



## RESEARCH ARTICLE - ANTS

## Structural Stability of Ant-plant Mutualistic Networks Mediated by Extrafloral Nectaries: Looking at the Effects of Forest Fragmentation in the Brazilian Amazon

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### Abstract

Rainforest fragmentation drastically affects biodiversity and species composition, mainly due to habitat loss. Several studies have already shown the effects of forest fragmentation on plant and ant communities. To date, however, there is limited empirical knowledge of how forest fragmentation affects ant-plant interaction in networks. We investigated the effects of the configuration of rainforest fragments on the structure of ant-plant interaction networks mediated by extrafloral nectaries (EFNs). We carried out this study in ten forest fragments, ranging in size from approximately 5 to 3,000 ha, located in the Brazilian Amazon. In each fragment we established a plot of 6,250 m<sup>2</sup>, in which all ant-plant interactions were recorded, and calculated the following network descriptors: number of interactions, network size, network specialization, diversity of interactions, and nestedness. We used four explanatory variables to investigate the effects of forest fragmentation on these network descriptors: three metrics of the configuration of fragments (i.e., fragment area, edge irregularity, and connectivity) and the forest structure within each fragment, represented by canopy cover. We did not detect any effect of the explanatory variables on the network descriptors. The structural stability of the networks sampled in forest fragments with different configurations is possibly related to the observed constancy of ant species in the central core of highly interacting species. Our results corroborate other studies highlighting the structural stability of these facultative ant-plant networks mediated by EFNs in different spatial and temporal gradients. Nonetheless, the low constancy of plant species in the generalist core should be understood as a warning, mainly because the functionality of this protective mutualism (i.e., food secretions in exchange for protection against herbivory) remains unknown.

### Introduction

Rainforest fragmentation is been a prominent topic of discussion between members of the scientific community for years (Skole & Tucker, 1993; Laurance et al., 200a; Vedovato et al., 2016). In general, historic forest fragmentation has occurred due to the subdivision of large areas of continuous

forest generating an altered landscape composed of forest remnants with different size, shape, and connectivity level (Klingbeil & Willig, 2009). This process is usually accompanied by habitat loss which involves the outright removal of habitat patches (Bartlett et al., 2016), thus making forest fragmentation one of the main drivers of biodiversity loss (Newbold et al., 2015). In the Brazilian Amazon, productive



activities such as logging, cattle ranching, and small-scale farming are the main types of land use responsible for this process of landscape change (Laurance et al., 2001a; Laurance et al., 2011).

Changes in landscape configuration (i.e., the spatial arrangement of habitat in a landscape), such as size, isolation and edge density (Haan et al., 2020), can lead to changes in plant and animal communities (Fischer & Lindenmayer, 2007; Laurance et al., 2011). For instance, forest area reduction may directly affect the rate of local species losses, with small forest remnants tending to lose species more quickly (Stouffer et al., 2008), due to their inability to support viable populations of certain groups (Didham et al., 1998). Connectivity reduction between forest fragments and/or continuous forests also tends to negatively affect the maintenance of some populations, since it changes resource availability spatially and, in consequence, the foraging behavior or pollination success of these populations (Haddad et al., 1999; Martensen et al., 2008; Hadley & Betts, 2011). Finally, the shape of forest fragments might also cause disruptions in community structure (DeSouza et al., 2001). For instance, more irregular forest fragments tend to present a higher proportion of edge in relation to the total area of the forest remnant, which can result in high proportions of pioneer species in regenerating and light demanding (Hill et al., 2003).

Ants are frequently studied in forest fragments (Vasconcelos et al., 2006; Leal et al., 2012). In general, the population density, number and diversity of ant species decline with reductions in the area of forest fragments (Bruhl et al., 2003; Vasconcelos et al., 2006; Hill et al., 2011). The ant species composition may also change due to habitat loss and fragmentation (Vasconcelos et al., 2006; Leal et al., 2012; Ahuatzin et al., 2019), mainly due to local extinctions, or generalist or even invasive species colonization (i.e., biotic homogenization) (Carvalho & Vasconcelos, 1999; Bruhl et al., 2003; Holway & Suarez, 2006; Solar et al., 2015). However, the species richness and species composition do not seem to vary with shape complexity of fragments (Sobrinho & Schoereder, 2007).

Many plant species, mainly in the tropics, secrete a liquid rich in carbohydrates and amino acids through specialized and non-floral glands called as a whole extrafloral nectaries (EFNs), which attracts different ant species (Koptur et al., 1998; Marques et al., 2015). In exchange for the food provided by the plant, some ants can protect their host plants against herbivores (Rico-Gray & Oliveira, 2007). At the community level, these mutualistic associations are usually evaluated using a network approach, in which different ant and plant species are depicted as nodes and their interactions as links (Dáttilo et al., 2013a). This network approach has provided important information about the organization of these ant-plant interactions (Lange et al., 2013; Dáttilo et al., 2013a, b; Dáttilo et al., 2014a). For instance, some studies have recently shown that ant-plant networks are highly nested, indicating that species with few links interact with a subset

of interactive species with several interactions (Del-Claro et al., 2018). Biologically, nestedness describes the organization of the niche breadth of an interactive community, in which more nested networks tend to have the highest niche overlap (Blüthgen, 2010).

In general, the structure of these ant-plant networks mediated by EFNs is relatively stable in terms of connectance, network specialization and nestedness, at different spatial (Dáttilo et al., 2013a) and temporal gradients (Díaz-Castelazo et al., 2013; Lange et al., 2013; Dáttilo et al., 2014a), or even after perturbations caused by tropical hurricanes (Sánchez-Galván et al., 2012). The structural stability of these networks is related to the facultative character of these ant-plant interactions, due the low fidelity of ant species when foraging on EFN-bearing plants (Schoereder et al., 2010). Furthermore, the ant species constituting the core of these networks (i.e., ant species that interact with several partner species at high frequencies) are mainly competitively superior species, which gives the network core certain spatial and temporal stability (Dáttilo et al., 2014b).

More specialized ant-plant interactions, such as the interactions mediated by domatia, tend to present networks structurally stable in the context of fragmentation (Passmore et al., 2012), since the plant presence determines the ant presence. On the other hand, it is possible that ant-plant networks mediated by EFNs, even being stable in different natural environments, have their structure altered by forest fragmentation, since the associated species can be differently affected by this process. So we wonder if the structure of these ant-plant networks mediated by EFNs responds to a disturbance gradient generated by habitat loss and forest fragmentation.

It is known that the structure of these ant-plant networks, for example, is influenced by the vegetation structure (Dáttilo & Dyer, 2014), which tends to be quite modified due to fragmentation (Ewers & Banks-Leite, 2013). Dáttilo and Dyer (2014) found that the diversity of ant-plant interactions may also be positively affected by canopy cover reduction, since some plant species secrete larger amounts of nectar in environments with higher light availability (Szabo, 1980; Kersch & Fonseca, 2005). Therefore, smaller, more irregular and less connected forest fragments, would present a greater number of interactions, with consequent increase in the overlap of pairwise interactions and nestedness. This is because forest fragments with a higher proportion of edges tend to present a reduction in canopy cover, with a consequent increase in light availability (Ewers & Banks-Leite, 2013). Sugiura (2010), in a study conducted on Japanese islands, showed that the connectance and nestedness values of ant-plant interaction networks mediated by EFNs tend to increase with decreasing island size. These results, although based on subtropical forest islands (Government of Japan, 2010), that present a matrix impossible to be used by ants and plants, at least suggested investigations on the effect of rainforest fragmentation on these ant-plant networks.

The aim of this study was therefore to investigate the effects of configurations of rainforest fragments on the structure of ant-plant interaction networks mediated by EFNs in the Brazilian Amazon. We based our research questions on hypotheses related to the configuration of forest remnants and the forest structure within the fragments, here represented by canopy cover. Specifically, we postulated that smaller, less connected, and more irregular forest fragments with lower canopy cover would present: (i) smaller network size, since less-preserved forest fragments tend to support fewer number of species (Ahuatzin et al., 2019); (ii) higher number of interactions, since extrafloral nectaries are more active in higher light environments (Radhika et al., 2010); (iii) less network specialization, since dominant ant species do not need to monopolize the resource (extrafloral nectar) when it is available in large amounts (Dáttilo et al., 2014b); (iv) lower diversity of interactions, due to the lower number of species expected for these fragments (Dáttilo & Dyer, 2014); and (v) greater nestedness, due to the greater overlap of pairwise interactions arising from the greater number of interactions expected (Dáttilo et al., 2013b).

