

Expanding the paradigm of ecological network research

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May 2013

Introduction

Describing the structure of ecological communities requires to know not only the identity of species, but also their interactions. Because interactions drive ecological dynamics within communities (Berlow et al. 2009), their organization will confer certain ecological properties. The structure of interactions has been described by species interaction networks (Dunne 2006), that is, a mathematical and conceptual representation of both *species*, and the *interactions* they establish. This view generated a rich literature primarily focused on how certain mathematical properties of the network related to the robustness (Dunne et al. 2002), productivity (Duffy et al. 2007), or tolerance to extinction (Memmott et al. 2004) of the community it represents. Although this approach classically focused on food webs (Ings et al. 2009), it can be applied equally to all types of ecological interactions (Kéfi et al. 2012). By large, this literature assumes that, short of changes in local densities due to ecological dynamics, networks are *static* objects. If two species are known to interact at one location, it is assumed that they will interact whenever they co-occur (see e.g. Havens 1992). Recently, we proposed that networks are *dynamic* objects, that have structured variation in α , β , and γ diversity, due not only to the change of species composition at different localities, but also to the fact that the same species will interact in different ways over time or space. Of these sources of variation in networks, the change of species composition has been addressed by previous literature [Gravel et al. (2011); others refs]. However, because this literature mostly assumes that interactions happen

consistently between species, it is ill-suited to address network variation as a whole, and needs to be supplemented with new concepts and mechanisms.

Recent studies on the sensitivity of network structure to environmental change provide some context for this question. Menke et al. (2012) showed that the structure of a plant–frugivore network changed along a forest–farmland gradient. Specifically, at the edges between two habitats, species were on average less specialized, interacting more evenly with a larger number of partners, when compared to habitat cores. Even within different forest strata, differing by proximity to the canopy and visitation by birds, differences in network structure were observed (Schleuning et al. 2011). Eveleigh et al. (2007) demonstrated that outbreaks of the spruce budworm were associated to changes in the structure of its trophic network, both in terms of species observed, and their interactions. Poisot et al. (2011) used a microbial system of hosts and pathogens to study the impact of productivity gradients on the realization of infection events. When the species were moved from high to medium to low productivity, some interactions were lost, and some other were gained. These results suggest that the existence of an interaction is not only contingent on the presence of the two species involved, but may also require particular environmental conditions, and perhaps presence of outside species.

Understanding these results requires a major change in the conceptualization of an ecological network: any observation of an ecological network is the realization of *potential* interactions, much in the same way that the observation of a community is a realization of a *potential* species pool in the meta-community theory (Leibold et al. 2004). Further, there is a need to identify and conceptualize the new mechanisms involved in giving networks their dynamics. We argue that this can be done within a simple framework describing the sources of network variation. Following Dunne (2006) and Poisot et al. (2012), the pool of potential interactions at the regional level is a *metaweb* (Figure 1). The composition of *realized* networks, *i.e.* those observed in nature, is determined by a series of sorting processes (on the species being present, then on the way they interact). As the mechanisms of species sorting have been described by meta-community theory (Leibold et al. 2004), there is a need to tear apart the mechanisms of interaction sorting.

% DG: expand the argument, it's not a clear statement

Community ecologists need to shift their focus on interacting species (*i.e.* regional, potential) to interacting populations (*i.e.* local, realized). Replicated sampling of interacting populations is required to observe their response to environment changes. This begs the questions of the similarity between population and species level assessments of ecological networks. Species-level networks reconstructed on the basis of literature survey, expert knowledge, or even potential trait-based relationships [Brose et al. (2006); Heckmann et al. (2012); @gravel2013_niche_allometric], are networks of potential interactions, but can seldom be used to predict whether two populations will interact at one particular location. When sampling populations enough times, either through time or space, we only gain knowledge on the probability of an interaction to realize, and it is therefore possible that some potential interactions are not encountered. Take, for example, the dataset of (Havens 1992), which describes the interactions between species in the Adirondack lakes. The species list for each lake is known from field observations. At the regional level, the interactions between all species were retrieved from literature surveys and expert knowledge. With this information in hand, it is only possible to describe the structure of *potential* interactions at the local scale, but not to describe the *realized* ones. The opposite standpoint is to assume that aggregating all realizations will give a good knowledge of the potential interactions in the metaweb. This, however, is the age old problem of proving a negative: % DG: rephrase next sentence, convoluted we are only certain that no potential interactions were missed insofar that we are confident in our ability to locally detect them (Copi 1953), and have sampled enough combinations of environmental conditions. Some networks will be more sensitive to sampling effects than others. % DG: what do you mean by sampling effects? Pollination or frugivory networks are typically sampled through several sessions of observation (Schleuning et al. 2012), and therefore rely on the skill of the observer, or the amount of people available to conduct the survey. On the other hand, macro-parasite networks (Stanko et al. 2002) or food webs (Shaner and Macko 2011) can be conducted by sampling individual hosts, and investigating them in the lab (through *e.g.* combing or stomach content analysis), meaning that it is harder to miss an interaction if enough individuals

