

# **Genotypic variation in a foundation tree results in heritable ecological network structure**

**Matthew K. Lau<sup>1,2</sup>, Louis J. Lamit<sup>1,3,4</sup>, Rikke Reese Næsborg<sup>1,5</sup>, Stuart R. Borrett<sup>6</sup>, Matthew A. Bowker<sup>7</sup>, and Thomas G. Whitham<sup>1,8</sup>**

<sup>1</sup>Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ 86011, USA

<sup>2</sup>Harvard Forest, Harvard University, 324 N Main St, Petersham, MA 01366, USA

<sup>3</sup>Department of Biology, State University of New York College of Environmental Sciences, Syracuse University, 107 College Place Syracuse, NY 13244, USA

<sup>4</sup>Department of Environmental Forest Biology and Forestry, Syracuse, NY 13210, USA

<sup>5</sup>Santa Barbara Botanic Garden, 1212 Mission Canyon Road, Santa Barbara, CA 93105

<sup>6</sup>Department of Biology and Marine Biology, University of North Carolina Wilmington, 601 South College Road, Wilmington, NC 28403, USA

<sup>7</sup>Duke Network Analysis Center, Duke University, Durham, NC 27708, USA

<sup>8</sup>School of Forestry, 200 E. Pine Knoll Dr., Northern Arizona University, Flagstaff, AZ

86011, USA

<sup>9</sup>Center for Adaptable Western Landscapes, Northern Arizona University, Flagstaff, AZ 86011, USA

## **ABSTRACT**

Biological evolution occurs in ecosystems whereby natural selection defines the structure of ecological networks. Therefore, elucidating the genetic basis to ecological network structure is fundamental to understanding evolution. Although previous work has demonstrated that genetic variation can influence food webs and trophic chains, we are unaware of a study that quantified the contribution of phenotypic variation to heritable variation in network structure. To examine this, in a 20+ year old common garden we observed epiphytic lichen associated with narrowleaf cottonwood (*Populus angustifolia*), a riparian ecosystem foundation species. We constructed and conducted genetic analyses of signed, weighted, directed lichen interaction networks on individual trees. We found three primary results. First, genotype identity significantly predicted lichen network similarity; i.e., replicates of the same genotype supported more similar lichen networks than different genotypes. Second, broad sense heritability estimates showed that plant genotype explained network similarity ( $H^2 = 0.41$ ), degree ( $H^2 = 0.32$ ) and centralization ( $H^2 = 0.33$ ). Third, of several tree phenotypic traits examined, bark roughness was both heritable ( $H^2 = 0.32$ ) and significantly predicted by lichen network similarity ( $R^2 = 0.26$ ). These results support a mechanistic, genetic pathway from variation in a heritable tree trait to ecological network structure and demonstrate that evolution can act at the community level to influence not only abundances of organisms but also interactions at the scale of entire networks. Given that network structure can influence system-wide stability and resilience, our findings have important implications for how evolution acts in ecosystems.

Keywords: networks | heritability | community | genetics | lichen | cottonwood | *Populus* | common garden

21 **INTRODUCTION**

22 Evolution occurs in the context of complex ecological networks. Community genetics  
23 studies have shown that genetic variation in foundation species, which have large effects  
24 on ecosystems by modulating and stabilizing local conditions (Ellison et al., 2005),  
25 plays a significant role in defining distinct communities of interacting organisms: such  
26 as endophytes, pathogens, lichens, arthropods, and soil microbes (Busby et al., 2015;  
27 Barbour et al., 2009; Lamit et al., 2015a). Multiple studies have now demonstrated that  
28 genetic variation influences numerous functional traits (e.g., phytochemical, phenologi-  
29 cal, morphological) that in combination result in a multivariate functional trait phenotype  
30 (Holeski et al., 2012) in which individual plant genotypes support different communities  
31 and ecosystem processes (Bailey et al., 2009; Whitham et al., 2012). Recently, the  
32 importance of genetic variation in structuring ecological systems was reviewed, and  
33 not only were many instances of strong genetic effects found in many ecosystems but  
34 the effect of intraspecific variation was at times greater than inter-specific variation  
35 (Des Roches et al., 2018). There is now evidence to support that selection, acting on  
36 this heritable variation, tends to occur among groups of species (Wade, 2007) and that  
37 genetic variation and phylogenetic relatedness contribute to variation in community  
38 assembly (Crutsinger, 2016) and species interactions (Whitham et al., 2006; Bailey et al.,  
39 2009; Moya-Laraño, 2011), which shape the structure of ecological interaction networks  
40 (Rezende et al., 2007; Guimarães et al., 2007; Gómez et al., 2009).

41 Empirical and theoretical work in network ecology and evolutionary biology point  
42 to the need for examinations of the genetic basis of ecological network structure. Anal-  
43 yses of ecological networks have demonstrated that indirect effects can lead to self-  
44 organization, producing sign-changing, amplifying and/or dampening effects (Newman,  
45 2006; Sole and Bascompte, 2006), and other studies have demonstrated that indirect ef-  
46 fects of interactions among species can lead to network structures that amplify or dampen  
47 the effects of selection, such as the formation of star-like structures in which there is  
48 a “central” species or group of species that interact with other peripheral species can  
49 amplify selection events (Lieberman et al., 2005). Also, work by Toju et al. (2014, 2016,  
50 2017) observed consistent patterns of centralized interactions of species modules (i.e.,  
51 groups of species that interact more strongly within their group than with other species)  
52 focused around hubs of plant-fungal interactions. In other words, a small number of  
53 plant and fungal symbionts tended to have disproportionate numbers of interactions with  
54 other species and likely are the drivers in determining community assembly, structure  
55 and dynamics. Interspecific indirect genetic effects (IIGE) theory (*sensu* Shuster et al.  
56 (2006)) in evolutionary biology also point to the importance of studying the genetics of  
57 interaction network structure. Genetically based differences in network structure among  
58 individuals can be acted upon by natural selection when there are fitness consequences  
59 of different networks of IIGEs, leading to community evolution per Whitham et al.  
60 (2020) and, by extension, network evolution. For example, although the analysis was  
61 of abundances rather than interaction networks, Gehring et al. (2014, 2017) found that  
62 the mycorrhizal communities on the roots of drought tolerant and intolerant trees are  
63 dominated by different orders of ectomycorrhizal fungal mutualists that also differ in the  
64 benefits they provide that enhance tree performance. Because drought tolerant genotypes  
65 are three times more likely to survive record droughts, selection acts both on the tree and

66 its fungal community and with increased drought the community phenotype has changed  
67 over time. Also, in an antagonistic interaction context, Busby et al. (2015) found that  
68 with the addition of a damaging leaf pathogen to cottonwoods in a common garden, the  
69 impacts of these strong interactors results in a different and diminished community of  
70 arthropods relative to control trees. This effect was dependent on the hybrid cross-type  
71 of the tree and was, therefore, determined by tree genetics. These examples collectively  
72 support the possibility that selection acting on the tree may alter the network structure  
73 of associated communities in which different networks of communities are most likely  
74 to survive pathogen outbreaks. Regardless of whether the IIGE is unilateral (i.e., tree  
75 affects the community) or reciprocal (i.e., the community also affects the relative fitness  
76 of the tree), selection at the level of the tree population or its community, or both, can  
77 change network structure and alter community dynamics (Whitham et al., 2020).

78 In this context, the “genetic similarity rule” of community genetics provides a useful  
79 framework we can apply to interaction networks at the nexus of ecological and evolution-  
80 ary dynamics. In a study combining experimental common gardens and landscape-  
81 scale observations of interactions between *Populus* spp. (cottonwoods) and arthropods,  
82 Bangert et al. (2006) observed that individual genotypes that are more genetically similar  
83 will tend to have similar phytochemical traits and thus tend to have similar interactions  
84 with other species. Although this is likely to have consequences for interactions and  
85 network structure, studies in the network ecology literature generally do not include a  
86 genetic component (Lau et al., 2017) and community genetics studies have primarily  
87 focused on community composition in terms of the abundance of species (Des Roches  
88 et al., 2018). Some studies have examined the effects of genetic variation on trophic  
89 chains in plant-associated communities (including *Populus*, *Solidago*, *Oenothera*, *Salix*)  
90 (Bailey et al., 2005; Johnson, 2008; Smith et al., 2011, 2015; Barbour et al., 2016) and  
91 generally found that increasing genotypic diversity leads to increased trophic complexity.  
92 Only two other studies, that we are aware of, have explicitly examined the effect of  
93 genotypic variation on the structure of interaction networks between tree individuals and  
94 associated herbivores (Lau et al., 2016a; Keith et al., 2017) and both found that genotypic  
95 diversity generates increased network modularity (i.e., compartmentalization). However,  
96 both of these studies were examining networks at the scale of forest stands, rather  
97 than networks associated with individual trees; therefore, neither was able to observe  
98 replicated networks in order to statistically test for genetic effects on network structure  
99 and quantify the genetic component (i.e., heritable variation) in network structure.

100 Here, we investigate how genetic variation in a foundation tree species determines  
101 the structure of a network of interactions among a community of tree associated lichens.  
102 Using a long-term (20+ years), common garden experiment with clonally replicated  
103 *Populus angustifolia* individuals of known genetic identity (Martinsen et al., 2001).  
104 We focused on a community of 9 epiphytic lichen species, as previous research has  
105 demonstrated significant compositional responses of epiphytes to genotypic variation  
106 (Winfrey et al., 2011; Zytynska et al., 2011). Applying a probability-theory based  
107 network modeling approach (Araújo et al., 2011), we constructed a set of interaction  
108 network models for the lichens associated with individual trees. Using these models,  
109 we then examined the genetic basis of the structure of these ecological networks via  
110 several network metrics that measure different aspects of network structure at the scale  
111 of individual species (i.e., nodes) or the entire network observed on each tree genotype.

