Physics and hydrology of mucilage-soil interactions

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Soil Physics

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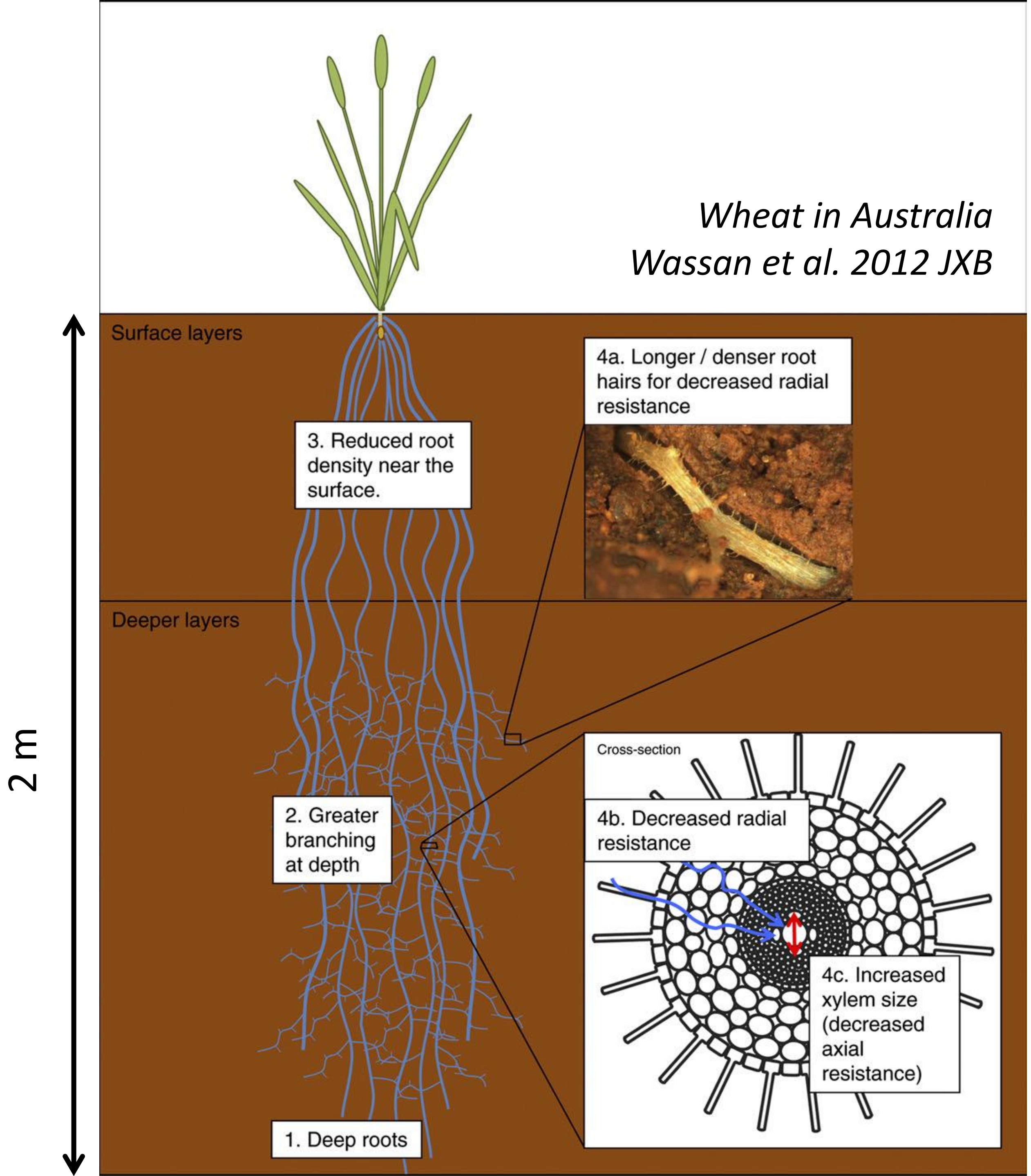
Motivation
Exploring the soil

Roots provide anchorage, as well as supply of water and nutrients to the plant.

As soil resources are heterogeneous, roots must be capable to explore the soil profile.

This ability depends on roots growth and branching – root architecture (scale of dm-m).



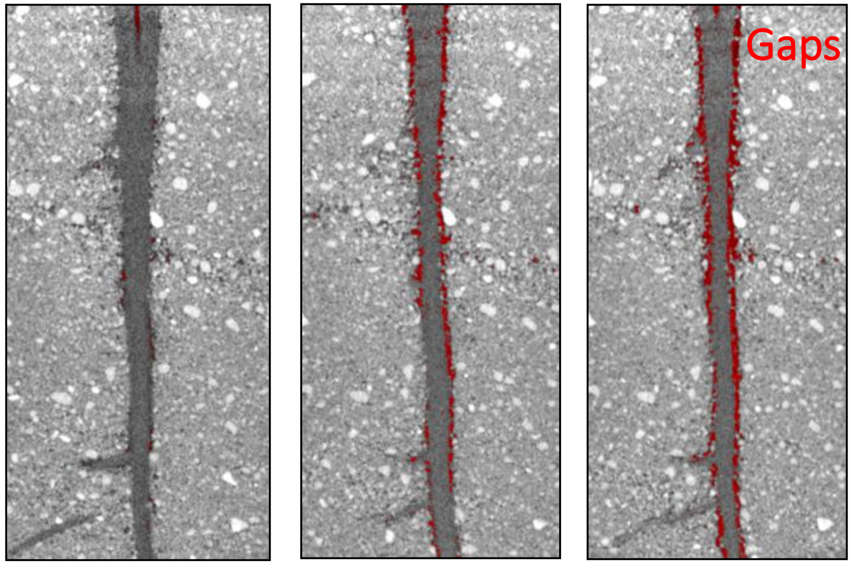
Motivation
In contact with the soil

Roots grow in larger pores and might have a poor contact to the soil water and nutrients.

Focus on the root-soil interface (scale µm-mm).

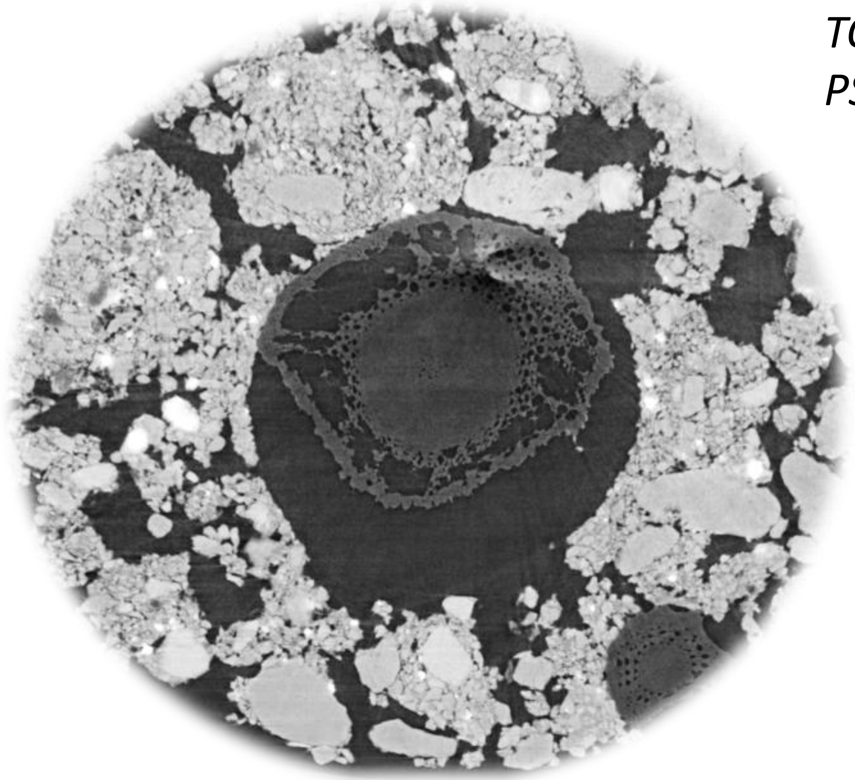
Root-soil contact (White and Kirgegaard 2012)

Mind the gap!



The root water potential changes by almost 1 MPa (10 bar) due to diurnal changes in transpiration and drops below -1.5 MPa as the soil dries. Consequently roots shrink and might lose the contact to the soil.

Carminati et al. Plant and Soil 2013



TOMCAT, PSI, 2018

How do roots maintain the physical and hydraulic contact to the soil during soil drying?

Hypothesis

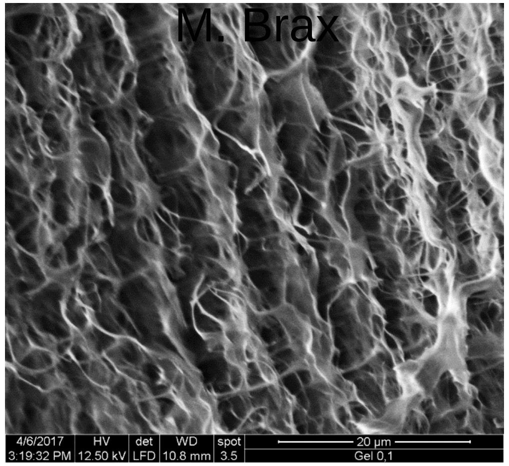
Mucilage and root hairs close the gap at the root-soil interface maintaing the roots in contact with soil water and nutrients.

The root-soil contact

Soil particles are attached to the root surface by root hairs and gluing substances (mucilage or extracellular polymeric substances EPS produced by microorganisms)

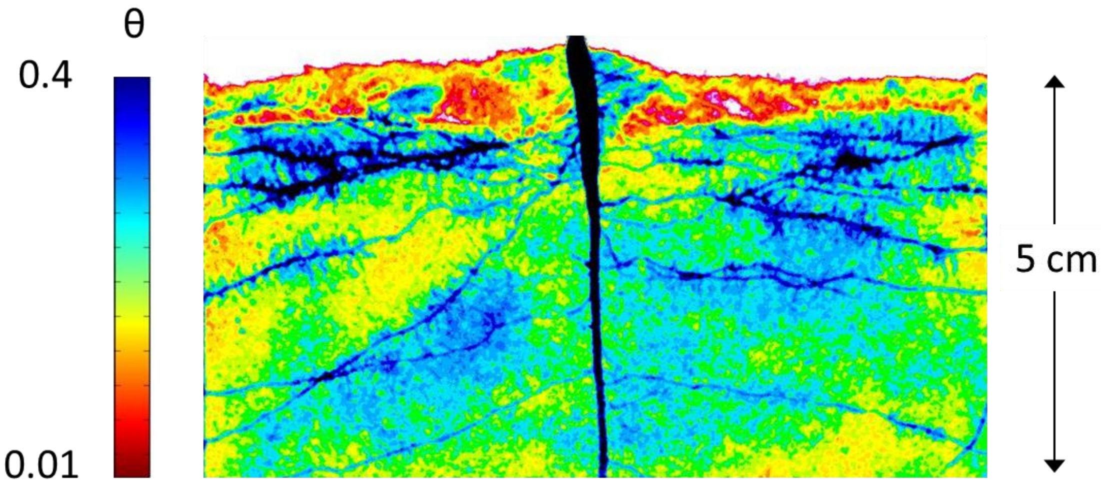
Mucilage properties

Network of root mucilage - courtesy of M. Brax



Mucilage is composed of a highly diverse blend of long chained polymers and lipids.