metaweb

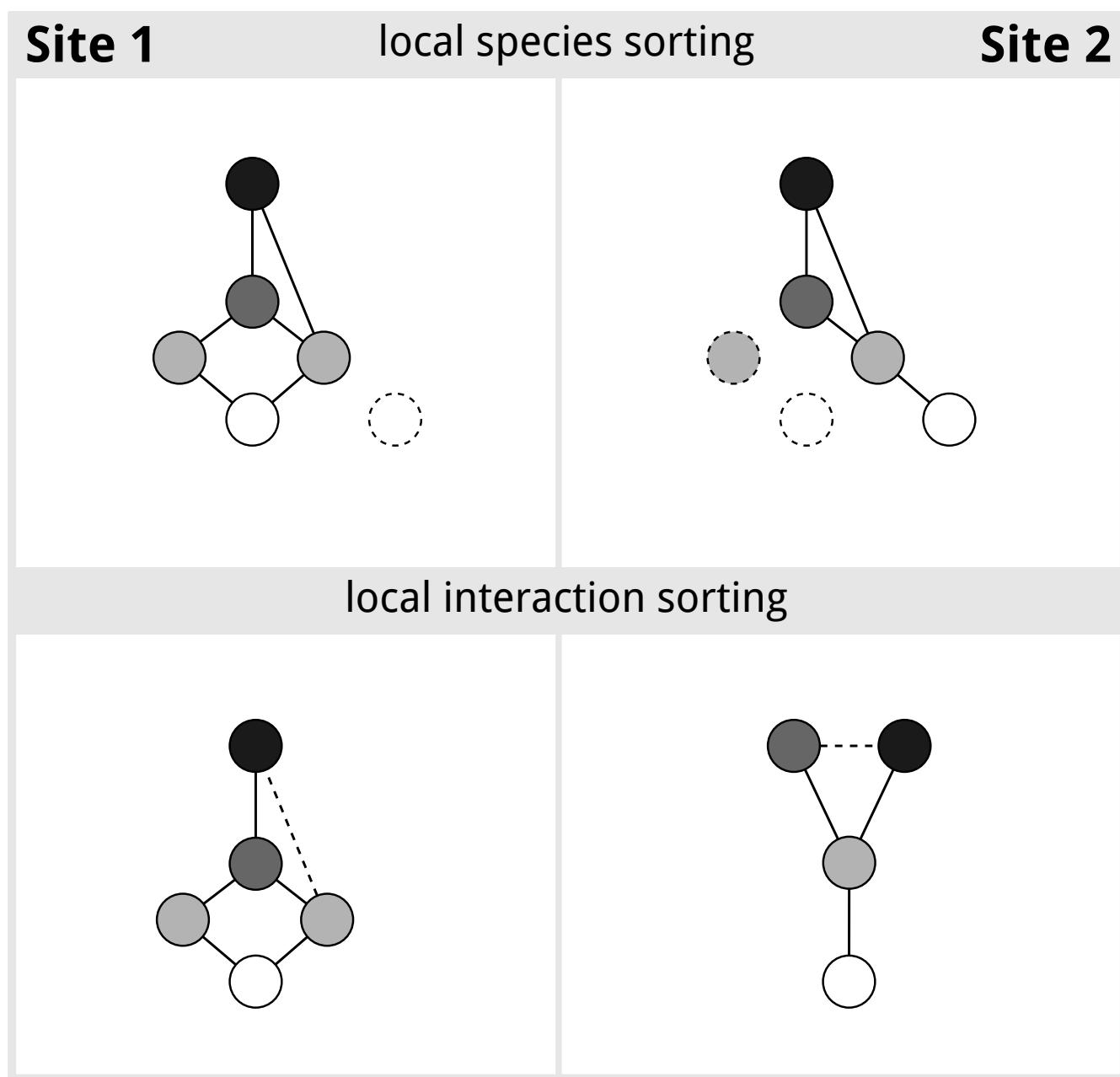
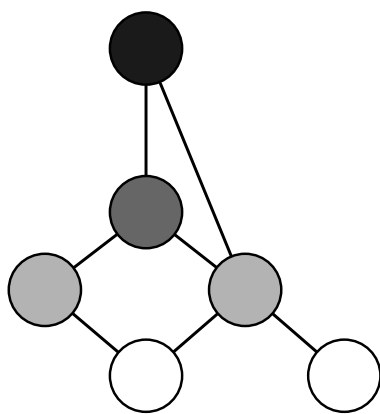


Figure 1: An illustration of the metaweb. In its simplest form, the metaweb is the list of all possible species and interactions between them for the system studied. The interactions could be based on observations or inferred from trait values and previous knowledge

are sampled. %DG: there is a drift toward the end of the paragraph, we lost the main thread.

Poisot et al. (2012) showed there is considerable uncertainty on the links of a metaweb even after aggregating more than a hundred independent samplings of a host–ectoparasite system. Three important consequences could be drawn from this result. First, the adequate sampling of potential interactions is a difficult task, akin to sampling local networks (Martinez et al. 1999). Second, the reconstruction of the metaweb could only be conducted with numerous samplings. Thirdly, the metaweb must integrate the variability of local interactions, meaning that it is best represented with a probabilistic mathematical representation. It is the realized interactions that will drive local community properties (Bascompte 2009, Poisot et al. 2013), not the potential ones. Interactions between populations are therefore the relevant scale at which to study ecological networks. % DG: I did work a bit the last sentence, but I'm not satisfied with this paragraph that I still find quite redundant. Next sentence is also repetitive In addition, because different realizations of a metaweb will show interaction turnover, it is important that we now focus our effort on understanding population-level interaction networks, because this seems the only way to understand the difference between potential and realized interactions, which is required to advance toward a biogeography theory of interactions. So that we can understand the relationship between the structure of potential and realized networks, *i.e.* in the terms of Poisot et al. (2012), the differences between a metaweb and its realizations, it is important to understand the ecological factors involved in making populations interact. % DG: last sentence has an important point (we need to understand the factors responsible for the variation of interactions), but it needs to be rephrased.

The goal of this paper is to evaluate how several ecological processes can create turnover in species interactions at the population level. % DG: you'll have to fix terminology. Do you want to talk about turnover, similarity or variation of interactions? Given the treatment coming later, I vote in this paper to work on variation. Turnover is too strongly linked to beta diversity and it is not exactly the purpose of the current paper, even though the variability of interactions is eventually driving interaction turnover and beta diversity. We evaluate the importance of neutral processes, trait distribution and matching, and context-dependence,

to (i) give a comprehensive overview of how and why they create turnover, and (ii) show how integrating them into our current analyses of networks will result in a more predictive network ecology. % DG: might be useful to refer to McGill et al. 2005 (TREE) here. He makes the argument that the study of pairwise interactions has been a waste of time with no general rules. I strongly disagree, I think we could achieve the equivalent for networks to the framework he is proposing for plants % DG: would remove the next sentence. Although most of the discussion is, for the sake of simplicity, about whether species will interact or not, the same mechanisms can be used in a probabilistic approach (Yeakel et al. 2012). This leads to an altered view of ecological networks, which is more focused on populations rather than species, as it appears as the natural scale of biological organization at which these mechanisms are expressed (Smallegange and Coulson 2012). Then after we discuss what to measure in the field when sampling interaction networks, and how we can design statistical approaches to better understand the interactions of the factors of turnover (we present one possible way to do so in *Box 1*). We conclude by discussing how the new knowledge gained this way will be applied to our understanding of species interactions, and how it will help us build more predictive models. % DG: last sentence does not say anything new.

% DG: would be important to announce the structure of the paper. How you want to satisfy those objectives. Short review of the concepts, what they means in terms of network. I would perhaps try to have a specific paragraph for each section on the implications of the process on the beta of networks, followed by clear predictions for each process. You could end on the evolutionary implications of the process.

