Imperial College London

Natural Environment Research Council

2024_46_DoLS_RE: Physical principles underlying the assembly and adaptation of complex microbial communities

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Accelerating the restoration of ecosystem functioning using engineering approaches is the new frontier for climate-change mitigation (Willemen *et al.* 2020 Nat Sustainability 3:164-166). Engineering successful restoration requires an understanding of the dynamics of below-ground microbiomes (bacterial and fungal communities) because these control above-ground plant community structure and functioning. However, despite significant progress in empirical microbial research, fundamental thermodynamic principles determining the evolution and adaptation of complex microbial communities are still very little understood. Thermodynamic principles are key to predicting the dynamics of microbiomes because they govern the interactions among the scores of microbial species present in natural ecosystems. The goal of this project is to develop a predictive understanding of microbial community dynamics in order to design microbiomes with desired properties that can enhance soil restoration. The specific aims will be:

Aim 1: Develop fundamental mathematical theory and computational simulations of microbial communities as biochemical reaction networks, focusing on their entropy production (heat dissipation) as a measure of energy turnover and vitality (the optimisation target) under external perturbations.

Aim 2: Synthesise empirical data on microbiome structure and models to develop a predictive framework for understanding the dominant controls on soil microbial community coalescence.

In Aim 2, the student will utilise the modelling framework from Aim 1 and empirical data to refine the modelling, gradually increasing the complexity to more realistic spatially-structured systems representative of real soils. This data-model dialogue will be key to improving microbiome transplantation success by guiding field interventions with mechanistic theory. In addition, there may be scope to study how temperature fluctuations enhance or inhibit microbiome functioning (e.g., invasion ability or resistance of target microbiomes).

The results of this study will help pave the way for more ambitious projects aiming to build new engineering techniques for climate change mitigation across ecosystems. In particular, a key novelty will be studying the evolution toward minimal and maximal entropy production networks using genetic algorithms and graph theory to capture mature near and young far-from-equilibrium microbial communities, and understanding what distinguishes these. Besides their heat dissipation, resulting networks will be characterised by metrics including connectivity, mean shortest path length, degree distribution, under/overrepresented network motifs, multistability, and cycle fluxes.

This highly interdisciplinary project will bring together expertise in biological physics (Endres lab), community-level metabolic theory (Pawar lab), Lab to Field experimental data (Waring lab), and real-world restoration expertise (Jepson and CreditNature). We anticipate that beyond microbiome engineering for restoration, the identified thermodynamic principles will be widely applicable to areas ranging from origin of life to complexity science.