It adsorbs large volumes of water (at full saturation 1 mg of dry mucilage adsorbs up to 100-500 mg of water) (McCully & Boyer 1997)

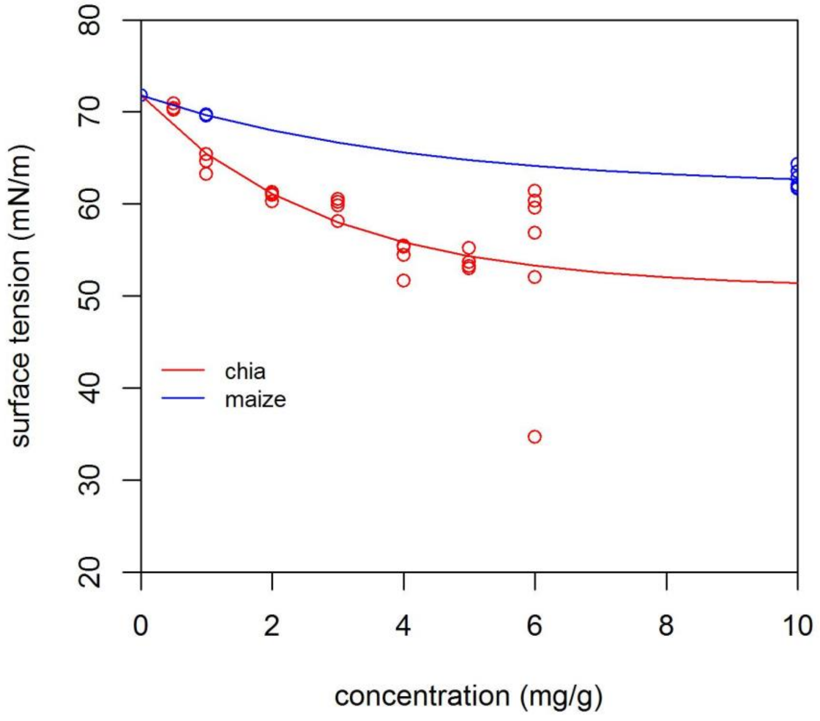


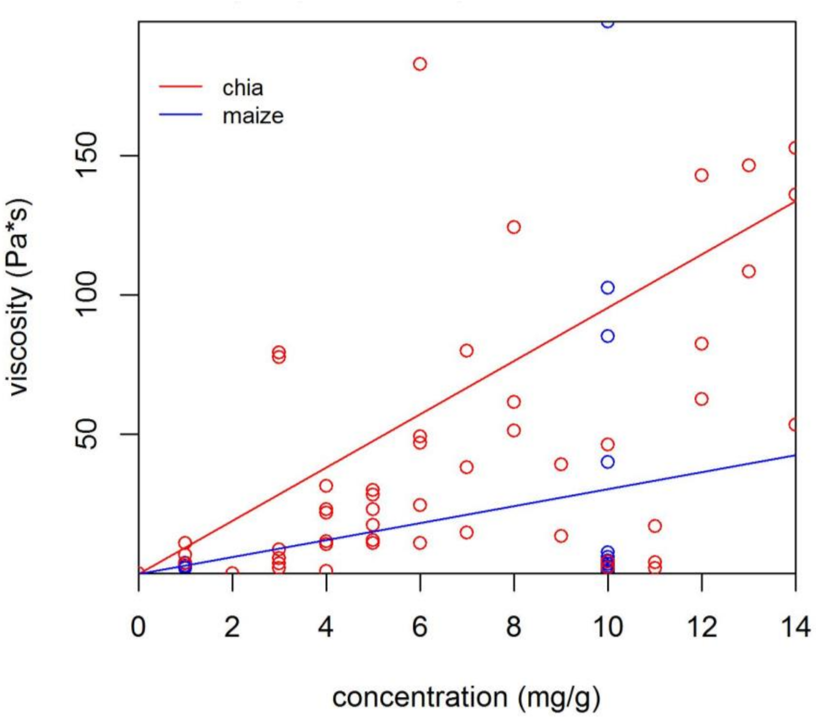
During drying the rhizosphere is wetter than the bulk soil (Carminati et al. 2010)

Mucilage properties

It increases the viscosity of the soil solution (Read and Gregory 1997).

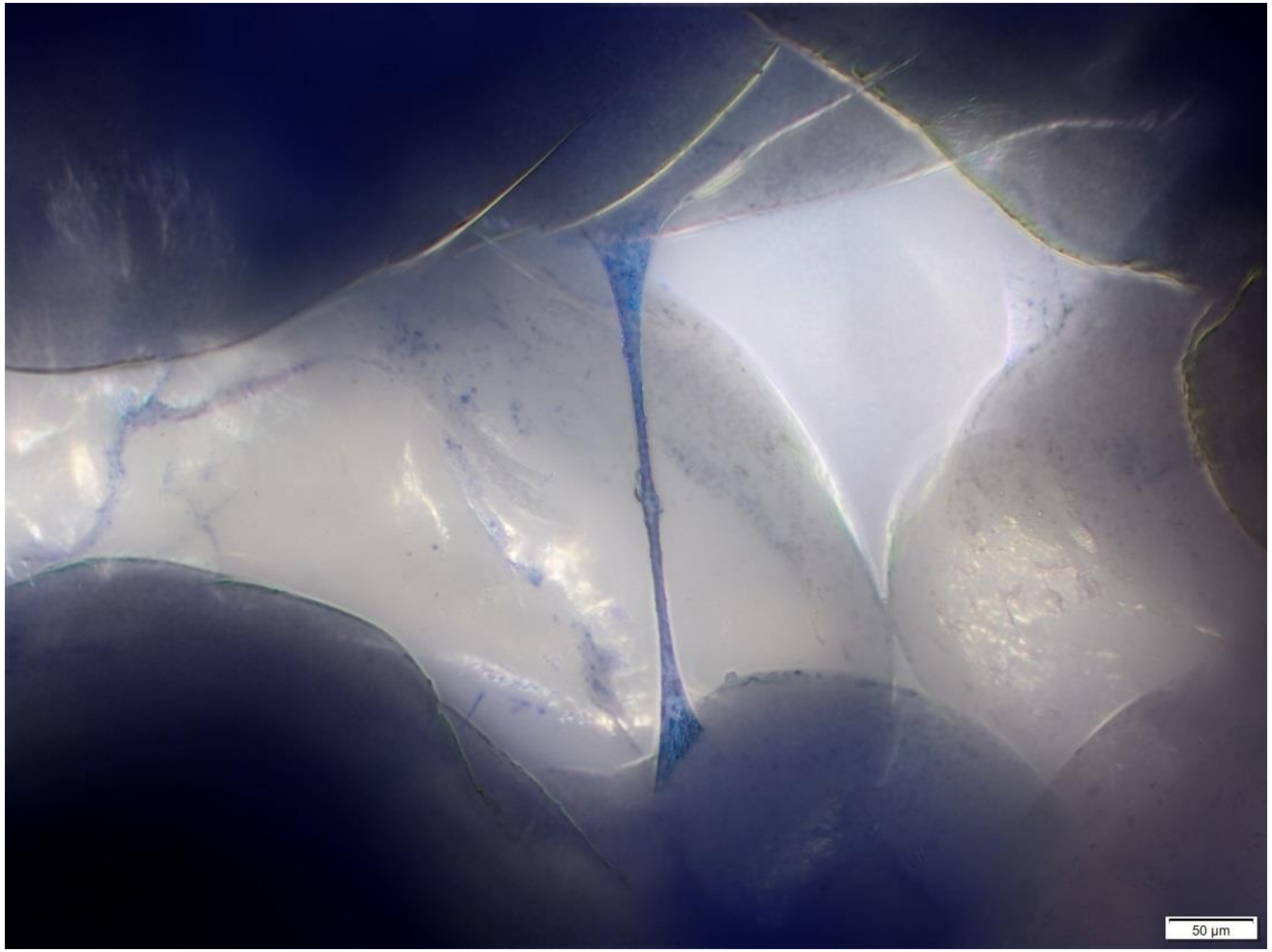
It decreases the surface tension of the soil solution (Read and Gregory 1997; Naveed et al. 2017; Benard et al. 2019).





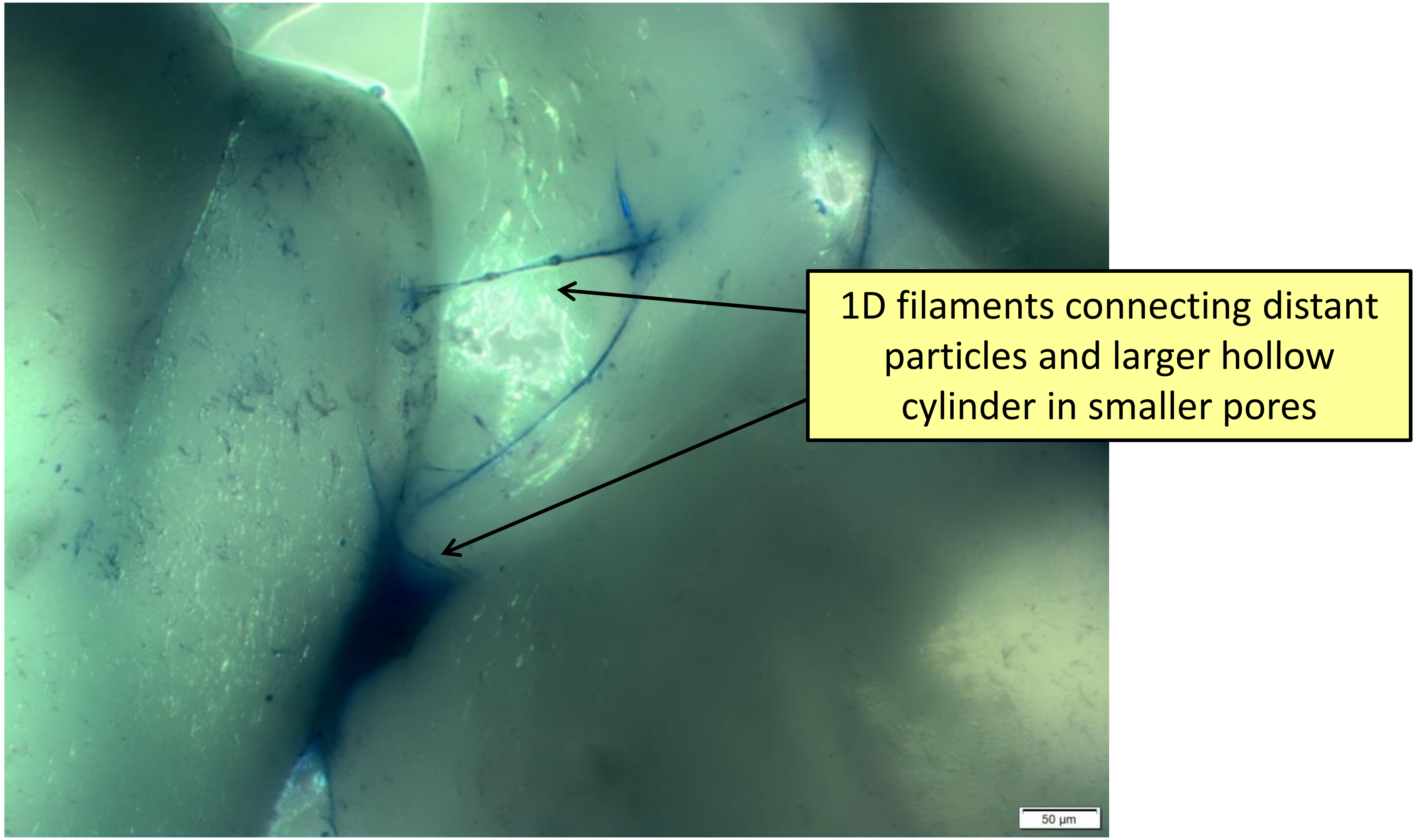
Mucilage alters the liquid configuration in soils

Filament connecting distant particles



Mucilage let dry in sand (Carminati et al. 2017)

Mucilage alters the liquid configuration in soils



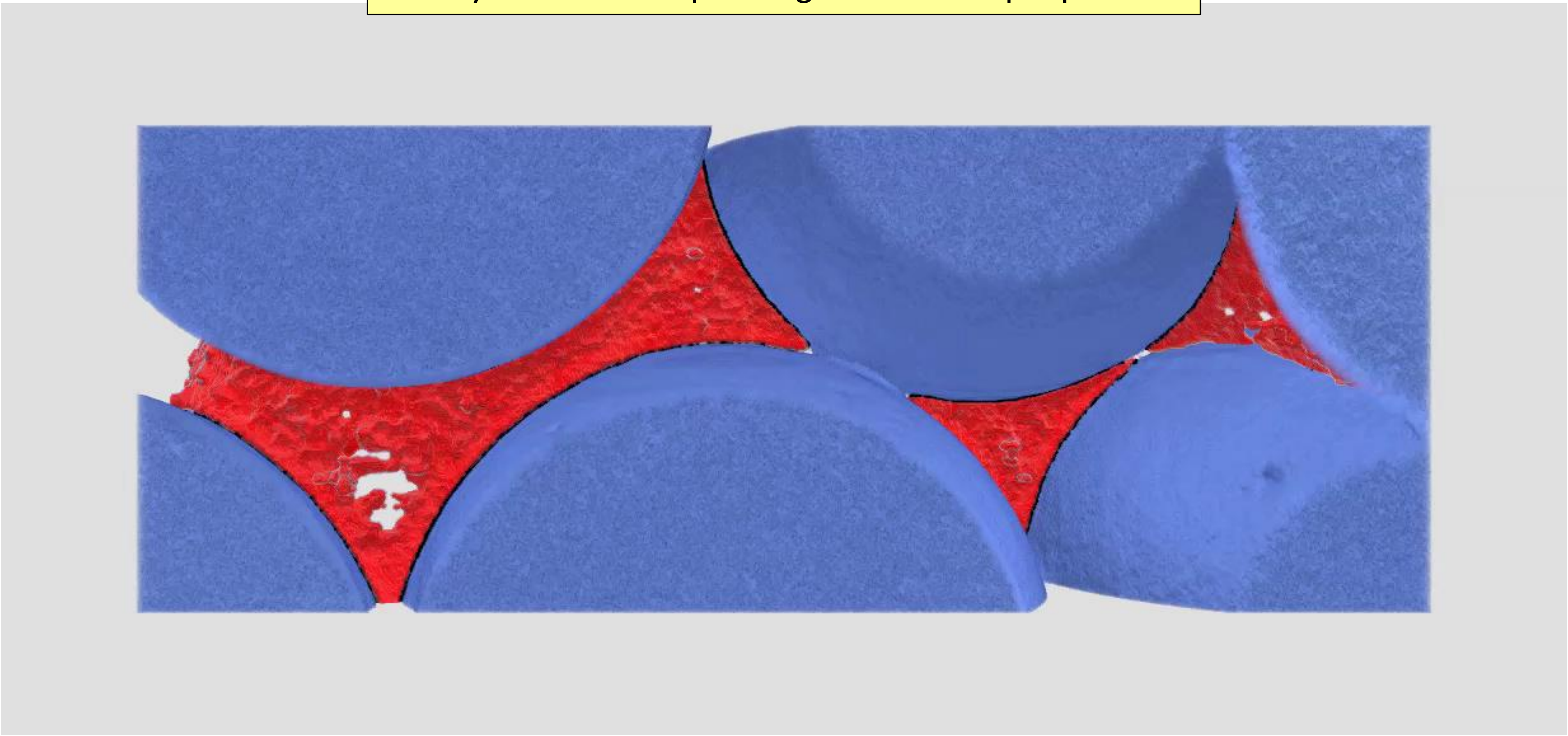
Mucilage alters the liquid configuration in soils

