

1 Genotypic variation in a foundation tree 2 results in heritable ecological network 3 structure

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20 ABSTRACT

Elucidating the genetic basis to ecological network structure is fundamental to understanding evolution in complex ecosystems. 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 lichens 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 (Fath and
45 Patten, 1998; Newman, 2006; Sole and Bascompte, 2006), and other studies have demon-
46 strated that indirect effects of interactions among species can lead to network structures
47 that amplify or dampen the effects of selection, such as the formation of star-like struc-
48 tures in which there is a “central” species or group of species that interact with other
49 peripheral species can amplify selection events (Lieberman et al., 2005). Also, work by
50 Toju et al. (2014, 2016, 2017) observed consistent patterns of centralized interactions of
51 species modules (i.e., groups of species that interact more strongly within their group
52 than with other species) focused around hubs of plant-fungal interactions. In other words,
53 a small number of plant and fungal symbionts tended to have disproportionate numbers
54 of interactions with other species and likely are the drivers in determining community
55 assembly, structure and dynamics. Interspecific indirect genetic effects (IIGE) theory
56 (*sensu* Shuster et al. (2006)) in evolutionary biology also point to the importance of
57 studying the genetics of interaction network structure. Genetically based differences in
58 network structure among individuals can be acted upon by natural selection when there
59 are fitness consequences of different networks of IIGEs, leading to community evolution
60 per Whitham et al. (2020) and, by extension, network evolution. For example, although
61 the analysis was of abundances rather than interaction networks, Gehring et al. (2014,
62 2017) found that the mycorrhizal communities on the roots of drought tolerant and intol-
63 erant trees are dominated by different orders of ectomycorrhizal fungal mutualists that
64 also differ in the benefits they provide that enhance tree performance. Because drought
65 tolerant genotypes are three times more likely to survive record droughts, selection acts

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

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

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

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 Lichens and Trait Observations

On each tree, presence or absence of each lichen species was assessed in 50 total 1 cm² cells arrayed in a checkerboard pattern. Given the small size and sessile nature of lichens,

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

165 The cell size and checkerboard sampling pattern was chosen to isolate the individuals
166 in each cell. *Xanthomendoza galericulata* thallus size in this common garden, we had
167 observed a median thallus size of $0.12 \pm 0.001\text{ cm}^2$ (1 S.E.) (Supporting Information,
168 Fig. 1). Based on the median thallus size, we expected thalli observed in each cell to
169 generally be spatially independent of thalli present in other cells but exposed to similar
170 micro-environmental conditions created by the bark and the location of the sampling area
171 on an individual tree. Therefore, we were confident in treating the cell-wise observations
172 in quadrats as independent with respect to lichen-lichen interactions. We quantified
173 the texture of the bark in the quadrat is the percent of 1 cm^2 cells with rough bark. In
174 addition to bark roughness, we also examined several bark chemistry traits by taking
175 bark samples immediately adjacent to each quadrat. We used previously collected
176 phytochemical data from Lamit et al. (2011), including the concentration of condensed
177 tannins, carbon and nitrogen. Additionally, we quantified bark pH for each tree using
178 bark collected adjacent to quadrats, to a depth of 2 mm. Bark pieces were air dried and
179 crushed with a mortar and pestle until all pieces were $<0.5\text{ cm}$ in diameter to homogenize
180 the size of bark samples, creating equivalent surface areas. For each sample, 0.5 g of
181 crushed bark was placed in a 15 ml Falcon collection tube with 5 ml of deionized water.
182 Tubes were capped and let sit for 24 hrs prior to pH measurement. **Collection date?**
183 **pH instrument?**

184 Lichen Network Modeling

185 For each tree, repeated observations of lichens were made in order to construct replicated
186 interaction networks for each genotype. We conducted a modified sampling procedure
187 originally developed by Lamit et al. (2015b) with the addition that we quantified the
188 presence of lichens in the 1 cm^2 cells on individual trees of *P. angustifolia*. Unipartite
189 networks were generated using the conditional probabilities of each species pair, i.e., the
190 probability of observing one species given an observation of another species $P(S_i|S_j)$,
191 based on the method developed by Araújo et al. (2011). To calculate conditional
192 probabilities, we quantified the individual probabilities of species occurrences $P(S_i)$ and
193 the joint probability of co-occurrences $P(S_i, S_j)$ using the frequencies of each species
194 and their co-occurrences. We were then able to calculate the conditional probabilities of
195 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
196 a matrix that could possibly be asymmetric, i.e., $P(S_i|S_j)$ does not have to be equal to
197 $P(S_j|S_i)$. Another important property of this matrix is that the diagonal, $P(S_i|S_i)$, was
198 equal to one for all species present and zero for species that were not observed in any
199 cell.

200 We then applied an analytical procedure to remove non-significant links between
 201 species. This procedure determines if the joint probability of a species pair (i.e., $P(S_i, S_j)$)
 202 is different from zero (Fig. 2). Here, a confidence interval $CI_{95\%}$ is calculated as as
 203 $CI_{95\%} = E[S_iS_j] * Z_{95\%} * \sqrt{V(S_iS_j)}$, where the expected frequency of co-occurrences
 204 $E(S_iS_j)$ is the total number of cells surveyed (N) times the independent probabilities of
 205 each species $P(S_i) * P(S_j)$, $Z_{95\%}$ is the Z-score for 95% from a Z-distribution and the
 206 expected variance of $E(S_iS_j)$ is the total number of cells times the expected probability
 207 of S_iS_j and its compliment (i.e., $V(S_iS_j) = N * E[P(S_i, S_j)] * (1 - E[P(S_i, S_j)])$). If
 208 the observed number of co-occurrence falls outside of the confidence interval, the
 209 joint probability $P(S_i, S_j)$ is determined to be equal to the product of the individual
 210 probabilities (i.e., $P(S_i)P(S_j)$), and the conditional probability reduces to the individual
 211 probability of that species $P(S_i)$. Therefore, unless the co-occurrence of a species pair
 212 falls outside the confidence interval, the probability that the observation of one species
 213 given the other is no different than simply observing that species alone. This enables us
 214 to remove links from a given network by re-scaling the resulting conditional probabilities
 215 through subtraction of the individual probabilities from the conditional probabilities (i.e.,
 216 how different the conditional probability is from the independent probability), which
 217 makes any species with a non-significant conditional probability zero.

