Microaggregate development in Soil

Glucose-stimulation of natural microbial activity causes transient aggregation and alteration of clay mineralogy in sandy and loamy sediments

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Summary

- Eight deep (0.3–36.3 m) soils were treated with glucose solution and observed during 30 days
- A transient increase of biomass and respiration, with maxima on days 4-10 after the treatment (**Slides 5-6**)
- Changes in clay mineralogy: the proportion of smectite layers in illite-smectite mixed layer minerals increased, as well as the overall imperfection of clay minerals (**Slide 8**)
- The formation of biofilm enmeshing loam aggregates and sand grains was visualized by SEM (**Slides 10-11**)
- A transient increase of the content of microaggregates (0.1-0.05 mm) (**Slide 12**)
- The changes resulted in 15-30% decrease of stress-strain properties during first 10 days of the experiment, following by soil stabilization (**Slide 14**)

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Motivation

- Microbial activity below topsoil is usually hindered due to the lack of nutrients
- Because of anthropogenic activities (construction sites, agricultural areas, industrial zones) nutrients may enter underground and quickly activate microbial communities
- This may result in changes in mineralogy, (micro)structure and, consequentially, properties
- It is unclear, if the observed changes in the composition, structure and engineering properties are permanent or transient, once the external carbon sources are exhausted and the microbial activity declines or even ceases

Goal of this study: analyse how artificially enhanced microbial activity influences engineering properties of soils and follow these changes in time. To explain the changes, we analysed alteration of clay mineralogy and microstructure

Materials and Methods

- We sampled 8 soil materials (4 sands, 4 loams) of different genesis, depth, texture and composition encompassing a wide range of engineering importance of the Moscow area

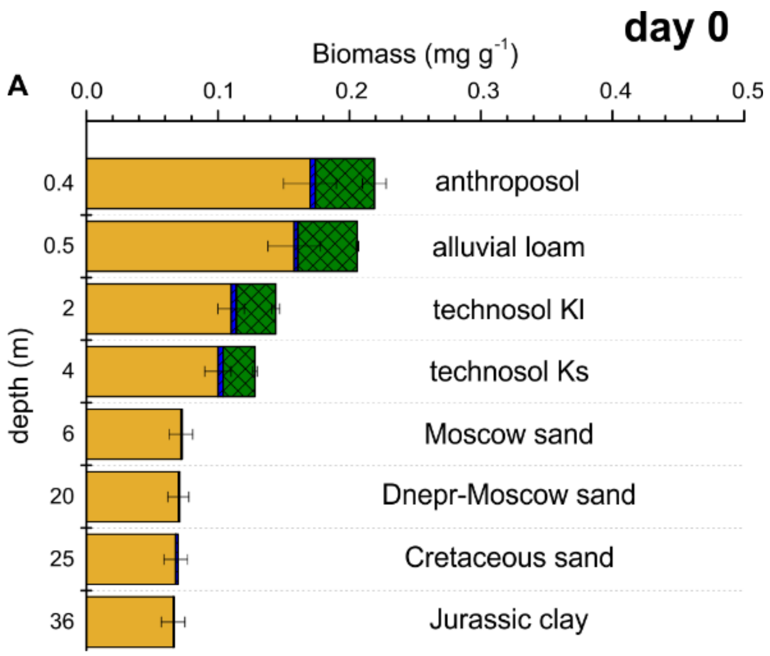
See **schematic geological profile** and detailed **tables** of soil characteristics in Appendix

- **One-shot** addition of glucose solution to all samples
- Analyses before the treatment and during next 30 days:
  - **Respiratory activity** (CO_2 emission) and **biomass development** (direct cell count);
  - **Clay mineralogy** by XRD on textured samples;
  - Imaging of the **microstructure** with SEM;
  - **Microaggregate size distribution** (pipette analysis after the Stokes equation);
  - **Stress-strain properties**: unconfined compression tests on consolidated loams, cohesion and internal friction angle of sands (direct shear test)

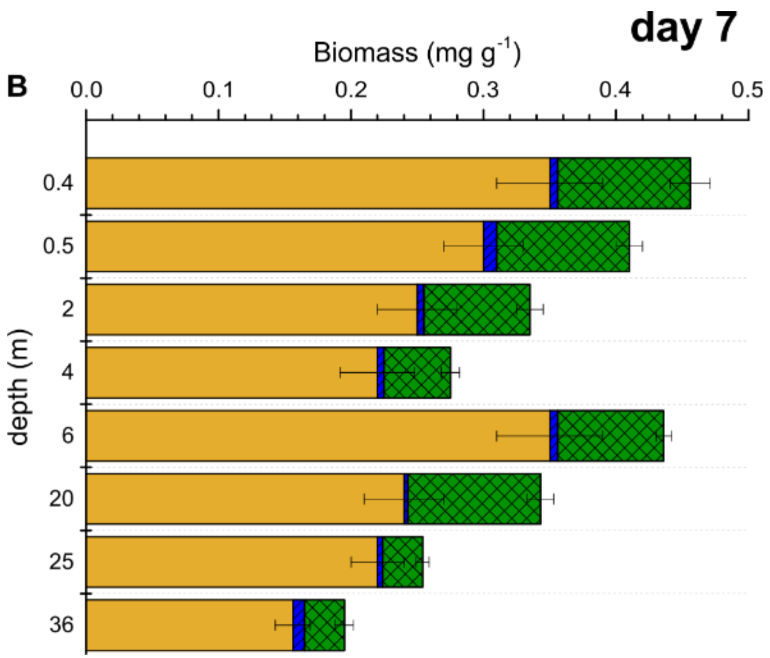
See **flowchart** in Appendix for illustration

