Modeling co-evolutionary dynamics of *L. pulmonaria* lichen symbiosis

Carrignon S, Ollé-Vila A, Adams J, Duran-Nebreda S

Outline

1. What is a lichen?

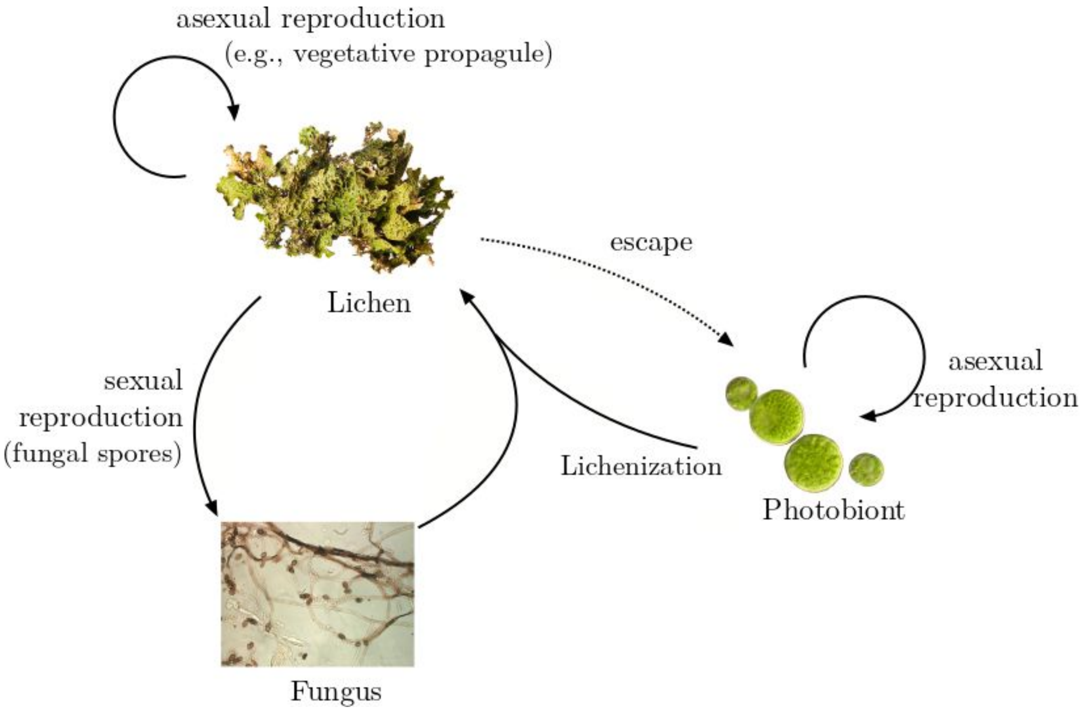
2. Computer Simulation, the “ECHO” model

3. Validation & Exploration

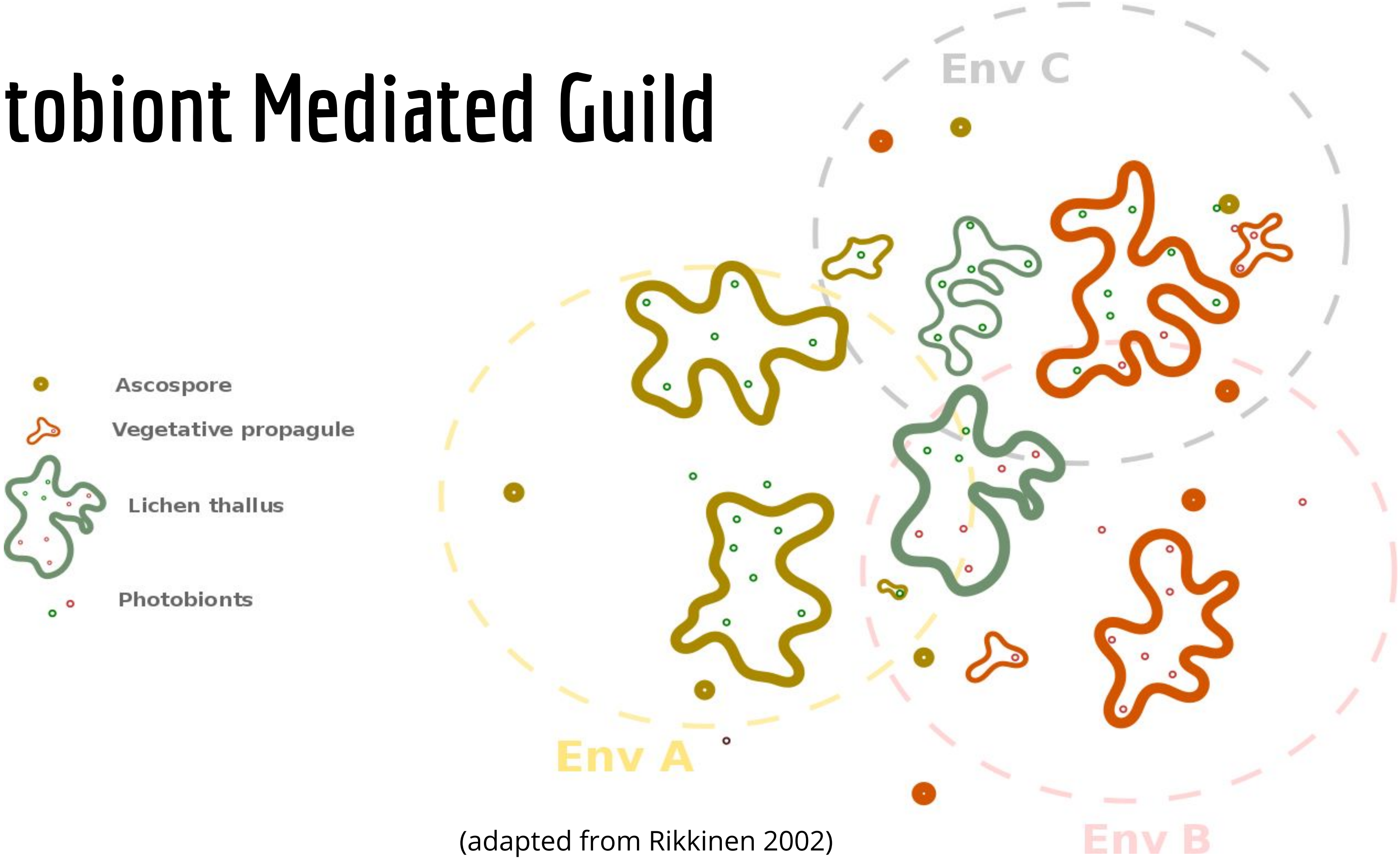
What is a lichen?

