Soil structure -soil microorganisms interactions: decomposing organic matter in a structured world

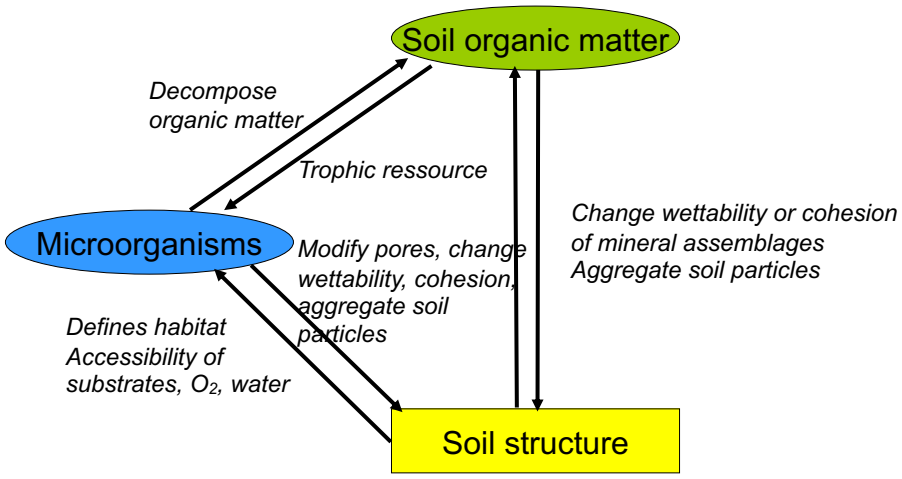
Claire Chenu

Soil structure - soil microorganisms interactions: *decomposing organic matter in a structured world*

Claire Chenu
INRAE - AgroParisTech
claire.chenu@inrae.fr

1

Interactions between microorganisms, soil structure and soil organic matter

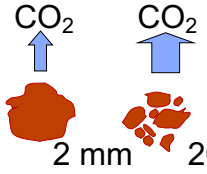


2

1- Does structure matter for biodegradation of organic matter ?

Soil structure does matter: crushing experiments

- Incubating intact and crushed aggregates



ΔCO_2 = physically protected SOC

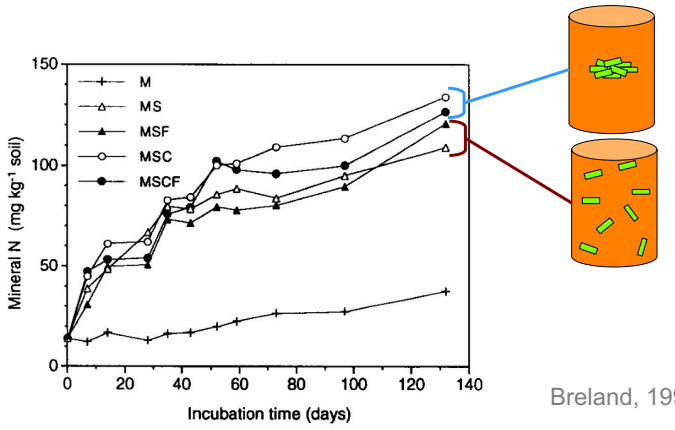
Treatment	Scale	C mineralization crushed/intact		
		nb	mean	range
Crushed <1 mm	Macroaggregates	6	1.3	0.8-2.3
Crushed < 0.25 mm	Microaggregates	12	1.17	1.04 -1.3
Crushed < 0.15 mm	Microaggregates	4	1.24	1.14 -1.34
Ground < 0.15 mm	Microaggregates	4	7.1	4.3-10.8

Litterature review (Balesdent et al. 2000)

➔Aggregates protect SOC and protection is more important at finer scales

Soil structure does matter: manipulative experiments

- N mineralization from soil after plant residues addition:

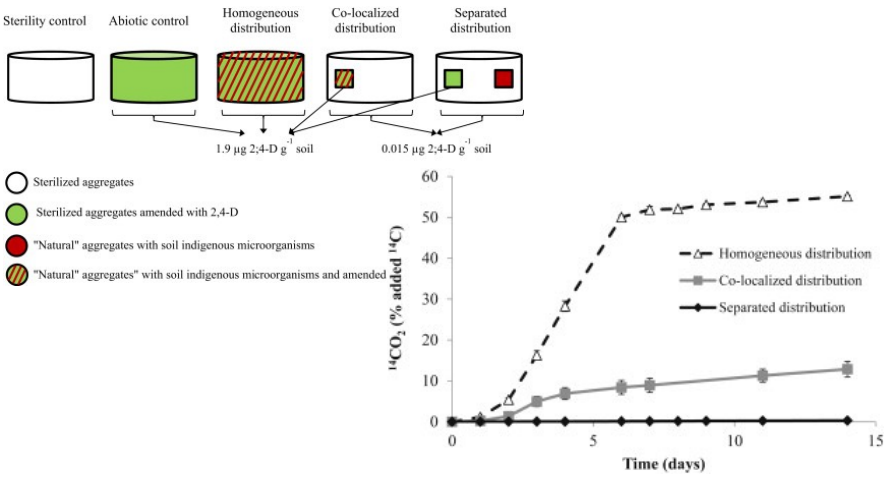


Breland, 1994, P&S

➔less N mineralization of homogenously distributed residues: protection by the matrix ?