Given the potential importance of focal or “central” nodes (e.g., species) for determining network dynamics (Lieberman et al., 2005), we focused on network metrics that measure centrality for individual species and centralization for whole networks. Both of these metrics measure how much a species is connected in the network relative to other species. As there is a preponderance of evidence that in natural systems evolution occurs in communities comprised of networks of interacting species (Lau et al., 2016a; Keith et al., 2017; Thompson, 2013; Bascompte et al., 2006), we set out to test two hypotheses. First, per the community similarity rule (Bangert et al., 2006) and IIGE theory (Whitham et al., 2020), we hypothesize that trees of the same genotype (i.e., clones) will support more similar lichen interaction networks relative to less related genotypes. In other words, epiphytic lichen network structure is heritable, which can be calculated via comparisons of within and among group variation in network structure. Second, heritability of lichen network structure is the result of underlying phenotypic covariation in tree traits important to interactions between trees and lichens and among lichens. Evidence that such trait covariance generates variation in interactions among community members provides an intermediate genetics-based mechanism for the underlying factors determining lichen distribution and abundance. In combination, evaluating these two hypotheses is fundamental to understanding variation and dynamics of network structure and evolution.

## MATERIALS AND METHODS

### Study System

The study was conducted along the Weber River, UT (USA), which is a cottonwood (*Populus* spp.) dominated riparian ecosystem. Although two native species, *Populus angustifolia* (James) and *Populus fremontii* (S. Watson), occur here and are known to hybridize, in order to focus on intra-specific genetic variation we only sampled pure or advanced generation back-crosses of *P. angustifolia*. Bark lichens have been intensively sampled in this system and provide an ideal community in which to observe and model interaction networks, as their sessile nature permits accurate identification of individuals and their highly localized, direct contact interactions and slow population turnover rates facilitate the assessment of interactions among lichen species on individual trees (Lamit et al., 2015b).

A long-term, common garden experiment was used to isolate the effect of tree genotype from the effect of the localized microenvironment associated with each individual and spatial autocorrelation. Established in 1992, asexually propagated clones of genotyped *P. angustifolia* individuals were obtained from wild collections and planted in fully randomized design at the Ogden Nature Center, Ogden, UT. From the population of established individuals in the common garden, we chose a total of ten genotypes, replicated between 3 and 8 times each, for sampling. We selected tree genotypes that generally had lichens present in order to permit the construction of interaction networks.

### Bark Lichen and Trait Observations

On each tree, presence or absence of each lichen species was assessed in 50 total 1 cm<sup>2</sup> cells arrayed in a checkerboard pattern. Given the small size and sessile nature of lichens, we were able to rapidly assess lichen interactions by quantifying thalli of

155 different species occurring in close proximity. Sampling was restricted to the northern  
156 aspect of the trunk to maximize the abundance of lichen and control for the effect of trunk  
157 aspect. Two adjacent  $100\text{ cm}^2$  quadrats centered at 50 cm and 95 cm from ground level  
158 were sampled (Fig 1). The observed lichen community included: *Athallia holocarpa*,  
159 *Candelariella subdeflexa*, *Myriolecis hagenii*, *Rinodina freyi*, *Physcia adscendens*,  
160 *Physciella melanchra*, *Physcia undulata*, *Xanthomendoza galericulata*, *Xanthomendoza*  
161 *montana*. Several other species were not observed in the present study but are known to  
162 occur in this region: *Melanohalea elegantula*, *Melanohalea sublivacea*, *Phaeophyscia*  
163 *ciliata* and *Phaeophyscia orbicularis*.

164 The cell size and checkerboard sampling pattern was chosen to isolate the individuals  
165 in each cell. *Xanthomendoza galericulata* thallus size in this common garden, we had  
166 observed a median thallus size of  $0.12 \pm 0.001\text{ cm}^2$  (1 S.E.) (Supporting Information,  
167 Fig. 1). Based on the median thallus size, we expected thalli observed in each cell to  
168 generally be spatially independent of thalli present in other cells but exposed to similar  
169 micro-environmental conditions created by the bark and the location of the sampling area  
170 on an individual tree. Therefore, we were confident in treating the cell-wise observations  
171 in quadrats as independent with respect to lichen-lichen interactions. We quantified  
172 the texture of the bark in the quadrat is the percent of  $1\text{ cm}^2$  cells with rough bark. In  
173 addition to bark roughness, we also examined several bark chemistry traits by taking  
174 bark samples immediately adjacent to each quadrat. We used previously collected  
175 phytochemical data from Lamit et al. (2011), including the concentration of condensed  
176 tannins, carbon and nitrogen. Additionally, we quantified bark pH data from dried bark  
177 samples collected in XXXX L JL INPUT. Samples were soaked in XX ml of XXX water  
178 for XX hours and pH was measured using a XX L JL INPUT.

### 179 **Lichen Network Modeling**

180 For each tree, repeated observations of lichens were made in order to construct replicated  
181 interaction networks for each genotype. We conducted a modified sampling procedure  
182 originally developed by Lamit et al. (2015b) with the addition that we quantified the  
183 presence of lichen in the  $1\text{ cm}^2$  cells on individual trees of *P. angustifolia*. Unipartite  
184 networks were generated using the conditional probabilities of each species pair, i.e., the  
185 probability of observing one species given an observation of another species  $P(S_i|S_j)$ ,  
186 based on the method developed by Araújo et al. (2011). To calculate conditional  
187 probabilities, we quantified the individual probabilities of species occurrences  $P(S_i)$  and  
188 the joint probability of co-occurrences  $P(S_i, S_j)$  using the frequencies of each species  
189 and their co-occurrences. We were then able to calculate the conditional probabilities of  
190 each species pair as  $P(S_i|S_j) = \frac{P(S_i, S_j)}{P(S_j)}$ , based on the axioms of probability. This yielded  
191 a matrix that could possibly be asymmetric, i.e.,  $P(S_i|S_j)$  does not have to be equal to  
192  $P(S_j|S_i)$ . Another important property of this matrix is that the diagonal,  $P(S_i|S_i)$ , was  
193 equal to one for all species present and zero for species that were not observed in any  
194 cell.

195 We then applied an analytical procedure to remove non-significant links between  
196 species. This procedure determines if the joint probability of a species pair (i.e.,  $P(S_i, S_j)$ )  
197 is different from zero (Fig. 2). Here, a confidence interval  $CI_{95\%}$  is calculated as as  
198  $CI_{95\%} = E[S_iS_j] * Z_{95\%} * \sqrt{V(S_iS_j)}$ , where the expected frequency of co-occurrences  
199  $E(S_iS_j)$  is the total number of cells surveyed ( $N$ ) times the independent probabilities of

200 each species  $P(S_i) * P(S_j)$ ,  $Z_{95\%}$  is the Z-score for 95% from a Z-distribution and the  
201 expected variance of  $E(S_i S_j)$  is the total number of cells times the expected probability  
202 of  $S_i S_j$  and its compliment (i.e.,  $V(S_i S_j) = N * E[P(S_i, S_j)] * (1 - E[P(S_i, S_j)])$ ). If  
203 the observed number of co-occurrence falls outside of the confidence interval, the  
204 joint probability  $P(S_i, S_j)$  is determined to be equal to the product of the individual  
205 probabilities (i.e.,  $P(S_i)P(S_j)$ ), and the conditional probability reduces to the individual  
206 probability of that species  $P(S_i)$ . Therefore, unless the co-occurrence of a species pair  
207 falls outside the confidence interval, the probability that the observation of one species  
208 given the other is no different than simply observing that species alone. This enables us  
209 to remove links from a given network by re-scaling the resulting conditional probabilities  
210 through subtraction of the individual probabilities from the conditional probabilities (i.e.,  
211 how different the conditional probability is from the independent probability), which  
212 makes any species with a non-significant conditional probability zero.

213 The resulting matrix ( $\mathbf{D} = D_{ij}$ ) can be interpreted as one species' impact on another  
214 with zero being no effect and values less than or greater than zero being negative and  
215 positive effects, respectively. We will refer to  $\mathbf{D}$  as a signed, weighted interaction  
216 matrix. As such,  $\mathbf{D}$  has the properties that it can be asymmetric (i.e.,  $D_{ij}$  does not  
217 necessarily equal  $D_{ji}$ ) and it scales between -1 and 1, and, therefore, does not have the  
218 mathematical properties of a probabilistic network (Poisot et al., 2016). Also, as the  
219 method does not track individuals within species and interactions such as competitive  
220 exclusion or facilitation within species would result in the same species being observed.  
221 Therefore, the results of intra-specific interactions always results in the same species  
222 being observed and a resulting  $D_{ii} = 0$ . In the context of these networks, asymmetry and  
223 positive/negative valued connections are distinct quantities. In-coming and out-going  
224 connections can be interpreted as “influenced by” and “influenced”, respectively; while  
225 positive and negative should be seen as one species increasing or decreasing, respectively,  
226 the probability of another species' occurrence.

