Alex Fuster (2024-10-19)

Context and inspiration for the idea

We are working on a study that proposes to define the concept of Ecological Network Coherence, i.e. the distribution of co-responses among interacting species within a community, and developed theory to investigate how this pattern affects ecosystem functioning (i.e. abundance shifts in front of push perturbations).

Species co-responses within a community can be summarized in a matrix, C, which comprises pairwise correlations. The distribution of these co-responses forms a community pattern that we define as the Ecological Coherence of the community, reflecting how coherent species responses are to the environment (Fig. 2).

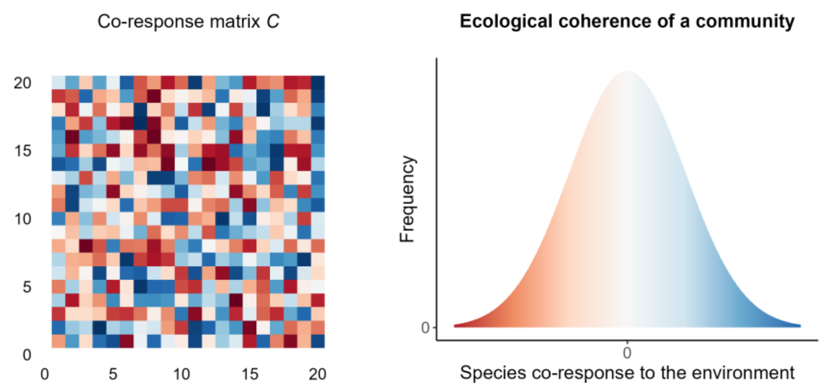

Fig. 1. A matrix of species co-responses to specific environmental variables (left) can be represented as a distribution (right), illustrating the Ecological Coherence of a community.

We can incorporate information on community structure by considering the co-responses between pairs of interacting species: the matrix C can be filtered out (multiplied) by the adjacency matrix of interactions A, which denotes the presence or absence of interactions. The distribution of the resulting filtered co-response matrix is a pattern that shows the degree of co-responses to specific environmental variables between interacting species within a community at a given location in space and time, which we define as Ecological Network Coherence.

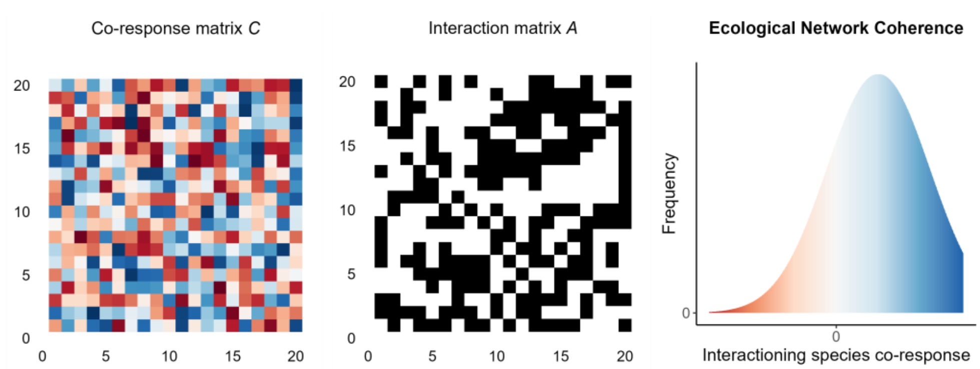

Fig. 2. By combining the co-response matrix *C* and the interaction matrix *A* (left), we derive the Ecological Coherence that accounts for interactions among species, termed the Ecological Network Coherence (ENC) of a community.

Summarizing the pattern of species co-responses and interactions in a community distribution, ENC provides an intuitive tool for predicting the consequences of various statistical modes on ecosystem functioning. This approach offers significant advantages by bridging empirical and theoretical work. ENC is constructed from commonly measured data, making it accessible and practical for empirical researchers. At the same time, it is represented as a clear statistical object, facilitating theoretical exploration and modeling. This dual utility fosters a common framework for both empiricists and theoreticians and intuitively summarizes complex community patterns enhancing our ability to understand and predict changes in ecosystem structure and function.