Results

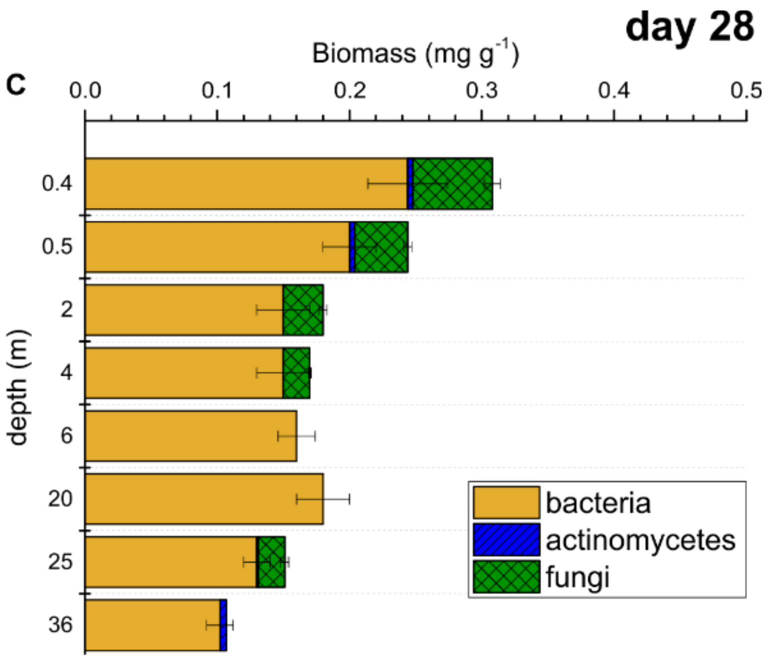
I. Microbial activity



Initial biomass decreases with depth and is proportional to the OM content, except for the Jurassic clay. In the Jurassic clay kerogene-like substances are less available



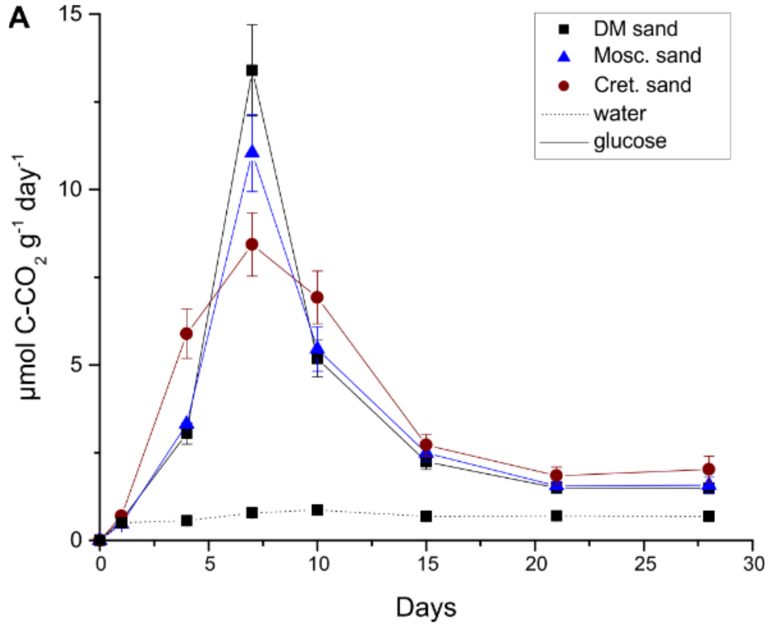
Glucose stimulated microbial growth and resulted in 200-300 % biomass buildup. Bacteria (and Archaea), actinomycetes and fungi were stimulated



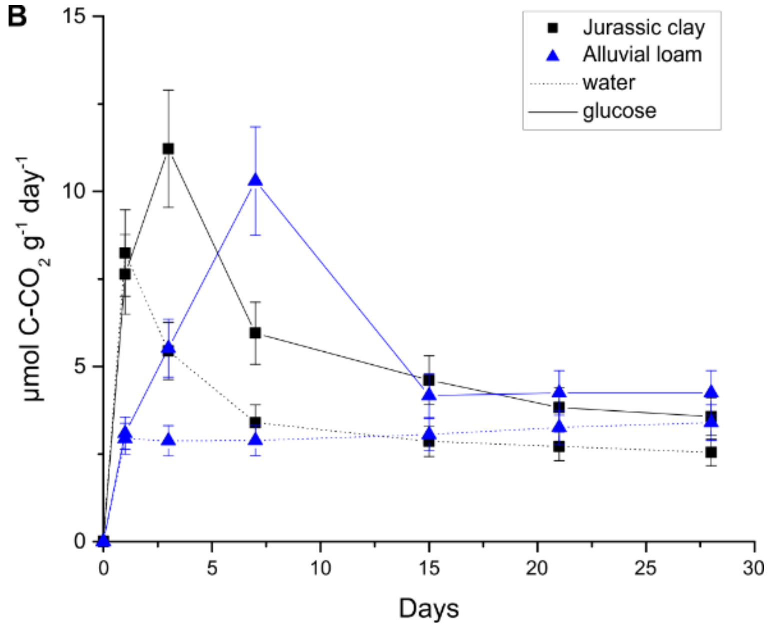
Along with the consumption of glucose, biomass decreased but remained higher than before the experiment

I. Microbial activity

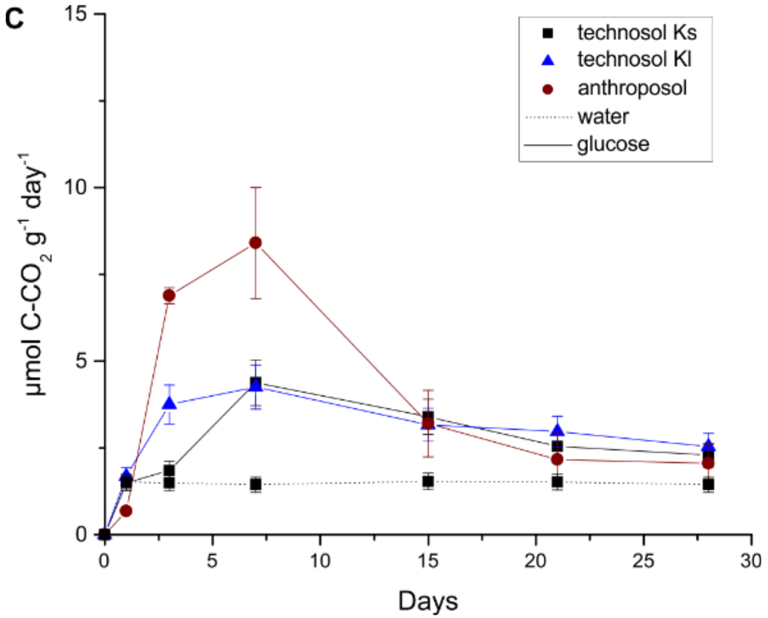
Sands



Natural clays



Technosols



Sharp maxima in respiratory activity in sands → substrate (glucose)-limited activity

Broader and lower peaks in loams → natural OM as additional nutrition and/or nutrient transport was limited due to a finer pore structure.
The Jurassic clay shows moistening effect → dissolution of fractions of authigenic OM made it more available. Addition of glucose led to a postponed higher peak.

