

## LETTER

# Seed-dispersal interactions in fragmented landscapes – a metanetwork approach

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### Abstract

Mutualistic interactions repeatedly preserved across fragmented landscapes can scale-up to form a spatial metanetwork describing the distribution of interactions across patches. We explored the structure of a bird seed-dispersal (BSD) metanetwork in 16 Neotropical forest fragments to test whether a distinct subset of BSD-interactions may mediate landscape functional connectivity. The metanetwork is interaction-rich, modular and poorly connected, showing high beta-diversity and turnover of species and interactions. Interactions involving large-sized species were lost in fragments < 10 000 ha, indicating a strong filtering by habitat fragmentation on the functional diversity of BSD-interactions. Persistent interactions were performed by small-seeded, fast growing plant species and by generalist, small-bodied bird species able to cross the fragmented landscape. This reduced subset of interactions forms the metanetwork components persisting to defaunation and fragmentation, and may generate long-term deficits of carbon storage while delaying forest regeneration at the landscape level.

### Keywords

Atlantic Forest, avian seed-dispersal interactions, beta-diversity of interactions, defaunation, ecological functions, habitat fragmentation, interaction centrality, meta-community, mobile links, tropical conservation.

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## INTRODUCTION

Worldwide habitat fragmentation and defaunation challenge the maintenance of species and their ecological functions (Fahrig 2003; Hagen *et al.* 2012; Dirzo *et al.* 2014) with cascading consequences for ecosystem services (Bello *et al.* 2015; Haddad *et al.* 2015). Yet, the remnant patches can surprisingly hold a significant fraction of biodiversity (Morante-Filho *et al.* 2016; Sfair *et al.* 2016; Beca *et al.* 2017). However, the long-term persistence of viable populations requires connectivity among patches (Hanski 1998; Leibold *et al.* 2004), which may crucially depend on the maintenance of functional ecological interactions. A critical step in the analysis of fragments' connectivity is to understand the consequences of interaction loss and interaction persistence for metacommunity dynamics (Valiente-Banuet *et al.* 2014), seeking for general approaches independent of spatially explicit models or specific details of movements of organisms (Leibold *et al.* 2004). However, research on how habitat fragmentation determines the loss of functional interactions lacks empirical studies at large spatial scales. We ignore to what extent remnant interactions may compensate the functional loss ensuing extinct interactions (Valiente-Banuet *et al.* 2014; McConkey & O'Farrill 2016).

Frugivores maintain seed-dispersal from local to large spatial scales, contributing to *in situ* regeneration, and rescuing plants from severe dispersal limitation in fragmented landscapes (Nathan & Muller-Landau 2000; Sekercioglu *et al.* 2007). Bird seed-dispersal (BSD) interactions shared among habitat remnants are those that persist after fragmentation, as well as to defaunation, another important driver of tropical forests disturbance (Galetti *et al.* 2013). Persistent interactions reflect the same ecological function occurring 'redundantly' (i.e. exactly the same species partners interacting; Tononi *et al.* 1999) at the landscape level. Therefore shared BSD-interactions may represent the potential for the remnant sites to remain functionally similar and integrated in contemporary time, contributing to cohesiveness in a metacommunity scenario (Leibold *et al.* 2004). Moreover, they represent the baseline boundary for potential effective movement of seeds across the landscape, and the birds involved may act as mobile links among forest patches, i.e. the potential for an identical seed-dispersal service by exactly the same specific frugivore species to persist across fragments (Lundberg & Moberg 2003; Kremen *et al.* 2007; Gonzalez-Varo *et al.* 2017). However, actual information from field data about the movement of either frugivores or plants is extremely limited, especially at the community level and over large spatial scales (but see Pizo 2007, Lees & Peres 2009; Pizo

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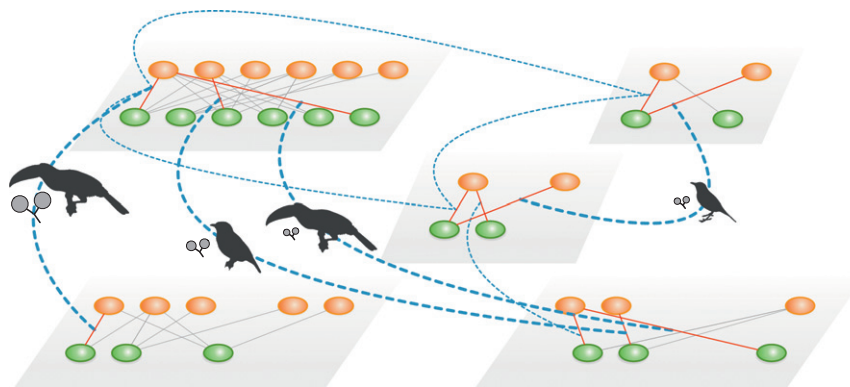
& dos Santos 2011; Neuschulz *et al.* 2013; Velez *et al.* 2015; Cornelius *et al.* 2017). Large-bodied frugivore species, expected to provide more effective medium- to long-distance seed-dispersal (Jordano *et al.* 2007) are the first to vanish when defaunation takes place (Galetti *et al.* 2013). Besides, species from disturbed habitats tend to have smaller body mass and generalist behaviour, allowing them to feed on, or to be dispersed by, a wider range of interacting partners (McKey 1975; Tabarelli *et al.* 2012; Morante-Filho *et al.* 2016). Thus we might expect that only a subset of the plant–frugivore interactions would persist in small forest remnants and contribute to contemporary seed-dispersal in highly fragmented landscapes.

Each fragment holds local assemblages of interacting species, forming distinct networks. Network theory helps to understand the distribution of interactions across fragments and to identify their shared ecological functions (Hagen *et al.* 2012; Bascompte & Jordano 2014; Howe 2016). A fraction of species interactions may be shared across a metanetwork (Hagen *et al.* 2012) of fragments (Fig. 1). Two or more local networks may thus keep functionally connected whenever they share an interaction, i.e. a redundant dispersal function at the landscape level (Hagen *et al.* 2012; Poisot *et al.* 2014; Schleuning *et al.* 2015). From a graph-theoretical perspective (Urban & Keitt 2001), such a metanetwork graph is connected if there exists a direct or indirect path between each pair of nodes. We will use ‘connectivity’ to imply the potential for shared ecological interactions. Thus, the links among fragments in Fig. 1, based on species and interactions co-occurrence, can be thought as proxies for ecologically similar functions performed by specific, pairwise plant–frugivore interactions, with potential to affect contemporary seed-dispersal events.

We can assess the importance of specific interactions in the metanetwork in numerous ways, including estimating their centrality and assessing its correlates with species traits. BSD-interactions occurring in two or more forest fragments would

form the central interactions, i.e. those most shared among fragments and conferring redundancy of ecological functions across the metanetwork. Central nodes promote network cohesiveness (Freeman 1979) and community stability (Jordan 2009), with a large number of their links connecting different parts of the network structure (González *et al.* 2010). Besides, recent studies have analysed the beta-component of interaction diversity and turnover of interactions across local networks (Poisot *et al.* 2012, 2014; Trøjelsgaard *et al.* 2015; CaraDonna *et al.* 2017). One can further identify which species traits are associated to higher centrality and more likely contributing to the persistence of a given interaction across many fragments.

Here we aim to understand the structure of a metanetwork of bird seed-dispersal (BSD) interactions in a tropical region, identify central interactions persisting across forest fragments, and test whether those interactions are random or distinct subsets of those in pristine areas. We gathered data of BSD-interactions in 16 forest fragments of the Atlantic Forest, a hotspot of biodiversity (Joly *et al.* 2014; Bello *et al.* 2017) that harbours a highly fragmented, matrix-laboured and yet relatively patch-connected landscape (Ribeiro *et al.* 2009) with high species beta-diversity (Morante-Filho *et al.* 2016; Sfair *et al.* 2016; Farah *et al.* 2017). Specifically, we aim to (1) estimate the potential for connectivity through shared interactions (i.e. metanetwork connectance), assessing whether fragments form distinct groups (i.e. metanetwork modularity), and how distinct the local assemblages of BSD-interactions are across fragments (i.e. beta-diversity, turnover and rewiring of interactions), (2) identify which interactions are most common among forest fragments and their role in the metanetwork structure (i.e. interaction centrality), and finally (3) determine the ecological correlates of species traits (body mass, seed diameter and bird movement) involved in central interactions potentially contributing to integrate a highly



**Figure 1** A spatial metanetwork of bird seed-dispersal interactions. Grey areas represent distinct forest fragments of distinct size and isolation that can be potentially connected in contemporary time through the activity and the functional outcomes of plant–bird seed-dispersal interactions. Each forest fragment includes a local network according to the local assemblages of bird species (orange nodes), plant species (green nodes) and their interactions (grey lines within networks). Blue, dashed, links indicate pairwise interactions that repeatedly appear in at least two local networks (red links in local assemblages), thus potentially acting as mobile links across the landscape. Silhouettes indicate distinct pairwise interactions that may involve, e.g. birds and fruits of different size. Those redundant interactions at the landscape level scale-up to form a metanetwork of forest fragments connected by the interactions they share. Shared interactions occurring in a larger number of fragments and connecting higher number of fragments, i.e. having higher centrality, are important to maintain network cohesiveness and stability. Those central interactions can potentially function as mobile links among forest fragments. Traits of both plant and bird species involved, such as body mass and seed diameter, are likely to determine which interactions perform the most central roles bounding the metanetwork.

fragmented landscape. We expect a modular metanetwork with high beta-diversity of interactions. Central interactions are expected to show distinct ecological traits of the interacting bird and plant partners, including small body mass and small seed size more likely to move in the fragmented landscape, and to persist in more disturbed habitats (Neuschulz *et al.* 2013; Morante-Filho *et al.* 2015).

## MATERIAL AND METHODS

### Data set

We compiled 16 studies of BSD-interactions in fragments of the SE Brazilian Atlantic Forest (see Table S1 and Fig. S1), a diverse and threatened tropical biome drastically reduced to *c.* 12% of its original cover (Ribeiro *et al.* 2009; Joly *et al.* 2014). The remaining landscape constitutes a complex mosaic formed mainly by small fragments (< 50 ha, *c.* 80% of the remaining area) and clusters of close neighbouring fragments (< 200 m apart) (Ribeiro *et al.* 2009). The surrounding matrix includes crop plantations, pastures, urban areas, non-sampled fragments of variable size and isolated trees that function as stepping-stones reducing forest isolation and favouring animal movement (Martensen *et al.* 2008; Uezu *et al.* 2008; Ribeiro *et al.* 2009; Boscolo & Metzger 2011). The studied fragments vary from 0.66 to 42 000 ha, in a gradient of disturbance from semi-pristine protected areas to secondary forests and restored plantations [mean distance between fragments: 309 km (min 26 km; max 1193 km)]. Our data set includes all studies designed to collect bird-eating-fruit interactions at the community level and over most of the annual seasonality in forest remnants of the Atlantic Forest. Therefore they did not necessarily record effective seed-dispersal; we carefully checked every data set and removed any interaction not characterising seed-dispersal events. We updated species names with taxise package (Chamberlain & Szocs 2013).

### Metanetwork structure

We built the metanetwork by pooling the 16 within-fragment communities in a single binary  $A_{mn}$  adjacency matrix in which  $m$  is the number of studied fragments (rows), and  $n$  is the number of pairwise BSD-interactions (columns); the  $mn$  elements represent the presence/absence of interaction  $i_{1..n}$  in fragment  $j_{1..m}$ . Interactions were determined by the unique pairwise combination of each bird and plant species recorded interacting in the study sites. Then, we characterised the metanetwork structure by estimating: (1) number of bird species, plant species and their interactions, (2) connectance,  $C$ : the ratio of the number of BSD-interactions recorded in each fragment relative to the number of all potential BSD-interactions (Dunne *et al.* 2002), (3) modularity,  $M$ : to test whether interactions present in each fragment form distinct groups (i.e. modules) or aggregate according to a gradient of disturbance in which interactions present in smaller, impoverished fragments would be a subset of larger, more pristine fragments. We used the DIRTLPAwb+ algorithm recently proposed for maximising modularity (Beckett 2016) that identifies groups

of nodes (here, BSD-interactions) that interact more strongly within than among modules (Girvan & Newman 2002), (4) interaction centrality: to identify which interactions show greater redundancy and potential for metanetwork connectivity we used an unipartite projection of the  $A_{mn}$  matrix in which  $n$  BSD-interactions are nodes and each pair of nodes is connected if the two interactions co-occur in at least one fragment. With this projection we estimated:

1 Degree,  $k$  – the number of fragments in which a given interaction occurs, implying the combined co-occurrence of its partner plant and bird species.

2 Betweenness centrality (hereafter, betweenness),  $B_C$  – the proportion of the shortest paths linking any pair of nodes in a network (Freeman 1979; González *et al.* 2010); here interpreted as the most parsimonious way to go from one fragment to another through the co-occurrence of BSD-interactions. Given that we have no data on effective movements across fragments in the study area, we use  $B_C > 0$  as a proxy to identify BSD-interactions most likely to contribute to enhance contemporary functional connectivity at the landscape scale. Besides, nodes with  $B_C > 0$  are theoretically important for network cohesiveness because they link different network parts that would be otherwise poorly connected, or even isolated (Urban & Keitt 2001; Jordan 2009).

We further investigated the role of individual species in the metanetwork structure, independently of the interactions they perform, by substituting the  $n^{\text{th}}$  vector element in the  $A_{mn}$  matrix by either the plant or bird species, and re-run the network metrics for plant and bird species, separately. Finally, we investigated whether interactions with higher centrality involved central bird or plant species using Pearson's correlation test with permutation. We tested the statistical significance of connectance and modularity against a set of null models (Table S3 for details) including an equiprobable null model distributing equally the interactions among fragments, a fixed-fixed model that maintains constant the interaction frequency and the total interactions per fragment while changing network structure [a *Quasiswap* variant, (Miklós & Podani 2004; Oksanen *et al.* 2017)], and two other variants preserving only the total interactions per fragment.

### Beta-diversity of species and interactions

We followed Baselga (2010) and Poisot *et al.* (2012, 2017) to investigate the contribution of different mechanisms to explain the variation in species and interaction composition among the Atlantic Forest fragments, using the  $A_{mn}$  matrix. Accordingly, we calculated (1) the total beta-diversity estimated from the Sørensen dissimilarity index and (2) its turnover component, using the Simpson dissimilarity index. Both indexes were estimated at the pairwise- and multiple-sites scales using the betapart package (Baselga *et al.* 2013). To test whether beta-diversity would be a primary consequence of geographical distance we performed Pearson's correlation tests among the pairwise geographical distances between fragments (Haversine distance [km]), and the pairwise Sørensen and Simpson dissimilarities of species and interactions between fragments, with their significance tested by randomisation. Then, we employed

Poisot *et al.* (2012, 2017) approach for estimating interaction rewiring across multiple-sites with high species turnover. It assumes that rewiring happens when the same pairwise species co-occur in different fragments but interact in only a subset of those. Thus, we calculated the difference between realised interactions within-fragments and the overall potential interactions at the metanetwork-regional level ( $\beta_{OS}$ ); values close to 0 indicate the presence of most potential interactions, whereas values close to 1 suggest the loss of most potential interactions at the local-fragment level. We further used analyses of variance to test for differences in  $\beta_{OS}$  caused by fragment area.

### Species traits and interaction centrality

We used bird species' body mass (g), plant seed diameter (mm) and bird's movement (as the capacity to move in the fragmented landscape) as determinants of plant-frugivore interaction outcomes (Jordano 2014) that may influence interactions persistence (see Suppl. Mat.). Metanetwork metrics were estimated in the bipartite package (Dormann *et al.* 2009). All analyses were run in R v. 3.3.3 (R Development Core Team 2014).

## RESULTS

### Metanetwork structure

The BSD metanetwork includes 335 plant species interacting with 170 bird species across 16 forest fragments of the Atlantic Forest (Fig. 2a). Combined, they comprised a total of 2587 BSD-interactions mostly exclusive to a single fragment (82.26%), forming a highly modular ( $M = 0.74$ ,  $P < 0.001$ ) and poorly connected ( $C = 0.07$ ) metanetwork. Each fragment formed a distinct module (i.e. 16 modules, Fig. 2a) functionally connected by a subset of core interactions (Fig. 2b). If the core interactions vanish, the metanetwork structure is lost and fragments become functionally isolated (Fig. 2c). Furthermore, modularity was lower when only bird or plant species were considered (Table S3, Fig. S3).

We identified high levels of beta-diversity among fragments considering the composition and turnover of species, genera and interactions (Table 1, S4 and S5). The pairwise dissimilarity in composition and turnover of species and interactions among fragments were significantly and positively correlated with the pairwise geographical distance (Table S6). Most potential interactions at the landscape level were realised at the local-fragment level ( $\beta_{OS}$  ranging from 0.043 to 0.326), whereas  $\beta_{OS}$  values were not related to fragment area ( $F_{1,14} = 0.109$ ,  $P = 0.746$ ,  $R^2 = -0.063$ ; Fig. S4).

### Central interactions

A low number of BSD-interactions occurred in at least two fragments [459 (17.74%);  $k \geq 2$ ; Fig. 2b] including just 200 bird-plant partner combinations connecting different parts of the metanetwork ( $B_C > 0$ ; Table S7). In contrast, most BSD-interactions (2128, 82.26%) occurred in a single fragment ( $k = 1$ ,  $B_C = 0$ ; Fig. 2c). Beta-diversity and turnover of central

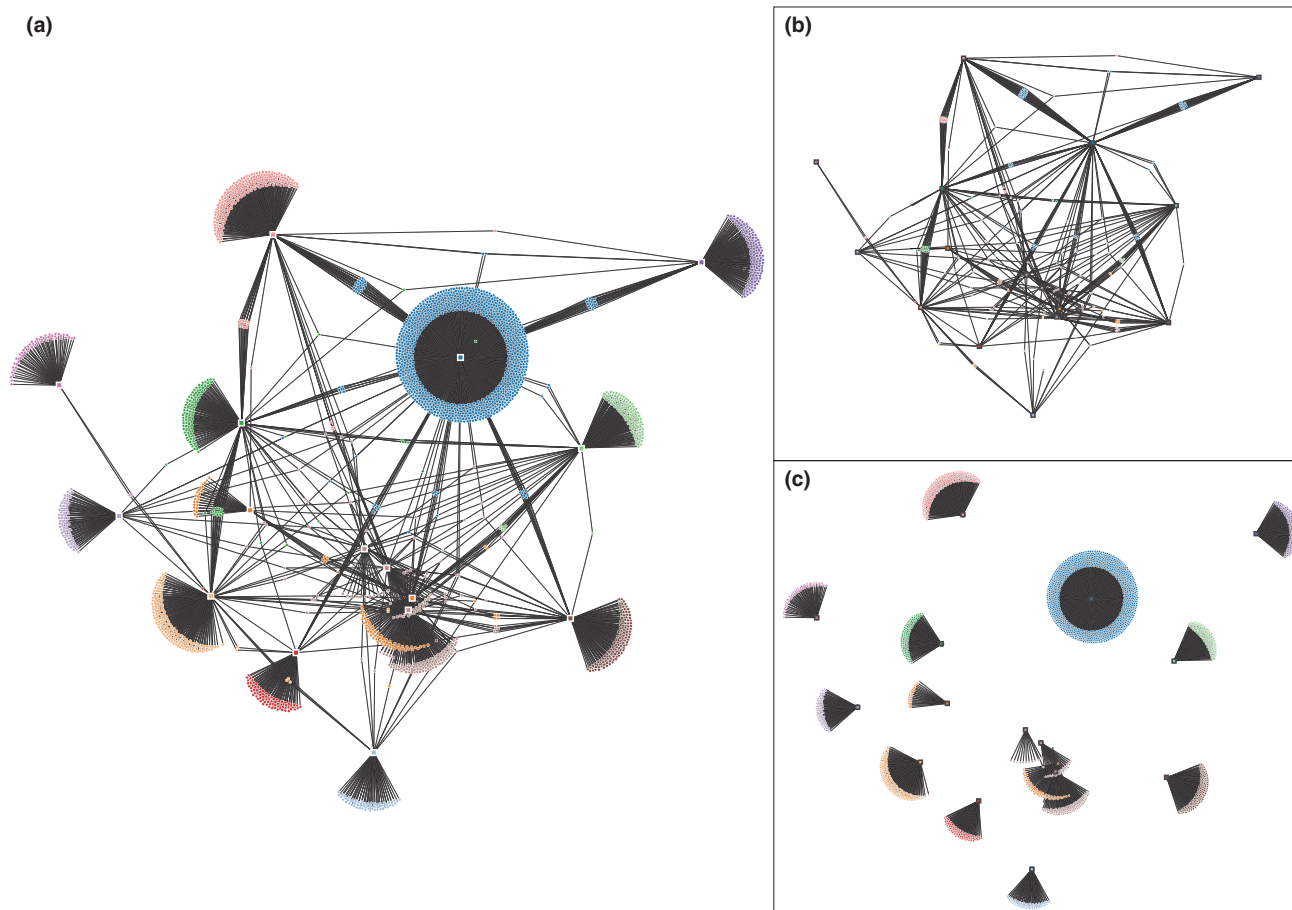
interactions ( $B_C > 0$ ) increased with distance among fragments ( $r_b = 0.44$ ,  $t = 7.76$ ,  $P < 0.001$ ;  $r_t = 0.36$ ,  $t = 6.25$ ,  $P < 0.001$ ). Highly central interactions were usually performed by highly central bird ( $r_k = 0.218$ ;  $r_{Bc} = 0.119$ ,  $P < 0.001$ ) or plant species ( $r_k = 0.394$ ;  $r_{Bc} = 0.227$ ,  $P < 0.001$ ) yet the variation was very high (Fig. S5). For example the great kiskadee *Pitangus sulphuratus* was recorded in all studied fragments ( $k = 16$ ,  $B_C = 0.061$ , Table S8) but performed only six out of the 200 interactions (2%) connecting the metanetwork (Table S7). In contrast, none of the plant species were present in all fragments; *Schinus terebinthifolius* (Anacardiaceae) was the plant with highest number of occurrences ( $k = 8$ ,  $B_C = 0.061$ ; Table S9), also involved in the highest central interaction (*Schinus terebinthifolius* and *Thraupis sayaca*,  $k = 7$ ,  $B_C = 0.054$ ) and in other 37 (18.41%) interactions connecting the metanetwork (Table S7).

