

The non-random assembly of functional motifs in plant-pollinator networks worldwide

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Abstract

Ecological processes leave distinct structural imprints on species interactions shaping the topology of mutualistic networks. Detecting those relationships is not trivial since they go beyond pair-wise interactions, but may get blurred when considering full network descriptors. However, recent work has shown the network meso-scale can capture this important information. The meso-scale describes network subgraphs representing patterns of interactions between a small number of species (i.e. motifs) and those constitute the building blocks of the whole network. Here, we have compiled 60 networks from 18 different studies and show that some motifs are consistently under- and over-represented worldwide, suggesting that the building blocks of plant-pollinator networks are not random. Furthermore, we found that distinct motif positions describing species ecological roles (e.g., generalization, indirect interactions) are occupied by different functional groups on both trophic levels. For instance, bees appear consistently in generalist motif positions and plants with higher levels of outcrossing tend to have a large number of indirect interactions. Interestingly, the realized combinations of different functional groups within a motif can not be retrieved from their joint probability distributions, indicating that functional group combinations are not random either. Our result highlight the non-random structure of indirect interactions in plant-pollinator networks and opens the door to predict novel interactions beyond pairwise interactions within a community context.

INTRODUCTION

Ecological communities are formed by a plethora of interacting species that form networks of interactions. Because of the tremendous complexity of these ecological networks, species interactions are generally condensed in metrics that summarize this information (Guimarães 2020). Plant-pollinator interactions are no exception, and they are often studied with indices that aggregate the information at the species (micro-scale) or network level (macro-scale). For example, plant-pollinator network level approaches have identified common invariant structural properties across networks, including a degree distribution that decays as a power law (Jordano 1987), nestedness (Bascompte et al. 2003), or modularity (Olesen et al. 2007). In addition, the local species

position within the network can define its degree of specialization (Blüthgen, Menzel, and Blüthgen 2006) or its role connecting the rest of the community (Olesen et al. 2007). Despite the unquestionable progress with the use of these metrics at both species and network level, condensing the information into a single metric implies the loss of relevant ecological information that obscures the understanding of the ecological processes (Cirtwill et al. 2018; Simmons, Cirtwill, et al. 2019).

Traditionally, plant-pollinator research has focused on direct interactions but overlooked indirect interactions (i.e., the mediated effect between two species by a third species), such as facilitative or competitive interactions between plants for pollinators (Moeller 2004; Sargent and Ackerly 2008). Despite the widespread nature of indirect interactions in ecological communities (Strauss 1991), plant-pollinator research often fails to finely capture those indirect interactions with the conventional analytical tools that condense the information either by species (e.g., interaction frequency) or in global topological indices (e.g., nestedness). Nonetheless, the emerging framework of network motifs (small sub-networks recorded within a given network) in plant-pollinator research allows to consider both direct and indirect interactions (Simmons, Cirtwill, et al. 2019). Motifs are often referred to as the building blocks of a network that depict subsets of interactions (Milo et al. 2002). The analysis of network motifs in plant-pollinator networks have revealed that the different ecological processes that govern species interactions (e.g., species abundances versus trait-matching) can lead to different patterns of indirect interactions (Simmons et al. 2020). Yet, the global patterns of indirect interactions in real plant-pollinator networks are still unknown (e.g., over- and under- represented motifs).

Despite motifs are abstract representations often decoupled from species ecology, linking the structural properties of the meso-scale with the species ecology can help the understanding of ecological processes. For instance, different motifs can have different ecological meanings (Simmons, Cirtwill, et al. 2019) and the position within a motif can determine the species functional role (Stouffer et al. 2012; Baker et al. 2015). However, it is unclear how the species ecology and life history traits determines the species' functional role within the network of interactions (Coux et al. 2016). For example, large pollinators can forage larger distances (Greenleaf et al. 2007), deposit greater pollen quantities (Földesi et al. 2021) and handle complex zygomorphic flowers in comparison with small pollinators that are restricted to lower floral complexity (Gong and Huang 2009). How this different pollinator behavior translates into their interaction topology is unknown. Similarly, recent empirical findings indicate that the meso-scale is the best descriptor of plant reproductive success (Allen-Perkins et al. 2021), but little is known about how plants reproductive strategies shape their position within the network of interactions. Although some studies have evaluated plant reproductive strategies in plant-pollinator networks (Tur, Castro-Urgal, and Traveset 2013; Lázaro et al. 2020), this is an often overlooked aspect in a community context (Devaux, Lepers, and Porcher 2014) and rarely incorporated

into plant-pollinator network studies. Hence, exploring how the main plant reproductive strategies integrate with the emergent motif framework can shed light on key aspects of ecosystem functioning.

Here, we used 60 plant-pollinator networks from 18 different studies and 14 countries, alongside functional groups of plants and floral visitors based on functional traits and taxonomic rank, respectively. To obtain plant functional groups, we used a comprehensive dataset that included floral, reproductive and vegetative traits compiled in a larger set of networks. Floral visitor functional groups were divided by the main taxonomic groups that differed in life form and behaviour. Once we split the different plant-pollinator networks into their motif elements, we explored: (i) if there is a common invariant structural property in the overall motif networks (i.e. over and under-represented motifs); (ii) which functional groups are over and under-represented in the different motif positions; and, (iii) if there are over and under-represented functional group combinations within a motif.

METHODS

Plant-pollinator studies

We have compiled 60 plant-pollinator networks from 18 different studies (**Table S1**). All studies sampled plant-pollinator interactions in natural systems and were selected based on wide geographical coverage and presence of interaction frequency as a measure of interaction strength. In total, there were 503 plant species, 1,111 floral visitors species and 6,248 pairwise interactions registered. For ease of data manipulation, plant and floral visitors species names were standardized with the help of the R package *taxize* version *0.9.99* (Chamberlain et al. 2020). All analyses and data manipulation were conducted in R *version 4.0.5* (R Core Team 2021).

Plant and floral visitors functional groups

First, plant species were grouped through hierarchical clustering into the optimal number of functional groups that summarized the main plant reproductive strategies. For this, we used the trait dataset collated in Chapter 1 that comprised a total of 1506 species including the 503 species considered in this study (Supplementary material Chapter 1 **Table S1**). This dataset consisted of 8 floral, 4 reproductive and 3 vegetative traits excluding traits with high percentage of missing values (over 30%; **Table S2**). We opted to calculate the plant functional groups on this larger set of species because of the higher accuracy when delimiting functional groups with that many variables and species (Dolnicar et al. 2014). To feed the clustering analysis, we calculated the distance between the different qualitative and scaled quantitative variables with Gower distance

(Gower 1971). For this, we used the function *gowdis* with method *ward.D2* from the package *FD* version 1.0-12 (Laliberté et al. 2014). Finally, we conducted hierarchical clustering with the function *hclust* from the *R* stats package version 4.0.5 and calculated the optimal number of clusters with the function *kgs* from the package *maptree* version 1.4-7 (White and Gramacy 2009).