Larger cylnders close to the contacts and longer filaments connecting distant particles

Maize root mucilage (10 mg g^{-1}) let dry in glass beads (diameter 2 mm)

Mucilage alters the liquid configuration in soils

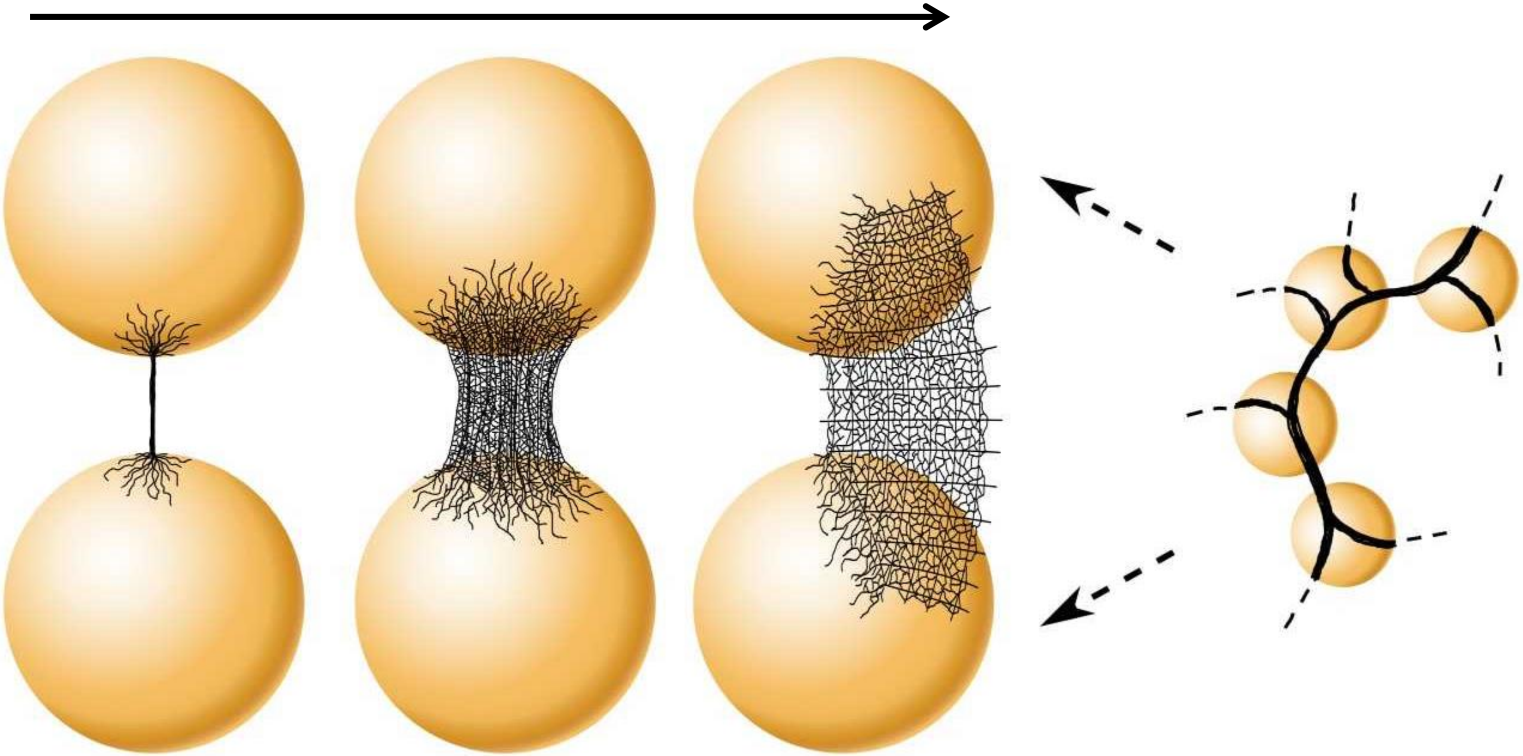
Polymer surface spanning across multiple pores



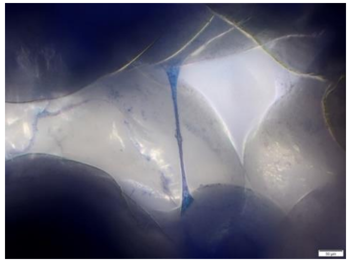
Maize mucilage (8 mg g^{-1}) let dry in glass beads (0.1-0.2 mm)
Imaged with X-ray CT at Tomcat, PSI (*Benard et al. 2019 VZJ*)

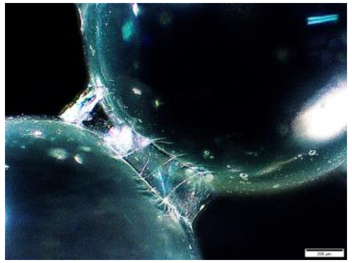
From 1D to 2D bridges between soil particles

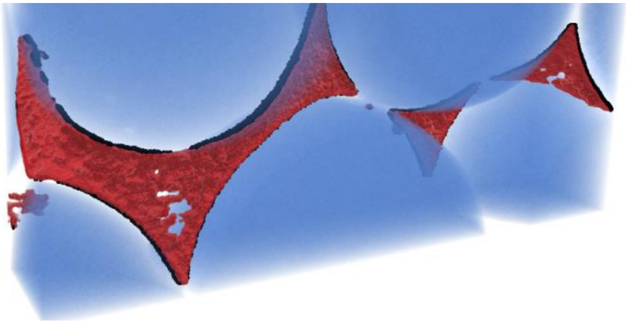
Increasing mucilage viscosity or content
or decerasing particle distance



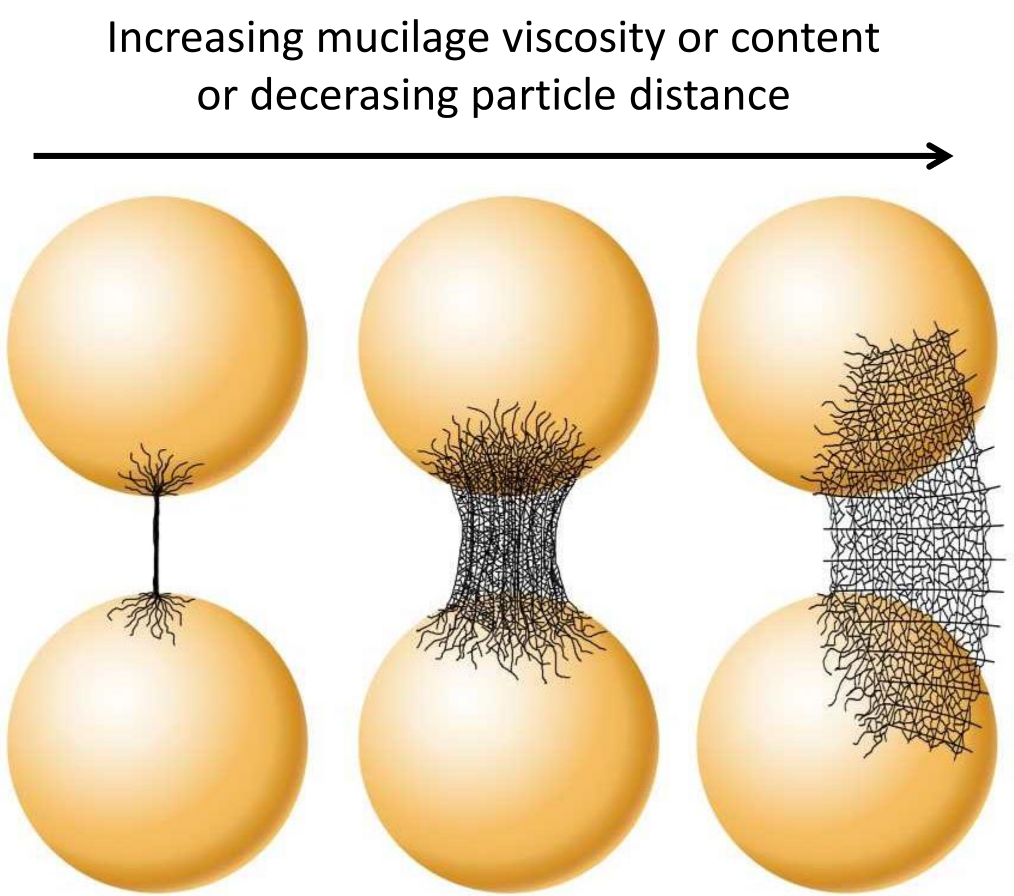
Mucilage structures merge into 2D inter-connected surfaces

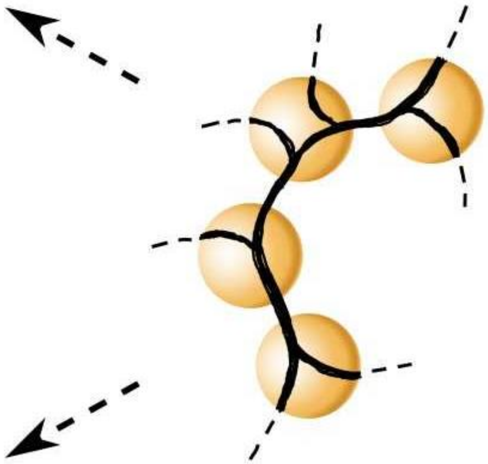






From 1D to 2D bridges between soil particles





Mucilage structures merge into 2D inter-connected surfaces

From 1D to 2D bridges between soil particles

Increasing mucilage viscosity or content
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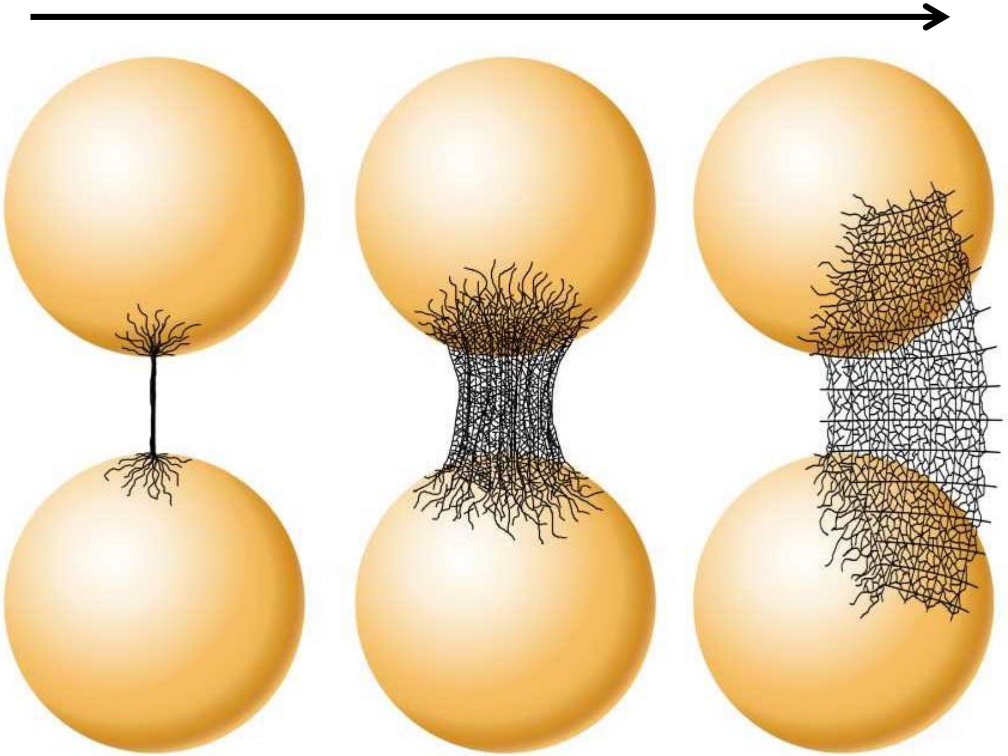
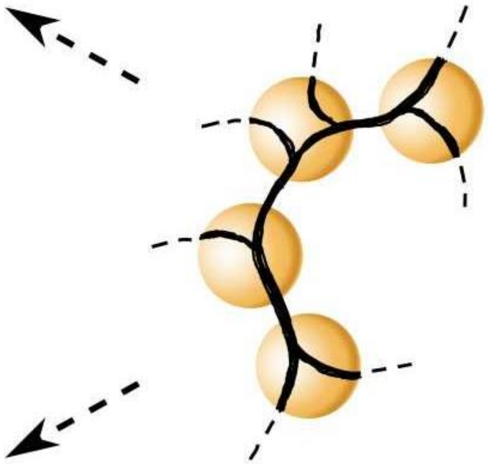
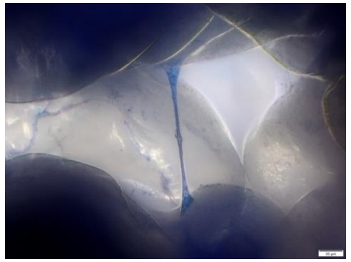
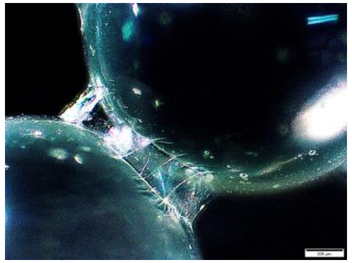
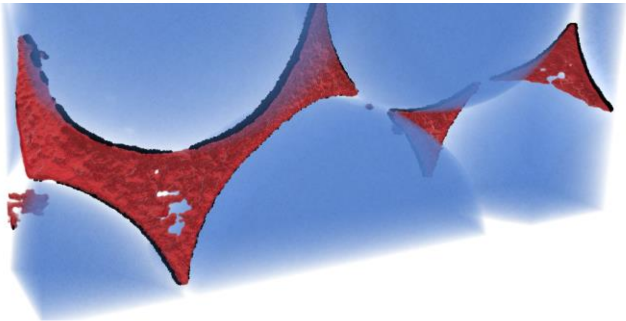




What processes mechanisms explain the formation of 1D filaments and 2D surfaces?