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

232 Analyses, Software and Data

233 To quantify the structural variation of lichen networks we calculated several metrics at
 234 both the level of node and whole networks. Although there are many other metrics, for
 235 the sake of simplicity we focus on a subset that represent the primary interesting features
 236 of network structure (see Lau et al. (2017)). We calculated the number of interactions or
 237 “links” in each network (degree), which provides a measure of the size of the network
 238 (Lau et al., 2016a; Borrett and Lau, 2014). We also calculated the centralization of each
 239 network using Freeman's centrality, which measures the evenness of the distribution of
 240 interactions among the species in the network, using the sna package (Butts, 2019).
 241 In a network with low centralization species have similar strengths and numbers of
 242 interactions. A network with high centralization tends to have one or small number
 243 of species that interact with other species. We used a related function to calculate
 244 the centrality of each species (i.e., node level centrality) in each network as well. To

245 calculate separate metrics for positive and negative links, as the networks contained not
246 only positive and negative connections but also directional connections (both in-coming
247 and out-going), we calculated the same network metrics for all combinations of these
248 types of connections using recently developed methods for signed, weighted and directed
249 networks (Everett and Borgatti, 2014) using the `signnet` package (Schoch, 2020).

250 We used a combination of parametric and non-parametric, permutation based frequentist
251 statistical analyses to test for the effects of genetic variation on lichen communities
252 and their interaction networks. To assess the effect of genotype on traits as univariate
253 response variables (including the metrics of network structure), we used additive, random
254 effects models with Restricted Maximum Likelihood (REML) conducted in R via the
255 `lme4` and `RLRsim` packages (Bates et al., 2015; Scheipl et al., 2008). To conform to
256 test assumptions, traits were root transformed with the exception of condensed tannin
257 concentration and carbon-nitrogen ratio, which were rank and \log_{10} transformed, respectively.
258 Differences in node level centrality among species was tested using ANOVA and
259 Tukey-HSD multiple comparison tests. Correlations among trait variables and network
260 metrics were quantified and tested using linear correlations of Pearson's r . For multivariate
261 response variables, such as lichen community composition and network structure,
262 we used distance based multivariate statistical approaches. To quantify the similarity of
263 lichen networks among individual trees, we calculated the pairwise Euclidean distance
264 of the **D** interaction matrices among all trees. To test for the effects of genotype and
265 other predictor variables on network similarity we conducted Permutational Analysis
266 of Variance (PERMANOVA) with `vegan` (Oksanen et al., 2019). For visualization of
267 multivariate patterns, we used Non-metric Multi-Dimensional Scaling (NMDS) (Goslee
268 and Urban, 2007) to produce dimensionally reduced ordinations of these multi-variate
269 responses and fitted vectors for continuous predictor variables to the ordinated values
270 (Oksanen et al., 2019). Using random initial configurations with a maximum of 500
271 iterations and a change in stress threshold of less than 10^{-12} . This was repeated for one
272 to four dimension configurations, and the configuration with the lowest dimensionality
273 and unexplained variation less than 10% was selected. For all tests where genotype was
274 used as a predictor, we quantified the heritability of the response variable. Because the
275 trees in the garden were clonal replicates of each genotype, we calculated broad-sense
276 heritability, which is the genotypic variance divided by the total phenotypic variance
277 (Conner and Hartl, 2004), which can be interpreted as a measure of the phenotypic
278 variance due to genotypic variation. All analyses were conducted using R version
279 4.0.2 (R Core Team, 2020). Code and data for the project are openly available as a
280 reproducible workflow using `drake` (Landau, 2018), which is archived via Zenodo
281 zenodo.com/doi/XXXXXX.

282 RESULTS

283 In support of our first hypotheses, we found that tree genotype influenced lichen net-
284 work structure and that multiple lichen network metrics were heritable. Tree genotype
285 significantly predicted the structural similarity of lichen networks and, overall, network-
286 level metrics responded significantly to tree genotype, including network degree and
287 centralization including both in-coming and out-going links or when separated into
288 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).

	Response	df	RLRT	H2	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.

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* 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 ($RLRT = 3.13$, $H^2 = 0.30$, $p\text{-value} = 0.0327$) perspectives, but not for either negative centrality metrics in-coming ($RLRT = 0$, $H^2 = 0$, $p\text{-value} = 1$) or out-going ($RLRT = 0$, $H^2 = 0$, $p\text{-value} = 0.4543$). None of the other species' centralities showed a genotypic response (Supporting Information, Fig. 2) with the exception of *X. montana* ($RLRT = 2.92$, $H^2 = 0.32$, $p\text{-value} = 0.0375$); 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 ($RLRT = 4.8526$, $H^2 = 0.3221$, $p\text{-value} = 0.0113$) and condensed tannins ($RLRT = 3.0522$, $H^2 = 0.3205$, $p\text{-value} = 0.0343$) both displayed significant responses to tree genotype. None of the other bark traits, pH ($RLRT = 0.00$, $H^2 = 0.00$, $p\text{-value} = 1.0000$) or carbon-nitrogen ratio ($RLRT = 0.0000$, $H^2 = 0.0000$, $p\text{-value} = 1.0000$), 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 ($df = 35$, $t = -2.13$, $r = -0.34$, $p\text{-value} = 0.04$) and centralization ($df = 35$, $t = -2.52$, $r = -0.39$, $p\text{-value} = 0.02$). In other words, trees with more similar levels of bark roughness tended to have lichen interaction networks

318 with similar structure. To quantify the genetic bases of this effect of bark roughness on
 319 network structure, we used the residual values from regressions of network degree and
 320 centralization in tests of the effect of tree genotype and found no significant effect of tree
 321 genotype for either degree ($RLRT = 0.00$, $H^2 = 0.00$, $p\text{-value} = 1.0000$) or centralization
 322 ($RLRT = 0.00$, $H^2 = 0.00$, $p\text{-value} = 1.0000$), suggesting that the observed relationship
 323 between bark roughness and lichen network structure was largely genetically based
 324 (Fig. 6).

	df	SS	R2	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.

325 DISCUSSION

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

340 Implications of Ecological Network Heritability

341 Significant heritability of lichen interaction network structure is in line with the genetic
 342 similarity rule, networks observed on trees of the same genotype tended to be structurally
 343 similar. Although previous studies have examined aspects of networks, such as trophic
 344 complexity (Barbour et al., 2016) and forest stand-level interaction network structure
 345 (Lau et al., 2016b; Keith et al., 2017), this is the first study that we are aware of to
 346 examine the heritability of network structure with replicated networks at the genotype
 347 scale. Previous work in the evolution of ecological networks have primarily focused on
 348 macro-evolutionary dynamics (Rezende et al., 2007; Weber et al., 2017; Valverde et al.,
 349 2018; Harmon et al., 2019) or have been simulation based individual-level models that

350 integrate intraspecific variation to the species level (Maliet et al., 2020), even though
351 recent syntheses have pointed to the importance of processes operating across scales of
352 organization (Guimarães, 2020). There are two important functional ramifications of
353 genetically based variation in network structure.

