

Genotypic variation in a foundation tree alters ecological network structure of an associated community

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1 Biological evolution occurs in the context of complex networks of
2 interacting species in which natural selection defines the structure
3 of ecological networks. Fundamental to this evolutionary process
4 is the discovery of a genetic basis to ecological network structure.
5 Although previous work has demonstrated that tree genotype con-
6 tributes to interaction network structure at the scale of forest stands,
7 the contribution of tree genetics to localized interaction networks
8 at the scale of individual trees has not yet been explored. To test
9 the degree to which tree genetics can contribute to network struc-
10 ture we conducted quantitative modeling of interaction networks. We
11 constructed networks of epiphytic lichen associated with individual
12 trees that were a part of a long-term experimental common garden
13 of genotypes of (*Populus angustifolia*), a foundation species. We
14 found three main results. First, tree genotype significantly predicted
15 lichen network similarity, i.e. trees of the same genotype had more
16 similar lichen networks. Second, bark roughness and condensed
17 tannin concentration were both predicted by tree genotype and cor-
18 related with lichen network similarity. Third, the network metrics, the
19 number of links and centrality, were both correlated with several tree
20 traits, including bark roughness and condensed tannin concentra-
21 tion. We conclude that tree genotype influences lichen interaction
22 network structure with two potential pathways through bark rough-
23 ness and condensed tannin concentration. These results provide
24 evidence that variation in ecological networks can result from genet-
25 ically based variation in foundation species.

networks | heritability | community | genetics | lichen | cottonwood |
Populus | common garden

- 1 Evolution occurs in complex ecosystems
- 2 Community genetics studies have demonstrated
3 the importance of genetics and evolutionary dynamics in structuring communities and ecosystems
- 4 Community composition, ecosystem processes have been shown to vary in response to the genetic variation of foundation species
- 5 Previous studies have examined aspects of networks but to date, no studies have examined the genetic basis of networks of interacting species
- 6 Here we examine the genetic basis of network structure on a community of sessile lignicolous

(i.e. bark) lichen on cottonwood trees. This system is ideal for examining for this kind of study because it:

- 1 Lichen do not move among trees, although
2 asexual propagules could move to other
3 trees in the garden
- 4 Is not unapproachably complex
- 5 Is comprised of distinct individuals that
6 are small enough for an entire community
7 to occur on a single tree but not too small
8 to be quantified easily

Significance Statement

Evolution occurs in the context of ecosystems comprised of complex ecological networks. Research at the interface of ecology and evolution has primarily focused on pairwise interactions among species and have rarely included a genetic component to analyses. Here, we use a long-term common garden experiment to reveal the effect that genotypic variation can have on networks of lichens that occur on the bark of a foundation tree species. We found that lichen interaction network structure is genetically based and is correlated with heritable bark traits, including roughness and condensed tannins. These findings demonstrate the importance of genetic variation and evolutionary dynamics in shaping ecological networks as evolved traits.

M.L. and L.L. conceived the study, M.L. and L.L. conducted the field work, R.N. assisted in lichen identifications, M.L. wrote the first draft of the manuscript, S.B. and T.W. contributed substantively to the conceptual development, T.W. established the common garden. All authors contributed to revisions of the manuscript.

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- 25 • We hypothesize that trees will vary in some
 26 phenotypic traits, such that trees of the same
 27 genotype will tend to have similar traits produc-
 28 ing similarities in lichen network structure. To
 29 test this hypothesis, we use a common garden
 30 of cottonwood trees with lichen communities.

31 **E**volution occurs in the context of complex eco-
 32 logical networks. Initially, evolution in a com-
 33 munity context was focused on examples of highly
 34 co-evolved pairs of species (e.g. Darwin's famous
 35 prediction of the Sphinx Moth and Christmas
 36 Orchid) citeWade2007. However, studies of dif-
 37 fuse co-evolution (*sensu* citeJanzen1980) citeStinch-
 38 combe2002, Strauss2007, Dicke2010, geographic mo-
 39 saics of co-evolution citeThompson2005 and com-
 40 munity genetics citeWhitham2006 have provided an
 41 in-road for ecological network approaches citeFor-
 42 tuna2009, Keith2017, Lau2016 to illuminate a more
 43 complex perspective of the interface between eco-
 44 logical and evolutionary dynamics. There is now
 45 evidence to support that selection tends to occur
 46 among groups of species citeWade2007, Pieterse2007,
 47 Dicke2010 favoring the development of small webs
 48 citeNuismer2006, Guimaraes2007, Gomez2009 and
 49 that genetic variation and phylogenetic relatedness
 50 contributes to variation in community assembly (1)
 51 and species interactions citeWhitham2006a, Bai-
 52 ley2009, Moya-Larano2011, which shapes the eco-
 53 logical interaction networks (2).

54 Community genetics studies (3) have shown that
 55 genetic variation in foundation species (4) plays a
 56 significant role in defining distinct communities of in-
 57 teracting organisms: such as, endophytes, pathogens,
 58 lichens, arthropods, and soil microbes. Multiple stud-
 59 ies have now demonstrated that genetic variation
 60 influences numerous functional traits (e.g., phyto-
 61 chemical, phenological, morphological) produces a
 62 multivariate phenotype (5) that contributes to varia-
 63 tion in associated communities (6). The importance
 64 of genetic variation in structuring ecological systems
 65 was recently reviewed by Des Roches et al. (2018).

66 Additional work has provided support for the hy-
 67 pothesis that not only does composition vary among
 68 genetically distinct genotypes of foundation species,
 69 it also impacts the structure of the network of species
 70 interactions in these communities. Two studies have
 71 demonstrated conceptually (7) and empirically (8).
 72 However, studies in the network ecology literature
 73 generally do not include a genetic component (see

74 review by Borrett et al. 2014) and community genet-
 75 ics papers do not have data on network structure of
 76 associated communities. Currently, we are aware of
 77 only one paper that empirically examines the genetic
 78 basis of network structure of a community citeBar-
 79 bour2019.

80 Here, we investigate how genetic variation in a
 81 foundation tree species determines the structure of a
 82 network of interactions among a community of tree
 83 associated lichen species. Using a long-term (20+
 84 years), common garden experiment with replicated
 85 individuals of known genetic identity and a naturally
 86 established stand of *Populus angustifolia*. We focused
 87 on a model community of 9 epiphytic lichen species,
 88 as previous research has demonstrated significant
 89 compositional responses of epiphytes to genotypic
 90 variation (9, 10). In addition, the life-history char-
 91 acteristics of lichens, having highly localized, direct
 92 contact interactions and slow population turnover
 93 rates, allowed us to assess interactions among lichen
 94 species on individual trees. We hypothesize that in
 95 natural systems evolution occurs in a community
 96 context involving interactions of complex networks
 97 of interacting species (7, 8, 11, 12). If correct, we
 98 expect to find that network structure is genetically
 99 based in which different plant genotypes support
 100 different interaction networks and that these interac-
 101 tions networks can function as indicators of ecologi-
 102 cal dynamics important for conserving biodiveristy.
 103 Applying a probability-theory based network mod-
 104 eling approach, we constructed a set of interaction
 105 network models for the lichens associated with indi-
 106 vidual trees. Using these models, we then examined
 107 the genetic basis of the structure of these ecological
 108 networks.

Materials and Methods

109 The study was conducted along the Weber River, UT
 110 (USA), which is a cottonwood (*Populus* spp.) dominated
 111 riparian ecosystem. Although two native species, *Populus*
 112 *angustifolia* (James) and *Populus fremontii* (S. Watson),
 113 occur here and are known to hybridize, only pure or
 114 advanced generation backcrosses of *P. angustifolia* were
 115 sampled. Bark lichens have been extensively studied
 116 in this system and provide an ideal system in which to
 117 observe and model lichen interaction networks, as their
 118 sessile nature permits accurate identification of individuals
 119 (13).

120 A long-term, common garden experiment was used
 121

123 to isolate the effect of tree genotype from the effect of
124 the localized microenvironment associated with each individual
125 and spatial autocorrelation. Established in 1992,
126 asexually propagated clones of genotyped *P. angustifolia*
127 individuals were obtained from wild collections and
128 planted in fully randomized design at the Ogden Nature
129 Center, Ogden, UT. From the population of established
130 individuals in the common garden, we chose a total of
131 thirteen genotypes, replicated between 3 and 8 times each,
132 for sampling.