Second, floral visitors were grouped into functional groups based on taxonomic rank as done similarly in past plant-pollinator studies (Fenster et al. 2004; Ollerton et al. 2009). We opted to divide floral visitors on the taxonomic rank level and not with functional traits because the main orders of floral visitors differed in form and behaviour and had lower superior taxonomical complexity (i.e., floral visitors had 6 orders versus plants that had 38). Thus, this allowed us to group floral visitors into functional groups that represented adequately the main life strategies of the possible pollinators: (i) bees (Hymenoptera-Anthophila), (ii) non-bee Hymenoptera (Hymenoptera-non-Anthophila), (iii) syrphids (Syrphidae-Diptera), (iv) non-syrphids-Diptera, (v) Lepidoptera and (vi) Coleoptera. However, a minor set of species belonged to other functional groups that were considered in analyses but not discussed further because of their low representation in the full set of networks (3.55% of the total interactions recorded). These functional groups were ‘lizards’, ‘birds’ and ‘other insects’. This last group was formed by a mix of uncommon insect taxa on the full set of networks.

Overall motif patterns

Following previous work (Simmons, Cirtwill, et al. 2019; Simmons et al. 2020), we broke down the plant-pollinator networks into their constituent motifs. Prior to analyses, we turned the quantitative networks into qualitative (or binary) ones, where interactions are present or absent. To test the effect of singletons, we ran all analysis to the same set of networks, but considering only interactions whose frequency was greater than one (64.98% of interactions). Results are qualitatively consistent and are not further discussed in the main text (**Figures S1 and S2**).

We calculated the frequency of all motifs up to five nodes (see **Figure 1**) for each empirical network, by using the *bmotif* package version 2.0.2 (Simmons, Sweering, et al. 2019). To control for variation in network size, motif frequencies were normalised as a proportion of the total number of motifs within each motif class (i.e., the number of nodes a motif contains). Like Simmons et al. (2020), we just used five-node motifs in our analyses for visualisation, interpretation and computational reasons. In addition, we also excluded two-node motifs (or links) from our analyses because their normalised frequencies would always equal one.

To assess the significance of the observed frequencies, we created 1,000 simulated networks for each binary network using the *nullmodel* function and the *vaznull* model in the *bipartite* package version 2.14 (Dormann et al. 2009). Generated networks had the same number of plants and floral visitors, as well as the same

same motif size class. Then, we calculated the percentile of the observed position frequencies for each group and network, just like we did with motif frequencies. To outline the general patterns of position frequencies across networks and functional groups, we fit a LMM per motif position, where the response variable was the observed position percentile per network. We used the functional group identifier as an explanatory variable and the study identifiers as a random intercept. By adding the functional group estimates to the model intercept, we assessed the average motif frequency, after controlling the variation at the study level. Finally, we visualized with the help of the package *ComplexHeatmap* version 2.6.2 (Gu, Eils, and Schlesner 2016) over- and under- representation of plant and pollinator functional groups on the different motif positions.

Over- and under-represented functional group combinations of motifs

Finally, we studied which combinations of functional groups tend to appear together within the same motifs (up to five nodes). That is which combinations are over or under-represented. This analysis use 57 out of the 60 networks available due to computational limitations to identify all the nodes in the motifs of the three networks with the highest number of links. To do so, for each of the 53,250 possible motif combinations, we estimated the observed and the expected probability of finding those combination in empirical networks, respectively. Then, we determined whether the observed probabilities are likely to come from the expected probabilities or not. To calculate the observed probability (p_i^O) of functional groups within a motif i (e.g., motif 3, ‘bee’ + ‘bee’ + ‘selfing herbs’), we divided the number of times that i appears in our set of empirical networks (n_i^O) by the sum of the number of times that each possible combination appeared: $p_i^O = n_i^O / \sum_{k=1}^{53,250} n_k^O$. To estimate the expected probability of a given motif combination i , p_i^E , firstly, we calculated the probability of finding a given functional group x in the position α of i , $p_i(x, \alpha)$. Then, by assuming the independency of $p_i(x, \alpha)$, we computed the expected probability of the combination i as the product of the probability of its pairs (x, α) , that is, $p_i^E = \prod_{(x, \alpha) \in i} p_i(x, \alpha)$. To obtain $p_i(x, \alpha)$, we proceeded as follows. First, we calculated the number of times that the functional group x appears in the position α in each empirical network η , denoted as $n_i^\eta(x, \alpha)$. Then, by controlling the variation at the network level, we assessed the average value of the absolute frequency of functional group x appears in the position α , $n_i(x, \alpha) = E[n_i^\eta(x, \alpha)]$, and estimated $p_i(x, \alpha)$ as $p_i(x, \alpha) = n_i(x, \alpha) / \sum_k n_i(k, \alpha)$. To obtain $n_i(x, \alpha)$, we fitted a LMM per motif position, where the response variable was the number of times that a given position was observed per network, the explanatory variable was functional group identifier, and the random intercept was given by network identifiers nested within the study identifiers.

Once we obtained p_i^O and p_i^E , we used a simulation approach to determine whether the former is likely to come from the latter or not. This approach was preferred since the large number of possible motif combinations and the small probabilities for some of them advise against using an exact test of goodness-of-fit or a Chi-square

one. Specifically, we created 1,000 random samples with repetition of possible motif combinations, where each sample contained 10 million elements and, for each combination, the probability of being selected was equal to its expected probability. From those random samples, we extracted the mean and the standard deviation of the expected probability of i , denoted as $E[p_i^E]$ and $\sigma[p_i^E]$, respectively, and calculated the z-scores of p_i^O as $z_i^O = (p_i^O - E[p_i^E]) / \sigma[p_i^E]$, for those motif combinations with $p_i^O > 0$. According to the usual interpretation of z-scores, combinations with $z_i^O > 1.96$ are over-represented, whereas those with $z_i^O < -1.96$ are under-represented, at the 95% confidence level. Notice that we focused on combinations with $p_i^O > 10^{-7}$ because, beyond the interest that can arouse the combinations that appear at most once, we do not have enough numerical resolution to accurately detect whether or not those combinations are under-represented (due to the limited size of our random samples).

RESULTS

Plant and floral visitor functional groups

The hierarchical cluster analysis divided the dataset into five different groups with different and overlapping characteristics (**Figure S3** and **Figure S4**). The first group referred to as ‘selfing herbs’ consisted on herbs with hermaphroditic flowers with high levels of autonomous selfing. The second group named ‘small outcrossing perennials’ had small perennial species with a mixed of life forms (i.e., trees shrubs and herbs) with outcrossing hermaphroditic flowers. The third group referred to as ‘self-incompatible perennials with large flowers’ comprised perennial species with a mixed of life forms and large self-incompatible hermaphroditic flowers with high number of ovules. The fourth group named ‘tall plants with small unisexual flowers’ had the tallest species, highest proportion of shrub and tree life forms, dioecious and monoecious breeding systems, small flowers and the highest numbers of flowers and inflorescences per plant. Finally, the fifth group named ‘short-lived outcrossers with long zygomorphic flowers’ consisted on small perennial and short-lived herbs with long self-compatible zygomorphic flowers that were unable to self-pollinate.

In total, there were 1,126 species of floral visitor with 6,325 interactions recorded with plants. Most plants interacted with bees (2,256 interactions) and non-syrphid Diptera (1,768) followed by syrphids (845), Lepidoptera (437), Coleoptera (432) and non-bee Hymenoptera (362).