## Materials and methods

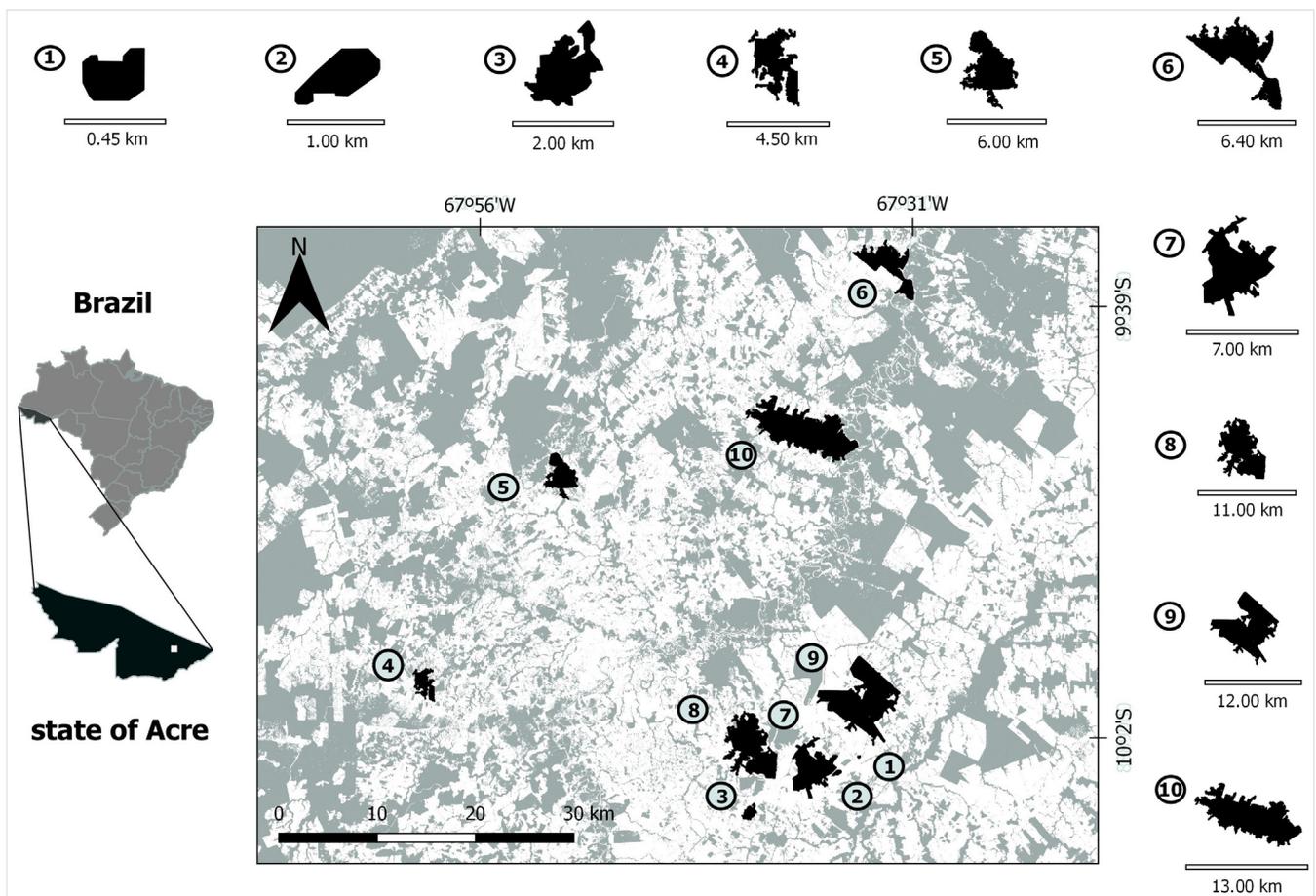
### Study area

This study involved ten forest fragments, ranging in size from approximately 5 to 3,000 ha (Fig 1 and Supplementary Material 1), situated in the west of the state of Acre, in the

Brazilian Amazon. All forest fragments result from human activities since the 1980s. Most of the primary type of vegetation was converted to croplands and pasture from this decade onwards (Acre, 2011). The matrix types (i.e., pasture, urban, agriculture) surrounding the forest remnants are decisive for the biodiversity in the landscapes (Prugh et al., 2008). The matrices will be more efficient from the point of view of functional connectivity if they are more similar in structure to the habitat patches (Prevedello & Vieira, 2010). For this reason, as an attempt to control the effect of matrix type, we selected only forest fragments surrounded by pasture. According to the Köppen (1936) climate classification, the region is classified as monsoon climate (Am), with an average rainfall of 1,450 mm per year (Macêdo et al., 2013) and marked seasonality, with most rainfall between November and March (Acre, 2006). The average annual temperature is 24°C (INMET, 2016) with a daily thermal amplitude of around 9°C (Acre, 2006). The region varies between 110 and 270 m.a.s.l. (Acre, 2006). The predominant vegetation type is open tropical rainforest (i.e., open ombrophilous forest) dominated by native species of bamboo and/or palm trees (Acre, 2006).

### Sampling ant-plant interactions

We established a plot of 6,250 m<sup>2</sup> (250 x 25 m) in each forest fragment, at a minimum distance of 100 meters from the edge, except for the smallest forest fragment, which was



**Fig 1.** Map of the study area showing all forest fragments sampled.

a plot beginning at approximately 20 meters from the edge. We decided not to establish the plots in regions under direct effects of edges, because in these regions the microclimatic conditions, and community composition, tend to be highly altered in any forest fragment (Laurance et al., 2002), which would make it difficult to detect structure changes in ant-plant networks resulting from a disturbance gradient caused mainly due to fragmentation. We recorded all interactions between ants and EFN-bearing plants with a height accessible to the collector (ranging from 0.5 to 3 m) between 09:00 am and 03:00 pm for each plot (Dáttilo & Dyer, 2014). All EFN-bearing plants were observed for five minutes. Ants were considered to be feeding on nectar when they were immobile, with mouthparts in contact with nectar secreting tissues during the observation period (Falcão et al., 2016). When the interaction was confirmed, we collected all foraging ants and a plant sample for further identification (see below). Plants in which we did not detect the presence of EFNs, but which had immobile ants with mouthparts in contact with plant tissues, were also collected for later confirmation of the presence of EFNs through stereoscope observations and literature review. Ants were manually collected with the aid of an entomological umbrella (Bestelmeyer et al., 2000) so as to record those that drop from the plant at the slightest sign of disturbance (Dáttilo & Dyer, 2014). Considering the temporal variation in ant-plant networks mediated by EFNs (i.e., phenological variation) (Lange et al., 2013; Falcão et al., 2016), we sampled each plot twice (June 2016 and February 2017).

Ants were identified by species or morphospecies using identification keys (Fernández, 2003; Wilson, 2003; Bolton et al., 2006) and by comparison with specimens deposited at the Laboratório de Mirmecologia of the Centro de Pesquisas do Cacau, Brazil (CPDC Collection), where voucher specimens were deposited. Plants were identified at species or morpho-species level using identification guides (Ribeiro et al., 1999; Pennington et al., 2004) and by comparison with specimens deposited at the Herbário do Parque Zoobotânico (HPZ) of the Universidade Federal do Acre, Brazil. Voucher specimens of plants were deposited at the Herbário (FUEL) of the Universidade Estadual de Londrina, Brazil.

### Canopy cover

To measure the canopy cover in the plots where the ant-plant interactions were sampled, we established a 250 m long transect within each plot, located along the longitudinal direction of the plot, and maintained the same distance from the sides (12.5 m). In each transect, we installed ten subplots of 100 m<sup>2</sup> (10 x 10 m) at intervals of 15 m. The first and last 100 subplots were installed 7.5 m from the beginning and end of transects, respectively. We estimated canopy cover using a spherical convex densiometer. The measurements were taken at the center and at the four edges of the 100 m<sup>2</sup> subplots. The mean of these five measurements was used to calculate the average canopy cover per sampling point. We used the average of all sampling points to characterize each fragment for canopy cover.

### Landscape descriptors

We used LANDSAT8 satellite images (path/row: 002/067) with a 30 m resolution, acquired on 07/23/2016, in the QGIS Software 2.18.10 (QGIS Development Team, 2016) to describe the configuration of the forest fragments. The images were classified into two categories: forested areas (primary and secondary forests) and non-forested areas (water bodies, built areas, and pastures). We described the configuration of each forest fragment through metrics: forest fragment area (ha), edge irregularity index, and connectivity index. The forest fragment area was calculated based on its polygon shape. Patton's diversity index (DI) (Patton, 1975) was adopted as the edge irregularity index, which evaluates the forest fragment regularity, defined as  $DI = P/2(\sqrt{\pi A})$ , where P = perimeter (m) and A = Area (m<sup>2</sup>). To measure the isolation and fragmentation degree around the forest focal fragments, we used the index of connectivity named proximity (PROX) (Gustafson & Parker, 1992), calculated by the following equation:

$$PROX = \sum_{s=1}^n \frac{a_{ijs}}{h_{ijs}^2}$$

In this equation,  $a_{ijs}$  represents the area (m<sup>2</sup>) of fragment  $ijs$  within specified neighborhood (m) of the focal fragment; and  $h_{ijs}$  represents the distance (m) between fragment  $ijs$  and the focal fragment based on fragment edge-to-edge distance. The connectivity index is the inverse of the isolation and fragmentation degree (Bender et al., 2003). We define buffers of 500 m around the focal fragment, established from the respective edge, to define the neighboring fragments considered for the calculation of the index. We used this buffer size for two main reasons: i) this distance explains the greater variation in the patterns of richness and diversity of ant species at the community level (Spiesman & Cumming, 2008); and ii) it is equivalent to the greater observed distance of an ant gyne's flight (Hölldobler & Wilson, 1990). All forest fragment metrics were calculated using QGIS Software 2.18.10 (QGIS Development Team, 2016).