354 First, heritability of network structure suggests that some amount of interaction
355 network complexity is determined and therefore could be predicted by genetic identity.
356 Variation in space and time create variation in ecological networks that influences evolution-
357 ary dynamics via shifts in ecological dynamics, such as population demographics
358 (Guimarães, 2020). Given that ecosystems are comprised of hundreds and thousands of
359 species, each having a multitude of interactions, the potential to find traction for making
360 predictions in the context of ecological, let alone evolutionary, dynamics seems daunting.
361 The promise of predictability lies in the presence of asymmetries in ecosystems, such as
362 hierarchy created by foundation species via differences in body size and/or life-history
363 strategies (Ellison et al., 2005). The second is that heritability (i.e., genetic determina-
364 tion) means that there is structure in the spatial or temporal variation that is created
365 by individuals of foundation species whose traits are in part determined by underlying
366 trait differences. Although this variation is inherently a function of both genetic and
367 environmental effects (Conner and Hartl, 2004), the community and network-level
368 effects are also a function of the scale of the interaction (Shuster et al., 2006).

369 Second, even if the composition of the communities is the same among individuals
370 and genotypes, interactions may not be. We didn't observe compositional differences
371 using the same data from which the lichen networks were derived. If we only had our
372 composition dataset from this study, we would have concluded no response of the lichen
373 community to tree genotype, even though the underlying interactions among lichen
374 species does vary among genotypes. As such differences in network structure could
375 occur without observable differences in species richness or community composition,
376 which have been the primary focus of almost all previous community genetics studies
377 (Des Roches et al., 2018). Community composition of lichens has previously been
378 observed to be different among tree genotypes in the same experimental garden (Lamit
379 et al., 2011, 2015b). The different results observed in the present study is likely a
380 result of differences in lichen quantification and the tree genotypes observed leading
381 to overall higher abundances of observed lichens to assure the possibility of observing
382 lichen interactions. The previous study used a visual percent cover estimation, unlike
383 the current study, which observed lichens at the scale of 1 cm² cells, which could
384 over-estimate cover depending on the frequency at which actual thallus size was less
385 than 1 cm², as well as both the northern and southern aspects of each tree. These
386 differences do not negate the findings of either study. The present study's finding of
387 differences in network structure without significant compositional differences points
388 to the importance of quantifying how network structure changes in response to genetic
389 variation in order to fully understand evolutionary dynamics in complex communities.
390 Having not observed a compositional effect of tree genotype without measuring the
391 network structure could lead to the conclusion of no genetic effect on the community,
392 even though differences in network structure are leading to altered, local evolutionary
393 dynamics. It is possible that these underlying differences in interactions among lichens
394 could lead to differences in community composition at a future point in time via their
395 effects on species abundances (Shuster et al., 2006); however, this is not needed for

396 evolutionary dynamics to occur via selection that leads to shifts in trait distributions
397 without shifting species abundance distributions, which is possible under stabilizing,
398 disruptive and directional selection (Conner and Hartl, 2004), so long as the relative
399 abundances of each species is imperceptibly changed. Thus, it is imperative that further
400 community genetics research assess or at least be aware of the potential effects of
401 variation in interactions and not just observe species abundances, otherwise community
402 level genetic effects may be underestimated, especially when cumulative interaction
403 effects are taken into account (Borrett et al., 2007, 2010).

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

427 **Evolution and Genetically Based Network Structure**

428 The demonstration of evolution at any scale of biological organization requires demon-
429 strating three key elements. First, there must be variation in the structure (composition,
430 abundance, species interactions, diversity, networks) of communities across the land-
431 scape. Second, these differences must be genetically based and heritable in which
432 community structure is passed from one generation to the next. For example, numerous
433 studies show that related individuals tend to support the same communities of insects
434 and microbes, and ecosystem processes of biodiversity, nutrient cycling and stabil-
435 ity, whereas unrelated individuals support more different communities and ecosystem
436 processes (Des Roches et al., 2018; Whitham et al., 2020). Importantly, the current
437 study shows that networks are also heritable traits that greatly increases its utility as a
438 community phenotype that selection can act upon. Third, selection must act on these
439 differences to favor some communities over others leading to change over time (i.e.,
440 community evolution). Since our findings show that networks are heritable, another

441 metric of community evolution is showing how networks change over time in response
442 to an invasive species, climate change, or some other agent of selection.

443 Intra-specific, genotypic diversity could be creating lichen meta-communities on
444 individual trees that form interaction modules with different dynamics. When commu-
445 nities are comprised of individuals whose habitat is primarily determined by another
446 organism, these communities inherently form modules within the larger ecosystem,
447 as they tend to interact more with each other than with other individuals (Lau et al.,
448 2017). Our study demonstrates that the environmental differences determined by the
449 genetic variation within a single species can not only impact community composition,
450 as repeatedly demonstrated in other community genetics studies (Whitham et al., 2006;
451 Des Roches et al., 2018), but also shape the structure of interactions among individuals.
452 Some network structures are likely to be more stable, either in response to disturbance
453 or via self-organized dynamics. For example, centralized networks, although more
454 efficient, are theorized to be more susceptible to targeted “attacks” in the terminology of
455 defense networks. As mentioned previously, one class of networks that are theorized to
456 have amplifying effects on networks have centralized “star” shapes with one or a few
457 species at the center and radiating interactions out from the central core (Lieberman
458 et al., 2005). This is structurally what we have observed with the networks that tend to
459 occur on some of the genotypes in our study, i.e., the more centralized networks. It is
460 likely that these networks could function as hot-spots of evolutionary dynamics resulting
461 from the amplifying effect the centralized network structure found on that tree genotype,
462 as multiple studies have found significant impacts of the removal of foundation species
463 in different systems (Keith et al., 2017; Des Roches et al., 2018).

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

486 Since lichen individuals are multi-species complexes, there is also the potential for

evolutionary dynamics to shift within the context of the lichen symbiosis. There is substantial evidence that lichens have served as the “cradle of symbiotic fungal diversification” (Arnold et al., 2009) and recent research has shown significant network structure of endolichenic fungi and lichens collected from across North America (Chagnon et al., 2016). Analysis of the structure of ecological networks has generally supported the conclusion that nestedness, or the degree to which species tend to interact with similar subsets of the community, tends to promote stability in mutualistic, primarily bipartite (i.e., two-mode), networks and modularity contributes to the stabilization of antagonistic networks (Elias et al., 2013; Grilli et al., 2016). Although there is growing evidence that the nestedness of mutualistic networks is not necessarily the result of selection for systems-level properties that promote stability but could be either product of asymptotic abundance distributions leading to uneven interaction frequencies (Staniczenko et al., 2013) and/or a by-product of selection and divergence creating network “spandrels” in ecosystems (Valverde et al., 2018), this does not preclude the functional consequences of network structure but rather the developmental or evolutionary processes that have produced the structure. In the present study, we did not examine nestedness or modularity of the lichen networks as we could not find metrics for analyzing networks that are not only weighted and directed but also signed. Hopefully future network theoretic developments will make the appropriate metrics available to conduct these analyses.