Soil structure does matter: manipulative experiments

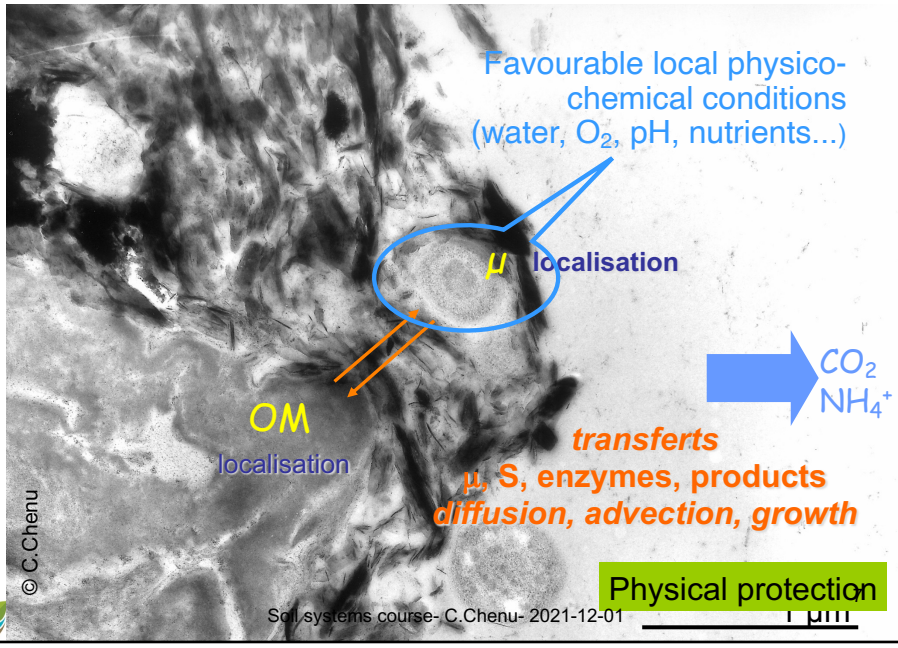
- Manipulating the spatial distribution of µ and substrates



➔accessibility controls mineralisation

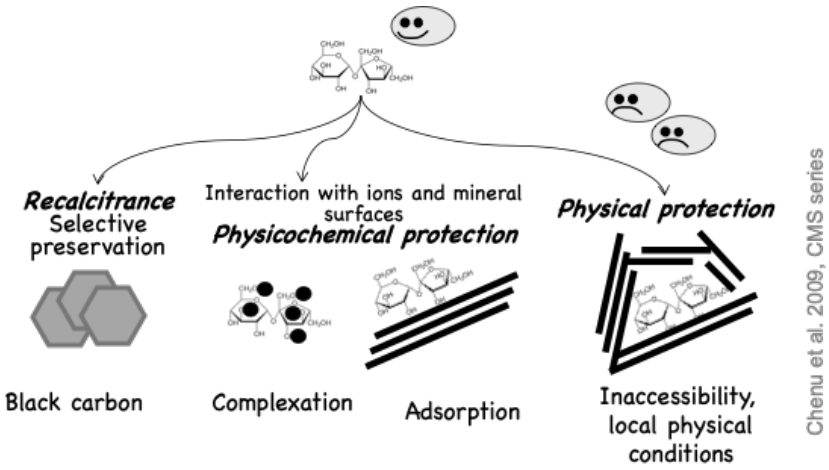
Pinheiro et al. 2015, SBB

For biodegradation to occur



7

Persistence of organic matter in soils

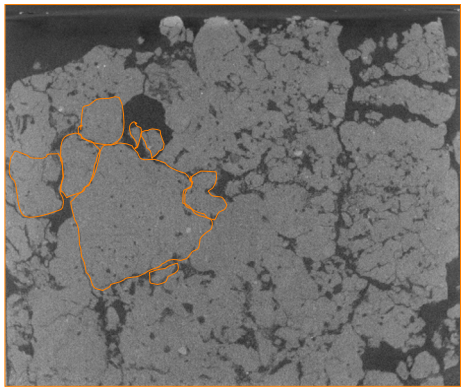


8

2- Spatial heterogeneity of microbally - mediated biodegradation

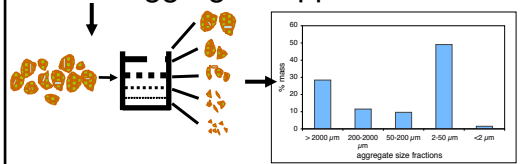
9

How is soil structure viewed ?



©W Otten

An aggregate approach



Aggregate size distribution

10

Separating SOM in different locations & measuring their residence time

- Aggregate of ≠ sizes

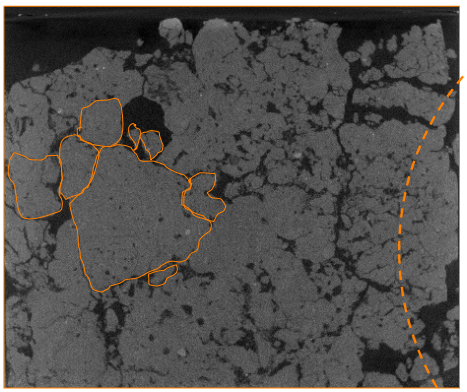
Ecosystem	macroaggregates		microaggregates	
	Size (µm)	MRT (y)	MRT (y)	Size (µm)
Tropical pasture	> 200	60	75	< 200
Temperate pasture	212-9500	140	412	53-212
Soybean	250-2000	1.3	7	100-250
Maize	>250	14	61	50-250
Maize	>250	42	691	50-250
Wheat-fallow, NT	250-2000	27	137	53-250
Wheat-fallow, CT	250-2000	8	79	53-250

Litterature review (Six & Jastrow, 2002)