- Symbiosis between a fungus and a photobiont (cyanobacteria, algae).
- They thrive in different *niche*: trees/rocks, dry/humid, etc.
- Hyperdiverse (morphologically and genetically), performing numerous ecological functions.

Lichen life cycle



Photobiont Mediated Guild



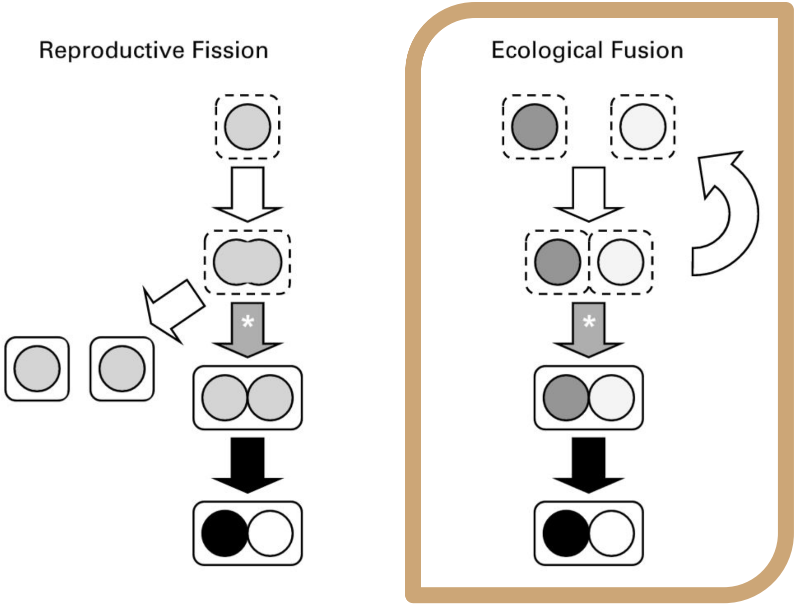
(adapted from Rikkinen 2002)

Major Transition

- Highly succesful symbiotic interaction between widely different and coevolving partners.

- Levels of selection. A frozen stage of a major transition in evolution?

What has shaped their coevolution and might continue to do so in the future?



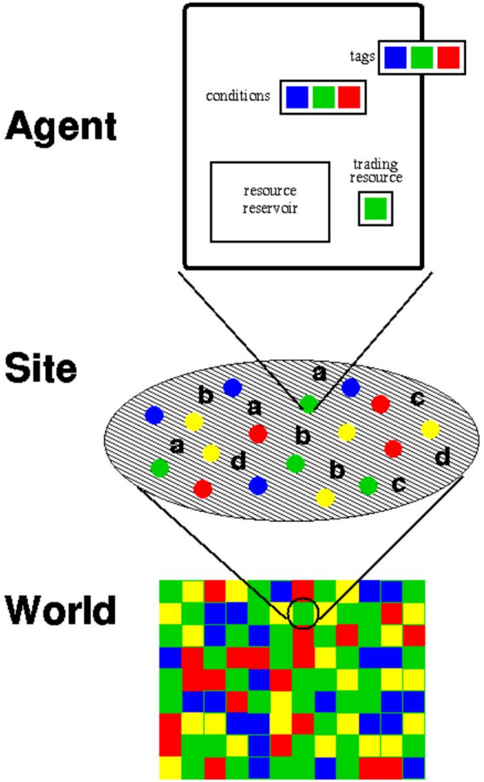
Kerr and Nahum (2011) *The Major Transitions in Evolution Revisited.*

Empirical Challenge

- Studies at large spatial and temporal scales

- Complex evolutionary dynamics involving heterogeneous and delicate biological entities

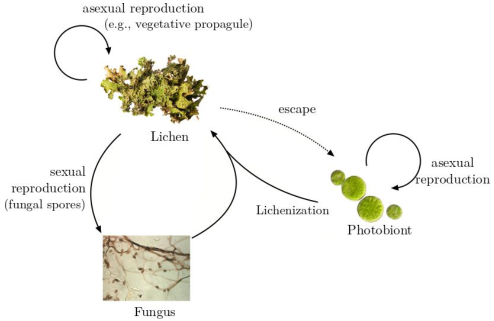
The ECHO model



fungi tag: 010101000101001

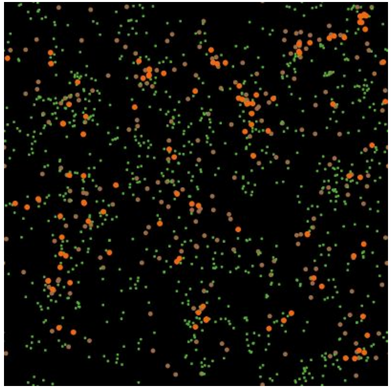
algae tag: 110101011001101

the more similar the more likely that lichen will be formed.



- ABM consisting of entities and a simplified spatial domain.

- Agents contain a genotype (symbol string) that mutates and directs interactions between entities (combat, trade, mating, etc.).