### Ant-plant interaction networks

Initially, we accumulated the data of the two samples per plot on different dates, in order to maximize the number of EFN-bearing plants species in our samples, considering the annual variation in the extrafloral nectar production by different plant species (Falcão et al., 2016). To verify whether our sampling was adequate to describe the ant-plant networks of each plot studied, we then generated accumulation curves with the number of ant and plant species and the number of distinct pairwise of interactions, as a function of the number of plants sampled (Falcão et al., 2016). We used the non-parametric bootstrapping estimator with 1000 replicates (Gotelli & Colwell, 2001) for all accumulation curves, to estimate the expected number of plant and ant species and interactions for each network.

The ant-plant interaction patterns were examined using an ecological network approach. The data of each plot was organized in a quantitative matrix in which the elements ( $aij$ ) represented the frequency (number of times) that plant species  $i$  interacted with ant species  $j$  inside the plot (Bascompte et al., 2003). To evaluate the constancy of the central core of highly interacting species among the different forest fragments sampled, we categorized ant and plant species according Dáttilo et al. (2013a):  $G_c = (k_i - k_{\text{mean}})/\sigma_k$ , where  $k_i$  = mean number of links for a given plant/ant species,  $k_{\text{mean}}$  = mean number of links for all plant/ant species in the network, and  $\sigma_k$  = standard deviation of the number of links for plant/ant species. When  $G_c \geq 1$ , the species presents a large number of interactions in relation to other species of the same trophic level, as a species constituting the generalist core. When  $G_c < 1$ , the species presents a lower number of interactions in relation to other species of the same trophic level, such as species constituting the periphery of networks.

We used three network descriptors established from a quantitative matrix (number of interactions, network specialization, and diversity of interactions), and two calculated from a binary matrix (network size and nestedness), to describe the patterns of ant-plant interactions in the fragment. We adopted binary matrices for nestedness to facilitate the discussion of our results compared to other published studies, since this data category has been widely used to assess the structure of ant-plant networks mediated by EFNs (Rico-gray et al., 2012; Díaz-Castelazo et al., 2013; Lange et al., 2013; Falcão et al., 2016; Dáttilo et al., 2014a; Díaz-Castelazo et al., 2020). Furthermore, the nestedness values calculated with binary and quantitative data have been shown to be highly correlated (Corso et al., 2015; Miranda et al., 2019). In frequency matrices, as mentioned above, the elements represent the number of times in which a plant species interacted with an ant species within the plot, whereas in binary matrices the elements (1 or 0) represent the presence or absence of an interaction between a plant and an ant species within the plot. These binary-weighted descriptors are the most commonly used in studies dealing with ant-plant networks, and they cover a wide range of possible structures with complementary biological meanings (Del-Claro et al., 2016). Network size was calculated by multiplying the number of plant species by the number of ant species. The number of interactions represents the total interactions observed in the network, considering all ant and plant species. The diversity of interactions was calculated using an index ( $H'$ ) based on the Shannon's diversity index, which ranges from zero to infinity (Bersier et al., 2002). We estimated specialization using the  $H_2'$  index, which describes how species restrict their interactions from those randomly expected based on a partner's availability (Blüthgen et al., 2006). In this index, the low specialization of an ecological network represents values close to  $H_2' = 0$ , and total specialization is  $H_2' = 1$ . Nestedness, which evaluates whether selective ant species only visit a

subset of plant individuals visited by the generalist ant species (Dáttilo et al., 2014c), was calculated using the *NODF*-metric (Nestedness Based on Overlap and Decreasing Fill) (Almeida-Neto et al., 2008) in the ANINHADO software (Guimarães & Guimarães, 2006), using binary matrices. These index values range from 0 (non-nested) to 100 (perfectly nested). The network specialization and diversity of interaction were calculated using the bipartite package (Dormann et al., 2017) in R 3.2.3 (R Core Team, 2016).

#### Data analysis

The *NODF* significance was estimated using p-values based on the Null Model II (1000 randomizations). In this null model, the probability of an interaction occurring is proportional to the observed number of interactions of both plant and ant species (Bascompte et al., 2003).

To evaluate the effect of rainforest fragmentation on ant-plant networks, we related each network descriptor (network size, number of interactions, network specialization -  $H_2'$ , diversity of interactions -  $H'$  and, nestedness - *NODF*) to the explanatory metrics of the configuration of forest fragments (fragment area, edge irregularity index, and connectivity index), and to canopy cover. Initially, we verified multicollinearity among all explanatory variables (fragment area, edge irregularity index, connectivity index, and canopy cover) using the variance inflation factor (VIF) value (Dormann et al., 2013). The VIF indicates the degree to which each explanatory variable is explained by another explanatory variable in the model. VIF values greater than 10 indicate high multicollinearity. As none of our exploratory variables showed collinearity between them, we included all four in the model selection. We used generalized linear models for all response variables (i.e., network descriptors). We used a negative binomial distribution for number of interactions and network size, due to an overdispersion of residues from our data, which occurs when the deviance of the response is greater than expected by the chosen distribution (Hinde & Demétrio, 1998). We used a Gaussian distribution for network specialization -  $H_2'$ , diversity of interaction -  $H'$ , and nestedness - *NODF*. For all response variables, candidate models were classified using the corrected Akaike Information Criterion for small samples (AICc) (Akaike, 1974). For each response variable, 16 competing models were used to explain the patterns, including a null model representing the lack of effect. We adopted balanced model sets (i.e., all explanatory variables were present in the same number of models) without considering the interaction effects between them. Subsequently, the corrected Akaike Information criterion for small samples was estimated, the  $\Delta\text{AICc}$  (difference between the AICc of each model in relation to the best model) and the Akaike weight (wAIC) (the probability of a given model being the best among a set of competing models) (Johnson & Omland, 2004). Models with  $\Delta\text{AICc} < 2.0$  and wAIC  $> 0.1$  were considered equally plausible to explain the patterns observed

(Burnham & Anderson, 2003). Model selections were made according to Akaike's Information Criterion (AIC) using the MuMIn package (Bartoń, 2016) and the model diagnostics were run with the RT4Bio package (Reis Jr. et al., 2013) in R 3.2.3 (R Core Team, 2016).

## Results

We observed 930 pairwise interactions between ants and EFN-bearing plants on the ten plots studied. We recorded a total of 56 ant species, distributed in 19 genera and seven subfamilies (Supplementary Material 2). The subfamily Myrmicinae comprised 48.2% of the total ant species ( $n = 27$  ant species), followed by Formicinae (26.8%,  $n = 15$ ) and Dolichoderinae (12.5%,  $n = 7$ ). Myrmicinae was also the subfamily that showed higher interaction frequency (64.6% of the total interactions,  $n = 601$  interactions), followed by Ectatomminae (13.6%,  $n = 126$ ) and Formicinae (8.9%,  $n = 83$ ). We recorded a total of 148 plant species, distributed in 44 genera and 25 families, where liana was the plant habit with the highest number of species (60.1% of the plant species,  $n = 89$  species) followed by trees (34.5%,  $n = 51$ ) (Supplementary

Material 3). The Fabaceae family comprised 37.8% of the total plant species ( $n = 56$  plant species), followed by Bignoniaceae (25.7%,  $n = 38$ ) and Malpighiaceae (6.8%,  $n = 10$ ). Fabaceae was also the family that had a higher interaction frequency (41% of the total interaction,  $n = 381$ ), followed by Bignoniaceae (16.7%,  $n = 155$ ) and Malpighiaceae (14.0%,  $n = 130$ ). The generalist core of ant species in the ant-plant networks tends to be more constant than the generalist core of plant species, between forest fragments. We observed that the generalist core of ant-plant networks ranged from one to five ant species, and from two to five plant species per forest fragment. Seven ant species were present in the generalist cores, taking into account all ten ant-plant networks evaluated, and the most common species was *Crematogaster brasiliensis* (present in the generalist core in 70% of the networks,  $n = 7$  forest fragments), followed by *Crematogaster carinata* (60%,  $n = 6$ ) and *Ectatomma tuberculatum* (50%,  $n = 5$ ) (Table 1). Twenty-one plant species were present in the generalist cores of the ant-plant networks evaluated, and the most common species were *Bauhinia* sp.1 (90%,  $n = 9$ ) followed by Polygonaceae sp.1 (50%,  $n = 5$ ) and *Senegalia* sp.2 (50%,  $n = 5$ ) (Table 1).

