

# SMEEB 2024 Abstracts

**Sara Mitri** - University of Lausanne

## **Predicting and controlling the ecological dynamics of small bacterial communities**

Microbial communities can be incredibly useful, if only we could control them and predict their dynamics. But since studying eco-evolutionary dynamics in natural systems is extremely challenging, in my lab we use small bacterial communities as model systems. I will present experiments and theory using such small communities, which suggest that bacterial species often engage in a mixture of positive and negative interactions whose balance depends on environmental conditions. This understanding has led us to develop a mathematical framework, which can predict how different species will organise in time, in space and whether they will coexist in the long term. Being able to predict and control community dynamics via the environment may give us the tools to manipulate microbial communities to our advantage, with many potential applications.

**Tobias Galla** - IFISC Mallorca

## **Non-Gaussian random matrices predict the stability of feasible Lotka-Volterra communities**

50 years ago Robert May used the eigenvalue spectra of random matrices to conclude that larger and more complex communities ought to be unstable. Given that large and complex ecosystems are observed, May asked what the "devious strategies" might be that nature uses to ensure stability. A decade-long debate has ensued, and is ongoing.

One major criticism of May's approach is that it does not address the question how the ecological community arises from a dynamics, and whether the equilibrium is 'feasible' or not. Here, I present recent work focusing on the community of surviving species in a dynamic Lotka-Volterra model. These communities emerge naturally and are feasible by construction. The interactions among the extant species turn out to be non-Gaussian, even if interactions in the original pool of species was Gaussian. It is this higher-order statistics of the survivors that encodes feasibility, thus hinting at one possible "devious strategy" of nature.

We demonstrate that random-matrix universality does not apply, that is a Gaussian calculation does not predict the leading eigenvalue for the community correctly. I will then show how the leading eigenvalue of the community matrix can be calculated using tools from the theory of disordered systems and spin glass physics. The stability criteria from these eigenvalue spectra agree with those obtained from the Lotka-Volterra equations. Hence, we have demonstrated how May's random-matrix approach can be used to characterise the stability of feasible equilibria. Our work highlights that accounting for non-Gaussian interactions is crucial in this enterprise, and that random matrix universality should not be invoked without careful consideration.

**Giulio Biroli** - ENS Paris

## **Dynamical regimes of high-diversity spatially extended heterogeneous ecosystems**

Using statistical physics methods we study the role of dynamical fluctuations in shaping the behavior of high-diversity ecosystems communities. We start with an introduction to the statistical physics approach developed to study the dynamics of species-rich ecosystems. We then discuss: (i) chaotic and aging dynamics (ii) endogenous fluctuations persisting for extremely long times, (iii) phase transitions due to demographic noise and dispersal between complete extinction and a self-sustained state with high-diversity. We also highlight connections and differences between the out of equilibrium dynamics of models of species-rich ecosystems and of glassy systems, and discuss the role played by non-reciprocal interactions.

**Silvia De Monte - CNRS Paris**

## **Chaotic turnover of strongly interacting species: a deterministic model and its stochastic approximation**

Microbial communities harbour hundreds or thousands of species, whose ecological dynamics is classically modelled by generalized Lotka-Volterra equations. In the absence of information about the structure of the community, interactions are typically chosen randomly according to a distribution of set the mean and variance. The dynamical phases of such equations when 'weak' interactions scale with the number of species revealed that many species can coexist out of equilibrium.

We have addressed the 'strong' interactions regime - where competition makes only a handful of species dominate the community - and with immigration - that prevents extinctions. Such low-dimensional dominant community coexists with a majority of 'rare' species, whose abundance decreases as a power law of exponent larger than 1 - as observed in plankton communities. Over time, the dominant community is regularly superseded by a subset of rare species, in a continuous chaotic turnover akin to observed fluctuations of plankton strains. Every species undergoes a boom-bust, intermittent dynamics that brings it - with variable frequency - to partake of the dominant sub-community.

We propose an approximate 'focal species' model with multiplicative, correlated noise that captures the common features of every species' dynamic: the prevalence of decay that is countered by positive fluctuations of the growth rate. We show that this model, parametrized on the time series of one species, predicts the dependence of the power-law exponent on the interaction statistics, and connects the microscopic and macroscopic description of the population. Moreover, we discuss how, in any community with a large but finite richness, species differ from one another in their dynamics.