% DG: might be great also to start with the statistical model. Kind of overarching, it helps to structure the discussion and fix every part to a central piece.

Population dynamics and neutral processes

Over the recent years, the idea of neutrality percolated into the analysis of the structure of ecological networks, most notably in bipartite networks (Blüthgen et al. 2006). Neutral (*i.e.*

abundance) and non-neutral (*i.e.* trait-based) effects can act simultaneously in a population, albeit with different intensities (Gravel et al. 2006). Several host–parasite datasets were re-analyzed, with the conclusion that changes in local species abundances triggers variation in parasite specificity (Vazquez et al. 2005). Recent results show that this logic also holds predictive power for food webs (Canard et al. 2012). In this section, we review recent studies investigating the consequences of neutral dynamics on the structure of interaction networks, and show how variations in population size can lead to interaction turnover.

The basic processes

% DG: I like the structure of each section, but I would almost try to limit it to one good paragraph per subsection. There are already three families of processes (and I propose a fourth one, see below), times 3 paragraphs per process, it already makes 9-12 paragraphs, which is considerable.

The reasoning for a neutral approach to species interaction networks is as follows. In order for two species to interact, there are essentially two types of requirements they must jointly meet (Combes (2001)): ecological (related to species encountering one another), and evolutionary (related to species falling within one another Eltonian fundamental niche, which are addressed in the following section). % DG: I would make the two points more straightforward: they must encounter and they be able to interact. Forget the reference to ecological and evolutionary terms, they are confusing and subject to debate.

Assuming that two species occupy the same locality, and are active at the same time of the day, then the likelihood of an interact is proportional to the product of their relative abundance. % DG: last point is important. It's not the abundance per se, rather the relative abundance that matters.

%DG: to be coherent with the purpose of the paper, there are some mention of “species” that should be converted to “population”, for instance in the following sentence: This means that two locally abundant species are more likely to interact than two locally rare ones, simply

because their individuals will meet more often. This approach can also be extended to the prediction of interaction strength (Blüthgen et al. 2006, Vázquez et al. 2007), *i.e.* how strong the consequences of the interaction will be. It predicts that locally abundant species should have more partners, and locally rare species should appear locally more specialized. In a purely neutral model, the identity of species do not matter (*i.e.* there are no trait-based processes involved), and it becomes easy to understand how this can lead to a situation where, because species vary regionally in abundance, some interactions display turnover. % Might be important to mention here that what is important is the neutrality of interactions. Abundance could be determined by non-neutral processes.

Canard et al. (2012) shown that neutral interaction networks can have a realistic structure. They proposed the term of “neutrally forbidden links” to refer to links that never occur because of the rarity of one of the species in the pair. Such forbidden links can generate interactions turnover over spatial or temporal extents, provided there is turnover in abundance (Box 2). A similar phenomenon was observed by Poisot et al. (2011). A soil community of bacteria (victims) and bacteriophages (enemies) was isolated from its natural environment, and all pairwise interactions were measured along a gradient of decreasing resource availability. The resulting lower abundance of the bacteria significantly decreased the encounter probability of the two species and thereby the network structure. This resulted in a strong link turnover, with some species being able to interact in the resource-rich environment, but not in the resource-poor ones. % DG: I did reduced the paragraph quite a lot. Much more compact now.

Benefits for network analysis

It is important to understand how local variations in abundance, wether neutral or not, cascades to the structure of neutral interaction networks. Simple statistical models can be used to quantify the effect of population sizes on local interaction occurrence or strength (Krishna et al. 2008). Furthermore, knowing the part of each interaction explained by neutrality, it is

possible to *remove* it from the observed values. One can then examine the structure of the networks after controlling for neutrality, This offers an extremely powerful tool to measure the consistency of neutral and trait-based components of interactions through time and space. % DG: last sentence seems critical, but needs to be reworded

% DG: next sentence is your dream coming true. How could you make this claim? As most data on interaction networks will now include estimates of population density as well as estimates of interaction strength, it is crucial that we develop standardized methods to isolate the neutral signal on interaction strength. Coming up with such a framework will complement theory surrounding the measurement of interaction strengths in nature (Wootton and Emmerson 2005). % DG: I do get the last point because you told me about, but otherwise I even doubt that Wootton could guess what you are talking about. Even more importantly, integrating neutral processes in our understanding of networks will benefit neutral theory: Wootton (2005) made the point that deviations of empirical communities from neutral predictions were most often explained by species trophic interactions, which are notoriously absent from the original formulation of the theory. Merging the two views will increase our explanatory power, and provide new ways to test neutral theory in interactive communities.

This also offers a new opportunity, namely to complete the integration of network structure with population dynamics. To date, most studies focused on the consequence of one species having a particular position within a food web on the dynamics of its biomass or abundance (Brose et al. 2006, Berlow et al. 2009). Adopting this neutral perspective allows to go back, in that the abundance of a species will also dictate its position in the network: changes in abundance can lead to gained or lost interactions, and these changes in abundance are in part caused by existing interactions. For this reason, there is a potential to link species and interactions dynamics, and more importantly, to do so in a way which accounts for the feedback effects. From a practical point of view, this requires repeated sampling of a system through time, so that changes in relative abundances can be related to changes in interaction strength (Yeakel et al. 2012). % DG: this will require some to open their minds. In their view (like Lafferty), consumer resource dynamics rule, and therefore abundance is only the result of in-

teractions. Not the other way around. . . . We might need to write something about this issue. I could show you a paragraph I wrote in the reply to Am Nat for Elsa's paper. They generate opposite predictions, so it's quite interesting.

Traits matching in space and time

% DG: it's a bit strange to start trait-matching on links that do not exist. Of course it's a matter of perspective, but I would try to start with links we could predict based on traits. . . % The jump into trait conservatism is also very fast. We need a smoother introduction to trait-matching, then co-evolution and then into trait conservatism. I have not edited the paragraph, I think it has to be reworked to yield a more straightforward introduction to the section.