**Table 1.** Frequency of ant and plant species in generalist core of ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017,  $n$ = number of fragments where the species was part of the core of the network.

Generalist core plant species	Occurrence frequency	Generalist core ant species	Frequency
<i>Bauhinia</i> sp.1	90% ( $n = 9$ )	<i>Crematogaster brasiliensis</i>	70% ( $n = 7$ )
Polygonaceae sp1	50% ( $n = 5$ )	<i>Crematogaster carinata</i>	60% ( $n = 6$ )
<i>Senegalia</i> sp.2	50% ( $n = 5$ )	<i>Ectatomma tuberculatum</i>	50% ( $n = 5$ )
<i>Fridericia</i> sp.8	40% ( $n = 4$ )	<i>Crematogaster limata</i>	40% ( $n = 4$ )
<i>Hirtella racemosa</i>	40% ( $n = 4$ )	<i>Dolichoderus attelaboides</i>	10% ( $n = 1$ )
<i>Banisteriopsis</i> sp.2	40% ( $n = 4$ )	<i>Wasmannia auropunctata</i>	10% ( $n = 1$ )
<i>Inga</i> sp.5	40% ( $n = 4$ )	<i>Ochetomyrmex semipolitus</i>	10% ( $n = 1$ )
<i>Palicourea</i> sp.1	40% ( $n = 4$ )		
<i>Senegalia</i> sp.3	30% ( $n = 3$ )		
<i>Fridericia</i> sp.19	20% ( $n = 2$ )		
<i>Memora</i> sp.2	20% ( $n = 2$ )		
<i>Zygia</i> sp.1	20% ( $n = 2$ )		
<i>Fridericia</i> sp.6	20% ( $n = 2$ )		
<i>Senegalia</i> sp.8	20% ( $n = 2$ )		
<i>Inga punctata</i>	20% ( $n = 2$ )		
<i>Aparisthmium cordatum</i>	10% ( $n = 1$ )		
<i>Fridericia</i> sp.2	10% ( $n = 1$ )		
<i>Inga</i> sp.16	10% ( $n = 1$ )		
<i>Senegalia</i> sp.4	10% ( $n = 1$ )		
<i>Bauhinia</i> sp.4	10% ( $n = 1$ )		
<i>Senegalia</i> sp.7	10% ( $n = 1$ )		

According to the species and interactions accumulation curves estimated, we collected an average (Mean  $\pm$  SD) of  $84.30 \pm 0.02\%$  of the ant species ( $n = 18.60 \pm 3.60$  species of the  $22.04 \pm 4.04$  species estimated) and  $80.60 \pm 0.01\%$  of the plant species ( $n = 31.90 \pm 4.53$  species of the  $39.61 \pm 5.81$  species estimated). We observed  $76.23 \pm 0.01\%$  of the interactions between ants and EFN-bearing plants ( $n = 63.70 \pm 11.06$  interactions of the  $83.57 \pm 14.44$  interactions estimated), indicating that we had sampled enough ant and plant species and interactions to describe the ant-plant networks of each plot.

We describe the values of the network descriptors (network-size, number of interactions, network specialization –  $H_2'$ , diversity of interactions –  $H'$ , and nestedness –  $NODF$ )

for each plot in Supplementary Material 4. Eighty percent ( $n = 8$  fragments) of the ant-plant networks presented a significant value for  $NODF$ , when compared to null models (Supplementary Material 4).

We did not detect any effect of the explanatory variables on the network descriptors. For number of interaction, network size, network specialization and diversity of interaction, the null model, which indicates no detectable effects, was the best selected model (Table 2). For nestedness, the edge irregularity index was the best explanatory variable, however the null model was also equally plausible to explain the observed pattern (Table 2). The results of all candidate models for each ant-plant network descriptor are in Supplementary Material 5.

**Table 2.** Summary of plausible models fitted to explain each ant-network descriptor in response to landscape structure metrics and forest structure (canopy cover) at 10 rainforest fragments located in the state of Acre, Brazilian Amazon.  $\Delta AICc$ , df, and wAICc indicate the difference in corrected Akaike values, degrees of freedom of the model, and Akaike weights, respectively. The values in bold represent the best model selected for each of the network descriptors evaluated.

Response variable	Model	$\Delta AICc$	d.f.	wAIC	Slope symbol
Number of interactions	Null model	0.00	2	0.39	
Network size	Null model	0.00	2	0.59	
Network specialization	Null Model	0.00	2	0.51	
Diversity of interaction	Null model	0.00	2	0.52	
$NODF$	Edge irregularity index	0.00	3	0.44	-
	Null model	1.20	2	0.247	

## Discussion

In general, we observed, contrary to our hypotheses, that the structure of ant-plant interaction networks mediated by EFNs remained stable in forest fragments with different landscape configurations. None of the five network descriptors we used (i.e., number of interactions, network size, network specialization, diversity of interactions, and nestedness) were affected by the metrics of the configuration of fragments and vegetation structure. We also did not find evidence that canopy cover shapes the structure of ant-plant interaction networks, suggesting that the self-organization of the networks is independent of local characteristics of canopy openness in our area of study.

The generalist core tended to be more constant among the sampled plots as regards ants rather than plants. Of the seven ant species observed in the generalist cores, four (57%) were core species in more than 40% of the networks. Between them, three are competitively superior due to their numerical dominance (*C. brasiliensis*, *C. carinata* and *Crematogaster limata*) (Parr, 2008; Baccaro et al., 2012) and one due to aggressive displacement of competitors (*E. tuberculatum*) (Hossaert-Mckey et al., 2001; Bächtold & Alves-Silva, 2013). This competitive nature is a feature of ant species of the generalist core (Dáttilo et al., 2014b), and is possibly one

of the main factors responsible for the relative constancy of ant species in the studied networks. In addition, most of the ant species of our generalist cores belonged to the functional group Generalist Myrmicinae (Silvestre et al., 2003; Silva & Brandão, 2010), and are highly tolerant of habitat modification (Hoffmann & Andersen, 2003), which allows them to a competitive advantage, even in forest fragments with a high disturbance level. Of the 21 plant species observed in the generalist cores, 12 (57%) were classified as in the central core of highly interacting species in less than 20% of the networks. This lowest constancy in the generalist core of plant species is possibly related to changes in plant species composition due to forest fragmentation, since the reduction in size tends to increase the mortality rate of trees, especially near the forest edge (Laurance, 1991; Ferreira & Laurance, 1997), favoring fast-growing pioneer trees and liana growth (Laurance et al., 2001b; Laurance et al., 2006; Santo-Silva et al., 2016). The plant species turnover in South American tropical forests is also relatively high, with forests 60 km distant from each other (i.e., the maximum distance between our forest fragments), sharing only some 35% of species (Condit et al., 2002).

When evaluating the effects of forest fragmentation on the structure of ant-plant networks, we found a structural stability in the face of perturbation. No network descriptor was related to the configuration of forest fragments. This

stability is possibly related to the low fidelity of ant species when foraging on EFN-bearing plants (Rico-Gray et al.; 1998, Schoereder et al., 2010), and to the constancy of ant species in the generalist cores observed in our study, as previously discussed in the literature (Dáttilo et al., 2013a; Lange et al., 2013; Dáttilo et al., 2014b). In fact, the ant-plant networks mediated by EFNs are shaped by a few generalist species, which are essential for the maintenance of network stability (Díaz-Castelazo et al., 2010; Mello et al., 2011). Dáttilo et al. (2013a) observed that the structure of ant-plant networks mediated by EFNs remains stable throughout space, as does the generalist core of species. Other studies have also detected the structural stability of these ant-plant networks mediated by EFNs over time (i.e., 20 years) (Díaz-Castelazo et al., 2013), between day and night periods (Dáttilo et al., 2014a), and after tropical hurricanes (Sánchez-Galván et al., 2012). More recently, Fagundes et al. (2018) also observed the limited effects of fire disturbances on the structure of ant-plant interaction networks mediated by EFNs. Corro et al. (2019) observed landscape effects on network specialization and on the diversity of interaction of ant-plant networks, but in this case, the authors used a conceptual framework based on co-occurrence records of ant-plant associations to build ant-plant co-occurrence networks.

No network descriptors were related to vegetation structure (i.e., canopy cover). According to our hypotheses, we expected an increase in the number of interactions and, consequently, in nestedness, due to the canopy cover reduction. Dáttilo et al. (2013b) found no effects of canopy cover on the nestedness in ant-plant networks mediated by EFNs, in a study also carried out in the Brazilian Amazon. Our results corroborate the discussion presented by Dáttilo et al. (2013b), that perhaps the presence of ants in EFN-bearing plant species is not primarily determined by the amount of nectar, but rather by the nectar quality (i.e., concentration and composition) (Blüthgen & Fiedler, 2004; Lach, 2005). The amount of nectar is positively influenced by the light availability (Szabo, 1980; Kersch & Fonseca, 2005), but also by the water availability (Carroll et al., 2001), which is an abundant factor in tropical rainforests, not directly related to canopy cover. On the other hand, nectar quality, directly related to soil nutrients (Burkle & Irwin, 2009), may influence the behavior and preference of animal species when recruiting this food resource (Parachnowitsch et al., 2019), being therefore an interesting factor to be investigated in structuring of these ant-plant networks.