133 **Bark Lichen Observations.** On each tree, presence or absence
134 of each lichen species was assessed in 50 total 1 cm²
135 cells arrayed in a checkerboard pattern. Given the small
136 size and sessile nature of lichens, we were able to rapidly
137 assess lichen interactions by quantifying thalli in close
138 contact. Sampling was restricted to the northern aspect
139 of the trunk to maximize the abundance of lichen and
140 control for the effect of trunk aspect. Two adjacent 10
141 cm² quadrats centered at 50 cm and 85 cm from ground
142 level were sampled (Fig 1 A and B). The observed lichen
143 community included (abbreviations are given for species
144 present in study): Xg = *Xanthomendoza galericulata*, Xm
145 = *X. montana*, Ch = *Caloplaca holocarpa*, Cs = *Candeliella subdeflexa*, Rg = *Rinodina glauca*, Lh = *Lecanora hagenii*, Pm = *Phyciella melanchra*, Pa = *Physcia adscendens*, Pu = *Physcia undulata*. Several other species were
149 not observed in the present study but are known to occur
150 in this region: *Phaeophyscia orbicularis*, *Phaeophyscia ciliata*, *Melanelia sublivacea*, *Meanelia elegantula*.

152 The cell size and checkerboard sampling pattern was
153 chosen to isolate the individuals in each cell. In a previous
154 survey of lichen thallus size in this common garden, we
155 had observed a median thallus size of 0.12 ± 0.001 cm² (1
156 S.E.) (see Supporting Information). Based on the median
157 thallus size, we expected thalli observed in each cell to
158 generally be spatially independent of thalli present in
159 other cells but exposed to similar micro-environmental
160 conditions created by the bark and the location of the
161 sampling area on an individual tree. Therefore, we were
162 confident in treating the cell-wise observations in quadrats
163 as independent with respect to lichen-lichen interactions.

164 We also measured several bark traits for each tree:
165 including, bark roughness and chemistry. **INSERT
166 FROM LAMIT.**

167 **Lichen Network Modeling and Analysis.** For each tree,
168 repeated observations of lichen were made in order to construct
169 replicated interaction networks for each genotype.
170 We quantified the presence of lichen in the 1 cm² cells on
171 individual trees of *P. angustifolia*. Unipartite networks
172 were generated using the conditional probabilities of each
173 species pair, i.e. the probability of observing one species
174 given an observation of another species $P(S_i|S_j)$, based on
175 the method developed by (14). To calculate conditional
176 probabilities, we quantified the individual probabilities

177 of species occurrences $P(S_i)$ and the joint probability
178 of co-occurrences $P(S_i, S_j)$ using the frequencies of each
179 species and their co-occurrences. We were then able to
180 calculate the conditional probabilities of each species pair
181 as $P(S_i|S_j) = \frac{P(S_i, S_j)}{P(S_j)}$, based on the axioms of probability.
182 This yielded a matrix that could possibly be asymmetric, i.e.
183 $P(S_i|S_j)$ does not have to be equal to $P(S_j|S_i)$. Another
184 important property of this matrix is that the diagonal
185 (S_{ii}) was equal to one for all species present and zero for
186 species that were not observed in any cell.

187 We then applied an analytical procedure to remove
188 non-significant links between species. This procedure
189 determines if the joint probability of a species pair
190 (i.e. $P(S_i, S_j)$) is different from zero (Fig. 2). Here, a
191 confidence interval $CI_{95\%}$ is calculated as $CI_{95\%} =$
192 $E[S_i S_j] * Z_{95\%} * \sqrt{V(S_i S_j)}$, where the expected
193 frequency of co-occurrences $E(S_i S_j)$ is the total number
194 of cells surveyed (N) times the independent probabilities
195 of each species $P(S_i) * P(S_j)$, $Z_{95\%}$ is the Z-score
196 for 95% from a Z-distribution and the expected variance
197 of $E(S_i S_j)$ is the total number of cells times the
198 expected probability of $S_i S_j$ and its compliment (i.e.
199 $V(S_i S_j) = N * E[P(S_i, S_j)] * (1 - E[P(S_i, S_j)])$). If the
200 observed number of co-occurrence falls outside of the
201 confidence interval, the joint probability $P(S_i, S_j)$ is de-
202 termined to be equal to the product of the individual
203 probabilities (i.e. $P(S_i)P(S_j)$), and the conditional prob-
204 ability reduces to the individual probability of that species
205 $P(S_i)$. Therefore, unless the co-occurrence of a species
206 pair falls outside the confidence interval, the probabil-
207 ity that the observation of one species given the other
208 is no different than simply observing that species alone.
209 This enables us to remove links from a given network by
210 re-scaling the resulting conditional probabilities by sub-
211 tracting the individual probabilities from the conditional
212 probabilities (i.e. how different the conditional probability
213 is from the independent probability), which makes any
214 species with a non-significant conditional probability zero.
215 The resulting matrix ($\mathbf{D} = D_{ij}$) can be interpreted as
216 how one species impacts another with zero being no effect
217 and values less than or greater than zero interpreted as
218 negative and positive effects, respectively. Here, we will
219 refer to this matrix (\mathbf{D}) as an interaction matrix with
220 the properties that it can be asymmetric (i.e. P_{ij} does not
221 necessarily equal P_{ji}), and the diagonal (P_{ii}) is zero (i.e.
222 a species does not influence its own probability of being
223 observed).

224 **Statistical Analyses, Software and Data.** We used a com-
225 bination of parametric and non-parametric, permutation
226 based frequentist statistical analyses to test for the effects
227 of genetic variation on lichen communities and their inter-
228 action networks. To assess the effect of genotype on uni-
229 partite responses, we used additive, random effects models
230 with Restricted Maximum Likelihood (REML). We used
231 a combination of Least Squares Regression, Analysis of



Fig. 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). Lichens were sampled within a fixed area (10 cm^2) on individual trees at two heights, 40cm and 80cm from the ground (A and B, respectively). (C) a photo of a typical community of bark lichen species interacting on the trunk of a cottonwood tree, including one of the more abundant species, *Xanthomendoza galericulata*, in the center. (D-K) shows the other lichen species observed, respectively: *X. montana*, *Candelariella subdeflexa*, *Rinodina* sp., *Caloplaca holocarpa*, *Physcia adscendens*, *Phyciella melanchra*, *Physcia undulata* and *Lecanora hagenii*. Photo Credits: L.J. Lamit (A-C) and R.R. Naesbourg (D-K).

232 Variance (ANOVA) and correlation tests to quantify and
 233 test for the relationship among other variables. Bark
 234 roughness, lichen cover and species richness were square-
 235 root transformed to meet the assumptions of homogeneity
 236 of variance and normality for these tests.

237 For multivariate response variables, such as lichen com-
 238 munity composition and network structure, we used dis-
 239 tance based multivariate statistical approaches, including
 240 Permutational Analysis of Variance (PERMANOVA) and
 241 Mantel tests. For some analyses, community composition
 242 was relativized by species maxima to reduce the effect
 243 of the highly abundant *X. galericulata*. For community
 244 composition we used Bray-Curtis dissimilarity, which has
 245 optimal performance with count data citepMinchen1998.
 246 To quantify the similarity of lichen networks among indi-
 247 vidual trees, we calculated the pairwise Euclidean distance
 248 of the **D** interaction matrices among all pairs of trees.

249 For visualization of multivariate patterns, we used Non-
 250 metric Multi-Dimensional Scaling (NMDS) citeecodist
 251 to produce dimensionally reduced ordinations of these
 252 multi-variate responses and fitted vectors for continuous
 253 predictor variables to the ordinated values citevegan. Us-
 254 ing random initial configurations with a maximum of 500

iterations and a change in stress threshold of less than
 10^{-12} . Final configurations has the lowest stress with at
 most a stress level of 0.10.

255 For each network, we also calculated metrics that mea-
 256 sure different structural aspects. Although there are many
 257 other metrics, for the sake of simplicity we focus on a sub-
 258 set that represent several interesting features of network
 259 structure (see (15)). We calculated the number of interac-
 260 tions or “links” in each network, which provides a measure
 261 of the size of the network citepLau2015, Borrett2014. We
 262 also calculated the centralization of each network, which
 263 measures the evenness of the distribution of interactions
 264 among the species in the network citeButts2005. In a net-
 265 work with a low level of centralization species have similar
 266 amount of interaction in the network, while a network
 267 with a high level of centralization tends to have one or
 268 small number of species that interact with other species.
 269 We used a related function to calculate the centrality of
 270 each species (i.e. node level centrality) in each network
 271 as well. The modularity of each network was also quanti-
 272 fied using a weighted algorithm citeBeckett2016, which
 273 measures the degree to which a given network is divided
 274 into groups of species more connected to each other than
 275

