Internship proposal (M2, Spring 2026)

Ecosystems in dynamic environments

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Possibility to continue as a PhD project: Yes, funding by the *Engineering for Health* Center, IP Paris.

Motivation

Classical models in theoretical ecology may neglect spatial structure and species displacement. Both components are essential to understand the propagation of bacterial communities in natural environments (e.g. the animal gut [1] or the soils). Generally, the combination of spatial heterogeneity and inter-species interactions generates non-trivial dynamics, see Fig. 1. This project aims to develop a theoretical framework to study the spatio-temporal dynamics of multi-species ecosystems by explicitly including diffusion, advection, and the topology of interaction networks in generalized Lotka–Volterra equations.

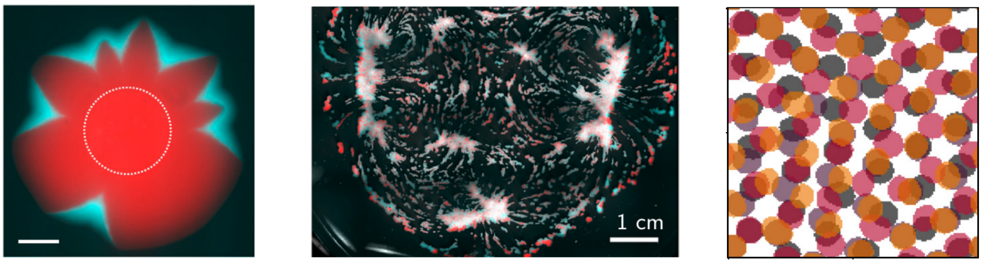

Figure 1: (Left) Two strains of bacteria put in coculture. Despite slower expansion of the mutant strain (blue) when set in culture alone, the mutant wins in coculture with wild type bacteria (red). Bar scale: 1 mm. More details in Ref. [2]. (Center) Fragmentation of two strains of a yeast colony and emerging flow generated by a baroclinic instability, see Ref. [3]. (Right) Solution of PDEs coupling the density fields of 50 species. Here we display 4 species taken at random (one color per species). A species occupies the nodes of a triangular lattice. These lattices are tilted for each species. More details in Ref. [4].

Scientific project

We want to understand the effect of transport in these complex ecosystems. How is space modifying the resilience of ecosystems? If species can diffuse in the system, will there be ecological niches appearing at different places? How does space introduce correlations between species interactions (preys, predators, cooperation, competition)? For ecosystem advected by a fluid (e.g. phytoplanktons), what is the impact of the flow on the biodiversity? The candidate is expected to be eager to interact with ecologists and biophysicists.

A possible model: Consider $N \gg 1$ species. Each species i, described by a local density field $\rho_i(x,t)$, can diffuse, undergoes logistic growth, and interacts with other species. The interaction coefficients A_{ij} can be fixed (quench disorder) [4, 5]. There is transport by a flow field $v(x,t)$ possibly governed by classic hydrodynamic equations [3, 6]. One has

$$\partial_t \rho_i(x,t) + \nabla\cdot(\rho_i v) = D_i \nabla^2 \rho_i + \rho_i\Big(1 - \rho_i + \sum_{j=1}^{N} A_{ij} C_{ij} \rho_j\Big).$$

Coefficients $C_{ij} \in \{0,1\}$ encode the fact that species do not necessarily interact with one another. The study will combine theory of complex systems, dynamical system analysis, and numerical simulations to identify phase transitions between stable, oscillatory, or chaotic regimes, and to characterize their spatial signatures (fragmentation, patches, invasion fronts). The results will contribute to a deeper understanding of the collective mechanisms driving biodiversity and the robustness of complex ecosystems.

References

1. Pasqualini, J. *et al.* Publisher: eLife Sciences Publications, Ltd (2025).
2. Lee, H., Gore, J. & Korolev, K. S. *PNAS* **119,** e2108653119 (2022).
3. Atis, S., Weinstein, B. T., Murray, A. W. & Nelson, D. R. *Phys. Rev. X* **9,** 021058 (2 2019).
4. Salvatore, A., Aguirre-López, F. & Zakine, R. *Phys. Rev. E* **112,** 024306 (2 2025).
5. Galla, T. *Europhysics Letters* **123,** 48004 (2018).
6. Bauermann, J., Benzi, R., Nelson, D. R., Shankar, S. & Toschi, F. *PNAS* **122,** e2417075122 (2025).