Overall motif patterns

Most motifs were under- and over-represented (close to the 1st and 99th percentile, respectively) in the comparison between empirical and simulated networks (**Figure 2**). Motifs 3, 5, 9, 10 and 14 were under-

represented in empirical networks, that is, all were close to the 1st percentile and under the 25th percentile. Interestingly, four out of five of these motifs belonged to the largest path length classification (i.e., core-peripheral). In addition, motifs 2, 6, 7, 16 and 17 were over-represented, all over the 75th percentile and thus the closest to the 99th percentile. In contrast to the under-represented motifs, over-represented motifs belonged to the two shortest path length groups (i.e., complete and fan). The remaining motifs (i.e., 4, 8, 11, 12, 13, and 15) were between the 25th and 75th percentile. Notably, the exclusion of singletons from this analysis did not change the observed results (**Figure S1**).

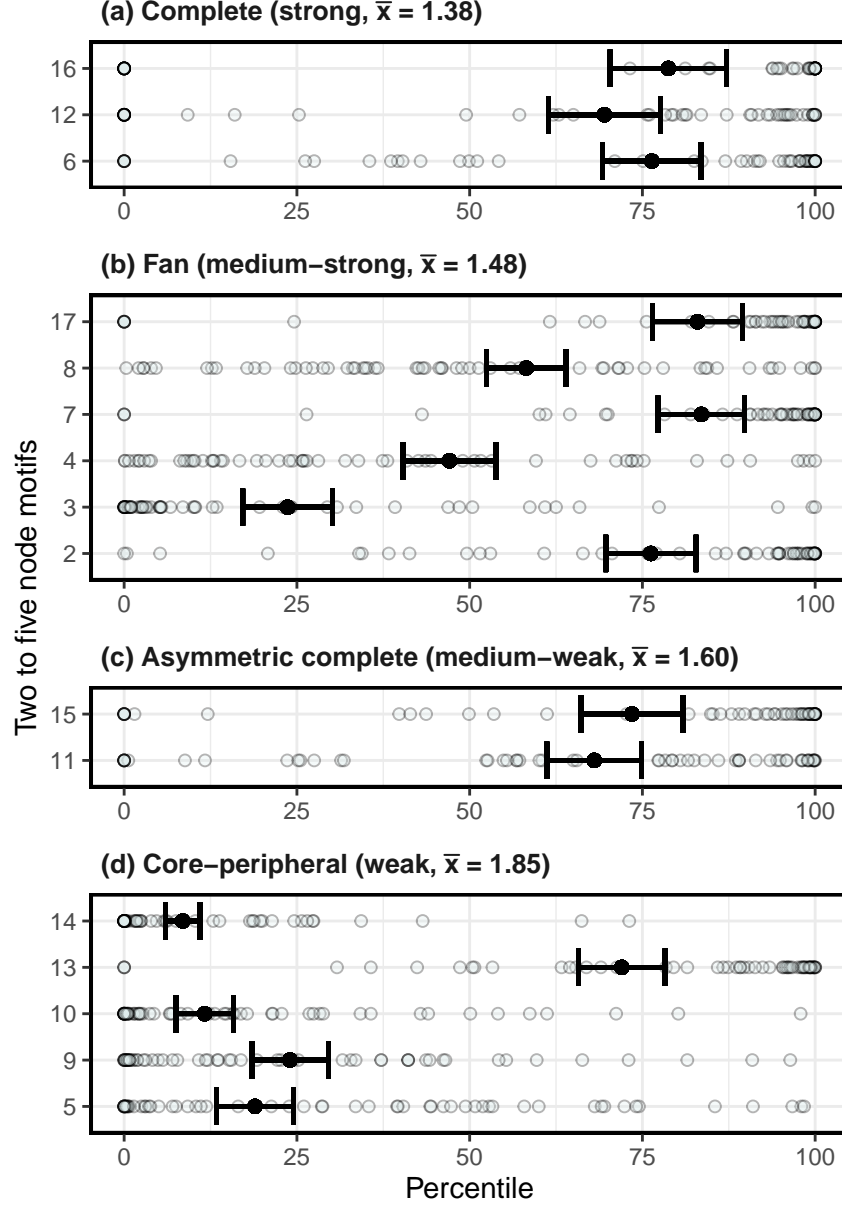


Figure 2. Comparison of motif frequencies between empirical and simulated networks grouped by average path length (plots a, b, c and d) as determined in Simmons et al. (2020). This is shown with the mean percentage of motif frequencies in empirical networks that were over the motif frequencies of the simulated ones (percentiles). This was done by network (light blue dots) and then averaged for all networks (black dots with error bars that correspond to the standard deviation).

Over and under-represented functional groups on motif positions

The comparison of the functional group frequencies per motif position between empirical and simulated networks showed a 6.36% and 25.38% of over- ($>75^{th}$) and under- ($<25^{th}$) represented functional groups in the different positions, respectively (**Figure 3**). Floral visitors showed a total of 4.55% and 32.58% of over- and under-represented functional groups in the different positions and plants 8.18% and 18.18% of over and

under-represented groups, respectively. Notably, the differences across functional groups were more marked for floral visitors than for plant functional groups (the differences between min and max percentiles per position were generally two-three times larger for floral visitors). From most over- to under-represented floral visitors functional groups on the different motif positions (indicated with the dendrogram order in **Figure 3**), we found: bees, non-syrphids Diptera, syrphids, Coleoptera, non-bee Hymenoptera and Lepidoptera. Although plant functional groups showed less differences between them, there were also more represented functional groups than others, thus from most over- to under-represented groups on the different motif positions we found: self incompatible perennials with large flowers, small outcrossing perennials, tall plants with unisexual flowers, selfing herbs and short lived outcrossers with long zygomorphic flowers.