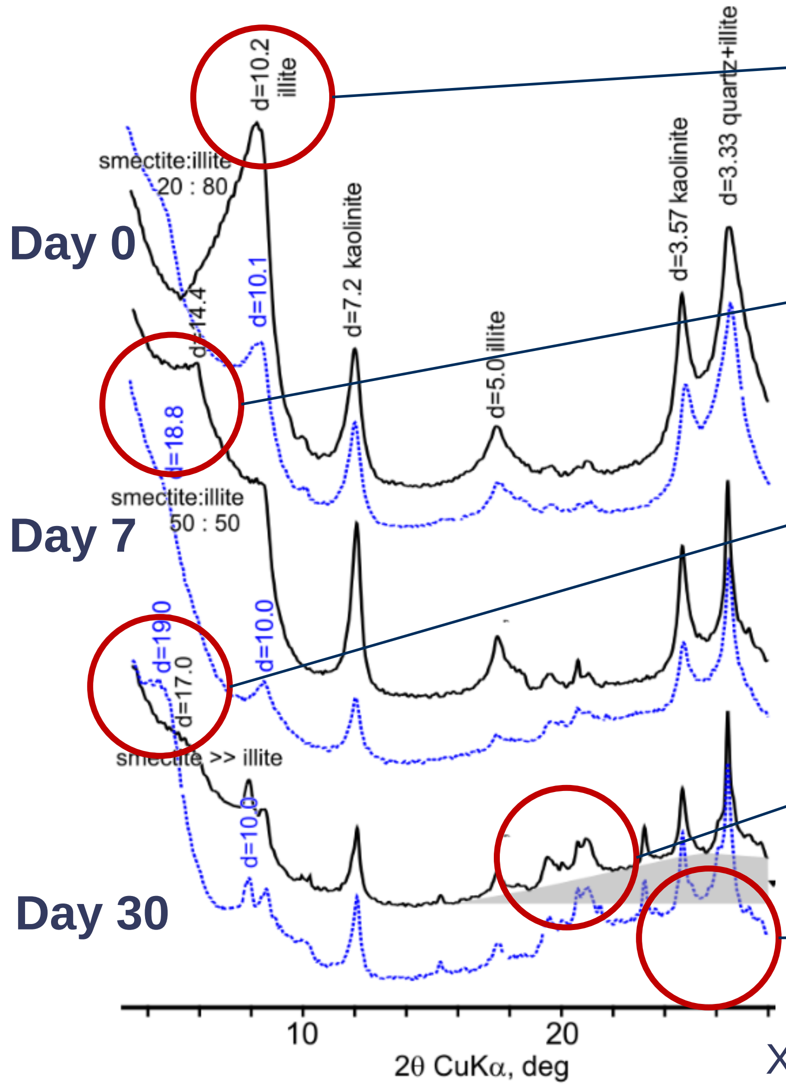
After 15-20 days, all samples approached a constant respiratory activity and a biomass content about 1.5-2 times higher than before glucose addition → stable microbial community was formed

I. Microbial activity

- Glucose addition caused a transient stimulation of microbial activity with its maximum on around 4-10 days after treatment;
- Microbial activity in OM poor samples was substrate-limited; in loams the consumption of authigenic OM may be stimulated;
- Bacteria (+Archaea), actinomycetes and fungi showed notable growth in all samples
- After 30 days, the samples still showed elevated biomass and respiration with respect to the original material

Results

II. Clay mineralogy



Asymmetric 10.2 Å reflex that partially shifts in glycolated state → presence of mixed layer illite-smectite clay mineral (MLM) with predominance of illite

Shift to ~14 Å for the air-dried and to ~18-19 Å for the glycolated samples → increased content of smectite layers in the MLM

Shift to ~17 Å for the air-dried and to 19 Å for the glycolated samples → predominance of smectite layers in the MLM

Lower intensities of clay mineral reflexes, hkl-planes reflexes of kaolinite and/or illite, and feldspar reflexes → partial destruction of clay minerals or an inferior orientation of the clay minerals