## 227 **Analyses, Software and Data**

228 To quantify the structural variation of lichen networks we calculated several metrics at  
229 both the level of node and whole networks. Although there are many other metrics, for  
230 the sake of simplicity we focus on a subset that represent the primary interesting features  
231 of network structure (see Lau et al. (2017)). We calculated the number of interactions or  
232 “links” in each network (degree), which provides a measure of the size of the network  
233 (Lau et al., 2016a; Borrett and Lau, 2014). We also calculated the centralization of each  
234 network using Freeman's centrality, which measures the evenness of the distribution of  
235 interactions among the species in the network, using the `sna` package (Butts, 2019).  
236 In a network with low centralization species have similar strengths and numbers of  
237 interactions. A network with high centralization tends to have one or small number  
238 of species that interact with other species. We used a related function to calculate  
239 the centrality of each species (i.e., node level centrality) in each network as well. To  
240 calculate separate metrics for positive and negative links, as the networks contained not  
241 only positive and negative connections but also directional connections (both in-coming  
242 and out-going), we calculated the same network metrics for all combinations of these  
243 types of connections using recently developed methods for signed, weighted and directed  
244 networks (Everett and Borgatti, 2014) using the `signnet` package (Schoch, 2020).

We used a combination of parametric and non-parametric, permutation based frequentist statistical analyses to test for the effects of genetic variation on lichen communities and their interaction networks. To assess the effect of genotype on univariate responses, we used additive, random effects models with Restricted Maximum Likelihood (REML). We used a combination of Least Squares Regression, Analysis of Variance (ANOVA) and correlation tests to quantify and test for the relationship among other variables. Bark roughness, lichen cover and species richness were square-root transformed to meet the assumptions of homogeneity of variance and normality for these tests.

For multivariate response variables, such as lichen community composition and network structure, we used distance based multivariate statistical approaches, including Permutational Analysis of Variance (PERMANOVA) and Mantel tests. To quantify the similarity of lichen networks among individual trees, we calculated the pairwise Euclidean distance of the **D** interaction matrices among all pairs of trees. For visualization of multivariate patterns, we used Non-metric Multi-Dimensional Scaling (NMDS) (Goslee and Urban, 2007) to produce dimensionally reduced ordinations of these multivariate responses and fitted vectors for continuous predictor variables to the ordinated values (Oksanen et al., 2019). Using random initial configurations with a maximum of 500 iterations and a change in stress threshold of less than  $10^{-12}$ . This was repeated for one to four dimension configurations, and the configuration with the lowest dimensionality and unexplained variation less than 10% was selected.

For all tests where genotype was used as a predictor, we quantified the heritability of the response variable. Because the trees in the garden were clonal replicates of each genotype, we calculated broad-sense heritability, which is the genotypic variance divided by the total phenotypic variance (Conner and Hartl, 2004). This can be interpreted as a measure of the phenotypic variance due to genotypic variation.

All analyses were conducted using R version 3.6.1 (R Development Core Team 2019). Code and data for the project are openly available as a reproducible workflow using drake (Landau, 2018), which is archived via Zenodo zenodo.com/doiXXXXXX.

## RESULTS

In support of our first hypotheses, we found that tree genotype influenced lichen network structure and that multiple lichen network metrics were heritable. Tree genotype significantly predicted the structural similarity of lichen networks and, overall, network-level metrics responded significantly to tree genotype, including network degree and centralization including both in-coming and out-going links or when separated into in-coming only or out-going only (Table 1, Fig. 4). Metrics including only positive links also showed a significant effect of tree genotype, including positive degree and positive in-going centralization. Metrics calculated with negative links were not significant, including degree (negative) and both in-coming (negative) and out-going centralization (negative).

The genetic response of network centralization was driven by variation in *Athallia holocarpa*. Centrality varied significantly among species ( $F_{8,324} = 7.99$ ,  $R^2 = 0.16$ ,  $p\text{-value} < 0.0001$ ). *Athallia holocarpa* centrality was the main species to exhibit a significant response to tree genotype in terms of positive centrality for both the in-coming ( $RLRT = 3.61$ ,  $H^2 = 0.32$ ,  $p\text{-value} = 0.0240$ ) and out-going ( $RLRT = 3.13$ ,  $H^2$

Response	df	RLRT	H <sup>2</sup>	p-value
Lichen Network Similarity	9	3.5821	0.41	0.0537
Degree	9	3.5175	0.32	0.0255
Degree (positive)	9	3.6925	0.32	0.0229
Degree (negative)	9	0.0327	0.03	0.3859
Centralization	9	4.0444	0.33	0.0184
Centralization In-Degree	9	4.4812	0.35	0.0142
Centralization In-Degree (positive)	9	3.9852	0.33	0.0190
Centralization In-Degree (negative)	9	0.3304	0.11	0.2508
Centralization Out-Degree	9	3.8615	0.32	0.0205
Centralization Out-Degree (positive)	9	3.5585	0.31	0.0248
Centralization Out-Degree (negative)	9	0.0862	0.05	0.3446

**Table 1.** Genotypic effects on the associated lichen network structure. *RLRT* is the statistic from the restricted likelihood ratio tests.

= 0.30, *p-value* = 0.0327) perspectives, but not for either negative centrality metrics in-coming (*RLRT* = 0,  $H^2$  = 0, *p-value* = 1) or out-going (*RLRT* = 0,  $H^2$  = 0, *p-value* = 0.4543). None of the other species' centralities showed a genotypic response (Supporting Information, Fig. 2) with the exception of *X. montana* (*RLRT* = 2.92,  $H^2$  = 0.32, *p-value* = 0.0375); however, the centrality of *X. montana* was much lower overall relative to *A. holocarpa* and the variation in *X. montana* centrality was restricted to two genotypes (Fig. 5).

In support of our second hypothesis, analysis of trait covariation revealed that genotype indirectly influenced lichen network centralization via genetically based variation in bark roughness. The percent cover of rough bark (*RLRT* = 4.8526,  $H^2$  = 0.3221, *p-value* = 0.0113) and condensed tannins (*RLRT* = 3.0522,  $H^2$  = 0.3205, *p-value* = 0.0343) both displayed significant responses to tree genotype. None of the other bark traits, pH (*RLRT* = 0.00,  $H^2$  = 0.00, *p-value* = 1.0000) or carbon-nitrogen ratio (*RLRT* = 0.0000,  $H^2$  = 0.0000, *p-value* = 1.0000), showed a significant response to tree genotype and none other than bark roughness was correlated with network similarity (Table 2); therefore, we focused our subsequent analyses on the indirect effect of genotype on lichen network structure via bark roughness. We found that bark roughness was significantly correlated with network similarity and other lichen network metrics, including negative correlations with overall network degree (*df* = 35, *t* = -2.13, *r* = -0.34, *p-value* = 0.04) and centralization (*df* = 35, *t* = -2.52, *r* = -0.39, *p-value* = 0.02). In other words, trees with more similar levels of bark roughness tended to have lichen interaction networks with similar structure. To quantify the genetic bases of this effect of bark roughness on network structure, we used the residual values from regressions of network degree and centralization in tests of the effect of tree genotype and found no significant effect of tree genotype for either degree (*RLRT* = 0.00,  $H^2$  = 0.00, *p-value* = 1.0000) or centralization (*RLRT* = 0.00,  $H^2$  = 0.00, *p-value* = 1.0000), suggesting that the observed relationship between bark roughness and lichen network structure was largely genetically based (Fig. 6).

	df	SS	R <sup>2</sup>	Pseudo-F	p-value
Bark Roughness	1	20850.09	0.26	12.9234	0.0101
Condensed Tannins	1	5993.66	0.07	3.7150	0.0813
pH	1	1273.19	0.02	0.7892	0.3712
Carbon:Nitrogen Ratio	1	3896.18	0.05	2.4150	0.1890
Residual	32	51627.33	0.64		
Total	36	80993.59	1.00		

**Table 2.** PERMANOVA Pseudo-*F* Table of lichen network similarity response to bark traits.

## 317 DISCUSSION

318 We found support for both of our hypotheses. First, tree genotype influenced the network  
 319 structure of lichen communities associated with narrowleaf cottonwoods in a riparian  
 320 forest ecosystem. Network similarity and metrics of network structure tended to be more  
 321 similar on trees of the same genotype. Generally, this genetic effect was manifested  
 322 in positive interactions and largely driven by *A. holocarpa*. Second, the genetically  
 323 based trait, bark roughness, was observed to affect network variation, largely via shifts  
 324 in positive in-coming and out-going interactions. Chemistry traits, whether genetically  
 325 based (e.g., tannin concentration) or not, were not significantly correlated with lichen  
 326 network structure. Bark roughness has been demonstrated previously to be under strong  
 327 genetic control (Bdeir et al., 2017), and bark roughness has also been shown to be an  
 328 important tree trait influencing bark lichens (Lamit et al., 2015b); however this is the  
 329 first demonstration of a link from genetics to lichen network structure. As such, these  
 330 results have important implications for the influence of genetically based variation in  
 331 ecosystems with networks of interacting species.

## 332 Implications of Ecological Network Heritability

333 Significant heritability of lichen interaction network structure is in line with the genetic  
 334 similarity rule, networks observed on trees of the same genotype tended to be structurally  
 335 similar. Although previous studies have examined aspects of networks, such as trophic  
 336 complexity (Barbour et al., 2016) and forest stand-level interaction network structure  
 337 (Lau et al., 2016b; Keith et al., 2017), this is the first study that we are aware of to  
 338 examine the heritability of network structure with replicated networks at the genotype  
 339 scale. Previous work in the evolution of ecological networks have primarily focused on  
 340 macro-evolutionary dynamics (Rezende et al., 2007; Weber et al., 2017; Valverde et al.,  
 341 2018; Harmon et al., 2019) or have been simulation based individual-level models that  
 342 integrate intraspecific variation to the species level (Maliet et al., 2020), even though  
 343 recent syntheses have pointed to the importance of processes operating across scales of  
 344 organization (Guimarães, 2020). There are two important functional ramifications of  
 345 genetically based variation in network structure.

