A Biophysical Index for Predicting Hydration-Mediated Microbial Diversity in Soil

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Introduction

- Quantitative exploration of the origins of soil biodiversity represents a scientific frontier of astonishing complexity (*Curtis and Sloan, 2004*)
- Present understanding of soil as a complex habitat for microbial life is sketchy and suffers from misconceptions regarding what constitutes favorable or unfavorable environments
- Soil pore spaces and fragmented aqueous habitats constrain nutrient transport and microbial motion, hence shapes microbial community structure and soil biodiversity
- We study mechanisms that support soil microbial diversity considering cell-based dynamic biophysical interactions at highly resolved spatial and temporal scales

Objectives

- To quantify hydration related analytical estimates of aqueous phase fragmentation, nutrient diffusivity and microbial cell velocity on unsaturated rough surfaces
- To develop a biophysical index that integrates hydration-mediated aquatic habitat fragmentation, nutrient diffusivity and cell dispersion for **prediction** of the onset of soil microbial coexistence
- To apply the new index for quantification of hydration conditions that support or limit microbial coexistence in soil

Aquatic microhabitats on partially hydrated rough surfaces and conceptualization

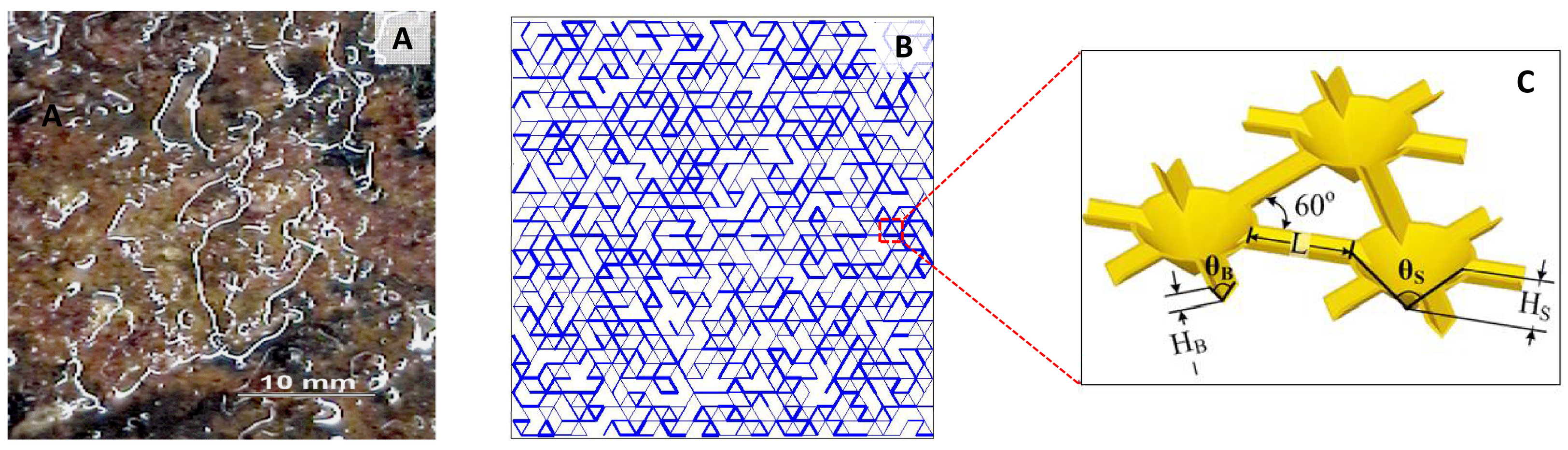


Fig. 1. Microbial aquatic habitats on partially hydrated rough surfaces:
(A) A real partially hydrated soil surface
(B) A conceptualized rough surface network, with abstracted roughness element as triangular channels
(C) A zoom-in illustrate of roughness network, with triangular channels connected by conic sites

Hydration controls water clusters, nutrient diffusion and motility on rough surfaces