The structural stability of these ant-plant networks mediated by EFNs evidences the resistance or resilience of these interactions in environments with different levels of disturbance. Even small, more irregular, and isolated forest fragments were able to maintain the dynamics of these ant-plant interactions, and therefore should be included in the definition of conservation strategies. Nonetheless, special attention should be directed to the low constancy of plant species in the generalist core. These small changes should be

understood as a warning, mainly because the functionality of this protective mutualism (i.e., food secretions in exchange for protection against herbivory) in these areas remains unknown. Moreover, habitat loss and fragmentation often reduce gene flow and genetic diversity in plant populations (Browne & Karubian, 2018), and possibly in ant populations, as gene flow in this group is mainly maintained by male dispersion (Jaffé et al., 2009). This possible reduction in the gene flow, in turn, could negatively affect the long term maintenance of some populations and, consequently, the structure of ant-plant networks mediated by EFNs. It is important to mention that these results were found in open tropical forests (Acre, 2006), and possibly greater effects of forest fragmentation and forest structure can be expected for dense tropical forests. Furthermore, we limited our sampling to three meters high, and we recognize the potentially serious implications of this sampling limitation on our results. We thus suggest that further studies evaluate how ant-plant interactions are structured along a vertical stratification gradient within the forest and to test their vulnerability to fragmentation and habitat loss.

In summary, we have provided some important insights into the effects of rainforest fragmentation on the structure of ant-plant interactions mediated by EFNs. In an interaction networks context, the ant species of the generalist core seem to be little affected by forest fragmentation compared to the plant species of the generalist core. Our results regarding the network descriptors indicate that the structure of ant-plant networks mediated by EFNs remains relatively stable in the face of the forest fragmentation, possibly due to the constancy of ant species in the generalist cores. In short, this study makes a valuable contribution to biodiversity and conservation, mainly because we show the vulnerability and robustness of tropical species-rich habitats to forest fragmentation.

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## Supplementary Material

Appendix S1. Location of the forest fragments sampled in State of Acre, Brazilian Amazon.

Fragment	Site	Geographic coordinates	Area (ha)
1	Senador Guiomard private fragment	10° 3'59.16"S and 67°59'20.12"W	5.26
2	Senador Guiomard private fragment	10° 4'52.34"S and 67°36'2.64"W	27.82
3	Senador Guiomard private fragment	10°6'58.02"S and 67°41'6.90"W	123.16
4	Forestry School	9°59'48.12"S and 67°59'20.12"W	332.15
5	Projeto de Assentamento Walter Arce	9°48'0.46"S and 67°51'26.95"W	681.05
6	Porto Acre private fragment	9°36'28.60"S and 67°34'6.15"W	1072.34
7	Catuaba Experimental Farm	10°04'48.9"S and 67°37'08.6"W	1282.42
8	Embrapa Acre	10°2'17.64"S and 67°40'54.24"W	1871.17
9	Senador Guiomard private fragment	10° 1'24.66"S and 67°35'48.66"W	2894.77
10	Humaitá Reserve	09°45'15.2"S and 67°39'44.9"W	3042.02

Appendix S2. Ant species present in the ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017.

Subfamily	Ant species	Frequency										Total
		F7	F8	F4	F3	F10	F6	F1	F2	F9	F5	
	<i>Azteca chartiflex</i>	0	0	0	0	0	0	0	1	0	0	<b>1</b>
	<i>Azteca</i> sp.1	5	2	0	0	0	6	0	6	1	3	<b>23</b>
Dolichoderinae	<i>Dolichoderus attelaboides</i> (Fabricius, 1775)	2	1	0	1	4	5	0	5	0	8	<b>26</b>
	<i>Dolichoderus bispinosus</i> (Olivier, 1792)	0	0	0	0	0	8	0	1	0	2	<b>11</b>
	<i>Dolichoderus debilis</i> Emery, 1890	0	0	0	0	0	6	10	0	0	0	<b>16</b>
	<i>Dolichoderus quadridenticulatus</i> (Roger, 1862)	0	0	0	0	1	0	0	0	0	0	<b>1</b>
	<i>Dolichoderus septemspinosus</i> Emery, 1894	1	0	0	0	0	1	0	2	0	0	<b>4</b>
			0	0	0	0	0	0	0	1	0	0
Ectoninae	<i>Eciton mexicanum</i> Roger, 1863	0	0	0	0	0	0	0	1	0	0	<b>1</b>
Ectatomminae	<i>Ectatomma tuberculatum</i> (Oliver, 1792)	14	21	1	28	2	0	13	9	24	11	<b>123</b>
	<i>Gnamptogenys moelleri</i> (Forel, 1912)	0	0	0	0	0	0	0	0	1	1	<b>2</b>
	<i>Gnamptogenys sulcata</i> (Smith, 1858)	0	0	0	0	0	0	0	0	0	1	<b>1</b>
Formicinae	<i>Brachymyrmex heeri</i> Forel, 1874	2	0	8	0	0	0	1	1	2	1	<b>15</b>
	<i>Camponotus bidens</i> Mayr, 1870	0	0	0	0	0	1	0	0	0	0	<b>1</b>
	<i>Camponotus cingulatus</i> Mayr, 1862	0	0	0	1	0	0	2	0	0	0	<b>3</b>
	<i>Camponotus depressus</i> Mayr, 1866	0	0	0	0	1	1	0	0	0	1	<b>3</b>
	<i>Camponotus femoratus</i> (Fabricius, 1804)	0	0	0	0	0	1	0	0	0	0	<b>1</b>
	<i>Camponotus godmani</i> Forel, 1899	0	0	0	0	0	0	0	1	0	0	<b>1</b>
	<i>Camponotus latangulus</i> Roger, 1863	4	3	0	1	0	10	2	11	2	0	<b>33</b>
	<i>Camponotus nidulans</i> (Fr. Smith, 1860)	0	1	0	0	2	5	0	0	2	2	<b>12</b>
	<i>Camponotus prox. novogranadensis</i>	3	0	0	0	0	0	0	0	0	0	<b>3</b>
	<i>Camponotus punctulatus andigenus</i> Emery, 1903	1	0	0	0	0	1	0	0	1	1	<b>4</b>

**Appendix S2.** Ant species present in the ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017. (Continuation)

Subfamily	Ant species	Frequency										Total
		F7	F8	F4	F3	F10	F6	F1	F2	F9	F5	
Formicinae	<i>Camponotus sexguttatus</i> (Fabricius, 1793)	0	1	0	0	0	0	0	0	0	0	1
	<i>Camponotus</i> sp.1	0	0	0	0	0	0	0	0	2	1	3
	<i>Gigantiops destructor</i> (Fabricius, 1804)	0	0	0	1	0	0	0	0	0	1	2
	<i>Nylanderia guatemalensis</i> (Forel, 1885)	0	0	0	0	0	1	0	0	0	0	1
Myrmicinae	<i>Cephalotes atratus</i> (Linnaeus, 1758)	0	1	0	0	0	0	0	0	0	0	1
	<i>Cephalotes marginatus</i> (Fabricius, 1804)	0	0	0	0	0	0	1	0	0	0	1
	<i>Cephalotes pinelii</i> (Guérin-Méneville, 1844)	1	0	0	0	0	0	0	0	0	0	1
	<i>Cephalotus opacus</i> Santschi, 1920	0	0	0	0	2	0	0	0	0	0	2
	<i>Crematogaster brasiliensis</i> Mayr, 1878	10	2	0	24	27	23	0	69	19	8	182
	<i>Crematogaster carinata</i> Mayr, 1862	0	5	26	40	16	12	69	1	0	9	178
	<i>Crematogaster curvispinosa</i> Mayr, 1862	0	0	0	0	0	2	0	0	0	0	2
	<i>Crematogaster erecta</i> Mayr, 1866	0	0	0	0	0	1	0	0	0	0	1
	<i>Crematogaster flavosensitiva</i> Longino, 2003	0	3	0	0	5	2	0	0	0	0	10
	<i>Crematogaster limata</i> Fr. Smith, 1858	14	8	1	0	2	16	1	8	12	16	78
	<i>Crematogaster longispina</i> Emery, 1890	2	0	0	1	2	0	9	0	0	0	14
	<i>Crematogaster nigropilosa</i> Mayr, 1870	1	0	4	1	1	0	0	1	0	0	8
	<i>Crematogaster</i> sp.1	0	0	0	0	2	0	0	0	0	0	2
	<i>Megalomyrmex balzani</i> Emery, 1894	0	0	0	0	2	0	0	0	0	0	2
	<i>Ochetomyrmex semipolitus</i> Mayr, 1878	2	7	2	2	9	1	7	1	2	5	38
	<i>Pheidole</i> (gr. <i>Fallax</i> ) sp.1	1	0	0	1	0	0	0	0	1	0	3
	<i>Pheidole</i> (gr. <i>Fallax</i> ) sp.2	2	0	0	0	0	0	0	0	0	0	2
	<i>Pheidole</i> (gr. <i>Fallax</i> ) sp.3	0	0	1	0	2	0	1	1	0	0	5
	<i>Pheidole</i> (gr. <i>Fallax</i> ) sp.4	0	1	0	0	1	0	1	2	0	1	6
	<i>Pheidole</i> (gr. <i>Flavens</i> ) sp.1	0	1	0	0	0	0	0	0	0	0	1
<i>Pheidole radoszkowskii</i> Mayr, 1884	0	0	2	1	1	0	1	0	1	3	9	
<i>Solenopsis globularia</i> (Smith, 1858)	0	0	1	0	0	0	1	0	0	0	2	
<i>Solenopsis</i> sp.1	0	6	2	0	0	0	0	1	0	0	9	
<i>Solenopsis</i> sp.3	1	3	0	0	0	0	1	0	4	0	9	
<i>Wasmannia auropunctata</i> (Roger, 1863)	2	5	3	2	8	3	3	0	3	5	34	
Ponerinae	<i>Neoponera carinulata</i> (Roger, 1861)	0	0	0	0	2	0	0	0	0	2	
	<i>Neoponera unidentata</i> Mayr, 1862	2	0	1	0	2	2	0	0	0	7	
	<i>Odontomachus haematodus</i> (Linnaeus, 1758)	1	0	0	0	0	7	2	0	0	10	
	<i>Odontomachus hastatus</i> (Fabricius, 1804)	0	0	0	0	0	0	0	0	0	1	
Pseudomyrmecinae	<i>Pseudomyrmex oculatus</i> (Smith, 1855)	0	0	0	0	0	2	0	1	1	4	
	<i>Pseudomyrmex tenuis</i> (Fabricius, 1804)	3	1	0	2	0	1	3	2	1	14	