### Species traits

From the pool of interactions with complete information on body mass and seed size (1298 interactions), most interactions in the metanetwork (1087; 83.74%) included small-bodied bird species (< 100 g) associated to small-seeded plant species (< 12 mm) (Fig. 3). However, the types of BSD-interactions across the gradient of fragment area (0.66 – 42 000 ha; Table S1) were very different depending on the combinations of partner species sizes. Interactions involving both small-bodied bird and small-seeded plant species appeared in the whole gradient of fragment sizes (Fig. 3). In contrast, interactions involving large-bodied bird and large-seeded plant species were restricted to the largest fragments (i.e. none of these interactions occurred in fragments < 10 000 ha). These interactions were exclusively recorded in two out of the three more pristine fragments (PE Intervals and PE Ilha do Cardoso), which also have the largest areas (Fig. 3). Among them (10 interactions in total), only the interaction between the large-seeded *Virola bicuhyba* (Myristicaceae; mean seed diameter = 16 mm] and the large-bodied *Ramphastos dicolorus* (Ramphastidae; mean body mass = 331 g) was a metanetwork connector ( $B_C = 0.005$ , Table S7). Less than 20% of the interactions involving species of contrasting sizes (e.g. large-bodied bird and small-seeded plant species) were recorded in fragments < 1000 ha, suggesting that fragment area may impose strong limitations to the appearance of seed-dispersal interactions involving any large-sized partner.

We next investigated if these differences in frequency of interactions were associated to differences in frequency of small and large-bodied bird and small and large-seeded plant species. In fact, small-seeded plants are prevalent in our dataset (< 12 mm, 91.43%; 128 out of 140 species with seed size information available), whereas only 12 plant species are large-seeded (8.57%). Large-seeded species performed an even lower frequency of interactions (1.35%, 35 interactions) and only two of those connected the metanetwork structure ( $B_C = 0.005$ , Table S7). Likewise, most seed-dispersers were small-bodied species (137 species, 84.57%) and just a small fraction was large-bodied species (25 species, 15.43%). In this case though the proportion of interactions performed by large-bodied species was similar to the proportion of large-bodied





**Figure 2** The metanetwork of Atlantic Forest fragments connected by shared pairwise interactions of frugivorous birds and fleshy-fruited plant species (a). The graph representation follows a force-directed drawing that organises nodes with greater centrality to more central positions (Bannister *et al.* 2013), displaying the fragments (squares) with different colours for each locality. Circles indicate pairwise bird seed-dispersal interactions. The interactions present in at least two fragments (betweenness score  $B_C > 0$ ) lie on the links (isolated in panel b). (a) The structure of the metanetwork of the Atlantic Forest including all bird seed-dispersal interactions recorded in each of the 16 fragments and the interactions shared among fragments. (b) The structural backbone of the metanetwork in which only interactions with a significant role in connecting the different parts of the metanetwork structure are maintained (i.e. only interactions with betweenness  $B_C > 0$ , and that occur in at least two fragments,  $k \geq 2$ ). (c) The opposite of panel b, representing the metanetwork structure when the 'connector' interactions are removed, resulting in completely isolated forest fragments. Figures built with Network3D package (Gandrud 2015), in R. An interactive version of panel (a) is available at [http://pedroj.github.io/AF\\_metanetwork/](http://pedroj.github.io/AF_metanetwork/).

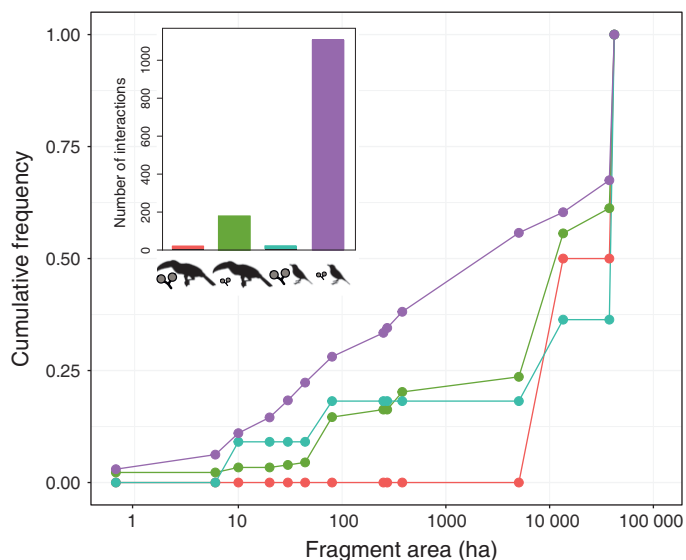
**Table 1** Results from the beta-diversity and turnover of bird seed-dispersal interactions among the 16 forest fragments of the Atlantic Forest. Both indexes were calculated for plants, birds and the interactions among them, at the genus and species level.  $N$ , number of taxa or interactions in each level.

	$N$	$\beta$ -diversity (Sørensen)	$\beta$ -turnover (Simpson)
Genus level			
Plants	113	0.899	0.846
Birds	96	0.842	0.757
Interactions	921	0.943	0.925
Species level			
Plants	335	0.956	0.907
Birds	170	0.878	0.795
Interactions	2328	0.987	0.972

species in the frugivore assemblage (296 interactions, 11.44% of all interactions). Relatively few interactions connected the metanetwork ( $B_C > 0$ , Table S7), 440 interactions performed

by small-bodied species and 14 interactions performed by large-bodied species.

We found evidence for decreasing body mass and seed diameter of species and interactions with higher centrality, despite the high variance and heteroscedasticity of the data. Bird species engaging in interactions occurring in a larger number of sites and connecting different parts of the metanetwork (i.e. higher betweenness) tended to have smaller body mass (Table 2). Likewise, plant species performing central interactions showed a marginal trend to have smaller seed diameter (Table 2). Examples of those interactions (mean seed diameter or body mass in parentheses) involve *Schinus terebenthifolia* (3.5 mm) – *Thraupis sayaca* (32.5 g), *Trema micrantha* (1.7 mm) – *Dacnis cayana* (13.0 g), *Casearia sylvestris* (1.3 mm) – *Tachyphonus coronatus* (20.3 g) (Table S7). When species were analysed independently of the interactions they performed, plant centrality was negatively correlated with seed diameter, whereas body mass showed no significant



**Figure 3** Frequencies of four functional groups of bird-fruit interactions in relation to fragment area. The inset shows the number of pairwise interactions recorded in the metanetwork involving: (1) large-bodied frugivore/large-seeded plant (red); (2) large-bodied frugivore/small-seeded plant (green); small-bodied frugivore/large-seeded plant (blue); and (4) small-bodied frugivore/small-seeded plant (purple). Lines show the cumulative proportion of interactions in each group occurring in fragments of increasing area, each dot indicating the probability of occurrence of an interaction in a given group in a fragment as large, or smaller, than the corresponding area. Functional groups were classified according to the pairwise combination of body mass (g) of the bird frugivore and seed diameter (mm) of the plant species involved in the interaction. The threshold for establishing large bird species was body mass > 100 g, and for large seeds we used seed diameter > 12 mm (Galetti *et al.* 2013).

correlation with bird centrality (Table 2, Table S8, S9). Finally, higher centrality of bird species, both at the species- and interaction-level, was significantly associated to their higher capacity to move in the fragmented landscape (see Suppl. Mat. for results, Fig. S6, S7). Larger bodied species were more sensitive to disturbance, whereas an intermediate body size seems to favour the capacity to cross the matrix and the dependence of forest habitats (Fig. S8).

## DISCUSSION

We found that forest fragments facing strong anthropogenic pressure still hold highly unique assemblages of bird seed-dispersal interactions. This translates into high beta-diversity at the landscape level, resulting in a metanetwork structured into modules and sparsely connected by an impressively reduced number of interactions, representing *c.* 8% of the overall interactions. Our approach implicitly assumes that a high occurrence of specific interactions across fragments is a proxy to identify those that may maintain fragments functionally integrated. These shared interactions represent (1) redundant functions (i.e. exactly the same partner species involved) and (2) may imply a strong potential as mobile links (Kremen *et al.* 2007) contributing to functional connections across the fragmented landscape (Urban & Keitt 2001). Interactions with higher centrality, therefore with higher potential to integrate

**Table 2** Results from the Spearman correlation tests between species traits (body mass and seed diameter) and network centrality estimated for each pairwise bird seed-dispersal interactions, and for each bird and plant species, composing the metanetwork of the Atlantic Forest. Species traits were tested individually against each centrality metric (degree and betweenness) according to the species involved in that interaction. Only complete pairwise interactions (i.e. with information of both birds' and plants' traits) were included in the analyses.

	Degree ( $k$ )		Betweenness ( $B_C$ )	
	$\rho$	$P$ -value	$\rho$	$P$ -value
Interactions				
Body mass (g)	-0.043	0.040	-0.042	0.042
Seed diameter (mm)	-0.051	0.065	-0.051	0.065
Species				
Body mass (g)	-0.013	0.548	0.023	0.262
Seed diameter (mm)	-0.165	< 0.001	-0.196	< 0.001

fragments, were performed by small-bodied bird species associated to small-seeded plant species characteristic of secondary forest growth (Blake *et al.* 1990). This mainly resulted from the constraints imposed by fragment area to the occurrence of large-sized species. The incidence of interactions involving large-sized species vanished in fragments < 10 000 ha, and < 20% of the interactions involving species of contrasting sizes (e.g. large-bodied bird and small-seeded plant species) were recorded in fragments < 1000 ha, indicating a strong filtering by habitat fragmentation acting over the functional diversity of BSD-interactions.

## Limitations

Research on multilayer representations of networks like the one studied here, with local networks connected across multiple spatial scales, is at its infancy (Genrich *et al.* 2017; Pilosof *et al.* 2017). Our analyses represent an initial empirical attempt in this direction, dealing with an extremely diverse network of interactions. The high turnover of interactions found here may be related to the ample spatial scale considered and to the fact that, for logistic limitations, not all forest patches in the study area were sampled (Fig. S1). Besides, high interaction turnover is expected due to autocorrelated effects, and to the high beta-diversity of birds and plants seen in the Atlantic Forest (Morante-Filho *et al.* 2016; Sfair *et al.* 2016; Farah *et al.* 2017).

A second limitation relates to the assumption that plant and bird species occupying more fragments will be the most likely to contribute to cross-fragments integration through redundant functions, detected by the higher centrality interactions in the metanetwork. Sampling limitations in high-diversity networks (Jordano 2016) may have biased our results for finding such a high frequency of interactions unique to a single fragment. Yet our analysis of sampling effort (Fig. S2; Bello *et al.* 2017) suggests sampling appears robust for the detection of species and their potential interactions (Fig. S2). When interactions are unique to a single fragment, we expect them to have a reduced potential for among-fragment movement compared to interactions where both partner species occupy multiple fragments.

### A highly diverse, defaunated and fragmented tropical metanetwork

The high modularity found for the Atlantic Forest metanetwork shows a regional pool of bird frugivore interactions split into fragments that hold distinct sets of species interactions. The resulting low connectance suggests low redundancy of seed-dispersal at the landscape level. In addition, when species are considered independently of the interactions they perform, modularity drops and connectance increases, indicating that the distribution of interactions in a metanetwork context does not necessarily reflect the distribution of the species involved. Thus, frugivorous bird species and bird-dispersed plant species are more redundant at the landscape level than the functional pairwise interactions they perform.

The metanetwork configuration may entail the isolation of species, and their interactions, within fragments. In the long term that may lead to gene flow depression among fragmented populations likely affecting species eco-evolutionary trajectories (Cote *et al.* 2017; Pérez-Méndez *et al.* 2017) that may respond differently to local-selective pressures (Thompson 2005). Yet, by decomposing the patterns of turnover in species richness turnover and species interaction turnover we showed that the former contributes unprecedented levels for the second. Therefore, understanding the distribution of interactions may provide insights not only about the persistence of species but also the persistence of communities in which interactions are organised in human-modified landscapes (Poist *et al.* 2017).

Small fragments may effectively contribute to connectivity across large areas (Urban & Keitt 2001). The mosaic landscape of the Atlantic Forest, interspaced by forest remnants of variable sizes, mostly < 200 m apart, provides opportunity for the movement of generalist bird species (Uezu *et al.* 2005; Martensen *et al.* 2008; Uezu *et al.* 2008) that can fly up to 300 m between fragments (Awade *et al.* 2017; Cornelius *et al.* 2017). Therefore, small fragments may act as 'stepping-stones' favouring the movement of bird and plant partners contributing to propagate the distinct subset of interactions that functionally integrate fragments in the metanetwork context (Uezu *et al.* 2005; Sekercioglu *et al.* 2007; Neuschulz *et al.* 2013). Field observations from the Chaco-Serrano Woodland showed that the small-sized, generalist bird species *Pitangus sulphuratus* and *Turdus amaurocholinus* can fly among fragments distant 300 m and 200 m apart respectively (Velez *et al.* 2015). These same species showed high centrality in our metanetwork and high capacity to move in the fragmented landscape; they are examples of species performing interactions that may enhance landscape connectivity in contemporary time.

Nonetheless, rare events of seed-dispersal can also contribute to species movement and gene flow in fragmented landscapes (Nathan 2006; Jordano *et al.* 2007; Sekercioglu *et al.* 2007; Tella *et al.* 2016; García & Borda-de-Água 2017). Diet-generalist, small-sized bird species contribute effectively to the seed-rain of pristine-forest species in rare events of dispersal among tropical forest fragments (Carlo & Morales 2016). Several frugivorous birds recorded in our metanetwork are regional, altitudinal or long-distance migrants (e.g. *Turdus* spp.) known to move considerable distances (Chesser 1994; Capllonch *et al.* 2008) that may eventually result in seed-

dispersal. For instance, radio-tracking recorded flying bouts for small *Tangara* and *Turdus* up to three and 5.8 km in a few hours (Sekercioglu *et al.* 2007). With distances between fragments in the Atlantic Forest varying from a few to several thousand metres, events of long-distance seed-dispersal are likely to be common depending on the matrix permeability and the bird flying capability. The 16 fragments studied here span a very large geographical scale and may result in an underestimated connectivity due to high species and interaction turnover. Yet our results emphasise the importance of small fragments as stepping-stones potentially connecting sites within fragmented landscapes, confirming previous connectivity models (e.g. Urban & Keitt 2001).

Central taxa present in a fragment do not necessarily become partners in a central interaction at the landscape level despite we found that central species tend to perform central interactions. This effect, contributing to the high beta-diversity of interactions, may be attributable to constraints from forbidden links (Olesen *et al.* 2011) due to a mismatch between bird occurrence and plant phenology, or size-related constraints for the interaction to occur (Galetti *et al.* 2013). Thus, interaction rewiring may change the identity of species partners maintaining network structure within and among fragments (CaraDonna *et al.* 2017; Pilosof *et al.* 2017). Indeed, some potential interactions at the local-fragment level were not realised, especially in restored areas and despite relatively low values (Fig. S4), suggesting some degree of rewiring within-local networks. Yet rewiring was not related to a reduction in fragment area but may be a consequence of the loss of interaction partners due to defaunation (Galetti *et al.* 2013). The loss of species and mismatches between interaction partners may result in lower dispersal rates among distinct fragments, leading to structural reorganisation of local networks (Thompson & Gonzalez 2017). Those factors combined suggest an arena in which forest fragments with higher selective pressure become hotspots of eco-evolutionary changes on interactions, whereas less disturbed fragments could be seen as cold spots in which changes are slower, or evolution is characterised by stabilising selection (Thompson 2005; Galetti *et al.* 2013; Cote *et al.* 2017).

### Functional downsizing of bird seed-dispersal interactions

Despite our results evidencing a trend for reduced body mass and seed size among the species involved in central interactions, we failed to capture strong evidences for interaction centrality co-varying with interaction traits. At most, the data reveal a decreasing centrality of taxa of larger size. Species traits were obtained at the species level, so the values attributed to each species are approximations of the average of intraspecific variation for a given trait in a given population. Therefore we could not capture all processes likely determining species associations, such as intraspecific variation on body mass due to reduced resource availability, or seed size variation due to environmental fluctuations (Violle *et al.* 2012). Besides, trait data were available for about 50% of the interactions, possibly underestimating the downsizing effect across fragments.

Yet, the downsized bird and plant species remaining in smaller area fragments seem to play the winners role in the



fragmented arena (Tabarelli *et al.* 2012), contributing to a higher incidence of smaller sized interactions in smaller area fragments. The prevalence of small–small interactions and the absence of interactions by large-bodied bird species throughout the range of fragment area translate into a distinct spatial organisation of bird–plant interactions, where any interaction involving large-bodied frugivorous birds and/or large-seeded plant species quickly vanishes when the fragment area is < 10 000 ha. Fragmentation thus conveys the pervasive extinction of a distinctly non-random set of plant–frugivore interactions, not just a ‘simple’ loss of individual species.