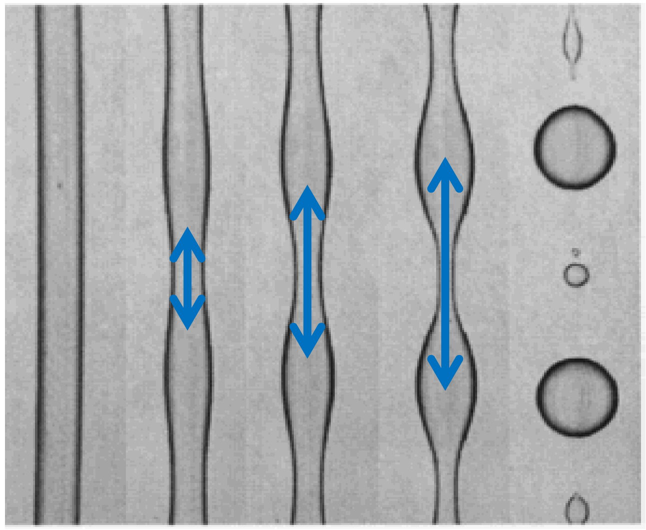






Formation of 1D filaments

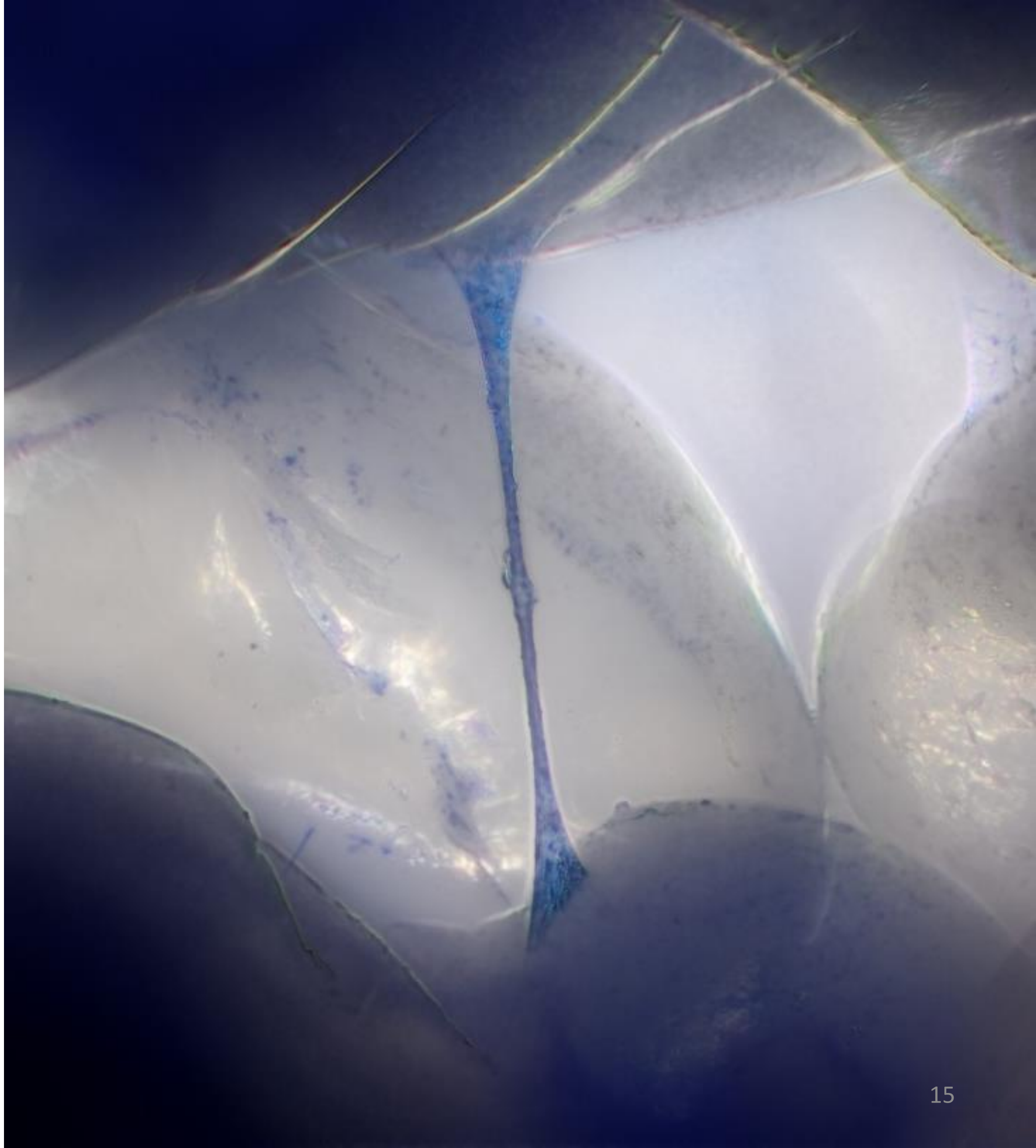
Water cannot have this shape



Rayleigh: The water column is unstable to any perturbations of the interface. Perturbations grow at increasingly faster velocity until the column breaks-up. The time scale t_R of the break up of an inviscid liquid is given by a balance of surface tension and inertia:

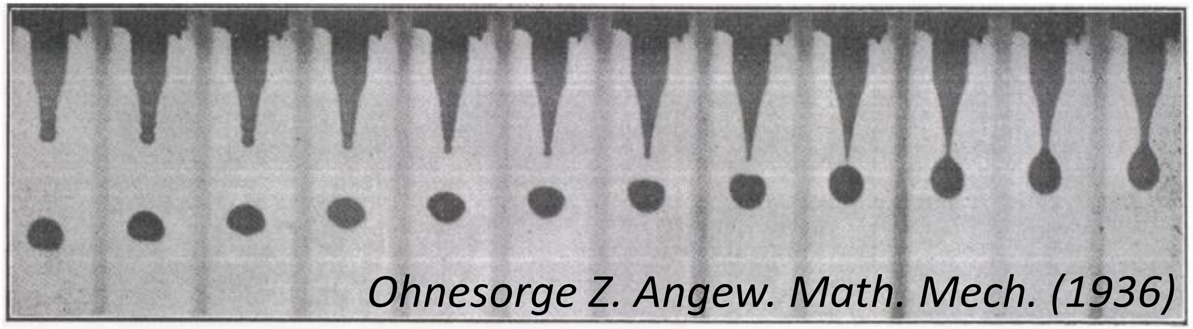
$$t_R = \sqrt{\frac{\rho r^3}{\gamma}}$$

For water with r=1 mm t_R = 4 ms



Formation of 1D filaments

The *Ohnesorge* number and the role of viscosity



Ohnesorge Z. Angew. Math. Mech. (1936)

Abbildung 26. „Statische“ Tropfenbildung: $\frac{r}{a} = 0{,}52$. Bildfrequenz: 300 sek.$^{-1}$ *).

$$Oh = \frac{\mu}{\sqrt{\sigma \rho d}}$$

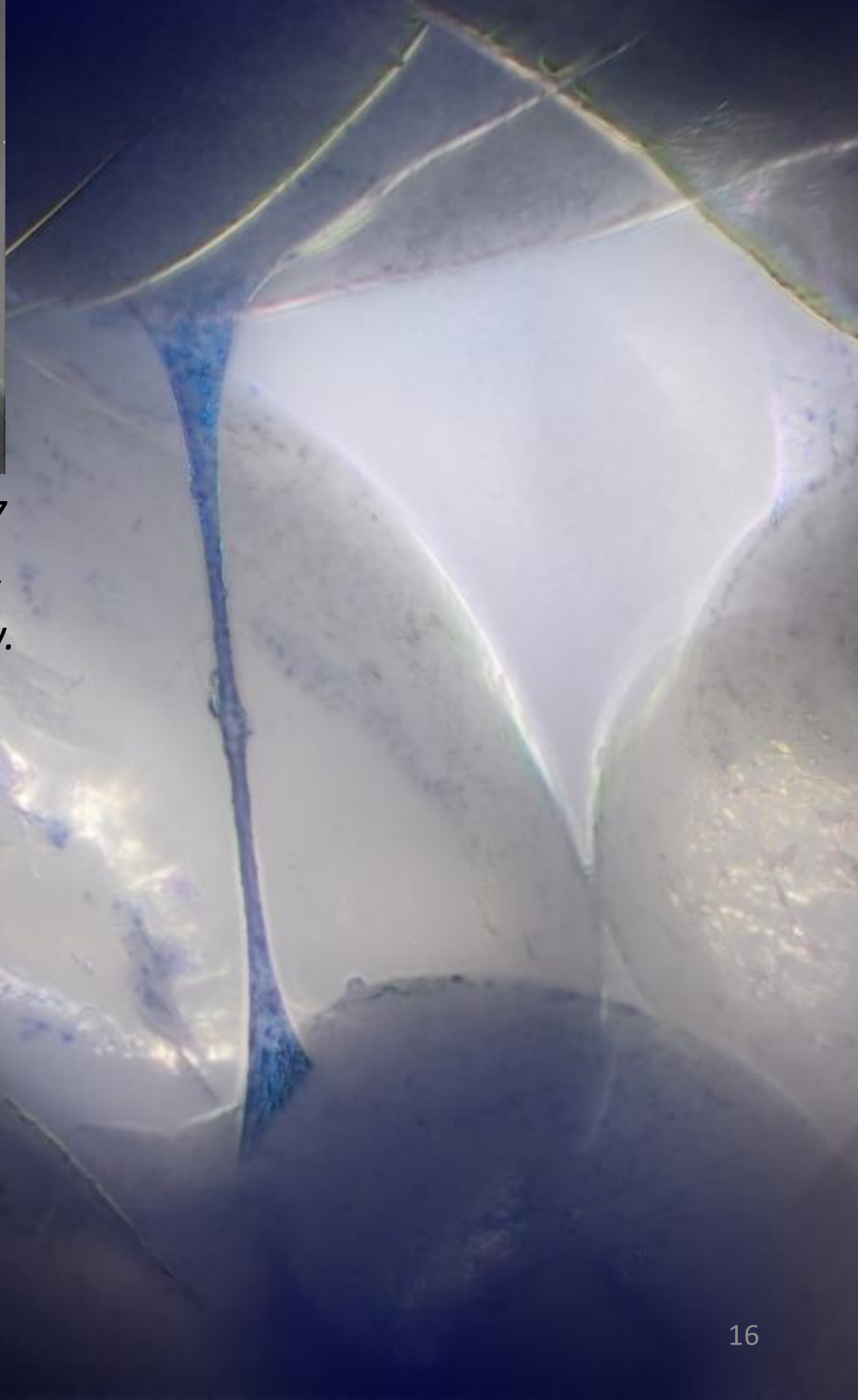
Were μ is the viscosity, σ is the surface tension, ρ is the density and d is a characteristic length (diameter of the filament).