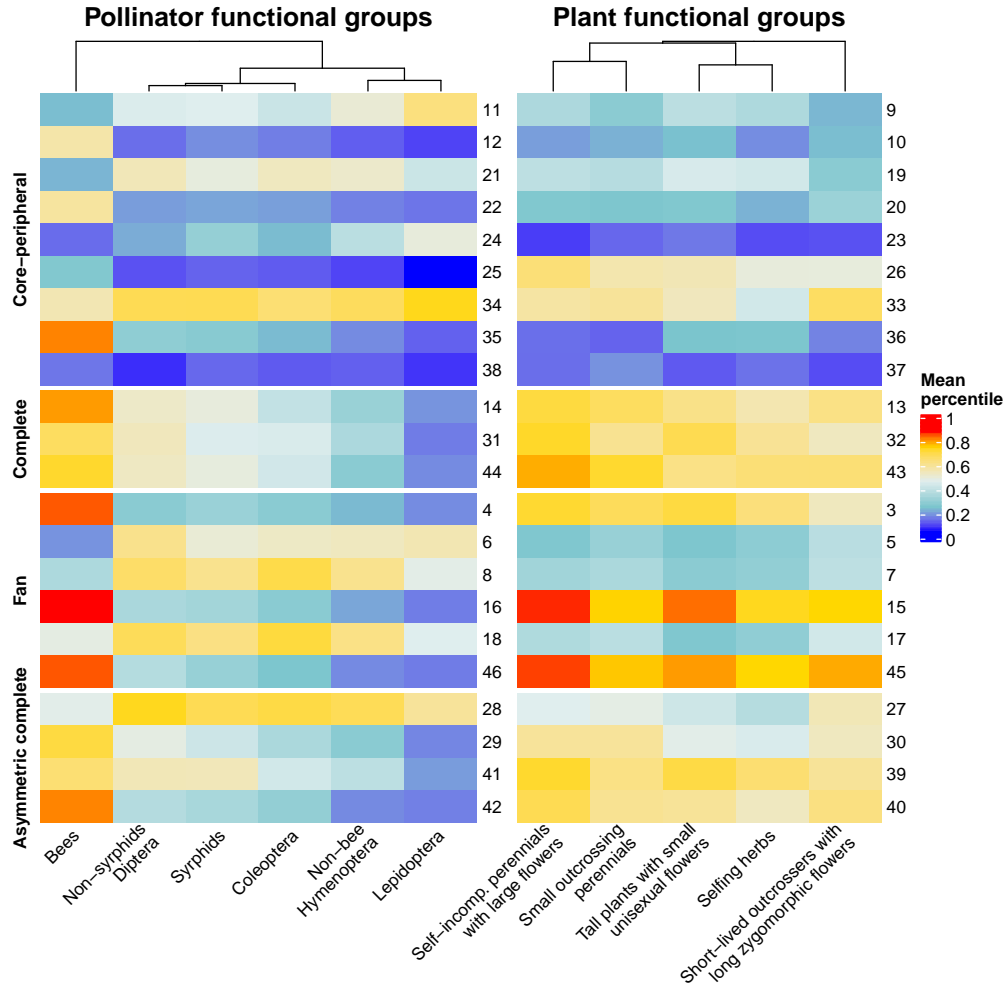


Figure 3. Heatmap indicating under- and over- representation of pollinator and plant functional groups in the different motif positions. The different motif positions are divided by the average path length clasification determined by Simmons et al. (2020). The superior dendrogram indicates the differences across groups with the more separated groups showing larger differences.

Over- and under-represented functional group combinations of motifs

The different observed frequencies on the different motif positions showed a hierarchical order of probabilities for floral visitors (**Figure 4**). That is, the functional group of ‘bees’ was the most abundant one on all motif positions followed by non-syrphid Diptera which was after bees, the second most frequent functional group on all positions. Then, the group of syrphids was the most abundant in all positions but two (positions 28 and 31 from motifs 11 and 12, respectively). After syrphids, Coleoptera was the most frequent group on the different positions followed by non-bee Hymenoptera and finally, Lepidoptera which was the less frequent group on all positions but two (positions 12 and 22 from motifs 5 and 9, respectively). Remarkably, plant functional groups were more variable on the different motif positions. However, there were also predominant functional groups found across the different motif positions. The three most frequent groups were ‘tall plants with small unisexual flowers’, ‘self-incompatible perennials with large flowers’ and ‘small outcrossing perennials’. On the contrary, the groups of ‘selfing herbs’ and ‘short lived outcrossers with long zygomorphic flowers’ had the lowest probability to be present on the different motifs plant positions.

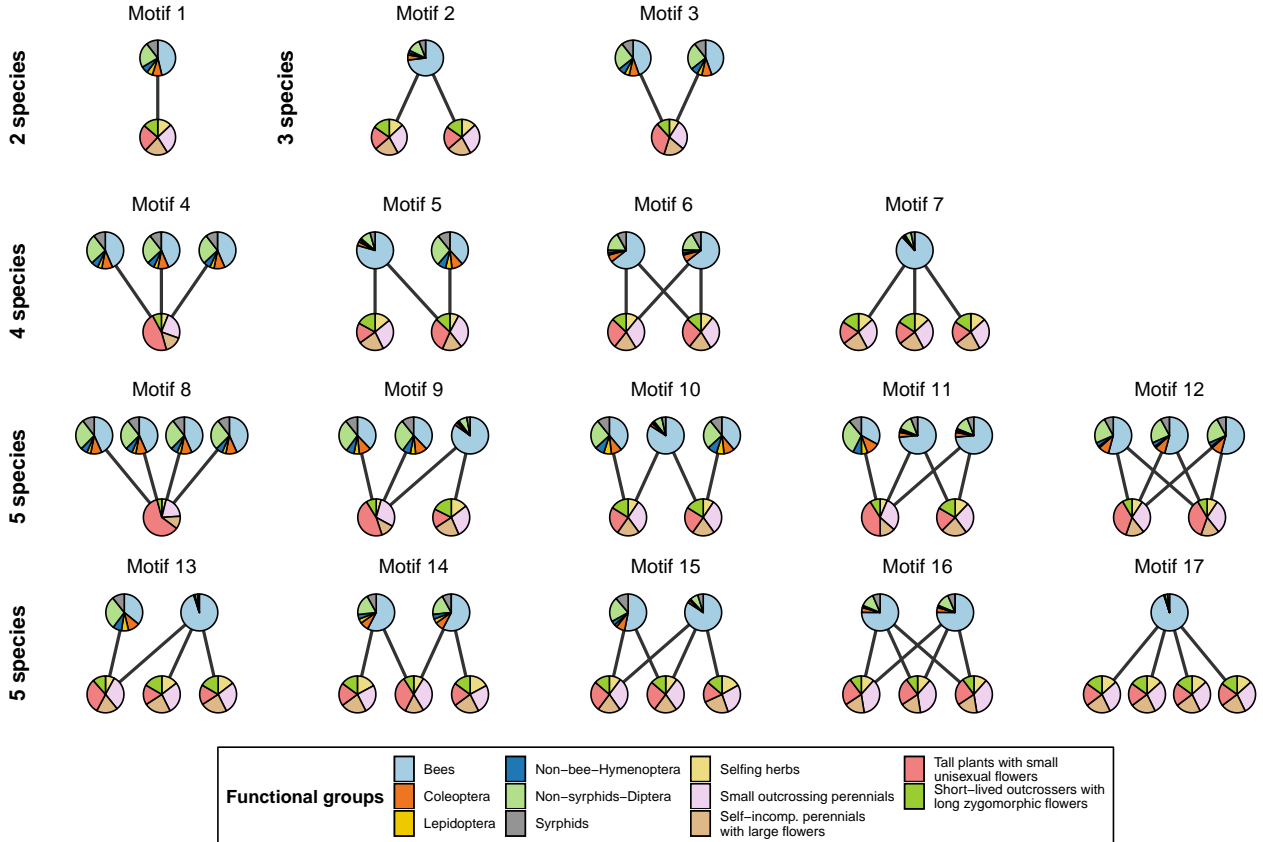


Figure 4. Graphical representation of the probability of finding a given functional group x in the position α of motif i , $p_i(x, \alpha)$, for all the possible motifs from two to five species in bipartite networks. The slices in the nodes for a given functional group x are proportional to the corresponding value of $p_i(x, \alpha)$.

The statistical comparison with z-scores between the observed and expected functional group combinations showed that we can not recover the observed combinations from its probability of occurrence. In fact, most combinations are under- or over- represented and follow a modified Gaussian distribution (Johnson's S_U) with 65% of under-represented group combinations, 20% of no statistical difference and 15% of under-represented ones (**Figure 5**). In addition, motifs with small node combinations (i.e., 2 and 3 nodes) only appeared as under-represented. Motifs with 4 and 5-node combinations appeared in the three statistical categories but 4 node motifs had a higher proportion in the under-represented category (10% in comparison with the 1% and the 3% of the no statistical difference and over-represented categories, respectively). Finally, 5-node motifs were in similar proportions in the no statistical difference and over-represented categories (99% and 97%, respectively) but they appeared in lower proportion in the under-represented category (89%). When, we explore the identity on the different positions of the most probable motif combinations we find as expected that the most common functional groups rule these positions on the most probable motif combinations (lower panel **Figure 5**).