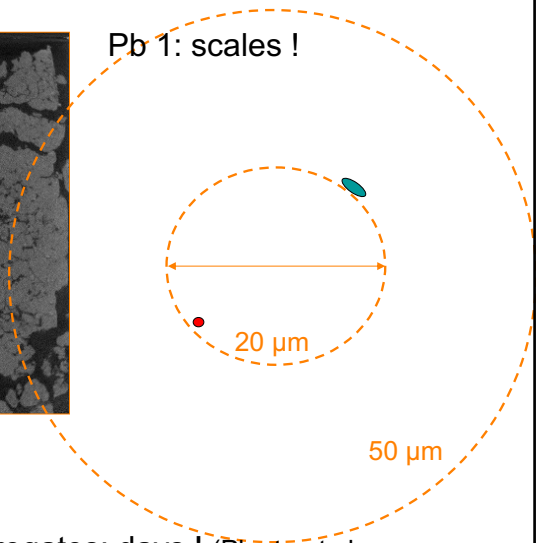
- Particulate organic matter free vs occluded
  - Higher residence time inside aggregates (Golchin et al. 1995, Besnard et al. 1996, Six et al. 1998, ect…)

➔Turnover of SOC is slower within aggregates and in small ones

Protection of OM by soil aggregates: problems

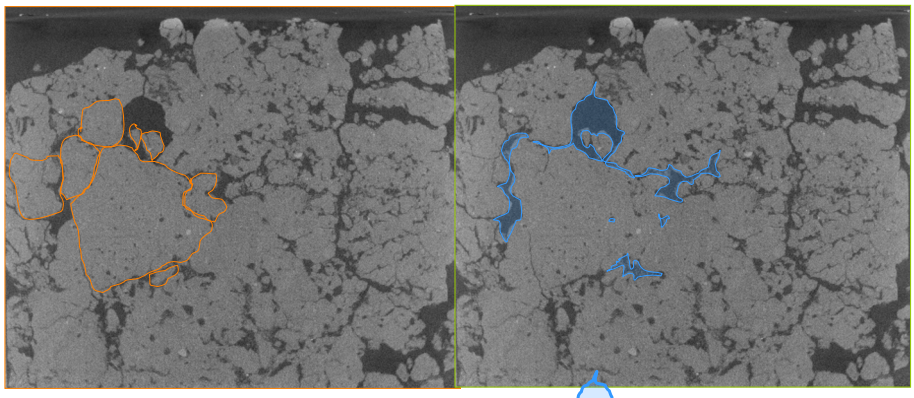


©W Otten



Pb 2: turnover rate of aggregates: days ! (Plante et al. 2002; de Gryze 2004) or a year (Virto et al. 2010)

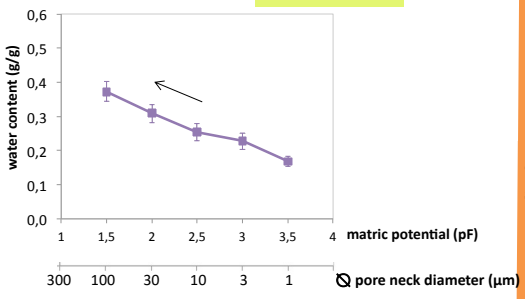
How is soil structure viewed ?

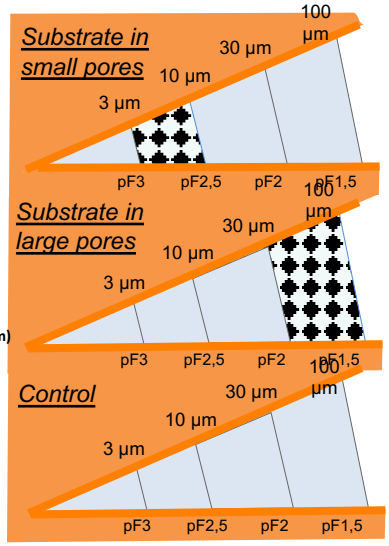


13

Manipulating the placement of substrates

Jurin Laplace law $\varnothing = \frac{2\,\gamma\,\cos\theta/g}{\Psi}$





- Limits:
  - Laplace law simplifies pore space
  - Water movements during equilibration
  - Solute diffusion to other pores

14

≠ microbial actvities in ≠ pores size classes?

Experiment 1 Native soil microbial community

- ^{13}C labelled fructose solution or water added at different matric potentials to soil cores

$$\varnothing = \frac{2\,\gamma\,\cos\theta/g}{\Psi}$$

Ψ (kPa)	⦰ pores targeted
-1000 → -100	0.3 → 3 μm
-315 → -3,15	1 →100 μm
-31,5 → -1	10 →300 μm

Postulate: consumption of ^{13}C labelled substrate primarily in pore size classes targeted

- Incubated for two weeks : total and ^{13}C-labelled CO_2
- At end of incubation: total PLFA profiles and ^{13}C-enriched PLFA profiles

Ruamps et al. (2011) Soil Biol & Biochem

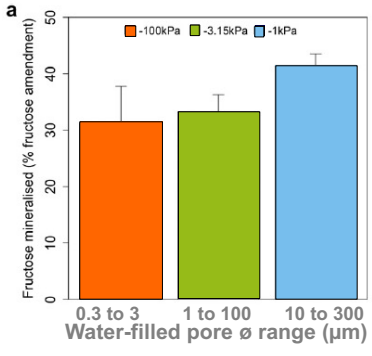
EJP SOIL INRAE Soil systems course- C.Chenu- 2021-12-01 15

15

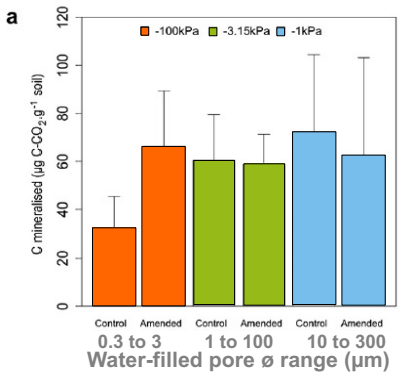
≠ microbial activities in ≠ pore size classes ?