Olesen et al. (2011) reported the existence of "forbidden links" in mutualistic interactions, that is interactions whose existence is prevented by the fact that species traits do not match. For example, the proboscis of a pollinator may be too short to reach the pollen of a plant species. Under this perspective, both the existence and absence of interactions can be mapped on trait values. In contrast to the neutral perspective, this can also be linked to evolutionary hypotheses on trait conservatism. Price (2003) proposed that a wide range of current macroecological patterns, including the identity of species that are interacted with, is a consequence of the macroevolutionary dynamics of traits, a view which is also at the core of community phylogenetics interpretation of interaction networks (Ives and Godfray 2006, Mouquet et al. 2012). Polidori et al. (2012) showed that fast-flying preys (a trait which has been evolved under pressures other than predation) were preferentially attacked by generalist parasitoid wasps, while specialist wasps favored slow-flying preys. Clearly trait values have far-reaching consequences on network structure.

% DG: This section should be kept However, rarely addressed is the fact that within species trait variation over space and time can show great variability and thus impact interaction turnover. In this section, we review how this granularity %DG: granularity??? in trait distribution can affect network structure. We propose that integrating it our description of networks will (i)

increase our ability to predict the existence of interactions, and (ii) allow to better ground the current structure of networks in an evolutionary context. % DG: try to have the same structure for the introduction paragraph. The one for neutral interactions do not state what are the consequences of this perspective to interactions.

The basic processes

% DG: the problem with this sentence is that you don't define what is the across species trait matching Within species trait variation will determine the occurrence of pairwise interactions much in the same way that across-species trait matching will do. We present an illustration of this hierarchy of trait variation at [Figure 2](#). In short, the species-level interaction network, because it is built by aggregating population-level interactions, which may have a large variability if the morphospace occupied by each species is large, can have unique emerging properties. %DG: I don't get the point of the previous sentence. But the keywords initiate a reflexion: could we get to the variability of network structure given knowledge of the variability of traits (including covariance among species)? Might worth some lines. A bottom up prediction of network dissimilarity (much like Elsa did on her analysis of beta div based on abundance turnover) The fact that the niche of species can appear large if it is the aggregation of narrow but differentiated individual or population niches is now well established (Bolnick et al. 2003, Devictor et al. 2010), and reinforced the need to understand intra-specific trait variation to describe the structure and dynamics of communities (Bolnick et al. 2011). This notion is yet, however, to percolate the literature on network structure.

There are several examples of intraspecific trait variation resulting in extreme interaction turnover. A particularly spectacular example is described by Ohba (2011): a giant waterbug is able to get hold of, and eventually consume, juveniles from a turtle species. This interaction can most likely exist only during a limited time of the "prey" life-span. Similarly, predation reversal is mostly contingent upon the traits of the individuals being in different configurations. Choh et al. (2012) demonstrated through behavioral assays that preys which evaded

predation when young, were more likely to predate juvenile predators, than the “naive” individuals. These two examples share a common feature: for interactions strongly regulated by trait-matching, the functional role of an individual is an emergent property of its traits, taken in combination with the traits of other individuals, rather than a species characteristic. % DG: I get your point and I think it is a fundamental one. But the wording should be simplified to make it more straightforward. % DG: the first example is a bit problematic because it is only driven by stage structure, I was expecting a trait-variation based on genotypic variability. But I was wrong, both are important to interaction turnover. Which leads to an interesting point of discussion you should emphasize: both phenotypic and genotypic variability are responsible for interaction turnover. Examples for each of them should be provided. You can even add behavioural/cultural variability. It is common to see mammal predators to develop specialization on certain types of preys after they found a particular technique of hunting. Could find examples for that.

Kuwae et al. (2012) showed that local differences in bird morphology led to them not consistently interacting with bacterial biofilm in an intertidal food web. % DG: I don't understand this interaction. The birds are grazing on the rocks? The local stratification of traits result in situations in which two populations will not be able to interact, even though they belong in each other fundamental Eltonian niche (at the species level). % DG: what do you mean by local stratification? % DG: I would avoid reference to the use of the Eltonian niche, it is a very heavy formulation with a lot of underlying meaning. Go straight to the point to avoid confusion. Assuming that some interaction-related traits can be under strong environmental forcing (for example, body size is expected to be lower in warm environments, Angilletta et al. (2004)), there can be covariation between environmental conditions and the occurrence of interactions. An empirical demonstration of this was provided by Woodward et al. (2012): through the simulation of ecosystem warming, they demonstrate that changes in food-web structure happen at the same time as changes in body mass. Integrating trait variation over spatial or temporal extents is now central if we are to understand network variation and response to environmental change.