#### Advancing the field and implications for conservation

To further test the metanetwork hypothesis we need a holistic framework that integrates key factors influencing species interaction persistence and landscape connectivity. The challenge ahead involves a detailed scanning of the movement of interacting species at different spatial scales, including frugivore movement patterns and their potential to contribute contemporary dispersal of plant propagules (Nathan & Muller-Landau 2000; García & Borda-de-Água 2017), intraspecific response to environmental changes (Awade *et al.* 2017; Cornelius *et al.* 2017) and the type of matrix (Emer *et al.* 2013; Biz *et al.* 2017) in which the metanetwork is embedded. Combining new technologies such as radio tracking (Nathan 2006; Cornelius *et al.* 2017) and DNA barcoding (Carvalho *et al.* 2016; Gonzalez-Varo *et al.* 2017; Pérez-Méndez *et al.* 2017) associated to spatially explicit analyses (Dale & Fortin 2010) and novel null models incorporating species traits and seasonal dynamics (Dormann *et al.* 2017; Tylianakis & Morris 2017) would enhance our understanding of how ecological processes scale-up from the local-individual level to the meta-community, regional-landscape level.

Fragments of the Atlantic Forest hold a unique heritage of species, and their interactions, remaining after centuries of overexploitation and habitat destruction. Therefore, if a single fragment disappears, even a small-sized one, unique interactions will also vanish (da Silva & Tabarelli 2000; Hagen *et al.* 2012; Tabarelli *et al.* 2012). Yet, we revealed that the dispersal of large-seeded plant species by large-bodied bird species requires large areas (> 10,000 ha). With more than 80% of the remaining Atlantic Forest fragments smaller than 50 ha, the conservation of specific functional groups of interactions is at risk and restricted to a few relict forest patches. Our results indicate that the preservation of the ecological functions conveyed in interactions between large-seeded plant and large-bodied bird species will not be preserved by the rewiring of the participant species in other forest remnants.

In the long run, the dominance of small-sized species in forest fragments associated to the local extinction of interactions performed by larger bodied frugivore species may select for smaller fruit and seed-sized plant species (Galetti *et al.* 2013; Carvalho *et al.* 2016). A negative functional effect of this selection towards small-seeded plant species is that they are generally associated to reduce carbon storage capacity, which may lead to a pervasive deficit in the carbon balance relative to semi-pristine forests (Bello *et al.* 2015). The documented changes in bird seed-dispersal interactions due to defaunation and habitat

fragmentation may cause structural changes in the Atlantic Forest vegetation, imposing long delays for the recovering of forest tracts and for the functional integration of forest fragments within a cohesive metanetwork.

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#### AUTHORSHIP

CE, PJ and MG conceived the study; MG, MAP, SM, AP and PJ gathered data; CE and PJ analysed the data; CE wrote a first version of the manuscript, with contributions by PJ, and both completed the final version with contributions by MG, MAP, PRG and AP.

#### DATA ACCESSIBILITY STATEMENT

Data are available at the Atlantic-Frugivory database (Bello *et al.* 2017), and the full dataset and R code are available in GitHub ([<https://doi.org/github.com/carineemer/metanetwork>]; <https://doi.org/10.5281/zenodo.1115562>).

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## SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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Issue photo-cover

# ECOLOGY LETTERS

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Cover caption: Black-fronted piping-guan (*Aburria jacutinga*, Cracidae) swallowing fruits of juçara palm (*Euterpe edulis*, Arecaceae). Jacutingas are major seed dispersal agents in the Atlantic rainforest of Brazil, now highly threatened by deforestation and hunting

Photo Credit: Pedro Jordano

From: Carine Emer, p. 484

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## **Supplementary Information**

### **SEED-DISPERSAL INTERACTIONS IN FRAGMENTED LANDSCAPES: A METANETWORK APPROACH**

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Supplementary data file is available at: <https://github.com/carineemer/Metanetwork>

## **Supporting Material and Methods**

### ***Species traits***

We used bird species' body mass (g), plant seed diameter (mm) and bird's movement (see below) as determinants of plant-frugivore interaction outcomes (Jordano 2014) that may influence interactions persistence in the fragmented landscape, potentially acting as mobile links among forest fragments. Body mass is associated to the range of seed sizes a bird species can disperse (Snow 1981; Wheelwright 1985) and to the flying distance it can reach (Dennis & Westcott 2006; Jordano *et al.* 2007). Seed size brings information about the species' ecological attributes that may determine its persistence in modified environments (Jordano 1995; Pizo 2007) and correlates with wood density, an indication of the species ability for carbon storage (Bello *et al.* 2015). Considering the extremely large number of interactions involved and the fact that the same plant and/or bird species may appear repeatedly in multiple interactions with different partners, we were interested in assessing the overall relationship between species-specific traits and centrality ( $k$  and  $B_c$ ) of the BSD-interactions. We also explored whether plant and bird species centrality solely were explained by these functional traits. The extremely large sample size caused an overfit of any tentative modelling attempt to assess the form of these relationships, so we resorted to use non-parametric Spearman correlation tests to highlight any non-random associations between traits and centrality scores. Species traits were obtained from Wilman *et al.* 2014 and Bello *et al.* 2015.

### ***Birds' movement***

Specific information on the movement of the Atlantic Forest birds is very scarce and restricted to a few species in a single landscape configuration (see Uezu *et al.*

2005; Pizo & Santo. 2011; Awade *et al.* 2017; Biz *et al.* 2017; Cornelius *et al.* 2017 for examples). Therefore we estimated birds' movement according to their capacity to move in the fragmented landscape (Table S2) according to (i) capacity to cross the matrix, based on field observations of local ornithologists (MA Pizo and C Gussoni, unpubl. data), who evaluated if a given bird species was able to move from one fragment to another, independently if performing a single long-distance flight or multiple short-distance flight steps; (ii) sensitivity to disturbance (adapted from Stotz *et al.* [1996]), and (iii) dependence of forest habitats (adapted from Silva [1995]), in which bird species with low dependence are those associated to open vegetation, whilst species that occur in both open and closed forest vegetation were considered to have medium forest dependence and those recorded mainly within forest-interior habitats were considered to have high forest dependence. We used analysis of variance tests to assess whether birds' movement categories differ in the centrality of bird species, centrality of BSD-interactions, and body mass.

When bird species were analysed independently of the interactions they performed, we found that species with higher degree, i.e., those that occur in a higher number of fragments, and higher betweenness i.e., play an important role as network connector and have higher potential to perform empirical connectivity among fragments, are those with a higher capacity to cross the matrix ( $k$ ,  $F_{2,2296} = 1117$ ,  $r^2 = 0.49$ ;  $B_c$ ,  $F_{2,2296} = 1026$ ,  $r^2 = 0.47$ ;  $p < 0001$ ), lower sensitivity to disturbance ( $k$ ,  $F_{2,2296} = 859.5$ ,  $r^2 = 0.43$ ;  $B_c$ ,  $F_{2,2296} = 718.4$ ,  $r^2 = 0.38$ ;  $p < 0001$ ) and depend less on forested habitats ( $k$ ,  $F_{2,2296} = 815.5$ ,  $r^2 = 0.42$ ;  $B_c$ ,  $F_{2,2296} = 789.4$ ,  $r^2 = 0.41$ ,  $p < 0001$ ) (Fig. S5). Similarly, bird species performing the higher centrality interactions showed higher capacity to cross the matrix ( $k$ ,  $F_{2,2296} = 30.86$ ,  $r^2 = 0.03$ ;  $B_c$ ,  $F_{2,2296} = 5.146$ ,  $r^2 = 0.004$ ;  $p = 0001$ ), lower sensitivity to disturbance ( $k$ ,  $F_{2,2296} = 28.7$ ,  $r^2 = 0.02$ ;  $B_c$ ,  $F_{2,2296} = 7.094$ ,  $r^2 = 0.005$ ;  $p < 0001$ ) and depend less on forested habitats ( $k$ ,  $F_{2,2296} = 34.4$ ,  $r^2 = 0.03$ ;  $B_c$ ,  $F_{2,2296} = 5.593$ ,  $r^2 = 0.004$ ,  $p < 0001$ ) (Fig. S6).



Note that the latest models poorly capture the large intrinsic variance of the interaction data, reinforced by the traits of the plant species they interact with. Finally, the analyses of body mass showed that larger bodied bird species are more sensitive to disturbance ( $F_{2,2295} = 222.4$ ,  $r^2 = 0.17$ ,  $p < 0.001$ ), while species with intermediate body mass seem to have higher capacity to cross the matrix ( $F_{2,2295} = 67.96$ ,  $r^2 = 0.06$ ,  $p < 0.0001$ ) and depend less of forest habitats ( $F_{2,2295} = 30.59$ ,  $r^2 = 0.02$ ,  $p < 0.001$ ) even though the latest models explain little of the variance (Fig. S7).

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**Table S1.** Description of the bird-seed dispersal interaction dataset used in this study. All studies were carried out in the Atlantic Forest biome. P= plant oriented, interactions based on focal observations; A= animal oriented, interactions based on diet analysis (e.g., faeces sampling).

Network*	Latitude	Longitude	Altitude (m asl)	Type of Forest	Area (ha)	Year	Sampling months	Sampling focus	N Animal species	N Plant species	N Interactions
1	-24.316965	-48.387175	800-1000	Ombrophilous	42000	1999-2000	14	PA	81	187	968
2	-24.131389	-47.949167	30-1000	Ombrophilous	37644	2013-2014	12	PA	61	30	240
3	-25.127786	-47.957463	150	Ombrophilous	13500	2001-2004	36	P	16	49	139
4	-22.536290	-42.277658	50-120	Ombrophilous	5052	1995-1996	NA	P	45	13	183
5	-23.548369	-45.062541	0-339	Ombrophilous	828	2005-2007	12	P	32	14	145
6	-22.818101	-47.113757	660	Semi Deciduous	250	1988-1991	44	P	29	35	146
7	-22.943263	-46.749949	800	Semi Deciduous	80	2002-2003	12	PA	45	30	139
8	-28.223141	-51.166857	900	Araucária	272	1996	12	P	22	14	56
9	-22.480979	-47.592293	700	Semi Deciduous	44	2008-2009	12	P	31	9	92
10	-20.802611	-42.858746	550-750	Semi Deciduous	380	2000-2002	27	P	29	25	90
11	-23.545856	-46.721177	750	Semi Deciduous	10	1994	NA	P	22	26	79
12	-22.767379	-43.694394	30	Ombrophilous	0.66	2010-2011	11	P	20	22	67
13	-22.825234	-47.427761	550	Restored (15-yr old)	30	2012-2013	24	PA	17	20	32
14	-22.568342	-47.504987	610	Restored (25-yr old)	20	2012-2013	24	PA	39	33	129
15	-22.671644	-47.204638	570	Restored (57-yr old)	30	2012-2013	24	PA	20	29	34
16	-22.708708	-47.610207	650	Restored (8-yr old)	6	2013-2014	10	P	26	6	48

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**Table S2.** Bird species capacity to move in the Atlantic Forest fragmented landscape. Data were obtained from field observations from local ornithologists according to bird species (i) capacity to cross the matrix, (MA Pizo and C Gussoni, unpubl data), (ii) sensitivity to disturbance (following Stotz et al. [1996]), and (iii) dependence of forest habitats (following Silva [1995]).

Bird species (authority, year)	Capacity to cross the matrix	Sensitivity to disturbance	Forest dependence
<i>Antilophia galeata</i> (Lichtenstein, 1823)	Medium	Low	High
<i>Arremon taciturnus</i> (Hermann, 1783)	Low	Medium	High
<i>Attila phoenicurus</i> Pelzeln, 1868	Low	High	High
<i>Attila rufus</i> (Vieillot, 1819)	Low	Medium	High
<i>Baryphthengus ruficapillus</i> (Vieillot, 1818)	Low	Medium	High
<i>Basileuterus flaveolus</i> (S. F. Baird, 1865)	Medium	Low	High
<i>Basileuterus culicivorus</i> (Deppe, 1830)	Medium	Low	High
<i>Cacicus chrysopterus</i> (Vigors, 1825)	Medium	Medium	High
<i>Cacicus haemorrhous</i> (Linnaeus, 1766)	Medium	Medium	High
<i>Camptostoma obsoletum</i> (Temminck, 1824)	High	Low	Low
<i>Capsiempis flaveola</i> (Lichtenstein, 1823)	Low	Low	High
<i>Carpornis cucullata</i> (Swainson, 1821)	Low	High	High
<i>Carpornis melanocephala</i> (Wied-Neuwied, 1820)	Low	High	High
<i>Celeus flavescens</i> (Gmelin, 1788)	Medium	Medium	High
<i>Chiroxiphia caudata</i> (Shaw, 1793)	Low	Low	High
<i>Chlorophonia cyanea</i> (Thunberg, 1822)	Medium	Medium	High

<i>Chrysomus ruficapillus</i> (Vieillot, 1819)	High	Low	Low
<i>Cissopis leverianus</i> (J. F. Gmelin, 1788)	Low	Medium	High
<i>Cnemotriccus fuscatus</i> (Wied-Neuwied, 1831)	Medium	Low	High
<i>Coereba flaveola</i> (Linnaeus, 1758)	High	Low	Medium
<i>Colaptes campestris</i> (Vieillot, 1818)	High	Low	Low
<i>Colaptes melanochloros</i> (Gmelin, 1788)	High	Low	Medium
<i>Conirostrum speciosum</i> (Temminck, 1824)	High	Low	High
<i>Conopias trivirgatus</i> (Wied-Neuwied, 1831)	Medium	Medium	High
<i>Coryphospingus cucullatus</i> (P. L. Stadius Muller, 1776)	High	Low	Medium
<i>Cranioleuca pallida</i> (Wied-Neuwied, 1831)	High	Medium	High
<i>Crotophaga ani</i> Linnaeus, 1758	High	Low	Low
<i>Cyanerpes cyaneus</i> (Linnaeus, 1766)	Medium	Low	High
<i>Cyanocorax cristatellus</i> (Temminck, 1823)	High	Low	Low
<i>Cyclarhis gujanensis</i> (Gmelin, 1789)	High	Low	Medium
<i>Dacnis cayana</i> (Linnaeus, 1766)	High	Low	Medium
<i>Elaenia flavogaster</i> (Thunberg, 1822)	High	Low	Medium
<i>Elaenia mesoleuca</i> (Deppe, 1830)	High	Low	High
<i>Elaenia obscura</i> (Orbigny & Lafresnaye, 1837)	High	Medium	High
<i>Elaenia</i> Sundevall, 1836			
<i>Elaenia spectabilis</i> Pelzeln, 1868	High	Low	High
<i>Empidonomus varius</i> (Vieillot, 1818)	High	Low	Medium

<i>Estrilda astrild</i> (Linnaeus, 1758)	High	Low	Low
<i>Euphonia chalybea</i> (Mikan, 1825)	Medium	Medium	High
<i>Euphonia chlorotica</i> (Linnaeus, 1766)	High	Low	Medium
<i>Euphonia pectoralis</i> (Latham, 1801)	Medium	Medium	High
<i>Euphonia violacea</i> (Linnaeus, 1758)	High	Low	High
<i>Fluvicola nengeta</i> (Linnaeus, 1766)	High	Low	Low
<i>Geothlypis aequinoctialis</i> (J. F. Gmelin, 1789)	High	Low	Low
<i>Gnorimopsar chopi</i> (Vieillot, 1819)	High	Low	Low
<i>Guira guira</i> (Gmelin, 1788)	High	Low	Low
<i>Habia rubica</i> (Vieillot, 1817)	Low	Medium	High
<i>Haplospiza unicolor</i> Cabanis, 1851	Medium	Medium	High
<i>Hemithraupis flavicollis</i> (Vieillot, 1818)	Low	Medium	High
<i>Hemithraupis ruficapilla</i> (Vieillot, 1818)	Low	Low	High
<i>Hylophilus amaurocephalus</i> (Nordmann, 1835)	Low	Medium	High
<i>Hylophilus poicilotis</i> Temminck, 1822	Low	Medium	High
<i>Icterus cayanensis</i> (Linnaeus, 1766)	High	Low	Medium
<i>Ilicura militaris</i> (Shaw, 1809)	Low	Medium	High
<i>Laniisoma elegans</i> (Thunberg, 1823)	Low	High	High
<i>Lathrotriccus euleri</i> (Cabanis, 1868)	Medium	Low	High
<i>Legatus leucophaeus</i> (Vieillot, 1818)	Medium	Low	Medium
<i>Lipaugus lanioides</i> (Lesson, 1844)	Low	High	High



<i>Machaeropterus regulus</i> (Hahn, 1819)	Low	Medium	High
<i>Manacus manacus</i> (Linnaeus, 1766)	Low	Low	High
<i>Megarynchus pitangua</i> (Linnaeus, 1766)	High	Low	Medium
<i>Melanerpes candidus</i> (Otto, 1796)	High	Low	Medium
<i>Melanerpes flavifrons</i> (Vieillot, 1818)	Medium	Medium	High
<i>Mimus saturninus</i> (Lichtenstein, 1823)	High	Low	Low
<i>Mionectes oleagineus</i> (Lichtenstein, 1823)	Low	Medium	High
<i>Mionectes rufiventris</i> Cabanis, 1846	Low	Medium	High
<i>Myiarchus ferox</i> (Gmelin, 1789)	High	Low	Medium
<i>Myiarchus</i> Cabanis, 1844			
<i>Myiarchus swainsoni</i> Cabanis & Heine, 1859	High	Low	Low
<i>Myiarchus tyrannulus</i> (Statius Muller, 1776)	High	Low	Medium
<i>Myiodynastes maculatus</i> (Statius Muller, 1776)	High	Low	High
<i>Myiopagis caniceps</i> (Swainson, 1835)	Medium	Medium	High
<i>Myiophobus fasciatus</i> (Statius Muller, 1776)	High	Low	Low
<i>Myiozetetes cayanensis</i> (Linnaeus, 1766)	High	Low	High
<i>Myiozetetes similis</i> (Spix, 1825)	High	Low	Medium
<i>Nemosia pileata</i> (Boddaert, 1783)	High	Low	High
<i>Neopelma aurifrons</i> (Wied-Neuwied, 1831)	Low	High	High
<i>Odontophorus capueira</i> (Spix, 1825)	Low	High	High
<i>Orchesticus abeillei</i> (Lesson, 1839)	Low	Medium	High

<i>Orthogonys chloricterus</i> (Vieillot, 1819)	Low	Medium	High
<i>Oxyruncus cristatus</i> Swainson, 1821	Low	High	High
<i>Pachyramphus castaneus</i> (Jardine & Selby, 1827)	Medium	Medium	High
<i>Pachyramphus polychopterus</i> (Vieillot, 1818)	Medium	Low	Medium
<i>Pachyramphus validus</i> (Lichtenstein, 1823)	Medium	Medium	High
<i>Parula pitiayumi</i> (Vieillot, 1817)	High	Low	High
<i>Patagioenas cayennensis</i> (Bonnaterre, 1792)	Medium	Medium	High
<i>Patagioenas picazuro</i> (Temminck, 1813)	High	Medium	Medium
<i>Patagioenas plumbea</i> (Vieillot, 1818)	Medium	High	High
<i>Patagioenas</i> Reichenbach, 1853			
<i>Patagioenas speciosa</i> (Gmelin, 1789)	Medium	Medium	Medium
<i>Penelope obscura</i> Temminck, 1815	Medium	Medium	High
<i>Penelope</i> Merrem, 1786			
<i>Penelope superciliaris</i> Temminck, 1815	Medium	Medium	High
<i>Phibalura flavirostris</i> Vieillot, 1816	Low	Medium	High
<i>Philydor atricapillus</i> (Wied-Neuwied, 1821)	Low	High	High
<i>Phyllomyias fasciatus</i> (Thunberg, 1822)	High	Medium	Medium
<i>Phylloscartes oustaleti</i> (P. L. Sclater, 1887)	Low	High	High
<i>Phylloscartes sylviolus</i> (Cabanis & Heine, 1859)	Low	Medium	High
<i>Picumnus cirratus</i> Temminck, 1825	Medium	Medium	Medium
<i>Pipile jacutinga</i> (Spix, 1825)	Low	High	High