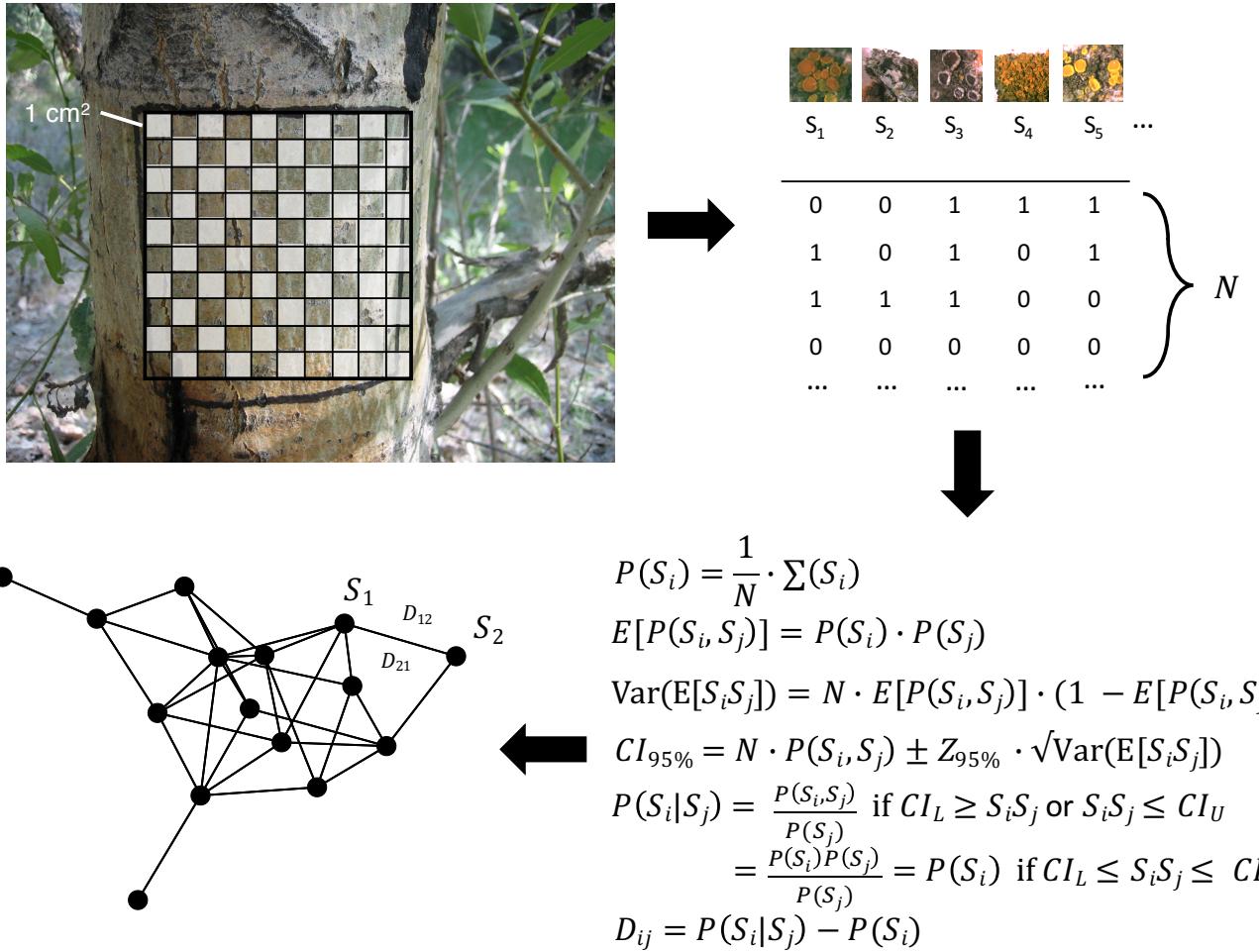


Fig. 2. Lichen interaction networks were constructed by conducting field observations in 1 cm^2 cells within a 10 cm^2 grid on each tree using a checkerboard pattern (grey cells). Thus, a set of N total cell observations were recorded for each tree with the presence or absence of each species recorded for each cell. Applying the probability-based network modeling method adapted from (14), 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_iS_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 .

other species. As with the other response variables, the number of links was log-transformed and both modularity and centralization scores were fourth-root transformed to meet variance and normality assumptions.

All code and data for the project are openly available online. Code and data are available at github.com/ecgen/comgen. The project is also archived via Zenodo at zenodo.com/doi/XXXXXX. All analyses were conducted using the programming language R version 3.6.1 (R Development Core Team 2019).

Results

1. Network structure responded to genotype
 - number of links responded
 - centrality responded
 - average mutual information responded

- Figure: chplot network metrics 293

2. Genotype indirectly influenced networks through bark roughness 294

- genotype predicted bark roughness (reml) 296
- bark roughness predicted network metrics 297
 - (L, Cen, AMI) 298
- Bark roughness was negatively correlated 299
 - with L, Cen and AMI 300
- genotype did not predict any residual variation 301
 - in lichen networks from bark roughness' effect 302
- Genotype didn't predict any other measured traits 304

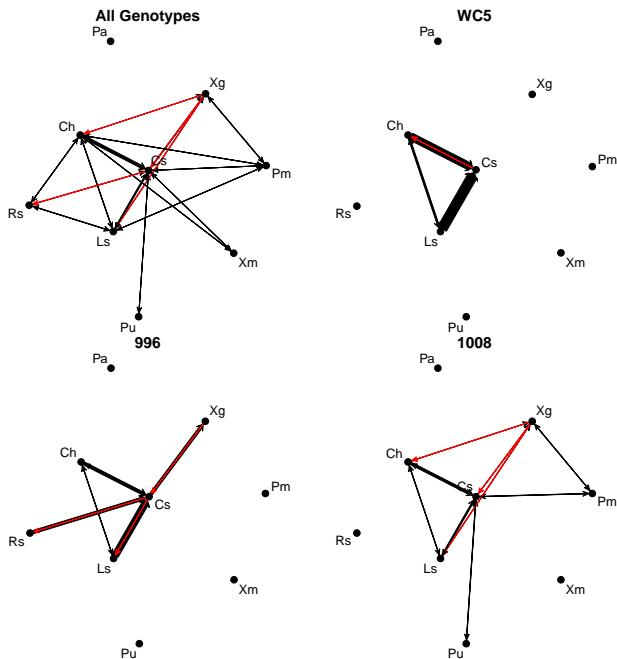


Fig. 3. Lichen networks varied in structure among tree genotypes. Network diagrams of the mean lichen interaction matrices averaged for all trees and for several individual genotypes showing a range of interaction network structure. Directionality (arrowheads) and sign (red = negative, black = positive) of interactions are shown as edges between species (abbreviated by the first letter of the genus and specific epithet), which are scaled by their magnitude. 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.

predictor of network similarity ($H^2 = 0.16$, *p-value* ≤ 0.001). Bark roughness ($H^2 = 0.38$, *p-value* ≤ 0.001) and condensed tannin concentration ($H^2 = 0.28$, *p-value* = 0.014) also showed a signature of tree genotype (Fig. 4); however, this was not the case for other tree traits, bark pH and carbon to nitrogen ratio. Also, none of the lichen network metrics were significantly predicted by tree genotype, either at the scale of the entire network (Table 1) or for individual species (see Supporting Information). Although both showed a response to tree genotype, bark roughness and condensed tannins were not correlated (Pearson's $r = 0.084$, *p-value* = 0.556).

| Response | H ² | p-value |
|-----------------------------|----------------|---------|
| Lichen Network Similarity | 0.413 | 0.0537 |
| Average Mutual Information | 0.3101 | 0.0253 |
| Degree Centralization | 0.3305 | 0.0196 |
| In-degree Centralization | 0.3487 | 0.0157 |
| Out-degree Centralization | 0.3193 | 0.0216 |
| In-Positive Centralization | 0.3309 | 0.0207 |
| In-Negative Centralization | 0.1057 | 0.2523 |
| Out-Positive Centralization | 0.3119 | 0.0252 |
| Out-Negative Centralization | 0.0513 | 0.3436 |
| Number of Network Links | 0.3156 | 0.0269 |
| Percent Lichen Cover | 0 | 1 |
| Lichen Species Diversity | 0 | 0.4558 |
| Lichen Species Richness | 0 | 0.458 |
| Lichen Species Evenness | 0 | 1 |
| Percent Rough Bark | 0.3221 | 0.0128 |
| pH | 0 | 1 |
| Carbon-Nitrogen (CN) Ratio | 0 | 1 |
| Condensed Tannins (CT) | 0.0041 | 0.4513 |
| BR-L Residuals | 0 | 1 |
| BR-Cen Residuals | 0.0113 | 0.4324 |
| BR-AMI Residuals | 0 | 1 |

Table 1. Genotypic effects on the associated lichen community.