We showed in an ongoing study that this pattern it is indeed key for driving ecosystem functioning. Now, data on both community time-series and networks of interactions is very scarce and we cannot compute ENC patterns, but **we can use the BioTime data to describe the Ecological Coherence pattern (Figure 1)**, as it provides much richer information that what studies describe on community coherence (community synchrony in the literature, described often simply with a mean). Note this is very similar to the final figure of our Ecography paper where we describe the correlations of all species' pairs! But in this case is a pattern for a given community. Describing this pattern in natural communities could be a nice contribution to inform theory.

We can already intuit consequences of this pattern, simply species' corresponses, on ecosystem functioning:

- Having distributions shifted towards positive correlations means species abundances change in the same direction, which could amplify their effects and lead to strong shifts in abundance.

- Conversely, mostly negative co-responses (i.e. distributions shifted towards negative values) means species abundances change in opposite ways. If these are interacting species such as a predator and a prey, strong negative co-responses could lead to the extinction of some species, but could also lead to offsetting effects and balancing of abundances in other cases (e.g. competition among predators).

- Having distributions mostly centered on zero should balance out the effect of positive and negative coresponses and offer higher stability.

- Having strong coresponses, either positive or negative, or both, should increase the risk of having explosive abundance dynamics and extinctions, disrupting community structure and functioning.

Proposed study: Describing Ecological Coherence patterns in communities

Motivation

Recent empirical investigations and theoretical advancements have underscored the significance of evaluating species' coherence in their responses to environmental changes within ecological communities—often referred to as community synchrony. This concept offers vital insights into the collective impact of species on ecosystem stability and helps anticipate shifts in community structure and function. However, a comprehensive global analysis of how natural communities exhibit coherence, and how this correlates with ecological and evolutionary patterns, remains elusive. Such an analysis could enhance mechanistic theories of community dynamics.

A key challenge lies in how we describe coherence within a community to extract the most functionally relevant information. Studies often report a simple mean of pairwise coherence from time series data, but the true value lies in examining the frequency and distribution of coherence magnitudes and directions. Most importantly, coherence must be viewed in the context of the community's interaction network, which influences how environmental effects propagate. While interaction networks are crucial for linking coherence with ecosystem functioning, empirical studies integrating community coherence and interaction patterns are scarce. With the growing availability of time-series data on community coherence and the development of global interaction databases like GLOBI, exploring how coherence patterns distribute across trophic structures and species' network roles can yield critical insights for ecological theory and ecosystem management.

Objective

We aim to describe **Ecological Coherence**—the distribution of species' co-responses in a community—and tie it to two key statistical constructs: (1) the co-response matrix, which reveals the structure and influence of species on community coherence, and (2) its frequency distribution, summarizing the magnitude and sign of co-responses. Together, these metrics can offer valuable insights into how coherence impacts ecosystem functioning. Our specific objectives are as follows:

1. **Describe Ecological Coherence patterns in multiple communities.**
2. **Test the relationship between coherence (mean and SD) and community size**: We hypothesize that the mean coherence converges toward zero in larger communities, due to the increased likelihood of balancing positive and negative species-pair co-responses. The standard deviation (SD) may increase with community size, as larger communities offer more opportunities for extreme co-responses to emerge.
3. **Describe the modular structure of coherence within communities**: We will examine the number and size of species groups that display more similar (coherent modules) or dissimilar (incoherent modules) co-responses, and how these change with community size. We predict that larger communities will have larger, more balanced coherent and incoherent modules.
4. **Identify taxonomic pairs involved in extreme co-responses**: Specifically, we will focus on pairs of genera or families exhibiting the most extreme coherent (0.75 to 0.8) and incoherent (-0.75 to -0.8) values.

Our second objective is to link Ecological Coherence patterns to species interaction structures. Given that interaction data for communities with ecological co-responses is often lacking, we will use GLOBI's global interaction database for a coarse-grained analysis. While we acknowledge the limitations of this dataset, it can offer valuable initial insights by analyzing broad-level interaction patterns, such as trophic roles or key interactions among abundant species.