346 First, heritability of network structure suggests that some amount of interaction  
 347 network complexity is determined and therefore could be predicted by genetic identity.  
 348 Variation in space and time create variation in ecological networks that influences evolu-  
 349 tionary dynamics via shifts in ecological dynamics, such as population demographics

(Guimarães, 2020). Given that ecosystems are comprised of hundreds and thousands of species, each having a multitude of interactions, the potential to find traction for making predictions in the context of ecological, let alone evolutionary, dynamics seems daunting. The promise of predictability lies in the presence of asymmetries in ecosystems, such as hierarchy created by foundation species via differences in body size and/or life-history strategies (Ellison et al., 2005). The second is that heritability (i.e., genetic determination) means that there is structure in the spatial or temporal variation that is created by individuals of foundation species whose traits are in part determined by underlying trait differences. Although this variation is inherently a function of both genetic and environmental effects (Conner and Hartl, 2004), the community and network-level effects are also a function of the scale of the interaction (Shuster et al., 2006).

Second, even if the composition of the communities is the same among individuals and genotypes, interactions may not be. We didn't observe compositional differences using the same data from which the lichen networks were derived. If we only had our composition dataset from this study, we would have concluded no response of the lichen community to tree genotype, even though the underlying interactions among lichen species does vary among genotypes. As such differences in network structure could occur without observable differences in species richness or community composition, which have been the primary focus of almost all previous community genetics studies (Des Roches et al., 2018). Community composition of lichens has previously been observed to be different among tree genotypes in the same experimental garden (Lamit et al., 2011, 2015b). The different results observed in the present study is likely a result of differences in lichen quantification and the tree genotypes observed leading to overall higher abundances of observed lichens to assure the possibility of observing lichen interactions. The previous study used a visual percent cover estimation, unlike the current study, which observed lichens at the scale of 1 cm<sup>2</sup> cells, which could over-estimate cover depending on the frequency at which actual thallus size was less than 1 cm<sup>2</sup>, as well as both the northern and southern aspects of each tree. These differences do not negate the findings of either study. The present study's finding of differences in network structure without significant compositional differences points to the importance of quantifying how network structure changes in response to genetic variation in order to fully understand evolutionary dynamics in complex communities. Having not observed a compositional effect of tree genotype without measuring the network structure could lead to the conclusion of no genetic effect on the community, even though differences in network structure are leading to altered, local evolutionary dynamics. It is possible that these underlying differences in interactions among lichens could lead to differences in community composition at a future point in time via their effects on species abundances (Shuster et al., 2006); however, this is not needed for evolutionary dynamics to occur via selection that leads to shifts in trait distributions without shifting species abundance distributions, which is possible under stabilizing, disruptive and directional selection (Conner and Hartl, 2004), so long as the relative abundances of each species is imperceptibly changed. Thus, it is imperative that further community genetics research assess or at least be aware of the potential effects of variation in interactions and not just observe species abundances, otherwise community level genetic effects may be underestimated, especially when cumulative interaction effects are taken into account (Borrett et al., 2007).

Furthermore, the demonstration of the heritability of interaction networks, without significant differences in community composition, provides clear empirical evidence that variation in network structure points to the need to expand IIGEs to encompass the structure of interaction networks. Although IIGE theory provides a quantitative framework within which to approach evolutionary theory at higher levels of biological organization (from populations to communities and ecosystems), this theory has focused on modeling the strong effects of foundation species (Shuster et al., 2006; Whitham et al., 2012, 2020) and has not yet integrated developments from the ecological or evolutionary network theory literature. Thus, it has not developed a way to examine complex interactions among species; however, previous studies have demonstrated this network context is likely to be important, as altering the structure of interaction networks provides a means for genetic effects to be dampened or magnified within the system of interacting species Smith et al. (2011); Keith et al. (2017). Although such a synthesis necessitates a much greater effort than can be afforded in this paper, it is possible to point to several productive pathways forward. In terms of interaction networks, foundation species are relatively central within the system of interactions, that is their direct and/or indirect effects are greater than other species. So, when the more centralized (foundation) species have genetically based interactions, genetic effects will tend to be propagated and possibly magnified in the community. Here, we found that even though more abundant or more centralized (i.e., “important”) species were present in the community, their effects were not the main component responding to genetic effects. Considering the impact of network structure would be a productive path forward for the theoretical development and application of the IIGE concept.

#### **Evolution and Genetically Based Network Structure**

The demonstration of evolution at any scale of biological organization requires demonstrating three key elements. First, there must be variation in the structure (composition, abundance, species interactions, diversity, networks) of communities across the landscape. Second, these differences must be genetically based and heritable in which community structure is passed from one generation to the next. For example, numerous studies show that related individuals tend to support the same communities of insects and microbes, and ecosystem processes of biodiversity, nutrient cycling and stability, whereas unrelated individuals support more different communities and ecosystem processes (Des Roches et al., 2018; Whitham et al., 2020). Importantly, the current study shows that networks are also heritable traits that greatly increase its utility as a community phenotype that selection can act upon. Third, selection must act on these differences to favor some communities over others leading to change over time (i.e., community evolution). Since our findings show that networks are heritable, another metric of community evolution is showing how networks change over time in response to an invasive species, climate change, or some other agent of selection.

Intra-specific, genotypic diversity could be creating lichen metacommunities on individual trees that form interaction modules with different dynamics. When communities are comprised of individuals whose habitat is primarily determined by another organism, these communities inherently form modules within the larger ecosystem, as they tend to interact more with each other than with other individuals (Lau et al., 2017). Our study demonstrates that the environmental differences determined by the genetic

441 variation within a single species can create differences that not only impact community  
442 composition, as repeatedly demonstrated in other community genetics studies (Whitham  
443 et al., 2006; Des Roches et al., 2018), but also the structure of interactions among  
444 individuals within these modules. Some network structures are likely to be more stable,  
445 either in response to disturbance or via self-organized dynamics. For example, central-  
446 ized networks, although more efficient, are theorized to be more susceptible to targeted  
447 “attacks” in the terminology of defense networks. As mentioned previously, one class  
448 of networks that are theorized to have amplifying effects on networks have centralized  
449 “star” shapes with one or a few species at the center and radiating interactions out from  
450 the central core (Lieberman et al., 2005). This is structurally what we have observed  
451 with the networks that tend to occur on some of the genotypes in our study, i.e., the  
452 more centralized networks. It is likely that these networks could function as hot-spots  
453 of evolutionary dynamics resulting from the amplifying effect the centralized network  
454 structure found on that tree genotype, as multiple studies have found significant impacts  
455 of the removal of foundation species in different systems (Keith et al., 2017; Des Roches  
456 et al., 2018).

457 Ecological network studies have focused on asymmetry and the quantification of  
458 its structure in communities. The impacts of asymmetry on evolution from community  
459 dynamics have primarily produced qualitative discussion (Bascompte et al., 2006;  
460 Díaz-Castelazo et al., 2010; Guimarães et al., 2011; Thompson, 2013). More specific  
461 predictions can be found in applications of evolutionary game theory, and although  
462 developed at the population scale, such theory can apply to communities (Lieberman  
463 et al., 2005). One seemingly useful direction is the classification of networks into two  
464 general categories, rooted and cyclic, in which rooted networks have interactions in  
465 which evolutionary effects emanate from one or multiple origins but these effects do  
466 not have feedbacks to the origin, whereas cyclic networks contain feedbacks to one or  
467 more origins. This is equivalent to “unidirectional” and “reciprocal” genetic effects in  
468 the context of IIGE theory (Whitham et al., 2020). As we do not have an estimate of the  
469 effect of the lichen on the fitness of the tree they occur on, we can not determine whether  
470 the lichen networks in this system are cyclic or not. In terrestrial ecosystems, lichen  
471 play important ecological roles, such as substrate stabilization (Root et al., 2011) and  
472 nitrogen fixation (Nelson et al., 2018). Some epiphytic lichens can have demonstrable  
473 effects on the availability of nutrients for the trees that they are associated with (Norby  
474 and Sigal, 1989). Although none of the lichens the present study’s system is known to  
475 fix nitrogen, it is possible that they might add micro-nutrients or provide some other  
476 un-observed benefit to their host trees. Elucidating the presence of and quantifying  
477 such feedbacks would allow for the determination of the cyclic nature and potential  
478 evolutionary dynamics.

479 Since lichen individuals are multi-species complexes, there is also the potential  
480 for evolutionary dynamics to shift within the context of the lichen symbiosis. There  
481 is substantial evidence that lichen have served as the “cradle of symbiotic fungal  
482 diversification” (Arnold et al., 2009) and recent research has shown significant net-  
483 work structure of endolichenic fungi and lichen collected from across North America  
484 (Chagnon et al., 2016). Analysis of the structure of ecological networks has generally  
485 supported the conclusion that nestedness, or the degree to which species tend to inter-  
486 act with similar subsets of the community, tends to promote stability in mutualistic,

487 primarily bipartite (i.e., two-mode), networks and modularity contributes to the stabi-  
488 lization of antagonistic networks (Elias et al., 2013; Grilli et al., 2016). Although there  
489 is growing evidence that the nestedness of mutualistic networks is not necessarily the  
490 result of selection for systems-level properties that promote stability but could be either  
491 product of asymptotic abundance distributions leading to uneven interaction frequencies  
492 (Staniczenko et al., 2013) and/or a by-product of selection and divergence creating  
493 network “spandrels” in ecosystems (Valverde et al., 2018), this does not preclude the  
494 functional consequences of network structure but rather the developmental or evolu-  
495 tionary processes that have produced the structure. In the present study, we did not  
496 examine nestedness or modularity of the lichen networks as we could not find metrics for  
497 analyzing networks that are not only weighted and directed but also signed. Hopefully  
498 future network theoretic developments will make the appropriate metrics available to  
499 conduct these analyses.