**Valentina Ros - LPTMS Paris-Saclay**

## **The multiple equilibria of many-species ecosystems: how many, how stable, how relevant?**

In an attempt to understand the complex dynamics of ecosystems, recently there has been quite a lot of interest in the study of high-dimensional dynamical systems describing many species interacting randomly, possibly in a non-reciprocal (asymmetric) way. These systems of equations generally exhibit a transition in the strength of the variability of the interactions: when the variability is weak, the dynamics quickly settle into a stationary state, converging to a unique equilibrium configuration; when the variability is high, the dynamics keep fluctuating, exhibiting signatures of progressive slowing down or chaos. This dynamical transition is expected to be concomitant with the emergence of glassiness, i.e. with a sudden explosion in the number of possible equilibrium configurations of the dynamical equations. In this talk, I will focus on a prototypical dynamical system with all-to-all random interactions, the so-called random Generalized Lotka-Volterra equations. I will discuss how to explicitly compute the number of equilibrium configurations and characterize their properties. I will focus in particular on the case of non-reciprocal interactions between the species, which render the system non-conservative, thereby ruling out some standard approaches developed in the field of glasses to treat conservative systems with randomness.

## **Sepp Kuehn- The University of Chicago**

### **Simplicity from complexity in microbial communities**

Microbial communities exhibit intricate abundance dynamics driven by diverse ecological interactions and environmental fluctuations. Amidst this complexity, simple and reliable functional properties emerge, such as pathogen inhibition and metabolic activities that drive global biogeochemical cycles. How do these functional aspects arise from constituent interactions? How does the community structure—comprising genotypes, phenotypes, and their interactions—determine emergent functions? How does nature construct such robustly functional communities?

In this talk, I will present our recent work on understanding these processes within microbial communities. We employ two key approaches inspired by successful strategies in physics: statistical analysis across ensembles of communities or species, and quantitative phenomenological models based on measurements. I will highlight our successes using these approaches to predict how the genomic and taxonomic structures of synthetic laboratory communities can predict emergent functional properties.

Additionally, I will present new data demonstrating that these methods can elucidate the functional properties of highly complex natural communities in the soil microbiome. Utilizing a vast dataset comprising sequencing and metabolic measurements from over 1000 microcosms, we reveal that a simple phenomenological model can link the abundances of hundreds of species to the emergent flux of metabolites in an ecosystem. This model hinges on two key variables: the quantity of active biomass and the availability of limiting nutrients, which together can globally explain abundance and metabolite dynamics.

Moreover, our formalism captures how the system responds to environmental perturbations, showing that the ecosystem transitions between three functional regimes based on the levels of these two variables. These regimes are characterized by the rates of metabolite flows through the system. These findings demonstrate that understanding the emergent properties of natural communities does not necessitate a detailed dissection of each interaction or process. Instead, it can be achieved through classic physics-based approaches.

## **Otto Cordero - MIT**

### **Substrate complexity leads to the emergence of positive interactions between bacteria**

Microbiomes are often conceptualized as static systems where taxa influence each other's growth in positive, neutral, or negative ways. This perspective is based on the implicit assumption that interactions are purely species-specific properties, disregarding the role of the environmental context in determining metabolic processes and behaviors. Such an approach has led to attempts at characterizing the distribution of interactions using classical minimal media conditions, where simple carbon sources (e.g., glucose) are the only limiting factor. Naturally, these experiments reveal that most interactions are negative (i.e., competition).

Here, I will present unpublished results showing the widespread emergence of mutualistic interactions between bacteria that degrade fucoidan, one of the most complex and recalcitrant organic molecules in the ocean. I will propose that such mutualisms are intrinsically linked to the complexity of the substrate, which requires division of labor and genetic repertoires of hundreds of dedicated hydrolases for its consumption. Finally, I will demonstrate how widespread mutualisms allow us to easily predict the biodegradation potential of communities on different types of algal organic matter, an important challenge for the future of algal biomass valorization.

## **Anne Florence Bitbol - EPFL**

### **Impact of population spatial structure on mutant fixation, from models on graphs to the gut**

Microbial populations often have complex spatial structures, with homogeneous competition holding only at a local scale. Population structure can strongly impact evolution, in particular by affecting the fixation probability of mutants.

I will first discuss a general model for describing structured populations on graphs. I will show that by tuning migration asymmetry in the rare migration regime, the star graph transitions from amplifying to suppressing natural selection.

Next, I will discuss the impact of increasing migration rates. In particular, I will show that suppression of selection is pervasive in the regime of frequent migrations.

Then I will show that the specific structure of the gut, with hydrodynamics and gradients of food and bacterial concentrations, can increase the fixation probability of neutral mutants. Our results can be rationalized by introducing an active population, which consists of those bacteria that are actively consuming food and dividing. Thus, the specific environment of the gut enhances neutral bacterial diversity.