**Appendix S3.** Plant species present in the ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017. Habitat: T = tree; L = liana; H = herb; ? = undefined.

Family	Plant species	Frequency										Total	Habitat
		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10		
Anonaceae	Anonaceae sp.1	0	0	0	0	1	0	0	0	0	0	1	T
Araceae	<i>Philodendron</i> sp.1	0	0	0	0	0	0	0	0	0	1	1	L
	<i>Fridericia</i> sp.1	0	0	0	0	0	0	1	0	0	0	1	L
	<i>Fridericia</i> sp.2	0	8	7	0	0	0	3	0	2	0	20	L
	<i>Fridericia</i> sp.3	3	0	0	0	0	0	0	4	0	0	7	L
	<i>Fridericia</i> sp.4	0	0	0	0	1	0	0	0	0	1	2	L
	<i>Fridericia</i> sp.5	0	0	1	0	2	1	0	4	0	2	10	L
	<i>Fridericia</i> sp.6	0	0	0	0	0	0	0	5	0	0	5	L
	<i>Fridericia</i> sp.7	0	0	0	0	0	0	1	0	3	0	4	L
	<i>Fridericia</i> sp.8	10	6	0	1	1	11	0	1	0	0	30	L
	<i>Fridericia</i> sp.9	1	0	0	0	1	0	0	0	2	0	4	L
	<i>Fridericia</i> sp.10	1	0	0	0	0	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.11	2	0	0	0	0	1	0	0	0	0	3	L
	<i>Fridericia</i> sp.12	1	0	0	0	0	0	0	0	2	0	3	L
	<i>Fridericia</i> sp.13	1	1	2	1	0	0	0	0	1	0	6	L
	<i>Fridericia</i> sp.14	2	0	0	0	0	0	0	0	0	0	2	L
	<i>Fridericia</i> sp.15	1	0	0	0	0	1	0	0	0	0	2	L
	<i>Fridericia</i> sp.16	0	3	0	0	0	0	0	0	1	0	4	L
	<i>Fridericia</i> sp.17	0	0	0	0	0	1	0	0	1	0	2	L
	<i>Fridericia</i> sp.18	0	0	0	0	0	1	0	0	0	0	1	L
Bignoniaceae	<i>Fridericia</i> sp.19	0	0	1	0	7	0	0	0	0	0	8	L
	<i>Fridericia</i> sp.20	0	0	2	0	0	0	0	0	0	0	2	L
	<i>Fridericia</i> sp.21	0	1	0	0	0	0	0	2	0	0	3	L
	<i>Fridericia</i> sp.22	0	0	0	1	0	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.23	0	0	0	0	1	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.24	0	0	0	0	2	0	0	0	0	0	2	L
	<i>Fridericia</i> sp.25	0	0	0	0	0	0	0	1	0	0	1	L
	<i>Fridericia</i> sp.26	0	0	1	0	0	0	0	3	0	0	4	L
	<i>Fridericia</i> sp.27	0	0	0	0	0	0	0	1	0	0	1	L
	<i>Fridericia</i> sp.28	0	0	1	0	0	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.29	0	0	0	0	1	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.30	0	0	0	0	0	0	0	0	0	1	1	L
	<i>Fridericia</i> sp.31	0	0	0	0	1	0	0	0	2	0	3	L
	<i>Fridericia</i> sp.32	0	0	0	0	0	0	0	2	1	0	3	L
	<i>Fridericia</i> sp.33	0	1	0	0	0	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.34	0	0	0	0	1	0	0	0	0	0	1	L
	<i>Fridericia</i> sp.35	0	1	0	0	3	0	0	1	1	0	6	L
	<i>Memora</i> sp.1	1	0	0	0	0	0	0	0	0	0	1	L
	<i>Memora</i> sp.2	0	1	0	0	5	0	0	0	0	0	6	L
	<i>Memora</i> sp.3	0	0	0	0	0	1	0	0	0	0	1	L

**Appendix S3.** Plant species present in the ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017. Habitat: T = tree; L = liana; H = herb; ? = undefined. (Continuation)

Family	Plant species	Frequency										Total	Habitat
		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10		
Chrysobalanaceae	<i>Hirtella racemosa</i> Lam.	0	0	0	0	9	1	0	6	0	0	<b>16</b>	T
	<i>Hirtella</i> sp.1	0	0	0	0	0	0	0	1	0	1	<b>2</b>	T
	<i>Hirtella</i> sp.2	0	0	0	0	0	0	0	0	1	0	<b>1</b>	T
Combretaceae	<i>Buchenavia</i> sp.1	1	0	0	0	0	0	0	0	0	0	<b>1</b>	T
Convolvulaceae	<i>Ipomoea philomega</i> (Vell.) House	0	0	0	0	0	0	0	0	1	0	<b>1</b>	L
	<i>Ipomoea regnellii</i> Meisn.	0	0	0	0	1	0	0	0	0	0	<b>1</b>	L
Costaceae	<i>Costus scaber</i> Ruiz & Pav.	0	1	0	1	0	0	1	1	0	2	<b>6</b>	H
Cucurbitaceae	Cucurbitaceae sp.1	0	0	1	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Gurania</i> sp.1	0	0	1	0	0	1	0	0	0	0	<b>2</b>	L
Euphorbiaceae	<i>Acalypha</i> sp.1	0	0	0	0	0	0	0	0	4	0	<b>4</b>	?
	<i>Aparisthium cordatum</i> (A. Juss.) Baill.	0	10	0	0	0	0	0	0	0	0	<b>10</b>	T
	<i>Dalechampia</i> sp.1	1	0	0	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Omphalea diandra</i> L.	0	0	0	0	0	2	2	0	0	2	<b>6</b>	L
Fabaceae	<i>Senegalia</i> sp.1	3	0	1	1	3	0	3	1	1	3	<b>16</b>	L
	<i>Senegalia</i> sp.2	7	4	2	1	0	6	9	3	8	1	<b>41</b>	L
	<i>Senegalia</i> sp.3	3	7	0	1	2	1	1	0	6	0	<b>21</b>	L
	<i>Senegalia</i> sp.4	1	0	1	11	0	0	3	0	0	0	<b>16</b>	L
	<i>Senegalia</i> sp.5	0	0	0	0	0	0	0	0	1	0	<b>1</b>	L
	<i>Senegalia</i> sp.6	0	0	0	0	1	0	0	0	0	0	<b>1</b>	L
	<i>Senegalia</i> sp.7	2	0	0	4	0	0	1	0	0	0	<b>7</b>	L
	<i>Senegalia</i> sp.8	1	0	1	3	1	0	3	1	5	0	<b>15</b>	L
	<i>Senegalia</i> sp.9	0	1	0	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Bauhinia</i> sp.1	33	15	16	0	0	9	17	2	7	0	<b>99</b>	L
	<i>Bauhinia</i> sp.2	0	0	0	1	0	0	0	0	0	0	<b>1</b>	L
	<i>Bauhinia</i> sp.3	0	0	0	0	0	1	0	0	0	0	<b>1</b>	L
	<i>Bauhinia</i> sp.4	0	0	0	3	0	0	0	0	0	0	<b>3</b>	L
	<i>Bauhinia</i> sp.5	0	0	0	0	0	0	0	1	0	0	<b>1</b>	L
	<i>Bauhinia</i> sp.6	0	0	0	0	0	2	0	0	0	0	<b>2</b>	L
	<i>Centrosema</i> sp.1	0	0	0	0	0	0	3	0	0	0	<b>3</b>	L
	<i>Centrosema</i> sp.2	0	0	0	0	0	0	2	0	0	0	<b>2</b>	L
	<i>Centrosema</i> sp.3	0	0	2	0	0	0	0	0	0	0	<b>2</b>	L
	<i>Erythrina</i> sp.1	0	0	1	2	0	0	0	0	0	0	<b>3</b>	T
	Fabaceae sp.1	0	1	3	0	0	0	0	0	0	0	<b>4</b>	?
<i>Inga acreana</i> Harms	0	0	0	0	0	1	0	0	0	1	<b>2</b>	T	
<i>Inga alba</i> (Sw.) Willd.	0	1	3	1	1	0	0	0	0	0	<b>6</b>	T	
<i>Inga calantha</i> Ducke	0	0	0	0	1	0	0	0	0	1	<b>2</b>	T	
<i>Inga capitata</i> Desv.	1	1	0	0	0	2	0	0	0	0	<b>4</b>	T	
<i>Inga chartacea</i> Poepp.	0	0	1	0	0	0	0	0	0	2	<b>3</b>	T	
<i>Inga densiflora</i> Benth.	0	1	2	0	0	2	0	1	0	0	<b>6</b>	T	