Diffuse reflection → accumulation of an amorphous phase and/or OM

XRD pattern for textured samples of the clay fraction of the anthroposol

II. Clay mineralogy

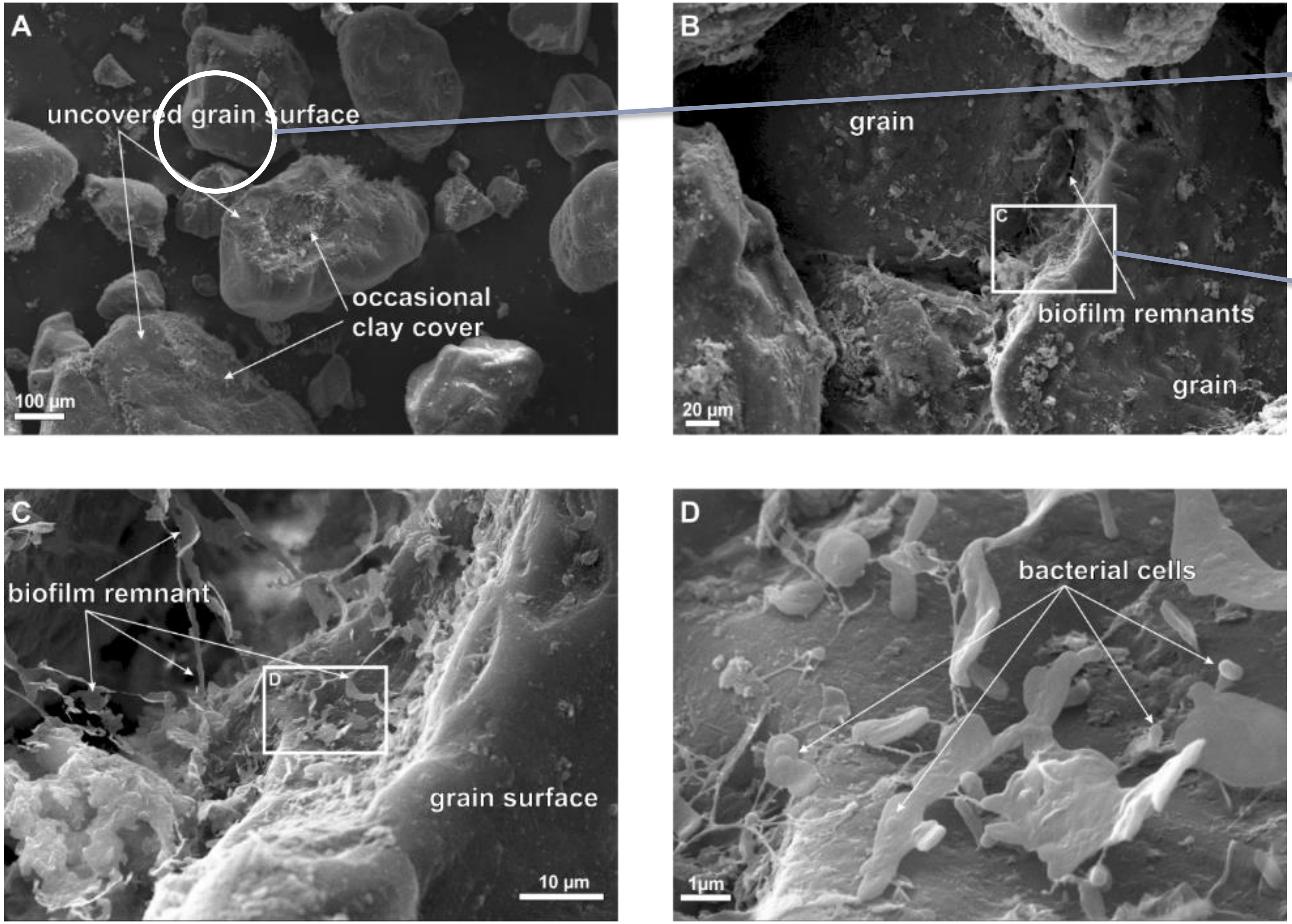
- Destruction of illite layers in MLM probably due to K^+ consumption by microorganisms. We assume that the K^+ concentration in the pore waters of the soils was not enough to support the microbial growth, so that additional K had to be extracted from the clay minerals

- “Pure” illite remained without major changes – MLM with a low state of ordering and a poor crystallinity are more “biodegradable”

- Destruction of clay minerals at day 30 of the experiment may be linked to microbial consumption of essential elements

Results

III. Biofilm formation and aggregation – air dried sand



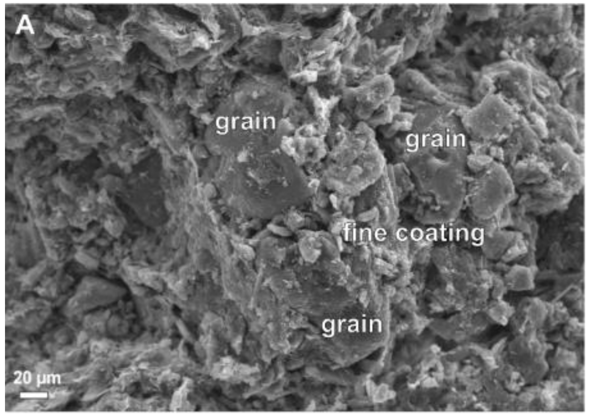
Before treatment: clean loose sand grains contacting via friction

After treatment: Organic structures (which we interpret to be the remnants of biofilms, i.e. EPS and cells) are found between grains.

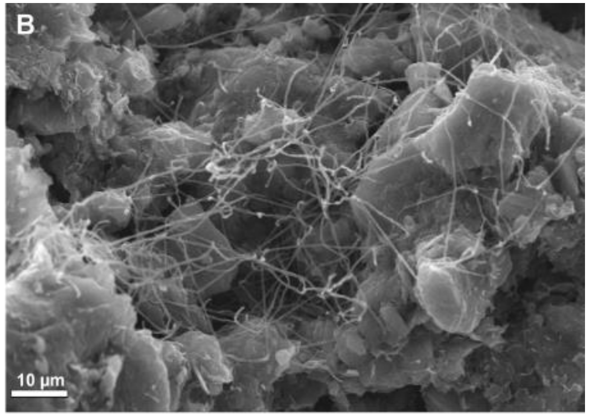
Neighbouring grains look glued together by this material

SEM images of Dnepr-Moscow sand: A – prior to glucose addition; B-D – on the 7th day after glucose addition

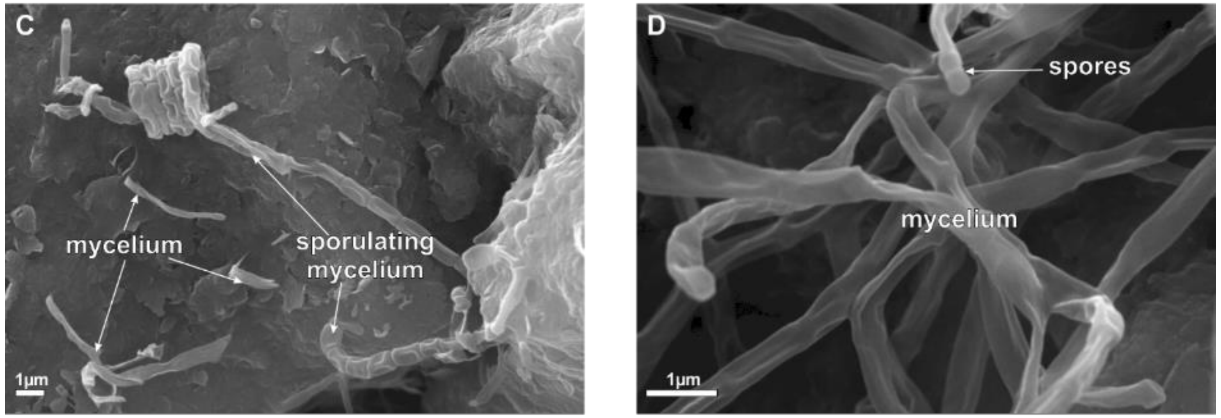
Results III. Biofilm formation and aggregation – lyophilized loams