500 **Conclusion**

501 In the face of the high degree of complexity and potential context dependency of  
502 ecological processes, the current study points to the utility of considering the spatial and  
503 temporal scales of interactions, as discussed in previous studies (Bangert et al., 2006;  
504 Zook et al., 2010; Zytynska et al., 2012). In the present research, we found that the  
505 assembly of ecological networks can have a measurable genetic basis depending on  
506 the spatial scale of interactions, due in part, to asymmetries in size and longevity of  
507 organisms. The importance of the scale of network organization to create hierarchical  
508 structure (Guimarães, 2020) and the potential for foundation species to create this  
509 structure in the vast majority of ecosystems (Ellison et al., 2005; Whitham et al., 2006)  
510 suggests that future work would be aided by determining these modules within the biotic  
511 community that include species with large differences in body-size and longevity. Also,  
512 as heritable variation is the raw material for natural selection to act upon, a genetic basis  
513 for interaction network structure indicates evolutionary dynamics should be considered  
514 at the community level and that conserving genetic variation is important to consider in  
515 efforts to restore or preserve complex species interactions and their associated ecosystem  
516 functions (Evans et al., 2013).

517 One possible path forward is for future work to extend the many previous community  
518 genetics studies that have focused on sessile organisms, such as galling insects (Bailey  
519 et al., 2005; Whitham et al., 2006; Crutsinger et al., 2014; Smith et al., 2011; Keith  
520 et al., 2017), to quantify the frequency of these interactions in the context of the larger  
521 community. This would provide an estimate of the relative impact of these focal, often  
522 termed foundation, species. In addition, community genetics theory has only quantified  
523 first order interactions, i.e., among pairs; therefore, indirect effects from higher order  
524 interactions are not explicitly accounted for (Shuster et al., 2006; Whitham et al., 2012,  
525 2020). Given that network structure could be influenced by genetic effects, assessing  
526 higher order interactions could provide a path forward for theoretical advances (e.g.,  
527 IIGEs) that could help with identifying important characteristics of sub-groups to focus  
528 on in empirical studies. That is, the combined interactions of communities of interacting  
529 species should be reflected in the differences of networks of individual plant genotypes  
530 and how they might differ across a landscape in which selection pressures change in  
531 response to local biotic and abiotic conditions, leading to the optimization of modules

under different selective pressures. Network modeling and analysis could prove useful for the identification of species within network modules that are most important to study in systems where little is known about the biology of the system. For example, in systems where background knowledge of the natural history of organisms is lacking, network analyses based on species occurrence and abundance direct researchers to species that could be focused on to best understand the dynamics of the system. Such investigations will bring us closer to understanding the evolutionary drivers of Darwin's entangled bank and the interconnectedness of species in complex communities (Darwin, 1859; Dátilo et al., 2016).

### Acknowledgments

This work was supported by the National Science Foundation grant (DEB-0425908) and Integrative Graduate Research Traineeship (IGERT) fellowships for M.L. and L.L. The Ogden Nature Center staff helped to maintain the common gardens. Lichen sampling was supported by Todd Wojtowicz, Luke Evans and David Solance Smith.

## REFERENCES

- Araújo, M. B., Rozenfeld, A., Rahbek, C., and Marquet, P. A. (2011). Using species co-occurrence networks to assess the impacts of climate change. *Ecography*, 34:897–908.
- Arnold, A. E., Miadlikowska, J., Higgins, K. L., Sarvate, S. D., Gugger, P., Way, A., Hofstetter, V., Kauff, F., and Lutzoni, F. (2009). A phylogenetic estimation of trophic transition networks for ascomycetous Fungi: Are lichens cradles of symbioticrophic Fungal diversification? *Systematic Biology*, 58(3):283–297.
- Bailey, J. K., Schweitzer, J. A., Ubeda, F., Koricheva, J., LeRoy, C. J., Madritch, M. D., Rehill, B. J., Bangert, R. K., Fischer, D. G., Allan, G. J., and Whitham, T. G. (2009). From genes to ecosystems: a synthesis of the effects of plant genetic factors across levels of organization. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 364(1523):1607–16.
- Bailey, J. K., Wooley, S. C., Lindroth, R. L., and Whitham, T. G. (2005). Importance of species interactions to community heritability: a genetic basis to trophic-level interactions. *Ecology Letters*, 0(0):051122062725008.
- Bangert, R. K., Turek, R. J., Rehill, B., Wimp, G. M., Schweitzer, J. A., Allan, G. J., Bailey, J. K., Martinsen, G. D., Keim, P., Lindroth, R. L., and Whitham, T. G. (2006). A genetic similarity rule determines arthropod community structure. *Molecular ecology*, 15:1379–1391.
- Barbour, M. A., Fortuna, M. A., Bascompte, J., Nicholson, J. R., Julkunen-Tiitto, R., Jules, E. S., and Crutsinger, G. M. (2016). Genetic specificity of a plant-insect food web: Implications for linking genetic variation to network complexity. *Proceedings of the National Academy of Sciences of the United States of America*, 113(8):2128–2133.
- Barbour, R. C., O'Reilly-Wapstra, J. M., Little, D. W. D., Jordan, G. J., Steane, D. A., Humphreys, J. R., Bailey, J. K., Whitham, T. G., Potts, B. M., De Little, D. W., Jordan, G. J., Steane, D. A., Humphreys, J. R., Bailey, J. K., Whitham, T. G., and Potts, B. M. (2009). A geographic mosaic of genetic variation within a foundation tree species and its community-level consequences. *Ecology*, 90(7):1762–1772.

- 575 Bascompte, J., Jordano, P., and Olesen, J. M. (2006). Asymmetric Coevolutionary  
576 Networks Facilitate Biodiversity Maintenance \r10.1126/science.1123412. *Science*,  
577 312:431–433.
- 578 Bdeir, R., Muchero, W., Yordanov, Y., Tuskan, G. A., Busov, V., and Gailing, O. (2017).  
579 Quantitative trait locus mapping of *Populus* bark features and stem diameter. *BMC  
580 Plant Biology*.
- 581 Borrett, S. R., Fath, B. D., and Patten, B. C. (2007). Functional integration of ecological  
582 networks through pathway proliferation. *Journal of Theoretical Biology*, 245(1):98–  
583 111.
- 584 Borrett, S. R. and Lau, M. K. (2014). enaR: An R package for Ecosystem Network  
585 Analysis. *Methods in Ecology and Evolution*, 5(11):1206–1213.
- 586 Busby, P. E., Lamit, L. J., Keith, A. R., Newcombe, G., Gehring, C. A., Whitham, T. G.,  
587 and Dirzo, R. (2015). Genetics-based interactions among plants, pathogens, and  
588 herbivores define arthropod community structure. *Ecology*, 96(7):1974–1984.
- 589 Butts, C. T. (2019). *sna: Tools for Social Network Analysis*. R package version 2.5.
- 590 Chagnon, P. L., U'Ren, J. M., Miadlikowska, J., Lutzoni, F., and Elizabeth Arnold,  
591 A. (2016). Interaction type influences ecological network structure more than local  
592 abiotic conditions: evidence from endophytic and endolichenic fungi at a continental  
593 scale. *Oecologia*, 180(1):181–191.
- 594 Conner, K. and Hartl, D. L. (2004). *A Primer of Ecological Genetics: a textbook*.  
595 Sinauer Associates, Inc., Sunderland, Massachusetts, 1st edition.
- 596 Crutsinger, G. M. (2016). A community genetics perspective: Opportunities for the  
597 coming decade. *New Phytologist*.
- 598 Crutsinger, G. M., Rudman, S. M., Rodriguez-Cabal, M. A., McKown, A. D., Sato,  
599 T., MacDonald, A. M., Heavyside, J., Gerald, A., Hart, E. M., LeRoy, C. J., and  
600 El-Sabaawi, R. W. (2014). Testing a ‘genes-to-ecosystems’ approach to understanding  
601 aquatic-terrestrial linkages. *Molecular Ecology*, 23(23):5888–5903.
- 602 Darwin, C. (1859). *On the Origin of Species*. Murray, London.
- 603 Dátilo, W., Lara-Rodríguez, N., Jordano, P., Guimarães, P. R., Thompson, J. N., Marquis,  
604 R. J., Medeiros, L. P., Ortiz-Pulido, R., Marcos-García, M. A., and Rico-Gray,  
605 V. (2016). Unravelling Darwin’s entangled bank: Architecture and robustness of  
606 mutualistic networks with multiple interaction types. *Proceedings of the Royal Society  
607 B: Biological Sciences*.
- 608 Des Roches, S., Post, D. M., Turley, N. E., Bailey, J. K., Hendry, A. P., Kinnison,  
609 M. T., Schweitzer, J. A., and Palkovacs, E. P. (2018). The ecological importance of  
610 intraspecific variation. *Nature Ecology and Evolution*, 2(1):57–64.
- 611 Díaz-Castelazo, C., Guimarães, P. R., Jordano, P., Thompson, J. N., Marquis, R. J., and  
612 Rico-Gray, V. (2010). Changes of a mutualistic network over time: Reanalysis over a  
613 10-year period. *Ecology*.
- 614 Elias, M., Fontaine, C., and Frank Van Veen, F. J. (2013). Evolutionary history and  
615 ecological processes shape a local multilevel antagonistic network. *Current Biology*,  
616 23(14):1355–1359.
- 617 Ellison, A. M., Bank, M. S., Clinton, B. D., Colburn, E. A., Elliott, K., Ford, C. R.,  
618 Foster, D. R., Kloeppe, B. D., Knoepp, J. D., Lovett, G. M., Mohan, J., Orwig,  
619 D. A., Rodenhouse, N. L., Sobczak, W. V., Stinson, K. A., Stone, J. K., Swan, C. M.,  
620 Thompson, J., Von Holle, B., and Webster, J. R. (2005). Loss of foundation species:

- consequences for the structure and dynamics of forested ecosystems. *Frontiers in Ecology and the Environment*, 3(9):479–486.
- Evans, D. M., Pocock, M. J. O., and Memmott, J. (2013). The robustness of a network of ecological networks to habitat loss. *Ecology letters*, 16:844–52.
- Everett, M. G. and Borgatti, S. P. (2014). Networks containing negative ties. *Social Networks*, 38(1):111–120.
- Gehring, C., Flores-Rentería, D., Sthultz, C. M., Leonard, T. M., Flores-Rentería, L., Whipple, A. V., and Whitham, T. G. (2014). Plant genetics and interspecific competitive interactions determine ectomycorrhizal fungal community responses to climate change. *Molecular Ecology*, 23(6):1379–1391.
- Gehring, C. A., Sthultz, C. M., Flores-Rentería, L., Whipple, A. V., and Whitham, T. G. (2017). Tree genetics defines fungal partner communities that may confer drought tolerance. *Proceedings of the National Academy of Sciences*.
- Gómez, J. M., Abdelaziz, M., Camacho, J. P. M., Muñoz-Pajares, A. J., and Perfectti, F. (2009). Local adaptation and maladaptation to pollinators in a generalist geographic mosaic. *Ecology Letters*, 12(7):672–682.
- Goslee, S. C. and Urban, D. L. (2007). The ecodist package for dissimilarity-based analysis of ecological data. *Journal of Statistical Software*, 22:1–19.
- Grilli, J., Rogers, T., and Allesina, S. (2016). Modularity and stability in ecological communities. *Nature Communications*, 7.
- Guimarães, P. R. (2020). The Structure of Ecological Networks Across Levels of Organization. *Annual Review of Ecology, Evolution, and Systematics*, 51(1).
- Guimarães, P. R., Jordano, P., and Thompson, J. N. (2011). Evolution and coevolution in mutualistic networks. *Ecology letters*, 14(9):877–85.
- Guimarães, P. R., Rico-Gray, V., Oliveira, P. S., Izzo, T. J., dos Reis, S. F., and Thompson, J. N. (2007). Interaction Intimacy Affects Structure and Coevolutionary Dynamics in Mutualistic Networks. *Current Biology*, 17(20):1797–1803.
- Harmon, L. J., Andreazzi, C. S., Débarre, F., Drury, J., Goldberg, E. E., Martins, A. B., Melián, C. J., Narwani, A., Nuismer, S. L., Pennell, M. W., Rudman, S. M., Seehausen, O., Silvestro, D., Weber, M., and Matthews, B. (2019). Detecting the macroevolutionary signal of species interactions. *Journal of Evolutionary Biology*, 32(8):769–782.
- Holeski, L. M., Hillstrom, M. L., Whitham, T. G., and Lindroth, R. L. (2012). Relative importance of genetic, ontogenetic, induction, and seasonal variation in producing a multivariate defense phenotype in a foundation tree species. *Oecologia*, 170:695–707.
- Johnson, M. T. J. (2008). Bottom-up effects of plant genotype on aphids, ants, and predators. *Ecology*.
- Keith, A. R., Bailey, J. K., Lau, M. K., and Whitham, T. G. (2017). Genetics-based interactions of foundation species affect community diversity, stability and network structure. *Proceedings of the Royal Society B: Biological Sciences*, 284(1854):20162703.
- Lamit, L., Bowker, M., Holeski, L., Næsborg, R. R., Wooley, S., Zinkgraf, M., Lindroth, R., Whitham, T., and Gehring, C. (2011). Genetically-based trait variation within a foundation tree species influences a dominant bark lichen. *Fungal Ecology*, 4(1):103–109.
- Lamit, L. J., Busby, P. E., Lau, M. K., Compson, Z. G., Wojtowicz, T., Keith, A. R., Zinkgraf, M. S., Schweitzer, J. A., Shuster, S. M., Gehring, C. A., and Whitham, T. G.

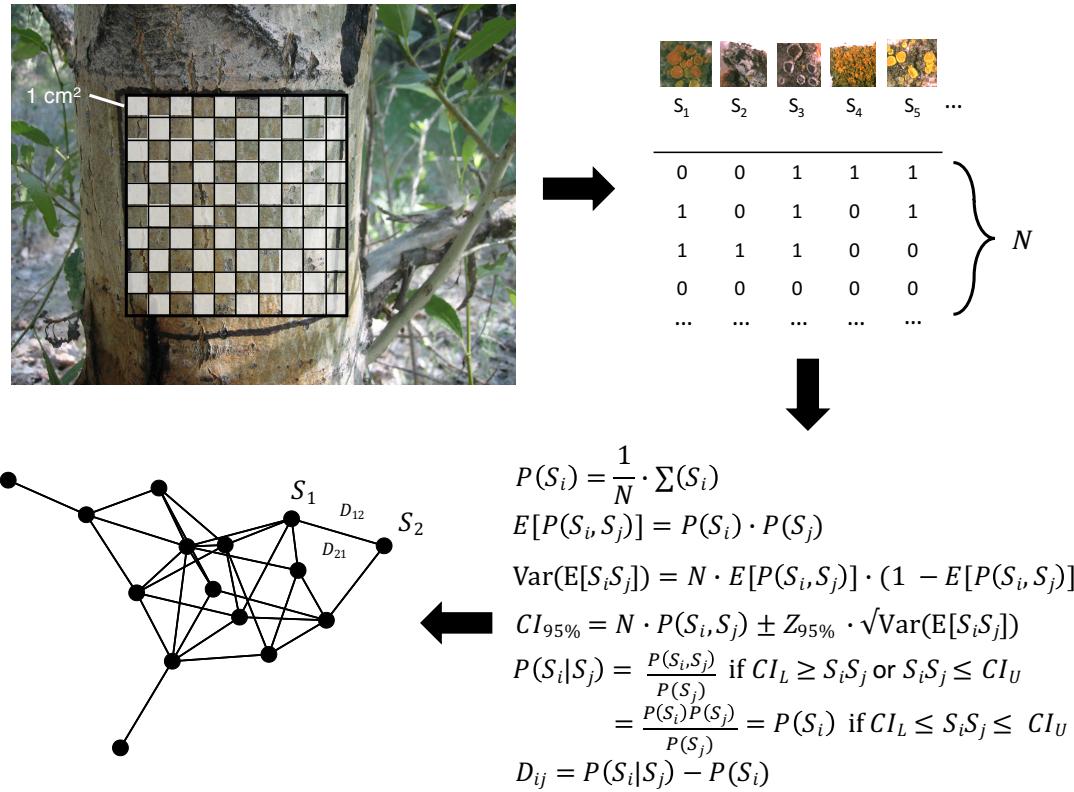
- 667 (2015a). Tree genotype mediates covariance among communities from microbes to  
668 lichens and arthropods. *Journal of Ecology*, 103(4):840–850.
- 669 Lamit, L. J., Lau, M. K., Næsborg, R. R., Wojtowicz, T., Whitham, T. G., and Gehring,  
670 C. A. (2015b). Genotype variation in bark texture drives lichen community assembly  
671 across multiple environments. *Ecology*, 96(4):960–971.
- 672 Landau, W. M. (2018). The drake r package: a pipeline toolkit for reproducibility and  
673 high-performance computing. *Journal of Open Source Software*, 3(21).
- 674 Lau, M. K., Borrett, S. R., Baiser, B., Gotelli, N. J., and Ellison, A. M. (2017). Ecological  
675 network metrics: opportunities for synthesis. *Ecosphere*, 8(8):e01900.
- 676 Lau, M. K., Keith, A. R., Borrett, S. R., Shuster, S. M., and Whitham, T. G. (2016a).  
677 Genotypic variation in foundation species generates network structure that may drive  
678 community dynamics and evolution. *Ecology*, 97(3):15–0600.
- 679 Lau, M. K., Keith, A. R., Borrett, S. R., Shuster, S. M., and Whitham, T. G. (2016b).  
680 Genotypic variation in foundation species generates network structure that may drive  
681 community dynamics and evolution. *Ecology*.
- 682 Lieberman, E., Hauert, C., and Nowak, M. A. (2005). Evolutionary dynamics on graphs.  
683 *Nature*, 433(7023):312–316.
- 684 Lieberman, E., Hauert, C., and Nowak, M. A. (2005). Evolutionary dynamics on graphs.  
685 *Nature*, 433(7023):312–316.
- 686 Maliet, O., Loeuille, N., and Morlon, H. (2020). An individual-based model for  
687 the eco-evolutionary emergence of bipartite interaction networks. *Ecology Letters*,  
688 23(11):1623–1634.
- 689 Martinsen, G. D., Whitham, T. G., Turek, R. J., and Keim, P. (2001). Hybrid populations  
690 selectively filter gene introgression between species. *Evolution*, 55(7):1325–1335.
- 691 Moya-Laraño, J. (2011). Genetic variation, predator-prey interactions and food web  
692 structure. *Philosophical transactions of the Royal Society of London. Series B,  
693 Biological sciences*, 366(1569):1425–37.
- 694 Nelson, P. R., McCune, B., Wheeler, T., Geiser, L. H., and Crisafulli, C. M. (2018).  
695 Lichen community development along a volcanic disturbance gradient at Mount St.  
696 Helens. In *Ecological Responses at Mount St. Helens: Revisited 35 years after the  
697 1980 Eruption*, pages 185–198. Springer New York.
- 698 Newman, M. E. J. (2006). Modularity and community structure in networks. *Proceedings  
699 of the National Academy of Sciences of the United States of America*, 103(23):8577–  
700 82.
- 701 Norby, R. J. and Sigal, L. L. (1989). Nitrogen fixation in the lichen *Lobaria pulmonaria*  
702 in elevated atmospheric carbon dioxide. *Oecologia*, 79(4):566–568.
- 703 Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin,  
704 P. R., O’Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoces, E., and  
705 Wagner, H. (2019). *vegan: Community Ecology Package*. R package version 2.5-6.
- 706 Poisot, T., Cirtwill, A. R., Cazelles, K., Gravel, D., Fortin, M., and Stouffer, D. B.  
707 (2016). The structure of probabilistic networks. *Methods in Ecology and Evolution*,  
708 7(3):303–312.
- 709 Rezende, E. L., Lavabre, J. E., Guimarães, P. R., Jordano, P., and Bascompte, J. (2007).  
710 Non-random coextinctions in phylogenetically structured mutualistic networks. *Nature*,  
711 448(7156):925–8.
- 712 Root, H. T., Miller, J. E. D., and McCune, B. (2011). Biotic soil crust lichen diversity