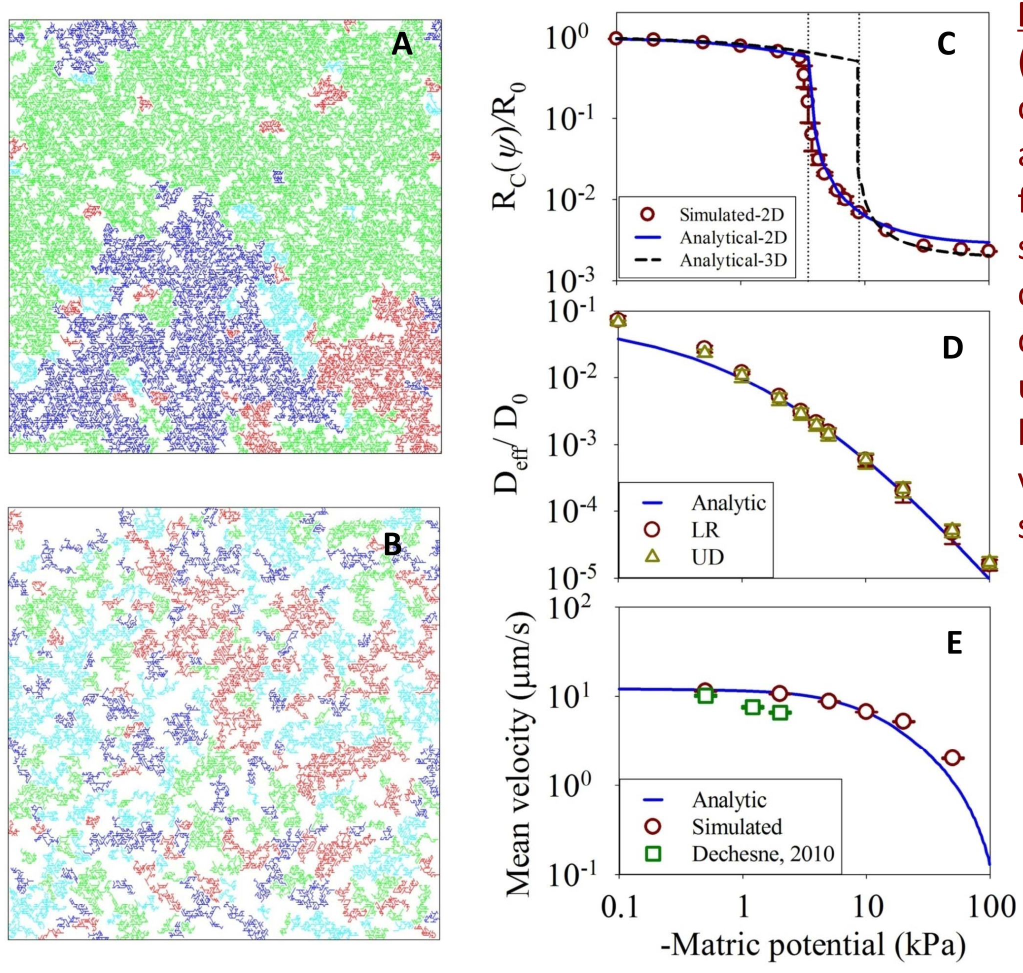


Fig. 2. Aqueous cluster distributions on (A) wet and (B) dry rough surfaces, colors mark different clusters, (C) analytical and simulated radii of water filled pore clusters, (D) analytical and simulated nutrient effective diffusion coefficients, UD and LR mark simulated diffusion coefficients with flux from upon to bottom and from left to right boundaries, (E) analytical mean cell velocity and comparisons with simulations and measurements

Analytical cluster radius:

$$R_C(\psi) = R_0[N_C(\psi)/N_0]^{1/\chi}$$

Analytical diffusion coefficient:

$$D_{eff}(\psi) = D_0 \frac{\langle\theta(\psi)\rangle^2}{\phi^{2/3}}$$

Analytical cell velocity:

$$V_{\alpha,H}(\psi) = V_0 \frac{F_M - F_C(\langle d(\psi)\rangle) - F_\lambda(\langle d(\psi)\rangle)}{F_M}$$

Results and discussion

Hydration controlled Coexistence Index

- We combine the extent of aqueous phase fragmentation (for 2-D in the following application – see Fig. 2A-C) represented by cluster radius $R_C(\psi)$, with the distance traversed by a microbial cell from the center of the cluster towards the boundaries during one generation R_G - a function of diffusion coefficient (Fig. 2D), mean cell velocity (Fig. 2E), and mean growth rate (these quantities are functions of hydration status as well)
- The ratio $\mathbf{R_G(\psi)/R_C(\psi)}$ reflects the likelihood of a microbial species to arrive to cluster boundary within one generation thereby guaranteeing it survival by residing on the cluster boundary and intercepting nutrient fluxes diffusing through thin liquid films (too thin to support cell motion)
- We argue that the ratio $\mathbf{R_G(\psi)/R_C(\psi)}$ defines a coexistence index (CI) in which values of CI>1 for the weakest species guarantee its survival and thus give rise to coexistence (at a specific hydration status, ψ) as depicted schematically in Fig. 3A.