<i>Pipra pipra</i> (Linnaeus, 1758)	Low	High	High
<i>Pipra rubrocapilla</i> Temminck, 1821	Low	High	High
<i>Pipraeidea melanonota</i> (Vieillot, 1819)	Medium	Low	High
<i>Pitangus sulphuratus</i> (Linnaeus, 1766)	High	Low	Low
<i>Poospiza lateralis</i> (Nordmann, 1835)	Medium	Medium	Medium
<i>Procnias nudicollis</i> (Vieillot, 1817)	Medium	Medium	High
<i>Pseudoleistes guirahuro</i> (Vieillot, 1819)	High	Low	Low
<i>Pteroglossus aracari</i> (Linnaeus, 1758)	High	Medium	High
<i>Pteroglossus bailloni</i> (Vieillot, 1819)	Medium	High	High
<i>Pyroderus scutatus</i> (Shaw, 1792)	Medium	Medium	High
<i>Pyrrhocomma ruficeps</i> (Strickland, 1844)	Low	Medium	High
<i>Ramphastos dicolorus</i> Linnaeus, 1766	Medium	Medium	High
<i>Ramphastos toco</i> Statius Muller, 1776	High	Medium	Medium
<i>Ramphastos vitellinus</i> Lichtenstein, 1823	Medium	High	High
<i>Ramphocelus bresilius</i> (Linnaeus, 1766)	Medium	Low	High
<i>Ramphocelus carbo</i> (Pallas, 1764)	High	Low	High
<i>Saltator fuliginosus</i> (Daudin, 1800)	Medium	Medium	High
<i>Saltator maximus</i> (P. L. Statius Müller, 1776)	Medium	Low	Medium
<i>Saltator similis</i> d'Orbigny & Lafresnaye, 1837	High	Low	Medium
<i>Satrapa icterophrys</i> (Vieillot, 1818)	High	Low	Low
<i>Schiffornis virescens</i> (Lafresnaye, 1838)	Low	Medium	High

<i>Selenidera maculirostris</i> (Lichtenstein, 1823)	Low	Medium	High
<i>Serpophaga subcristata</i> (Vieillot, 1817)	High	Low	Medium
<i>Sicalis flaveola</i> (Linnaeus, 1766)	High	Low	Low
<i>Sirystes sibilator</i> (Vieillot, 1818)	Low	Medium	High
<i>Sporophila caerulea</i> (Vieillot, 1823)	High	Low	Low
<i>Stephanophorus diadematus</i> (Temminck, 1823)	Medium	Medium	High
<i>Tachyphonus coronatus</i> (Vieillot, 1822)	High	Low	High
<i>Tachyphonus cristatus</i> (Linnaeus, 1766)	High	Medium	Low
<i>Tachyphonus rufus</i> (Boddaert, 1783)	High	Low	High
<i>Tangara cayana</i> (Linnaeus, 1766)	High	Low	Medium
<i>Tangara cyanoventris</i> (Vieillot, 1819)	Medium	Medium	High
<i>Tangara desmaresti</i> (Vieillot, 1819)	Medium	Medium	High
<i>Tangara mexicana</i> (Linnaeus, 1766)	Medium	Medium	High
<i>Tangara peruviana</i> (Desmarest, 1806)	Medium	Medium	High
<i>Tangara preciosa</i> (Cabanis, 1850)	Medium	Low	High
<i>Tangara seledon</i> (P. L. Stadius Muller, 1776)	Medium	Medium	High
<i>Tersina viridis</i> (Illiger, 1811)	High	Low	High
<i>Thlypopsis sordida</i> (d'Orbigny & Lafresnaye, 1837)	High	Low	Medium
<i>Thraupis cyanocephala</i> (d'Orbigny & Lafresnaye, 1837)	Medium	Medium	High
<i>Thraupis cyanoptera</i> (Vieillot, 1817)	Medium	Medium	High
<i>Thraupis ornata</i> (Sparrman, 1789)	Medium	Medium	High

<i>Thraupis palmarum</i> ( <a href="#">Wied</a> , 1821)	High	Low	Medium
<i>Thraupis sayaca</i> (Linnaeus, 1766)	High	Low	Medium
<i>Tityra cayana</i> (Linnaeus, 1766)	High	Medium	High
<i>Tityra inquisitor</i> (Lichtenstein, 1823)	Medium	Medium	High
<i>Tolmomyias flaviventris</i> (Wied-Neuwied, 1831)	Low	Low	High
<i>Tolmomyias sulphurescens</i> (Spix, 1825)	Medium	Low	High
<i>Trichothraupis melanops</i> (Vieillot, 1818)	Low	Medium	High
<i>Troglodytes aedon</i> Vieillot, 1809	High	Low	Low
<i>Trogon rufus</i> Gmelin, 1788	Low	Medium	High
<i>Trogon surrucura</i> Vieillot, 1817	Low	Medium	High
<i>Trogon viridis</i> Linnaeus, 1766	Low	Medium	High
<i>Turdus albicollis</i> Vieillot, 1818	Medium	Medium	High
<i>Turdus amaurochalinus</i> Cabanis, 1850	High	Low	Medium
<i>Turdus flavipes</i> Vieillot, 1818	Medium	Medium	High
<i>Turdus leucomelas</i> Vieillot, 1818	High	Low	Medium
<i>Turdus rufiventris</i> Vieillot, 1818	High	Low	Low
<i>Turdus</i> Linnaeus, 1758			
<i>Turdus subalaris</i> (Seebohm, 1887)	High	Low	High
<i>Tyrannus melancholicus</i> Vieillot, 1819	High	Low	Low
<i>Tyrannus savana</i> Daudin, 1802	High	Low	Low
<i>Veniliornis spilogaster</i> (Wagler, 1827)	High	Medium	Medium

<i>Vireo olivaceus</i> (Linnaeus, 1766)	Medium	Low	High
<i>Volatinia jacarina</i> (Linnaeus, 1766)	High	Low	Low
<i>Xolmis cinereus</i> (Vieillot, 1816)	High	Low	Low
<i>Xolmis velatus</i> (Lichtenstein, 1823)	High	Medium	Low
<i>Zonotrichia capensis</i> (P. L. Stadius Muller, 1776)	High	Low	Low



**Table S3.** Results from different null models testing the significance of the metrics calculated for the Atlantic Forest seed-dispersal metanetwork. Significance was tested against 100 simulations for each different model, and for the adjacency matrix of bird-seed dispersal interactions, bird species and plants species separately. The *equiprobable* null model distributes equally the interactions among each row (here, each individual fragment) in the matrix, therefore all fragments have the same chance of receiving an interaction, independently of the number of interactions observed. *Quasiswap* is an optimized version of the ‘*swap*’ (a fixed-fixed model that maintains marginal totals while changing the structure of the network) that reduces numbers above one to maintain marginal totals. *r1* and *r2* use different methods to distribute interaction frequencies to each site and both preserve the marginal totals per row, ie., maintain constant the number of interactions per site as the observed values. We used the ‘*nullmodel*’ function in *bipartite* (for equiprobable null model) and the ‘*oecosimu*’ function in the *vegan* package, both in R, to randomize the matrices based on the observed interactions. For full description of each null model see the vignette of both packages.

<b>Null model</b>	<b>Connectance (mean, z-score)</b>	<b>Modularity (mean, z-score)</b>
<b>Interactions</b>	<b>Observed value = 0.069</b>	<b>Observed value = 0.738</b>
equiprobable	0.068, 7.784	0.760, -4.049
quasiswap	0.069, 0	0.744, -6.791
r1	0.099, -110.659	0.526, 39.042
r2	0.105, -102.455	0.491, 53.154
<b>Birds</b>	<b>Observed value = 0.187</b>	<b>Observed value = 0.341</b>
equiprobable	0.161, 10.713	0.372, -4.011
quasiswap	0.187, ns	0.308, 7.498
r1	0.214, -44.120	0.276, 9.819
r2	0.272, -31.375	0.223, 15.588
<b>Plants</b>	<b>Observed value = 0.091</b>	<b>Observed value = 0.573</b>
equiprobable	0.086, 6.236	0.609, -4.050
quasiswap	0.091, ns	0.560, 5.189
r1	0.117, -47.739	0.446, 13.542
r2	0.132, -44.087	0.393, 18.965

**Table S4.** Pairwise beta-diversity of bird seed-dispersal interactions among forest fragments of the Atlantic Forest, estimated using Sørensen dissimilarity index that accounts for differences on species, or interactions, composition among fragments. A) Beta-diversity results for seed-dispersal interactions of plant species and bird species among forest fragments. B) Beta-diversity results for plant species among forest fragments, and C) beta-diversity results for frugivore bird-species among forest fragments. Note fragments are presented in a decreasing order of area.

A) Plant species – bird species interactions

	Intervales	Botelho	Cardoso	Rebio	Anchieta	F_MG	Araucaria	SGenebra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.96	0.97	0.99	0.98	0.99	1.00	0.98	0.99	0.99	1.00	0.99	1.00	0.99	0.99	0.99
Botelho	0.96	0.00	0.98	1.00	0.92	1.00	1.00	1.00	0.99	0.98	1.00	0.99	0.99	0.99	0.99	0.99
Cardoso	0.97	0.98	0.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rebio	0.99	1.00	1.00	0.00	0.89	0.99	0.98	0.97	0.99	0.97	0.99	0.95	0.99	0.98	1.00	0.98
Anchieta	0.98	0.92	0.99	0.89	0.00	0.98	1.00	1.00	0.96	0.98	1.00	0.94	0.98	1.00	0.96	0.96
F_MG	0.99	1.00	1.00	0.99	0.98	0.00	1.00	0.99	0.97	0.99	0.98	1.00	1.00	1.00	0.99	1.00
Araucaria	1.00	1.00	1.00	0.98	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SGenebra	0.98	1.00	1.00	0.97	1.00	0.99	1.00	0.00	0.99	0.95	0.95	0.99	1.00	0.97	1.00	0.92
Itatiba	0.99	0.99	1.00	0.99	0.96	0.97	1.00	0.99	0.00	0.96	0.90	0.94	0.99	0.99	0.97	0.97

Rest2 5	0.99	0.98	1.00	0.97	0.98	0.99	1.00	0.95	0.96	0.00	0.91	0.89	0.96	1.00	0.98	0.91
F_RC	1.00	1.00	1.00	0.99	1.00	0.98	1.00	0.95	0.90	0.91	0.00	1.00	0.91	0.96	0.99	0.96
Rest1 5	0.99	0.99	1.00	0.95	0.94	1.00	1.00	0.99	0.94	0.89	1.00	0.00	0.97	0.98	0.96	0.83
Rest5 7	1.00	0.99	1.00	0.99	0.98	1.00	1.00	1.00	0.99	0.96	0.91	0.97	0.00	1.00	1.00	1.00
F_RJ	0.99	0.99	1.00	0.98	1.00	1.00	1.00	0.97	0.99	1.00	0.96	0.98	1.00	0.00	1.00	0.93
F_SP	0.99	0.99	1.00	1.00	0.96	0.99	1.00	1.00	0.97	0.98	0.99	0.96	1.00	1.00	0.00	0.92
Rest8	0.99	0.99	1.00	0.98	0.96	1.00	1.00	0.92	0.97	0.91	0.96	0.83	1.00	0.93	0.92	0.00

**Table S4. Continued.**

## B) Plant species

	Intervales	Botelho	Cardoso	Rebio	Anchieta	F_MG	Araucaria	SGenebra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.86	0.79	0.96	0.95	0.91	0.97	0.88	0.94	0.93	0.98	0.97	0.97	0.96	0.92	0.98
Botelho	0.86	0.00	0.87	0.95	0.81	0.96	1.00	1.00	0.91	0.85	1.00	0.90	0.95	0.96	0.96	0.89
Cardoso	0.79	0.87	0.00	0.94	0.94	0.84	0.90	0.98	0.91	0.97	0.97	1.00	0.97	0.94	0.87	1.00
Rebio	0.96	0.95	0.94	0.00	0.62	0.89	0.93	0.92	0.93	0.94	0.91	0.92	0.93	0.83	1.00	0.89
Anchieta	0.95	0.81	0.94	0.62	0.00	0.89	1.00	0.96	0.86	0.89	1.00	0.84	0.93	1.00	0.95	0.89
F_MG	0.91	0.96	0.84	0.89	0.89	0.00	1.00	0.93	0.85	0.92	0.94	0.89	0.95	0.91	0.88	1.00
Araucaria	0.97	1.00	0.90	0.93	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SGenebra	0.88	1.00	0.98	0.92	0.96	0.93	1.00	0.00	0.92	0.86	0.91	0.83	0.92	0.96	1.00	0.90
Itatiba	0.94	0.91	0.91	0.93	0.86	0.85	1.00	0.92	0.00	0.79	0.83	0.85	0.86	0.95	0.85	0.90
Rest25	0.93	0.85	0.97	0.94	0.89	0.92	1.00	0.86	0.79	0.00	0.81	0.60	0.78	0.87	0.88	0.79
F_RC	0.98	1.00	0.97	0.91	1.00	0.94	1.00	0.91	0.83	0.81	0.00	1.00	0.74	0.81	0.94	0.87
Rest15	0.97	0.90	1.00	0.92	0.84	0.89	1.00	0.83	0.85	0.60	1.00	0.00	0.69	0.94	0.95	0.67

Rest5 7	0.97	0.95	0.97	0.93	0.93	0.95	1.00	0.92	0.86	0.78	0.74	0.69	0.00	0.89	1.00	1.00
F_RJ	0.96	0.96	0.94	0.83	1.00	0.91	1.00	0.96	0.95	0.87	0.81	0.94	0.89	0.00	1.00	0.93
F_SP	0.92	0.96	0.87	1.00	0.95	0.88	1.00	1.00	0.85	0.88	0.94	0.95	1.00	1.00	0.00	0.88
Rest8	0.98	0.89	1.00	0.89	0.89	1.00	1.00	0.90	0.90	0.79	0.87	0.67	1.00	0.93	0.88	0.00

**Table S4. Continued.**

## C) Frugivore bird species

	Intervales	Botelho	Cardoso	Rebio	Anchieta	F_MG	Araucaria	SGenebra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.38	0.73	0.70	0.63	0.65	0.73	0.71	0.68	0.76	0.73	0.77	0.85	0.84	0.73	0.78
Botelho	0.38	0.00	0.74	0.62	0.52	0.60	0.73	0.62	0.64	0.67	0.57	0.74	0.76	0.78	0.59	0.61
Cardoso	0.73	0.74	0.00	0.80	0.74	0.78	0.73	0.73	0.84	0.87	0.79	0.74	0.86	0.78	0.74	0.81
Rebio	0.70	0.62	0.80	0.00	0.53	0.70	0.76	0.62	0.62	0.59	0.47	0.63	0.69	0.75	0.58	0.58
Anchieta	0.63	0.52	0.74	0.53	0.00	0.57	0.62	0.43	0.55	0.53	0.45	0.48	0.64	0.69	0.47	0.44
F_MG	0.65	0.60	0.78	0.70	0.57	0.00	0.68	0.59	0.70	0.66	0.60	0.68	0.67	0.88	0.57	0.64
Araucaria	0.73	0.73	0.73	0.76	0.62	0.68	0.00	0.72	0.61	0.68	0.69	0.67	0.82	0.80	0.63	0.70
SGenebra	0.71	0.62	0.73	0.62	0.43	0.59	0.72	0.00	0.59	0.62	0.47	0.64	0.52	0.67	0.45	0.53
Itatiba	0.68	0.64	0.84	0.62	0.55	0.70	0.61	0.59	0.00	0.51	0.53	0.60	0.69	0.63	0.58	0.55
Rest25	0.76	0.67	0.87	0.59	0.53	0.66	0.68	0.62	0.51	0.00	0.37	0.45	0.57	0.67	0.57	0.45
F_RC	0.73	0.57	0.79	0.47	0.45	0.60	0.69	0.47	0.53	0.37	0.00	0.57	0.50	0.65	0.43	0.37
Rest15	0.77	0.74	0.74	0.63	0.48	0.68	0.67	0.64	0.60	0.45	0.57	0.00	0.50	0.66	0.57	0.51



Rest5 7	0.85	0.76	0.86	0.69	0.64	0.67	0.82	0.52	0.69	0.57	0.50	0.50	0.00	0.76	0.54	0.54
F_RJ	0.84	0.78	0.78	0.75	0.69	0.88	0.80	0.67	0.63	0.67	0.65	0.66	0.76	0.00	0.67	0.65
F_SP	0.73	0.59	0.74	0.58	0.47	0.57	0.63	0.45	0.58	0.57	0.43	0.57	0.54	0.67	0.00	0.42
Rest8	0.78	0.61	0.81	0.58	0.44	0.64	0.70	0.53	0.55	0.45	0.37	0.51	0.54	0.65	0.42	0.00

**Table S5.** Pairwise turnover of bird seed-dispersal interactions among forest fragments of the Atlantic Forest, estimated using Simpson dissimilarity index that accounts for the nested component of beta-diversity considering species, or interaction, richness. A) Turnover results for seed-dispersal interactions of plant species and bird species among forest fragments. B) Turnover results for plant species among forest fragments, and C) turnover results for of frugivore bird-species among forest fragments. Note fragments are presented in a decreasing order of area.