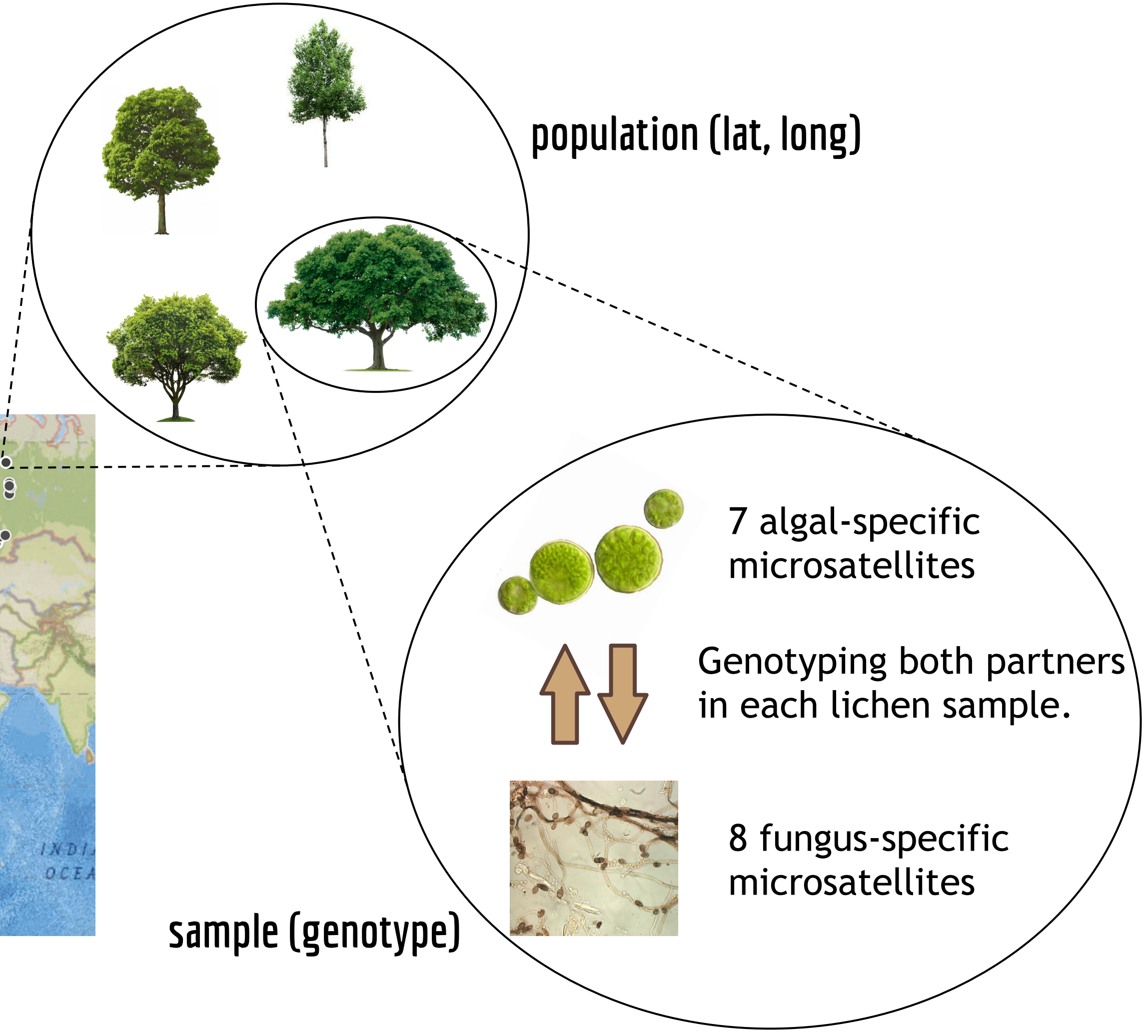


Validation step

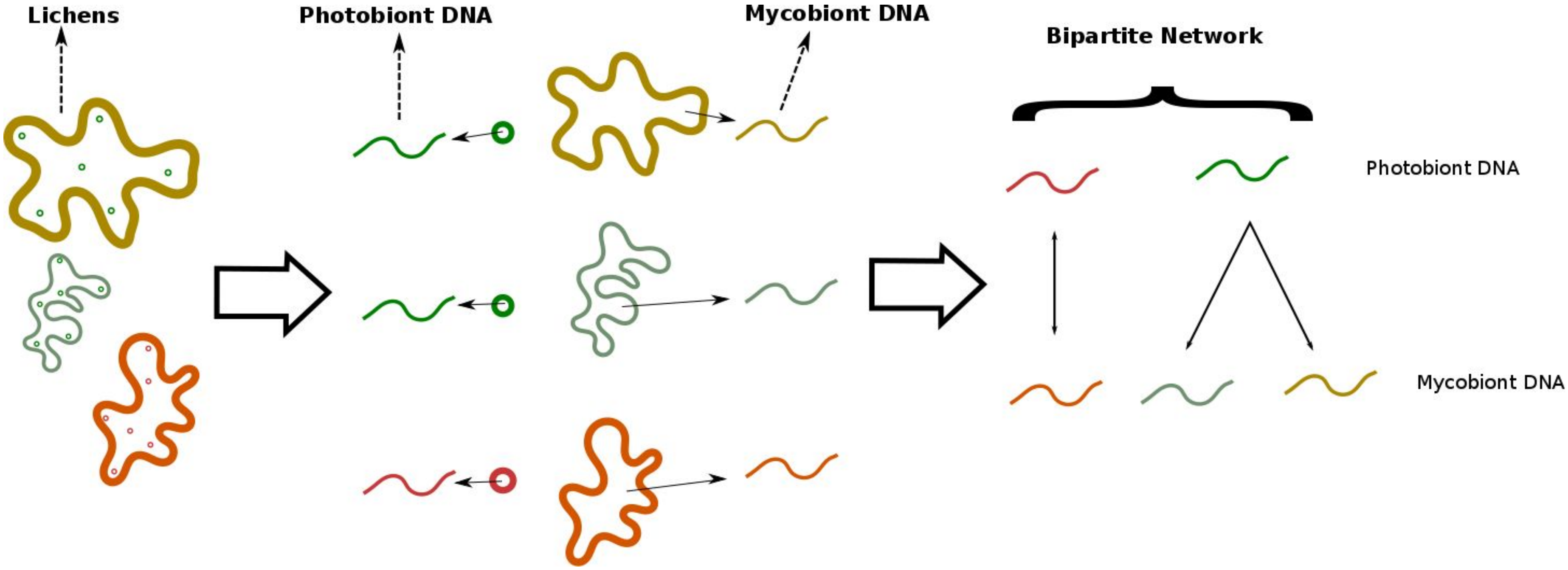
Verify that the model is able to reproduce properties observed in real systems
(data set used: Dal Grande et al. 2012)