Experiment 1 Native soil microbial community

^{13}C-fructose mineralisation



Native SOM C mineralisation



Differences in activity: due to µ or local conditions?

EJP SOIL INRAE Soil systems course- C.Chenu- 2021-12-01 *Ruamps et al. (2011) Soil Biol & Biochem* 16

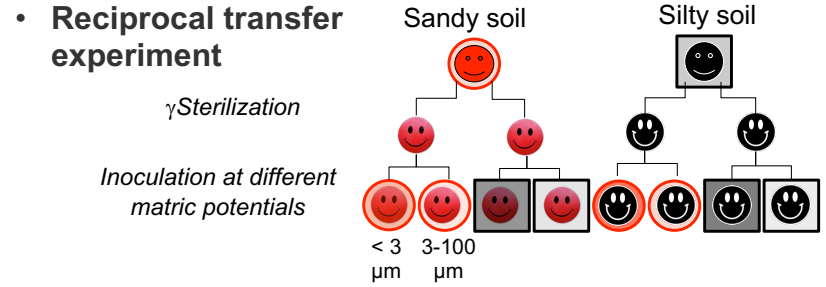
16

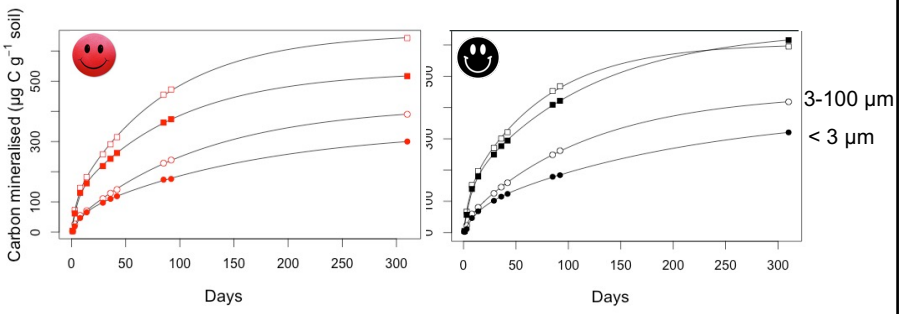
Microbes as probes for habitats ?

- **Reciprocal transfer experiment**

γSterilization

Inoculation at different matric potentials





Nunan et al. 2017, Scientific reports

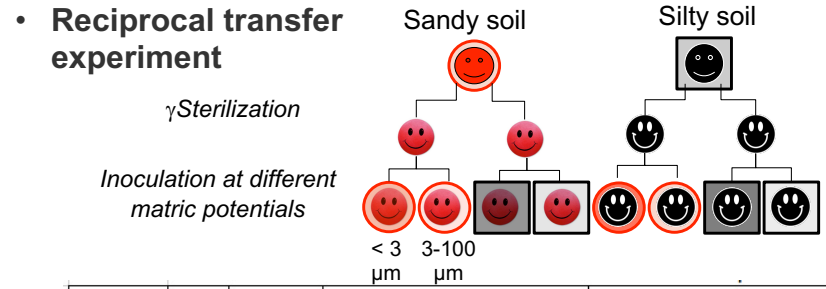
17

Microbes as probes for habitats ?

- **Reciprocal transfer experiment**

γSterilization

Inoculation at different matric potentials



Inoculum	Soil	Pore necks	rapid pool		slow pool	
			α	a	β	b
			mgC kg^{-1} soil	d^{-1}	mgC kg^{-1} soil	d^{-1}
silty	silty	Large	0.187±0.009abc	118±4ab	0.0134±0.0004a	486±8abc
silty	silty	Small	0.143±0.014bc	141±9b	0.0087±0.0010c	513±32ab
silty	sandy	Large	0.171±0.005bc	37.4±3.4c	0.0086±0.0004c	411±25bd
silty	sandy	Small	0.079±0.007c	67.1±8.2d	0.0049±0.0010d	338±31de
sandy	silty	Small	0.187±0.005abc	112±2a	0.0105±0.0004bc	421±10bcd
sandy	silty	Large	0.225±0.009ab	103±7a	0.0117±0.0003ab	556±27a
sandy	sandy	Large	0.285±0.055a	29.9±4.3c	0.0082±0.0003c	392±13cde
sandy	sandy	Small	0.107±0.009c	53.8±5.0cd	0.0062±0.0011c	295±27e

Nunan et al. 2017, Scientific reports

18

Microbes as probes for habitats ?