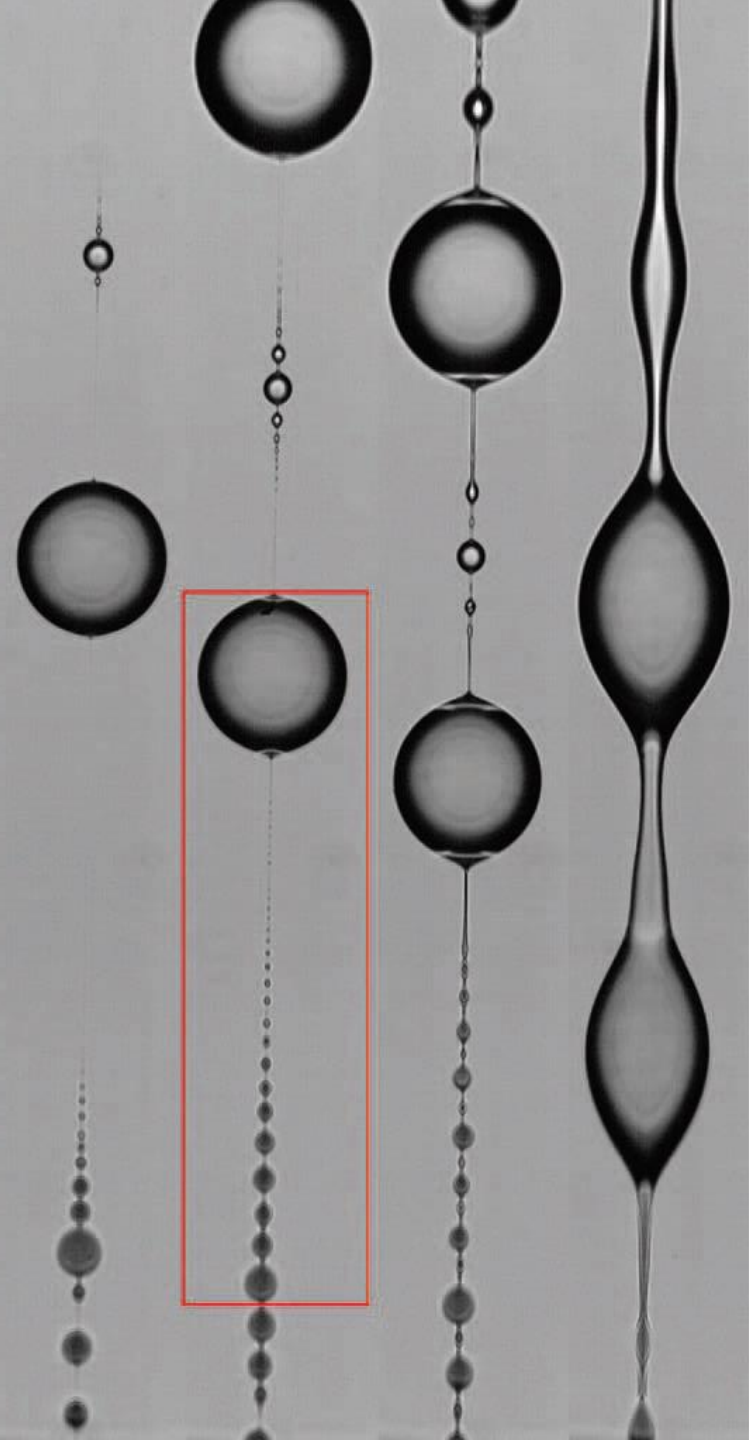
$$Oh = \frac{t_{visc}}{t_R}$$

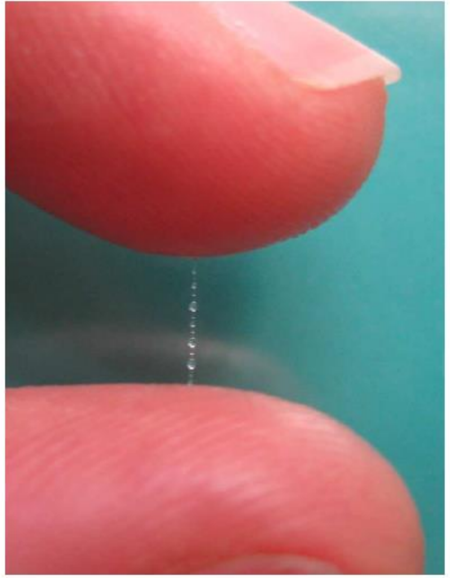
For *Oh>>1* viscosity controls the time scale of break-up of the liquid bridge.

von Ohnesorge 1937

Ohnesorge Z. Angew. Math. Mech. (1936)

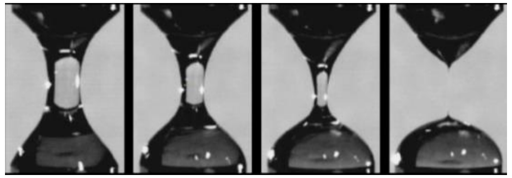




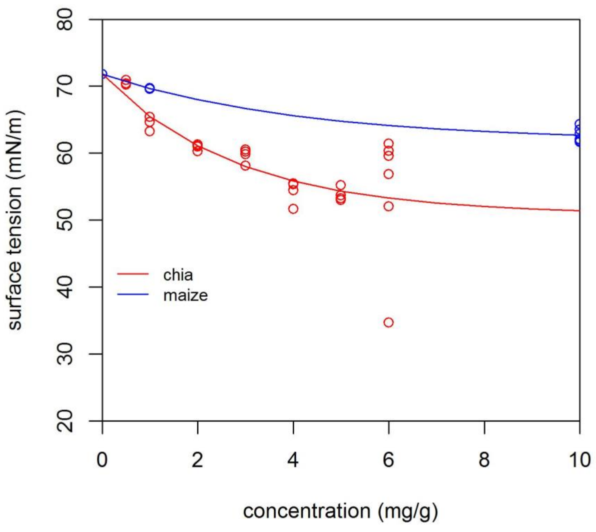


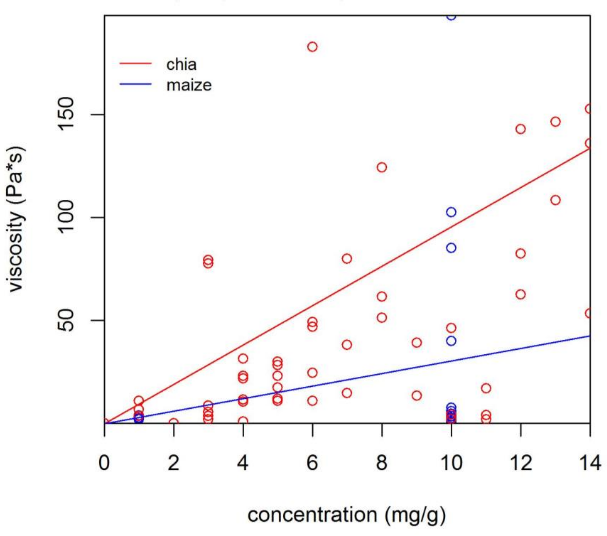
Formation of 1D filaments

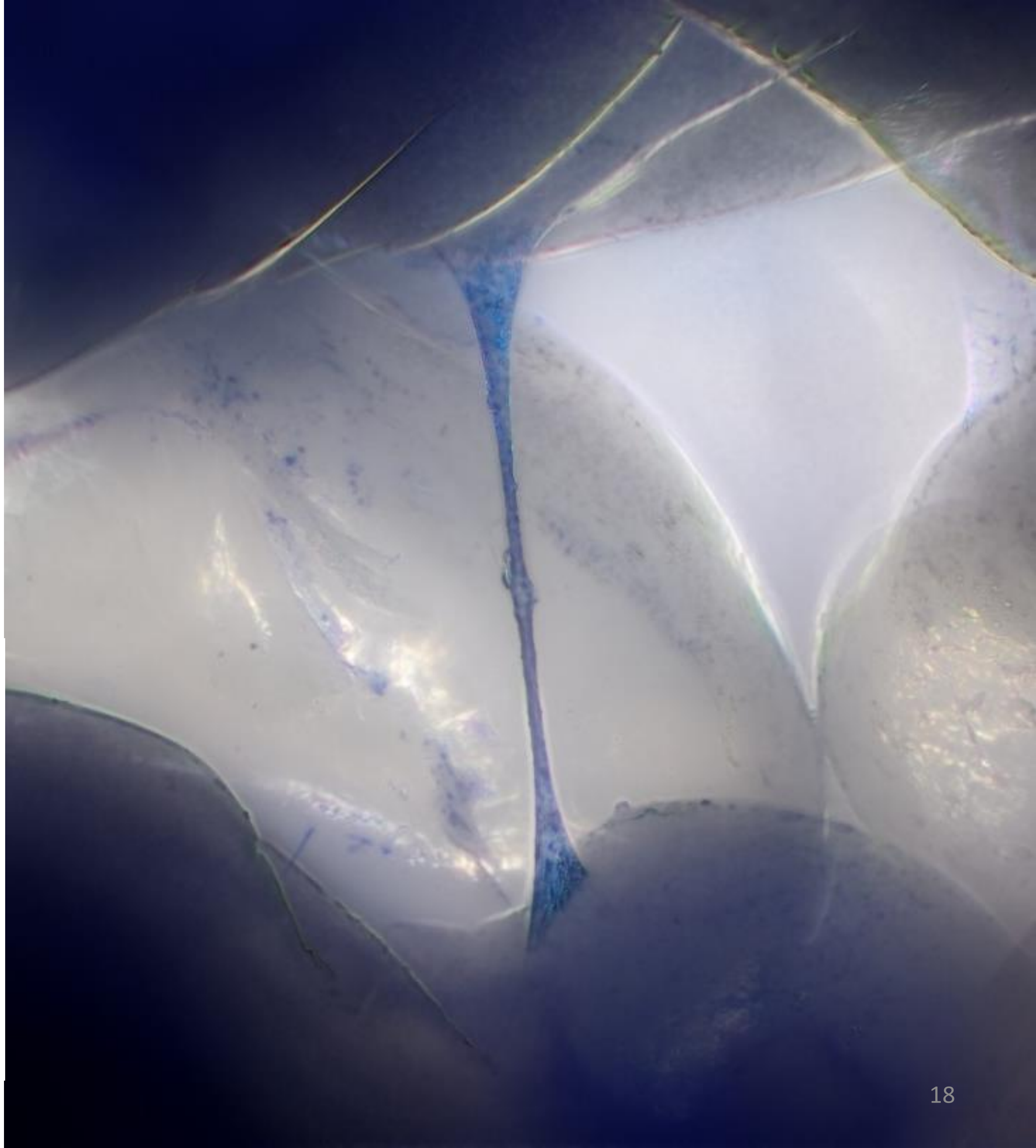
For $Oh \gg 1$: $\frac{\partial R}{\partial t} = -\frac{1}{6}\frac{\sigma}{\mu}$

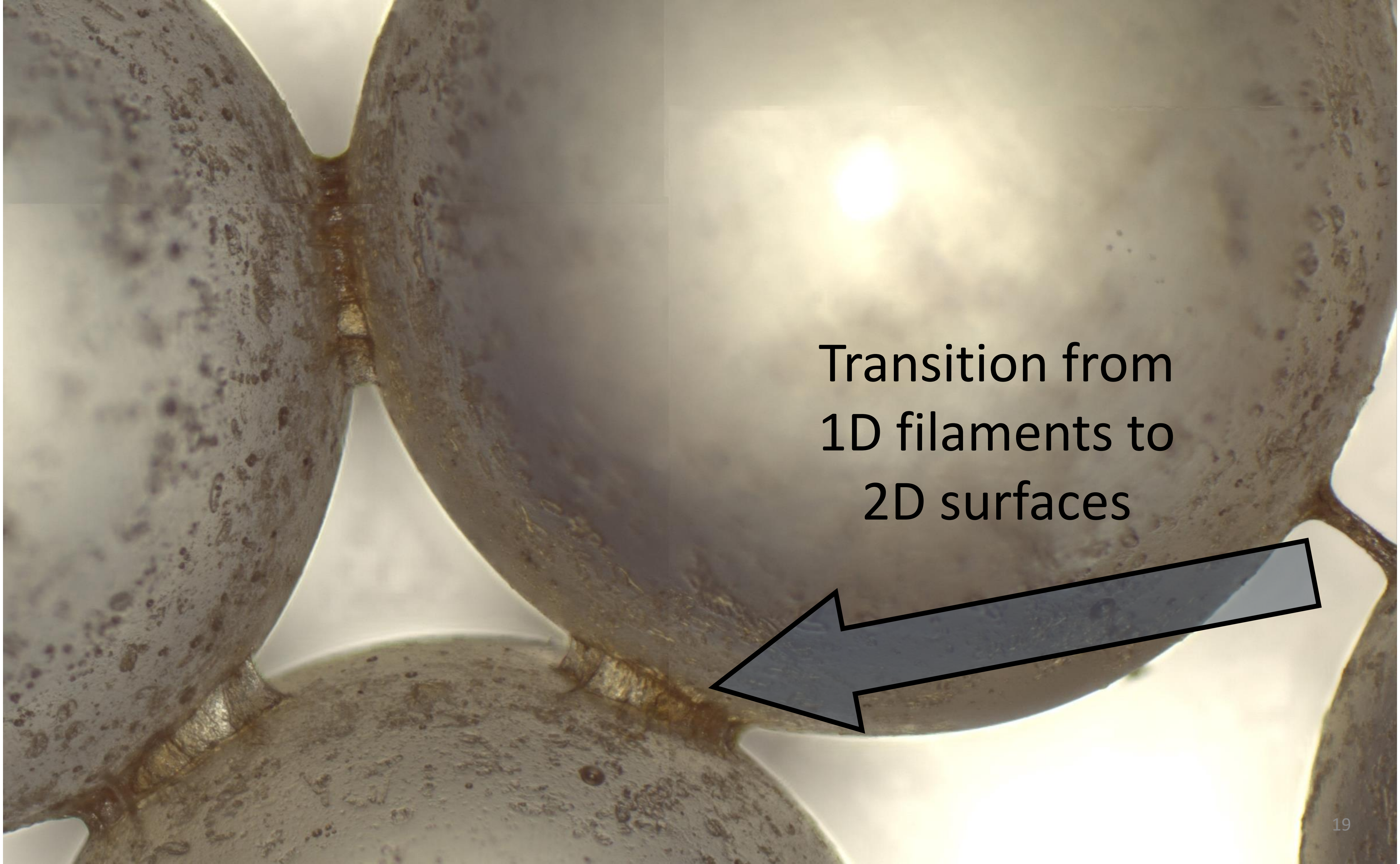


Where R is the bridge radius.
In polymer solutions μ increases during thinning preventing the break-up of the bridge.
(*Sattler et al. 2012 Physics of Fluids).*