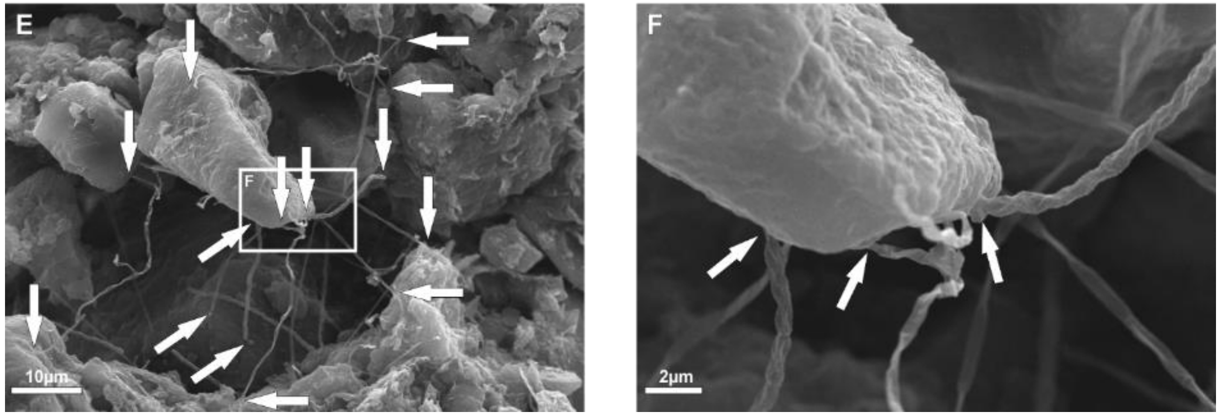
Initial loam:
“coagulation structure”



Newly formed biogenic structures – aggregates enmeshed by mycelium



Actinomycete mycelium in different stages of development



Mycelium penetrates into fine coatings of grains and aggregates and “stitch” them together

SEM on lyophilized loam showed actinomycete hyphae, which seem to enmesh soil aggregates.

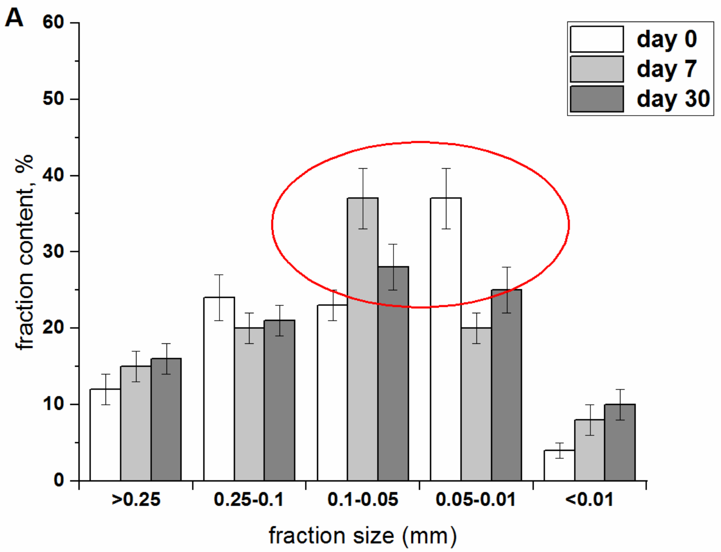
SEM images of alluvial loam: A – prior to glucose addition; B-F – on the 7th day after glucose addition.

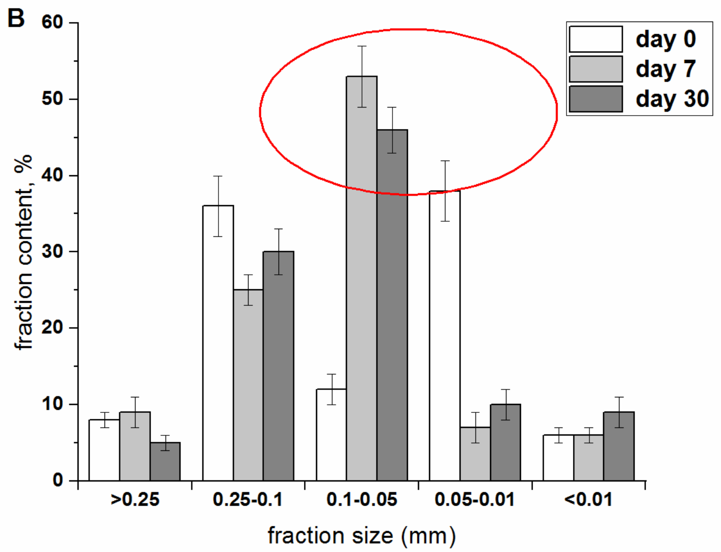
Results

III. Biofilm formation and aggregation

Alluvial loam

Jurassic clay





Aggregation in **microaggregates 0.1-0.05 mm and 0.05-0.01 mm** in size → probably due to adhesion of bacterial cell and/or EPS to soil particles and enmeshing of aggregates with actinomycetes and fungi

With the decline of microbial activity and biomass, the previously-formed microaggregates partially disintegrated → after consumption of glucose the microorganisms might live on biomass and EPS**,** thereby removing previously formed glue and mycelium meshes from the aggregates

On the 30th day of our experiment, aggregate size distribution differed from the original state before glucose addition, and respiratory activity and biomass were higher than before the treatment. We assume that the remaining dead and alive cells and EPS still held together the particles.