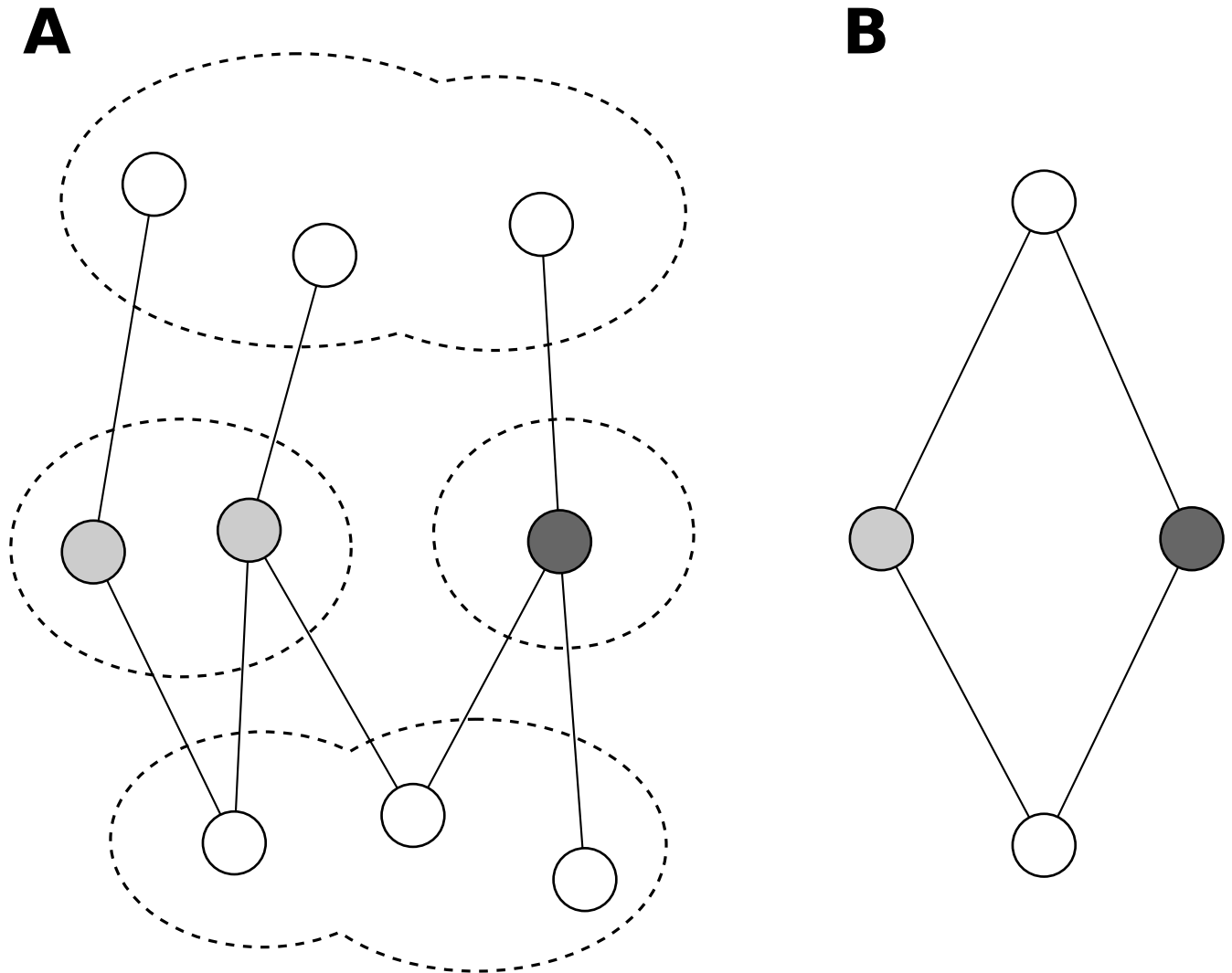


Figure 2: Panel **a** represents the interactions between different populations (circles) of four species, identified by the boundaries of their morphospaces (dashed lines). This network is mostly made of linear food chains, and has one generalist consumer. When aggregated at the species level however, as shown in **B**, it becomes a “diamond” food-web, with different dynamical consequences. Because the trait values of populations within a species differ, each individual population can interact differently than the species it belongs to..

Benefits for network analysis

Although tools now exist to measure the turnover of interactions (Poisot et al. 2012), there is a need to link this turnover in a mechanistic understanding. % DG: stange sentence. Looks like we did propose a tool but we did not knew what it was for (it's a close to what really happenned, but we need to formulate it alternatively)

Spatial and temporal intra-specific trait variation is, as we illustrated above, a promising avenue. % DG: incomplete sentence. State more clearly why it is a promising avenue. We propose in *Box 1* a way to understand the impact of traits and neutral effects on the occurence of interactions. % DG: I think this box should be included in the main text and come first. Or alternatively, at the start say that you will present the pieces and then regroup them in a single framework. To be put in practice, this requires that when assembling a network locally, traits of interacting populations are measured. For obvious reasons, the traits cannot be extracted from reference databases, as this will assum that all populations of a species are equal. With the accumulation of data, this new perspective will allow to better understand how networks vary along environmental gradients. Price (2003) shows how specific biomechanic response to water input in shrubs can have pleiotropic effects on traits involved in the interaction with insects. So as to make sense of the variation of plant–insect interactions on the gradient, one needs to look at trait interactions, and trait responses to environmental constraints. At a macro scale, since current traits reflect adaptation to past environments (Diniz-Filho and Bini 2008), looking for trait conservatism will help highlight historical contingencies on the structure of current networks. % DG: I think we will need to brainstorm more on those concepts. I find that the right ideas are there, but they still need to be develop more, I have the feeling that the thinking is not completely accomplished.

% DG: I like the ideas of the next paragraph, but the logic still needs to be further developped. There is a bunch of ideas, but they are not fully accomplished.

Finally, paying more attention to trait variation and how it impacts the realization of ecological interactions will contribute to the integration of coevolution and network analysis. Trait-

trait correlation, and trait-fitness correlation, are one of the basic ingredients for reciprocal selection (Gomulkiewicz et al. 2000, Nuismer et al. 2003), and needs be studied at the scale of the population, so as to be able to address the spatial dynamics (Thompson 2005). % DG: too much stuff and jargon in the previous sentence. You want to say too many things at once. Several authors discussed how migration between populations can disrupt local selection dynamics (brockhurst_impact_2007; Morgan et al. 2007, Gandon et al. 2008, Burdon and Thrall 2009). Understanding how the realization of potential interactions are affected by local trait distribution will allow not only to understand how a new species will integrate into the existing network of interactions, but also how it can affect its evolutionary dynamics. %DG: last sentence redundant In parallel, the bulk of community phylogenetics (Webb et al. 2006) was developed to re-analyse community structure through the phylogenetic conservatism of traits (Cavender-Bares et al. 2009, Mouquet et al. 2012). %DG: this idea is not fully developed, I don't understand where you are going. If enough realizations are sampled, for which we know even coarsely the phylogenetic structure of traits (Chamberlain et al. 2012), we will have a strong database on which to carry out statistical analyses to determine when interactions will occur. This effort will provide a strong mechanistic basis for previous work showing a phylogenetic and ecological structure of complex networks (Baskerville et al. 2011, Eklof et al. 2011). In addition to providing this more mechanistic insight, better linking traits and their phylogenetic structure to the local occurrence of an interactions is a promising way to incorporate more evolutionary hypotheses and mechanisms in the study of network dynamics. % DG: there is not much on the environmental dependance of interactions. How do you account for the fact that, for instance, a lemming is protected from the fox by the snow cover. Low snow fall one year will promote predation; it's not a neutral effect, it's not an effect of traits, it's simply environmental dependance of interactions. Should we have an extra section on this? I would see at least two effects of the environment: one on the abundance, the other on the strenght of the interaction. And perhaps even a third one, at the regional level on the species pool

Beyond direct interactions

In this section, we argue that although networks offer a direct access to direct interactions, there is potential in addressing indirect effects too. % DG: define what you mean by direct vs indirect interactions % DG: as I told you, I think this section is particularly relevant and original. We present evidences showing that this can be done by understanding the effects that direct interactions have on one another, and outline the benefits of doing so to further reinforce the links between species interactions and species distribution (Thuiller et al. 2013).