- 713 and conservation in shrub-steppe habitats of Oregon and Washington. *The Bryologist*,  
714 114(4):796.
- 715 Schoch, D. (2020). *signnet: An R package to analyze signed networks*.
- 716 Shuster, S. M., Lonsdorf, E. V., Wimp, G. M., Bailey, J. K., and Whitham, T. G. (2006).  
717 COMMUNITY HERITABILITY MEASURES THE EVOLUTIONARY CONSE-  
718 QUENCES OF INDIRECT GENETIC EFFECTS ON COMMUNITY STRUCTURE.  
719 *Evolution*, 60(5):991.
- 720 Smith, D. S., Bailey, J. K., Shuster, S. M., and Whitham, T. G. (2011). A geographic  
721 mosaic of trophic interactions and selection: trees, aphids and birds. *Journal of*  
722 *evolutionary biology*, 24(2):422–9.
- 723 Smith, D. S., Lamit, L. J., Lau, M. K., Gehring, C. A., Shuster, S. M., and Whitham,  
724 T. G. (2015). Introduced elk alter traits of a native plant and its plant-associated  
725 arthropod community. *Acta Oecologica*, 67:8–16.
- 726 Sole, R. and Bascompte, J. (2006). *Self-Organization in Complex Ecosystems*. Princeton  
727 University Press, Princeton, N.J.
- 728 Staniczenko, P. P., Kopp, J. C., and Allesina, S. (2013). The ghost of nestedness in  
729 ecological networks. *Nature Communications*, 4(1):1–6.
- 730 Thompson, J. N. (2013). *Relentless Evolution*. University of Chicago Press.
- 731 Toju, H., Guimarães, P. R., Olesen, J. M., and Thompson, J. N. (2014). Assembly of  
732 complex plant-fungus networks. *Nature Communications*.
- 733 Toju, H., Yamamichi, M., Guimarães, P. R., Olesen, J. M., Mougi, A., Yoshida, T., and  
734 Thompson, J. N. (2017). Species-rich networks and eco-evolutionary synthesis at the  
735 metacommunity level.
- 736 Toju, H., Yamamoto, S., Tanabe, A. S., Hayakawa, T., and Ishii, H. S. (2016). Network  
737 modules and hubs in plant-root fungal biomes. *Journal of the Royal Society Interface*.
- 738 Valverde, S., Piñero, J., Corominas-Murtra, B., Montoya, J., Joppa, L., and Solé, R.  
739 (2018). The architecture of mutualistic networks as an evolutionary spandrel. *Nature*  
740 *Ecology and Evolution*, 2(1):94–99.
- 741 Wade, M. J. (2007). The co-evolutionary genetics of ecological communities.
- 742 Weber, M. G., Wagner, C. E., Best, R. J., Harmon, L. J., and Matthews, B. (2017).  
743 Evolution in a Community Context: On Integrating Ecological Interactions and  
744 Macroevolution.
- 745 Whitham, T. G., Allan, G. J., Cooper, H. F., and Shuster, S. M. (2020). Intraspecific Ge-  
746 netic Variation and Species Interactions Contribute to Community Evolution. *Annual*  
747 *Review of Ecology, Evolution, and Systematics*, 51(1).
- 748 Whitham, T. G., Bailey, J. K., Schweitzer, J. A., Shuster, S. M., Bangert, R. K., LeRoy,  
749 C. J., Lonsdorf, E. V., Allan, G. J., DiFazio, S. P., Potts, B. M., Fischer, D. G.,  
750 Gehring, C. A., Lindroth, R. L., Marks, J. C., Hart, S. C., Wimp, G. M., and Wooley,  
751 S. C. (2006). A framework for community and ecosystem genetics: from genes to  
752 ecosystems. *Nature reviews. Genetics*, 7:510–523.
- 753 Whitham, T. G., Gehring, C. A., Lamit, L. J., Wojtowicz, T., Evans, L. M., Keith, A. R.,  
754 and Smith, D. S. (2012). Community specificity: Life and afterlife effects of genes.
- 755 Winfree, R., Gross, B. J., and Kremen, C. (2011). Valuing pollination services to  
756 agriculture. *Ecological Economics*, 71:80–88.
- 757 Zook, A. E., Eklof, A., Jacob, U., and Allesina, S. (2010). Food webs: Ordering species  
758 according to body size yields high degree of intervality. *Journal of theoretical biology*,

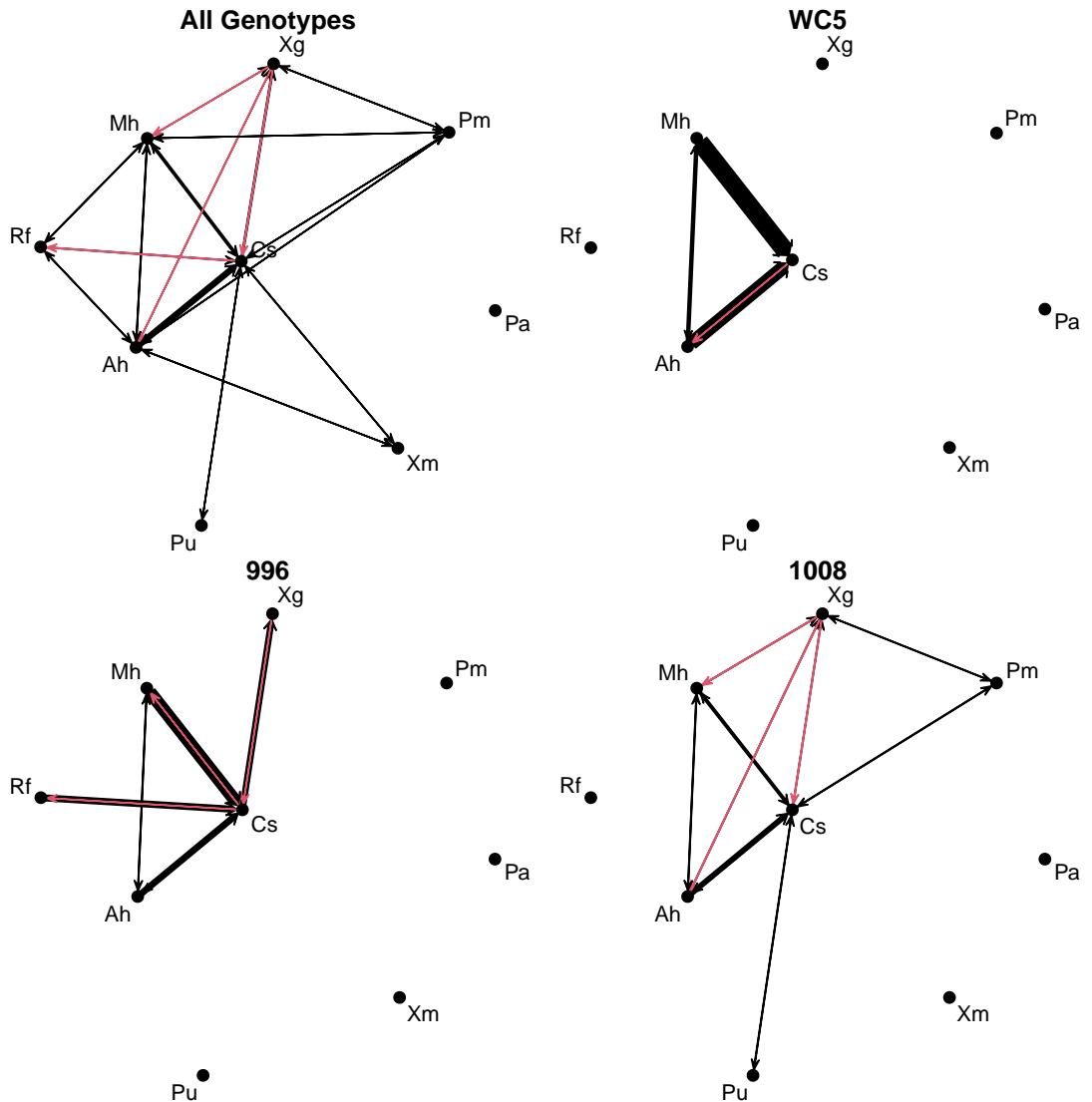
- 759 271(1):106–113.
- 760 Zytynska, S. E., Fay, M. F., Penney, D., and Preziosi, R. F. (2011). Genetic variation  
761 in a tropical tree species influences the associated epiphytic plant and invertebrate  
762 communities in a complex forest ecosystem. *Philosophical transactions of the Royal  
763 Society of London. Series B, Biological sciences*, 366:1329–1336.
- 764 Zytynska, S. E., Khudr, M. S., Harris, E., and Preziosi, R. F. (2012). No Title. *Oecologia*,  
765 170(2).