Tree traits and lichen community metrics were correlated with lichen networks. The genetically based traits, bark roughness and condensed tannins were both significant predictors of network similarity (Table 2). Bark C:N ratio was also a significant predictor of network similarity, but, as shown previously (see Table 1), there is not sufficient evidence support a genetic basis for it. Bark pH was not a significant predictor of lichen network similarity (Table 2). The abundance, richness, evenness and diversity of the bark lichen community, although also not predicted by tree genotype, were all significantly correlated with lichen network structure (Table 2). Lichen community composition was not correlated with lichen network similarity, either when species abundances were relativized (Mantel R = -0.09, *p-value* = 0.139)

- No other bark traits predicted network metrics

3. Centrality was a collective response

- centrality varied among species
- individual species centrality did not respond to genotype
- mantel?
- Figure: barplot + post-hoc

4. The lichen networks also responded to non-genetically based variation in the community

- Bark roughness not correlated with lichen PC, SR, SE, SD
- PC negatively correlated with Cen
- SR positively correlated with L
- SE positively correlated with L
- SD positively correlated with L, Cen

Network similarity and several tree traits were genetically based. Tree genotype was a significant

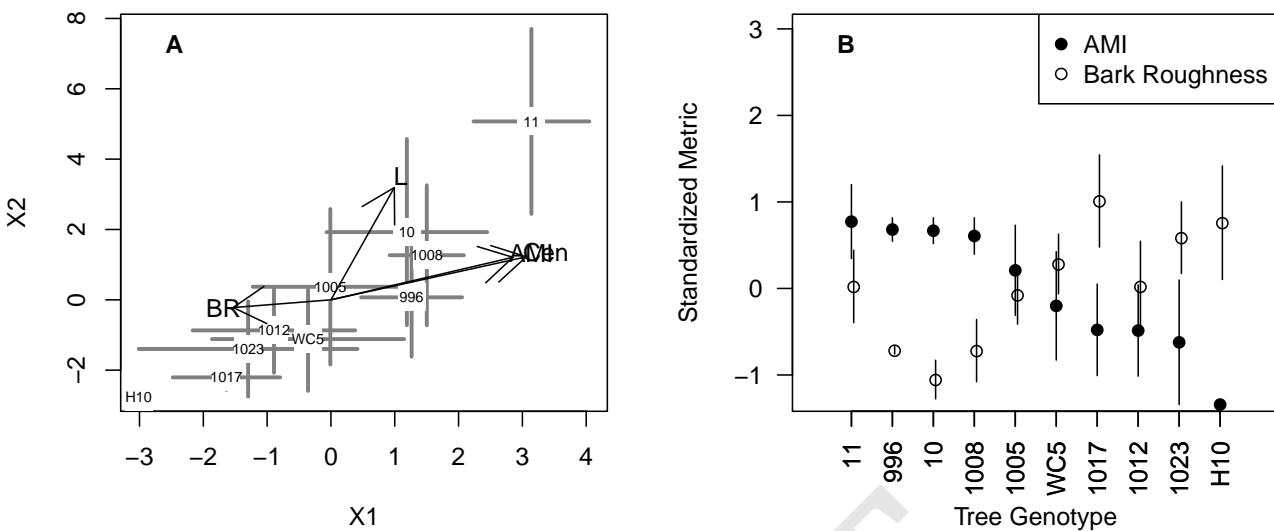


Fig. 4. Tree genotype affected lichen networks and several bark traits. A. The plot shows genotype centroids of NMDS ordinated ($R^2 = 0.999$, stress = 0.008) lichen networks (± 1 S.E.). Centroids that are closer are more similar in the structure of their lichen networks. B. Plot showing the standardized ($\frac{x - \bar{x}}{\sigma}$) means (± 1 S.E.) for the two genetically based tree traits: tree bark roughness and condensed tannin concentration.

353 or not (Mantel $R = -0.03$, $p\text{-value} = 0.573$).

| | df | SS | R2 | F | p-value |
|----------|---------|------------|--------|--------|---------|
| geno | 9.0000 | 44078.1327 | 0.5442 | 3.5821 | 0.0537 |
| Residual | 27.0000 | 36915.4605 | 0.4558 | | |
| Total | 36.0000 | 80993.5932 | 1.0000 | | |

Table 2. PERMANOVA Pseudo-F Table of lichen network similarity to genotype.

354 Discussion

- 355 • We found:
 - 356 – Lichen networks genetically based
 - 357 – Bark roughness was the primary genetically
 - 358 – based trait driving network structure
 - 359 – Lichn networks also varied with cover, rich-
 - 360 – ness and diversity of the lichen commu-
 - 361 – nity, which were not correlated with rough-
 - 362 – ness and primarily driven by one dominant
 - 363 – species
- 364 • What mechanisms could be at play?
- 365 • Habitat filtering of communities (richness, com-
- 366 – position) vs environmental influence on inter-
- 367 – actions. Likely a combination of both of these
- 368 – factors.

- Lichen network structure correlated with species richness, evenness and diversity
- Lichen community composition not correlated with network structure
- None of these were genetically based
- An important consequence for diversity is that genotypes could be supporting unique communities, even if the composition of the communities is the same among individuals and genotypes.
- Genetic diversity could be influencing the stability of communities through the effects on interactions. Some network structures are likely to be more stable, either in response to disturbance or via self-organized dynamics. Although, none of the metrics examined, such as the number of links, modularity or centrality, showed a genetic signature.
- Important factors to consider in studies of other ecological networks:
 - Relative body size
 - Mobility
 - Reproductive isolation

- 391 • Future work should consider the potential influence
392 on evolutionary dynamics of communities
393 – Network structure influences network stability
394 – Are the communities nested subsets?
395

396 **TGW: I think window is too vague and this**
397 **topic sentence needs to be much stronger for**
398 **a journal like PNAS. Might be stronger by**
399 **saying "Our findings argue there is a genetic**
400 **component to network structure, which im-**
401 **pplies that network structure could be subject**
402 **to selection and networks can evolve."**

403 **TGW: Could we also make the comparsion**
404 **that genetically more similar trees also have**
405 **more similar communities? We've done this**
406 **in the past and it has worked, e.g., Randy's**
407 **genetic similarity rule.**

- 408 • Genetic assembly rule = similar genetics will
409 have more similar communities
410 • What we don't know is whether or not these
411 interactions will also lead to similar interactions
412 among other species.
413 • Thus, it would be possible for genetics to not
414 only influence other species directly, but also
415 indirectly by influencing the interactions among
416 other species.

417 We observed significant lichen interaction struc-
418 ture that varied among genotypes of a foundation
419 tree species, narrowleaf cottonwood (*P. angustifo-*
420 *lia*). We found that a genetically based trait, bark
421 roughness, partially explained the variation in lichen
422 interaction networks. Some of this variation in lichen
423 networks was related to both the overall abundance
424 and species richness of lichen; though, statistically
425 controlling for the effect of genotype on these vari-
426 ables indicates that a significant portion of the vari-
427 ance in lichen species richness is due to a factor
428 other than tree genotype. By using network metrics,
429 we were also able to probe for specific characteris-
430 tics of how these networks were responding to tree
431 genotype. We found that both number of links and
432 the centralization of the networks were highly corre-
433 lated with network similarity and that tree genotype
434 significantly predicted network centrality but only
435 marginally predicted the number of network links.

This latter result could be due to the relationship
436 between species richness and the number of links
437 in the network, which were significantly correlated
438 with each other. We also found that bark roughness
439 did not significantly predict either the number of
440 links or the centrality of lichen networks, suggesting
441 that bark roughness has some other effect on the
442 structure of the lichen networks. Taken together,
443 these findings support the hypothesis that genotypic
444 variation in a foundation species contributes to the
445 structure of a network of interacting species.
446

LJL: I wonder if you need to have so much
447 **on richness here. Overall, I think you want to**
448 **focus on the network responses and patterns**
449 **among genotype first, and then go into mech-**
450 **anism later. I think we don't quite have a**
451 **good mechanism yet so I don't think it needs**
452 **to come up in the first paragrph of the dis-**
453 **cussion.**
454

These findings point to the importance of under-
455 standing the community level effects of genetic varia-
456 tion in plant functional traits and highlights the
457 potential for indirect effects of genetic variation to
458 propagate through networks of interacting species
459 and trophic levels.
460

This work corroborates previous findings of the
461 importance of plant genetics in shaping community
462 structure and ecosystem processes. citepBangert2008
463

Altering the structure of interaction networks
464 presents a means for genetic effects to be magni-
465 fied within the system of interacting species. For
466 example, (8) showed that the genetics based interac-
467 tions of aphid resistant and aphid susceptible trees
468 resulted in different interaction networks of their
469 associated arthropod communities composed of 139
470 species. At the scale of ecosystems, trophic net-
471 works or food webs direct and control the rates of
472 energy and nutrient flux (16). Furthermore, in a
473 predator-prey-plant study, Smith (17), showed that
474 the interactions among species across trophic levels
475 depended on plant genotype.
476

Also, work by (18–20) observed consistent pat-
477 terns of centralized interactions of species modules
478 focused around hubs of plant-fungal interactions. In
479 other words, a small number of plant and fungal
480 symbionts tended to have disproportionate numbers
481 of interactions with other species and likely are the
482 drivers in determining community assembly, struc-
483 ture and dynamics.
484

485 More on the importance of ecological networks
486 (21, 22).
487

From Thompson2014

- 488 • Pairwise interactions are usually influenced by
489 other species
- 490 • Selection favors the development of small webs
- 491 • Evolution of new lifestyles leads to changes in
492 selection on large and small webs

493 Specific hypothesis from Thompson2014

494 **LJL:** If I recall, the Elamo paper just looks
495 at genetic correlations between pairwise individual
496 abundances. I would suggest maybe it
497 doesn't deserve to be in this 1st paragraph.
498 Perhaps it actually should be in the 2nd or
499 3rd paragraph, just as a reference that points
500 to the potential for genotype to influence networks.
501 Definately our 2015 JOE paper goes
502 much further, too, since it has whole communities
503 being correlated. But, again, I
504 woudl put both of these as citation in the community
505 genetics paragraphs (2 of 3) instead
506 of the first paragrphah, which focuses on the
507 general network lit.