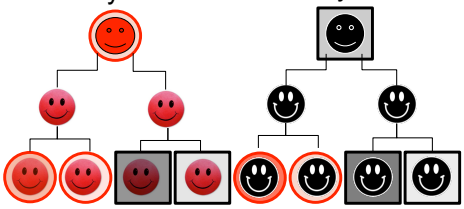
- **Reciprocal transfer experiment**

γSterilization

Inoculation at different matric potentials

Sandy soil

Silty soil



< 3 µm 3-100 µm

Inoculum	Soil	Pore	rapid pool		slow pool	
			α	a	β	b

Correlated with inoculum soil, pores

Correlated with soil, pores

➔mineralisation of "slow" SOM controlled by habitat rather than by microbial community structure

➔faster mineralisation rates in larger neck pores

Kuzyakhov and Blagodatskaya Scientific reports

19

Indicators of soil structure controls on decomposition

- Pore-based approach

"Local porosity" (350 µm shell)
Connection to macropores

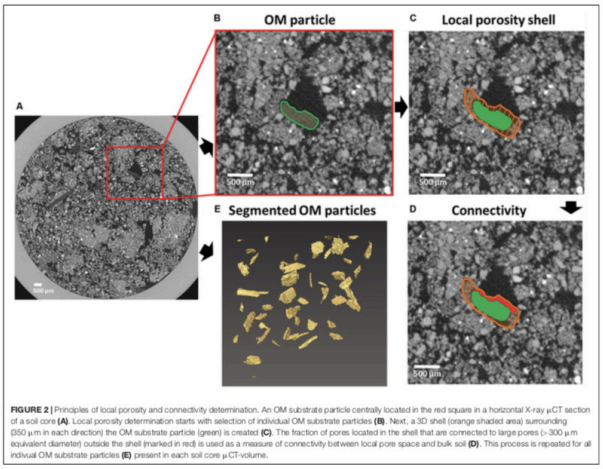


FIGURE 2 | Principles of local porosity and connectivity determination. An OM substrate particle centrally located in the red square in a horizontal X-ray µCT section of a soil core (A). Local porosity determination starts with selection of individual OM substrate particles (B). Next, a 3D shell (orange shaded area) surrounding (350 µm in each direction) the OM substrate particle (green) is created (C). The fraction of pores located in the shell that are connected to large pores (> 300 µm equivalent diameter) outside the shell (marked in red) is used as a measure of connectivity between local pore space and bulk soil (D). This process is repeated for all indivual OM substrate particles (E) present in each soil core µCT-volume.

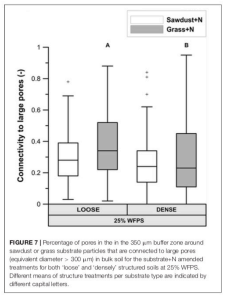
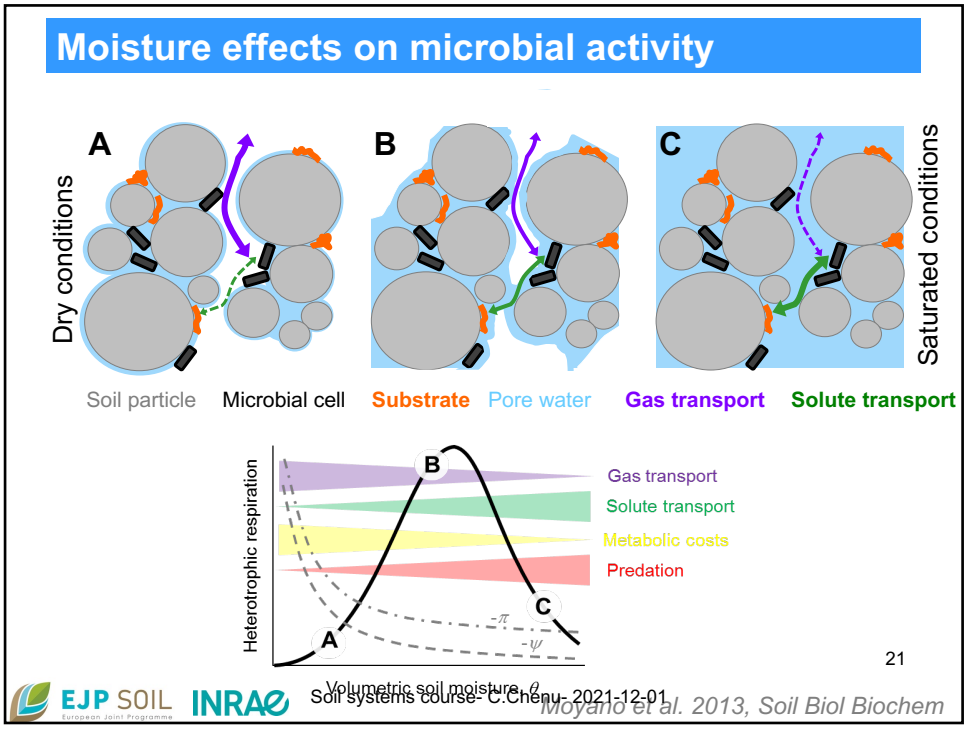


