Microbial Communities with Spatial Structure

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Short Abstract — Highly diverse microbial communities exist in the environment and within multicellular organisms, but resource-competition models predict that the number of species cannot exceed the number of resources. Recent work shows that models with metabolic trade-offs can support coexistence in a well-mixed environment. We present a model with metabolic trade-offs that embeds populations and nutrients in physical space, and find that spatial structure strongly influences the composition and function of microbial communities.

I. BACKGROUND

Microbial communities are ubiquitous and play critical roles in macroscopic ecosystems [1,2] and as the microbiota of multicellular organisms [3], but a mechanistic understanding of their population dynamics and system-level properties remains elusive. Particularly at issue is the emergence and robustness of biodiversity. Traditional resource-competition models give rise to the competitive exclusion principle, which states that the number of coexisting species cannot exceed the number of limiting resources [4]. Nature contradicts this principle at every turn, however, with some marine ecosystems hosting more than 100 species of phytoplankton [5] competing for only a few nutrients [6]. It has recently been shown that a model with metabolic trade-offs can resolve the discrepancy and support unlimited coexistence in the well-mixed case [7]. How might spatial structure affect these results? Real ecosystems are not homogeneous in general, and the dimensionality of a physical system can have drastic effects on its behavior (in phase transitions, for example), so we introduce a model to describe microbes interacting with the environment and each other in a Euclidean space with the corresponding metric. We observe the phenomenon of coexistence, but find that the optimal metabolic strategy depends on spatial structures absent from the well-mixed model.

II. RESULTS

We can study the local distributions of microbes and nutrients by specifying the population density and nutrient concentrations at each point in space, instead of treating them as global variables. As a result, the characteristics of the species and the nutrient supply no longer suffice to determine the behavior of the system: the fixed points of population size depend strongly on the spatial arrangement of the microbes as well. We can therefore explore correlations between metabolic strategy, physical distance, and relative success. We can also tune the diffusion coefficient as a parameter, allowing us to study how ecosystem behavior varies in different physical regimes. Because the interactions are mediated by a spatially-varying nutrient concentration field, the model tells us how the microbes are shaping their environment. This is vital for characterizing the system-level function of the community and placing it in the context of the microbiome or macroscopic ecosystems.

Fig 1: Fixed-point nutrient concentrations for 1-d case, with 2 resources and 4 species. The black bars indicate what fraction of the line each species occupies.

III. CONCLUSIONS

By introducing metabolic trade-offs and spatial structure into a simple resource-competition model, we can study how the physical properties of microbial communities affect biodiversity, population dynamics, and ecosystem function. Our model describes mechanistic interactions in a physical space, and thus provides a framework with which to search for general theoretical principles governing the behavior of complex ecological systems throughout nature.

REFERENCES


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