The basic processes

Several authors (Golubski and Abrams 2011) showed that biotic interactions themselves interact. % DG: again, a definition would be useful. The occurrence or absence of a biotic interaction can either affect either the realization of other interactions, or the presence of other species, as we will illustrate below. There are two broad situations which can happen. First, the occurrence of one interaction will be a necessary condition for the presence of a second. For example, opportunistic pathogens have a greater success of infection on hosts which are already immunocompromised by previous infections Olivier (2012) . Second, already established interactions can prevent future partners from interacting. Such is notably the case in protective symbioses, *i.e.* those in which a resident symbiont decreases the infection probability of a new pathogen (Heil and McKey 2003, Koch and Schmid-Hempel 2011). Note that in both cases, the driver of interaction turnover is the patchiness of species distribution, emphasizing why the two concepts ought to be integrated.

Direct interactions can also interfere with each others when there is preference in the selection of interaction partners. Lafferty (1992) documents some examples of predators avoiding preys infected by parasites. Schmitz (2008) show that two predators, whose difference is the hunting mode, are able to trigger a diet shift in their prey. Similarly, Singer et al. (2004) show that caterpillars change the proportion of different plant species in their diet, favoring low quality items to load on chemical compounds which are toxic for their parasitoids. However, low

quality food result in birds having a greater impact on caterpillar populations (Singer et al. 2012). The rich natural history of this relatively simple community module clearly illustrates that interactions between direct interactions needs be accounted for. % DG: be careful, there is a big difference between an interaction changing the strenght of another, to an interaction changing the abundance of another species and thus the likelihood of an interaction. The first one will have an effect on the beta link, while the second will only have an effect on the species turnover part of the beta. % DG: But just made me thought that all of indirect interactions (in the traditional sense, with a cascade of interactions) are drivers of beta diversity of interactions. It's a purely species composition component, but still it is very interesting.

A common feature of the examples mentionned in this part is that pinpointing the exact mechanism through which species interaction interfere requires most often a good knowledge of the system's natural history. In their current state, ecological networks most often account for a single type of interactions (although new datasets are starting to emerge, *e.g.* Mouritsen et al. 2011 and). Our ability to understand these complex phenomenon will be contingent on our ability (i) integrate different types of interactions in ecological networks (Kéfi et al. 2012), and (ii) to provide rich meta-data regarding the identity of each node in the network. % DG: you have to go further than a ref to Kefi here, this section adress interactions that are not considered by Kefi. You can have a look instead at Goudard and Loreau Goudard, A. & Loreau, M. (2008). Non-trophic interactions, biodiversity and ecosystem functioning : an interaction web model. *The American Naturalist*, 171 : 91–106.

Benefits for network analysis

Accounting for the relationships between biotic interactions can be a powerful explanation for species co-occurrence. A recent experimental work by Sanders and van Veen (2012) showed that some predators species can only be maintained if another predator species is present, which regulates a competitively superior prey, hence allowing prey coexistence. These effects involving several species and several types of interactions across trophic levels are complex

(and for this reason, have been deemed unpredictable in the past, Tack et al. 2011), and can only be understood by comparing communities in which different species are present/absent. To better understand these effects, it is important that several networks with similar species compositions are sampled. Assuming that interactions are present is obviously not enough, and the data needed to characterize these mechanism need to include a precise measure of interaction strength between each species. It is true that such data are orders of magnitude more difficult to gather than literature surveys or expert knowledge, but they are the only way to go beyond the current paradigm of seeing networks as mostly a collection of pairwise interactions.

% DG: Isn't co-occurrence also important to other processes? It will contribute to the turnover of interactions under all three processes. It is only through this one though that it will affect the interaction strenght (beta link).

From a biogeographic standpoint, it require that we develop a theory based on interaction co-occurrence, in addition to the current knowledge encompassing only species co-occurrence. Araújo et al. (2011) and Allesina and Levine (2011) introduced the idea tha competitive interactions can leave a trace in species co-occurrence network. It is now time to apply this logic to other types of interactions. In part, this can be done through the re-analysis of already existing datasets, although the statistical foundation of such a work is still mostly unknown (Thuiller et al. 2013).

% DG: I dropped here, there is considerable work to be done above before going back to the conclusions. We'll talk more about it. There is interesting stuff though below that might worth being moving up (e.g. the effect of the environment on the beta)

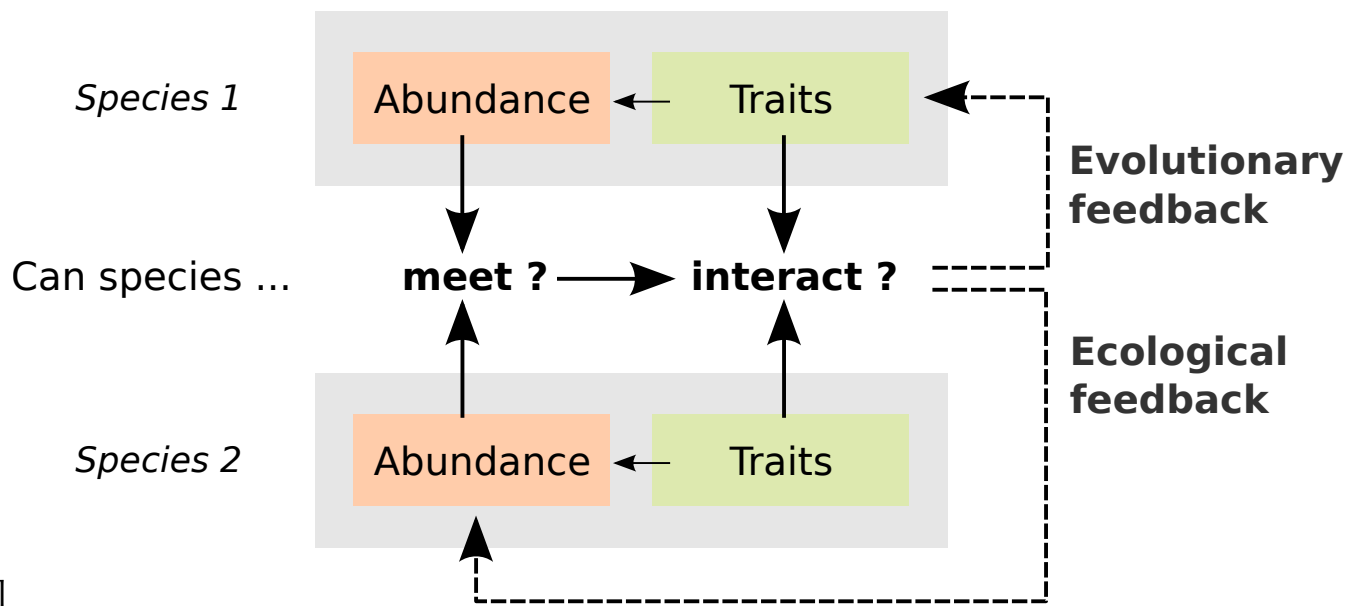
Conclusions

The notion of "species interaction networks" is an epistemological obstacle, as it shift our focus away from the level of organization at which most of the relevant processes happen —