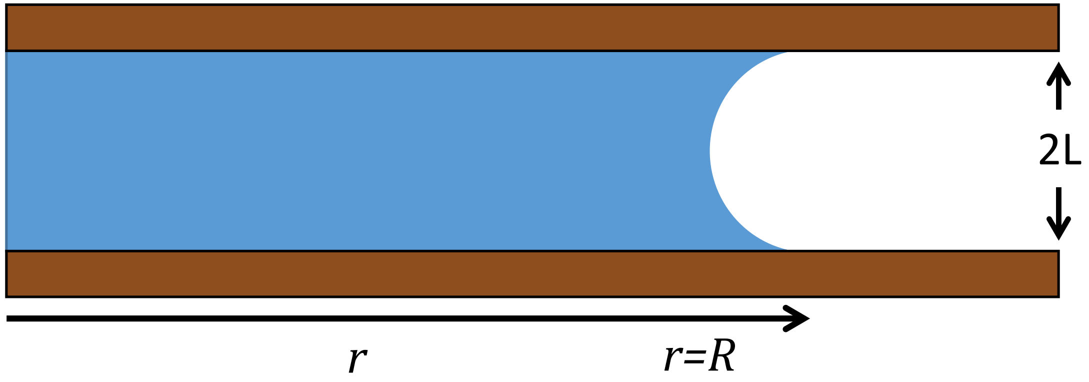


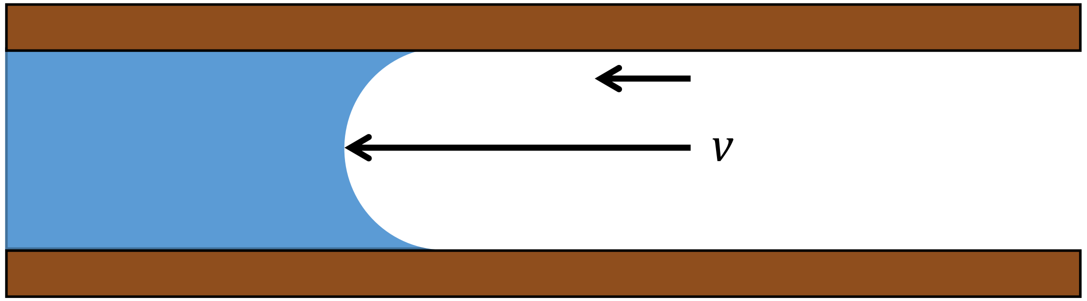


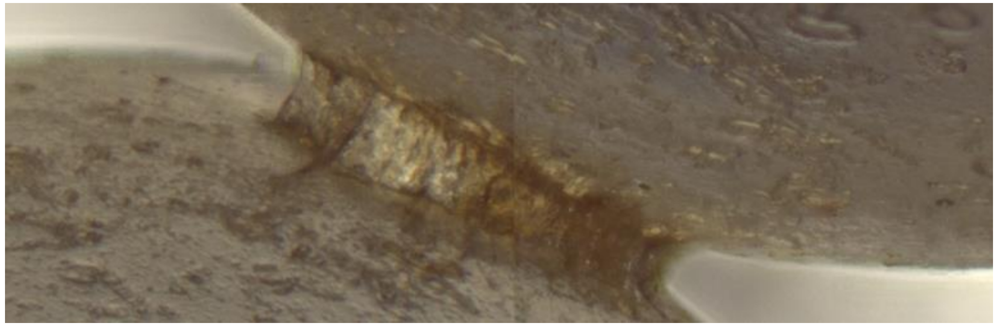



Transition from
1D filaments to
2D surfaces

Formation of 2D surfaces







Idea: When water is drained more rapidly than the capacity of the gel to stretch, the concentration of the gel network at the gas-liquid interface increases until a critical point, when the gel stops moving. The limit is the gel viscosity.

Two forces are considered:

1. Friction between the polymers and the soil particles acts against the receding of the polymers.
2. Polymers are pulled toward the regions with lower concentration (water adosrbed by polymers).

When the two forces are in equilibrium: $\frac{\partial P(C)}{\partial r} = -\mu(C)\frac{v}{L^2}$

with $P = -\, a_1\, C^{a_2}$ and $\mu = b_1\, C^{b_2}$

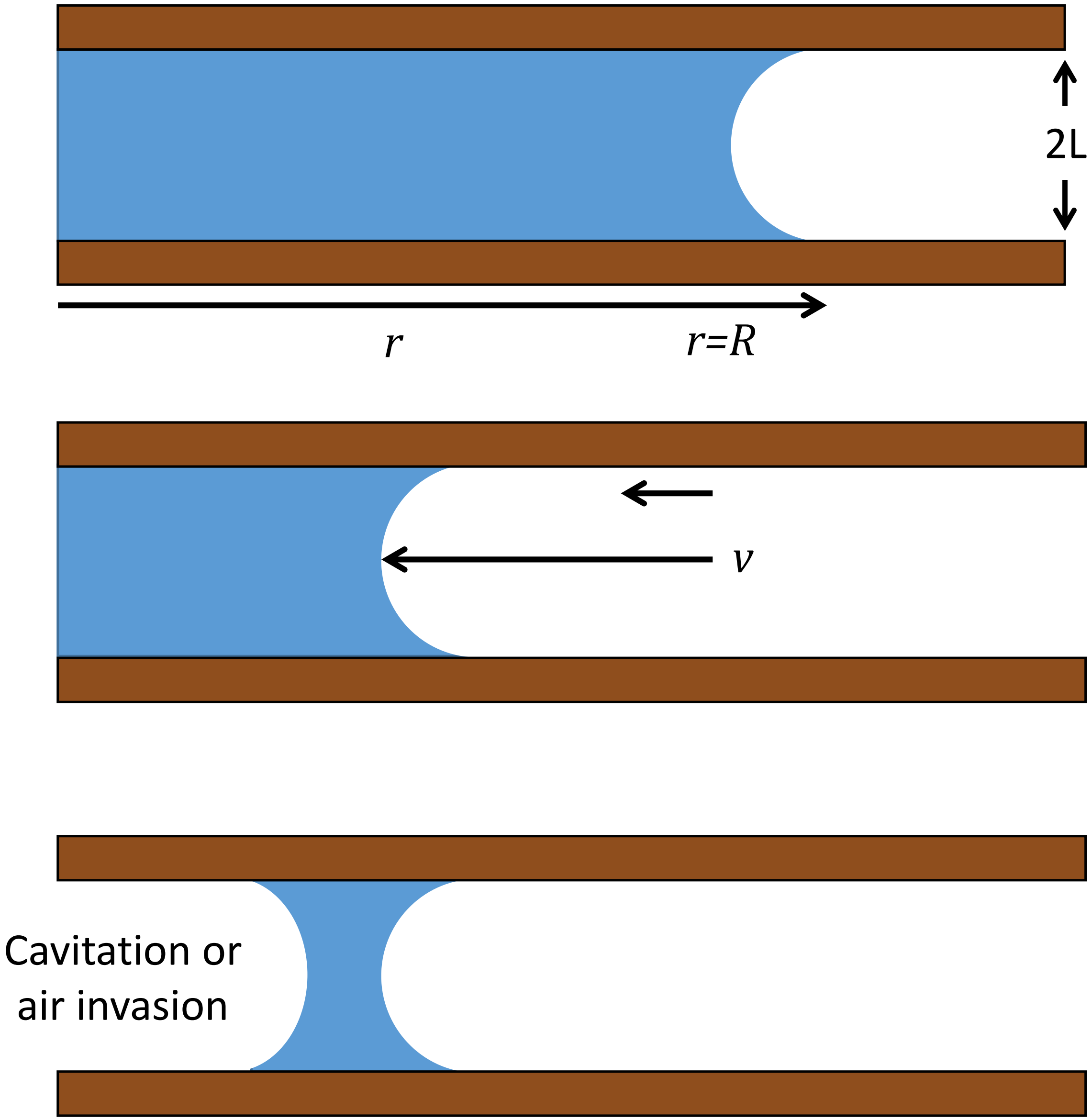
P=water potential; μ = viscosity

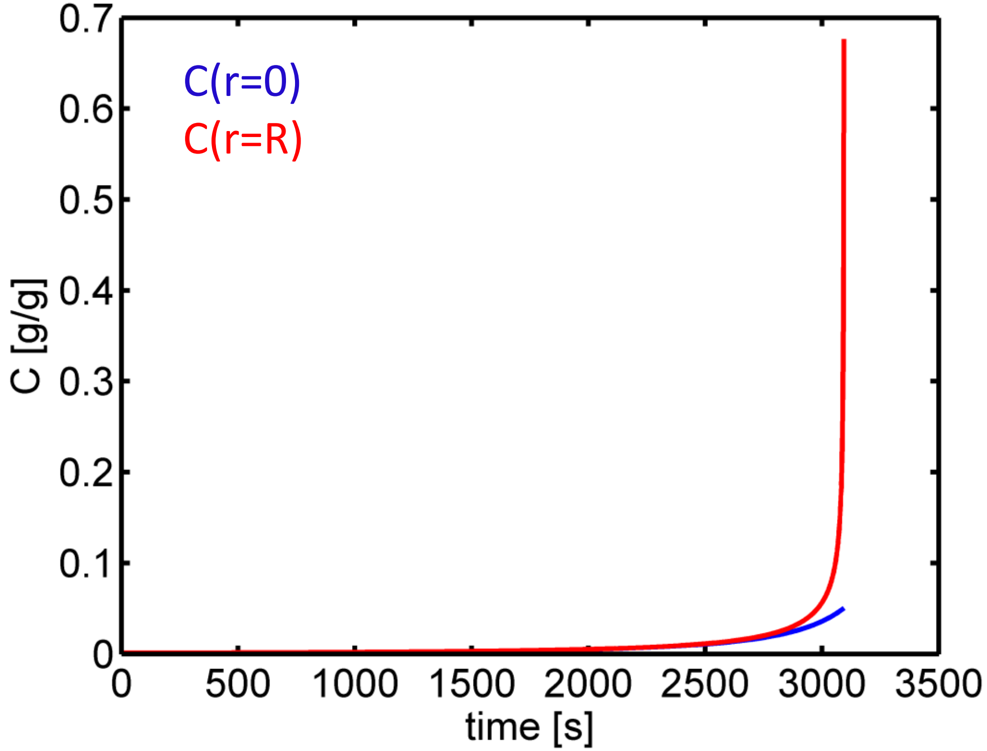
C=mucilage concentration (polymer mass per liquid volume)

v=velocity of the receding meniscus

Formation of 2D surfaces

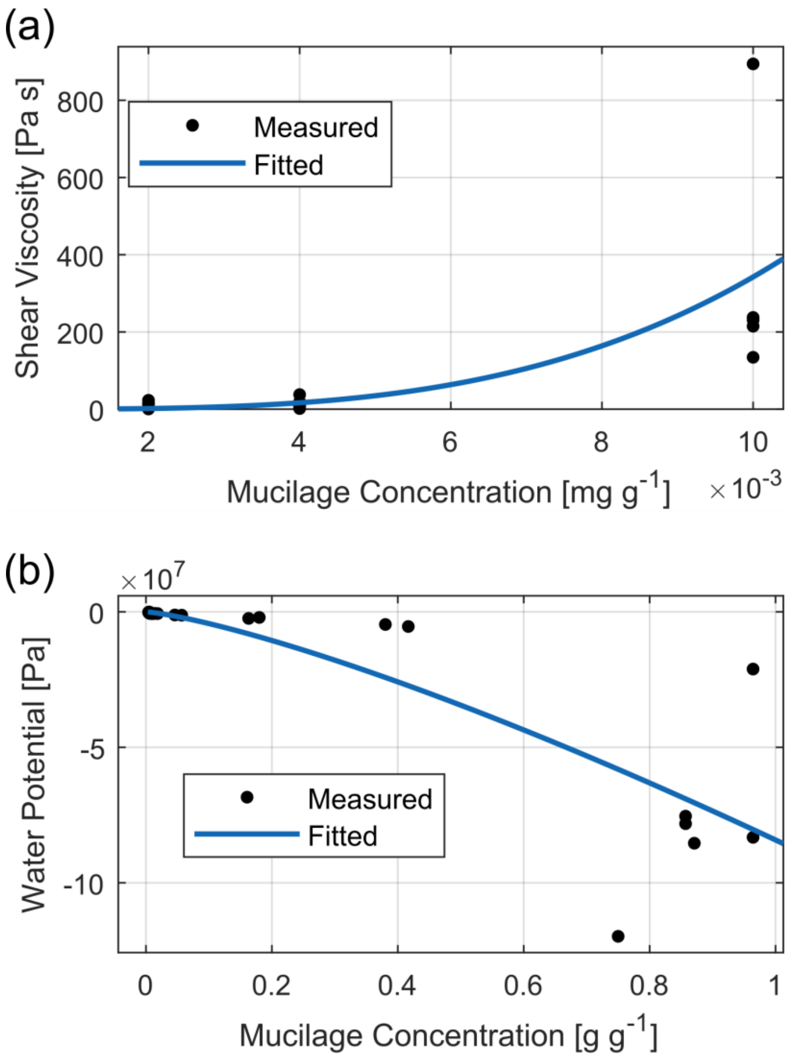
$$\frac{\partial P(C)}{\partial r} = -\mu(C)\frac{v}{L^2}$$