Data set

L. Pulmonaria
(Dal Grande *et al*. 2012)



Symbionts bipartite network



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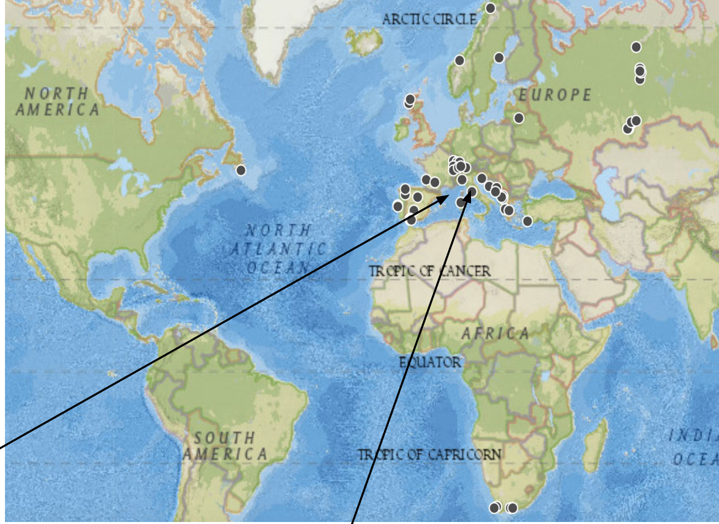
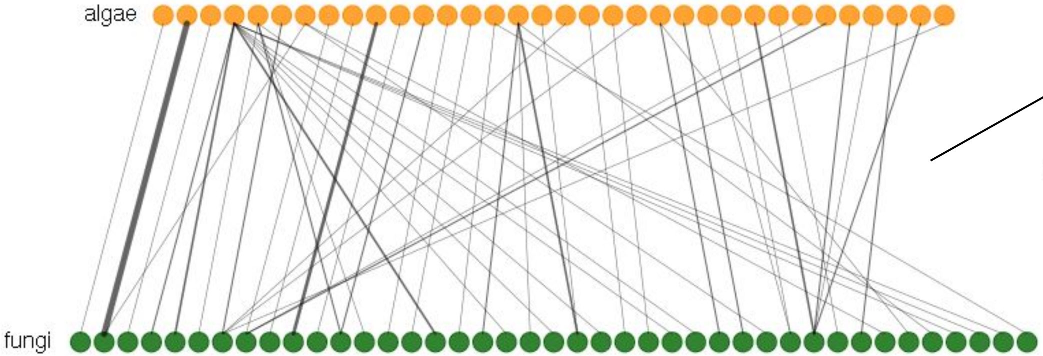
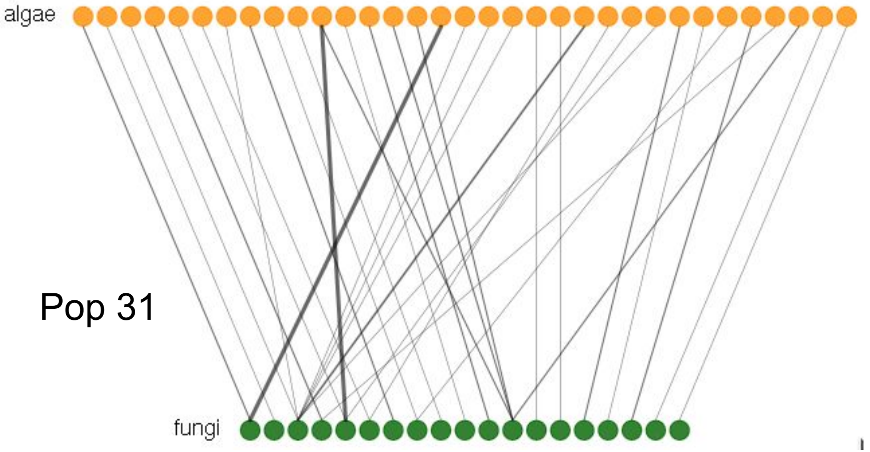