5. **Test whether coherent and incoherent modules correspond to positive and negative interactions in GLOBI**, respectively.
6. **Identify species that contribute the most to community coherence**: We will explore whether these species play important ecological roles, such as super-generalists or keystone species, and discuss their potential influence on community dynamics during environmental perturbations.
7. **Examine Ecological Coherence within and between trophic levels**: We will focus on three main trophic levels—plants, herbivores, and carnivores. These levels define the base trophic chain, where direct and indirect effects are tightly linked to ecosystem functioning. We expect higher incoherence between consumers and resources (e.g., herbivores and plants, which exhibit negative direct interactions), and greater coherence between guilds that correlate positively via indirect effects (e.g., predators and plants).
8. **Test whether species with more documented interactions in GLOBI exhibit less coherence**: We hypothesize that generalist species will display lower coherence with their partners, as they respond to diverse biotic effects. Conversely, specialists are expected to show stronger coherence with their partners, responding more tightly to abundance shifts.

METHODS

From the previous study, we already have genus correlations in abundance change in each study site. Here, I show results I run from our filtered data using these genus correlations. The idea would be to do this **AT THE SPECIES LEVEL**.

1. Describe Ecological Coherence patterns in multiple communities

- Obtain the correlation matrix between genus (>10 years of data) and plot the distributions. Here, I am filtering out communities with less than 8 genus, but these would be included if we have species-level data.

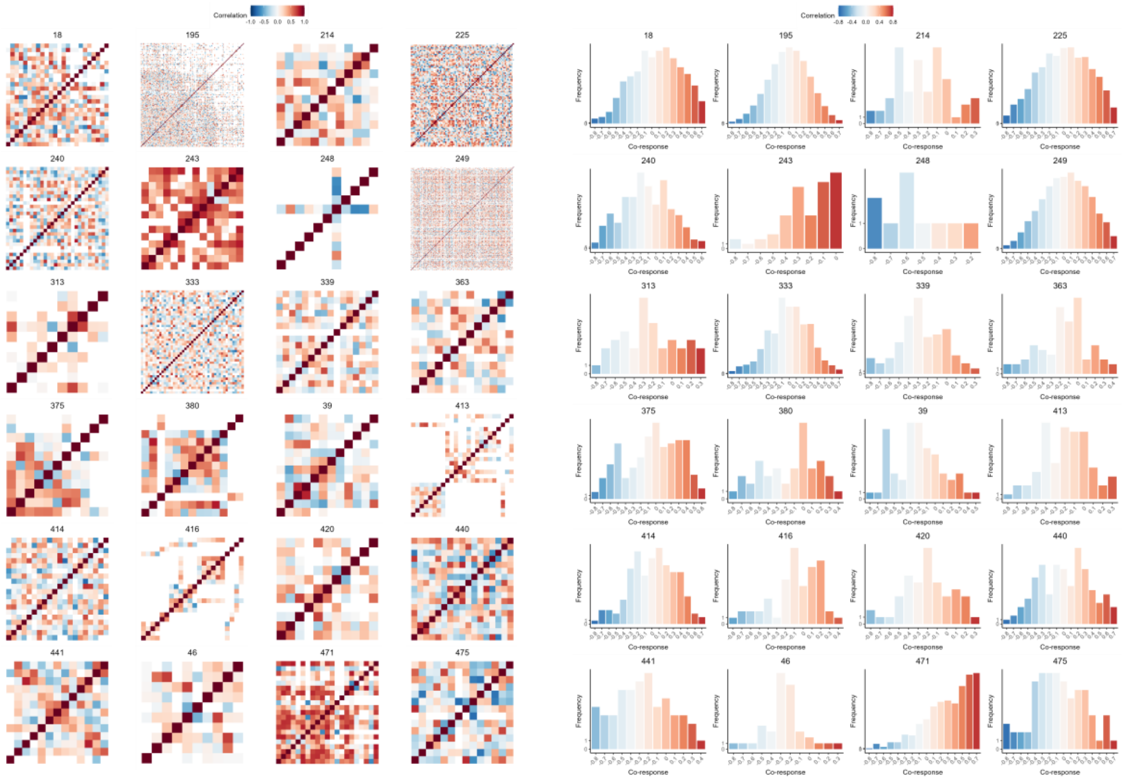

Fig. 3. Ecological Coherence patterns of genus in each study: correlation matrices in the left and distribution of these values in the right.