A) Plant species – bird species interactions

	Intervales	Botelho	Cardoso	Rebio	Anchieta	F_MG	Araucaria	SGenebra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.90	0.88	0.98	0.92	0.92	1.00	0.91	0.96	0.97	0.98	0.91	1.00	0.96	0.95	0.85
Botelho	0.90	0.00	0.97	1.00	0.90	1.00	1.00	1.00	0.99	0.97	1.00	0.94	0.97	0.99	0.99	0.96
Cardoso	0.88	0.97	0.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rebio	0.98	1.00	1.00	0.00	0.88	0.98	0.96	0.97	0.99	0.97	0.98	0.84	0.97	0.96	1.00	0.96
Anchieta	0.92	0.90	0.99	0.88	0.00	0.98	1.00	1.00	0.96	0.98	1.00	0.84	0.94	1.00	0.95	0.92
F_MG	0.92	1.00	1.00	0.98	0.98	0.00	1.00	0.99	0.96	0.99	0.98	1.00	1.00	1.00	0.99	1.00
Araucaria	1.00	1.00	1.00	0.96	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SGenebra	0.91	1.00	1.00	0.97	1.00	0.99	1.00	0.00	0.99	0.95	0.94	0.97	1.00	0.96	1.00	0.83
Itatiba	0.96	0.99	1.00	0.99	0.96	0.96	1.00	0.99	0.00	0.95	0.87	0.84	0.97	0.99	0.96	0.94

Rest25	0.97	0.97	1.00	0.97	0.98	0.99	1.00	0.95	0.95	0.00	0.89	0.72	0.91	1.00	0.97	0.83
F_RC	0.98	1.00	1.00	0.98	1.00	0.98	1.00	0.94	0.87	0.89	0.00	1.00	0.82	0.96	0.99	0.94
Rest15	0.91	0.94	1.00	0.84	0.84	1.00	1.00	0.97	0.84	0.72	1.00	0.00	0.97	0.97	0.94	0.78
Rest57	1.00	0.97	1.00	0.97	0.94	1.00	1.00	1.00	0.97	0.91	0.82	0.97	0.00	1.00	1.00	1.00
F_RJ	0.96	0.99	1.00	0.96	1.00	1.00	1.00	0.96	0.99	1.00	0.96	0.97	1.00	0.00	1.00	0.92
F_SP	0.95	0.99	1.00	1.00	0.95	0.99	1.00	1.00	0.96	0.97	0.99	0.94	1.00	1.00	0.00	0.90
Rest8	0.85	0.96	1.00	0.96	0.92	1.00	1.00	0.83	0.94	0.83	0.94	0.78	1.00	0.92	0.90	0.00

**Table S5. Continued.**

## B) Plant species

	Intervales	Botelho	Cardoso	Rebio	Anchieta	F_MG	Araucaria	SGenebra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.50	0.49	0.69	0.62	0.64	0.79	0.63	0.60	0.70	0.78	0.75	0.79	0.82	0.69	0.67
Botelho	0.50	0.00	0.83	0.92	0.69	0.96	1.00	1.00	0.87	0.83	1.00	0.83	0.93	0.95	0.96	0.67
Cardoso	0.49	0.83	0.00	0.85	0.85	0.76	0.79	0.97	0.80	0.96	0.89	1.00	0.93	0.91	0.81	1.00
Rebio	0.69	0.92	0.85	0.00	0.62	0.85	0.92	0.85	0.92	0.92	0.89	0.92	0.92	0.77	1.00	0.83
Anchieta	0.62	0.69	0.85	0.62	0.00	0.85	1.00	0.92	0.85	0.85	1.00	0.83	0.92	1.00	0.92	0.83
F_MG	0.64	0.96	0.76	0.85	0.85	0.00	1.00	0.92	0.80	0.91	0.89	0.83	0.93	0.91	0.88	1.00
Araucaria	0.79	1.00	0.79	0.92	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SGenebra	0.63	1.00	0.97	0.85	0.92	0.92	1.00	0.00	0.87	0.83	0.78	0.67	0.86	0.95	1.00	0.67
Itatiba	0.60	0.87	0.80	0.92	0.85	0.80	1.00	0.87	0.00	0.73	0.78	0.83	0.86	0.93	0.80	0.83
Rest25	0.70	0.83	0.96	0.92	0.85	0.91	1.00	0.83	0.73	0.00	0.67	0.42	0.71	0.86	0.87	0.50
F_RC	0.78	1.00	0.89	0.89	1.00	0.89	1.00	0.78	0.78	0.67	0.00	1.00	0.67	0.67	0.89	0.83
Rest15	0.75	0.83	1.00	0.92	0.83	0.83	1.00	0.67	0.83	0.42	1.00	0.00	0.67	0.92	0.92	0.50

Rest5 7	0.79	0.93	0.93	0.92	0.92	0.93	1.00	0.86	0.86	0.71	0.67	0.67	0.00	0.86	1.00	1.00
F_RJ	0.82	0.95	0.91	0.77	1.00	0.91	1.00	0.95	0.93	0.86	0.67	0.92	0.86	0.00	1.00	0.83
F_SP	0.69	0.96	0.81	1.00	0.92	0.88	1.00	1.00	0.80	0.87	0.89	0.92	1.00	1.00	0.00	0.67
Rest8	0.67	0.67	1.00	0.83	0.83	1.00	1.00	0.67	0.83	0.50	0.83	0.50	1.00	0.83	0.67	0.00

**Table S5. Continuous.**

## C) Frugivore bird species

	Inter vales	Botel ho	Card oso	Rebio	Anchie ta	F_MG	Arauca ria	SGene bra	Itatiba	Rest25	F_RC	Rest15	Rest57	F_RJ	F_SP	Rest8
Intervales	0.00	0.28	0.19	0.58	0.32	0.34	0.33	0.45	0.56	0.55	0.52	0.27	0.46	0.60	0.36	0.54
Botelho	0.28	0.00	0.38	0.56	0.29	0.38	0.48	0.41	0.58	0.48	0.35	0.33	0.31	0.55	0.23	0.35
Cardoso	0.19	0.38	0.00	0.63	0.63	0.69	0.69	0.63	0.69	0.81	0.69	0.73	0.85	0.75	0.69	0.75
Rebio	0.58	0.56	0.63	0.00	0.42	0.62	0.62	0.52	0.62	0.48	0.35	0.27	0.31	0.60	0.36	0.42
Anchieta	0.32	0.29	0.63	0.42	0.00	0.55	0.52	0.41	0.45	0.52	0.45	0.20	0.38	0.60	0.36	0.38
F_MG	0.34	0.38	0.69	0.62	0.55	0.00	0.62	0.59	0.62	0.66	0.59	0.53	0.46	0.85	0.50	0.62
Araucaria	0.33	0.48	0.69	0.62	0.52	0.62	0.00	0.67	0.38	0.62	0.62	0.60	0.77	0.80	0.62	0.67
SGenebra	0.45	0.41	0.63	0.52	0.41	0.59	0.67	0.00	0.48	0.62	0.45	0.47	0.23	0.60	0.36	0.50
Itatiba	0.56	0.58	0.69	0.62	0.45	0.62	0.38	0.48	0.00	0.38	0.42	0.20	0.31	0.40	0.36	0.38
Rest25	0.55	0.48	0.81	0.48	0.52	0.66	0.62	0.62	0.38	0.00	0.34	0.20	0.31	0.60	0.50	0.42
F_RC	0.52	0.35	0.69	0.35	0.45	0.59	0.62	0.45	0.42	0.34	0.00	0.33	0.15	0.55	0.32	0.31
Rest15	0.27	0.33	0.73	0.27	0.20	0.53	0.60	0.47	0.20	0.20	0.33	0.00	0.46	0.60	0.47	0.33
Rest57	0.46	0.31	0.85	0.31	0.38	0.46	0.77	0.23	0.31	0.31	0.15	0.46	0.00	0.69	0.38	0.31
F_RJ	0.60	0.55	0.75	0.60	0.60	0.85	0.80	0.60	0.40	0.60	0.55	0.60	0.69	0.00	0.65	0.60
F_SP	0.36	0.23	0.69	0.36	0.36	0.50	0.62	0.36	0.36	0.50	0.32	0.47	0.38	0.65	0.00	0.36
Rest8	0.54	0.35	0.75	0.42	0.38	0.62	0.67	0.50	0.38	0.42	0.31	0.33	0.31	0.60	0.36	0.00

**Table S6.** Pearson’s correlation tests between the pairwise Haversine distance (km) among study sites and the overall dissimilarity distance in the beta-diversity components of plant species, bird species and bird-seed dispersal interactions, at the species and genus level. Haversine distance is estimated with the ‘`rdist.earth.vec`’ function, in the `fields` package [Nychka *et al.* 2015] and assuming 6371 as the Earth mean radius). Beta-diversity is partitioned to separately account for dissimilarities on species, or interactions, composition among fragments (Sorensen index) and the turnover of species, or interactions, due to the nested component of species, or interactions, richness among fragments (Simpson index), following Baselga 2010. All estimations showed p value < 0.001 (Mantel’s test with 999 permutation).

	Plants		Birds		Interactions	
<i>Species level</i>	<i>r</i>	<i>t</i>	<i>r</i>	<i>t</i>	<i>r</i>	<i>t</i>
$\beta$ -diversity (Sørensen)	0.430	7.594	0.470	8.486	0.360	6.145
Turnover (Simpson)	0.483	8.797	0.538	10.169	0.390	6.753
<i>Genus Level</i>	<i>r</i>	<i>t</i>	<i>r</i>	<i>t</i>	<i>r</i>	<i>t</i>
$\beta$ -diversity (Sørensen)	0.421	7.391	0.414	7.247	0.331	5.583
Turnover (Simpson)	0.456	8.157	0.423	7.430	0.361	6.177



**Table S7.** Bird-seed dispersal interactions with a significant role on connecting the metanetwork (betweenness centrality  $B_c > 0$ ) and the traits of both plant and bird species performing the interaction. Degree, number of fragments where the interaction has been recorded.

Plant species + Bird species interaction	Degree, $k$	Betweenness, $B_c$	Seed diameter (mm)	Wood density (g/cm <sup>3</sup> )	Body mass (g)
<i>Schinus terebinthifolius</i> + <i>Thraupis sayaca</i>	7	0.0543	3.50	0.645	32.5
<i>Trema micrantha</i> + <i>Dacnis cayana</i>	5	0.0616	1.70	0.250	13.0
<i>Casearia sylvestris</i> + <i>Thraupis sayaca</i>	4	0.0077	1.30	0.745	32.5
<i>Casearia sylvestris</i> + <i>Dacnis cayana</i>	4	0.0080	1.30	0.745	13.0
<i>Casearia sylvestris</i> + <i>Tachyphonus coronatus</i>	4	0.0334	1.30	0.745	29.3
<i>Cecropia pachystachya</i> + <i>Thraupis sayaca</i>	4	0.0022	0.61	0.330	32.5
<i>Citharexylum myrianthum</i> + <i>Turdus leucomelas</i>	4	0.0062	5.50	0.600	69.1
<i>Schinus terebinthifolius</i> + <i>Turdus rufiventris</i>	4	0.0172	3.50	0.645	69.4
<i>Schinus terebinthifolius</i> + <i>Tangara cayana</i>	4	0.0035	3.50	0.645	18.0
<i>Trema micrantha</i> + <i>Tyrannus melancholicus</i>	4	0.0180	1.70	0.250	37.4
<i>Trema micrantha</i> + <i>Thraupis sayaca</i>	4	0.0047	1.70	0.250	32.5
<i>Trema micrantha</i> + <i>Elaenia flavogaster</i>	4	0.0180	1.70	0.250	24.8
<i>Aegiphila integrifolia</i> + <i>Turdus rufiventris</i>	3	0.0050	7.00	0.430	69.4
<i>Aegiphila integrifolia</i> + <i>Dacnis cayana</i>	3	0.0126	7.00	0.430	13.0
<i>Casearia sylvestris</i> + <i>Elaenia sp</i>	3	0.0019	1.30	0.745	NA
<i>Casearia sylvestris</i> + <i>Myiodynastes maculatus</i>	3	0.0019	1.30	0.745	43.2
<i>Cecropia pachystachya</i> + <i>Turdus leucomelas</i>	3	0.0004	0.61	0.330	69.1
<i>Cecropia pachystachya</i> + <i>Ramphocelus carbo</i>	3	0.0017	0.61	0.330	25.9

<i>Citharexylum myrianthum</i> + <i>Elaenia flavogaster</i>	3	0.0072	5.50	0.600	24.8
<i>Citharexylum myrianthum</i> + <i>Thraupis sayaca</i>	3	0.0063	5.50	0.600	32.5
<i>Citharexylum myrianthum</i> + <i>Myiodynastes maculatus</i>	3	0.0037	5.50	0.600	43.2
<i>Citharexylum myrianthum</i> + <i>Tyrannus melancholicus</i>	3	0.0024	5.50	0.600	37.4
<i>Citharexylum myrianthum</i> + <i>Myiarchus ferox</i>	3	0.0024	5.50	0.600	27.5
<i>Citharexylum myrianthum</i> + <i>Megarynchus pitangua</i>	3	0.0032	5.50	0.600	69.9
<i>Citharexylum myrianthum</i> + <i>Pitangus sulphuratus</i>	3	0.0032	5.50	0.600	62.9
<i>Clusia criuva</i> + <i>Dacnis cayana</i>	3	0.0097	1.80	0.560	13.0
<i>Clusia criuva</i> + <i>Tyrannus melancholicus</i>	3	0.0107	1.80	0.560	37.4
<i>Eugenia uniflora</i> + <i>Thraupis sayaca</i>	3	0.0029	11.40	0.830	32.5
<i>Eugenia uniflora</i> + <i>Turdus leucomelas</i>	3	0.0004	11.40	0.830	69.1
<i>Euterpe edulis</i> + <i>Turdus flavipes</i>	3	0.0116	10.00	0.230	65.1
<i>Maytenus gonoclada</i> + <i>Turdus albicollis</i>	3	0.0116	5.70	0.590	54.0
<i>Melia azedarach</i> + <i>Turdus leucomelas</i>	3	0.0023	1.60	NA	69.1
<i>Psidium guajava</i> + <i>Thraupis sayaca</i>	3	0.0189	3.50	0.735	32.5
<i>Schinus terebinthifolius</i> + <i>Turdus leucomelas</i>	3	0.0008	3.50	0.645	69.1
<i>Schinus terebinthifolius</i> + <i>Pitangus sulphuratus</i>	3	0.0029	3.50	0.645	62.9
<i>Schinus terebinthifolius</i> + <i>Tachyphonus coronatus</i>	3	0.0068	3.50	0.645	29.3
<i>Schinus terebinthifolius</i> + <i>Dacnis cayana</i>	3	0.0144	3.50	0.645	13.0
<i>Schinus terebinthifolius</i> + <i>Mimus saturninus</i>	3	0.0110	3.50	0.645	63.7
<i>Syzygium cumini</i> + <i>Thraupis sayaca</i>	3	0.0047	8.80	NA	32.5

<i>Syzygium cumini</i> + <i>Turdus leucomelas</i>	3	0.0040	8.80	NA	69.1
<i>Trema micrantha</i> + <i>Vireo olivaceus</i>	3	0.0369	1.70	0.250	16.1
<i>Trema micrantha</i> + <i>Tachyphonus coronatus</i>	3	0.0074	1.70	0.250	29.3
<i>Trema micrantha</i> + <i>Myiozetetes similis</i>	3	0.0056	1.70	0.250	28.0
<i>Aegiphila integrifolia</i> + <i>Myiozetetes similis</i>	2	0.0018	7.00	0.430	28.0
<i>Aegiphila integrifolia</i> + <i>Tachyphonus coronatus</i>	2	0.0014	7.00	0.430	29.3
<i>Aegiphila integrifolia</i> + <i>Ramphocelus bresilius</i>	2	0.0018	7.00	0.430	32.9
<i>Aegiphila integrifolia</i> + <i>Vireo olivaceus</i>	2	0.0015	7.00	0.430	16.1
<i>Aegiphila integrifolia</i> + <i>Turdus amaurochalinus</i>	2	0.0018	7.00	0.430	57.9
<i>Aegiphila integrifolia</i> + <i>Myiarchus ferox</i>	2	0.0018	7.00	0.430	27.5
<i>Aegiphila integrifolia</i> + <i>Megarynchus pitangua</i>	2	0.0037	7.00	0.430	69.9
<i>Aegiphila integrifolia</i> + <i>Coereba flaveola</i>	2	0.0018	7.00	0.430	10.0
<i>Aegiphila integrifolia</i> + <i>Turdus leucomelas</i>	2	0.0014	7.00	0.430	69.1
<i>Aegiphila integrifolia</i> + <i>Thraupis sayaca</i>	2	0.0014	7.00	0.430	32.5
<i>Alchornea triplinervia</i> + <i>Turdus albicollis</i>	2	0.0048	4.10	0.490	54.0
<i>Casearia sylvestris</i> + <i>Trichothraupis melanops</i>	2	0.0056	1.30	0.745	22.6
<i>Casearia sylvestris</i> + <i>Vireo olivaceus</i>	2	0.0004	1.30	0.745	16.1
<i>Casearia sylvestris</i> + <i>Turdus rufiventris</i>	2	0.0086	1.30	0.745	69.4
<i>Casearia sylvestris</i> + <i>Turdus leucomelas</i>	2	0.0004	1.30	0.745	69.1
<i>Casearia sylvestris</i> + <i>Saltator similis</i>	2	0.0012	1.30	0.745	43.3
<i>Casearia sylvestris</i> + <i>Tangara cayana</i>	2	0.0004	1.30	0.745	18.0

<i>Casearia sylvestris</i> + <i>Elaenia flavogaster</i>	2	0.0004	1.30	0.745	24.8
<i>Casearia sylvestris</i> + <i>Turdus albicollis</i>	2	0.0048	1.30	0.745	54.0
<i>Casearia sylvestris</i> + <i>Myiozetetes similis</i>	2	0.0004	1.30	0.745	28.0
<i>Casearia sylvestris</i> + <i>Pitangus sulphuratus</i>	2	0.0009	1.30	0.745	62.9
<i>Casearia sylvestris</i> + <i>Cyclarhis gujanensis</i>	2	0.0004	1.30	0.745	28.8
<i>Cecropia glaziovii</i> + <i>Selenidera maculirostris</i>	2	0.0048	0.62	0.410	164.0
<i>Cecropia glaziovii</i> + <i>Thraupis sayaca</i>	2	0.0025	0.62	0.410	32.5
<i>Cecropia pachystachya</i> + <i>Coereba flaveola</i>	2	0.0011	0.61	0.330	10.0
<i>Cecropia pachystachya</i> + <i>Tachyphonus coronatus</i>	2	0.0011	0.61	0.330	29.3
<i>Cecropia pachystachya</i> + <i>Dacnis cayana</i>	2	0.0011	0.61	0.330	13.0
<i>Cecropia pachystachya</i> + <i>Pitangus sulphuratus</i>	2	0.0011	0.61	0.330	62.9
<i>Cecropia pachystachya</i> + <i>Myiozetetes similis</i>	2	0.0003	0.61	0.330	28.0
<i>Cecropia pachystachya</i> + <i>Thraupis palmarum</i>	2	0.0003	0.61	0.330	39.0
<i>Cestrum mariquitense</i> + <i>Turdus leucomelas</i>	2	0.0001	2.70	0.585	69.1
<i>Citharexylum myrianthum</i> + <i>Turdus amaurochalinus</i>	2	0.0005	5.50	0.600	57.9
<i>Citharexylum myrianthum</i> + <i>Turdus rufiventris</i>	2	0.0027	5.50	0.600	69.4
<i>Citharexylum myrianthum</i> + <i>Ramphocelus carbo</i>	2	0.0011	5.50	0.600	25.9
<i>Citharexylum myrianthum</i> + <i>Myiozetetes similis</i>	2	0.0027	5.50	0.600	28.0
<i>Clusia criuva</i> + <i>Turdus albicollis</i>	2	0.0048	1.80	0.560	54.0
<i>Clusia criuva</i> + <i>Thraupis cyanocephala</i>	2	0.0015	1.80	0.560	18.0
<i>Cordia africana</i> + <i>Turdus leucomelas</i>	2	0.0001	NA	NA	69.1

<i>Cupania vernalis</i> + <i>Vireo olivaceus</i>	2	0.0039	7.40	0.655	16.1
<i>Eugenia sp</i> + <i>Thraupis sayaca</i>	2	0.0062	NA	NA	32.5
<i>Eugenia uniflora</i> + <i>Ramphocelus carbo</i>	2	0.0003	11.40	0.830	25.9
<i>Euterpe edulis</i> + <i>Ramphastos dicolorus</i>	2	0.0032	10.00	0.230	331.0
<i>Euterpe edulis</i> + <i>Turdus albicollis</i>	2	0.0048	10.00	0.230	54.0
<i>Euterpe edulis</i> + <i>Procnias nudicollis</i>	2	0.0048	10.00	0.230	172.0
<i>Euterpe edulis</i> + <i>Selenidera maculirostris</i>	2	0.0048	10.00	0.230	164.0
<i>Ficus luschnathiana</i> + <i>Chiroxiphia caudata</i>	2	0.0051	0.70	0.420	25.6
<i>Ficus sp</i> + <i>Thraupis sayaca</i>	2	0.0008	NA	NA	32.5
<i>Geonoma gamiova</i> + <i>Turdus albicollis</i>	2	0.0039	6.10	NA	54.0
<i>Guapira opposita</i> + <i>Chiroxiphia caudata</i>	2	0.0056	3.84	0.830	25.6
<i>Guarea guidonia</i> + <i>Tyrannus melancholicus</i>	2	0.0023	10.00	0.622	37.4
<i>Guarea guidonia</i> + <i>Pitangus sulphuratus</i>	2	0.0023	10.00	0.622	62.9
<i>Guarea guidonia</i> + <i>Coereba flaveola</i>	2	0.0023	10.00	0.622	10.0
<i>Guarea macrophylla</i> + <i>Chiroxiphia caudata</i>	2	0.0056	8.60	0.650	25.6
<i>Maclura tinctoria</i> + <i>Thraupis sayaca</i>	2	0.0057	2.10	0.837	32.5
<i>Maytenus gonoclada</i> + <i>Carpornis cucullata</i>	2	0.0039	5.70	0.590	74.2
<i>Melia azedarach</i> + <i>Thraupis sayaca</i>	2	0.0006	1.60	NA	32.5
<i>Melia azedarach</i> + <i>Euphonia chlorotica</i>	2	0.0006	1.60	NA	11.0
<i>Melia azedarach</i> + <i>Myiozetetes similis</i>	2	0.0006	1.60	NA	28.0
<i>Melia azedarach</i> + <i>Pitangus sulphuratus</i>	2	0.0006	1.60	NA	62.9