Pop 29

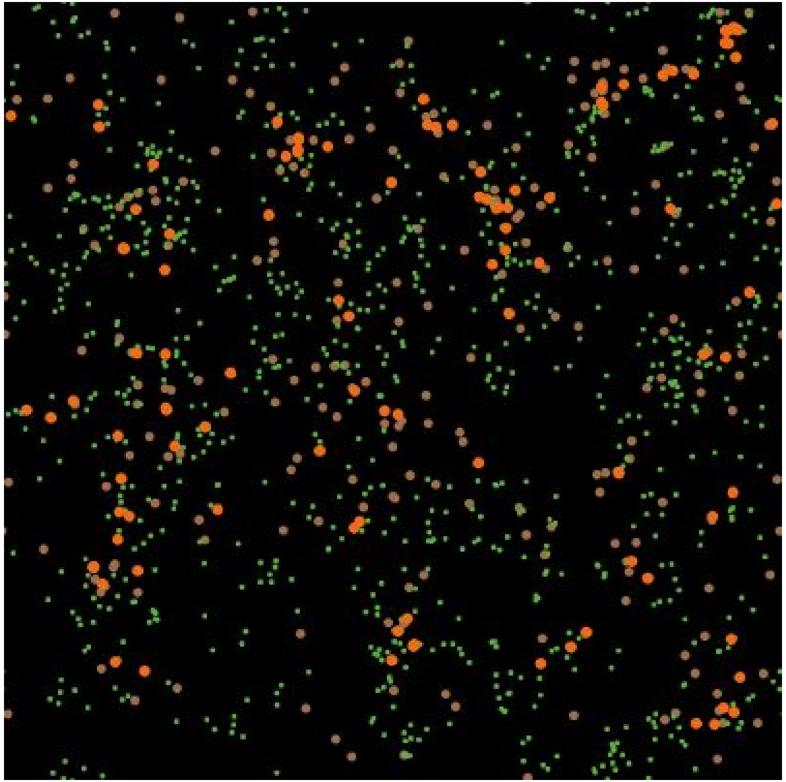




Pop 31

Scale Model Result

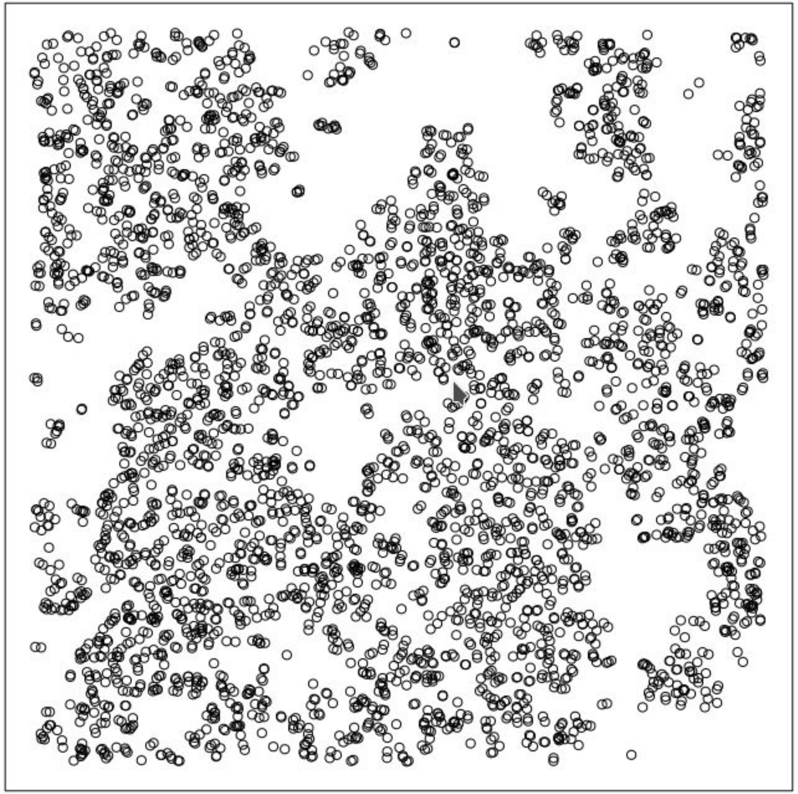
Original model result:



Scale Model Result

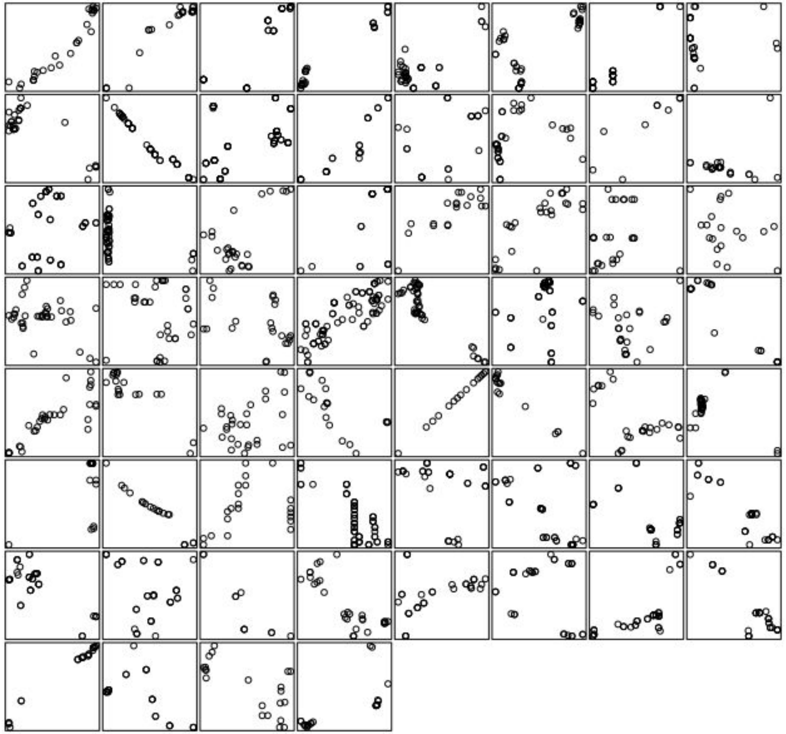
Original model result:

Model ouptut
after 10000 timestep

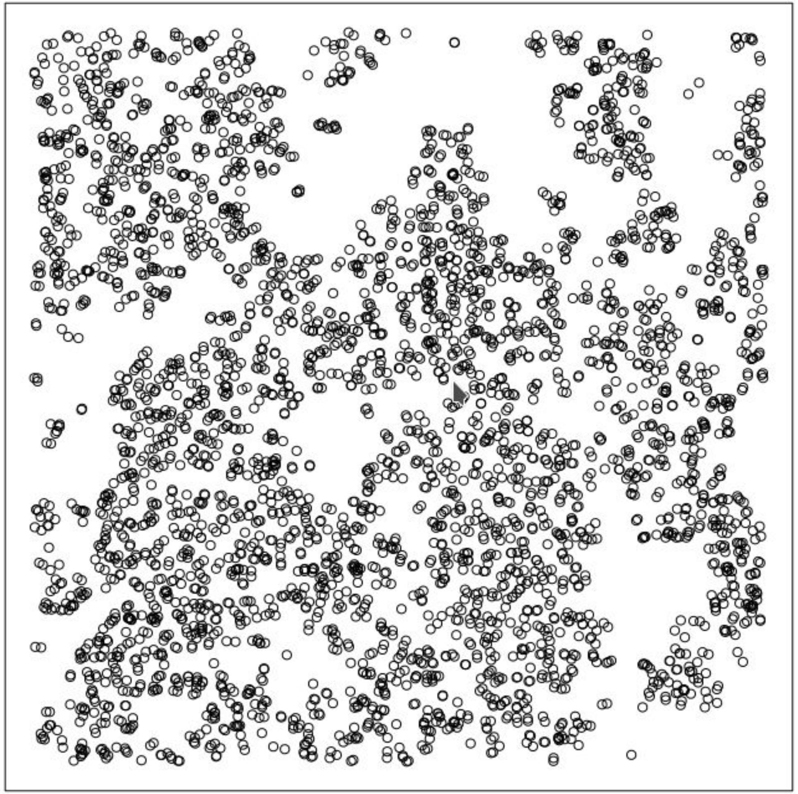


Scale Model Result

Spatial Dispertion of Sample
within each pop (real Data)