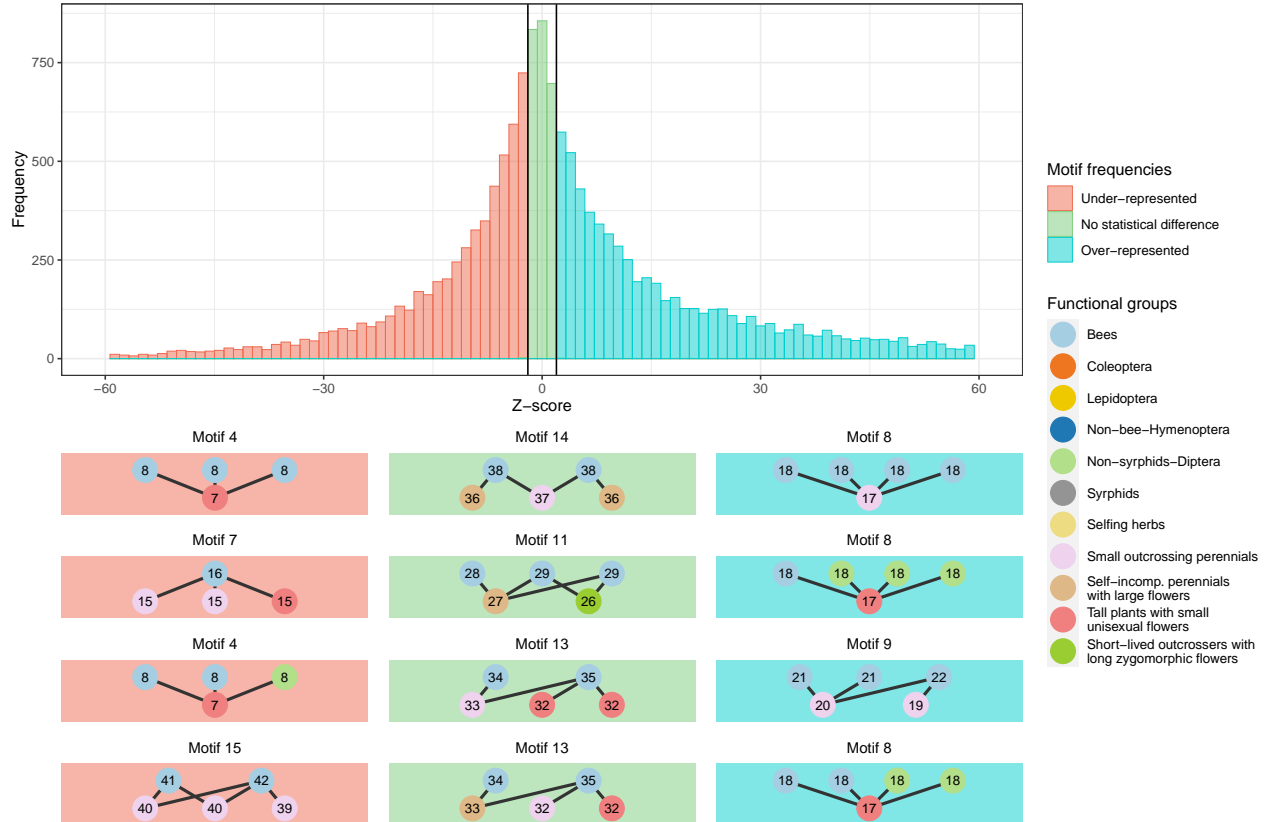


Figure 5. Z-score comparison (95% confidence level) of the observed and expected frequencies of motif combinations with four specific graphical examples of the most probable motifs of being observed for each category delimited by the z-score critical values: under-represented, no statistical difference and over-represented.

DISCUSSION

Understanding the global patterns of network structure is key to unravel the processes that govern community dynamics (Bascompte and Jordano 2007; Bastolla et al. 2009; Guimarães 2020). However, common analytical approaches are unable to capture the full complexity of ecological systems (Simmons, Cirtwill, et al. 2019). Because network motifs can capture both direct and indirect interactions, by analysing over- and under-representation of motifs we are able to explore in greater detail ecological interactions (Stouffer et al. 2007). We have explored for the first time the overall structure and representation of network motifs in real plant-pollinator networks and shown that the different motifs up to five nodes are consistently over- and under-represented in comparison with simulated networks indicating the presence of ecological processes shaping their structure. Despite the presence of multiple ecological processes likely operating at the same time (e.g., neutral effects, morphological matching or phenological overlap), we found a tendency for over-represented structures with more densely connected motifs (i.e., complete, fan and asymmetric complete) suggesting that neutral effects are likely the predominant processes governing the structure of these network motifs (Simmons et al. 2020). Thus, as indicated for other network properties like nestedness (Krishna et al. 2008; Suweis et al. 2013), species relative abundances (i.e., neutral effects) are possibly one of the main determinants of indirect interactions in real plant-pollinator networks. brillante el parrafo!

From a pollinator perspective, we found that generalist network motifs were consistently over-represented (e.g. fan-type motifs; **Figure 2**). For instance, when we compare motifs with equal structure for both trophic levels, we found that floral visitors had always over-representation in the positions that implied the highest number of links. Despite this is in good agreement with the current view of the generalist tendency of pollinators (Waser et al. 1996; Olesen and Jordano 2002; Ollerton 2017), we found that this over-representation of the generalist network motifs was largely driven by the functional group of bees (e.g., positions 42, 46, 16, 4, 14 and 35 in motifs 15, 17, 7, 2, 6 and 13, respectively; see **Figure 3** for positions and **Figure 4** for motifs) while the rest of the functional groups tended to be under-represented in these generalist motifs and over-represented in motif positions with specialist roles (e.g., positions 11, 21, 28 and 34 in motifs 5, 9, 11 and 13, respectively; see **Figure 3** for positions and **Figure 4** for motifs). This large effect of bees on the overall patterns is no surprise, as bees were the functional group with largest number of interaction records in the whole set of networks as also recorded for other broad scale plant-pollinator network studies (Carvalho et al. 2014; Ollerton 2017). Unlike floral visitors, plant functional groups showed little differences on its appearance in different motif positions, and thus similar probability of appearing on all of them. If anything, the groups that involved higher levels of outcrossing showed a tendency to be

more over-represented and probable on different motif positions. For instance, the group of self-incompatible perennials with large flowers, one of the groups that is expected to have higher levels of outcrossing rate (Goodwillie et al. 2010), showed the highest over-representation of all plant functional groups (**Figure 3**); and the group of tall plants with unisexual flowers, the one that is expected to have the highest dependence of pollinators on reproduction (Rodger et al. 2021), was the most probable on the generalist motif for plant positions (i.e., plant nodes with 3 to 4 links; **Figure 4**).

The probabilities of appearance of each functional group on the different motif positions were insufficient to predict most of the observed network position combinations (**Figure 5**). This implies that not just the representation of network motifs types but also the identity of the elements of their structure is influenced by ecological processes that determine under- and over-representation of the different position combinations. In addition, we found that just 30% of the possible 53,250 motif combinations are realized. Thus, similarly to the presence of forbidden links at the network level (Olesen et al. 2011; Jordano 2016), we also found the existence of forbidden motif positions and those represented almost two thirds of the total possible combinations of indirect interactions. This concurs well with the general idea that plant-pollinator networks have a high proportion of non-realized direct interactions (Jordano, Bascompte, and Olesen 2003; Bascompte and Jordano 2013), and as a result, also a high proportion of non-realized combinations of indirect interactions. Some of this non-observed interactions are probably due to under-sampling (Dorado et al. 2011; Jordano 2016). However, a large fraction of the possible interactions do not take place because of life history constraints such as species co-occurrence, trait matching processes and phenological uncoupling (Olesen et al. 2011; Bartomeus et al. 2016; Jordano 2016). Despite the advances in the understanding on the ecological processes that influence species pairwise interactions (Bartomeus et al. 2016; Peralta et al. 2020), we still know little of how these processes determine competitive and facilitative interactions in mutualistic networks. Thus, as suggested by Simmons et al. (2020), exploring the proportion of these realized network motifs that are competitive or facilitative is a necessary next step to improve our understanding of the architecture of biodiversity (Bascompte and Jordano 2007).

