Multi-Species Microbial Biofilms: Cooperation, Competition, and Spatial Dynamics

Uttam

Key Theoretical Models of Microbial Symbiosis, Cooperation, and Cheating

- **Allen et al. (2013) – *Spatial dilemmas of diffusible public goods*, [1].** Allen et al. build a graph-based model of public-good diffusion in microbial colonies. They derive analytic conditions for cooperation vs. cheating in terms of benefits, costs, and diffusion geometry. Importantly, they show that limited diffusion and low-dimensional colony structure favor cooperation. In general, cooperation is predicted only when diffusion of the shared metabolites is slow, colony geometry is low-dimensional, and decay rates are small.

- **Momeni et al. (2013) – *Spatial self-organization favors heterotypic cooperation over cheating*, [2].** Using a spatial individual-based model and engineered yeast strains exchanging two essential metabolites, Momeni et al. study heterotypic mutualism in the presence of a cheating strain. Even without partner recognition, spatial growth causes cooperators to cluster with their partners. This self-organization stabilizes mutualism by assorting cooperators and suppressing cheating.

- **Oliveira et al. (2014) – *Evolutionary limits to cooperation in microbial communities*, [3].** This eco-evolutionary model simulates microbial genotypes exchanging costly metabolites under cyclic growth and mixing. The authors show that stable cooperative exchange arises only at intermediate genetic mixing levels. Cooperation often manifests as mutual exploitation and reduces overall community productivity. Spatial structure may even inhibit cooperation by impeding partner encounters.

- **Stump et al. (2018) – *Local interactions and self-organized spatial patterns stabilize microbial cross-feeding against cheaters*, [4].** Stump et al. simulate two mutualist strains and a cheater in a stochastic lattice model. They identify two spatial mechanisms that stabilize cooperation: self-organization into spatial patterns and density-driven segregation. Both mechanisms prevent cheaters from accessing all necessary public goods simultaneously.

- **van Tatenhove-Pel et al. (2021) – *Population dynamics of microbial cross-feeding are determined by co-localization probabilities and cooperation-independent cheater growth*, [5].** Combining microfluidic experiments and stochastic modeling, this study demonstrates that cooperation is favored only when cooperator co-localization is high and cheaters cannot grow autonomously. Spatial compartmentalization supports cooperation within a narrow parameter window.

- **Los et al. (2025) – *Time of first contact determines cooperator success in a three-member microbial consortium*, [6].** Using 3D simulations and engineered microbial consortia, the authors show that early cooperator encounters are essential for mutualism. Delays in cooperator contact allow cheaters to dominate. This highlights the importance of initial spatial configuration in community dynamics.

- **Vet et al. (2020) – *Mutualistic cross-feeding in microbial systems generates bistability via an Allee effect*, [7].** Vet et al. derive a nutrient-explicit ODE model showing that mutualistic cross-feeding produces an Allee effect. Below a critical density, both species go extinct; above it, mutualism is stable. This work links dilution rate and nutrient flux to mutualistic stability.

- **Peaudecerf et al. (2020) – *Mutualism between microbial populations in structured environments: the role of geometry in diffusive exchanges*, [8].** This model of two spatially separated auxotrophs linked by a diffusion channel explores how geometry affects mutualism. Surprisingly, longer diffusion paths can sometimes enhance stability. The results emphasize how spatial architecture and diffusion constraints shape interaction outcomes.

References

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