<i>Miconia albicans</i> + <i>Dacnis cayana</i>	2	0.0018	1.00	NA	13.0
<i>Miconia albicans</i> + <i>Myiozetetes similis</i>	2	0.0018	1.00	NA	28.0
<i>Miconia albicans</i> + <i>Tachyphonus coronatus</i>	2	0.0018	1.00	NA	29.3
<i>Miconia albicans</i> + <i>Ramphocelus bresilius</i>	2	0.0018	1.00	NA	32.9
<i>Miconia albicans</i> + <i>Thraupis sayaca</i>	2	0.0018	1.00	NA	32.5
<i>Miconia budlejoides</i> + <i>Chiroxiphia caudata</i>	2	0.0056	1.00	NA	25.6
<i>Miconia budlejoides</i> + <i>Trichothraupis melanops</i>	2	0.0056	1.00	NA	22.6
<i>Miconia cinnamomifolia</i> + <i>Pteroglossus baironii</i>	2	0.0056	0.30	0.730	146.0
<i>Miconia cinnamomifolia</i> + <i>Thraupis cyanocephala</i>	2	0.0044	0.30	0.730	18.0
<i>Miconia cinnamomifolia</i> + <i>Turdus amaurochalinus</i>	2	0.0037	0.30	0.730	57.9
<i>Miconia cinnamomifolia</i> + <i>Dacnis cayana</i>	2	0.0025	0.30	0.730	13.0
<i>Miconia discolor</i> + <i>Chiroxiphia caudata</i>	2	0.0051	NA	NA	25.6
<i>Miconia pusilliflora</i> + <i>Tachyphonus coronatus</i>	2	0.0039	1.70	NA	29.3
<i>Miconia pusilliflora</i> + <i>Chiroxiphia caudata</i>	2	0.0039	1.70	NA	25.6
<i>Miconia pusilliflora</i> + <i>Tangara seledon</i>	2	0.0039	1.70	NA	18.7
<i>Miconia pusilliflora</i> + <i>Thraupis cyanocephala</i>	2	0.0039	1.70	NA	18.0
<i>Miconia racemifera</i> + <i>Chiroxiphia caudata</i>	2	0.0039	NA	NA	25.6
<i>Miconia racemifera</i> + <i>Mionectes rufiventris</i>	2	0.0039	NA	NA	13.3
<i>Miconia racemifera</i> + <i>Thraupis cyanocephala</i>	2	0.0039	NA	NA	18.0
<i>Miconia racemifera</i> + <i>Tachyphonus coronatus</i>	2	0.0039	NA	NA	29.3
<i>Miconia racemifera</i> + <i>Turdus albicollis</i>	2	0.0039	NA	NA	54.0

<i>Miconia sp + Turdus leucomelas</i>	2	0.0001	NA	NA	69.1
<i>Miconia sp + Manacus manacus</i>	2	0.0041	NA	NA	16.7
<i>Myrcia hebeptala + Chiroxiphia caudata</i>	2	0.0051	NA	0.780	25.6
<i>Myrcia pubipetala + Turdus albicollis</i>	2	0.0048	0.30	0.812	54.0
<i>Myrcia splendens + Ramphocelus bresilius</i>	2	0.0018	NA	0.870	32.9
<i>Myrcia splendens + Trogon surrucura</i>	2	0.0044	NA	0.870	73.3
<i>Myrcia splendens + Coereba flaveola</i>	2	0.0018	NA	0.870	10.0
<i>Myrcia splendens + Turdus leucomelas</i>	2	0.0044	NA	0.870	69.1
<i>Myrcia splendens + Cacicus haemorrhous</i>	2	0.0294	NA	0.870	83.7
<i>Myrcia splendens + Dacnis cayana</i>	2	0.0044	NA	0.870	13.0
<i>Myrcia splendens + Thraupis cyanocephala</i>	2	0.0044	NA	0.870	18.0
<i>Myrcia splendens + Thraupis palmarum</i>	2	0.0018	NA	0.870	39.0
<i>Myrsine coriacea + Thraupis ornata</i>	2	0.0039	NA	0.590	33.0
<i>Myrsine coriacea + Tangara cayana</i>	2	0.0034	NA	0.590	18.0
<i>Myrsine coriacea + Thraupis palmarum</i>	2	0.0034	NA	0.590	39.0
<i>Myrsine coriacea + Myiozetetes similis</i>	2	0.0034	NA	0.590	28.0
<i>Myrsine coriacea + Tangara seledon</i>	2	0.0039	NA	0.590	18.7
<i>Myrsine coriacea + Turdus leucomelas</i>	2	0.0034	NA	0.590	69.1
<i>Myrsine coriacea + Thraupis cyanocephala</i>	2	0.0039	NA	0.590	18.0
<i>Myrsine coriacea + Tangara desmaresti</i>	2	0.0039	NA	0.590	20.4
<i>Myrsine coriacea + Dacnis cayana</i>	2	0.0039	NA	0.590	13.0



<i>Myrsine coriacea</i> + <i>Myiodynastes maculatus</i>	2	0.0105	NA	0.590	43.2
<i>Myrsine coriacea</i> + <i>Tachyphonus coronatus</i>	2	0.0039	NA	0.590	29.3
<i>Myrsine coriacea</i> + <i>Turdus amaurochalinus</i>	2	0.0105	NA	0.590	57.9
<i>Myrsine ferruginea</i> + <i>Vireo olivaceus</i>	2	0.0241	NA	NA	16.1
<i>Myrsine ferruginea</i> + <i>Pachyramphus polychopterus</i>	2	0.0241	NA	NA	20.8
<i>Myrsine umbellata</i> + <i>Dacnis cayana</i>	2	0.0015	3.50	0.820	13.0
<i>Myrsine umbellata</i> + <i>Myiozetetes similis</i>	2	0.0015	3.50	0.820	28.0
<i>Myrsine umbellata</i> + <i>Tachyphonus coronatus</i>	2	0.0015	3.50	0.820	29.3
<i>Myrsine umbellata</i> + <i>Turdus rufiventris</i>	2	0.0015	3.50	0.820	69.4
<i>Myrsine umbellata</i> + <i>Myiodynastes maculatus</i>	2	0.0015	3.50	0.820	43.2
<i>Myrsine umbellata</i> + <i>Thraupis cyanocephala</i>	2	0.0015	3.50	0.820	18.0
<i>Myrsine umbellata</i> + <i>Turdus albicollis</i>	2	0.0063	3.50	0.820	54.0
<i>Myrsine umbellata</i> + <i>Turdus leucomelas</i>	2	0.0015	3.50	0.820	69.1
<i>Myrsine umbellata</i> + <i>Thraupis ornata</i>	2	0.0039	3.50	0.820	33.0
<i>Myrsine umbellata</i> + <i>Chiroxiphia caudata</i>	2	0.0015	3.50	0.820	25.6
<i>Myrsine umbellata</i> + <i>Thraupis sayaca</i>	2	0.0015	3.50	0.820	32.5
<i>Nectandra membranacea</i> + <i>Procnias nudicollis</i>	2	0.0048	10.00	0.614	172.0
<i>Nectandra membranacea</i> + <i>Turdus albicollis</i>	2	0.0048	10.00	0.614	54.0
<i>Plinia cauliflora</i> + <i>Thraupis sayaca</i>	2	0.0011	NA	0.641	32.5
<i>Psidium guajava</i> + <i>Cacicus chrysopterus</i>	2	0.0039	3.50	0.735	36.2
<i>Rubus rosifolius</i> + <i>Thraupis sayaca</i>	2	0.0105	NA	NA	32.5

<i>Rubus rosifolius</i> + <i>Tachyphonus coronatus</i>	2	0.0105	NA	NA	29.3
<i>Rubus urticifolius</i> + <i>Turdus rufiventris</i>	2	0.0086	NA	NA	69.4
<i>Rubus urticifolius</i> + <i>Tachyphonus coronatus</i>	2	0.0086	NA	NA	29.3
<i>Rudgea jasminoides</i> + <i>Turdus albicollis</i>	2	0.0048	NA	NA	54.0
<i>Schefflera angustissima</i> + <i>Turdus albicollis</i>	2	0.0048	2.00	0.470	54.0
<i>Schinus terebinthifolius</i> + <i>Thraupis palmarum</i>	2	0.0019	3.50	0.645	39.0
<i>Schinus terebinthifolius</i> + <i>Myiozetetes similis</i>	2	0.0007	3.50	0.645	28.0
<i>Schinus terebinthifolius</i> + <i>Coereba flaveola</i>	2	0.0020	3.50	0.645	10.0
<i>Schinus terebinthifolius</i> + <i>Thraupis cyanocephala</i>	2	0.0015	3.50	0.645	18.0
<i>Schinus terebinthifolius</i> + <i>Elaenia sp</i>	2	0.0007	3.50	0.645	NA
<i>Schinus terebinthifolius</i> + <i>Turdus amaurochalinus</i>	2	0.0007	3.50	0.645	57.9
<i>Schinus terebinthifolius</i> + <i>Zonotrichia capensis</i>	2	0.0002	3.50	0.645	20.3
<i>Schinus terebinthifolius</i> + <i>Elaenia flavogaster</i>	2	0.0044	3.50	0.645	24.8
<i>Struthanthus marginatus</i> + <i>Turdus rufiventris</i>	2	0.0081	NA	NA	69.4
<i>Syzygium cumini</i> + <i>Coereba flaveola</i>	2	0.0006	8.80	NA	10.0
<i>Trema micrantha</i> + <i>Turdus amaurochalinus</i>	2	0.0020	1.70	0.250	57.9
<i>Trema micrantha</i> + <i>Myiodynastes maculatus</i>	2	0.0051	1.70	0.250	43.2
<i>Trema micrantha</i> + <i>Saltator similis</i>	2	0.0051	1.70	0.250	43.3
<i>Trema micrantha</i> + <i>Trichothraupis melanops</i>	2	0.0051	1.70	0.250	22.6
<i>Trema micrantha</i> + <i>Manacus manacus</i>	2	0.0027	1.70	0.250	16.7
<i>Trema micrantha</i> + <i>Ramphocelus carbo</i>	2	0.0005	1.70	0.250	25.9

<i>Trema micrantha</i> + <i>Thraupis palmarum</i>	2	0.0007	1.70	0.250	39.0
<i>Trema micrantha</i> + <i>Tangara cayana</i>	2	0.0008	1.70	0.250	18.0
<i>Trichilia claussemi</i> + <i>Tangara cayana</i>	2	0.0007	9.00	0.681	18.0
<i>Trichilia claussemi</i> + <i>Thlypopsis sordida</i>	2	0.0008	9.00	0.681	17.0
<i>Trichilia claussemi</i> + <i>Turdus leucomelas</i>	2	0.0007	9.00	0.681	69.1
<i>Trichilia claussemi</i> + <i>Elaenia flavogaster</i>	2	0.0007	9.00	0.681	24.8
<i>Trichilia claussemi</i> + <i>Ramphocelus carbo</i>	2	0.0007	9.00	0.681	25.9
<i>Trichilia claussemi</i> + <i>Vireo olivaceus</i>	2	0.0008	9.00	0.681	16.1
<i>Trichilia claussemi</i> + <i>Dacnis cayana</i>	2	0.0007	9.00	0.681	13.0
<i>Trichilia claussemi</i> + <i>Tachyphonus coronatus</i>	2	0.0008	9.00	0.681	29.3
<i>Urera baccifera</i> + <i>Tachyphonus coronatus</i>	2	0.0051	2.00	0.170	29.3
<i>Urera baccifera</i> + <i>Trichothraupis melanops</i>	2	0.0051	2.00	0.170	22.6
<i>Virola bicuhyba</i> + <i>Ramphastos dicolorus</i>	2	0.0048	16.00	0.610	331.0
<i>Virola bicuhyba</i> + <i>Turdus flavipes</i>	2	0.0048	16.00	0.610	65.1

**Table S8.** Bird species with a significant role on connecting the metanetwork (betweenness centrality  $B_C > 0$ ) and the traits associated to each species. Degree, number of fragments where the bird species has been recorded.

Family	Bird species	Degree, $k$	Betweenness, $B_C$	Body mass (g)	Group	Gape Size (mm)
Tyrannidae	<i>Pitangus sulphuratus</i>	16	0.061	63.33	Small birds	17.00
Thraupidae	<i>Thraupis sayaca</i>	15	0.056	32.49	Small birds	10.11
Turdidae	<i>Turdus amaurochalinus</i>	15	0.048	57.90	Small birds	11.40
Turdidae	<i>Turdus rufiventris</i>	13	0.054	69.44	Small birds	12.14
Thraupidae	<i>Dacnis cayana</i>	12	0.038	13.00	Small birds	7.00
Tyrannidae	<i>Elaenia flavogaster</i>	12	0.043	24.80	Small birds	9.94
Tyrannidae	<i>Myiodynastes maculatus</i>	12	0.049	43.20	Small birds	17.00
Thraupidae	<i>Tachyphonus coronatus</i>	12	0.038	29.30	Small birds	9.10
Thraupidae	<i>Tangara cayana</i>	12	0.029	18.00	Small birds	8.80
Turdidae	<i>Turdus leucomelas</i>	12	0.036	69.10	Small birds	11.90
Tyrannidae	<i>Tyrannus melancholicus</i>	12	0.045	37.40	Small birds	NA
Coerebidae	<i>Coereba flaveola</i>	10	0.036	10.01	Small birds	NA
Vireonidae	<i>Vireo olivaceus</i>	9	0.030	16.06	Small birds	7.92
Tyrannidae	<i>Elaenia sp</i>	8	0.015	NA	NA	NA
Tyrannidae	<i>Megarynchus pitangua</i>	8	0.026	69.91	Small birds	17.81
Tyrannidae	<i>Myiozetetes similis</i>	8	0.027	28.00	Small birds	10.16
Thraupidae	<i>Thraupis palmarum</i>	8	0.021	39.00	Small birds	10.55
Emberizidae	<i>Zonotrichia capensis</i>	8	0.013	20.31	Small birds	NA

Cardinalidae	<i>Saltator similis</i>	7	0.018	43.30	Small birds	13.00
Picidae	<i>Celeus flavescens</i>	6	0.022	139.00	Large birds	12.90
Thraupidae	<i>Conirostrum speciosum</i>	6	0.010	8.80	Small birds	NA
Tyrannidae	<i>Empidonomus varius</i>	6	0.015	27.10	Small birds	10.98
Tyrannidae	<i>Myiarchus ferox</i>	6	0.009	27.50	Small birds	NA
Turdidae	<i>Turdus albicollis</i>	6	0.011	54.00	Small birds	13.08
Pipridae	<i>Chiroxiphia caudata</i>	5	0.009	25.60	Small birds	11.01
Vireonidae	<i>Cyclarhis gujanensis</i>	5	0.005	28.80	Small birds	NA
Mimidae	<i>Mimus saturninus</i>	5	0.017	63.70	Small birds	12.90
Columbidae	<i>Patagioenas picazuro</i>	5	0.006	279.00	Large birds	10.50
Thraupidae	<i>Ramphocelus carbo</i>	5	0.003	25.92	Small birds	9.98
Thraupidae	<i>Thlypopsis sordida</i>	5	0.004	17.00	Small birds	7.86
Thraupidae	<i>Trichothraupis melanops</i>	5	0.009	22.58	Small birds	NA
Fringillidae	<i>Euphonia chlorotica</i>	4	0.008	11.00	Small birds	6.51
Cardinalidae	<i>Habia rubica</i>	4	0.006	32.46	Small birds	11.53
Thraupidae	<i>Nemosia pileata</i>	4	0.004	16.00	Small birds	8.37
Cracidae	<i>Penelope obscura</i>	4	0.006	1770.00	Large birds	23.40
Ramphastidae	<i>Ramphastos dicolorus</i>	4	0.004	331.00	Large birds	30.70
Thraupidae	<i>Tersina viridis</i>	4	0.011	29.00	Small birds	13.21
Turdidae	<i>Turdus flavipes</i>	4	0.012	65.14	Small birds	NA
Tyrannidae	<i>Tyrannus savana</i>	4	0.006	31.90	Small birds	NA

Icteridae	<i>Cacicus chrysopterus</i>	3	0.004	36.16	Small birds	NA
Tyrannidae	<i>Camptostoma obsoletum</i>	3	0.005	8.10	Small birds	6.17
Fringillidae	<i>Euphonia violacea</i>	3	0.009	15.00	Small birds	7.39
Thraupidae	<i>Hemithraupis ruficapilla</i>	3	0.004	11.00	Small birds	NA
Pipridae	<i>Manacus manacus</i>	3	0.005	16.70	Small birds	8.36
Tyrannidae	<i>Mionectes rufiventris</i>	3	0.004	13.30	Small birds	NA
Tyrannidae	<i>Myiarchus swainsoni</i>	3	0.008	25.10	Small birds	NA
Cotingidae	<i>Pachyramphus polychopterus</i>	3	0.006	20.80	Small birds	NA
Thraupidae	<i>Pipraeidea melanonota</i>	3	0.001	21.00	Small birds	6.94
Cotingidae	<i>Pyroderus scutatus</i>	3	0.003	357.00	Large birds	26.70
Thraupidae	<i>Tachyphonus cristatus</i>	3	0.010	18.80	Small birds	NA
Thraupidae	<i>Thraupis cyanocephala</i>	3	0.003	18.00	Small birds	NA
Cotingidae	<i>Tityra cayana</i>	3	0.005	68.10	Large birds	18.70
Trogonidae	<i>Trogon surrucura</i>	3	0.004	73.29	Large birds	18.00
Momotidae	<i>Baryphthengus ruficapillus</i>	2	0.001	141.65	Large birds	17.20
Icteridae	<i>Cacicus haemorrhous</i>	2	0.007	83.71	Large birds	12.40
Cotingidae	<i>Carpornis cucullata</i>	2	0.001	74.19	Large birds	14.40
Picidae	<i>Colaptes campestris</i>	2	0.006	158.00	Large birds	NA
Picidae	<i>Colaptes melanochloros</i>	2	0.001	127.27	Large birds	NA
Cuculidae	<i>Crotophaga ani</i>	2	0.002	110.09	Large birds	NA
Corvidae	<i>Cyanocorax cristatellus</i>	2	0.001	178.00	Large birds	17.50

Tyrannidae	<i>Elaenia mesoleuca</i>	2	0.001	17.60	Small birds	NA
Fringillidae	<i>Euphonia pectoralis</i>	2	0.002	14.40	Small birds	7.69
Cuculidae	<i>Guira guira</i>	2	0.002	141.00	Large birds	NA
Vireonidae	<i>Hylophilus poicilotis</i>	2	0.001	11.59	Small birds	NA
Icteriadae	<i>Icterus cayanensis</i>	2	0.001	35.44	Small birds	NA
Pipridae	<i>Ilicura militaris</i>	2	0.002	12.70	Small birds	8.93
Picidae	<i>Melanerpes flavifrons</i>	2	0.001	57.78	Small birds	NA
Thraupidae	<i>Orthogonys chloricterus</i>	2	0.001	40.00	Small birds	9.80
Cotingidae	<i>Oxyruncus cristatus</i>	2	0.001	42.00	Small birds	10.80
Cotingidae	<i>Pachyramphus validus</i>	2	0.006	43.00	Small birds	NA
Parulidae	<i>Parula pitaiyumi</i>	2	0.001	6.82	Small birds	NA
Columbidae	<i>Patagioenas cayennensis</i>	2	0.003	229.00	Large birds	NA
Columbidae	<i>Patagioenas plumbea</i>	2	0.001	178.77	Large birds	9.00
Cracidae	<i>Penelope superciliaris</i>	2	0.001	849.99	Large birds	19.50
Cracidae	<i>Pipile jacutinga</i>	2	0.002	1240.96	Large birds	24.00
Cotingidae	<i>Procnias nudicollis</i>	2	0.002	172.04	Large birds	24.50
Ramphastidae	<i>Pteroglossus bailloni</i>	2	0.002	146.00	Large birds	NA
Ramphastidae	<i>Ramphastos toco</i>	2	0.001	617.99	Large birds	31.86
Thraupidae	<i>Ramphocelus bresilius</i>	2	0.001	32.90	Small birds	NA
Cotingidae	<i>Schiffornis virescens</i>	2	0.001	21.50	Small birds	NA
Ramphastidae	<i>Selenidera maculirostris</i>	2	0.002	164.00	Large birds	25.20

Thraupidae	<i>Stephanophorus diadematus</i>	2	0.002	35.40	Small birds	9.24
Thraupidae	<i>Tangara desmaresti</i>	2	0.001	20.40	Small birds	7.01
Thraupidae	<i>Tangara seledon</i>	2	0.001	18.70	Small birds	8.35
Thraupidae	<i>Thraupis cyanoptera</i>	2	0.001	21.53	Small birds	NA
Thraupidae	<i>Thraupis ornata</i>	2	0.001	33.00	Small birds	9.44
Cotingidae	<i>Tityra inquisitor</i>	2	0.001	43.10	Small birds	14.95
Tyrannidae	<i>Tolmomyias sulphurescens</i>	2	0.001	14.30	Small birds	NA
Trogonidae	<i>Trogon rufus</i>	2	0.001	53.80	Large birds	17.80
Turdidae	<i>Turdus subalaris</i>	2	0.002	49.50	Small birds	12.19
Picidae	<i>Veniliornis spilogaster</i>	2	0.006	34.00	Small birds	NA
Thraupidae	<i>Volatinia jacarina</i>	2	0.001	9.94	Small birds	NA
Tyrannidae	<i>Xolmis velatus</i>	2	0.001	49.08	Small birds	NA



**Table S9.** Plant species with a significant role on connecting the metanetwork (betweenness centrality  $B_c > 0$ ) and the traits associated to each species. Degree, number of fragments where the plant species has been recorded.

