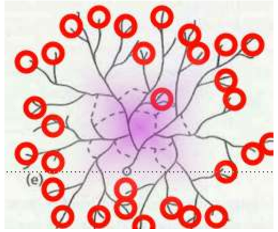
Closer look into the 3-D pore space……

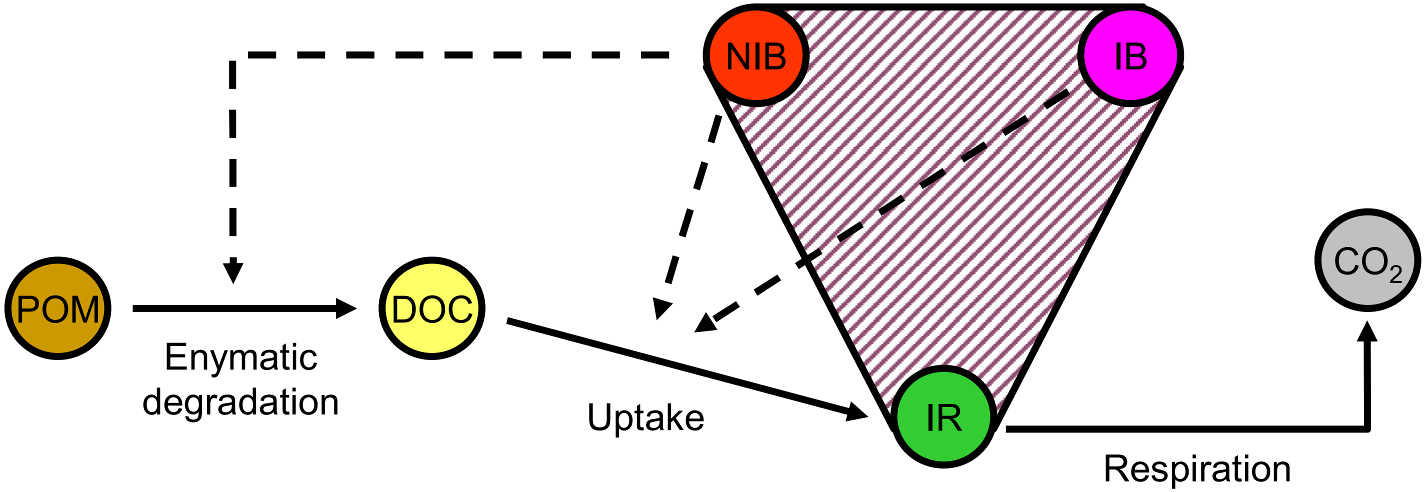
Falconer 2005:

-Non-Insulated Biomass (NIB): propagates (diffuses) in the porous space

-Insulated Biomass (IB): static

-Internal Ressource (IR): propagates (diffuses) in the mycelium

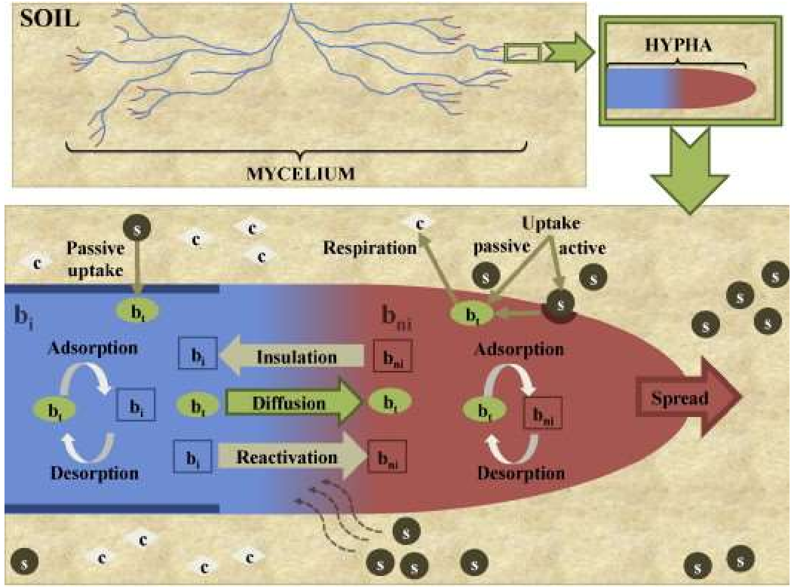




Enzymatic degradation & uptake: Michaelis-Menten processes.

POM: Particulate Organic Matter (solid phase).

DOC: Dissolved Organic Carbon (liquid phase).



$$\frac{\partial b_{ni}}{\partial t} = D\nabla^2 b_{ni} - \zeta_{ni} b_{ni} + \zeta_i b_i s + \alpha_{ni}\pi_{ni}^{\theta} b_t - \beta_{ni} b_{ni} \tag{A.1}$$

spread − insulation + reactivation + adsorption − desortion

$$\frac{\partial b_i}{\partial t} = \zeta_{ni} b_{ni} - \zeta_i b_i s + \alpha_i \pi_i^{\theta} b_t - \beta_i b_i \tag{A.2}$$

insulation − reactivation + adsorption − desorption

$$\frac{\partial b_t}{\partial t} = D_v \nabla^2 b_t + \varepsilon_1 \left\{ \left(\frac{V_{max}}{K_m + s} + \lambda_{ni} \right) s b_{ni} + \lambda_i s b_i \right\} - \left(\alpha_{ni}\pi_{ni}^{\theta} b_t - \beta_{ni} b_{ni} + \alpha_i \pi_i^{\theta} b_t - \beta_i b_i \right) \tag{A.3}$$

spread + active uptake b_{ni} + passive uptake b_{ni}
+passive uptake b_i − adsorption b_{ni} + desorption b_{ni}
−adsorption b_i + desorption b_i

$$\frac{\partial s}{\partial t} = - \left\{ \left(\frac{V_{max}}{K_m + s} + \lambda_{ni} \right) s b_{ni} + \lambda_i s b_i \right\} \tag{A.4}$$

−active uptake b_{ni} − passive uptake b_{ni} − passive uptake b_i

$$\frac{\partial c}{\partial t} = (1 - \varepsilon_1) \left\{ \left(\frac{V_{max}}{K_m + s} + \lambda_{ni} \right) s b_{ni} + \lambda_{ni} s b_i \right\} \tag{A.5}$$

active uptake b_{ni} + passive uptake b_{ni} + passive uptake b_i

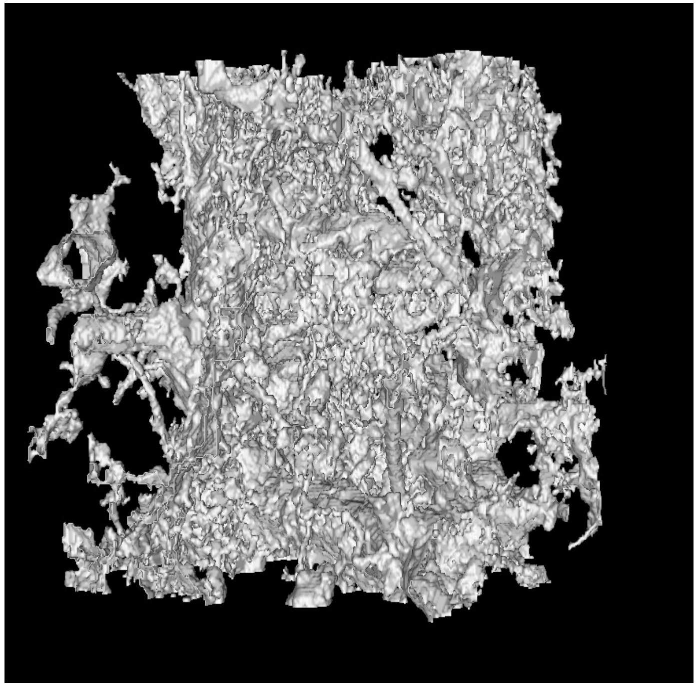
where:

$$\pi_{ni} = \frac{b_{t_{ni}}}{b_t} = \frac{b_{ni}(\beta_{ni}/\alpha_{ni})}{b_{ni}(\beta_{ni}/\alpha_{ni}) + b_i(\beta_i/\alpha_i)} \quad \text{and}$$

