Structural dynamics of plant-pollinator mutualistic networks

In-block nested networks, Nestedness, Modularity, Plant–pollinator networks, Dynamical properties

Mutualistic interactions are essential for ecosystem functioning [1]. These interactions are known to respond to biotic and abiotic conditions and vary across geographic regions and annual cycles [2]. At the system's meso- and macro-scales, the emergence of these structured interactions has been attributed to various dynamical processes, including different levels of complexity and detail: niche patterns, eco-evolutionary mechanisms, etc. While these models have greatly enriched our understanding of ecological communities, some of the dynamical properties responsible for the emerging resilience and adaptability of such structured interactions remain unknown. Plant–pollinator and seed-dispersal networks often display two key structural patterns. Nestedness, where specialists interact with subsets of generalists, is widespread and linked to beneficial properties such as higher diversity, greater species abundance, and feasibility. In contrast, modularity, characterized by tightly connected groups with sparse links between them, has been associated with improved system stability. Yet, while nestedness favors feasibility, it often reduces stability, highlighting a potential structural trade-off between these two arrangements. In fact, nestedness and modularity may even be structurally incompatible, challenging earlier assumptions. Most studies have examined structure–dynamics links in a one-to-one fashion, but this approach overlooks the possibility that ecological communities evolve by simultaneously optimizing multiple, often correlated, properties. A recent line of research, currently attracting growing interest, focuses on hybrid structural patterns that combine multiple arrangements across different scales.

In this talk, based on our recently published paper [3], we will attempt to link the temporal analysis of plant–pollinator networks with insights obtained from time-aggregated real community samples. Starting from a temporal analysis of real plant–pollinator communities (top panels of Fig. 1), we examine how structural organization changes throughout the pollination season and how this variability relates to key dynamical properties. Specifically, we assess the extent to which these structural shifts reflect underlying ecosystem parameters during community assembly and disassembly. Focusing on in-block nested structures—hybrid arrangements that integrate nested communities, as illustrated in the top-left panel of Fig. 1—we empirically identify a prevalent transition from modular to compound (hybrid) patterns at the peak of the season. By analyzing how community size and connectance evolve across the pollination season (left-bottom panel of Fig. 1), we conclude that networks close to their average size and connectance often display compound nested modules, whereas deviations from these conditions tend to favor pure modular structures, highlighting trends of structural robustness. Motivated by these findings, we perform a theoretical analysis within the Lotka–Volterra framework, focusing on two key properties: local asymptotic stability (hereafter stability) and feasibility. Using a generative model, we reveal a trade-off between nested and modular arrangements: no single structural pattern maximizes both dynamic properties (see bottom-central panel of Fig. 1). Instead, in-block nested structures mediate between stability and feasibility, offering a plausible explanation for their prevalence in real plant–pollinator networks. Our analysis also identifies distinct regimes where nested, modular, and hybrid structures confer specific advantages. Notably, in-block nested architectures provide an effective balance between stability and feasibility, particularly in low- to mid-sized communities (see bottom-right panel of Fig. 1).

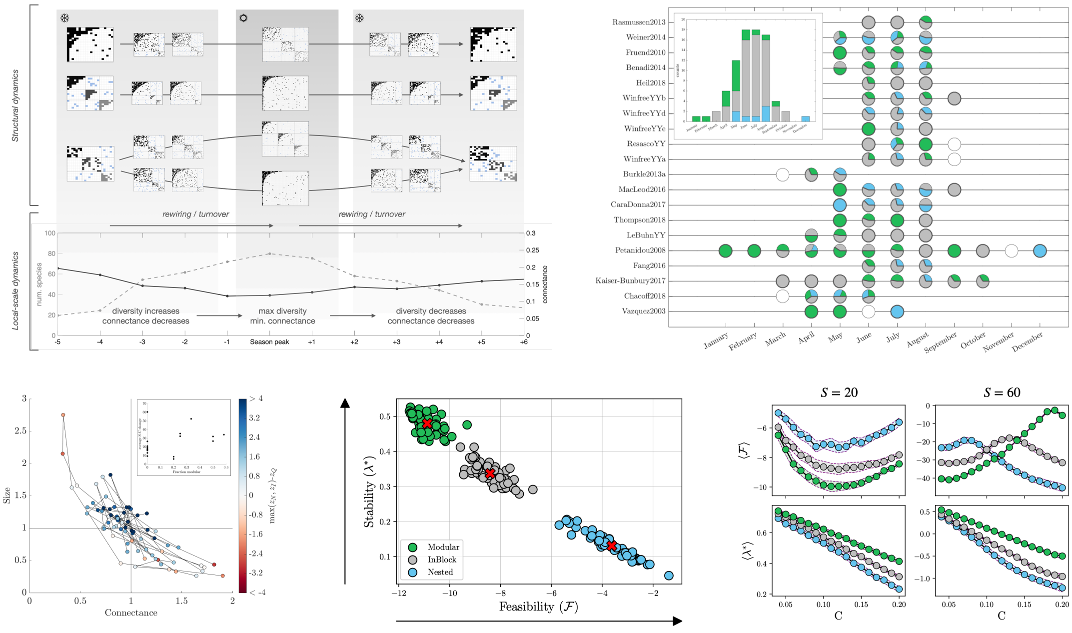

Figure 1: Left-top panel illustrates potential transitions and correlations in plant–pollinator networks across the pollination season and empirical trends in community size and connectance. Right-top panel shows the structural patterns emerging in 20 plant–pollinator communities across the pollination season, showing shifts between modular (green), nested (blue), and in-block nested (gray) organizations. Left-bottom panel shows the relationship between community size, connectance, and structural organization, showing that deviations from average conditions tend to favor modular structures. Central-bottom panel shows the stability–feasibility trade-off in synthetic mutualistic networks: modular structures (green) maximize stability, nested ones (blue) maximize feasibility, and in-block nested (gray) mediate between both. Finally, the right-bottom panel shows the dependence of stability and feasibility on connectance, C. In small communities with few species, S, the trade-off is consistent, while in larger ones, feasibility shows a non-monotonic pattern.

Overall, this work suggests that community assembly is not driven by a single organizing principle, but by a balance of multiple dynamical requirements that vary over time. Understanding these structural transitions may help anticipate how mutualistic systems respond to environmental change, offering insights for the conservation and management of ecological communities.

References

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