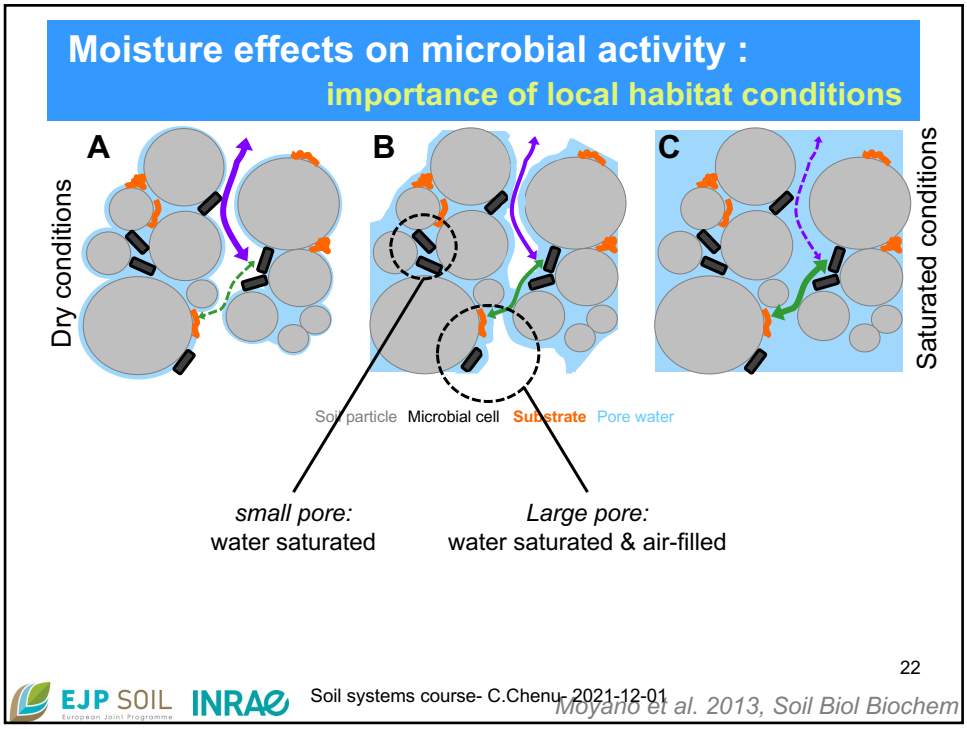
FIGURE 7 | Percentage of pores in the in the 350 µm buffer zone around sawdust or grass substrate particles that are connected to large pores (equivalent diameter > 300 µm) in bulk soil for the substrate-N amended treatments for both 'loose' and 'densely' structured soils at 25% WFPS. Different means of structure treatments per substrate type are indicated by different capital letters.

Maenhout et al. 2018, Frontiers

20

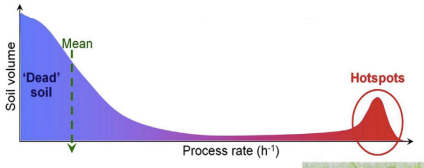

Moisture effects on microbial activity
A
B
C
Dry conditions
Saturated conditions
Soil particle
Microbial cell
Substrate
Pore water
Gas transport
Solute transport
Heterotrophic respiration
Gas transport
Solute transport
Metabolic costs
Predation
-π
-ψ
Volumetric soil moisture, θ
21
EJP SOIL
INRAE
Soil systems course- C.Chenu- 2021-12-01
Moyano et al. 2013, Soil Biol Biochem

21


Moisture effects on microbial activity :
importance of local habitat conditions
A
B
C
Dry conditions
Saturated conditions
Soil particle
Microbial cell
Substrate
Pore water
small pore:
water saturated
Large pore:
water saturated & air-filled
22
EJP SOIL
INRAE
Soil systems course- C.Chenu- 2021-12-01
Moyano et al. 2013, Soil Biol Biochem

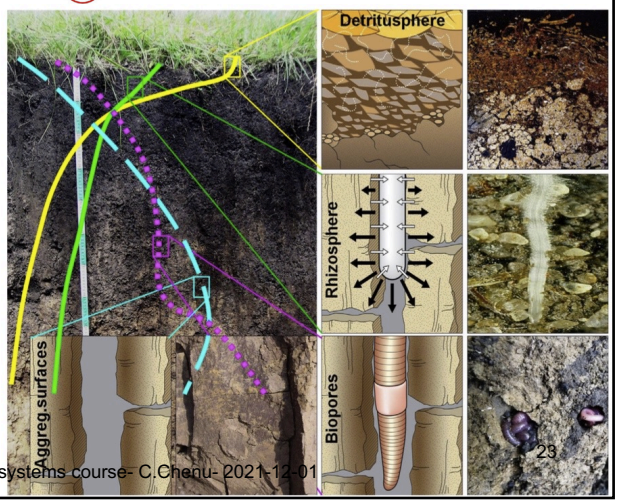
22

Hot spots and hot moments



« Hotspots are small volumes of soil with much higher process rates and intensive interactions compared to the average soil conditions »