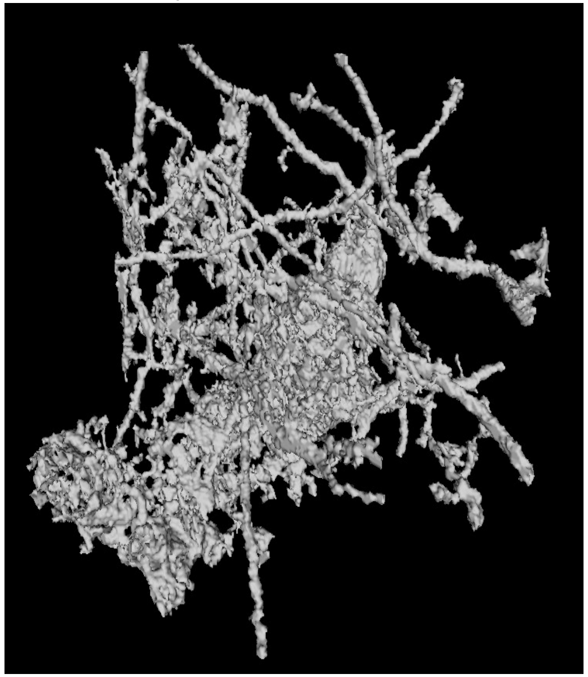
$$\pi_i = \frac{b_{t_i}}{b_t} = \frac{b_i(\beta_i/\alpha_i)}{b_{ni}(\beta_{ni}/\alpha_{ni}) + b_i(\beta_i/\alpha_i)} \tag{A.6}$$

soil structure and soil management

Native successions since 1989

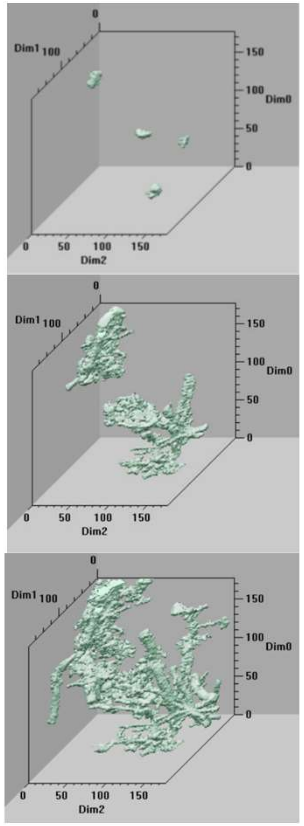


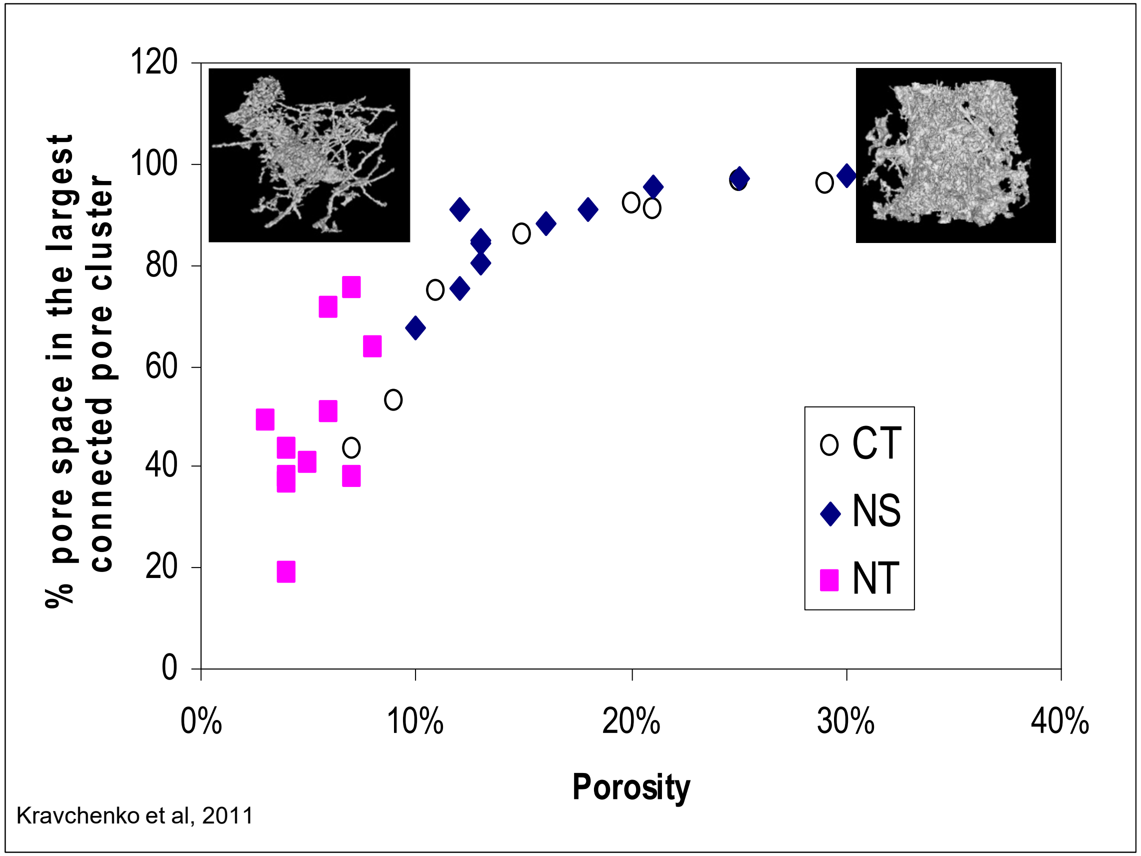
no tillage
Corn-Soybean Wheat rotation



Largest connected pore cluster in 2 contrasting management strategies

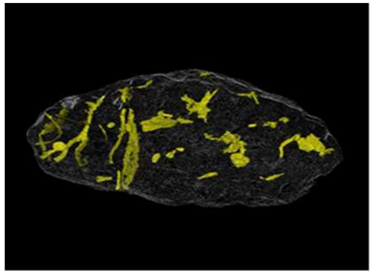
No till enhances macro-pores but reduces connectivity

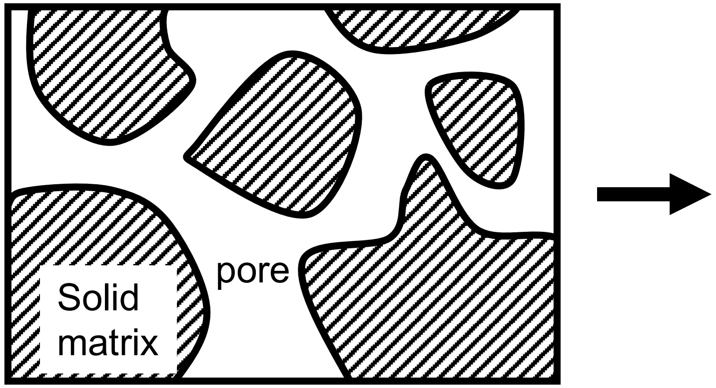


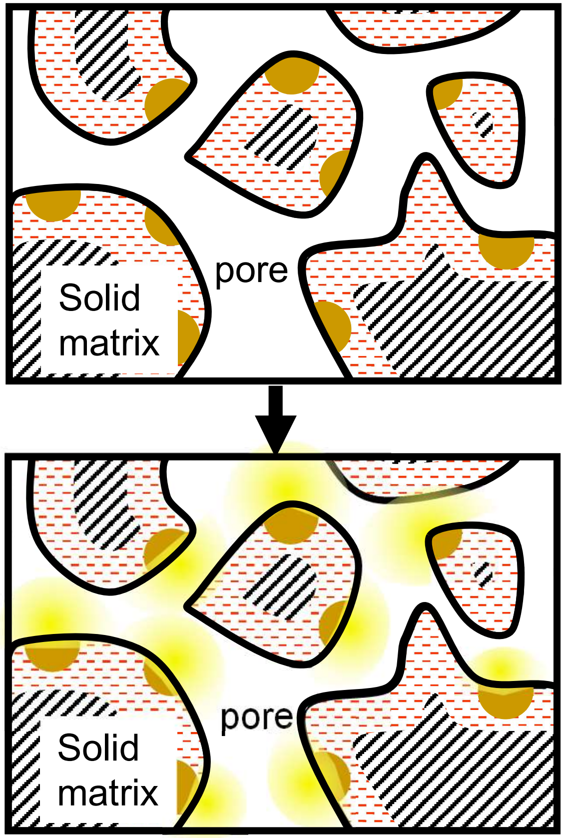


More fragmented pore space of the NT treatment will hinder invasion, Large connected pores of the NS and CT promotes invasion

Scenario modelling: integrate and explore the unknown?





