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A Statistical Analysis of Ecosystem Stability from Local and Global Interaction Structure

The relationship between community stability and community interaction structure is of historical and ongoing interest in ecology. In the 1970s, Robert May and others investigated this relationship by analyzing statistically how the average connectance of random community matrices affects the largest eigenvalue of the Jacobian at the interior fixed point, which determines the stability of the community. In doing so, they were able to establish a statistical relationship between stability and a particular global measure of the community's interaction structure (average connectance). At the crux of their analysis was the assumption that the matrices in their ensemble have elements drawn from independent distributions. However, many random matrix ensembles of ecological interest will have elements that are highly correlated with one another, which violates the independence assumption. In this scenario the average connectance no longer characterizes the stability properties of the system. Nevertheless, there is evidence that higher order measures of interaction structure like nestedness or modularity do correlate with the stability of the system. The mechanisms by which the correlation arises and the conditions under which this pattern occurs have yet to be elucidated. Our goal is to extend the classical work of May to determine the relationship between stability and higher order measures of interaction structure that take into account correlations between interactions. Identifying these mechanisms and determining under what conditions they exist should prove useful in reasoning about the significance of patterns of nestedness or modularity observed in natural communities.

In this work, we make an explicit connection between the stability of Lotka-Volterra systems and network metrics of interest through a structured mean field theory. Our mean field approach allows us to reason about the effects of both the global interaction structure (as seen through the fictitious mean species) and the local interaction structure (as seen by a particular species under the mean field approximation). By distinguishing between local and global contributions to network metrics and their effect on stability we can understand, for example, how removal of species with small or large contributions to nestedness affects the asymptotic composition of communities (e.g. through extinction events or gross changes in abundance). In addition to making an explicit connection between stability and networks metrics, we can also examine the indirect connection between these metrics and other aggregate measures of the ecosystem such as total population abundance, productivity and the like.

Finally, we pay special attention to a class of competitive Lotka-Volterra systems with parameterized community matrices, where the parameter controls the strength of interspecific competition. In the limit of weak interspecific competition, there is a single interior fixed point that is also a global attractor. In the limit of strong interspecific competition the eigenvalues of the community matrix itself will tend to determine the stability of the system, as noted in the classical work of May on random competition. In the intermediate regime the stability of interior and boundary fixed points is non-trivial. Nevertheless we can apply our mean field approach in this regime, and so offer insight into the statistical behavior of competitive Lotka-Volterra systems as a function of the relative level of interspecific competition.