Conclusion

In the face of the high degree of complexity and potential context dependency of ecological processes, the current study points to the utility of considering the spatial and temporal scales of interactions, as discussed in previous studies (Bangert et al., 2006; Zook et al., 2010; Zytynska et al., 2012). In the present research, we found that the assembly of ecological networks can have a measurable genetic basis depending on the spatial scale of interactions, due in part, to asymmetries in size and longevity of organisms. The importance of the scale of network organization to create hierarchical structure (Guimarães, 2020) and the potential for foundation species to create this structure in the vast majority of ecosystems (Ellison et al., 2005; Whitham et al., 2006) suggests that future work would be aided by determining these modules that include species with large differences in body-size and longevity. As heritable variation is the raw material for natural selection to act upon, a genetic basis for interaction network structure indicates that conserving genetic variation is important to consider in efforts to restore or preserve complex species interactions and their associated ecosystem functions (Whitham et al., 2012; Evans et al., 2013; Whitham et al., 2020). Going forward, future work could extend the many previous community genetics studies that have focused on sessile organisms, such as galling insects (Bailey et al., 2005; Whitham et al., 2006; Crutsinger et al., 2014; Smith et al., 2011; Keith et al., 2017), to quantify the frequency of these interactions in the context of the larger community. Network modeling and analysis will provide useful tools for the identification of species within network modules that are most important to study in systems where little is known about the natural history of organisms in an ecosystem is lacking. 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

532 et al., 2016).

533 **Acknowledgments**

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

538 **REFERENCES**

- 539 Araújo, M. B., Rozenfeld, A., Rahbek, C., and Marquet, P. A. (2011). Using species
540 co-occurrence networks to assess the impacts of climate change. *Ecography*, 34:897–
541 908.
- 542 Arnold, A. E., Miadlikowska, J., Higgins, K. L., Sarvate, S. D., Gugger, P., Way, A.,
543 Hofstetter, V., Kauff, F., and Lutzoni, F. (2009). A phylogenetic estimation of trophic
544 transition networks for ascomycetous Fungi: Are lichens cradles of symbioticrophic
545 Fungal diversification? *Systematic Biology*, 58(3):283–297.
- 546 Bailey, J. K., Schweitzer, J. A., Ubeda, F., Koricheva, J., LeRoy, C. J., Madritch, M. D.,
547 Rehill, B. J., Bangert, R. K., Fischer, D. G., Allan, G. J., and Whitham, T. G. (2009).
548 From genes to ecosystems: a synthesis of the effects of plant genetic factors across
549 levels of organization. *Philosophical transactions of the Royal Society of London.
Series B, Biological sciences*, 364(1523):1607–16.
- 550 Bailey, J. K., Wooley, S. C., Lindroth, R. L., and Whitham, T. G. (2005). Importance
551 of species interactions to community heritability: a genetic basis to trophic-level
552 interactions. *Ecology Letters*, 0(0):051122062725008.
- 553 Bangert, R. K., Turek, R. J., Rehill, B., Wimp, G. M., Schweitzer, J. A., Allan, G. J.,
554 Bailey, J. K., Martinsen, G. D., Keim, P., Lindroth, R. L., and Whitham, T. G. (2006).
555 A genetic similarity rule determines arthropod community structure. *Molecular
ecology*, 15:1379–1391.
- 556 Barbour, M. A., Fortuna, M. A., Bascompte, J., Nicholson, J. R., Julkunen-Tiitto, R.,
557 Jules, E. S., and Crutsinger, G. M. (2016). Genetic specificity of a plant-insect food
558 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.
- 559 Barbour, R. C., O'Reilly-Wapstra, J. M., Little, D. W. D., Jordan, G. J., Steane, D. A.,
560 Humphreys, J. R., Bailey, J. K., Whitham, T. G., Potts, B. M., De Little, D. W., Jordan,
561 G. J., Steane, D. A., Humphreys, J. R., Bailey, J. K., Whitham, T. G., and Potts, B. M.
562 (2009). A geographic mosaic of genetic variation within a foundation tree species
563 and its community-level consequences. *Ecology*, 90(7):1762–1772.
- 564 Bascompte, J., Jordano, P., and Olesen, J. M. (2006). Asymmetric Coevolutionary
565 Networks Facilitate Biodiversity Maintenance\r10.1126/science.1123412. *Science*,
566 312:431–433.
- 567 Bates, D., Mächler, M., Bolker, B., and Walker, S. (2015). Fitting linear mixed-effects
568 models using lme4. *Journal of Statistical Software*, 67(1):1–48.
- 569 Bdeir, R., Muchero, W., Yordanov, Y., Tuskan, G. A., Busov, V., and Gailing, O. (2017).
570 Quantitative trait locus mapping of *Populus* bark features and stem diameter. *BMC
Plant Biology*.