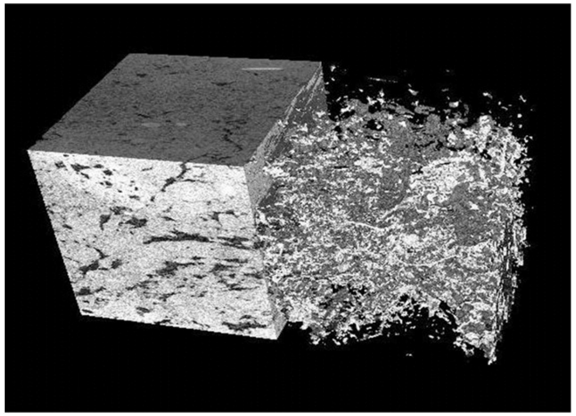


POM

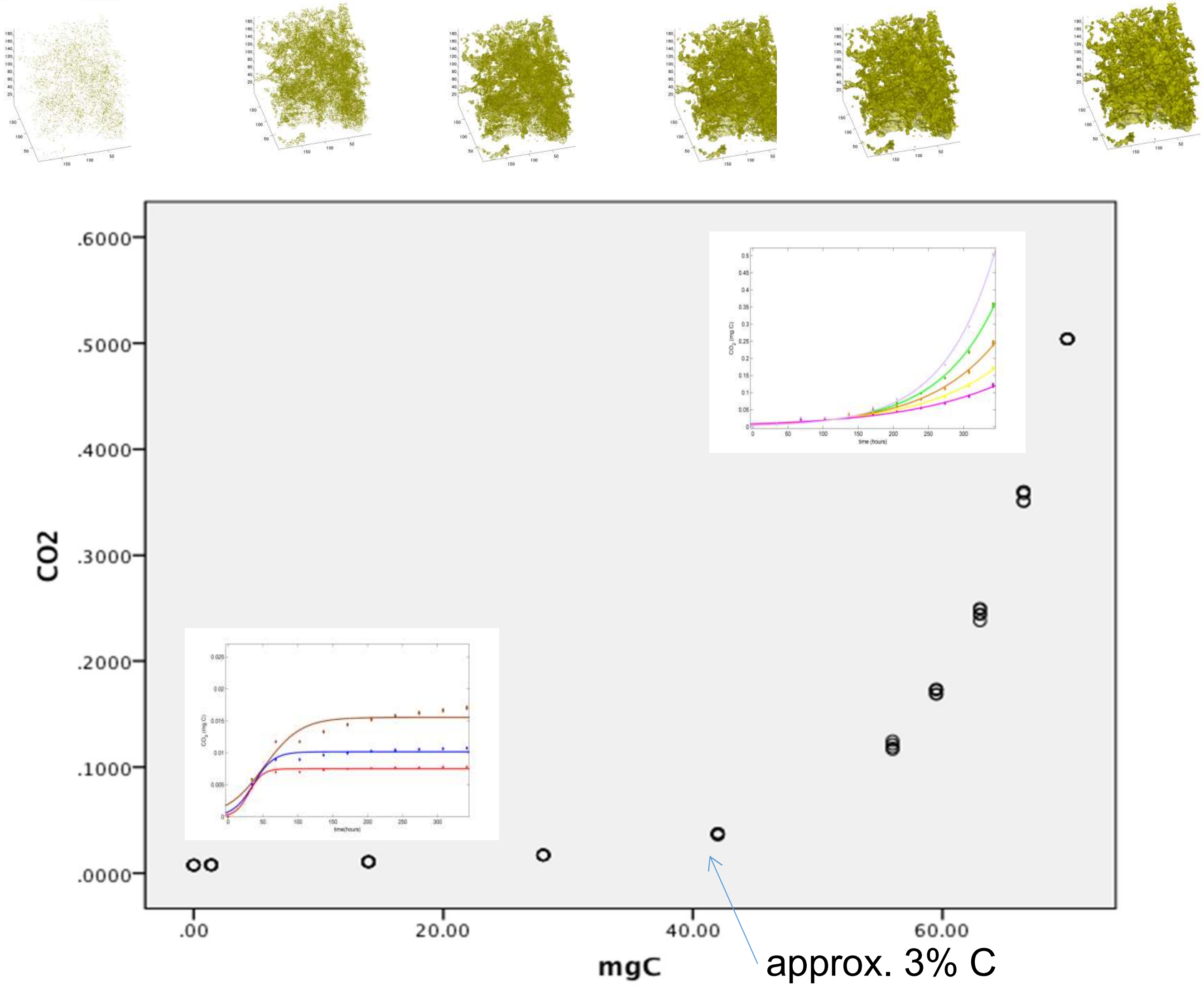
(solid phase)

DOC

(liquid phase)



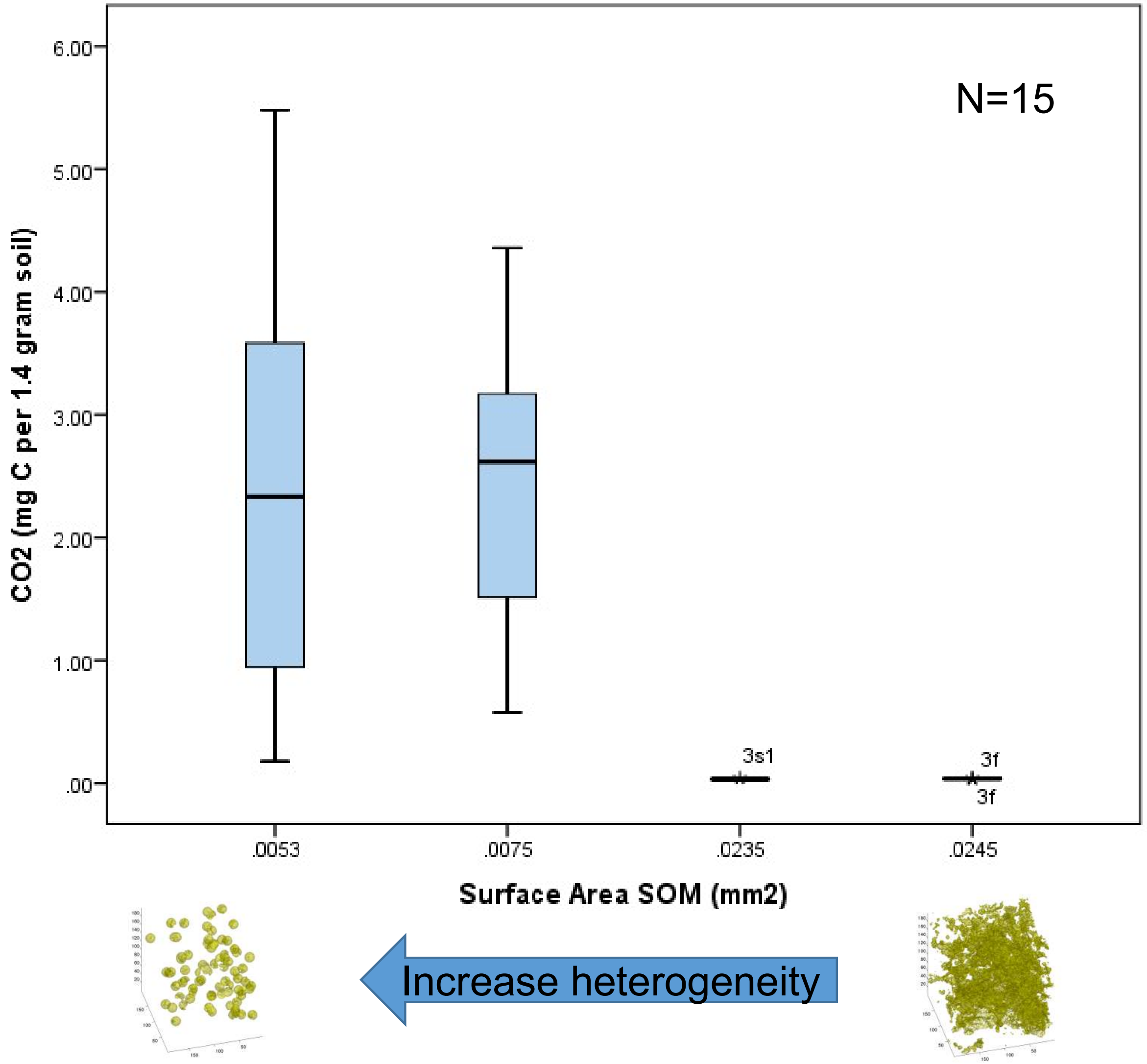
Scenario modelling: 1. organic matter content



non-linear response to C concentration.