Results

III. Biofilm formation and aggregation

- SEM: on air dried sand we observed biofilm remnants with individual cells that “glue” neighbouring grains together; while loams showed actinomycetes enmeshing the soil aggregates

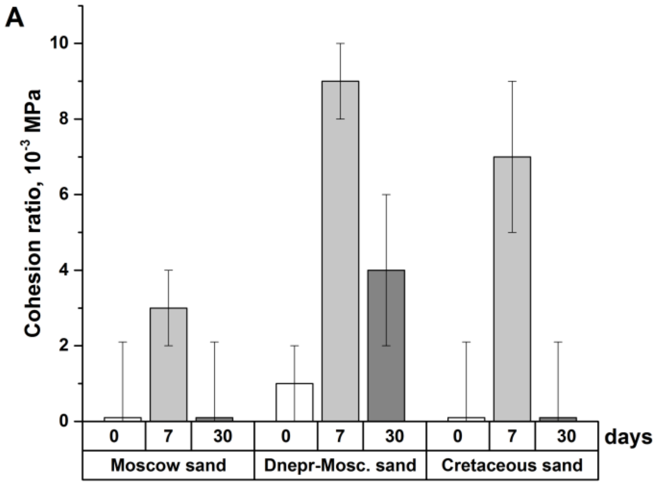
- Pipette analysis showed a transient increase of the content of microaggregates of 0.1-0.05 mm in size

- We therefore conclude that biofilm formation directly affected soil microstructure by creating new biogenic contacts between individual grains and by enmeshing grains with hyphae

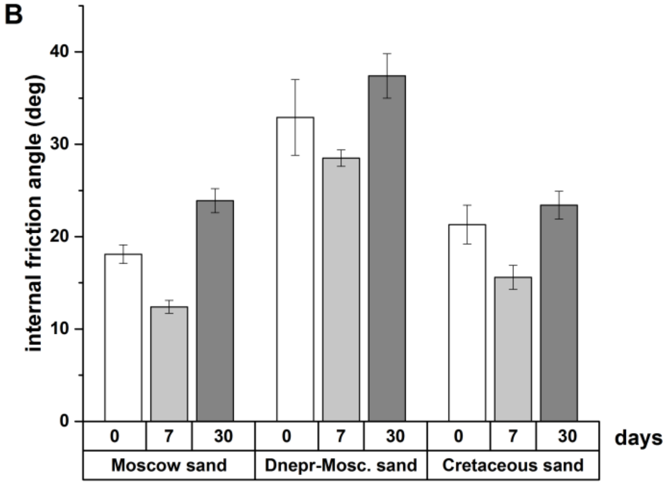
- Decline of microbial activity resulted in partial dissipation of microaggregates – probably due to partial consumption of enmeshing EPS and biomass by still living microorganisms

IV. Stress-strain properties

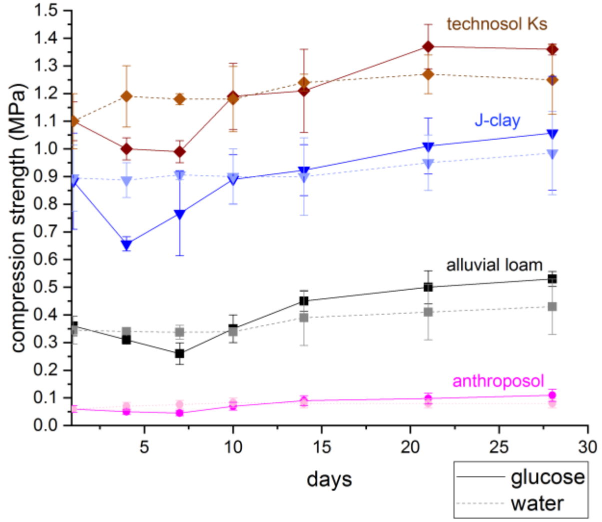
Cohesion in sands



Friction in sands



Compressive strength in loams



Day 7: increase of cohesion and decrease of 15-30 % of internal friction angle.

Day 30: recovery of cohesion; friction slightly higher than before the treatment

Day 4-10: drop in uniaxial unconfined compressive strength (up to 20-30 %)

Day 14-30: increaseв strength compared to control samples

IV. Stress-strain properties

- Sands: during high microbial activity (day 7) cohesion appeared due to enmeshing of grains with EPS with a certain cohesive strength. Drop of friction because EPS modified surface properties and caused lubrication effect

- Loams: decreased strength due to development of EPS to lower friction; formation of CO_2 because of respiration to affect porous pressure

- Further transformation of EPS (aging and consumption by microorganisms) and irreversible changes of clay mineralogy and aggregate size distribution may modify grain surface properties and result in increased friction/strength

General outcome and conclusion

- Glucose addition caused a transient increase of microbial biomass and respiration. After 30 days, a microbial community with constant respiratory activity and biomass 1.5-2 times higher than before treatment remained
- Microbial activity resulted in a transformation of illite layers into smectite in illite-smectite mixed layer minerals and later in a destruction of clay minerals
- Glucose stimulation resulted in a transient increase of aggregates of 0.05-0.01 mm in size due to biofilm growth. This was observed directly both on sands and loams via SEM
- Enhanced microbial activity caused a drop in engineering properties on days 4-10
- Improvement of properties after 30 days may happen due to irreversible changes in clay mineralogy, remaining microbial activity and the presence of “aged” biofilm with possible stabilization effect
- The shown decrease of up to 30% of engineering properties during high microbial activity may threaten significantly the safety of buildings where inputs of organic substances or other missing nutrients to the grounds is possible (e.g. powerplant dams, paper mills, food industry objects, urban area due to sewage spills, rural area due to adding of fertilizers)
- Our results may be taken as a first guide for risk assessment and planning of the specific engineering surveys of the grounds

Further discussion and acknowledgements

For detailed information and discussion please refer to:
Ivanov, P., Manucharova, N., Nikolaeva, S., Safonov, A., Krupskaya, V., Chernov, M., Eusterhues, K., Totsche, K.U. (2020). Glucose-stimulation of natural microbial activity changes composition, structure and engineering properties of sandy and loamy soils. *Engineering Geology*, 265. 105381. DOI: 10.1016/j.enggeo.2019.105381