Model ouptut
after 10000 timestep



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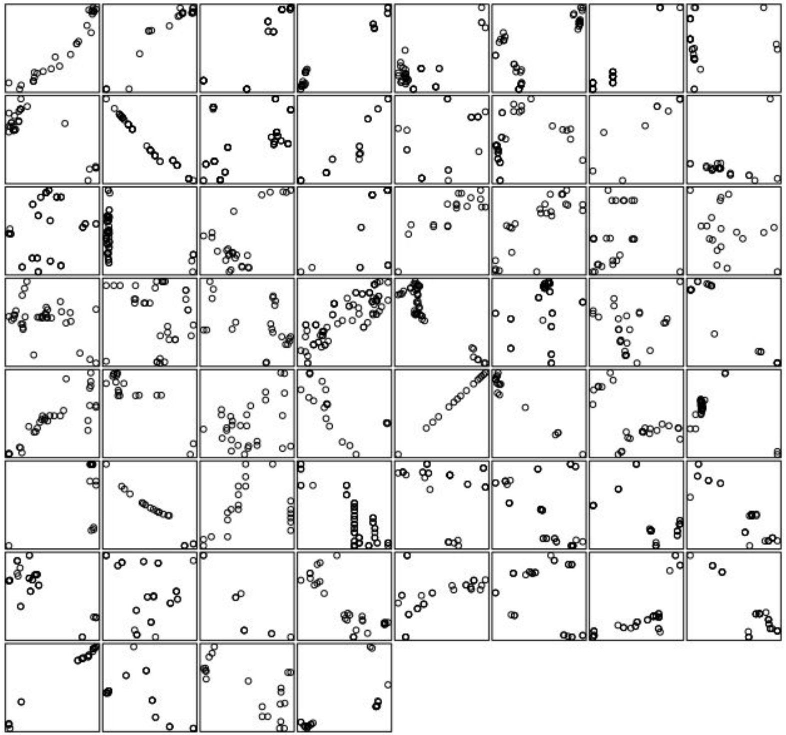
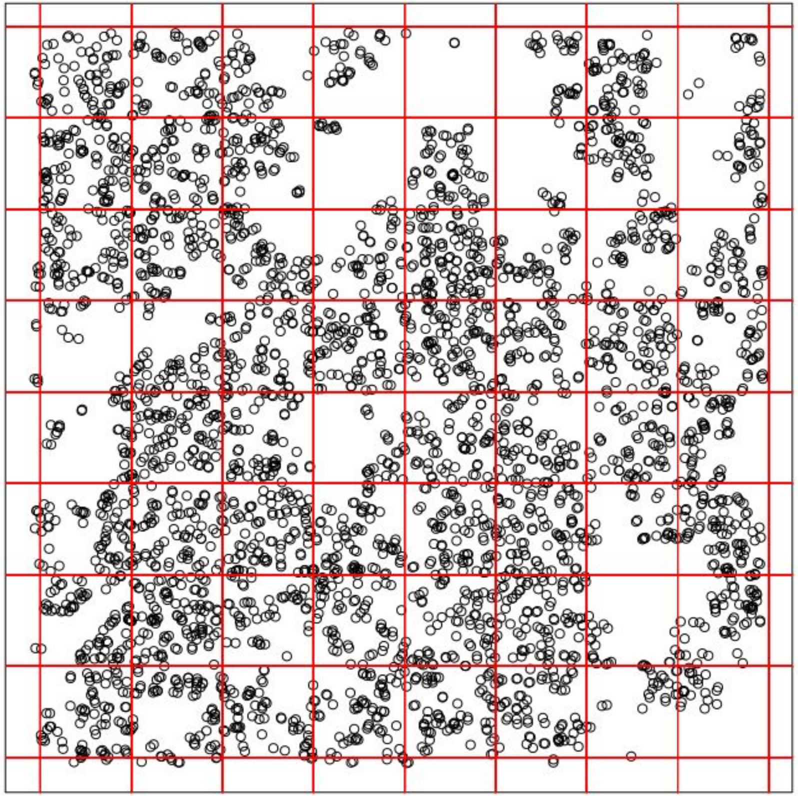
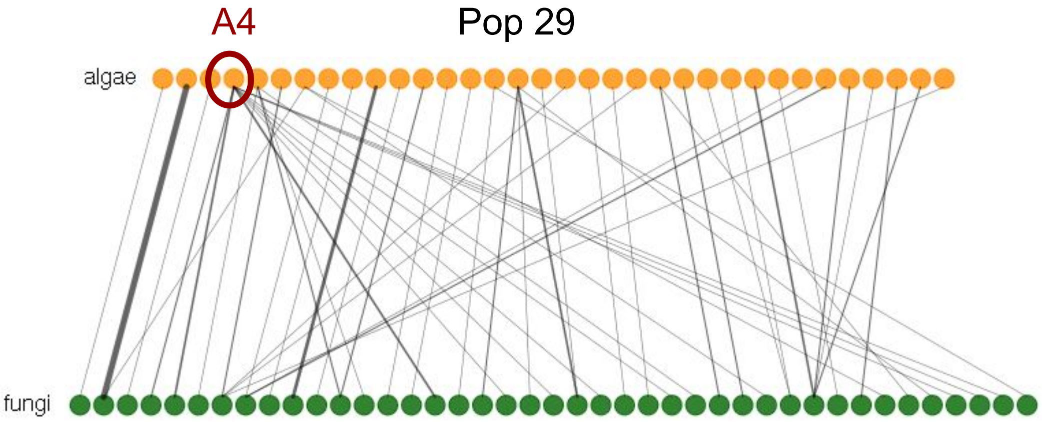