Complex interaction between pore geometry and C distribution result in unexpected changes in CO2 evolution.

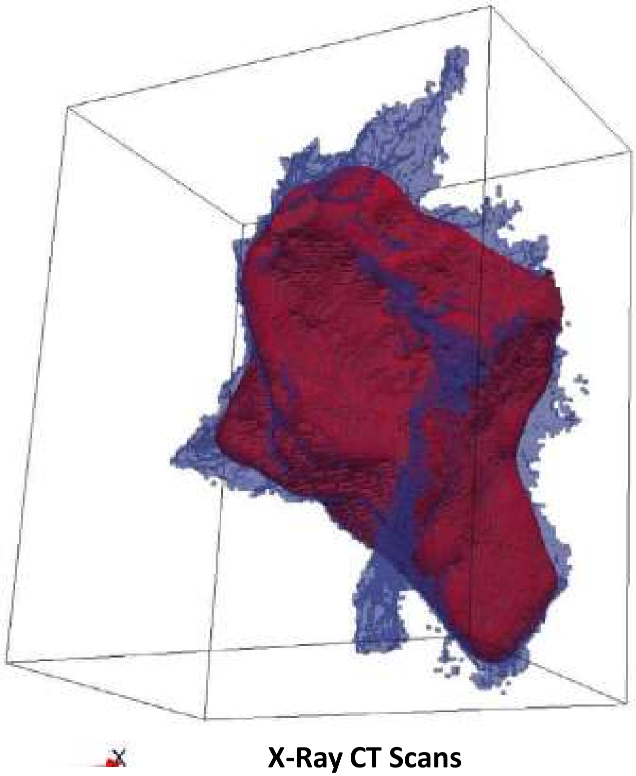
Microscopic distribution of OM Drives $C0_2$ emission



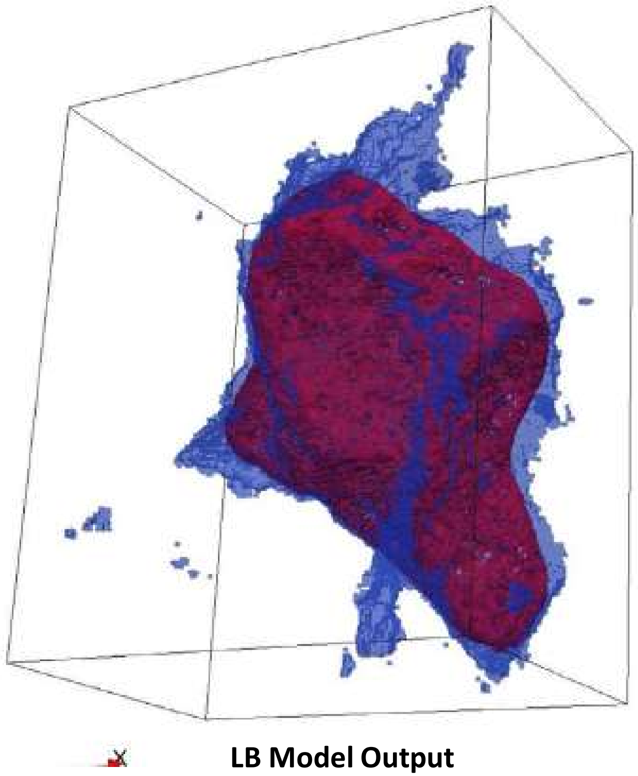
- **Very large variability at identical 'bulk' properties:**
  ➔ Bulk sample C content not enough!

- **Counterintuitive and non-linear response**

modelling offers a reliable way forward to identify connected water pathways in soil



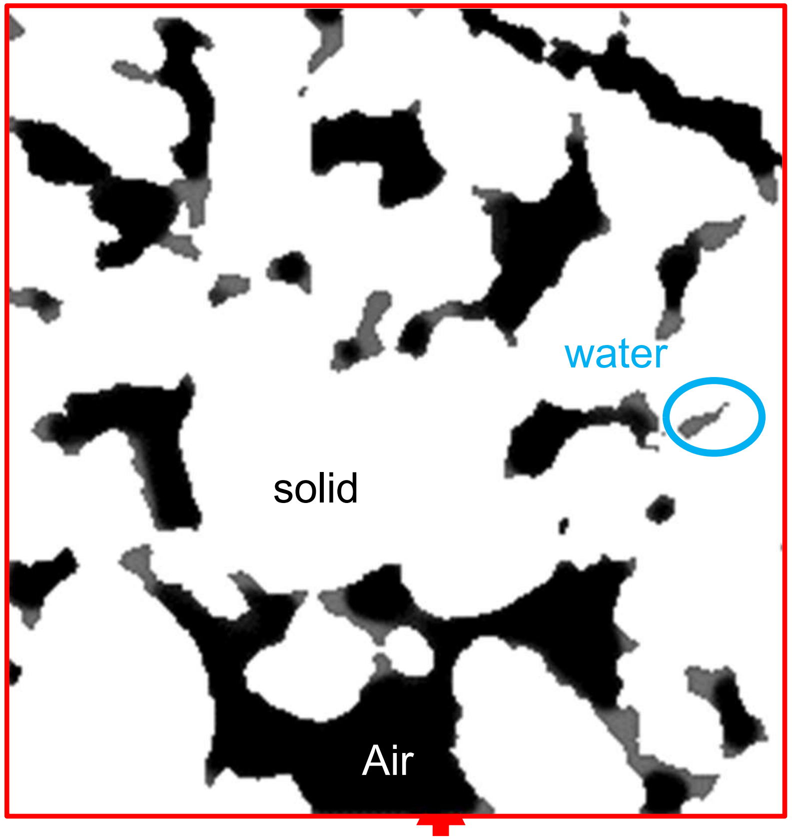
X-Ray CT Scans



LB Model Output

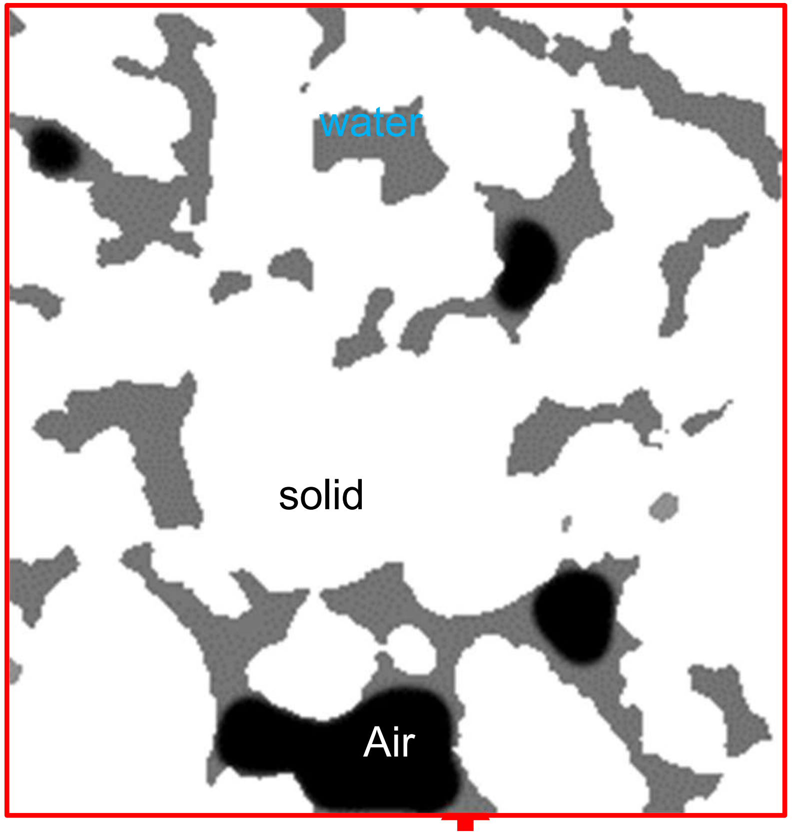
Pot et al. (2015)