## Appendix S3. Plant species... (Continuation)

Family	Plant species	Frequency										Total	Habitat
		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10		
Fabaceae	<i>Inga edulis</i> Mart.	2	0	1	1	0	0	1	0	1	0	<b>6</b>	T
	<i>Inga heterophylla</i> Willd.	1	0	0	0	0	0	0	0	0	0	<b>1</b>	T
	<i>Inga lateriflora</i> Miq.	1	0	2	1	2	0	3	0	1	0	<b>10</b>	T
	<i>Inga laurina</i> (Sw.) Willd.	6	2	2	4	0	0	0	0	0	4	<b>18</b>	T
	<i>Inga microcoma</i> Harms	0	0	0	0	1	0	0	0	0	0	<b>1</b>	T
	<i>Inga punctata</i> Willd.	0	0	0	1	0	0	0	0	0	5	<b>6</b>	T
	<i>Inga sertulifera</i> DC.	0	0	2	0	3	3	0	0	0	0	<b>8</b>	T
	<i>Inga suaveolens</i> Ducke	1	0	0	0	0	0	0	0	0	0	<b>1</b>	T
	<i>Inga tenuistipula</i> Ducke	0	0	0	0	2	0	1	1	0	3	<b>7</b>	T
	<i>Inga</i> sp.1	0	0	0	0	0	1	0	0	0	0	<b>1</b>	T
	<i>Inga</i> sp.2	0	0	0	0	0	0	0	0	2	0	<b>2</b>	T
	<i>Inga</i> sp.3	0	0	0	0	0	2	1	0	0	0	<b>3</b>	T
	<i>Inga</i> sp.4	1	0	0	1	0	0	0	1	0	2	<b>5</b>	T
	<i>Inga</i> sp.5	0	0	0	0	1	1	1	6	0	6	<b>15</b>	T
	<i>Inga</i> sp.6	0	0	0	0	0	0	0	0	0	1	<b>1</b>	T
	<i>Inga</i> sp.7	0	0	2	0	0	1	0	0	0	0	<b>3</b>	T
	<i>Inga</i> sp.9	1	0	0	0	0	0	0	0	2	0	<b>3</b>	T
	<i>Inga</i> sp.10	0	0	0	1	0	0	0	1	0	0	<b>2</b>	T
	<i>Inga</i> sp.12	0	0	0	2	0	0	0	0	0	0	<b>2</b>	T
	<i>Inga</i> sp.13	0	0	0	2	0	0	0	0	0	0	<b>2</b>	T
	<i>Inga</i> sp.14	0	0	1	0	0	0	1	0	1	0	<b>3</b>	T
	<i>Inga</i> sp.15	0	1	0	0	0	0	0	0	0	0	<b>1</b>	T
	<i>Inga</i> sp.16	0	0	3	0	0	0	0	0	0	0	<b>3</b>	T
	<i>Inga</i> sp.18	0	0	0	0	0	1	0	0	0	0	<b>1</b>	T
	<i>Inga</i> sp.20	0	0	0	0	0	1	0	0	0	0	<b>1</b>	T
	<i>Senna</i> sp.1	0	0	0	0	1	0	0	0	0	0	<b>1</b>	T
<i>Zygia</i> sp.1	0	0	1	0	4	0	0	0	1	0	<b>6</b>	T	
<i>Zygia</i> sp.2	0	3	0	0	0	0	0	0	0	0	<b>3</b>	T	
<i>Zygia</i> sp.3	0	1	0	0	0	0	0	0	0	0	<b>1</b>	T	
<i>Zygia</i> sp.4	0	1	0	0	0	0	0	0	0	0	<b>1</b>	T	
Lecythidaceae	<i>Gustavia augusta</i> L.	0	0	0	0	2	0	0	0	2	0	<b>4</b>	T
	Lecythidaceae sp.1	0	0	0	0	3	0	0	0	0	0	<b>3</b>	T
Loganiaceae	<i>Strychnos panurensis</i> Sprague & Sandwith	0	0	0	1	1	0	0	0	0	0	<b>2</b>	L
Malpighiaceae	<i>Banisteriopsis</i> sp.1	0	0	0	0	0	4	0	0	0	0	<b>4</b>	L
	<i>Banisteriopsis</i> sp.2	2	0	0	3	0	44	3	2	0	41	<b>95</b>	L
	<i>Banisteriopsis</i> sp.3	1	1	0	0	0	1	1	0	0	0	<b>4</b>	L
	<i>Banisteriopsis</i> sp.4	0	1	1	0	0	0	0	0	0	0	<b>2</b>	L
	<i>Banisteriopsis</i> sp.5	0	9	1	0	0	0	0	0	0	0	<b>10</b>	L
	<i>Banisteriopsis</i> sp.6	0	0	0	0	3	0	0	0	0	0	<b>3</b>	L
	<i>Banisteriopsis</i> sp.7	0	0	0	0	1	0	0	0	0	0	<b>1</b>	L
	<i>Banisteriopsis</i> sp.8	0	0	0	0	0	0	0	0	0	1	<b>1</b>	L
	<i>Heteropterys</i> sp1	0	1	0	0	2	0	0	0	0	0	<b>3</b>	L
	<i>Tetrapteryx</i> sp.1	1	0	0	0	0	0	2	0	0	4	<b>7</b>	?

**Appendix S3.** Plant species... (Continuation)

Family	Plant species	Frequency										Total	Habitat
		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10		
Malvaceae	<i>Byttneria benensis</i> Britton	0	0	0	0	0	5	0	0	1	0	<b>6</b>	L
Menispermaceae	<i>Abuta</i> sp.1	0	0	0	0	0	0	0	0	1	0	<b>1</b>	L
	<i>Abuta</i> sp.2	0	0	0	0	0	0	0	1	0	0	<b>1</b>	L
Ochinaceae	<i>Ouratea</i> sp.2	0	0	0	0	3	1	0	1	0	0	<b>5</b>	T
Olacaceae	<i>Heisteria</i> sp.1	0	0	0	2	3	0	0	1	0	1	<b>7</b>	?
Passifloraceae	<i>Dilkea</i> sp.1	0	0	1	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Passiflora coccinea</i> Aublet.	1	0	2	0	0	0	0	0	0	0	<b>3</b>	L
	<i>Passiflora</i> sp.1	1	0	0	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Passiflora</i> sp.2	0	0	0	0	0	0	1	0	0	0	<b>1</b>	L
	<i>Passiflora</i> sp.3	0	0	0	0	0	1	0	0	0	0	<b>1</b>	L
	<i>Passiflora</i> sp.4	0	0	0	0	0	0	0	1	0	0	<b>1</b>	L
Polygonaceae	<i>Polygonaceae</i> sp.1	26	38	31	0	2	1	2	8	11	0	<b>119</b>	?
	<i>Polygonaceae</i> sp.2	0	0	0	0	0	0	1	0	0	0	<b>1</b>	T
Rhamnaceae	<i>Gouania frangulifolia</i> Radlk.	0	0	0	0	0	0	0	0	1	0	<b>1</b>	L
Rubiaceae	<i>Tocoyena</i> sp.1	0	0	1	0	0	0	0	0	0	0	<b>1</b>	T
	<i>Palicourea</i> sp.1	0	3	2	0	1	5	2	6	2	5	<b>26</b>	T
Sapindaceae	<i>Paullinia</i> sp.1	0	0	0	0	0	0	2	1	0	0	<b>3</b>	L
	<i>Paullinia</i> sp.2	3	0	0	1	1	0	0	0	0	1	<b>6</b>	L
	<i>Paullinia</i> sp.3	3	0	0	0	0	0	0	0	0	0	<b>3</b>	L
	<i>Paullinia</i> sp.5	1	0	0	0	0	0	0	0	0	0	<b>1</b>	L
	<i>Paullinia</i> sp.6	0	0	0	0	0	0	0	0	1	0	<b>1</b>	L
	<i>Serjania clematidea</i> Triana & Plach.	0	0	0	0	0	0	0	0	2	2	<b>4</b>	L
Solanaceae	<i>Solanum</i> sp.1	0	0	1	0	0	0	0	0	0	0	<b>1</b>	?
Vitaceae	<i>Cissus</i> sp.1	0	0	0	0	0	0	0	1	0	0	<b>1</b>	L
Volchysiaceae	<i>Qualea grandiflora</i> Mart.	0	0	2	0	0	0	2	0	0	0	<b>4</b>	T
	<i>Volchysia</i> sp.1	0	0	0	0	0	1	0	0	0	0	<b>1</b>	T