I am open for questions any time at pavel.ivanov@uni-jena.de

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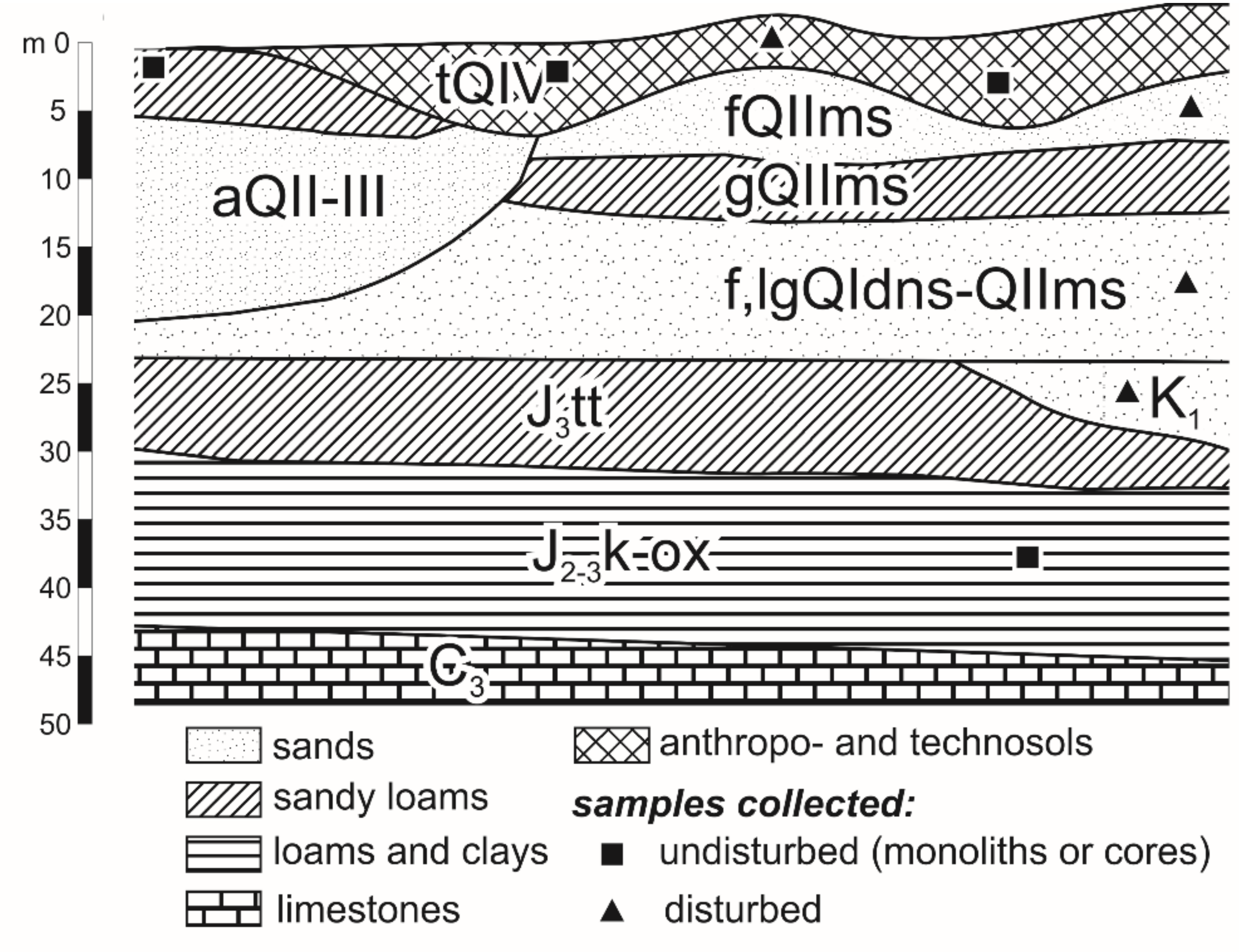
Appendix I

Schematic geological profile of the Moscow area with sampled soils

tQIV – recent manmade deposits; *aQII-III* – upper-mid Pleistocene alluvial deposits of the Moscow river valley; *fQIIms* – mid Pleistocene fluvioglacial deposits of the Moscow deglacial period; *gQIIms* – mid Pleistocene moraine deposits of the Moscow glacial period; *f,lgQIdns-QIIms* – lower-mid Pleistocene glaciolacustrine deposits of the Dnepr-Moscow deglacial period; K_1 – Cretaceous marine deposits (undifferentiated); J_3tt – upper-Jurassic Tithonian marine deposits; $J_{2-3}k\text{-}ox$ – mid-upper Jurassic Callovian-Oxfordian marine deposits; C_3 – upper Carboniferous marine deposits (undifferentiated)



Appendix II

Initial characteristics of soils

Nr.	Denomination	Texture class	Provenience	Location	Depth, m	Grain size distribution, %			Microaggregate size distribution, %		
						sand (2-0.05 mm)	silt (0.05-0.001 mm)	clay (<0.001 mm)	sand (2-0.05 mm)	silt (0.05-0.001 mm)	clay (<0.001 mm)
1	Anthroposol	Loamy sand	anthroposol, occupation layer (tQIV)	Novodevichiy convent, Moscow	0.3-0.4	82	13	5	84	14	2
2	Alluvial loam	Sandy loam	alluvic unconsolidated sediment, subsoil (aQIII)	Moscow River floodplain, Zvenigorod, Moscow region	0.4-0.5	61	33	6	59	39	2
3	Technosol (Kolomenskaya)	Sandy loam	dumped technosol (tQIV)	Kolomenskaya metro station, Moscow	2.0-2.2	61	31	8	78	16	6
4	Technosol (Kashirskaya)	Sandy loam	dumped technosol (tQIV)	Kashirskaya metro station, Moscow	4.0-4.3	72	20	8	75	18	7
5	Moscow sand	Loamy sand	fluvioglacial sand of Moscow deglacial period (fQIIms)	Construction site, Dolgoprudniy, Moscow region	6.0-6.1	74	18	8	-	-	-
6	Dnepr-Moscow sand	Fine sand	fluvioglacial sand of Dnepr-Moscow deglacial period (fQIdns-IIms)	Construction site, Dolgoprudniy, Moscow region	20.0-20.1	97	<2	<1	-	-	-
7	Cretaceous sand	Loamy coarse sand	marine Cretaceous sand (K_1)	Construction site, Dolgoprudniy, Moscow region	25.1-25.2	79	13	8	-	-	-
8	Jurassic clay	Loam	marine Oxfordian Jurassic clay (J3ox)	Okskaya metro station, Moscow	36.0-36.3	45	33	22	56	43	1