- 575 Borrett, S. R., Fath, B. D., and Patten, B. C. (2007). Functional integration of ecological
576 networks through pathway proliferation. *Journal of Theoretical Biology*, 245(1):98–
577 111.
- 578 Borrett, S. R. and Lau, M. K. (2014). enaR: An R package for Ecosystem Network
579 Analysis. *Methods in Ecology and Evolution*, 5(11):1206–1213.
- 580 Borrett, S. R., Whipple, S. J., and Patten, B. C. (2010). Rapid development of indirect
581 effects in ecological networks. *Oikos*, 119(7):1136–1148.
- 582 Busby, P. E., Lamit, L. J., Keith, A. R., Newcombe, G., Gehring, C. A., Whitham, T. G.,
583 and Dirzo, R. (2015). Genetics-based interactions among plants, pathogens, and
584 herbivores define arthropod community structure. *Ecology*, 96(7):1974–1984.
- 585 Butts, C. T. (2019). *sna: Tools for Social Network Analysis*. R package version 2.5.
- 586 Chagnon, P. L., U'Ren, J. M., Miadlikowska, J., Lutzoni, F., and Elizabeth Arnold,
587 A. (2016). Interaction type influences ecological network structure more than local
588 abiotic conditions: evidence from endophytic and endolichenic fungi at a continental
589 scale. *Oecologia*, 180(1):181–191.
- 590 Conner, K. and Hartl, D. L. (2004). *A Primer of Ecological Genetics: a textbook*.
591 Sinauer Associates, Inc., Sunderland, Massachusetts, 1st edition.
- 592 Crutsinger, G. M. (2016). A community genetics perspective: Opportunities for the
593 coming decade. *New Phytologist*.
- 594 Crutsinger, G. M., Rudman, S. M., Rodriguez-Cabal, M. A., McKown, A. D., Sato,
595 T., MacDonald, A. M., Heavyside, J., Gerald, A., Hart, E. M., LeRoy, C. J., and
596 El-Sabaawi, R. W. (2014). Testing a ‘genes-to-ecosystems’ approach to understanding
597 aquatic-terrestrial linkages. *Molecular Ecology*, 23(23):5888–5903.
- 598 Darwin, C. (1859). *On the Origin of Species*. Murray, London.
- 599 Dátillo, W., Lara-Rodríguez, N., Jordano, P., Guimarães, P. R., Thompson, J. N., Marquis,
600 R. J., Medeiros, L. P., Ortiz-Pulido, R., Marcos-García, M. A., and Rico-Gray,
601 V. (2016). Unravelling Darwin’s entangled bank: Architecture and robustness of
602 mutualistic networks with multiple interaction types. *Proceedings of the Royal Society
B: Biological Sciences*.
- 604 Des Roches, S., Post, D. M., Turley, N. E., Bailey, J. K., Hendry, A. P., Kinnison,
605 M. T., Schweitzer, J. A., and Palkovacs, E. P. (2018). The ecological importance of
606 intraspecific variation. *Nature Ecology and Evolution*, 2(1):57–64.
- 607 Díaz-Castelazo, C., Guimarães, P. R., Jordano, P., Thompson, J. N., Marquis, R. J., and
608 Rico-Gray, V. (2010). Changes of a mutualistic network over time: Reanalysis over a
609 10-year period. *Ecology*.
- 610 Elias, M., Fontaine, C., and Frank Van Veen, F. J. (2013). Evolutionary history and
611 ecological processes shape a local multilevel antagonistic network. *Current Biology*,
612 23(14):1355–1359.
- 613 Ellison, A. M., Bank, M. S., Clinton, B. D., Colburn, E. A., Elliott, K., Ford, C. R.,
614 Foster, D. R., Kloeppe, B. D., Knoepp, J. D., Lovett, G. M., Mohan, J., Orwig,
615 D. A., Rodenhouse, N. L., Sobczak, W. V., Stinson, K. A., Stone, J. K., Swan, C. M.,
616 Thompson, J., Von Holle, B., and Webster, J. R. (2005). Loss of foundation species:
617 consequences for the structure and dynamics of forested ecosystems. *Frontiers in
618 Ecology and the Environment*, 3(9):479–486.
- 619 Evans, D. M., Pocock, M. J. O., and Memmott, J. (2013). The robustness of a network
620 of ecological networks to habitat loss. *Ecology letters*, 16:844–52.

- 621 Everett, M. G. and Borgatti, S. P. (2014). Networks containing negative ties. *Social*
622 *Networks*, 38(1):111–120.
- 623 Fath, B. D. and Patten, B. C. (1998). Network synergism: Emergence of positive
624 relations in ecological systems. *Ecological Modelling*, 107(2):127 – 143.
- 625 Gehring, C., Flores-Rentería, D., Sthultz, C. M., Leonard, T. M., Flores-Rentería,
626 L., Whipple, A. V., and Whitham, T. G. (2014). Plant genetics and interspecific
627 competitive interactions determine ectomycorrhizal fungal community responses to
628 climate change. *Molecular Ecology*, 23(6):1379–1391.
- 629 Gehring, C. A., Sthultz, C. M., Flores-Rentería, L., Whipple, A. V., and Whitham, T. G.
630 (2017). Tree genetics defines fungal partner communities that may confer drought
631 tolerance. *Proceedings of the National Academy of Sciences*.
- 632 Gómez, J. M., Abdelaziz, M., Camacho, J. P. M., Muñoz-Pajares, A. J., and Perfectti, F.
633 (2009). Local adaptation and maladaptation to pollinators in a generalist geographic
634 mosaic. *Ecology Letters*, 12(7):672–682.
- 635 Goslee, S. C. and Urban, D. L. (2007). The ecodist package for dissimilarity-based
636 analysis of ecological data. *Journal of Statistical Software*, 22:1–19.
- 637 Grilli, J., Rogers, T., and Allesina, S. (2016). Modularity and stability in ecological
638 communities. *Nature Communications*, 7.
- 639 Guimarães, P. R. (2020). The Structure of Ecological Networks Across Levels of
640 Organization. *Annual Review of Ecology, Evolution, and Systematics*, 51(1).
- 641 Guimarães, P. R., Jordano, P., and Thompson, J. N. (2011). Evolution and coevolution
642 in mutualistic networks. *Ecology letters*, 14(9):877–85.
- 643 Guimarães, P. R., Rico-Gray, V., Oliveira, P. S., Izzo, T. J., dos Reis, S. F., and Thompson,
644 J. N. (2007). Interaction Intimacy Affects Structure and Coevolutionary Dynamics in
645 Mutualistic Networks. *Current Biology*, 17(20):1797–1803.
- 646 Harmon, L. J., Andreazzi, C. S., Débarre, F., Drury, J., Goldberg, E. E., Martins,
647 A. B., Melián, C. J., Narwani, A., Nuismer, S. L., Pennell, M. W., Rudman, S. M.,
648 Seehausen, O., Silvestro, D., Weber, M., and Matthews, B. (2019). Detecting the
649 macroevolutionary signal of species interactions. *Journal of Evolutionary Biology*,
650 32(8):769–782.
- 651 Holeski, L. M., Hillstrom, M. L., Whitham, T. G., and Lindroth, R. L. (2012). Relative
652 importance of genetic, ontogenetic, induction, and seasonal variation in producing a
653 multivariate defense phenotype in a foundation tree species. *Oecologia*, 170:695–707.
- 654 Johnson, M. T. J. (2008). Bottom-up effects of plant genotype on aphids, ants, and
655 predators. *Ecology*.
- 656 Keith, A. R., Bailey, J. K., Lau, M. K., and Whitham, T. G. (2017). Genetics-based inter-
657 actions of foundation species affect community diversity, stability and network struc-
658 ture. *Proceedings of the Royal Society B: Biological Sciences*, 284(1854):20162703.
- 659 Lamit, L., Bowker, M., Holeski, L., Næsborg, R. R., Wooley, S., Zinkgraf, M., Lindroth,
660 R., Whitham, T., and Gehring, C. (2011). Genetically-based trait variation within a
661 foundation tree species influences a dominant bark lichen. *Fungal Ecology*, 4(1):103–
662 109.
- 663 Lamit, L. J., Busby, P. E., Lau, M. K., Compson, Z. G., Wojtowicz, T., Keith, A. R.,
664 Zinkgraf, M. S., Schweitzer, J. A., Shuster, S. M., Gehring, C. A., and Whitham, T. G.
665 (2015a). Tree genotype mediates covariance among communities from microbes to
666 lichens and arthropods. *Journal of Ecology*, 103(4):840–850.