**Appendix S4.** Network size, number of interaction, network specialization, diversity of interaction and nestedness (*NODF*) of the ant-plant networks sampled in 10 rainforest fragments located in the state of Acre, Brazilian Amazon, between June 2016 and February 2017.

Fragment	Network size	Number of interactions	Network specialization	Diversity of interaction	<i>NODF</i>
1	648	128	0.15	3.81	36.70*
2	580	125	0.19	3.70	37.32*
3	518	106	0.17	3.75	32.29*
4	312	52	0.26	3.54	22.78
5	798	81	0.15	4.24	16.40
6	816	118	0.15	4.21	27.57*
7	609	74	0.21	3.96	19.05*
8	576	72	0.20	4.04	20.15*
9	561	79	0.27	3.97	26.52*
10	525	94	0.21	3.78	29.60*
Mean ± SD	594.2 ± 136.28	82.90 ± 33.08	0.20 ± 0.04	3.90 ± 0.23	26.84 ± 7.27

\*Significant descriptor value (95% CI).

**Appendix S5.** Model selection analysis to explain the five ant-network descriptors in response to landscape structure metrics and forest structure at 10 rainforest fragments located in the state of Acre, Brazilian Amazon. The  $\Delta AICc$ , df, and wAICc indicate the difference in corrected Akaike values, degrees of freedom of the model, and Akaike weights, respectively. Ed = Edge irregularity index; Co = Connectivity index; Ar = Fragment area; Cc = Canopy cover. The values in bold represent the models selected for each of the network descriptors evaluated.

Response variable	Model	$\Delta AICc$	d.f.	wAIC	Slope symbol
Number of interaction	<b>null model</b>	<b>0</b>	<b>2</b>	<b>0.396</b>	
	Ed	0.75	3	0.273	-
	Co	2.91	3	0.093	-
	Cc	3.02	3	0.087	-
	Ar	3.04	3	0.087	-
	Ed+Co	6.45	4	0.016	-Ed+Co
	Ed+Cc	6.55	4	0.015	-Ed-Cc
	Ar+Ed	6.72	4	0.014	-Ar-Ed
	Cc+Co	8.12	4	0.007	-Cc-Co
	Ar+Cc	8.33	4	0.006	-Ar-Cc
	Ar+Co	8.51	4	0.006	-Ar-Co
	Ed+Cc+Co	15.31	5	0.000	-Ed-Cc+Co
	Ar+Ed+Co	15.4	5	0.000	-Ar-Ed+Co
	Ar+Ed+Cc	15.54	5	0.000	-Ar-Ed-Cc
	Ar+Cc+Co	16.91	5	0.000	-Ar-Cc-Co
	Ar+Ed+Cc+Co	30.28	6	0.000	-Ar-Ed-Cc+Co
Network size	<b>null model</b>	<b>0</b>	<b>2</b>	<b>0.597</b>	
	Cc	2.75	3	0.151	-
	Co	4.2	3	0.073	+
	Ar	4.27	3	0.070	-
	Ed	4.28	3	0.070	+
	Cc+Co	8.33	4	0.009	-Cc+Co
	Ed+Cc	8.42	4	0.009	Ed-Cc
	Ar+Cc	8.66	4	0.008	Ar-Cc
	Ed+Co	10.07	4	0.004	-Ed+Co
	Ar+Co	10.12	4	0.004	-Ar+Co
	Ar+Ed	10.26	4	0.004	-Ar+Ed
	Ed+Cc+Co	17.32	5	0.000	Ed-Cc+Co
	Ar+Cc+Co	17.33	5	0.000	Ar-Cc+Co
	Ar+Ed+Cc	17.42	5	0.000	Ar+Ed-Cc
	Ar+Ed+Co	19.03	5	0.000	-Ar-Ed+Co
	Ar+Ed+Cc+Co	32.32	6	0.000	-Ar+Ed-Cc+Co
Network specialization	<b>null model</b>	<b>0</b>	<b>2</b>	<b>0.514</b>	
	Ar	1.63	3	0.228	+
	Ed	3.88	3	0.074	+
	Co	3.91	3	0.073	+
	Cc	4.16	3	0.064	+
	Ar+Ed	7.59	4	0.012	Ar-Ed
	Ar+Co	7.59	4	0.012	Ar-Co
Ar+Cc	7.63	4	0.011	Ar-Cc	

**Appendix S5.** Model selection analysis to explain the five ant-network descriptors in response to landscape structure metrics and forest structure at 10 rainforest fragments located in the state of Acre, Brazilian Amazon. (Continuation)

Response variable	Model	$\Delta AICc$	d.f.	wAIC	Slope symbol	
Network specialization	Ed+Co	9.85	4	0.004	Ed+Co	
	Cc+Co	9.87	4	0.004	Cc+Co	
	Ed+Cc	9.87	4	0.004	Ed+Cc	
	Ar+Ed+Co	16.59	5	0.000	Ar-Ed-Co	
	Ar+Ed+Cc	16.59	5	0.000	Ar-Ed+Cc	
	Ar+Cc+Co	16.59	5	0.000	Ar+Cc-Co	
	Ed+Cc+Co	18.83	5	0.000	Ed+Cc+Co	
	Ar+Ed+Cc+Co	31.58	6	0.000	Ar-Ed+Cc-Co	
Diversity of interaction	<b>null model</b>	<b>0.00</b>	<b>2</b>	<b>0.521</b>		
	Ed	2.81	3	0.127	+	
	Co	2.9	3	0.122	+	
	Ar	3.59	3	0.086	+	
	Cc	3.73	3	0.081	-	
	Ed+Cc	6.32	4	0.022	Ed-Cc	
	Cc+Co	7.42	4	0.013	-Cc+Co	
	Ar+Cc	8.54	4	0.007	Ar-Cc	
	Ed+Co	8.69	4	0.007	Ed+Co	
	Ar+Ed	8.74	4	0.007	Ar+Ed	
	Ar+Co	8.79	4	0.006	Ar+Co	
	Ar+Ed+Cc	15.19	5	0.000	Ar+Ed-Cc	
	Ed+Cc+Co	15.29	5	0.000	Ed-Cc+Co	
	Ar+Cc+Co	16.15	5	0.000	Ar-Cc+Co	
	Ar+Ed+Co	17.63	5	0.000	Ar+Ed+Co	
	Ar+Ed+Cc+Co	30.17	6	0.000	Ar+Ed-Cc+Co	
	NODF	<b>Ed</b>	<b>0.00</b>	<b>3</b>	<b>0.449</b>	-
		<b>null model</b>	<b>1.20</b>	<b>2</b>	<b>0.247</b>	
Co		2.38	3	0.137	-	
Ar		4.60	3	0.045	-	
Cc		5.09	3	0.035	-	
Ed+Cc		5.84	4	0.024	-Ed+Cc	
Ar+Ed		5.96	4	0.023	Ar-Ed	
Ed+Co		6.00	4	0.022	-Ed+Co	
Cc+Co		8.34	4	0.007	-Cc-Co	
Ar+Co		8.35	4	0.007	-Ar-Co	
Ar+Cc		10.42	4	0.002	-Ar-Cc	
Ar+Ed+Co		14.80	5	0.000	Ar-Ed+Co	
Ed+Cc+Co		14.83	5	0.000	-Ed+Cc+Co	
Ar+Ed+Co		14.96	5	0.000	Ar-Ed+Co	
Ar+Cc+Co		17.32	5	0.000	-Ar-Cc-Co	
Ar+Ed+Cc+Co		29.80	6	0.000	Ar-Ed+Cc+Co	