Kuzyakov and Blagodatskay, 2015 SBB



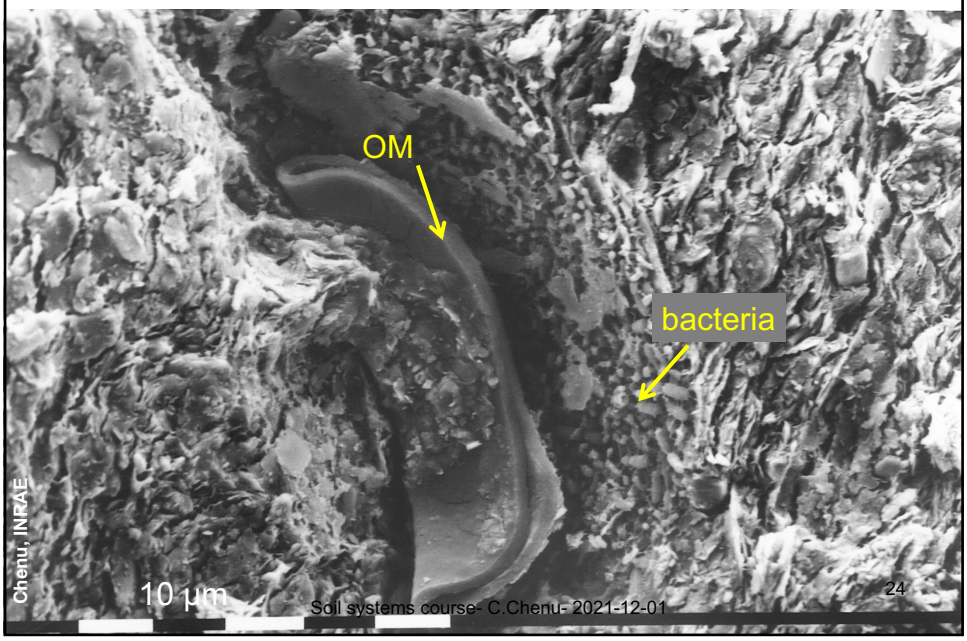
EJP SOIL European Joint Programme INRAE

Soil systems course- C.Chenu- 2021-12-01

23

23

A hot spot in soil…



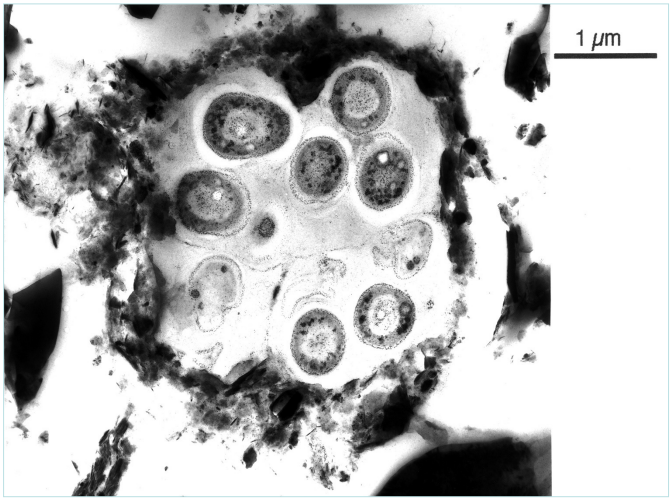
Soil systems course- C.Chenu- 2021-12-01

24

24

3- Feedbacks: effects of microorganisms on soil structure *(related to OM decomposition)*

Bacterial microaggregate

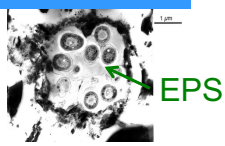


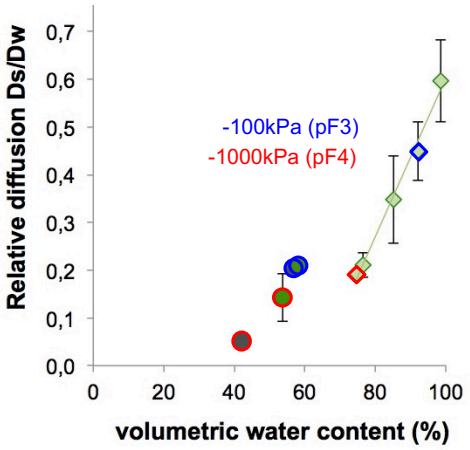
© Chenu

Transmission electron microscopy
Staining of polysaccharides with silver proteinate

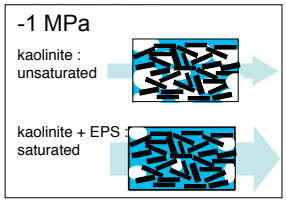
Modifying conditions in the habitat

- Diffusion of glucose in models of the immediate environment of microbes





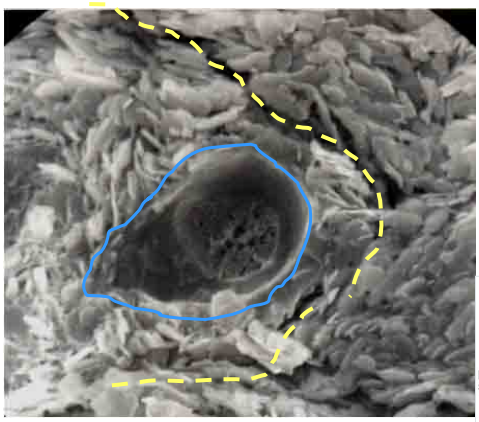
xanthan (EPS)
kaolinite
kaolinite +1% xanthan



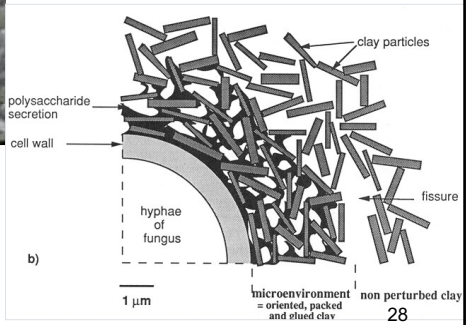
EPS secretion facilitates substrate diffusion especially in dry conditions