Appendix II

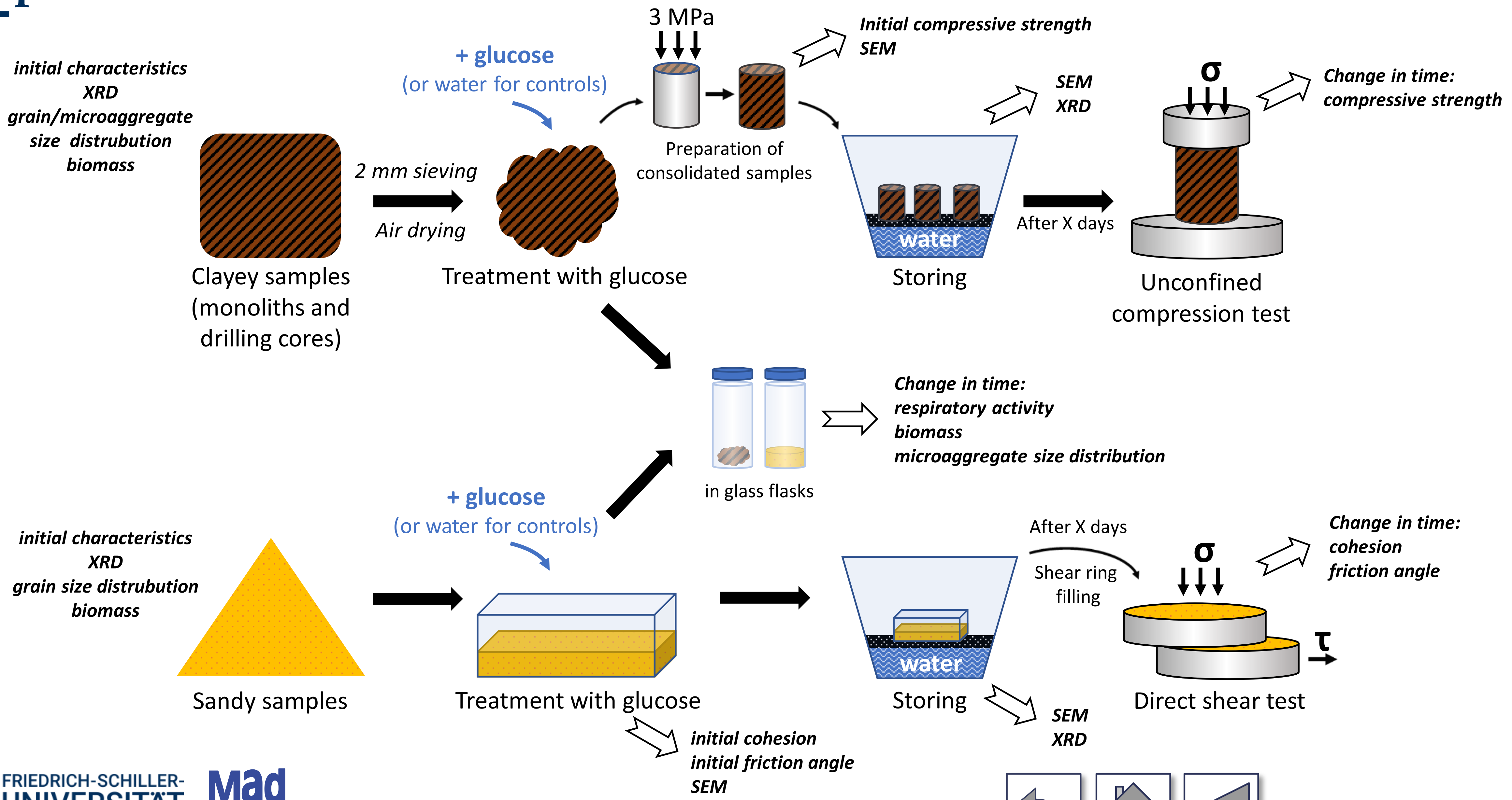
Initial characteristics of soils

Nr.	Denomination	Mineral composition, %									Sample water content, %[1]	pH of the water extract	Total organic matter content, mg g^{-1}
		quartz	feldspar	gypsum	pyrite	carbonate	kaolinite	smectite	Illite (+chlorite)	mixed layer illite-smectite			
1	Anthroposol	> 95		-	-	3	+[2]	+	+	++	10	7.7	6
2	Alluvial loam	61[3]	18	-	-	5	-	+	+	++	8	7.6	6
3	Technosol (Kolomenskaya)	> 95		+	-	2	+	+	+	+	7	7.9	7
4	Technosol (Kashirskaya)	> 95		+	-	2	+	+	+	+	9	8.0	3
5	Moscow sand	> 95		-	-	+	+	+	+	++	4	5.9	<1
6	Dnepr-Moscow sand	> 95		-	-	-	+	+	+	++	11	5.8	<1
7	Cretaceous sand	> 95		-	-	-	+	++	+	+	10	5.5	1
8	Jurassic clay	37	8	4	3	14	-	+	+	++	25	6.4	23

[1]The water content was estimated in the laboratory prior to experiments
[2]Relative content of minerals: "++" -high; "+" - low, "-" - not detected
[3]Quartz, feldspar, pyrite and gypsum content were calculated based on bulk powder XRD, carbonates – calcimeter measurements

Appendix III

Experiment setup



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