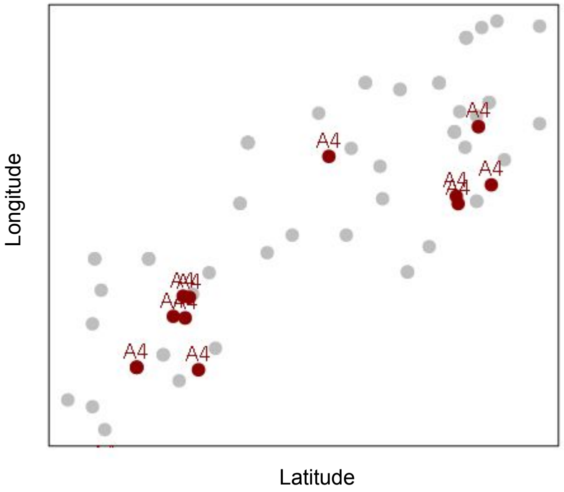
Model ouptut
after 10000 timestep



Population Structure



Spatial repartition of lichens within Pop 29



Population Structure

Betweenness centrality

Importance of a node as a connector between different parts of the network. Nodes with BC>0 connect areas of the network that would otherwise be sparsely or not connected at all. Species which are important to the cohesiveness of the network will have a positive BC.

$$BC_i = \sum_{jk} \frac{g_{jk}(i)}{g_{jk}}$$

$g_{jk}(i)$, number of shortest paths between j and k going through i

g_{jk}, number of shortest paths linking j and k

Goal: Link node properties with spatial structure

Newman M. E. J. Networks: an introduction. Oxford University Press, 2010

Opsahl T, Agneessens F, Skvoretz J. Node centrality in weighted networks: Generalizing degree and shortest paths. Social Networks 32 (2010) 245-251

Population Structure

Betweenness centrality

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$$BC_i^{w\alpha} = \sum_{jk} \frac{g_{jk}^{w\alpha}(i)}{g_{jk}^{w\alpha}}$$

$$d^{w\alpha}(i,j) = min\left(\frac{1}{(w_{ih})^{\alpha}}\right) + \ldots + \frac{1}{(w_{hj})^{\alpha}}$$

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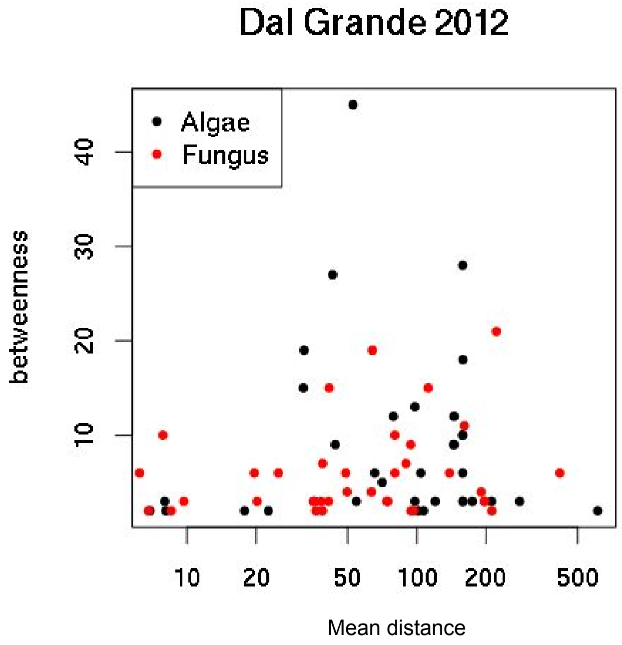
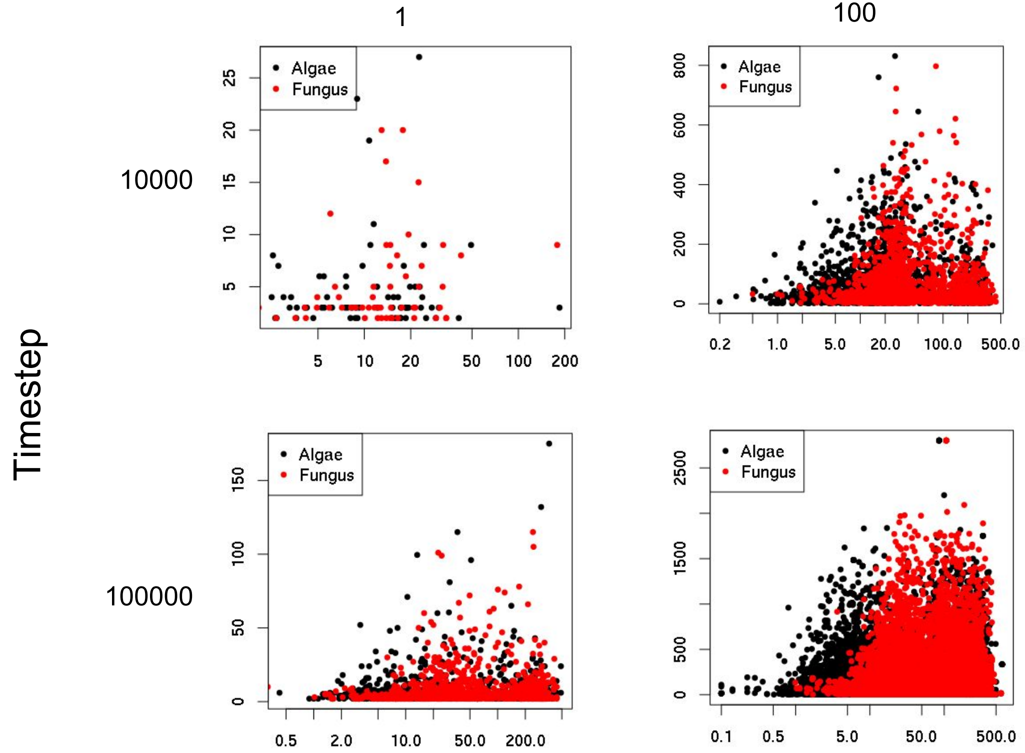
Population Structure