508 **LJL:** It could be useful to point out that
509 our findings are not related to trophic interactions,
510 which is pretty cool. Also,we talk
511 about interaction networks but it is not clear
512 to me if the interactions tend to be positive
513 or negative. Can we get at that with the approach used?

515 **TGW:** Is there any adaptive component to
516 the tree in having certain lichen communities?
517 e.g., can they feed back to affect tree
518 performance in some way or is this a passive
519 outcome of a trait that affects bark for
520 other adaptive reasons and lichens are passive
521 players that tag along for the ride? I
522 could envision that lichens covering the bark
523 of a tree act as a barrier between insects and
524 pathogens, much like ectomycorrhizae cover
525 fine roots as a first line of defense by invading
526 microorganisms. Uptake of N that gets
527 passed to the tree??

528 **LJL:** I agree that there is a general over-
529 arching theme that evolution occurs in a com-
530 munity network context, but I'm not sure

that we should state that as our main hypothesis. It seems more that this is a fundamental foundation for our work. The hypothesis is more what we are testing directly, but we don't test this directly. I guess I don't want to give the impresison that our communities are necessarily the result of each species evolving into its place in the community on these tree genotypes (although I do understand this as Shuster et al 2006's fundamental explanation for why we see different communities on different genotypes; I don't necessarily agree that this is the only reason we woudl see different communities on dif genotypes). Most of these are pretty generalist lichens, which could be found on other deciduous trees in the surrounding city or natural areas. I would look at it more like an assembling of lichen species into unique configurations on genetically different substrates. There may be some selection for different genotype of lichen during the community assembly process but we can't really tell that just by differences in species abundances or coocurneces. I guess to me the evolutionary context that is more direclty related to this work is that the tree genotype is a central controller (indeed a sort of hub species in the network) of network structure. By anchoring the lichen network to tree genotype (and variation among networks to variation among tree genotypes) , our study highlights the possibility that natural selection acting on the trees may have an extended consequence for the network structure of organisms living on the trees...the extra thing we add to the field is that we show interaction networks are sensitive to genotype. I doubt the lichens have a direct effect on tree fitness, but favorability of some tree genotypes over others during natural selection will then go on to favor and disfavor certain lichen communities of different network structures. By being sensitive to tree genotype, the lichen community networks are passive riders on the waves of evolutionary dynamics that occur within the tree species they inhabit.

MKL: In response to Lamit's comment above, I agree that it is not reuired that

580 there is co-evolution. Another, perhaps simpler, explanation is that there is variation in
581 environmental filtering of lichen individuals
582 created in part by genetic variation in tree
583 individuals.
584

585 TGW: might be good to cite papers on
586 competition in lichens or other organizing fac-
587 tors to back up the least expected statement.
588 as epiphytes we might not expect them to
589 care.

590 TGW: I think we need to emphasize the
591 long-term nature of our common garden
592 study as very few common garden studies of
593 lichens likely exist. Any refs on this? If true
594 might want to mention this up front in intro.

595 MKL: Environmental filtering is evidenced
596 by species richness, but also possibly species
597 interaction varying based on environment as
598 networks varied in terms of sign and magni-
599 tude as well.

600 MKL: The effect of bark roughness on
601 network similarity was primarily genetically
602 based, and there are likely other factors at
603 play.

604 Discussion of network implications for sta- 605 bility with genetics.

606 Bark roughness had previously been shown to be
607 an important tree trait influencing bark lichens (13)
608 that is under strong genetic control (23).

609 Although our study was conducted with a commu-
610 nity of lichens, these results should be generalized
611 to other groups of diverse organisms around the
612 world that also exhibit significant genetic signals at
613 the community level (24, 25). In the face of the
614 high degree of complexity and potential context de-
615 pendence of ecological processes, the current study
616 points to the utility of considering the spatial and
617 temporal scales of interactions, as discussed to some
618 in previous studies (26–28). In the present study,
619 we found that community assembly processes, such
620 as environmental filtering and species interactions,
621 are genetically based. This is likely due, in part,
622 to the large difference in the differences in size and
623 longevity of the lichen and cottonwood individuals
624 with the trees determining the environment in which
625 the lichen occur. We suggest that future work would
626 be aided by determining these modules within the
627 biotic community that include species with similar
628 differences in body-size and time-scales. As heritable

629 variation is the raw material for natural selection
630 to act upon, a genetic basis for interaction network
631 structure indicates evolutionary dynamics should be
632 considered at the community level and that con-
633 serving genetic variation is important to consider in
634 efforts to restore or preserve complex species interac-
635 tions and their associated ecosystem functions (29).
636 With such findings, it appears that we are closer to
637 understanding the evolutionary drivers of Darwin's
638 entangled bank and the interconnectedness of species
639 in complex communities.

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646 and David Solance Smith.

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Assessment and Results

- Network similarity not genetically based 707
- Genetically based number of links and centrality but 709
not modularity 710
- Lichen cover, richness, evenness, diversity and com- 711
position not genetically based 712
- Roughness genetically based but not bark condensed 713
tannins, CN or pH 714
- Bark roughness correlation with number of links 715
(yes) and centrality (yes)? <- TODO add figure A 716
= mdc.plot(L, Cen), B = (ch.plot(L,Cen,geno), BR 717
vector)) 718
- Centrality values for species <- censpp.pdf 719
- Redo haritability calculations 720
- Jamie double check genotype network permanova in 721
PRIMER 722
- Jamie double check reml's in R 723

Tables.

724

| Response | H2 | p-value |
|-----------------------------|--------|---------|
| Lichen Network Similarity | 0.413 | 0.0537 |
| Average Mutual Information | 0.3101 | 0.0253 |
| Degree Centralization | 0.3305 | 0.0196 |
| In-degree Centralization | 0.3487 | 0.0157 |
| Out-degree Centralization | 0.3193 | 0.0216 |
| In-Positive Centralization | 0.3309 | 0.0207 |
| In-Negative Centralization | 0.1057 | 0.2523 |
| Out-Positive Centralization | 0.3119 | 0.0252 |
| Out-Negative Centralization | 0.0513 | 0.3436 |
| Number of Network Links | 0.3156 | 0.0269 |
| Percent Lichen Cover | 0 | 1 |
| Lichen Species Diversity | 0 | 0.4558 |
| Lichen Species Richness | 0 | 0.458 |
| Lichen Species Evenness | 0 | 1 |
| Percent Rough Bark | 0.3221 | 0.0128 |
| pH | 0 | 1 |
| Carbon-Nitrogen (CN) Ratio | 0 | 1 |
| Condensed Tannins (CT) | 0.0041 | 0.4513 |
| BR-L Residuals | 0 | 1 |
| BR-Cen Residuals | 0.0113 | 0.4324 |
| BR-AMI Residuals | 0 | 1 |

Table 1. Genotypic effects on the associated lichen community.

| | Df | SumOfSqs | R2 | F | Pr(>F) |
|----------|---------|------------|--------|---------|--------|
| BR | 1.0000 | 21021.8765 | 0.2595 | 13.0299 | 0.0096 |
| CT | 1.0000 | 2349.3142 | 0.0290 | 1.4562 | 0.2016 |
| pH | 1.0000 | 2098.8999 | 0.0259 | 1.3010 | 0.2899 |
| CN | 1.0000 | 3896.1757 | 0.0481 | 2.4150 | 0.1890 |
| Residual | 32.0000 | 51627.3270 | 0.6374 | | |
| Total | 36.0000 | 80993.5932 | 1.0000 | | |

Table 3. PERMANOVA Pseudo-F Table of lichen network similarity response to bark traits.

| | L | Cen | AMI |
|----|------|-------|------|
| PC | 0.00 | -0.46 | 0.00 |
| SR | 0.47 | 0.00 | 0.00 |
| SE | 0.45 | 0.00 | 0.00 |
| SD | 0.59 | 0.33 | 0.00 |

Figures.