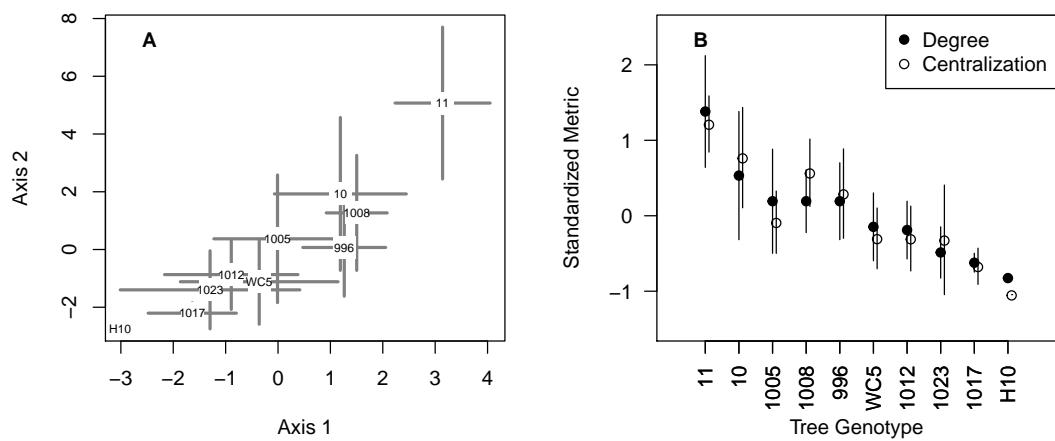
**Figure 1.** The communities of bark lichens were observed in a common garden of replicated genotypes of narrowleaf cottonwood trees (*P. angustifolia*) at the Ogden Nature Center (Ogden, UT). (A) Lichens were sampled within a fixed area ( $100 \text{ cm}^2$ ) on individual trees at two heights, 50cm and 95cm from the ground. (B-I) Close-up photos show the other lichen species observed, respectively: *Xanthomendoza montana*, *Candelariella subdeflexa*, *Rinodina freyi*, *Athallia holocarpa*, *Physcia adscendens*, *Physciella melanchra*, *Physcia undulata* and *Myriolecis hagenii*. Photo Credits: L.J. Lamit (B-D) and R. Reese Næsborg (E-I).



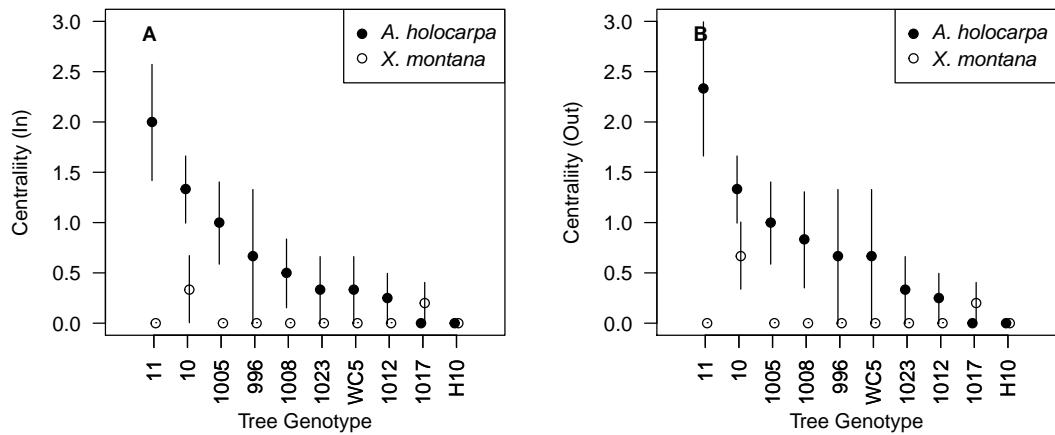
**Figure 2.** Lichen interaction networks were constructed by conducting field observations in  $1 \text{ cm}^2$  cells within a  $100 \text{ cm}^2$  grid on each tree using a checkerboard pattern (grey cells). Thus, a set of  $N$  total cell observations were recorded for each tree with the presence or absence of each species recorded for each cell. Applying the probability-based network modeling method adapted from (Araújo et al., 2011), we calculated the conditional probabilities,  $P(S_i | S_j)$ , for all species pairs and removed (i.e., set equal to zero) species pairs whose joint probabilities,  $P(S_i S_j)$ , were not significant using a confidence interval based comparison of their observed co-occurrence frequency,  $S_i S_j$ , to that expected due to chance alone,  $E[P(S_i S_j)] = P(S_i) P(S_j)$ , and  $P(S_i | S_j)$  reduces to  $P(S_i)$ , the observed individual probability of species  $S_i$ .



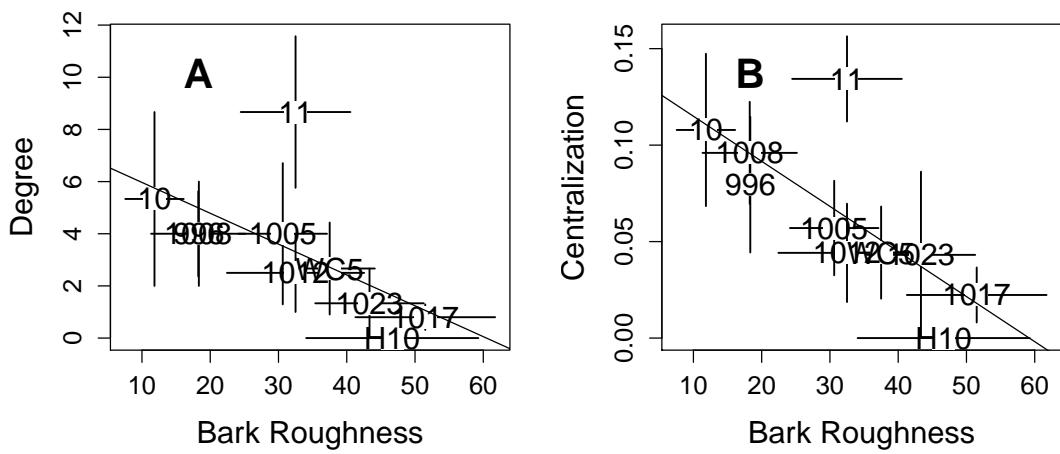
**Figure 3.** Lichen networks varied in structure among tree genotypes. Network diagrams of the mean lichen interaction matrices averaged for all trees and for illustrative genotypes (996, WC5 and 1008) showing a range of interaction network structure. Directionality (arrowheads) and sign (red = negative, black = positive) of interactions are shown as edges between species, which are scaled by their magnitude. Species names are abbreviated by the first letter of the genus and specific epithet: Ah = *Athallia holocarpa*, Cs = *Candelariella subdeflexa*, Mh = *Myriolecis hagenii*, Rf = *Rinodina freyi*, Pa = *Physcia adscendens*, Pm = *Physciella melanachra*, Pu = *Physcia undulata*, Xg = *Xanthomendoza galericulata*, Xm = *Xanthomendoza montana*. The sign of the interaction is indicative of greater (positive) or lesser (negative) paired occurrences than expected relative to the overall frequency of occurrence of each species. Ecologically, the links in the network are likely the product of multiple types of interactions (e.g. mutualism, parasitism, competition, facilitation) that could vary over both space and time.



**Figure 4.** The similarity of lichen networks varied among tree genotypes. A. The plot shows genotype centroids of NMDS ordinated ( $R^2 = 0.999$ , stress = 0.008) lichen network similarity ( $\pm 1$  S.E.). Genotype centroids that are closer together tend to have more similar lichen network structure. Arrows showing the direction (arrowhead) and magnitude (length) of the vectors of correlation between bark roughness (BR) and network centralization (Cen) and the ordinated network similarity. B. Plot showing the standardized ( $\frac{x-\bar{x}}{\sigma}$ ) means ( $\pm 1$  S.E.) for the two of the genetically based lichen network metrics: overall degree (i.e., total number of links) and centralization, which is a measure of the dominance of one species in the network.



**Figure 5.** Dot-plots showing the mean (dot) and  $\pm 1$  SE of in-degree (A) and out-degree (B) centrality for two species, *A. holocarpa* and *X. montana*. *Caloplaca holocarpa* centrality was highly variable among genotypes. *Xanthomendoza montana* centrality, both in- and out-degree, was only non-zero for two genotypes, and only out-degree centrality displayed a significant response to genotype.



**Figure 6.** Bivariate plots of the negative relationship between bark roughness and two network metrics: A) degree and B) centralization. Each plot displays the genotype mean ( $\pm 1$  S.E.) for both variables and a least-squares regression line calculated using the genotype means. Generally, as roughness increased the number of interactions (degree) and dominance of those interactions (centralization) decreased.