- ➔ More positive correlations than negative
- ➔ Distributions are highly variable
- ➔ Most distributions show more weak correlations than strong, but there are exceptions (study 243, 248, 313, 415, 471).

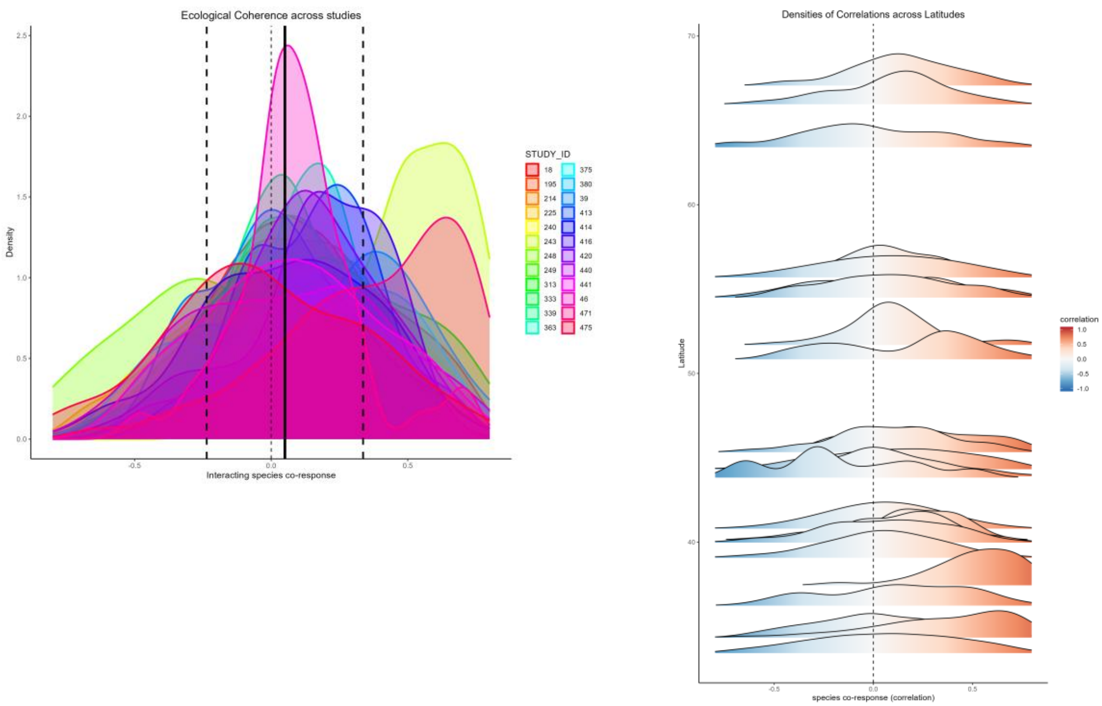

Fig. 4. Some visualizations. Overall Ecological Coherence patterns in each community (left), and throughout latitude (right).

2. Relationship between mean and SD coherence with community size.

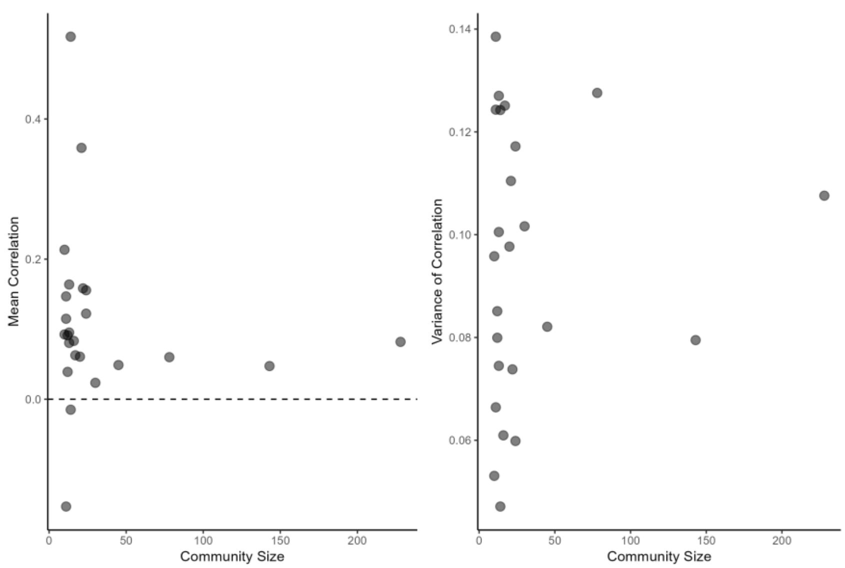

Fig. 4. Mean and variance in correlations and community size.