Connected fractions in pore space



Sw=20%

Air-filled pores connected



Sw=80%

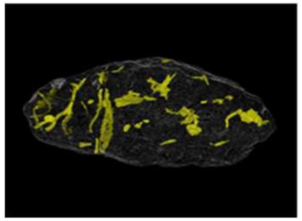
Water-filled pores connected

Trait based approach for Fungi
R, K-strategists

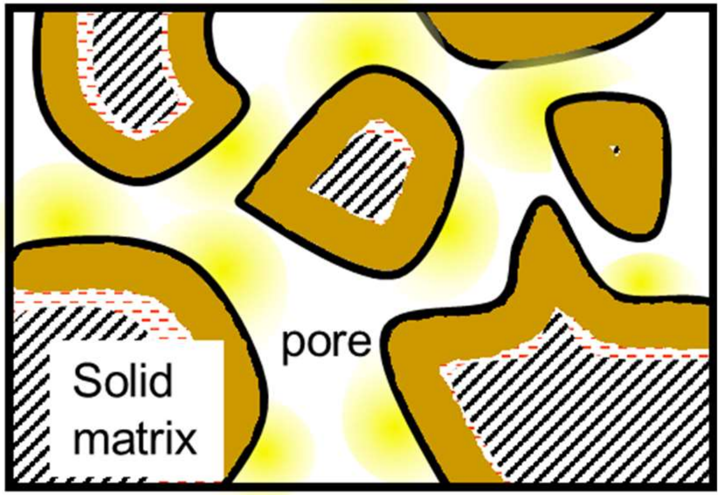
	R-strategists	K-strategists
1	Short-lived	Long-lived
2	Rapid growth	Slow growth
3	Low investment into self-maintenance	High investment into self-maintenance
4	Rapid reproduction	Slow reproduction
5	Low offspring	High offspring

Is the differentiation between R and K strategists a function of the environment?

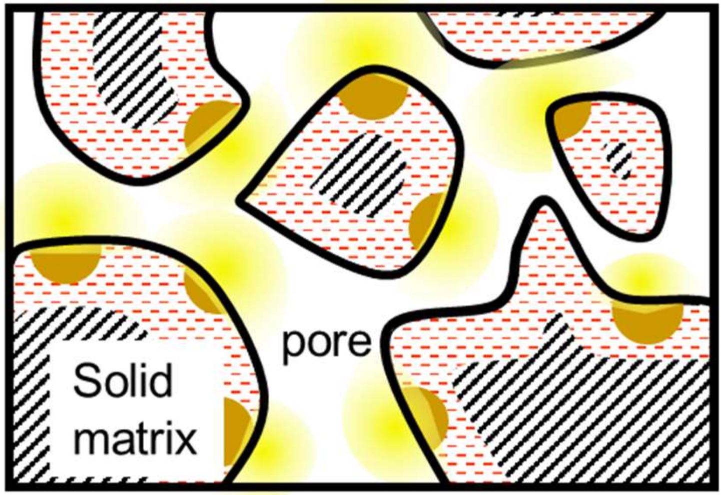
Resource connectivity



POM on the pore/solid



POM in a Patchy distribution

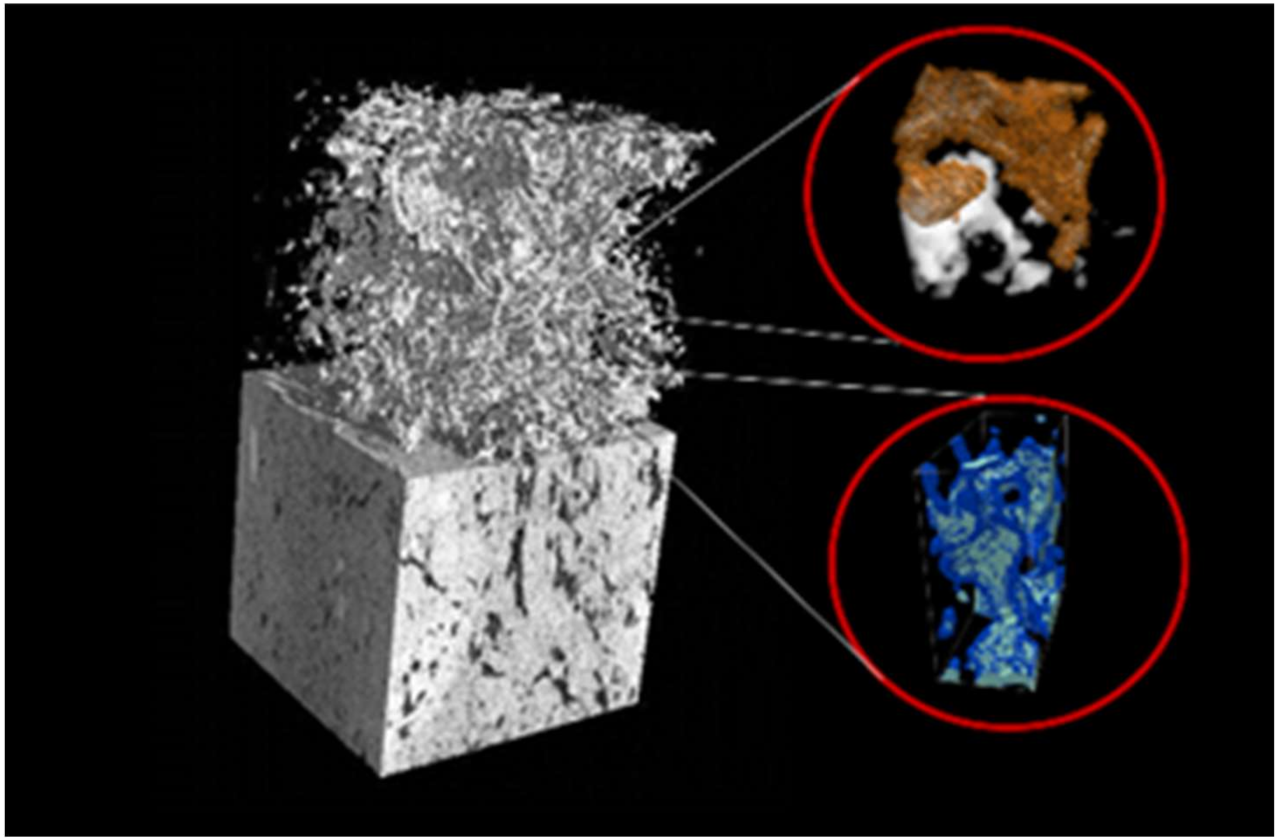


22.73 g of POM (5% for a 1.4 g cm^{-3} soil)

What are important aspects of connectivity in case we are interested in C dynamics