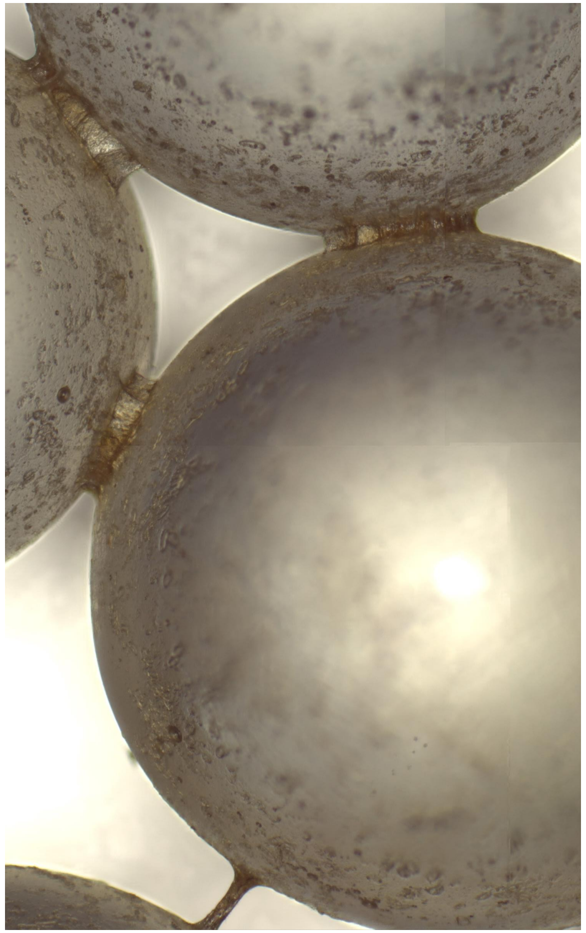




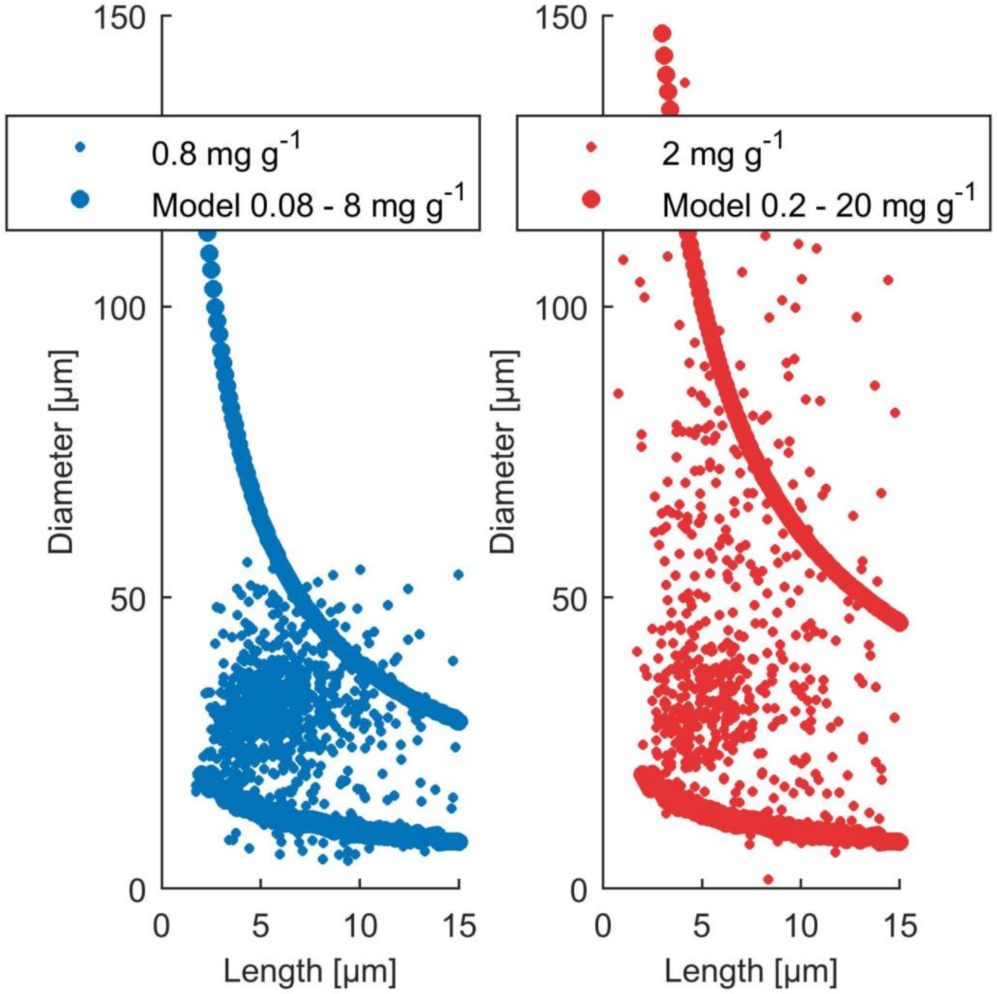
At a critical point, the gel network at the gas-liquid interface becomes becomes dry and it does not recede. As water continues to be drained (by root uptake or evaporation) the tension in the liquid increases and air enters the network by invasion or by cavitation.

Modelling and experimental results



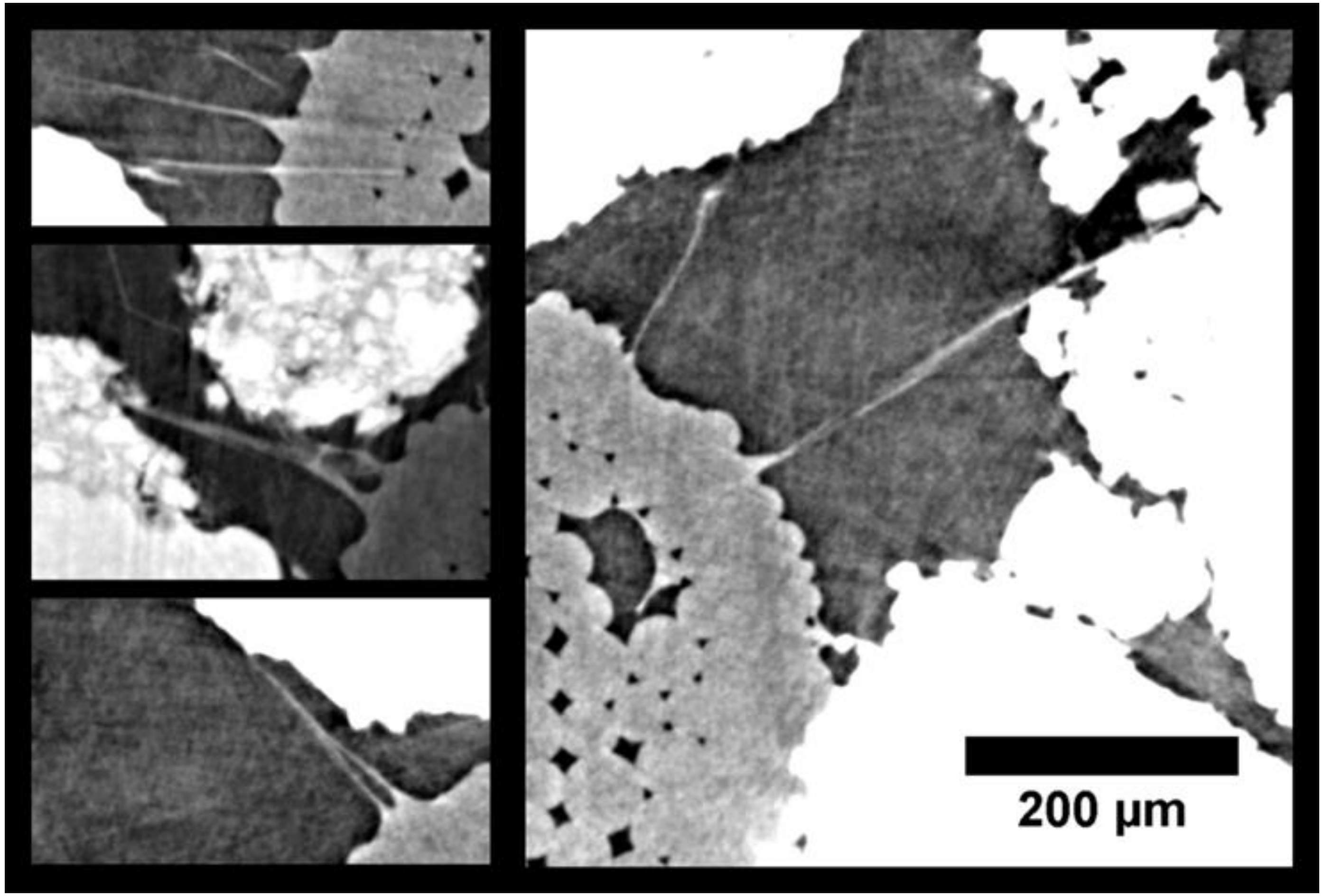


Glass beads
(diameter 100-200 µm)



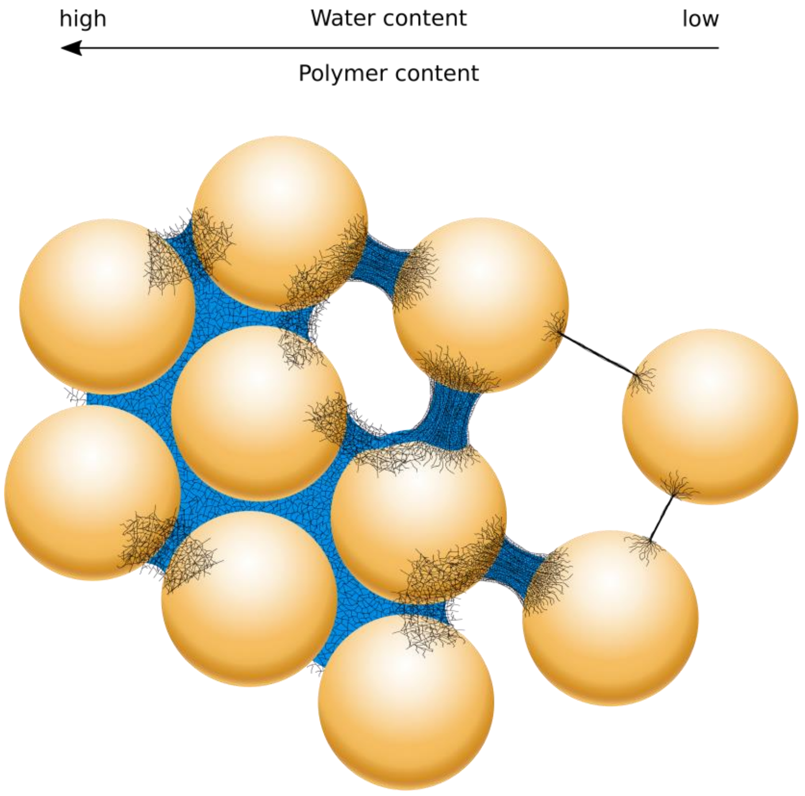
Consequences for plants

Presence of filaments at the root-soil interface



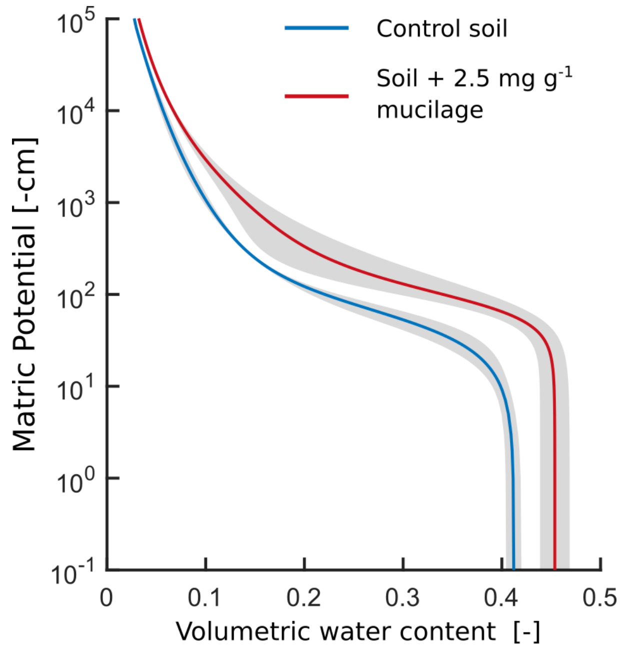
Consequences for soil water dynamics

The maintained connectivity of the liquid phase results into an increase in soil retention and transport properties