populations. As of now, it is difficult to understand how wrong we are (if at all), because data to properly separate the impact of different families of mechanisms on the variability of species interactions are scarce. Even when such data are available (*e.g.* Schleuning et al. 2011 , Menke et al. 2012, Schleuning et al. 2012), they were often not analyzed in this way, because the methodology is still mostly lacking. Some preliminary methods have been proposed. Blüthgen et al. (2008) claim that the impact of traits distribution on network structure can be inferred simply by removing the impact of neutrality (population densities), based on the idea that many rare links were instances of sampling artifacts. Their result is however of limited generality, because their simulation approach assumes no trait matching, and thus allows the maximal generality of each species. Under this framework, what is measured is sampling bias, but not trait (mis)matching. So as to understand the impact of neutrality and traits distributions, it is crucial that not only interactions, but also population densities (needed to define the neutral expectation) and local trait distribution (needed to quantify the niche processes), are sampled. In a recent contribution, we proposed to measure the turnover of interactions between communities (Poisot et al. 2012). The origins of this turnover will require more data to be fully appreciated, and the development of a new methodology partitioning the causes of variability in interactions. In the next sections, we synthesize the mechanisms mentioned in this paper, and conclude by stating the need to scale down the observation: from species to population, from occurrence to population density, and from trait values to local trait distribution.

A synthesis

Perhaps more importantly, all of these mechanisms will allow looking at the impact of environmental variation on the structure of networks. As illustrated in Fig. [fig:synth], because different environmental conditions will (i) affect local trait distributions and (ii) change population sizes, we expect a strong effect of these changes on network structure. Looking at networks as a collection of interacting populations will allow testing the mechanisms through which environmental change affects network structure.



[tb]

[fig:synth]

Alesina et Eklof: number of traits and dimensions

Perspective: time to scale down

The common thread to all the processes reviewed here is that they act at the population level. Incidentally, they can be measured at the population level. So as to understand why there is turnover in the interactions in a metaweb, we need to gather more informations about the species. The value of relevant traits is an important information to have, and which traits are relevant can often be intuited from the natural history of the species. For example, proboscis length in pollination, jaw size in predation, attachment organs shape in ecto-parasitism, and so forth. Melián et al. (2011) showed that there is promise in studying interactions at the individual level, as it will bring in new knowledge about the eco-evolutionary dynamics. However, building a general theory of interactions biogeography will require a large number of accurately described metawebs, and expecting that each of them will be sampled to the individual level is not reasonable. Populations, although they aggregate individual-level mechanisms, can be reliably sampled over time and space (Stanko et al. 2002, Krasnov et al. 2004). We certainly do not call for the dismissal of species-level approaches, or of network inference based on databases of species traits. Rather than being used to draw ecological or

evolutionary conclusions, these should be used at a good approximation of the space of all possible interactions. Which of these interactions will be realized, hence taking part in ecosystem functioning and emerging community properties, is regulated locally by population-level processes.

The recent years saw a surge in the number of articles focused on describing the variation, structure, and dynamics of interactions networks over space. Most of these works were focused on food webs, but given the simple elements upon which they rely, it is likely that their conclusions will hold in other systems. Calcagno et al. (2011) demonstrated that meta-community dynamics allowed predicting the maximal length of trophic chains. Gravel et al. (2011) expanded the classical model of the *Theory of Island Biogeography* (MacArthur and Wilson 2001) to food webs, showing it predicted local connectance and richness of two large datasets accurately in any system which can be modeled as a series of connected islands. Pillai et al. (2011) showed that the regional structure of interactions can vary as a consequence of changes in competition for resources in local patches. While all these papers represent major advances, as they contribute to merge the fields of network analysis and biogeography (Cumming et al. 2010), they only address network-wide properties. Understanding the bases of variations between networks will be easier if we understand the sources of interaction variability (Poisot et al. 2012), and are able to predict it. The propositions made in this paper seek to make this understanding easier, through grounding it in well known mechanisms.

The next logical step is to build upon the knowledge of each of these mechanisms to refine our statistical approach of network structure. We see several important directions for future research in this field. First, it is important to decorticate the impact of large families of processes on network structure. We provide some insights about these approaches in *Box 1*. When traits and population sizes are known locally, approaches like variance partitioning can (i) measure the importance of trait-based and neutral processes, and (ii) remove these influences together, or in turn, and compare the resulting network structure. This is not possible by assuming that species interact in a consistent way across all locations. Second, ecologists working with networks should engage in a collective reflection about the relevant traits and informations

needed to characterize a network. Homogenizing sampling procedures and meta-data will increase our ability to conduct meta-analyses, thus describing in much more depth the mechanisms involved in the variation of network structure.

Boxes

Box 1: A statistical framework for population level interactions

In this contribution, we propose that at the population level, the occurrence (and intensity) of ecological interactions relies on several factors, including relative local abundances, local trait distribution. It is important to tell apart these different factors, so as to better disentangle neutral and niche processes. In an ANOVA-like context, this amounts to see the occurrence of an interaction as a simple linear model of the general form

$$\mathbf{A}_{ij} = [(N_i \times N_j) \times (T_i \times T_j)] + \epsilon$$

wherein N_k is the local abundance of population k , and T_k is a measure of its position in a trait space; ϵ is an error term. \mathbf{A}_{ij} can take the form of, according to what is measured in the field, either presence and absence of interactions, or a measure of interaction strength. The term $(T_i \times T_j)$ can be as complex as needs be, and can rely on the use of latent variables (Rohr et al. 2010) rather than actual traits values. Re-casting the question of the occurrence of an interaction as a statistical one can at first seems at odd with our goal to incorporate more explicit feedbacks between traits, population sizes, and interactions. However, it bears two important advantages. First, it allows to identify broad patterns, namely which kind of interactions are more affected by neutral and niche processes. Second, it allows to partition the impact of said processes on the occurrence of interactions; this, in turn, allows to derive the structure of interactions *in the absence* of any niche, or neutral effects, which will find useful applications as it is a null model of species interactions. Further, in a multi-site context, we can reformulate the above linear model as

$$\mathbf{A}_{ijx} = [(N_{ix} \times N_{jx}) \times (T_{ix} \times T_{jx})] + \epsilon_{ijx}$$

In which the x indice denotes one site at which the interaction is either present or absent. The structure of the error term, *i.e.* its spatial or temporal auto-correlation, or covariance with either population sizes or trait values, can then be analyzed to further refine our predictions on species interaction variability.