➔ The smaller the community, the more variable in both mean and variance coherence can be.

3. Modular structure of coherence within communities

- ➔ Apply modularity detection algorithm to the correlation matrix to detect modules.
- ➔ The correlation matrix includes both positive and negative values, and I couldn’t find algorithms that detect modules when there are – signs. A solution I thought is to first detect coherent modules by setting all negative correlations to NA. Then, detect incoherent modules by setting all positive correlations to NA and convert the negative correlations to positive.

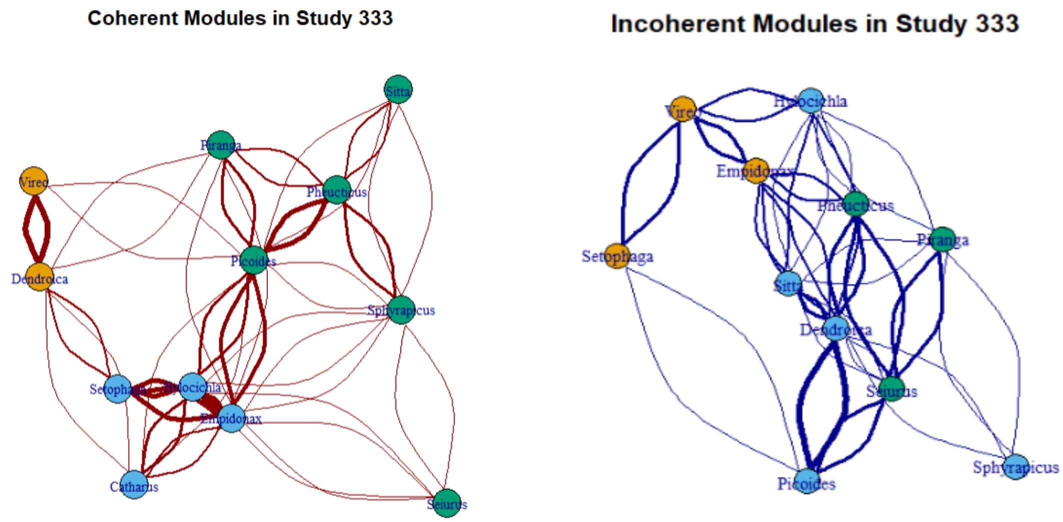

Fig. 5. Coherent and incoherent modules for a single study. Modules are detected using multi-level modularity optimization algorithm Cluster_Louvain from the igraph package. Coherent modules are computed after dropping all negative correlations. Incoherent modules are computed after dropping all positive correlations.

Now, number and size of modules across communities:

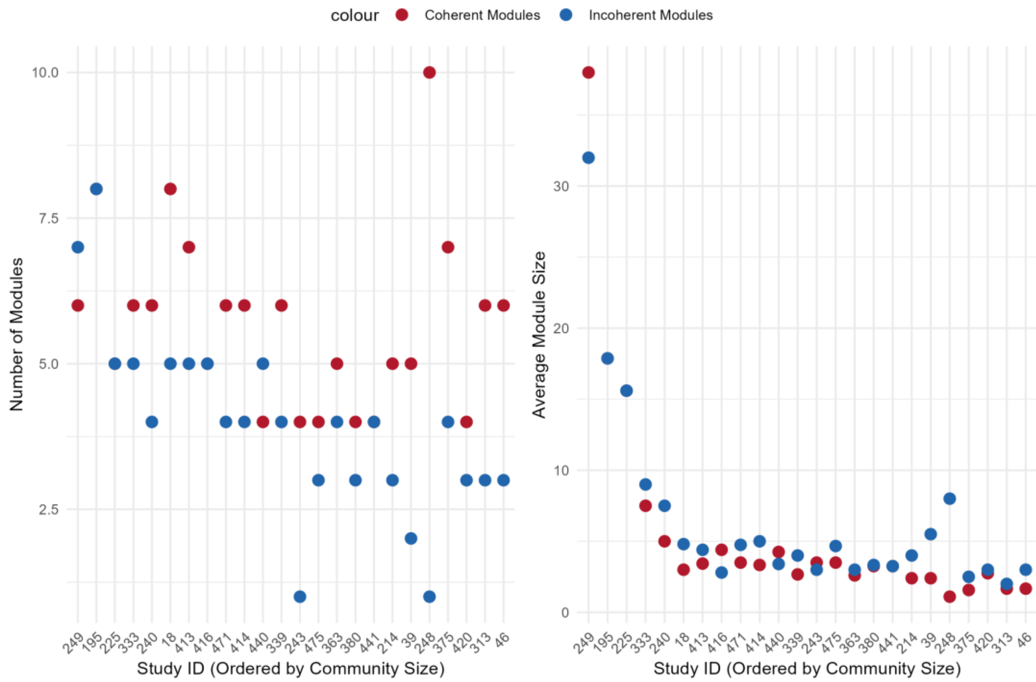

Fig. 6. Number and size of coherent and incoherent modules within communities.

4. Identify taxa involved in extreme correlations.

- ➔ Get the taxa pairs showing extreme correlations (between -0.75 ans 0.8 and 0.75 and 0.8).
- ➔ See what taxonomic groups (genus, families, class) are often involved.

5. Test whether coherent and incoherent modules correspond to positive and negative interactions in GLOBI

- ➔ Get the interaction types (positive or negative) from GLOBI
- ➔ Compute the % of positive and negative interactions in coherent and incoherent modules.

6. Identify species that contribute more to coherence

- ➔ Compute the contribution of each species to coherence. This is done by calculating the column means of the correlation matrix, in absolute values: species with higher mean show higher correlations with all the other species.
- ➔ Identify the top 2 or 3 species in each community and manually search for their characteristics. Are these species super-generalists or keystone species? If these top species are super-generalists—interacting with many others and playing a crucial role in maintaining the network structure—they can be considered key species for the functioning of the community. Any perturbation affecting them is likely to propagate throughout the network, causing other species to respond strongly in turn, thus causing strong disruptions in the community structure and functioning.

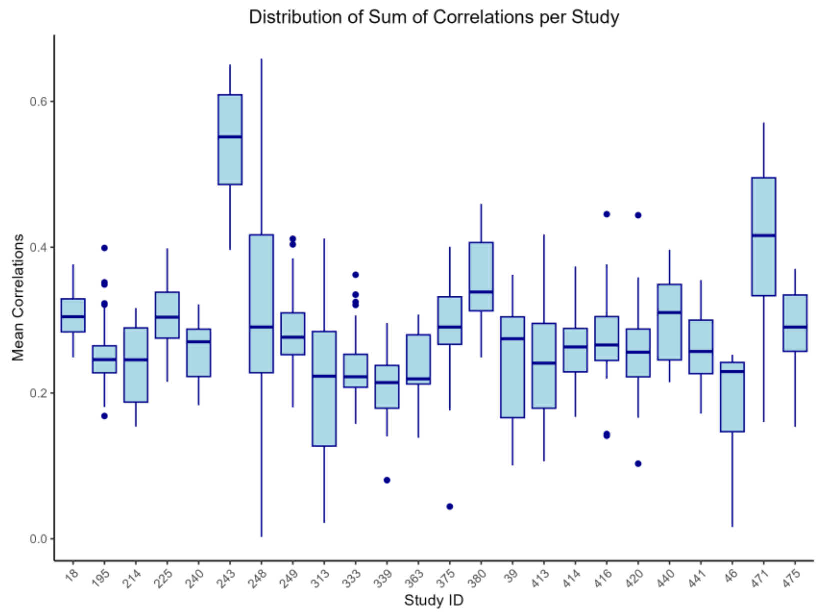

Fig. 6. Contribution of species to coherence (i.e. mean of absolute correlation values with other species).