Family	Plant species	Degree $k$	Betweenness $B_c$	Seed diameter (mm)	Wood density (g/ cm <sup>3</sup> )	Status	Habit
Anacardiaceae	<i>Schinus terebinthifolius</i>	8	0.061	3.500	0.65	native	tree
Salicaceae	<i>Casearia sylvestris</i>	7	0.068	1.300	0.75	native	tree
Verbenaceae	<i>Citharexylum myrianthum</i>	6	0.016	5.500	0.60	native	tree
Cannabaceae	<i>Trema micrantha</i>	6	0.056	1.700	0.25	native	tree
Lamiaceae	<i>Aegiphila integrifolia</i>	5	0.015	7.000	0.43	native	tree
Moraceae	<i>Ficus sp</i>	5	0.049	NA	NA	NA	NA
Meliaceae	<i>Guarea macrophylla</i>	5	0.036	8.600	0.65	native	tree
Melastomataceae	<i>Miconia sp</i>	5	0.034	NA	NA	NA	NA
Myrtaceae	<i>Syzygium cumini</i>	5	0.010	8.800	NA	natural ized	tree
Urticaceae	<i>Cecropia glaziovii</i>	4	0.029	0.620	0.41	native	tree
Urticaceae	<i>Cecropia pachystachya</i>	4	0.004	0.610	0.33	native	tree
Solanaceae	<i>Cestrum mariquitense</i>	4	0.003	2.700	0.59	native	scrub
Clusiaceae	<i>Clusia criuva</i>	4	0.019	1.800	0.56	native	tree
Myrtaceae	<i>Eugenia sp</i>	4	0.028	NA	NA	NA	tree
Myrtaceae	<i>Eugenia uniflora</i>	4	0.004	11.400	0.83	native	tree
Nyctaginaceae	<i>Guapira opposita</i>	4	0.038	3.840	0.83	native	tree
Melastomataceae	<i>Miconia cinnamomifolia</i>	4	0.020	0.300	0.73	native	scrub
Primulaceae	<i>Myrsine umbellata</i>	4	0.019	3.500	0.82	native	tree
Myrtaceae	<i>Psidium guajava</i>	4	0.038	3.500	0.73	natural ized	tree
Euphorbiaceae	<i>Alchornea triplinervia</i>	3	0.011	4.100	0.49	native	tree
Annonaceae	<i>Annona neosericea</i>	3	0.018	3.700	0.47	native	tree

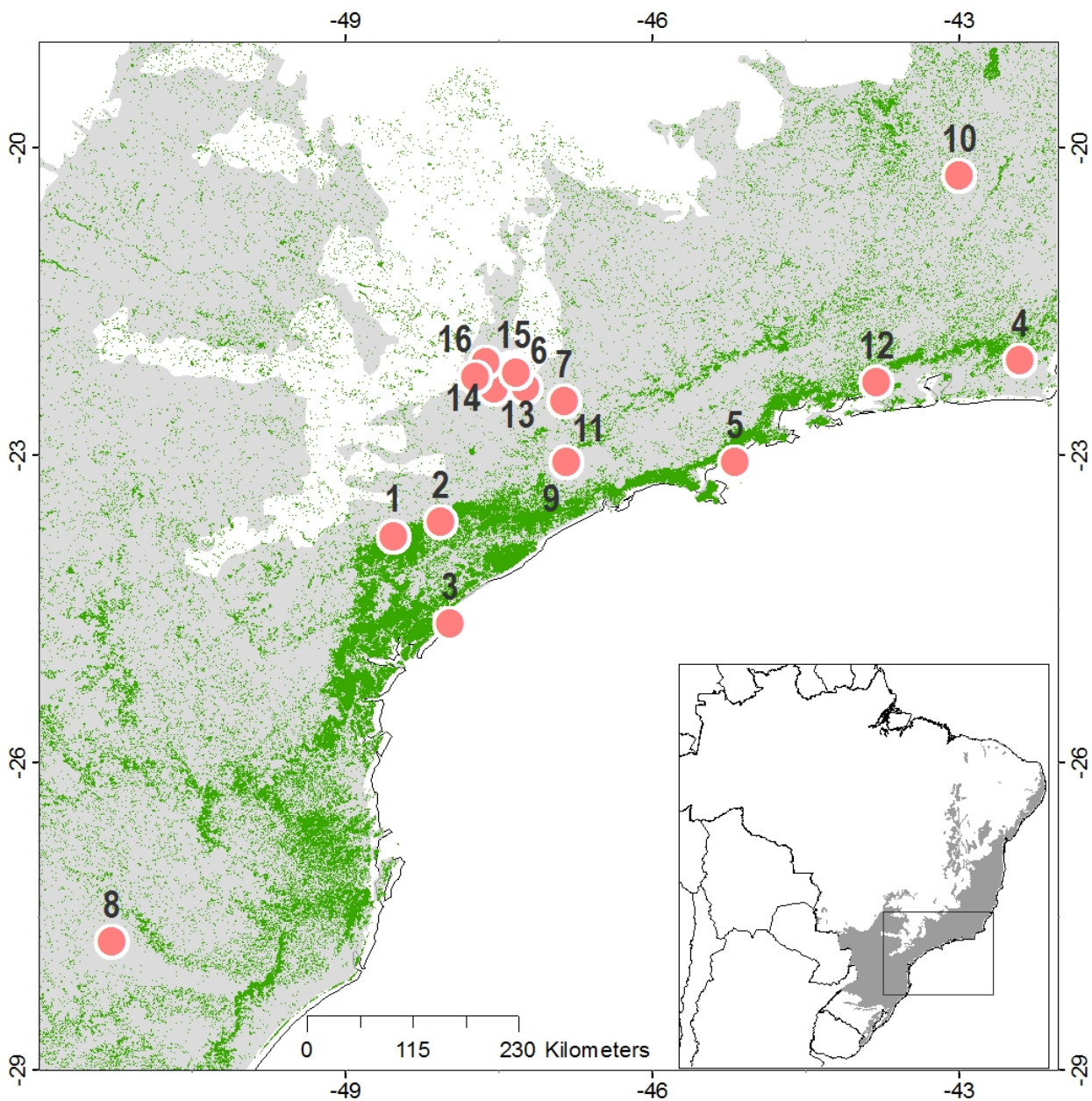
Meliaceae	<i>Cabralea canjerana</i>	3	0.022	9.000	0.57	native	tree
Sapindaceae	<i>Cupania oblongifolia</i>	3	0.011	9.700	0.67	native	tree
Arecaceae	<i>Euterpe edulis</i>	3	0.010	10.000	0.23	native	palm
Celastraceae	<i>Maytenus gonoclada</i>	3	0.010	5.700	0.59	native	tree
Meliaceae	<i>Melia azedarach</i>	3	0.002	1.600	NA	cultivated	tree
Myrtaceae	<i>Myrcia splendens</i>	3	0.011	NA	0.87	native	tree
Primulaceae	<i>Myrsine coriacea</i>	3	0.013	NA	0.59	native	tree
Piperaceae	<i>Piper sp</i>	3	0.017	NA	NA	NA	NA
Burseraceae	<i>Protium heptaphyllum</i>	3	0.013	7.500	0.66	native	tree
Rubiaceae	<i>Rudgea jasminoides</i>	3	0.018	NA	NA	native	scrub
Meliaceae	<i>Trichilia claussoni</i>	3	0.004	9.000	0.68	native	tree
Sapindaceae	<i>Allophylus edulis</i>	2	0.007	5.740	0.65	native	scrub
Myrtaceae	<i>Calyptranthes concinna</i>	2	0.004	5.000	0.77	NA	NA
Salicaceae	<i>Casearia decandra</i>	2	0.016	6.000	0.68	native	tree
Canellaceae	<i>Cinnamodendron dinisii</i>	2	0.004	7.000	0.62	native	tree
Boraginaceae	<i>Cordia africana</i>	2	<0.0010	NA	NA	exotic	tree
Boraginaceae	<i>Cordia ecalyculata</i>	2	0.003	8.000	1.03	native	tree
Lauraceae	<i>Cryptocarya moschata</i>	2	0.004	8.000	0.72	native	tree
Sapindaceae	<i>Cupania vernalis</i>	2	0.005	7.400	0.66	native	tree
Moraceae	<i>Ficus benjamina</i>	2	0.002	NA	NA	exotic	tree
Moraceae	<i>Ficus insipida</i>	2	0.001	1.700	0.38	native	tree
Moraceae	<i>Ficus luschnathiana</i>	2	0.008	0.700	0.42	native	hemiepiphyte
Arecaceae	<i>Geonoma gamiova</i>	2	0.005	6.100	NA	native	palm
Meliaceae	<i>Guarea guidonia</i>	2	0.001	10.000	0.62	native	tree
Phyllanthaceae	<i>Hieronyma alchorneoides</i>	2	0.004	2.000	0.78	native	tree
Fabaceae	<i>Inga sp.</i>	2	0.002	NA	NA	NA	NA

Verbenaceae	<i>Lantana camara</i>	2	0.012	NA	NA	native	scrub
Lauraceae	<i>Lauraceae</i>	2	0.016	NA	NA	NA	NA
Melastomataceae	<i>Leandra australis</i>	2	0.005	NA	NA	native	shrub
Moraceae	<i>Maclura tinctoria</i>	2	0.002	2.100	0.84	native	tree
Melastomataceae	<i>Miconia albicans</i>	2	<0.001	1.000	NA	native	scrub
Melastomataceae	<i>Miconia budlejoides</i>	2	0.007	1.000	NA	native	scrub
Melastomataceae	<i>Miconia cabucu</i>	2	0.005	1.300	0.75	native	scrub
Melastomataceae	<i>Miconia cubatanensis</i>	2	0.004	NA	0.82	native	scrub
Melastomataceae	<i>Miconia discolor</i>	2	0.008	NA	NA	native	scrub
Melastomataceae	<i>Miconia pusilliflora</i>	2	0.005	1.700	NA	native	scrub
Melastomataceae	<i>Miconia racemifera</i>	2	0.005	NA	NA	native	scrub
Melastomataceae	<i>Miconia tristis</i>	2	0.005	NA	NA	native	scrub
Cucurbitaceae	<i>Momordica charantia</i>	2	0.001	NA	NA	natural ized	liana
Moraceae	<i>Morus alba</i>	2	<0.001	1.000	NA	invasiv e	tree
Myrtaceae	<i>Myrcia brasiliensis</i>	2	0.016	NA	NA	native	scrub
Myrtaceae	<i>Myrcia hebeptala</i>	2	0.008	NA	0.78	native	tree
Myrtaceae	<i>Myrcia ilheosensis</i>	2	0.004	NA	NA	native	scrub
Myrtaceae	<i>Myrcia pubipetala</i>	2	0.004	0.300	0.81	native	tree
Primulaceae	<i>Myrsine ferruginea</i>	2	0.003	NA	NA	native	tree
Primulaceae	<i>Myrsine sp</i>	2	0.002	NA	NA	NA	tree
Lauraceae	<i>Nectandra membranacea</i>	2	0.004	10.000	0.61	native	tree
Myrtaceae	<i>Neomitranthes glomerata</i>	2	0.004	11.000	NA	native	NA
Lauraceae	<i>Ocotea corymbosa</i>	2	0.008	6.000	0.80	native	tree
Lauraceae	<i>Ocotea pulchella</i>	2	0.004	5.000	0.65	native	tree
Lauraceae	<i>Ocotea sp</i>	2	0.008	NA	NA	NA	NA
Sapindaceae	<i>Paullinia sp</i>	2	0.004	NA	NA	NA	NA

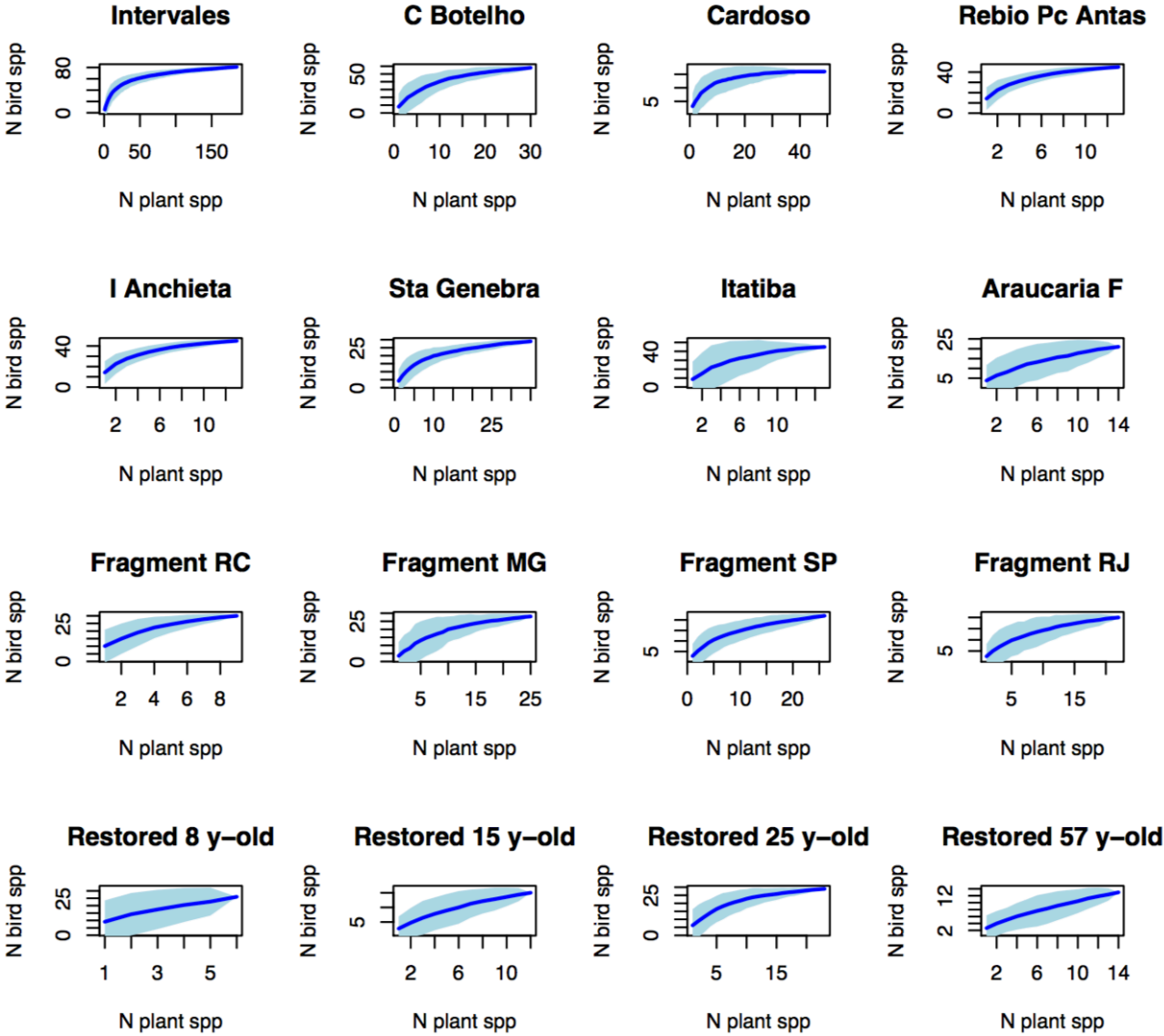
Lauraceae	<i>Persea willdenovii</i>	2	0.004	NA	0.68	native	tree
Piperaceae	<i>Piper aduncum</i>	2	0.010	NA	NA	native	scrub
Myrtaceae	<i>Plinia cauliflora</i>	2	0.001	NA	0.64	native	tree
Myrtaceae	<i>Psidium cattleianum</i>	2	0.004	2.500	1.12	native	tree
Rubiaceae	<i>Psychotria sp</i>	2	0.002	NA	NA	NA	NA
Cactaceae	<i>Rhipsalis sp</i>	2	0.008	NA	NA	NA	NA
Rosaceae	<i>Rubus rosifolius</i>	2	0.008	NA	NA	native	scrub
Rosaceae	<i>Rubus urticifolius</i>	2	0.004	NA	NA	native	scrub
Araliaceae	<i>Schefflera angustissima</i>	2	0.004	2.000	0.47	native	tree
Loranthaceae	<i>Struthanthus marginatus</i>	2	0.012	NA	NA	NA	parasitic
Loranthaceae	<i>Struthanthus sp</i>	2	0.012	NA	NA	NA	NA
Symplocaceae	<i>Symplocos uniflora</i>	2	0.004	6.400	0.42	native	tree
Urticaceae	<i>Urera baccifera</i>	2	0.008	2.000	0.17	native	scrub
Myristicaceae	<i>Virola bicuhyba</i>	2	0.004	16.000	0.61	native	tree
Annonaceae	<i>Xylopi brasiliensis</i>	2	0.008	4.100	0.70	native	tree