Box 2: Between-site variability under neutral and trait-based assumptions

We use a simple conceptual model to generate predictions about the dissimilarity between networks in which only neutral effects, or neutral and traits effects, regulate the existence of interactions. Starting with a pool of 50 species establishing trophic interaction (see the reference to the model for details), we generate 50 replicates run, each starting with equal size of each population. After 2500 timesteps, we record the current state of the network, by pooling all the interactions which occurred over the last 20 timesteps. For the neutral and trait scenario, we reconstructed the metaweb, *i.e.* the regional pool of all species and their realizations. Based on this information, we (1) measure the dissimilarity between the 50 replicated networks (*i.e.* how different do we expect these networks to be in nature – top row of the figure), and (2) measure the distance between each of these networks and their respective metaweb (bottom row), using the β -diversity measures of networks proposed by Poisot et al. (2012). This analysis shows that the networks in which only neutral effects acts are more dissimilar (β_{WN}) than when traits regulate interactions. This also true of the way shared pairs of species (β_{OS}) interact. When measuring the contribution of species turnover to network turnover ($\beta_{contrib}$), it is clear that it is far less important in the neutral situation (*i.e.* because traits are not important, all species are functionally equivalent provided that their abundances are similar). Similarly, networks in the trait-based situation are relatively similar to their metaweb (approx. 20 % of difference), whereas the neutral ones are not (approx. 80 % of difference). This last result allows to estimate the error made when assuming that all interactions reported in the metaweb consistently occur over space (*e.g.* Havens 1992). Finally,

these results assume an homogeneous environment, *i.e.* the feeding niche of the species are not affected by local environmental conditions. Should it be the case, we expect an increased variability in the networks in which traits determine the interactions.

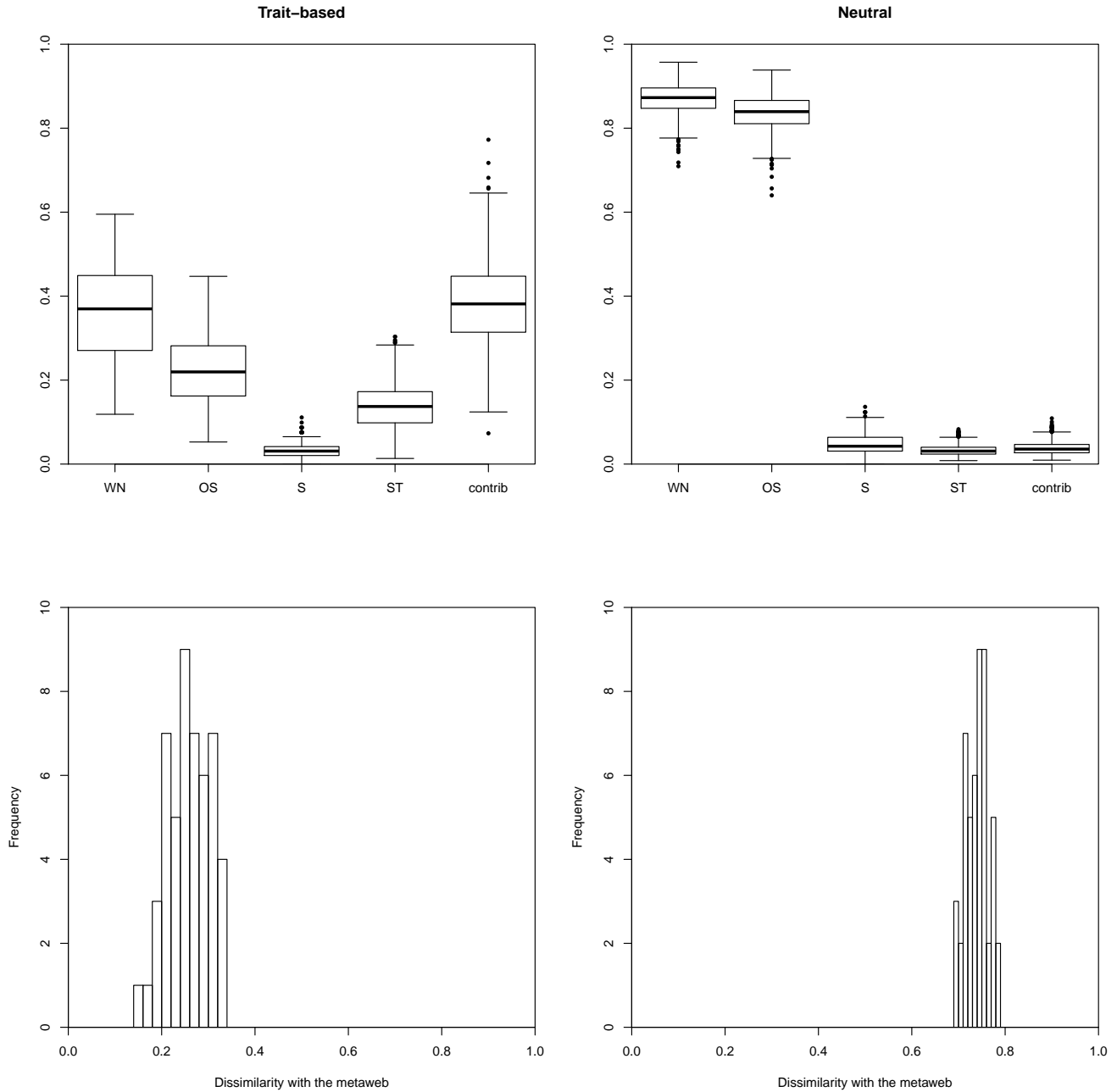


Figure 3: image

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