Predictions of CI for multiple microbial species - *comparisons with simulations*

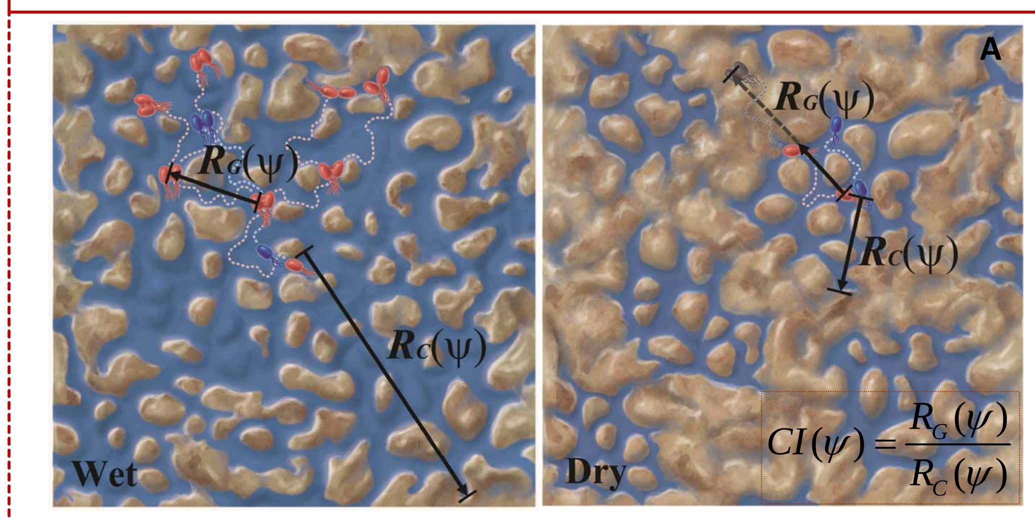
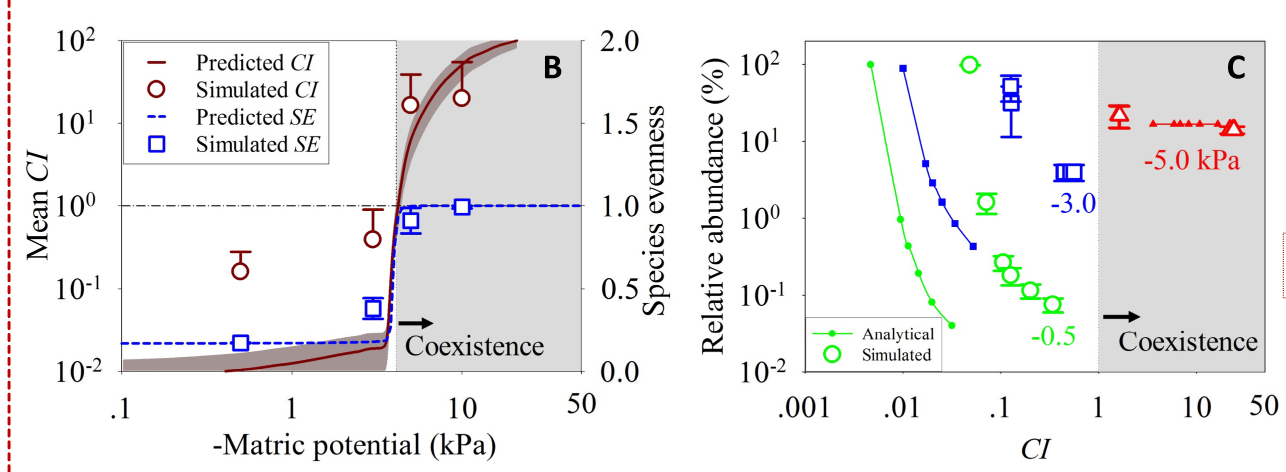


Fig. 3. (A) A schematic of hydration conditions and associated aqueous cluster sizes and generation length in the basis of the coexistence index, (B) analytical microbial CI predictions and corresponding Simpson species evenness, and comparisons with simulated CI values and Simpson evenness, (C) analytical predictions and simulation results of relative abundance as a function of CI