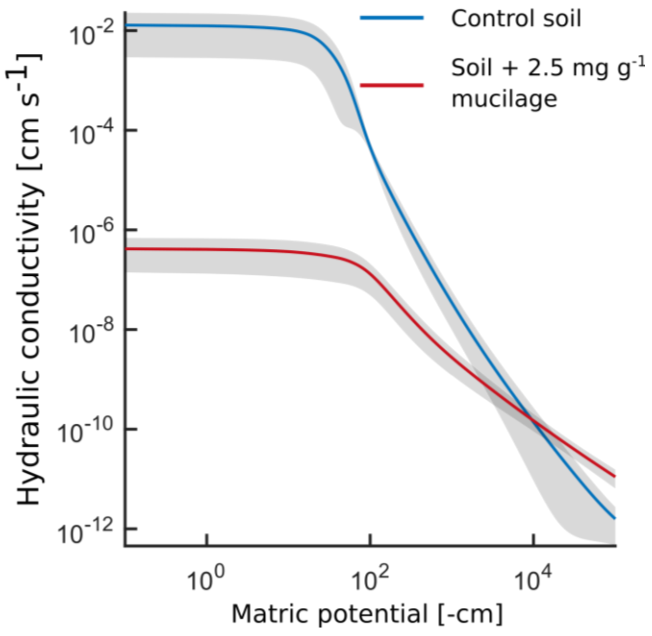


Benard et al. 2019 VZJ

Chia seed mucilage in loamy sand



Enhanced retention



Lower K^{sat} but smaller decrease in K(h)

Consequences for soil water dynamics

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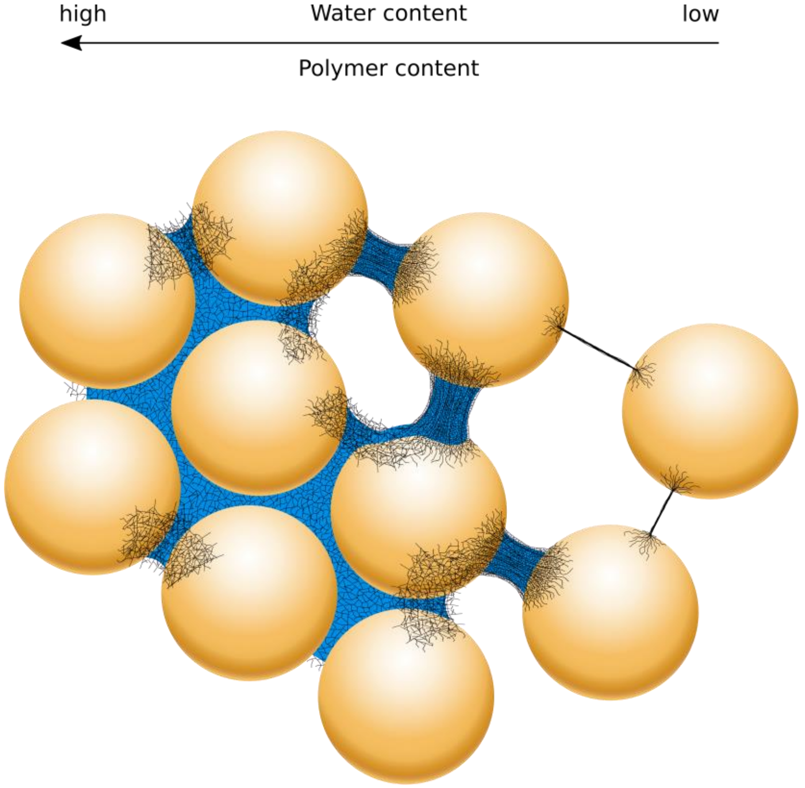
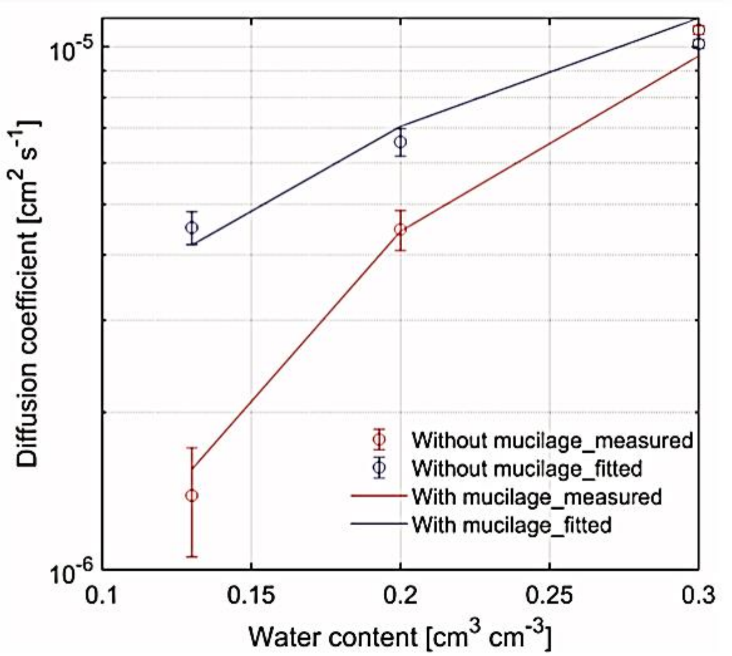


Benard et al. 2019 VZJ

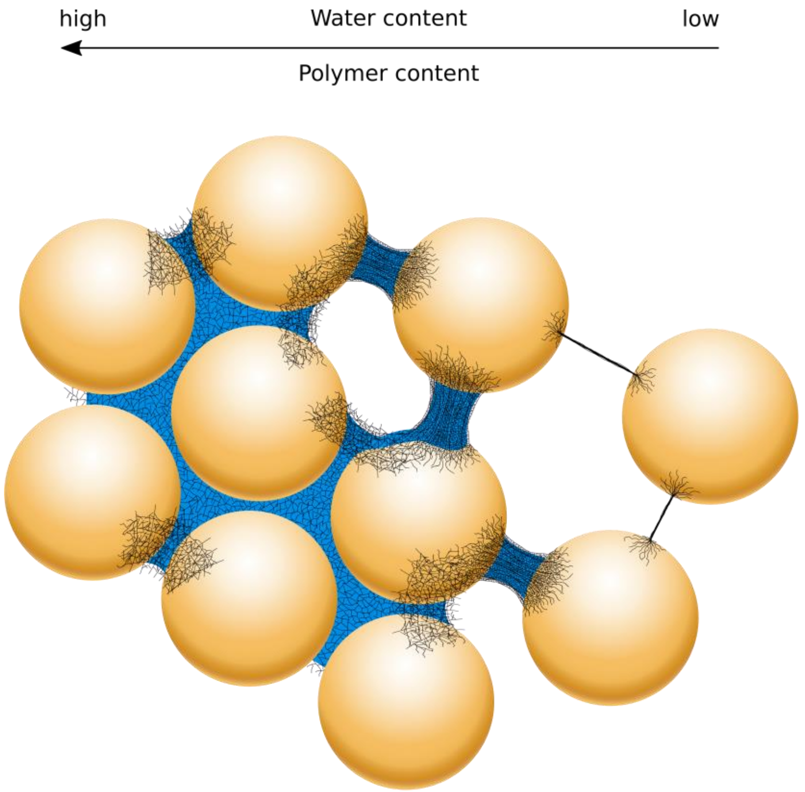
Zarebanadkouki et al. 2019 VZJ

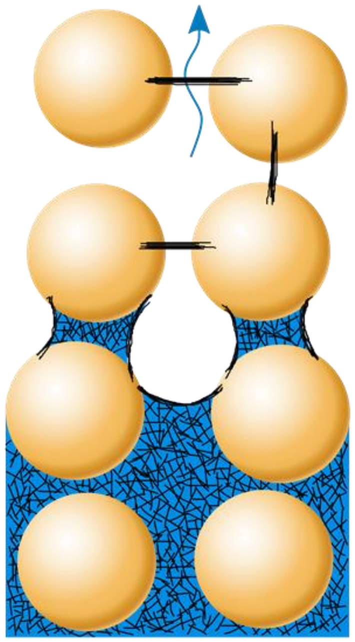


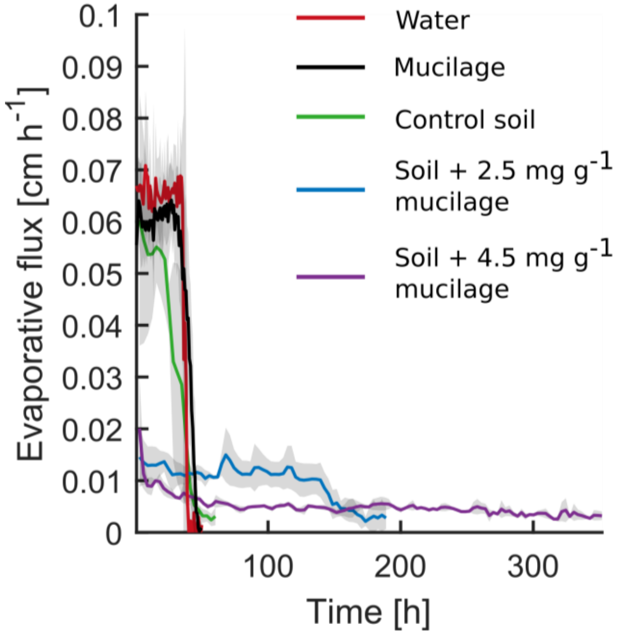
Enhanced diffusion

Consequences for soil water dynamics

The maintained connectivity of the liquid phase reduces the gas diffusivity (e.g. lower evaporation rates)







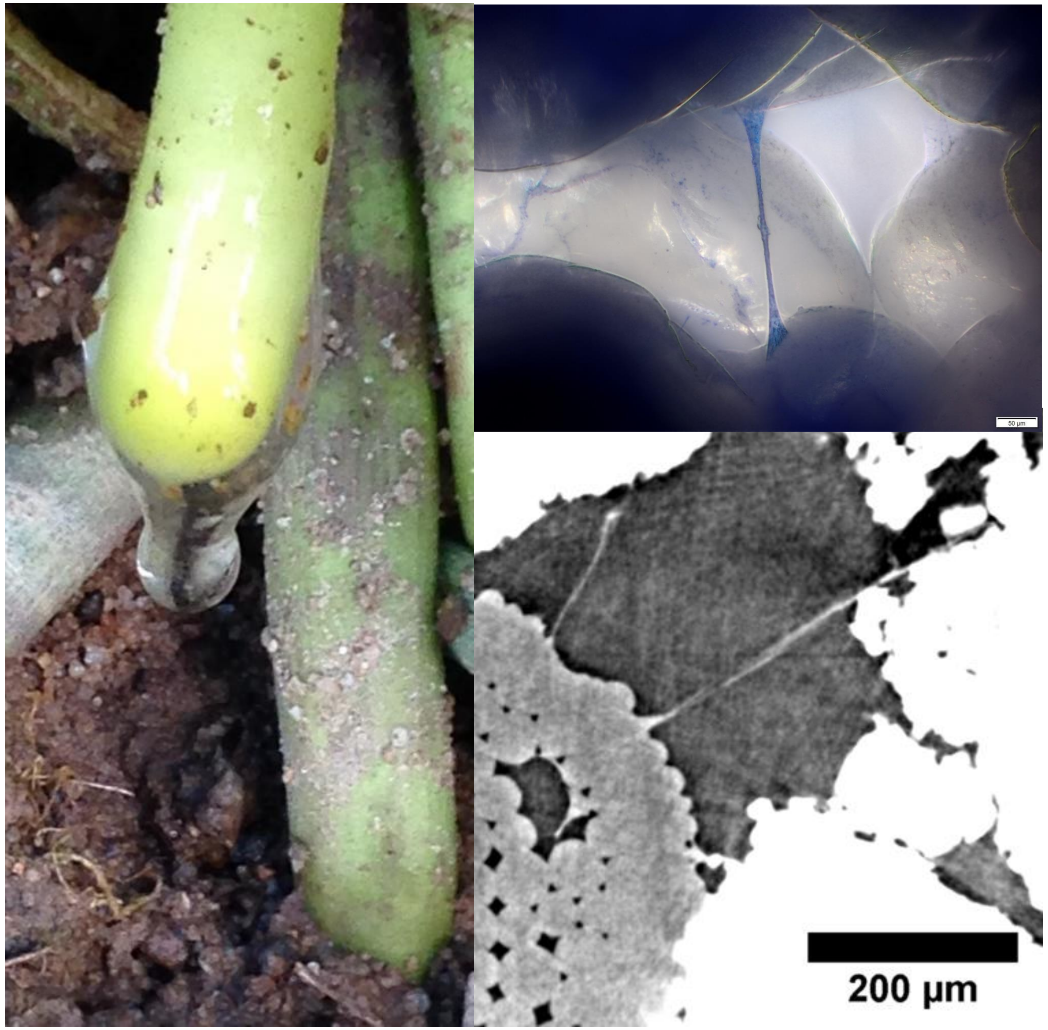
Benard et al. 2019 VZJ

Reduced evaporation

Summary

Mucilage (and EPS) adsorbs water, increases viscosity and decreases the surface tension of the liquid phase.

This induces the formation of 1D and 2D interconnected structures in soils, which enhance the contact between the root surface and the soil matrix, and which increase soil water retention, soil hydraulic conductivity and diffusion (through the liquid phase).



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Mohsen Zarebanadkouki

Mutez Ahmed

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