725

| | R2 | p-value |
|--------|-------|---------|
| br_L | 0.210 | 0.005 |
| br_Cen | 0.190 | 0.006 |
| br_AMI | 0.170 | 0.012 |
| ct_L | 0.020 | 0.359 |
| ct_Cen | 0.010 | 0.641 |
| ct_AMI | 0.000 | 0.831 |
| ph_L | 0.000 | 0.948 |
| ph_Cen | 0.000 | 0.746 |
| ph_AMI | 0.000 | 0.825 |
| cn_L | 0.020 | 0.432 |
| cn_Cen | 0.030 | 0.345 |
| cn_AMI | 0.020 | 0.435 |

| | df | SS | R2 | F | p-value |
|----------|---------|------------|--------|--------|---------|
| geno | 9.0000 | 44078.1327 | 0.5442 | 3.5821 | 0.0537 |
| Residual | 27.0000 | 36915.4605 | 0.4558 | | |
| Total | 36.0000 | 80993.5932 | 1.0000 | | |

Table 2. PERMANOVA Pseudo-F Table of lichen network similarity to genotype.

| | Df | SumOfSqs | R2 | F | Pr(>F) |
|----------|---------|----------|--------|--------|--------|
| geno | 9.0000 | 1.5049 | 0.2001 | 0.7507 | 0.8878 |
| Residual | 27.0000 | 6.0143 | 0.7999 | | |
| Total | 36.0000 | 7.5193 | 1.0000 | | |

Table 4. Pseudo-F Table of lichen community similarity PERMANOVA.