- 667 Lamit, L. J., Lau, M. K., Næsborg, R. R., Wojtowicz, T., Whitham, T. G., and Gehring,
668 C. A. (2015b). Genotype variation in bark texture drives lichen community assembly
669 across multiple environments. *Ecology*, 96(4):960–971.
- 670 Landau, W. M. (2018). The drake r package: a pipeline toolkit for reproducibility and
671 high-performance computing. *Journal of Open Source Software*, 3(21).
- 672 Lau, M. K., Borrett, S. R., Baiser, B., Gotelli, N. J., and Ellison, A. M. (2017). Ecological
673 network metrics: opportunities for synthesis. *Ecosphere*, 8(8):e01900.
- 674 Lau, M. K., Keith, A. R., Borrett, S. R., Shuster, S. M., and Whitham, T. G. (2016a).
675 Genotypic variation in foundation species generates network structure that may drive
676 community dynamics and evolution. *Ecology*, 97(3):15–0600.
- 677 Lau, M. K., Keith, A. R., Borrett, S. R., Shuster, S. M., and Whitham, T. G. (2016b).
678 Genotypic variation in foundation species generates network structure that may drive
679 community dynamics and evolution. *Ecology*.
- 680 Lieberman, E., Hauert, C., and Nowak, M. A. (2005). Evolutionary dynamics on graphs.
681 *Nature*, 433(7023):312–316.
- 682 Lieberman, E., Hauert, C., and Nowak, M. A. (2005). Evolutionary dynamics on graphs.
683 *Nature*, 433(7023):312–316.
- 684 Maliet, O., Loeuille, N., and Morlon, H. (2020). An individual-based model for
685 the eco-evolutionary emergence of bipartite interaction networks. *Ecology Letters*,
686 23(11):1623–1634.
- 687 Martinsen, G. D., Whitham, T. G., Turek, R. J., and Keim, P. (2001). Hybrid populations
688 selectively filter gene introgression between species. *Evolution*, 55(7):1325–1335.
- 689 Moya-Laraño, J. (2011). Genetic variation, predator-prey interactions and food web
690 structure. *Philosophical transactions of the Royal Society of London. Series B,
691 Biological sciences*, 366(1569):1425–37.
- 692 Nelson, P. R., McCune, B., Wheeler, T., Geiser, L. H., and Crisafulli, C. M. (2018).
693 Lichen community development along a volcanic disturbance gradient at Mount St.
694 Helens. In *Ecological Responses at Mount St. Helens: Revisited 35 years after the
695 1980 Eruption*, pages 185–198. Springer New York.
- 696 Newman, M. E. J. (2006). Modularity and community structure in networks. *Proceedings
697 of the National Academy of Sciences of the United States of America*, 103(23):8577–
698 82.
- 699 Norby, R. J. and Sigal, L. L. (1989). Nitrogen fixation in the lichen *Lobaria pulmonaria*
700 in elevated atmospheric carbon dioxide. *Oecologia*, 79(4):566–568.
- 701 Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin,
702 P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoces, E., and
703 Wagner, H. (2019). *vegan: Community Ecology Package*. R package version 2.5-6.
- 704 Poisot, T., Cirtwill, A. R., Cazelles, K., Gravel, D., Fortin, M., and Stouffer, D. B.
705 (2016). The structure of probabilistic networks. *Methods in Ecology and Evolution*,
706 7(3):303–312.
- 707 R Core Team (2020). *R: A Language and Environment for Statistical Computing*. R
708 Foundation for Statistical Computing, Vienna, Austria.
- 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 Scheipl, F., Greven, S., and Kuechenhoff, H. (2008). Size and power of tests for a zero
716 random effect variance or polynomial regression in additive and linear mixed models.
717 *Computational Statistics & Data Analysis*, 52(7):3283–3299.
- 718 Schoch, D. (2020). *signnet: An R package to analyze signed networks*.
- 719 Shuster, S. M., Lonsdorf, E. V., Wimp, G. M., Bailey, J. K., and Whitham, T. G. (2006).
720 COMMUNITY HERITABILITY MEASURES THE EVOLUTIONARY CONSE-
721 QUENCES OF INDIRECT GENETIC EFFECTS ON COMMUNITY STRUCTURE.
722 *Evolution*, 60(5):991.
- 723 Smith, D. S., Bailey, J. K., Shuster, S. M., and Whitham, T. G. (2011). A geographic
724 mosaic of trophic interactions and selection: trees, aphids and birds. *Journal of*
725 *evolutionary biology*, 24(2):422–9.
- 726 Smith, D. S., Lamit, L. J., Lau, M. K., Gehring, C. A., Shuster, S. M., and Whitham,
727 T. G. (2015). Introduced elk alter traits of a native plant and its plant-associated
728 arthropod community. *Acta Oecologica*, 67:8–16.
- 729 Sole, R. and Bascompte, J. (2006). *Self-Organization in Complex Ecosystems*. Princeton
730 University Press, Princeton, N.J.
- 731 Staniczenko, P. P., Kopp, J. C., and Allesina, S. (2013). The ghost of nestedness in
732 ecological networks. *Nature Communications*, 4(1):1–6.
- 733 Thompson, J. N. (2013). *Relentless Evolution*. University of Chicago Press.
- 734 Toju, H., Guimarães, P. R., Olesen, J. M., and Thompson, J. N. (2014). Assembly of
735 complex plant-fungus networks. *Nature Communications*.
- 736 Toju, H., Yamamichi, M., Guimarães, P. R., Olesen, J. M., Mougi, A., Yoshida, T., and
737 Thompson, J. N. (2017). Species-rich networks and eco-evolutionary synthesis at the
738 metacommunity level.
- 739 Toju, H., Yamamoto, S., Tanabe, A. S., Hayakawa, T., and Ishii, H. S. (2016). Network
740 modules and hubs in plant-root fungal biomes. *Journal of the Royal Society Interface*.
- 741 Valverde, S., Piñero, J., Corominas-Murtra, B., Montoya, J., Joppa, L., and Solé, R.
742 (2018). The architecture of mutualistic networks as an evolutionary spandrel. *Nature*
743 *Ecology and Evolution*, 2(1):94–99.
- 744 Wade, M. J. (2007). The co-evolutionary genetics of ecological communities.
- 745 Weber, M. G., Wagner, C. E., Best, R. J., Harmon, L. J., and Matthews, B. (2017).
746 Evolution in a Community Context: On Integrating Ecological Interactions and
747 Macroevolution.
- 748 Whitham, T. G., Allan, G. J., Cooper, H. F., and Shuster, S. M. (2020). Intraspecific Ge-
749 netic Variation and Species Interactions Contribute to Community Evolution. *Annual*
750 *Review of Ecology, Evolution, and Systematics*, 51(1).
- 751 Whitham, T. G., Bailey, J. K., Schweitzer, J. A., Shuster, S. M., Bangert, R. K., LeRoy,
752 C. J., Lonsdorf, E. V., Allan, G. J., DiFazio, S. P., Potts, B. M., Fischer, D. G.,
753 Gehring, C. A., Lindroth, R. L., Marks, J. C., Hart, S. C., Wimp, G. M., and Wooley,
754 S. C. (2006). A framework for community and ecosystem genetics: from genes to
755 ecosystems. *Nature reviews. Genetics*, 7:510–523.
- 756 Whitham, T. G., Gehring, C. A., Lamit, L. J., Wojtowicz, T., Evans, L. M., Keith, A. R.,
757 and Smith, D. S. (2012). Community specificity: Life and afterlife effects of genes.
- 758 Winfree, R., Gross, B. J., and Kremen, C. (2011). Valuing pollination services to