Despite the obvious usefulness of functional groups in summarizing species ecological roles (e.g., similar reproductive biology and behaviour of pollinators), delimiting species into functional groups is not often trivial. For instance, taxonomic diversity and trait availability limit our ability to properly represent the wide range of reproductive strategies (Dellinger 2020) and different clustering analysis can lead to distinct outcomes (e.g., k-means and hierarchical clustering). Further, here we divided floral visitors on the taxonomic rank level because it represented adequately the pollinator species ecological roles without the need of the tremendous effort of compiling trait data for over 1000 species of floral visitors. However, further groupings

with traits could help revealing greater relevance of trait-matching processes on indirect interactions. We believe that this could be investigated by exploring which proportion of over- and under-represented motifs present high and low trait-matching, respectively. Moreover, we analysed network motifs focusing exclusively on presence-absence interactions which assume that all interactions are equally important but as suggested by Simmons et al. (2020), further work should account for quantitative measurements of the strength of plant-pollinator interactions. Finally, despite the wide geographical coverage of our plant-pollinator dataset, there are major gaps for some regions of the world with a clear bias towards Europe, America and islands which have long been interested ecologist (MacArthur and Wilson 1963; Warren et al. 2015). These biases are also found in global datasets of networks where the data is highly fragmented across space (Poisot et al. 2021) and more efforts are needed to capture global patterns of plant-pollinator interactions.

In conclusion, by following the framework of Simmons et al. (2020) we have been able to explore competitive and facilitative interactions in plant-pollinator networks worldwide and found that indirect interactions are non-random and are more strongly related to neutral processes than any other ecological process. Further, we found that motif combinations of functional groups are strongly constrained and that the distinct motif positions are associated with different functional groups with different ecological roles (e.g., generalization versus specialization). Although in this study we do not predict indirect interactions, our work is a first step to elucidate novel interactions beyond pairwise interactions.

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SUPPLEMENTARY MATERIAL

TABLES

Table S1 List of plant-pollinator network studies.

Table S2 Type of plant traits used in this study.

FIGURES

Figure S1 Over and under-estimated motif frequencies.

Figure S2 Over and under-estimated functional groups on motif positions.

Figure S3 Plant trait composition of functional groups.

Figure S4 Plant dendrogram with functional groups.

Table S1. List of studies ordered by author with the year of publication, number of contributed networks and digital object identifier

First author	Year	Number of networks	Country	DOI
Arroyo-Correa	2019	3	New Zealand	https://doi.org/10.1111/1365-2745.13332
Bartomeus	2008	6	Spain	https://doi.org/10.1007/s00442-007-0946-1
Bartomeus	2015	16	Spain	https://github.com/ibartomeus/BeeFunData
Bundgaard	2003	1	Denmark	Unpublished, Master thesis
Burkle	2013	1	United States	https://doi.org/10.1126/science.1232728
Dicks	2002	2	England	https://doi.org/10.1046/j.0021-8790.2001.00572.x
Dupont	2003	3	Denmark	https://doi.org/10.1111/j.1365-2656.2008.01501.x
Elberling	1999	1	Sweden	https://doi.org/10.1111/j.1600-0587.1999.tb00507.x
Fang	2008	1	China	https://doi.org/10.1111/1749-4877.12190
Inouye	1988	1	United States	https://doi.org/10.1111/j.1442-9993.1988.tb00968.x
Kaiser-Bunbury	2017	8	Seychelles	https://doi.org/10.1038/nature21071
Kaiser-Bunbury	2011	6	Seychelles	https://doi.org/10.1111/j.1365-2745.2010.01732.x
Kaiser-Bunbury	2010	2	Mauritius	https://doi.org/10.1016/j.ppees.2009.04.001
Lundgren	2005	1	Denmark (Greenland)	https://doi.org/10.1657/1523-0430(2005)037[0514:TDAHCW]2.0.CO;2
Olesen	2002	2	Mauritius and Portugal (Azores)	https://doi.org/10.1046/j.1472-4642.2002.00148.x
Peralta	2006	4	Argentina	https://doi.org/10.1111/ele.13510
Small	1976	1	Japan	/13960/t4km08d21

Table S1. List of studies ordered by author with the year of publication, number of contributed networks and digital object identifier (*continued*)

First author	Year	Number of networks	Country	DOI
Souza	2017	1	Brazil	https://doi.org/10.1111/1365-2745.12978

Table S2. Traits used to delimit the different plant functional groups divided in quantitative and categorical traits.

Quantitative traits		Categorical traits	
Type	Traits	Type	Traits
Vegetative	Plant height (m)	Vegetative	Lifepan
Floral	Flower width (mm)	Vegetative	Life form
Floral	Flower length (mm)	Floral	Flower shape
Floral	Inflorescence width (mm)	Floral	Flower symmetry
Floral	Style length (mm)	Reproductive	Autonomous selfing
Floral	Ovules per flower	Reproductive	Compatibility system
Floral	Flowers per plant	Reproductive	Breeding system
Reproductive	Autonomous selfing (fruit set)		