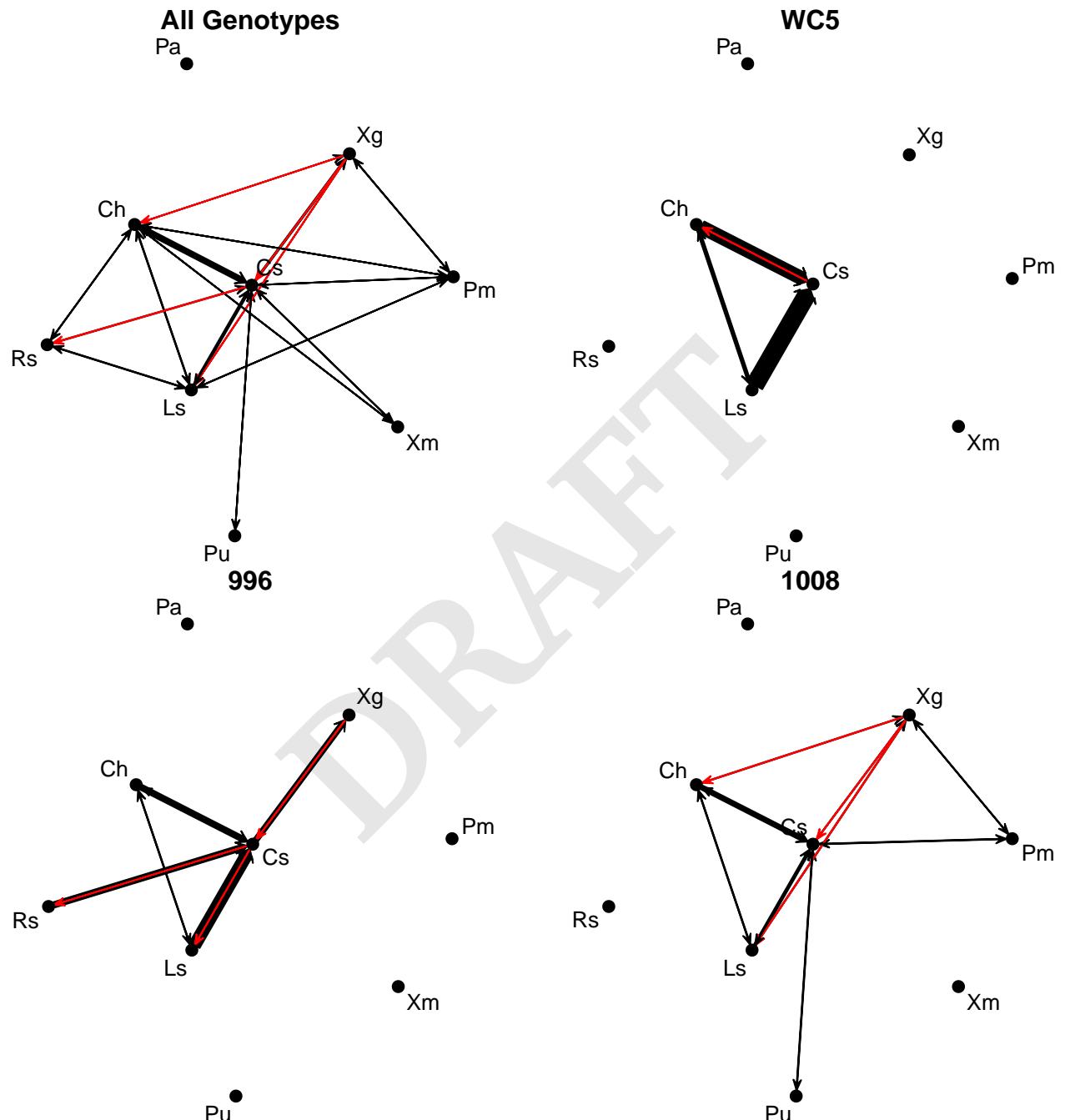


Fig. 1

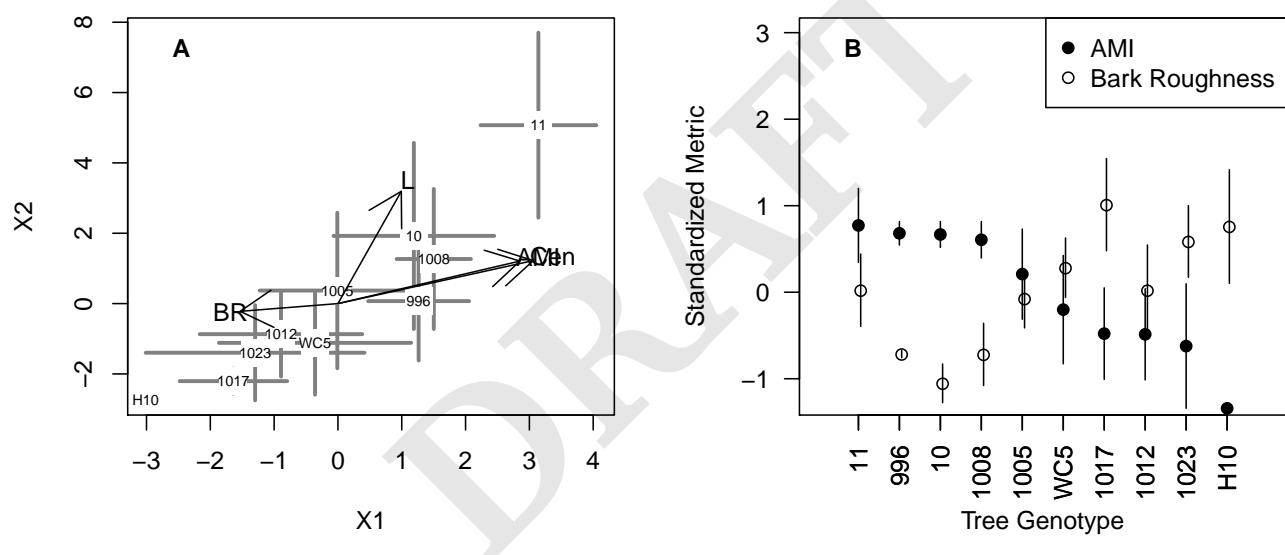


Fig. 2

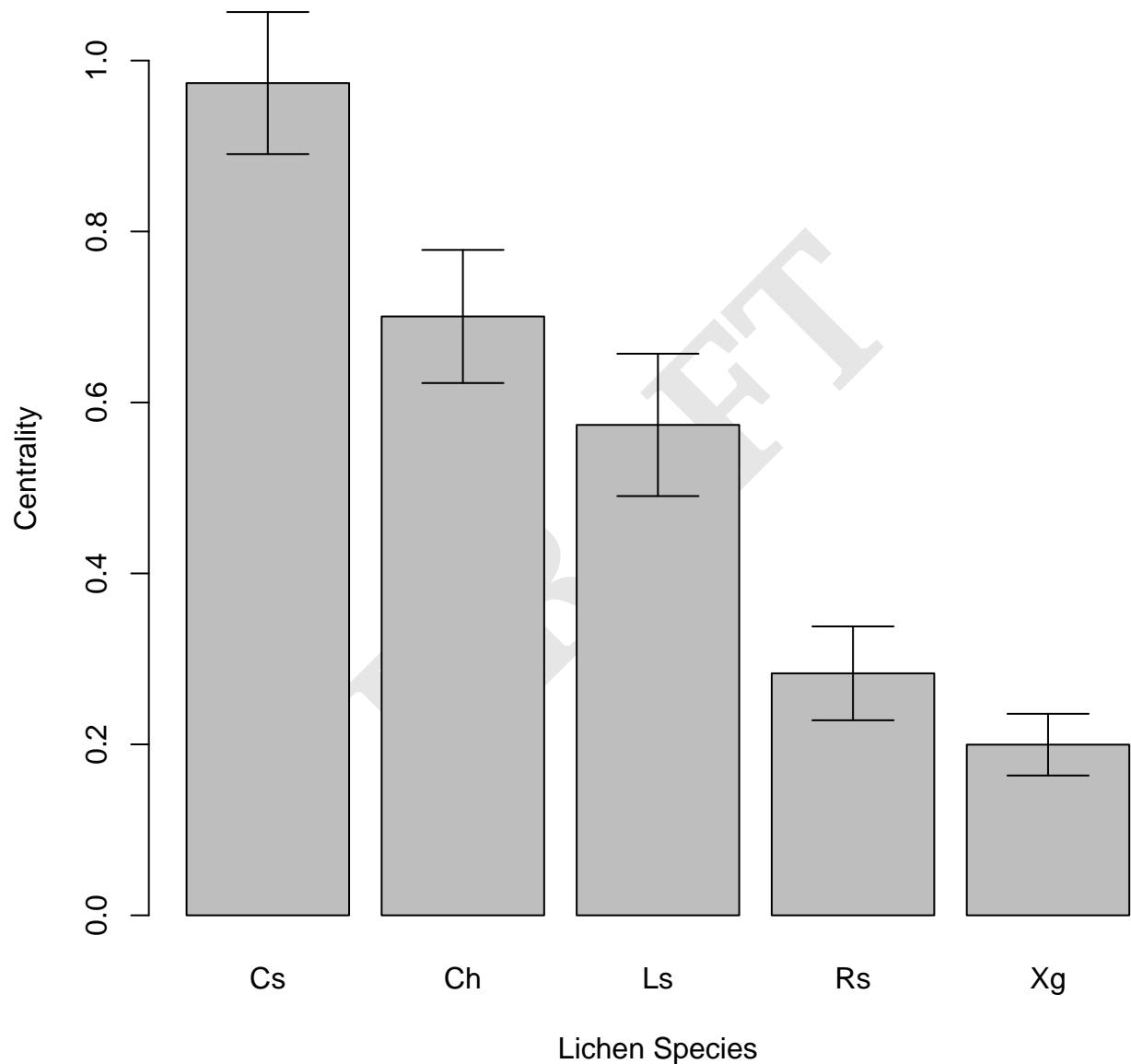


Fig. 3

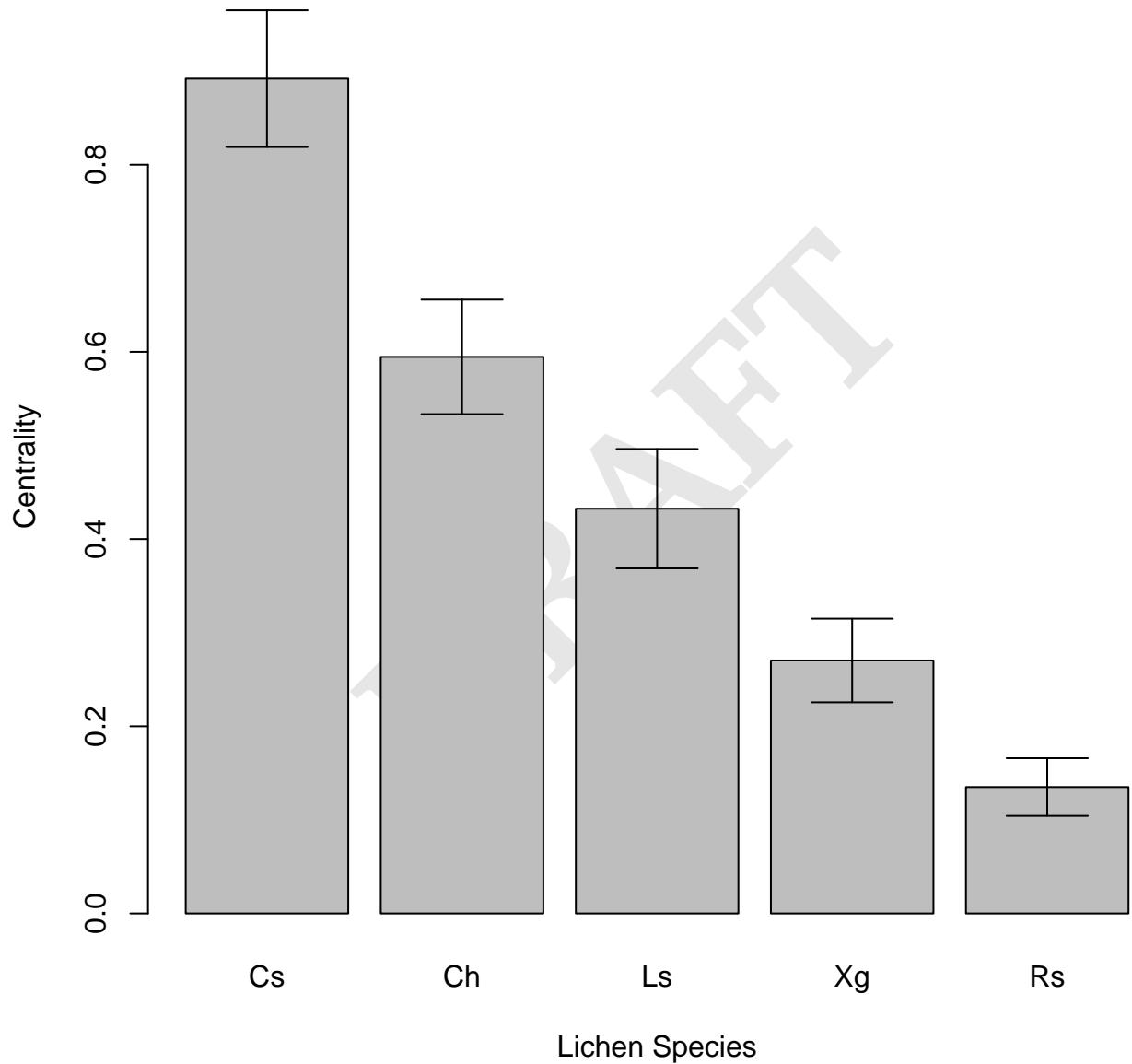