- 759 agriculture. *Ecological Economics*, 71:80–88.
- 760 Zook, A. E., Eklof, A., Jacob, U., and Allesina, S. (2010). Food webs: Ordering species
761 according to body size yields high degree of intervality. *Journal of theoretical biology*,
762 271(1):106–113.
- 763 Zytynska, S. E., Fay, M. F., Penney, D., and Preziosi, R. F. (2011). Genetic variation
764 in a tropical tree species influences the associated epiphytic plant and invertebrate
765 communities in a complex forest ecosystem. *Philosophical transactions of the Royal
766 Society of London. Series B, Biological sciences*, 366:1329–1336.
- 767 Zytynska, S. E., Khudr, M. S., Harris, E., and Preziosi, R. F. (2012). No Title. *Oecologia*,
768 170(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 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).

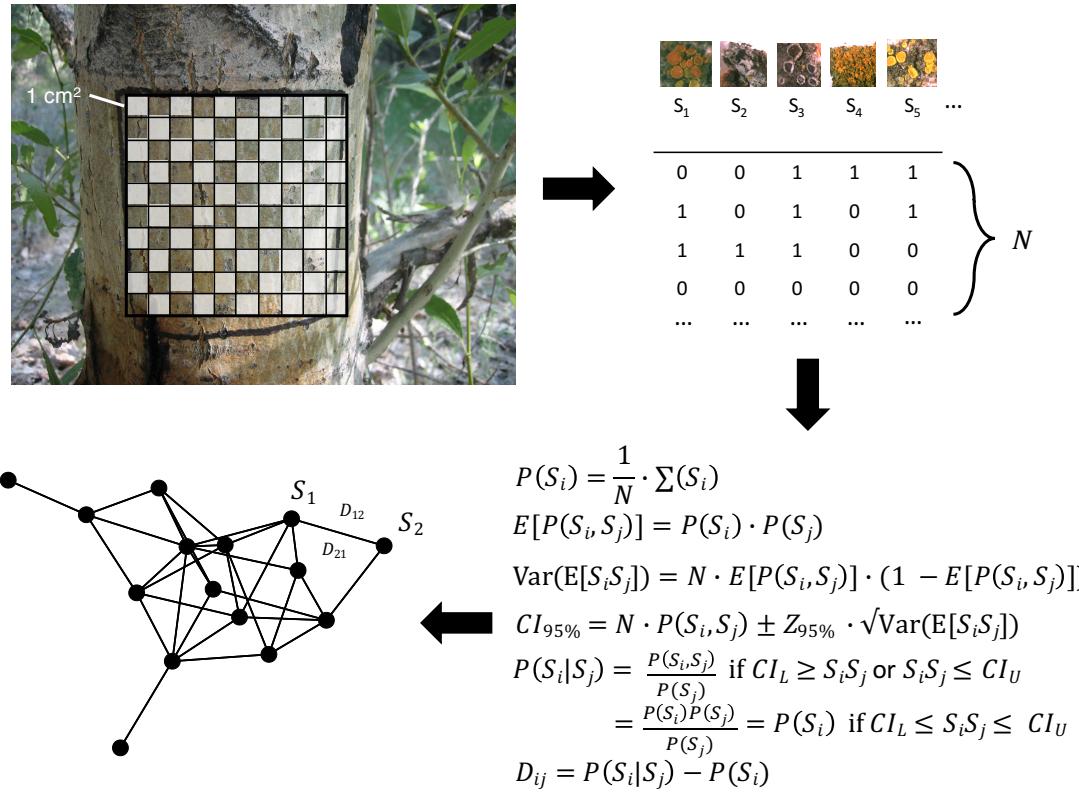


Figure 2. Lichen interaction networks were constructed by conducting field observations in 1 cm^2 cells within a 100 cm^2 grid on each tree using a checkerboard pattern (grey cells). Thus, a set of N total cell observations were recorded for each tree with the presence or absence of each species recorded 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 .