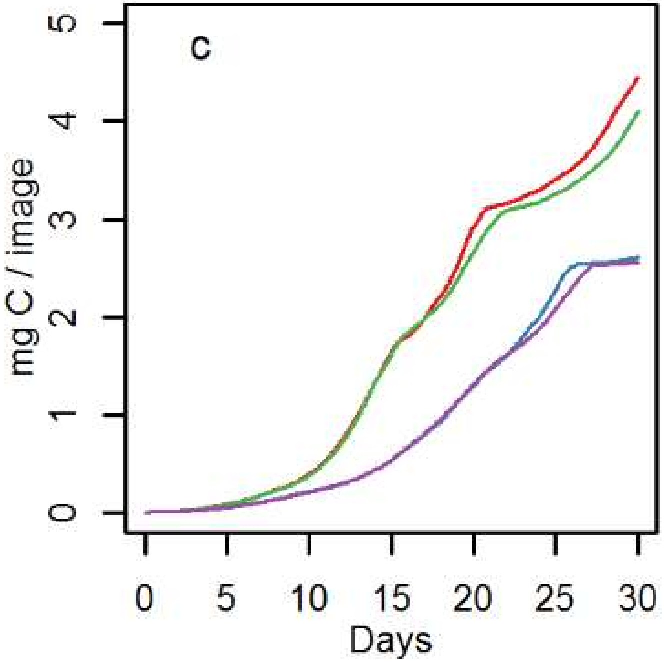
- **Connected pore space:**
  - ✓ Essential to allow for fungal spread
- **Connected air phase:**
  - ✓ Preferentially followed by fungi (higher spread rate)
- **Connected water phase:**
  - ✓ Enhanced diffusion of dissolved organic carbon.
- **Resources connectivity(POM distribution):**
  - ✓ Beneficial for slow growing fungi.
- **Spread and translocation:**
  - ✓ Spread between sites and translocation of C.

Synthesising insights:
modelling fungal spread in soil

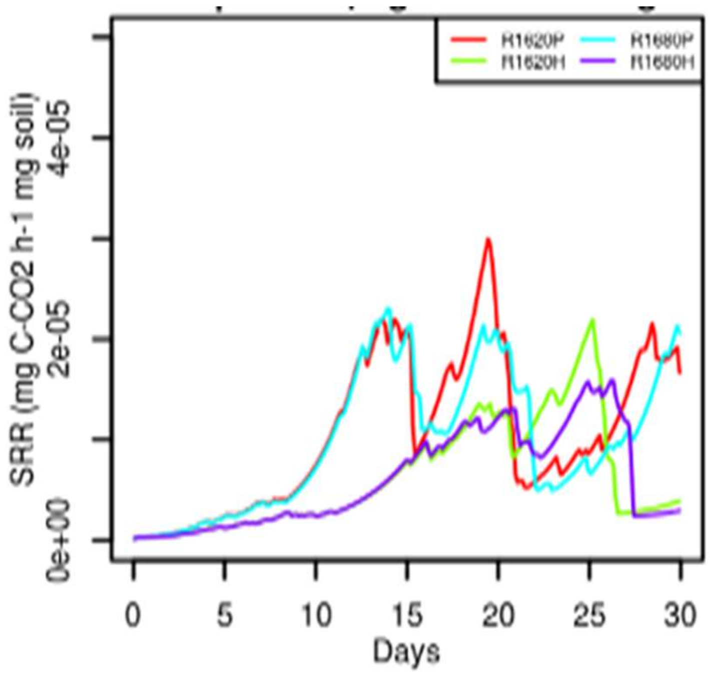


Connected habitats

Fungal growth



Respiration



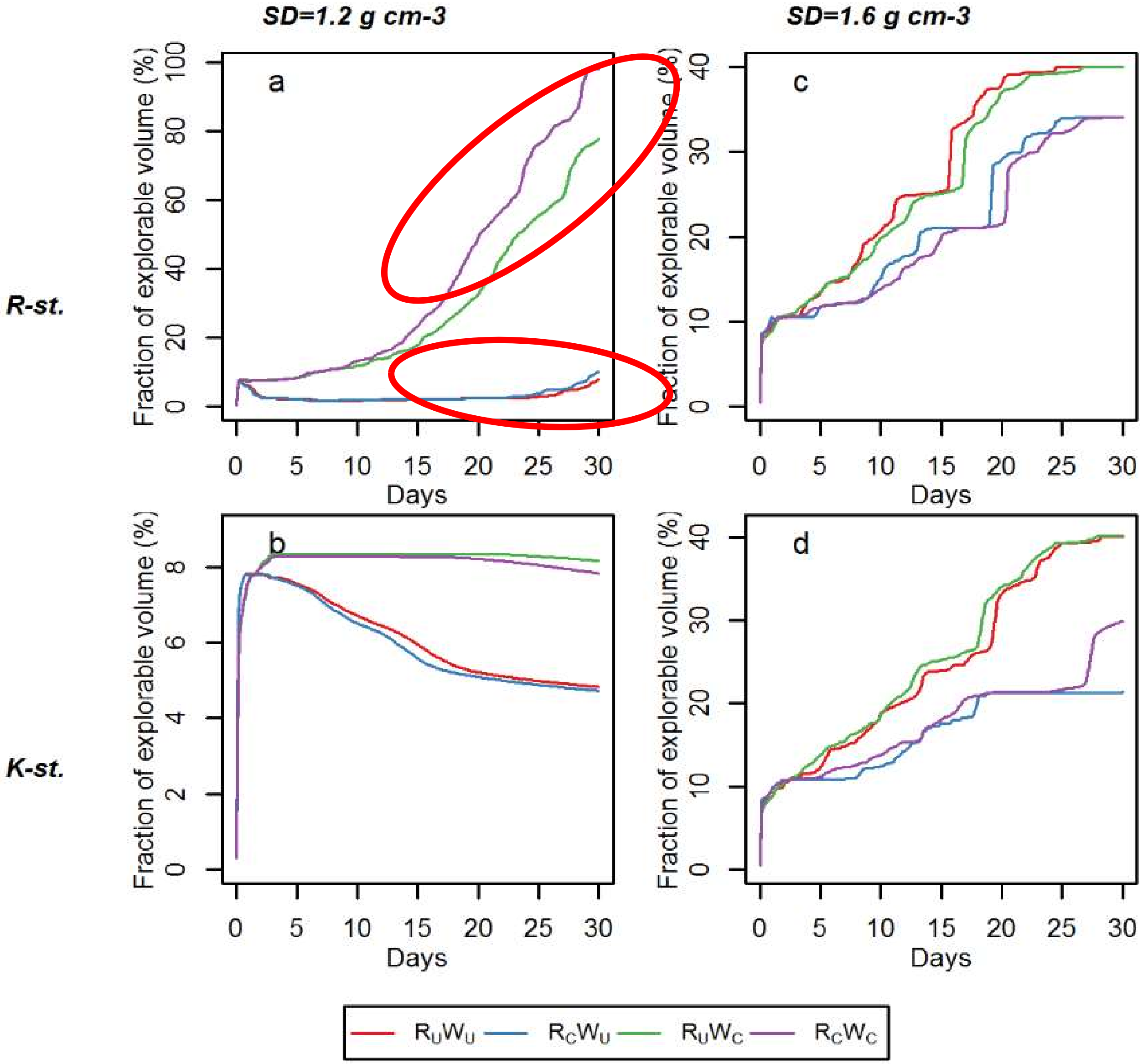
Unconnected Resource and Water phase ($R_U W_U$)

Connected Resource and Unconnected Water ($R_C W_U$)