Fig. 4

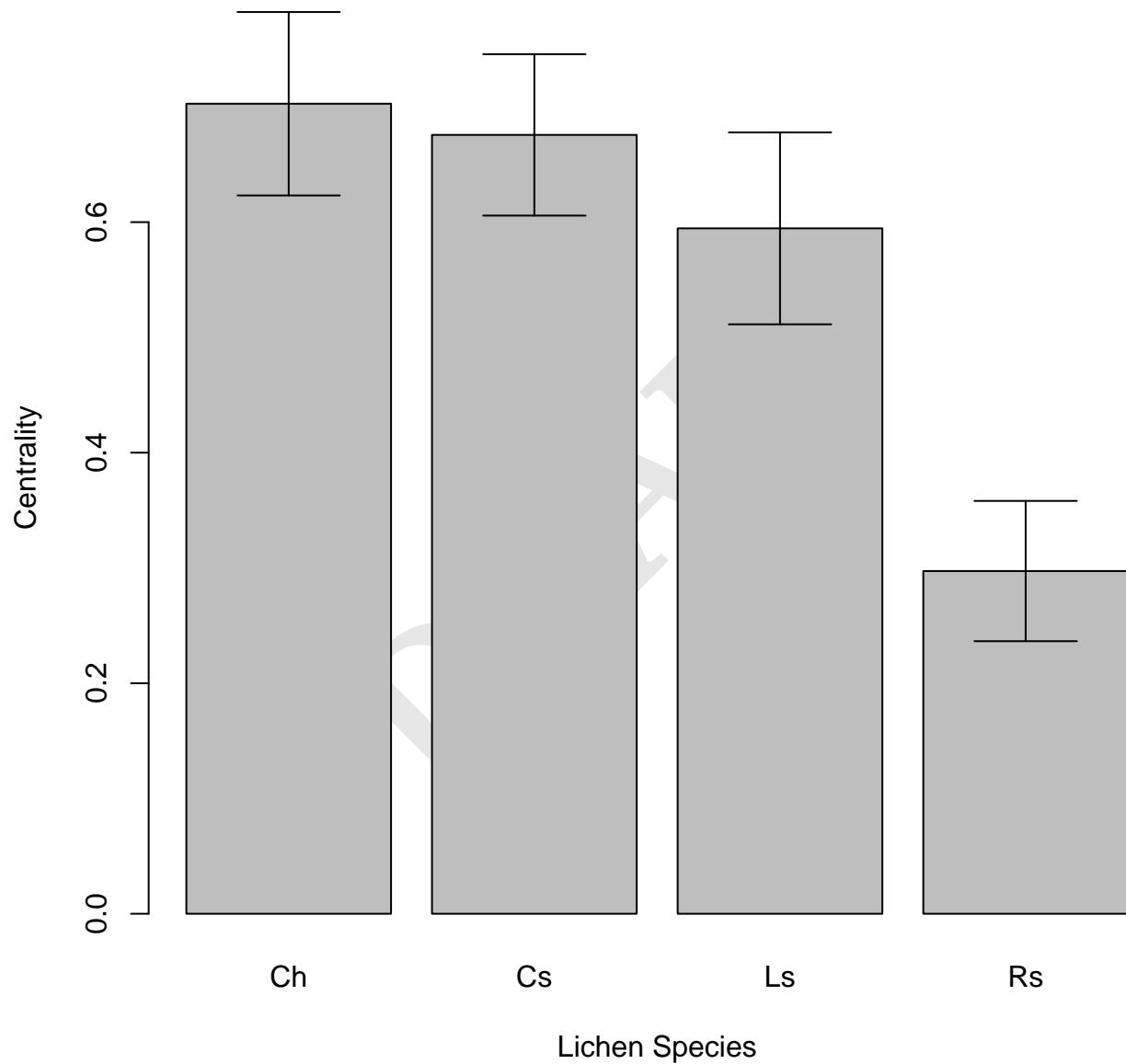


Fig. 5

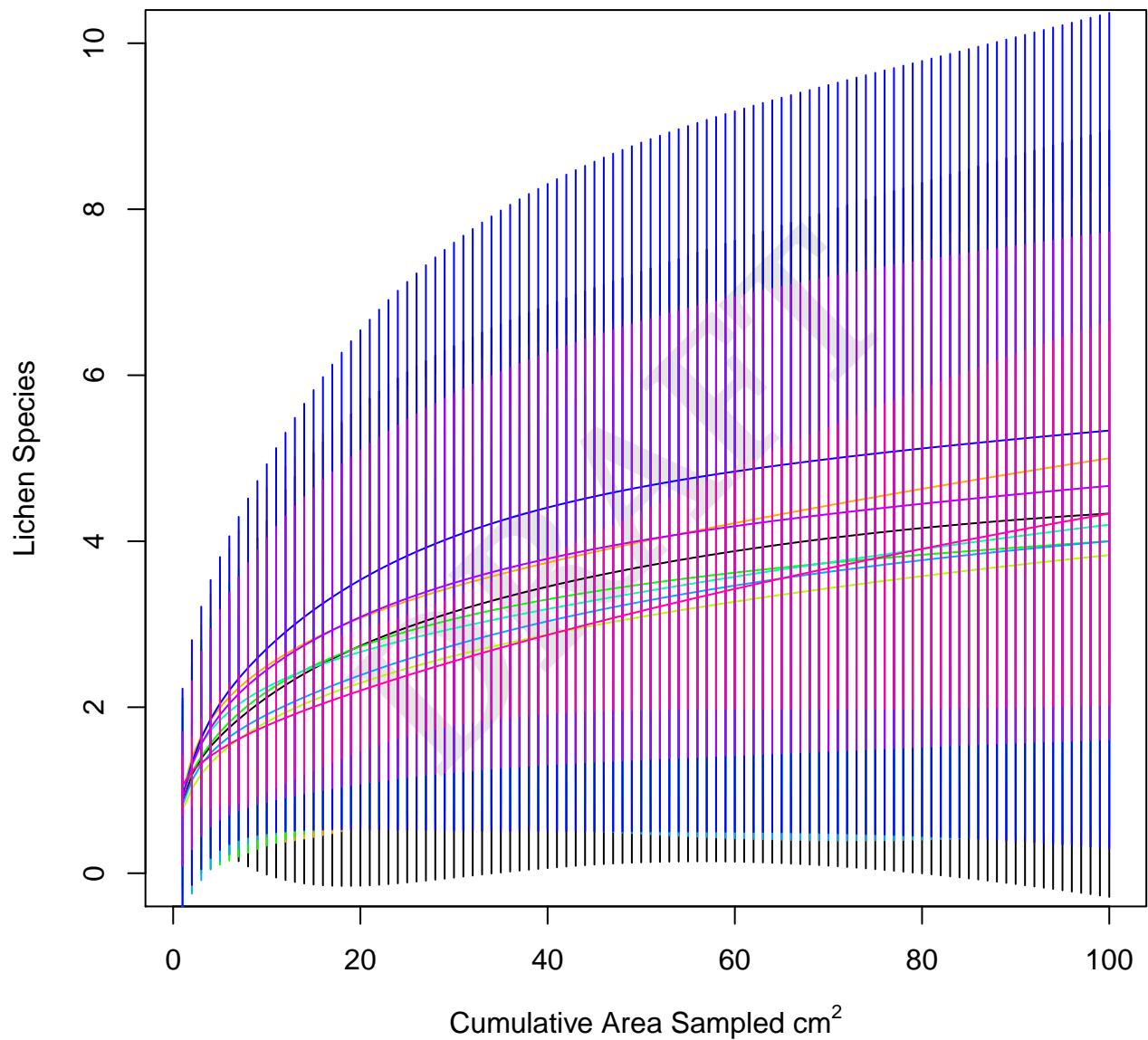


Fig. 6. Species area curve by genotype.

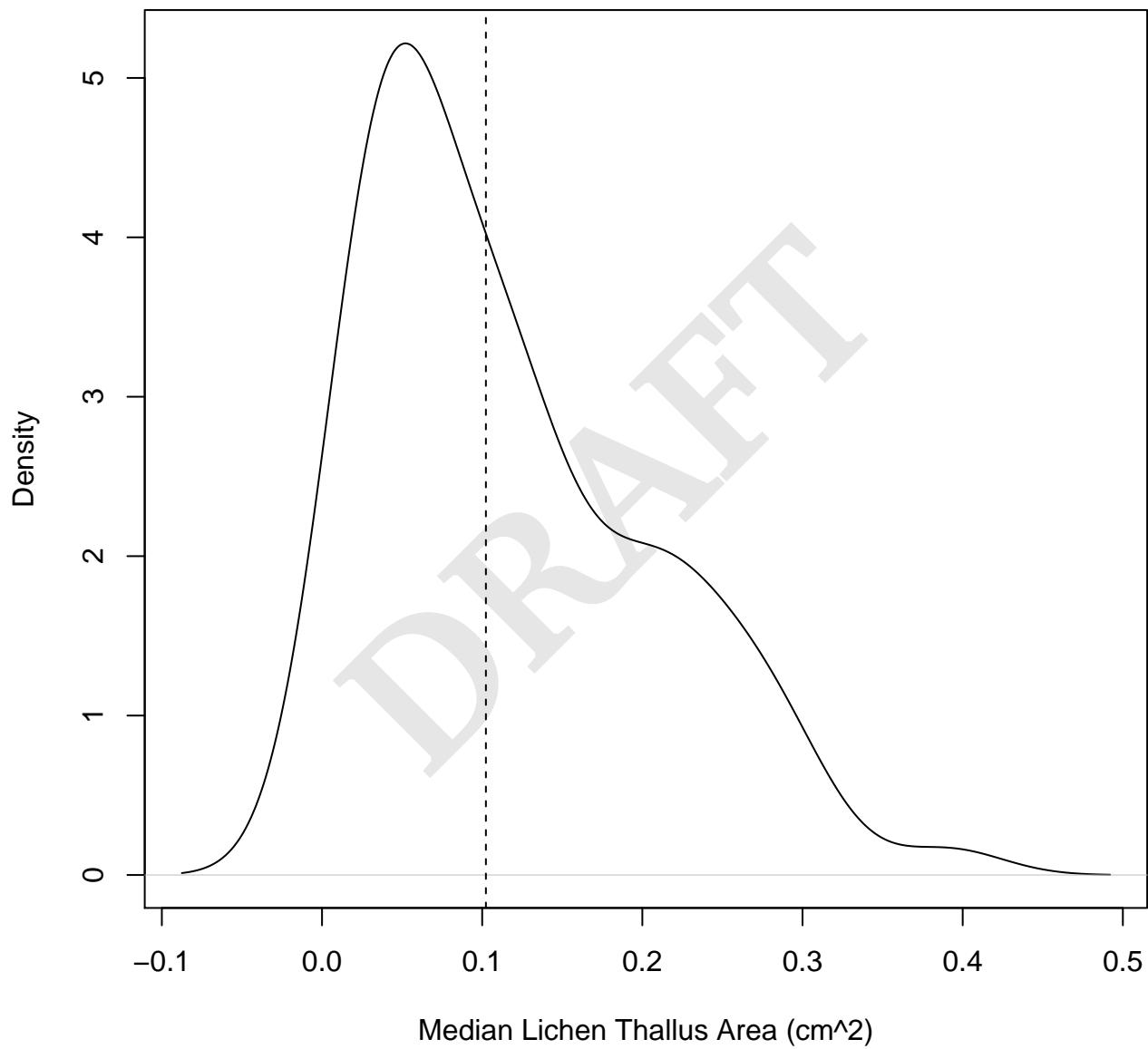


Fig. 7