Chenu & Roberson, 1996, SBB

Microorganisms modify pore size distribution

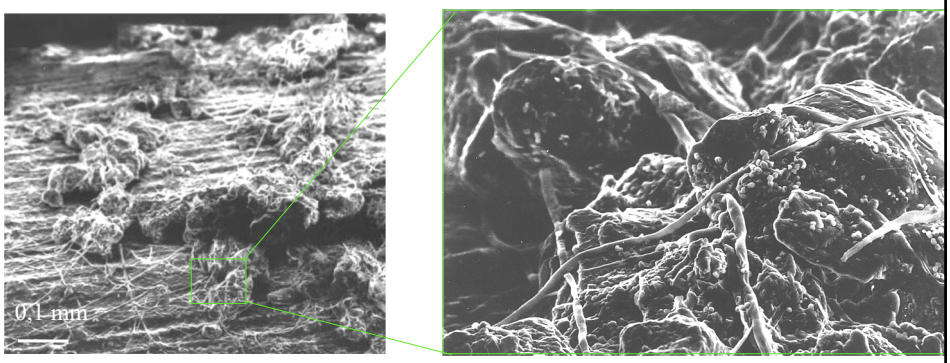


Dorioz et al. 1993



Robert and Chenu, 1992

Soil aggregation by microbial decomposers: physical entanglement



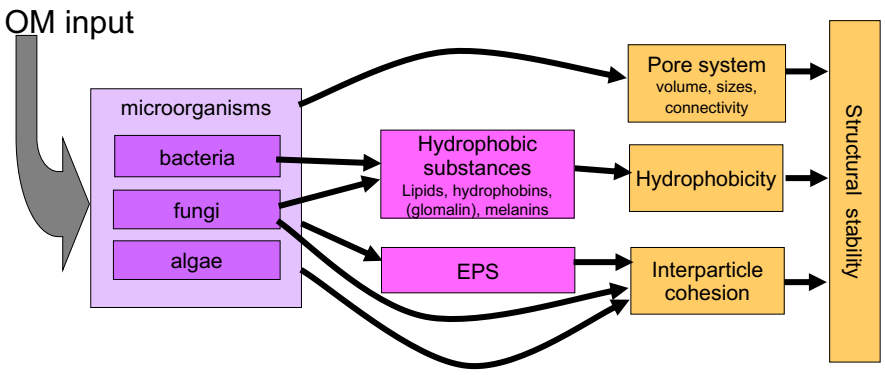
Angers & Chenu, 1998

29

EJP SOIL INRAE Soil systems course- C.Chenu- 2021-12-01

29

Microbial controls on aggregate stability



Chenu & Cosentino, CABI 2011

30

EJP SOIL INRAE Soil systems course- C.Chenu- 2021-12-01

30

References cited

Angers, D.A., Chenu, C., 1997. Dynamics of soil aggregation and C sequestration. In: R. Lal, J. Kimble, R.F. Follet, B.A. Stewart (Eds.), Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, pp. pp 199-206.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage. Soil & Tillage Research 53, 215-230.

Breland, T.A., 1994. Enhanced mineralization and denitrification as a result of heterogeneous distribution of clover residues in soil. Plant and Soil 166, 1-12.

Chenu, C., Virto, I., Plante, A.F., Elsass, F., 2009. Clay-size organo-mineral complexes in temperate soils: relative contributions of sorptive and physical protection. In: D.A. Laird, J. Cervini-Silva (Eds.), Carbon Stabilization by Clays. CMS workshop lectures. The Clay Minerals Society, Chantilly, VA, pp. 120-135.

Chenu, C., Cosentino, D., 2011. Microbial regulation of soil structural dynamics. In: K. Ritz, I.M. Young (Eds.), Architecture and biology of soils : life in inner space. CABI, pp. 37-70.

Chenu, C., Roberson, E.B., 1996. Diffusion of glucose in microbial extracellular polysaccharide as affected by water potential. Soil Biology & Biochemistry 28, 877-884.

De Gryze, S., Six, J., Merckx, R., 2006. Quantifying water-stable soil aggregate turnover and its implication for soil organic matter dynamics in a model study. European Journal of Soil Science 57(5 %R doi:10.1111/j.1365-2389.2006.00760.x), 693-707.

Dorioz, J.M., Robert, M., Chenu, C., 1993. The role of roots, fungi and bacteria on clay particle organization. An experimental approach. Geoderma 56, 179-194.

Golchin, A., 1994. Soil Structure and Carbon Cycling. Australian Journal of Soil Research 32, 1043-1068.

Kuzyakov, Y., Blagodatskaya, E., 2015. Microbial hotspots and hot moments in soil: Concept & review. Soil Biology and Biochemistry 83, 184-199.

Maenhout, P., Van den Bulcke, J., Van Hoorebeke, L., Cnudde, V., De Neve, S., Sleutel, S., 2018. Nitrogen Limitations on Microbial Degradation of Plant Substrates Are Controlled by Soil Structure and Moisture Content. Frontiers in Microbiology 9.

Moyano, F.E., Manzoni, S., Chenu, C., 2013. Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. Soil Biology & Biochemistry 59, 72-85.

Nunan, N., Leloup, J., Ruamps, L.S., Pouteau, V., Chenu, C., 2017. Effects of habitat constraints on soil microbial community function. Scientific Reports 7.

Pinheiro, M., Garnier, P., Beguet, J., Martin Laurent, F., Vieublé-Gonod, L., 2015. The millimetre-scale distribution of 2,4-D and its degraders drives the fate of 2,4-D at the soil core scale. Soil Biology & Biochemistry 88, 90-100.

Plante, A.F., McGill, W.B., 2002. Soil aggregate dynamics and the retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. Soil & Tillage Research 66(1), 79-92.

Ruamps, L.S., Nunan, N., Chenu, C., 2011. Microbial biogeography at the soil pore scale. Soil Biology & Biochemistry 43, 280-286.

Six, J., Elliott, E.T., Paustian, K., Doran, J.W., 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Science Society of America Journal 62(5), 1367-1377.

Six, J., Jastrow, J., 2002. Organic matter turnover, Encyclopedia of Soil Science. Marcel Dekker Inc., New York, pp. 936-942.

Virto, I., Moni, C., Swanston, C., Chenu, C., 2010. Turnover of intra- and extra-aggregate organic matter at the silt-size scale. Geoderma 156(1/2), 1-10.