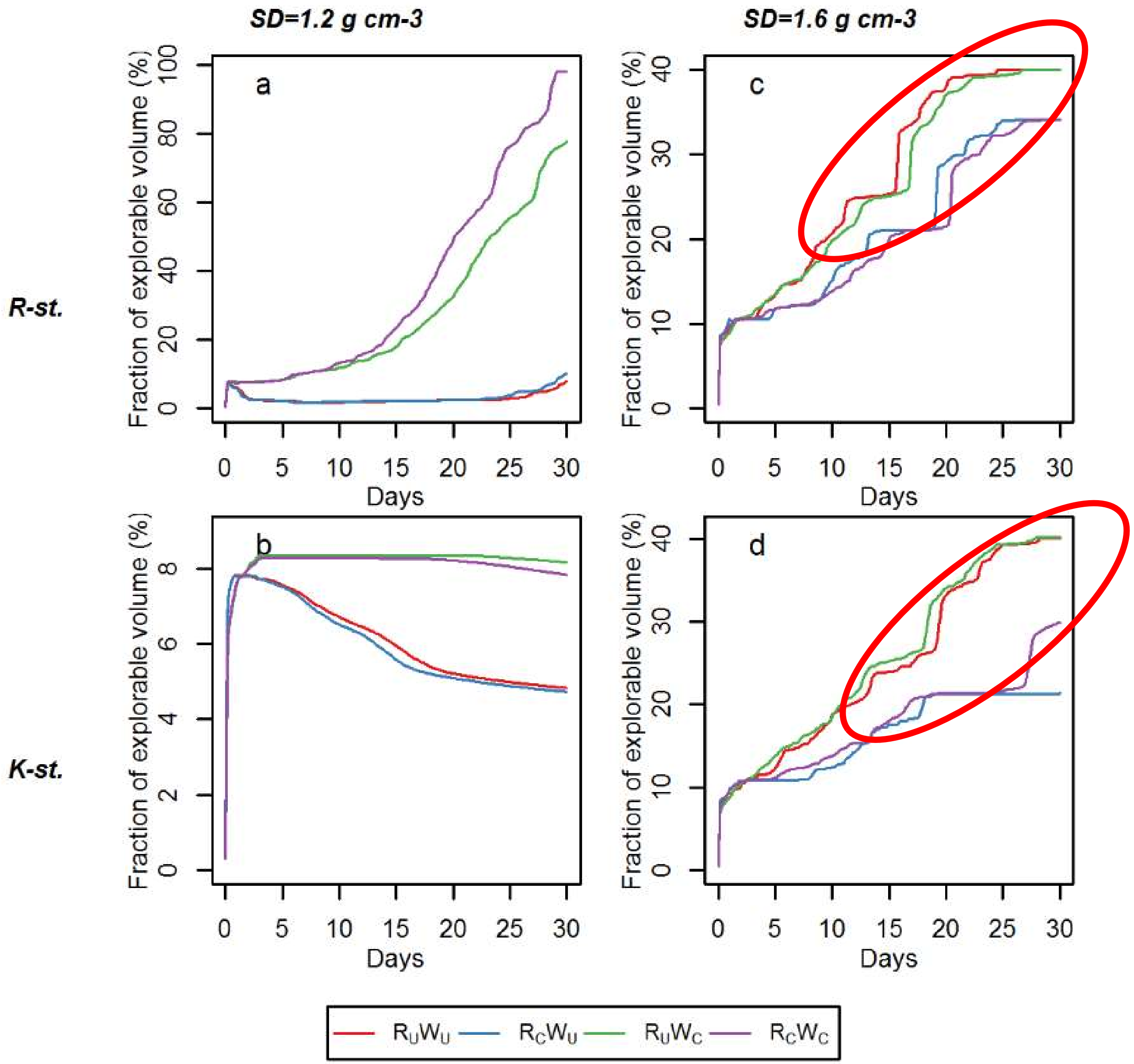
Unconnected Resource and Connected Water ($R_U W_C$)

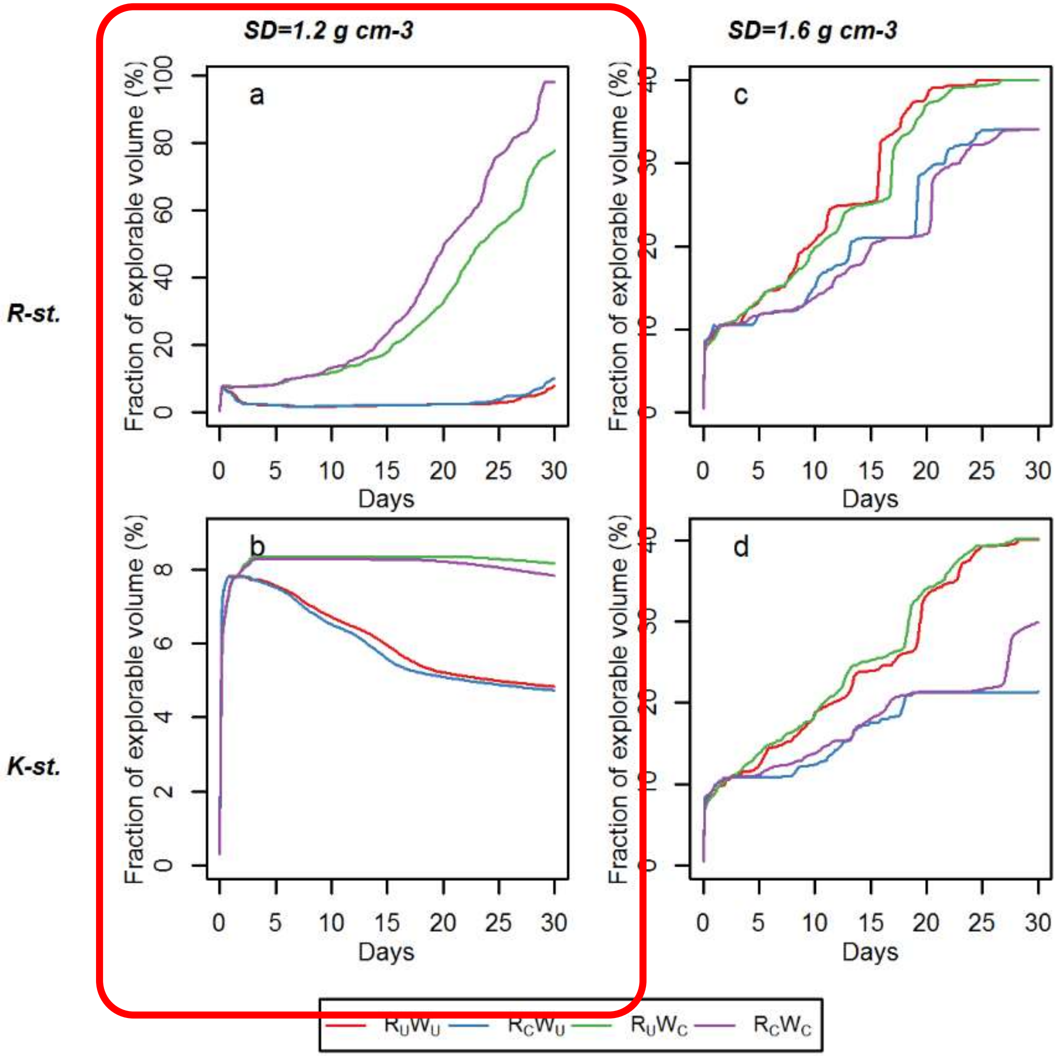
Connected Resource and Water ($R_C W_C$)

In low bulk density, a connected water phase promotes fungal spread.