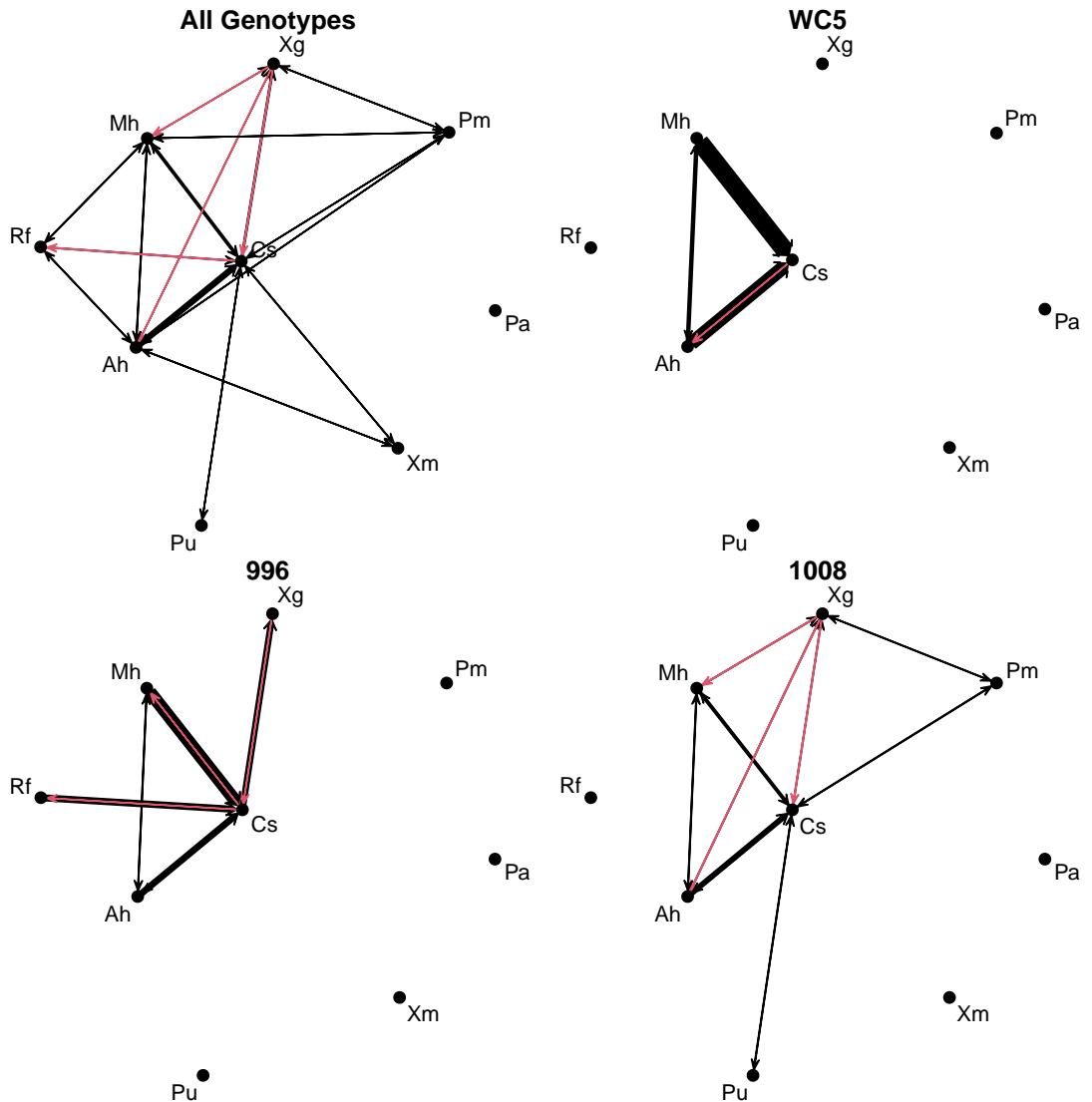


Figure 3. Lichen networks varied in structure among tree genotypes. Network diagrams of the mean lichen interaction matrices averaged for all trees and for illustrative genotypes (996, WC5 and 1008) showing a range of interaction network structure. Directionality (arrowheads) and sign (red = negative, 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.

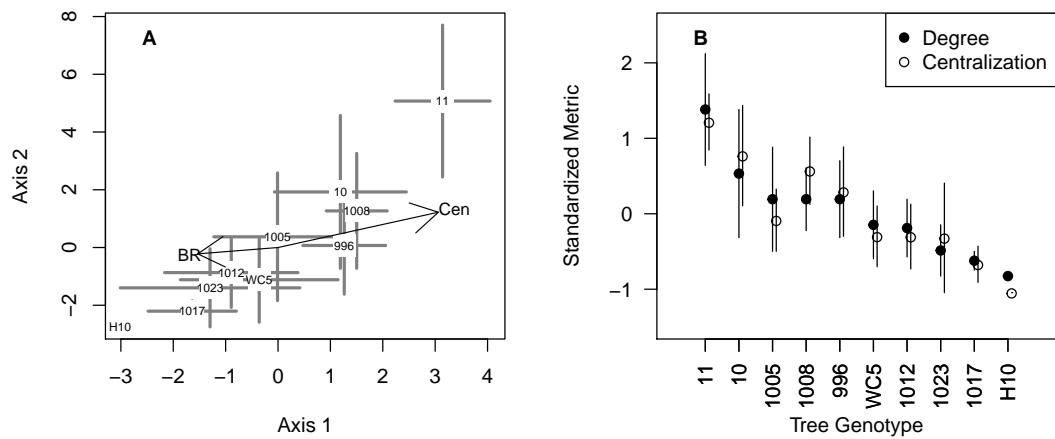


Figure 4. The similarity of lichen networks varied among tree genotypes. A. The plot shows genotype centroids of NMDS ordinated ($R^2 = 0.999$, stress = 0.008) lichen network similarity (± 1 S.E.). Genotype centroids that are closer together tend to have more similar lichen network structure. Arrows showing the direction (arrowhead) and magnitude (length) of the vectors of correlation between bark roughness (BR) and network centralization (Cen) and the ordinated networks. B. Plot showing the standardized ($\frac{x-\bar{x}}{\sigma}$) means (± 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.

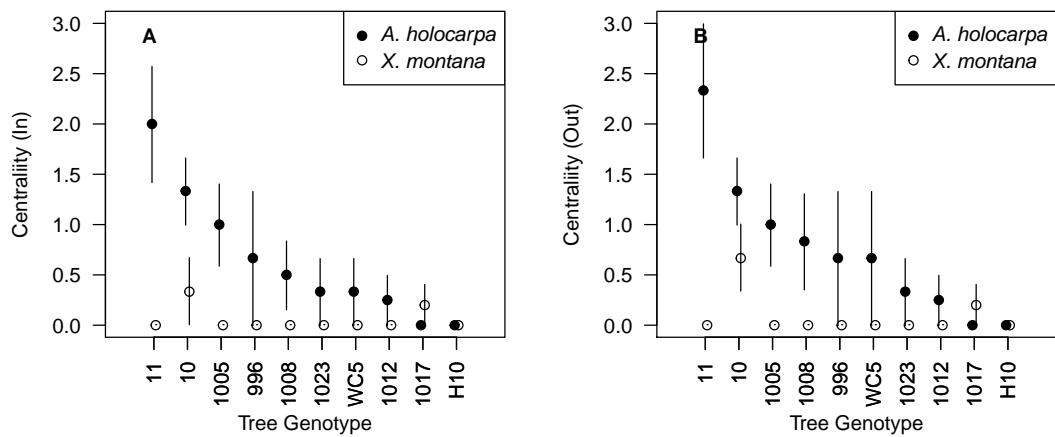


Figure 5. Dot-plots showing the mean (dot) and ± 1 SE of in-degree (A) and out-degree (B) centrality for two species, *A. holocarpa* and *X. montana*. *Athallia holocarpa* centrality was highly variable among genotypes. *Xanthomendoza montana* centrality, both in- and out-degree, was only non-zero for 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 (± 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.