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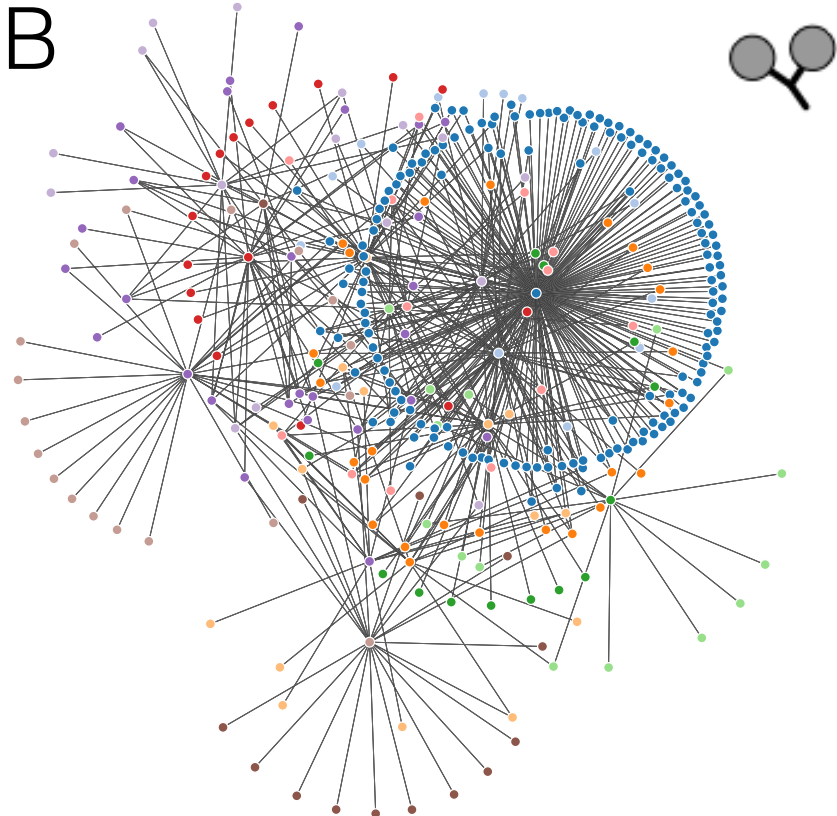
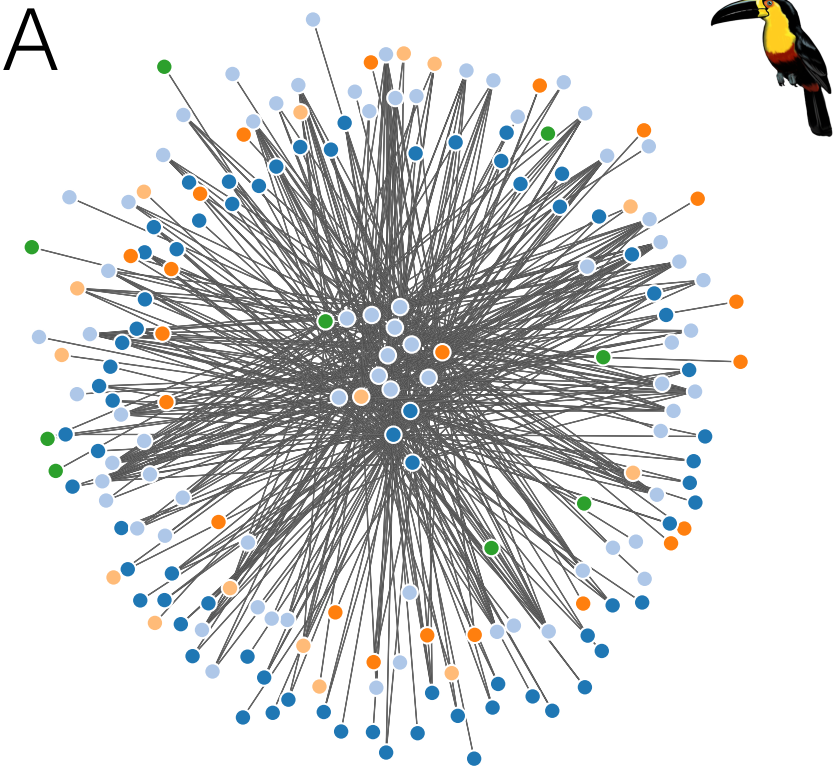
**Figure S1.** The location of the 16 frugivorous bird-fruited plant communities in the Atlantic Forest. The inset shows the original distribution of the Atlantic Forest biome throughout the eastern coast of Brazil (grey area) focusing on the distribution of the 16 fragments studied here. In the larger map, the green areas represent the remaining Atlantic Forest fragments surrounding each of the studied communities. Communities are numbered according to a gradient of disturbance from more pristine areas (1-4), to larger fragments (5-8), smaller fragments (9-12), and restored areas (13-16): 1- Parque Estadual (PE) Intervales; 2- PE Carlos Botelho; 3- PE Ilha do Cardoso; 4- PE Poço das Antas; 5- PE Ilha Anchieta; 6- Mata Santa Genebra; 7- Itatiba fragment; 8- Estação Ecológica de Aracuri; 9- Rio Claro fragment; 10- Minas Gerais fragment; 11- São Paulo fragment; 12- Rio de Janeiro fragment; 13- restored area 15 years old; 14- restored area 25 years old; 15- restored area 57 years old; 16- restored area 8 years old. Map built by Carolina Bello.



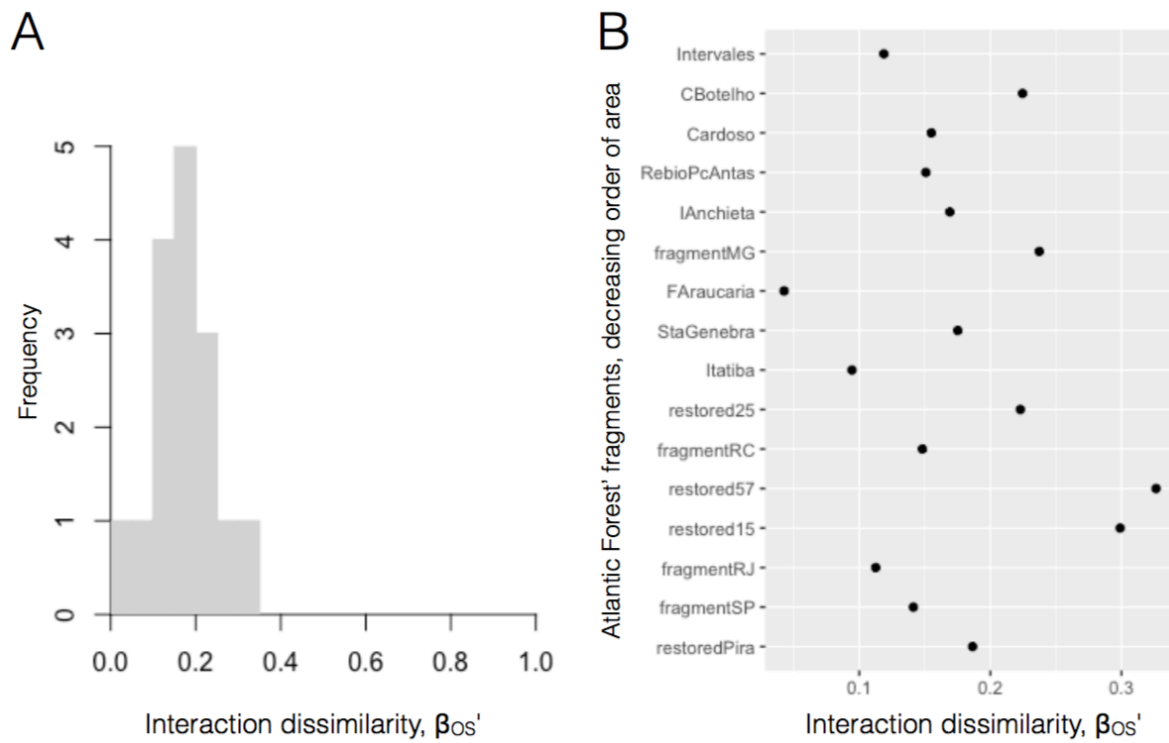
**Figure S2.** Accumulation curves for the number of bird species recorded in each fragment of the Atlantic Forest as a function of the number of plant species found in each studied site.



**Figure S3.** Graph representation of the Atlantic Forest metanetwork considering the occurrence of bird species (A) and plant species (B) among forest fragments, separately. For statistical results, see Table S3.

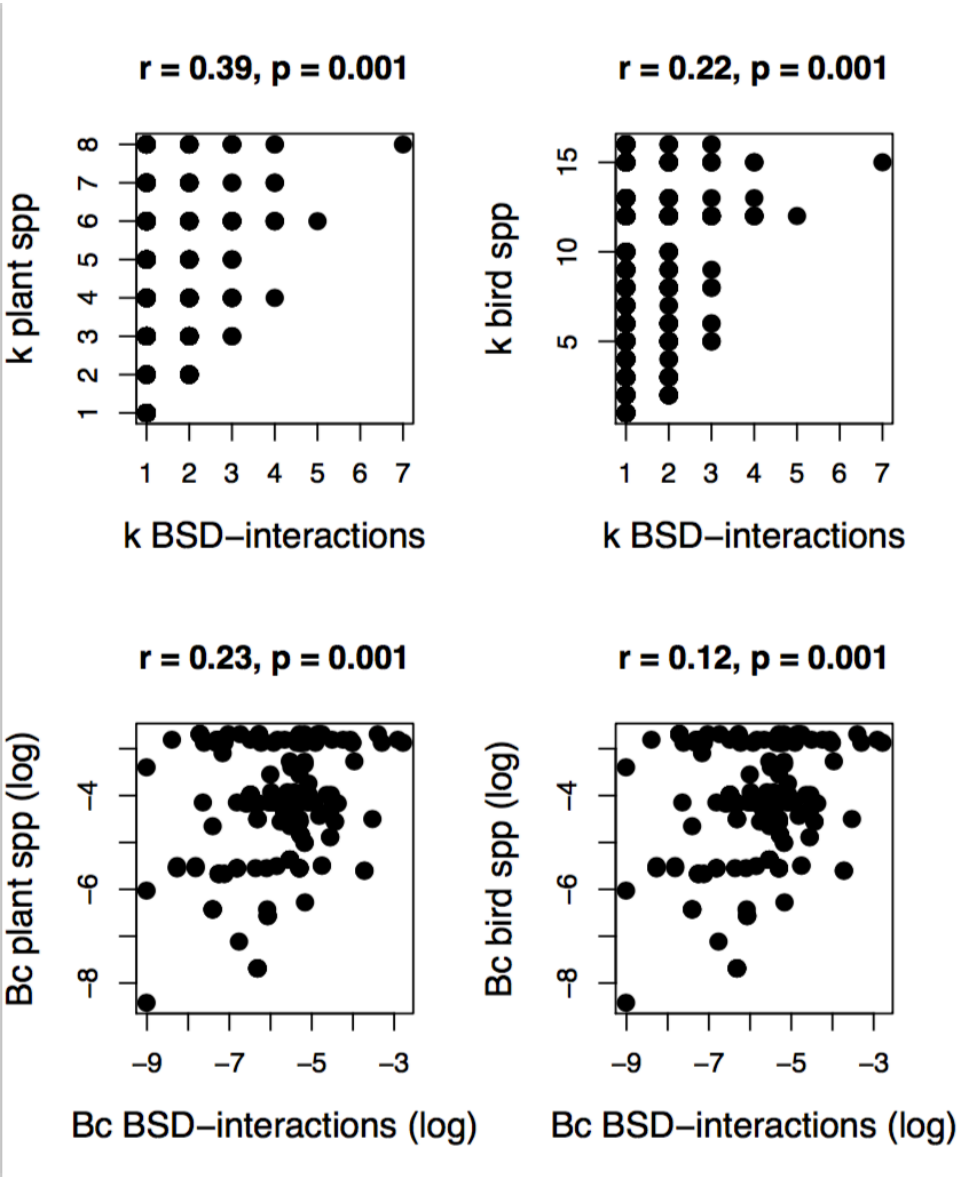


**Figure S4.** Distribution of  $\beta_{os'}$  values indicating to which extent the realized and potential interactions differ among communities. Values close to 0 indicate that all potential interactions are realized, and values close to 1 indicate that almost all potential interactions are lost. a) Frequency distribution of  $\beta_{os'}$  values in the Atlantic Forest metanetwork. b) Values of  $\beta_{os'}$  across the Atlantic Forest fragments, note that fragments in the y-axis are in descending order of fragment area. The effect of area on  $\beta_{os'}$  was not significant ( $F_{1,14} = 0.109$ ,  $p = 0.746$ ,  $r^2 = -0.063$ ).

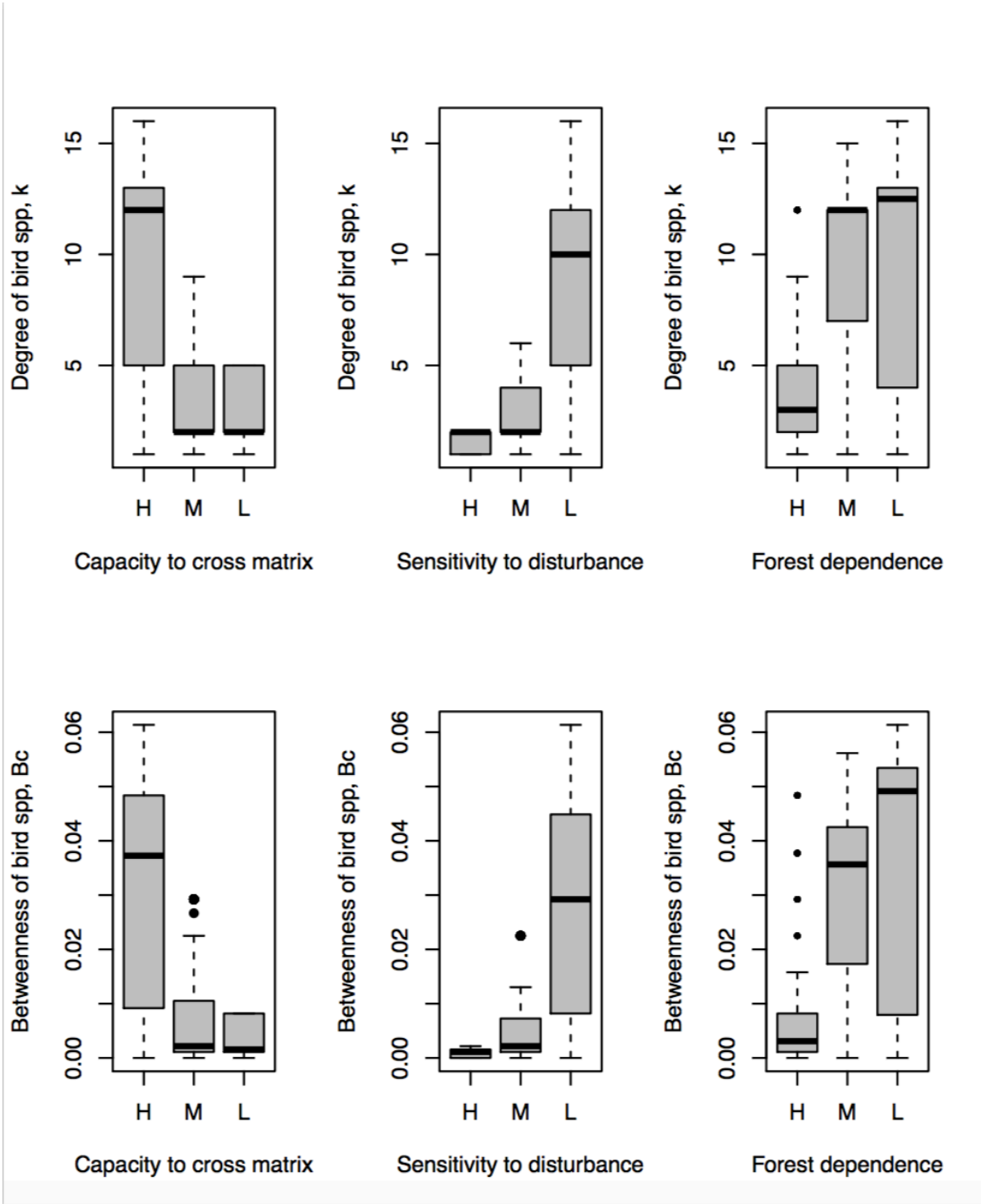




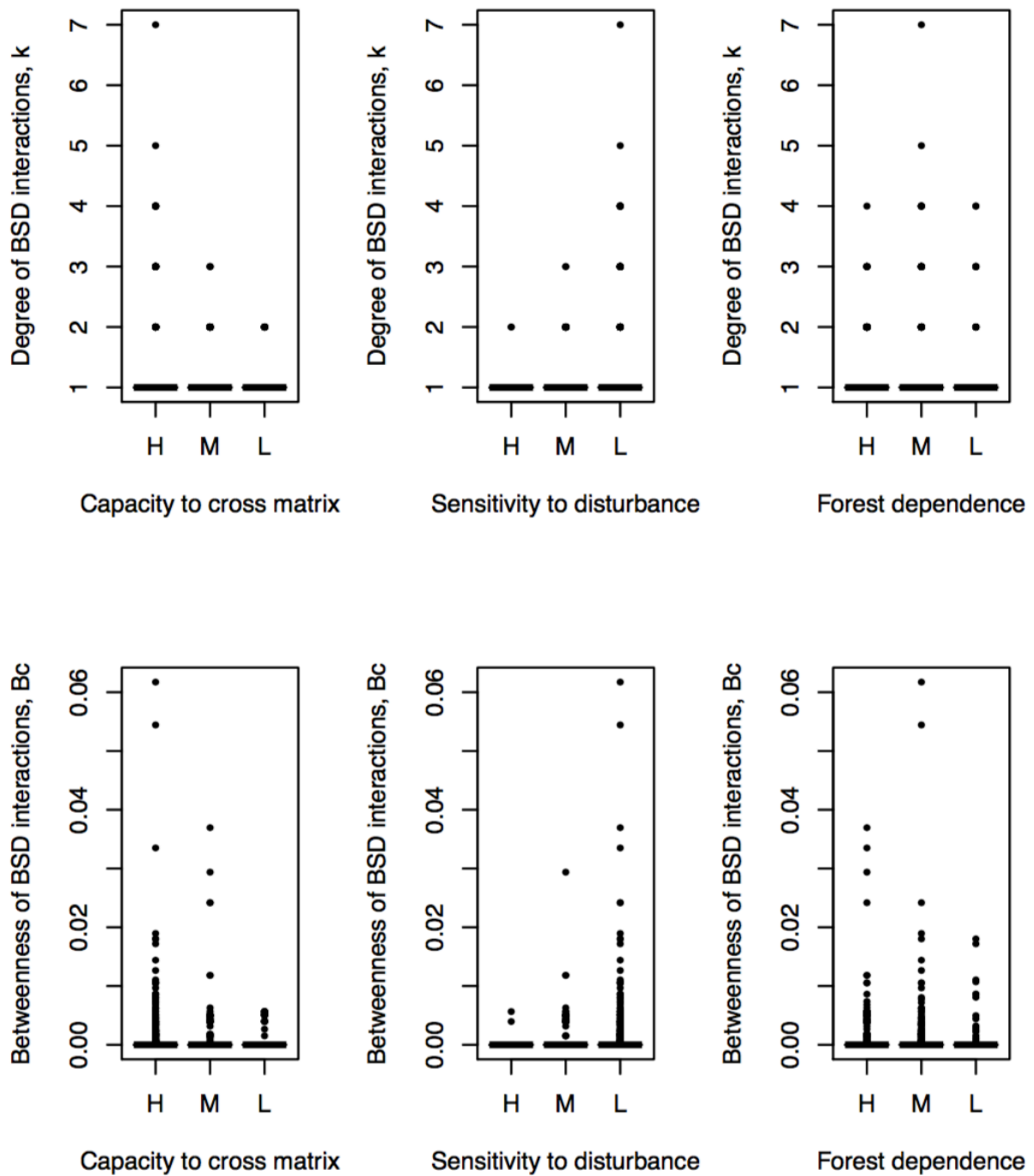
**Figure S5.** Correlations between the centrality (degree,  $k$ , and betweenness,  $B_c$ ) of bird-seed dispersal interactions and the centrality of plant and bird species in the Atlantic Forest metanetwork.



**Figure S6.** Analyses of Variance testing the relationship among the centrality of bird species (degree,  $k$ , and betweenness,  $B_c$ ) recorded in the Atlantic Forest metanetwork and their capacity to move in the fragmented landscape. H - high, M - medium, L - low.



**Figure S7.** Analyses of Variance testing the relationship among the centrality of bird-seed dispersal (BSD) interactions (degree,  $k$ , and betweenness,  $Bc$ ) and the associated bird species capacity to move in the fragmented landscape. H - high, M - medium, L - low.



**Figure S8.** Analyses of Variance testing whether body mass of the bird species recorded in the Atlantic Forest metanetwork was explained by their capacity to move in the fragmented landscape. H - high, M - medium, L - low.