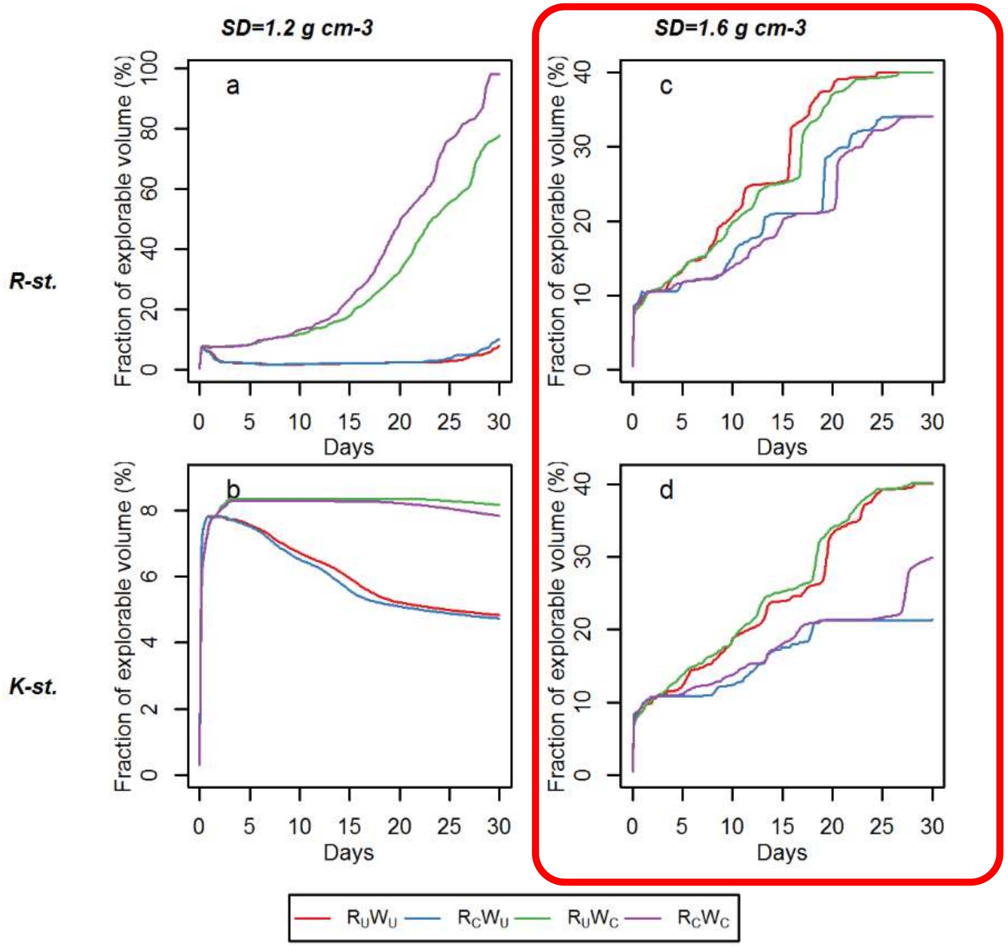


In high bulk density, fungal spread is similar when the water phase is well connected (Sw=80%) or unconnected (Sw=20%).

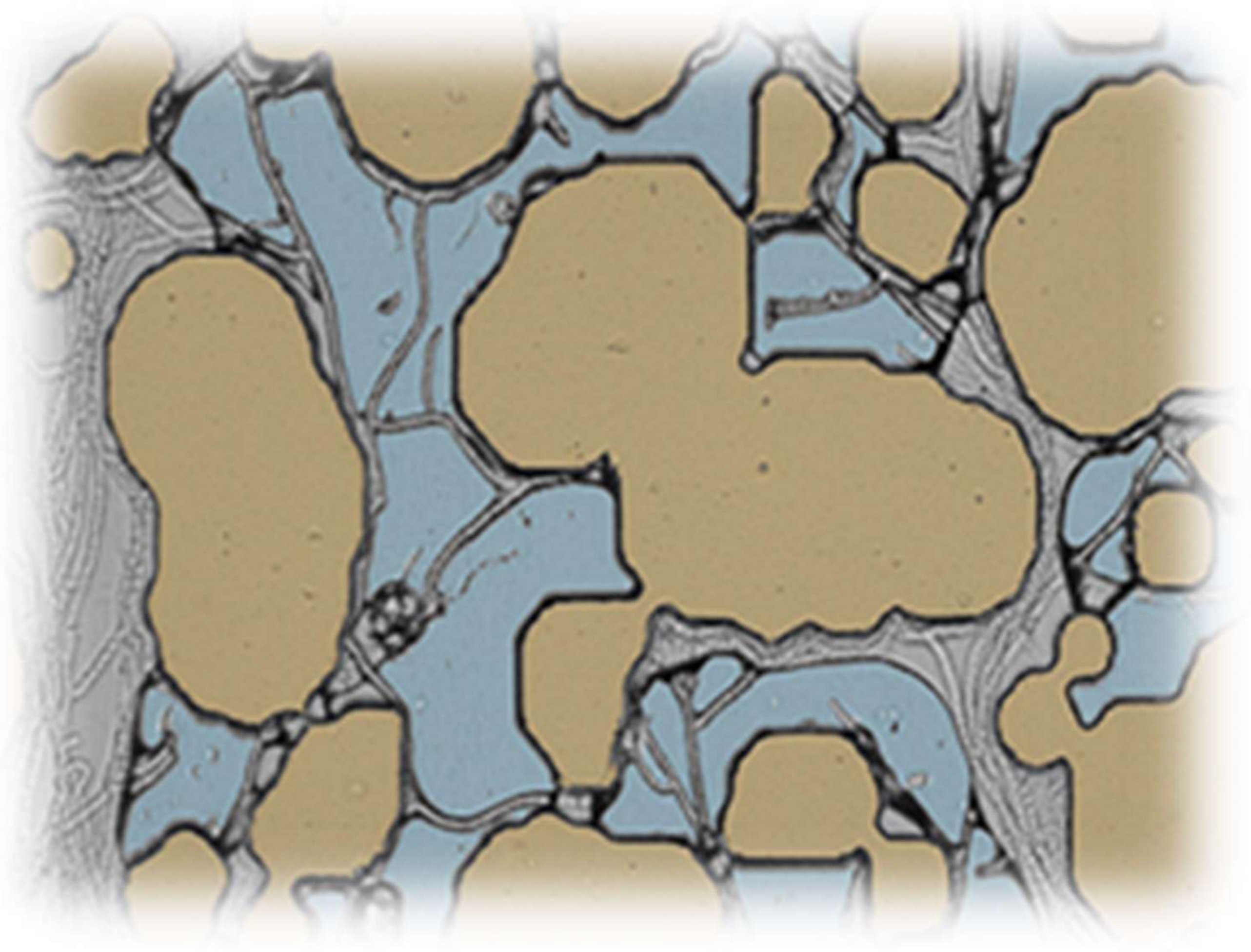




At low bulk density the R-strategist spread faster than the K-strategist.



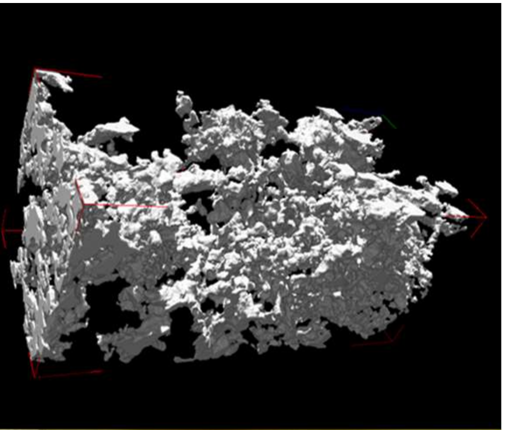
At high bulk density the R-strategist and the K-strategist spread at comparable rates.

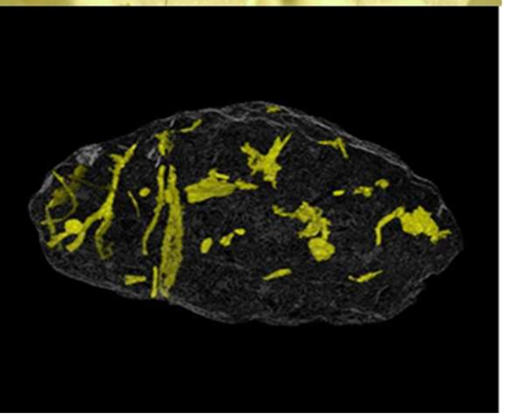


The ‘behaviour’ of a fungal species is as much determined by the physical environment as it is by fungal traits

The behaviour of soil as a system is determined by interactions between components rather than properties themselves

Soufan R, Delaunay Y, Gonod LV, Shor LM, Garnier P, Otten W and Baveye PC (2018) Pore-Scale Monitoring of the Effect of Microarchitecture on Fungal Growth in a Two-Dimensional Soil-Like Micromodel. Front. Environ. Sci. 6:68. doi: 10.3389/fenvs.2018.00068





A few points of what we have learned?

- **Attribution of traits to fungi depends on the environment.**
- **As a result, selective pressures can be expected to be mediated by physical conditions**
- **Small changes in the environment can invoke rapid changes in fungal colonization. ➔ risk of tipping points?**
- **Multiple pathways of connectivity contribute to the outcome of a soil function.**
  - **Connectivity matters: study soils as ‘intact’ systems**
  - **We need to rethink what we call connectivity for microbially mediated processes.**
- **Different pathways can compensate, enhancing stability of the function. The expectation is that this impacts on resilience of soils to perturbations.**

Too Complex?
Perhaps, but…..