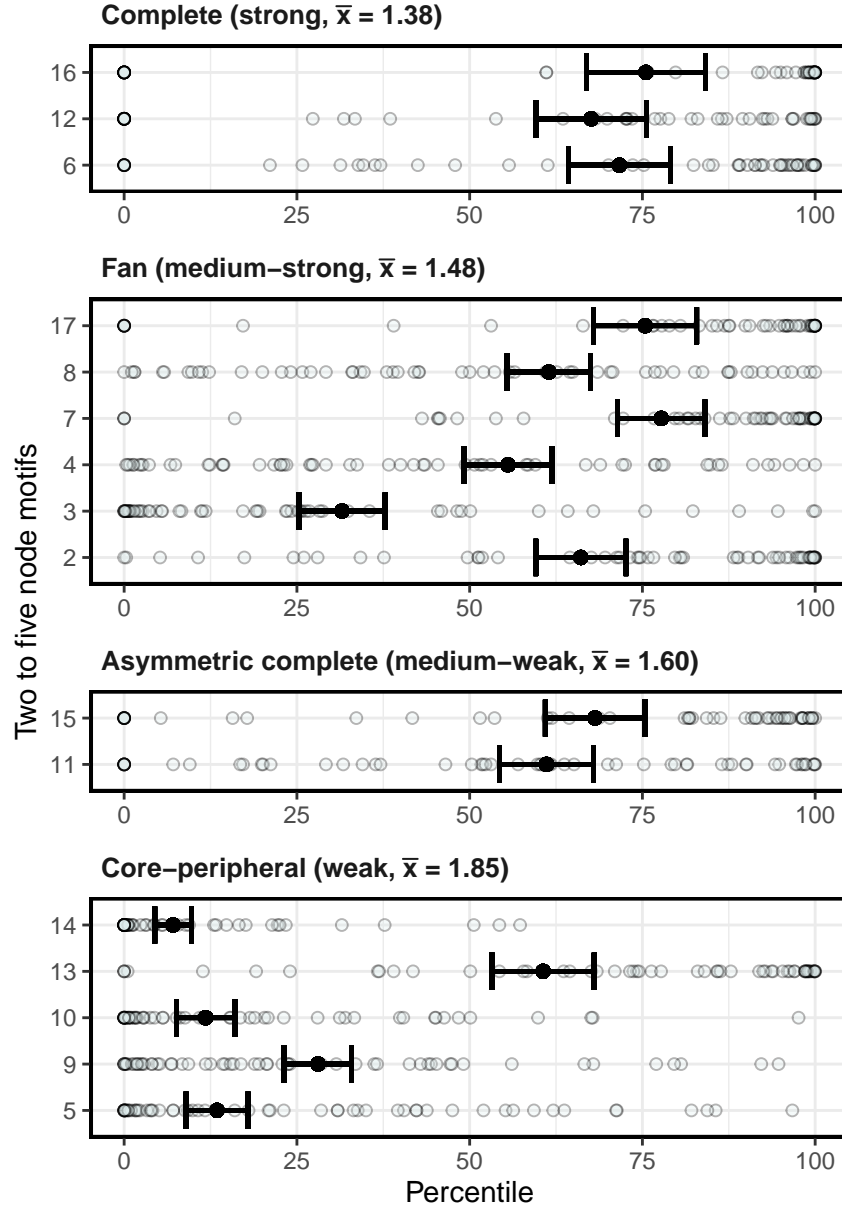


Figure S1. Comparison of motif frequencies between empirical and simulated networks grouped by average path length (plots a, b, c and d) as determined in Simmons et al. (2020) without considering singletons. This is shown with the mean percentage of motif frequencies in empirical networks that were over the motif frequencies of the simulated ones (percentiles). This was done by network (light blue dots) and then averaged for all networks (black dots with error bars that correspond to the standard deviation).

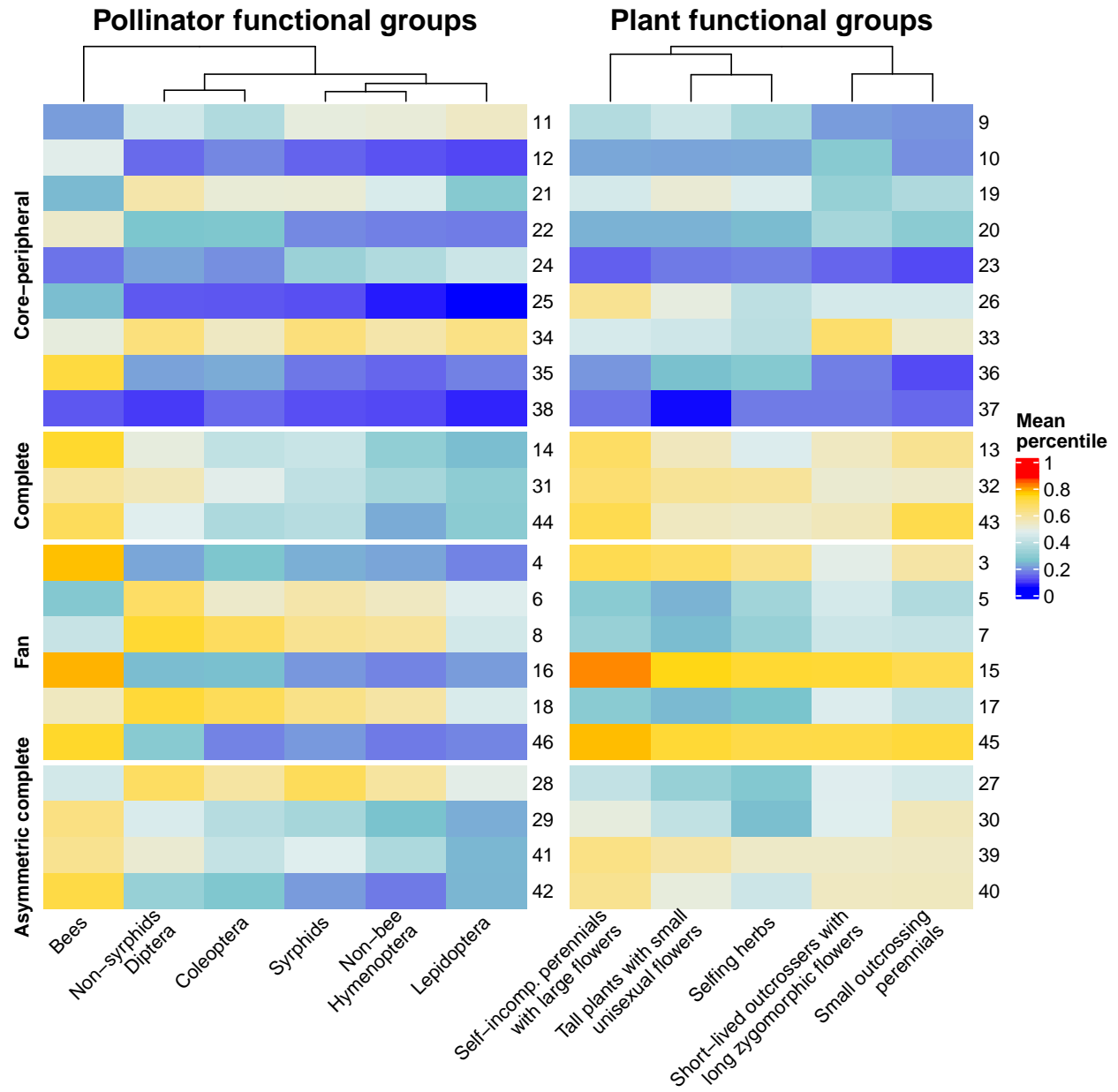


Figure S2. Heatmap indicating under- and over- representation of pollinator and plant functional groups in the different motif positions after removing non-robust links (singletons). The different motif positions are divided by the average path length classification by Simmons et al. (2020). The superior dendrogram indicates the differences across groups with the more separated groups showing larger differences.

