Phase Transitions and Critical Phenomena in Mutualistic Communities under Invasion

Samuel R. Bray[1], Yuhang Fan[1], and Bo Wang[1,2]

***Short Abstract* — Natural ecological communities often experience tipping points – where little changes can make a big, abrupt difference in community composition in response to species invasion and changing environments. The nature of these tipping points is still poorly understood. By analytically solving for species-resource interactions in a mutualistic community, we demonstrate these tipping points represent phase transitions similar to those described in many physical systems. The order of these transitions offers insight to the underlying community network and suggests strategies to construct barriers in combating generalized invasions such as antibiotic resistant pathogens and cancer cells.**

***Keywords* — Synthetic ecosystem, microbial communities, population modeling**

INTRODUCING novel species to an ecosystem is a fundamental problem that has many practical applications, including probiotic therapy, collective antibiotic resistance, biodiversity preservation, and ecological engineering. Introduction of "invader" species can lead to a variety of outcomes, ranging from native community stabilization to complete community collapse and replacement by invader [1]. While empirical studies exist [2], it remains a challenge to predict invasion outcome based on species' interaction network topography and invader strategy. Previous theoretical work on community structure have mostly focused on either analyzing the stability of an ecosystem under small perturbations around a certain equilibrium (so-called dynamical stability) [2], or defining the range of parameters in which the system remains stable and always returns to a fixed point (so-called structural stability) [3]. However, these studies have not yet addressed how and when an ecosystem may switch from one stable point to another under strong perturbations. The challenge of species invasion is one obvious perturbation of such kind.

Transitions between stable states are often characterized by phase transitions, a universal phenomenon in the physical world. Phase transitions include first-order transitions, during which the system can change only abruptly from one state to another, and second-order transitions, when systems can change continuously but discontinuity, or divergence, exists in the susceptibility of the system to external perturbations. The nature of the phase transition reflects the organization and interactions within the system. The conceptual difficulty here is that physical phase transitions typically emerge in systems with long-range correlations, which are difficult to capture and often analytically intractable with classical ecological models that primarily rely on pairwise species interactions [4]. Here we explore the impact of boundary conditions, specifically the availability of resources, on ecosystems under invasion. Our mechanistic approach builds on a simple mutualistic community that contains cross-feeding species with limiting resources explicitly modeled. This model builds on the classic consumer-resource model, in which resources are required for species growth, and no other nonlinear or long-range interactions are considered [2]. The stability and dynamics of such systems have been extensively characterized both theoretically and experimentally [2,4], providing a well-defined start point to solve for their behaviors under invasion.

The analytical tractability of this model enables us to show that community composition undergoes phase transitions in response to species invasion. The exact outcome can be predicted based on community topography and constraints of environmental resources. The high susceptibility of the system around phase boundaries also predicts nonlinear amplifications of variations during community assembly and species invasion, a phenomenon that has been widely reported in empirical studies [2,5]. The discontinuous nature of the transitions offers a new explanation for the unpredictability in adaptation, where small beneficial changes can build up to catastrophic outcomes. The observed phase transitions have implications in a broad practical problem set, including spatial patterning arising from ecological interactions, rejection of antibiotic resistant bacterial strains using commensal communities, and early preventive strategies to stop invasion of healthy tissue by cancer cells [6].

[1]Department of Bioengineering, Stanford University. E-mail: wangbo@stanford.edu

[2]Department of Developmental Biology, Stanford School of Medicine.

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