- ➔ We could check whether outliers or the species with the most contribution in each community could be a key species in the interaction structure (e.g. a super-generalist or abundant species).

7. Ecological Coherence within and among trophic levels

- ➔ Get trophic level from GLOBI: plant, herbivore, predator
- ➔ Compute EC pattern for within and among trophic levels

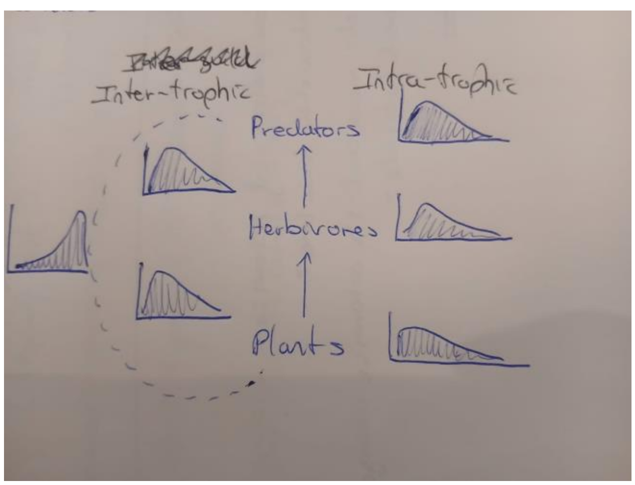

Fig. 7. Between and within trophic level Ecological Coherence (figure idea).

8. Do species with more recorded interactions (GLOBI) show less coherence with the community?

- ➔ Get the number of interactions of each species with the rest of species in the community from GLOBI.
- ➔ Test the relationship coherence ~ n interactions of species.

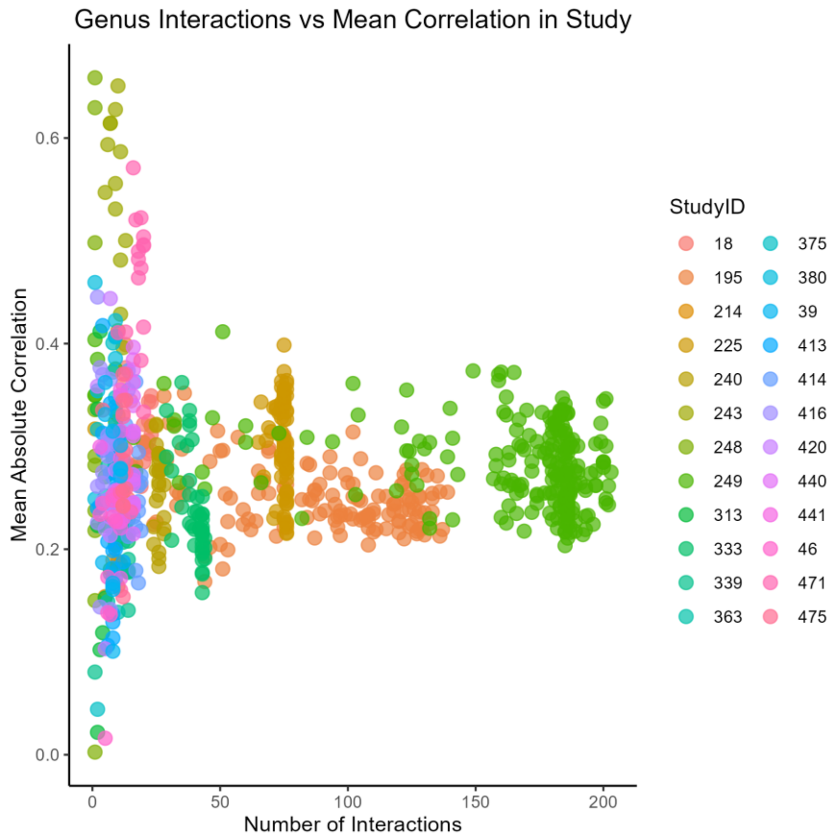

Fig. 8. N interactions and contribution to coherence of each genus in each community. Because it is at genus level, the number of interactions scales up a lot.