Plant functional group composition

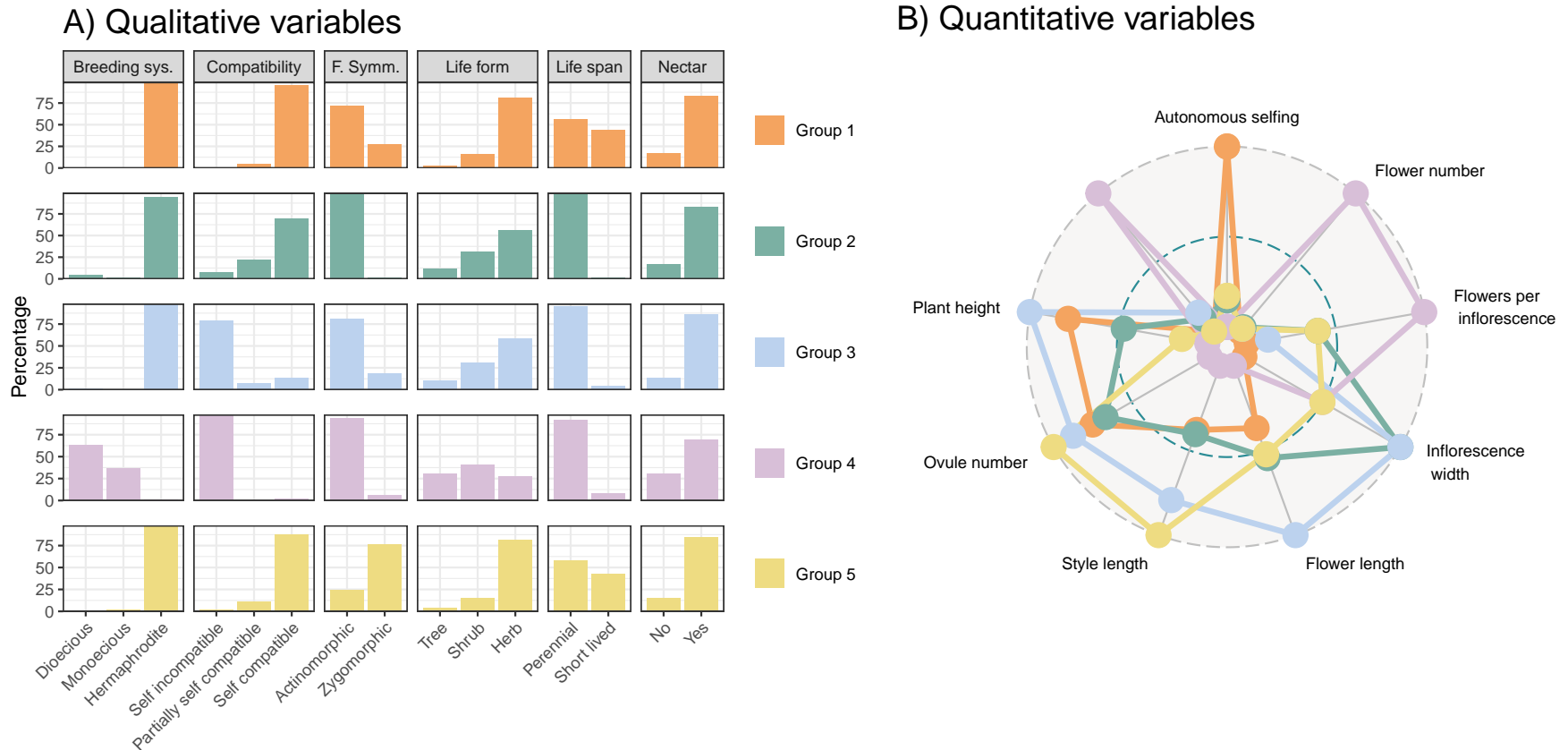


Figure S3. Plant functional group composition separated in qualitative and quantitative variables. Panel A) shows the percentage of the different categories within trait represented with different colours for each functional group. Plot B) shows the radar plot of the different quantitative variables standardized on the same scale also coloured with the same patterns of colours as qualitative variables per cluster or functional group. Group 1 corresponds to short-lived selfers; group 2 to small outcrossing perennials; group 3 to self-incompatible perennials with large flowers; group 4 to tall plants with small unisexual flowers; and, group 5 to short-lived outcrossers with long zygomorphic flowers.

Plant functional groups

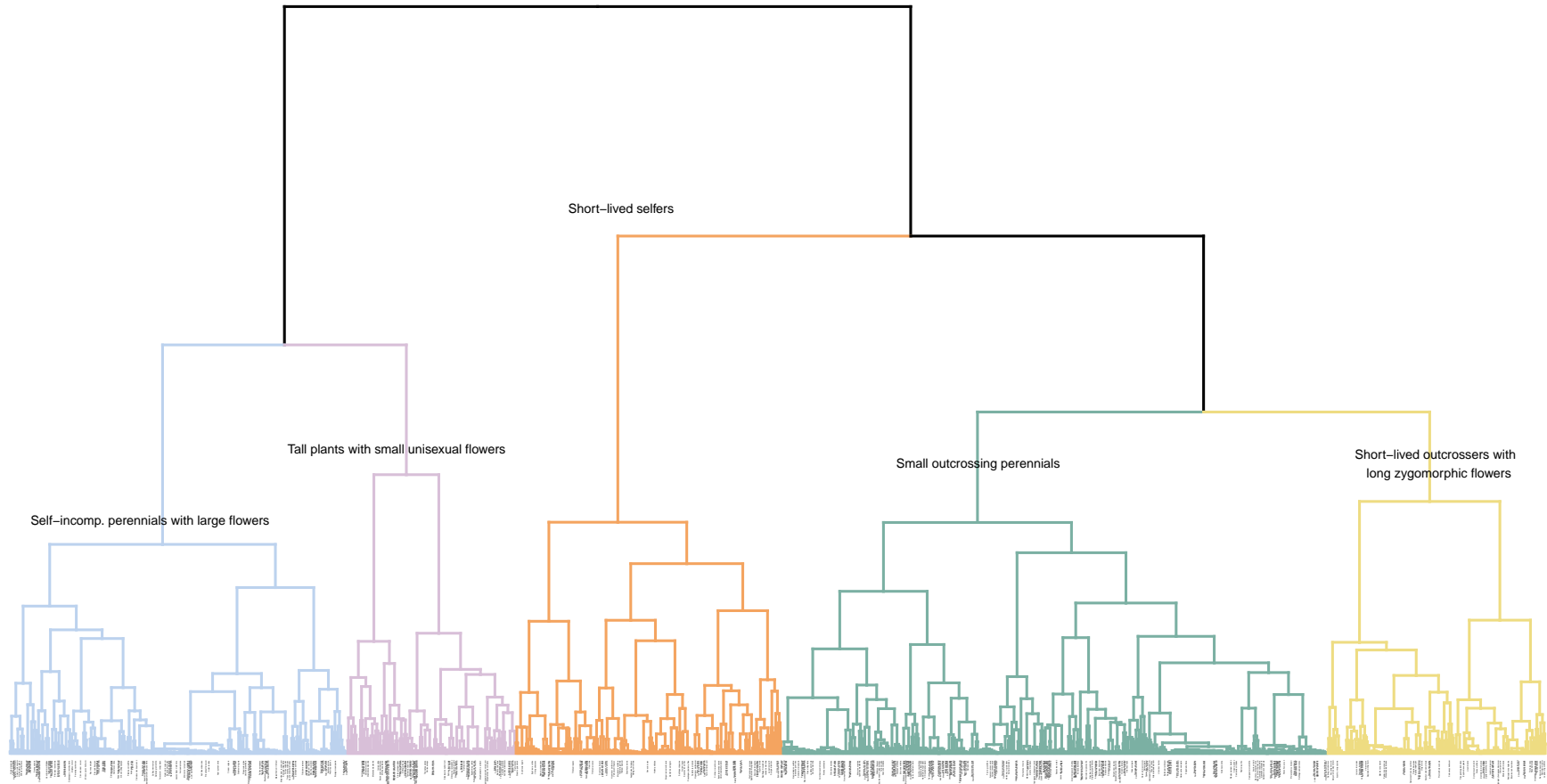


Figure S4. Hierarchical clustering dendrogram with the branches coloured by the optimal number of clusters (5). The labels of the subgroup of species ($N = 524$) used in this study are coloured in black in order to show the evenness of the distribution of the species across clusters. The rest of species labels are omitted for visualization purposes ($N = 982$).