Generation length:

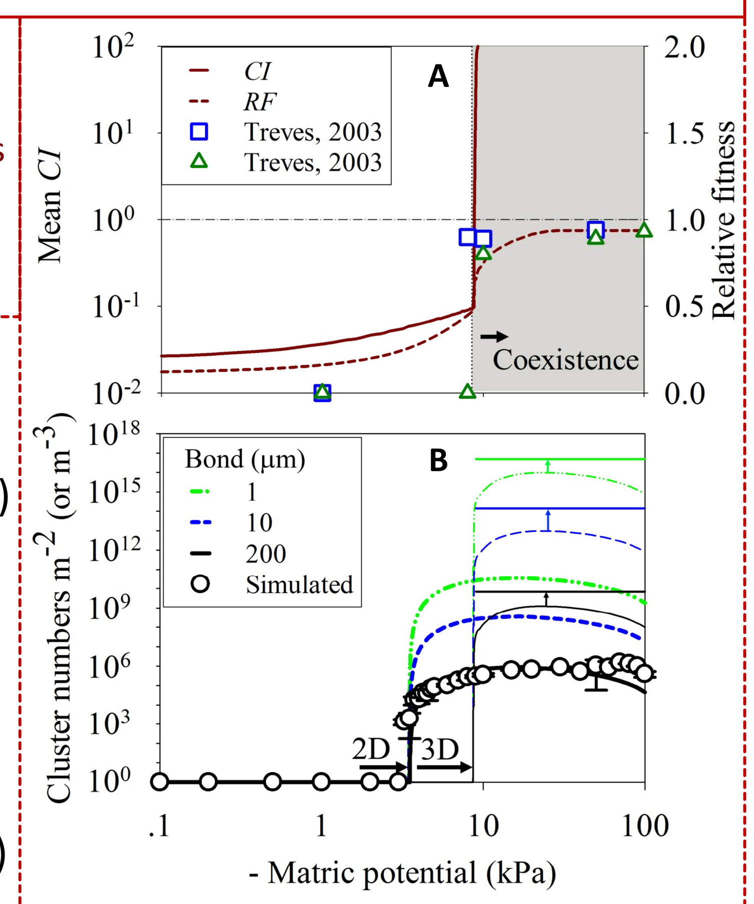
$$R_G = f\left\{V(\psi), D_{eff}(\psi), \mu_0\right\}$$

Applications of the Coexistence Index (CI) - *simulations and experiments*

- Analytical CI value increases gradually with decreasing matric potential value, with a critical transition occurs at CI=1 marking conditions for onset of coexistence of many species consistent with ***species evenness (SE)*** predictions and with simulations (Fig. 3B)
- Predictions in relative population abundance in agreement with numerical simulations of many competing species cohabiting rough surfaces, with the trend towards evenness that marks coexistence mode under dry conditions consistent with CI predictions (Fig. 3C)

CI predictions and cluster numbers - *comparisons of RF with experimental data*

Fig. 4. (A) Analytical CI predictions and relative fitness for 3D porous media, and comparisons in RF with experimental data, (B) predicted aqueous cluster numbers for 2D surface and 3D media, and comparisons with simulations (symbols) and with measurements (color bars with arrows mark total soil grains per m^3)



- Predicted CI values for 3D media cross at CI=1 consistent with predicted ***relative fitness (RF)*** and in good agreement with experiment (Fig. 4A)
- Predicted aqueous cluster numbers of 2D rough surfaces and 3D porous spaces consistent with numerical simulations (2D), and in close agreement with measurements of total grain numbers serving as upper bounds for maximum aqueous cluster number per soil volume (Fig. 4B)

Summary

- We proposed a new hydration-based biophysical index that integrates key physical processes towards predicting the onset and extent of coexistence of competing microbial populations cohabiting unsaturated soil surfaces
- The coexistence index (CI) predicts a surprisingly narrow hydration range (only a few kPa) for emergence of species coexistence consistent with simulations and limited experiments
- The approach provide a first step towards linking microscale processes with key ecological interactions essential for life in soil
- The results enable systematic hypotheses testing for factors regulating microbial populations, and thus provide insights on the role of microbial diversity within the context of biogeochemical cycling, soil bioremediation activities, and advance basic understanding of microbial ecology associated with food industry

References

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