Betweennes Centrality vs Mean distance

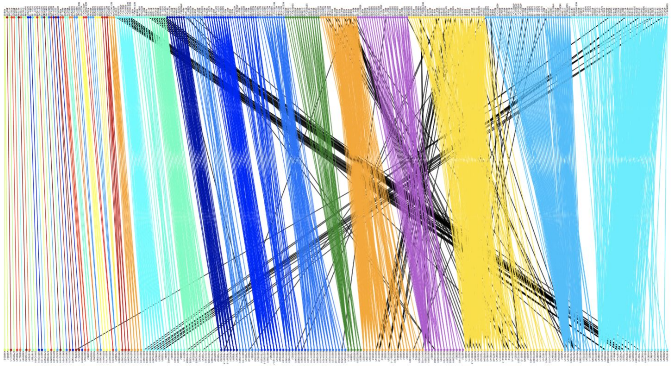


Sexual reproduction



Population Structure

Modularity



$$Q = \frac{1}{|E|}\sum_{ij}(B_{ij} - \frac{k_i d_j}{|E|})\delta(g_i, h_j)$$

$|E|$, number of links in the network

B_{ij}, adjacency matrix

k_i, d_j, degree of nodes i and j

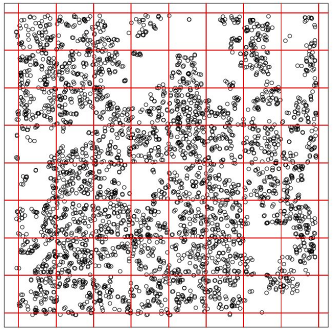
g_i, h_j, modules indices of nodes i (belongs to set R) and j (belongs to set C

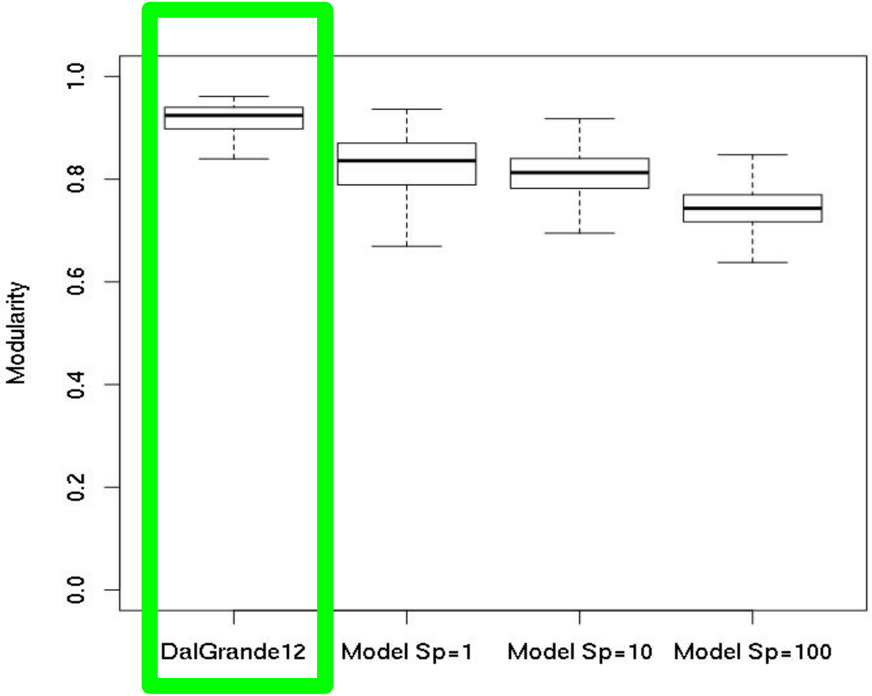
Newman, M. E. J. 2006. Finding community structure in networks using the eigenvectors of matrices. Physical Review E, 74, 036104.

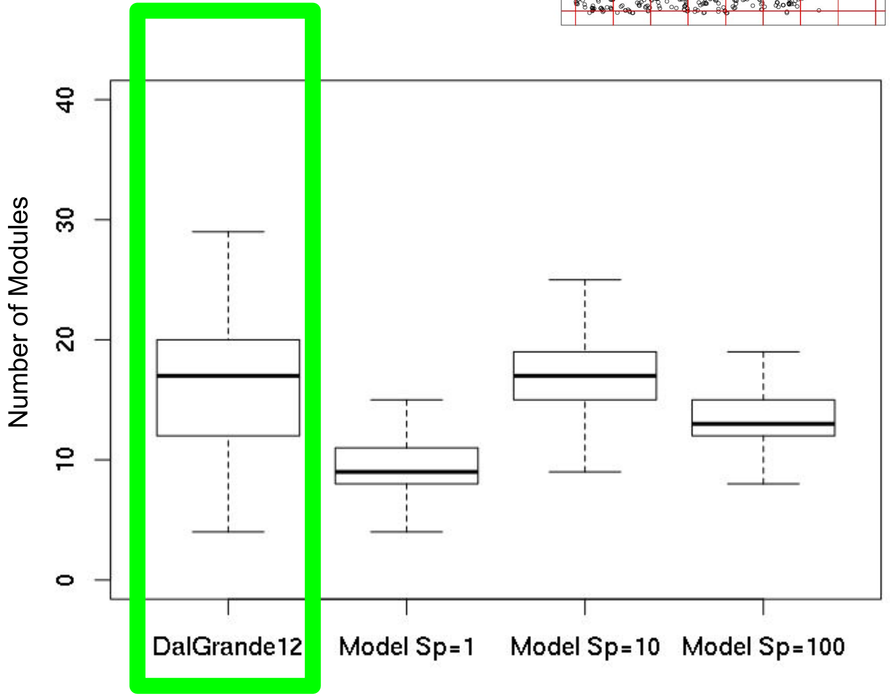
Barber MJ. 2007. Modularity and community detection in bipartite networks. Physical Review E, 76: 066102

Flores C, Poisot T, Valverde S Weitz J. 2016. BiMat: a MATLAB package to facilitate the analysis of bipartite networks. Methods in Ecology and Evolution, 7:127–132.

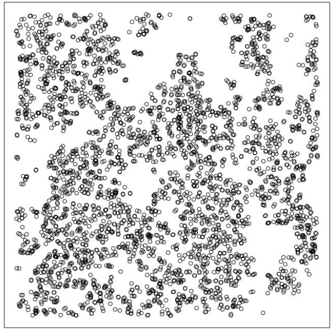
Modularity

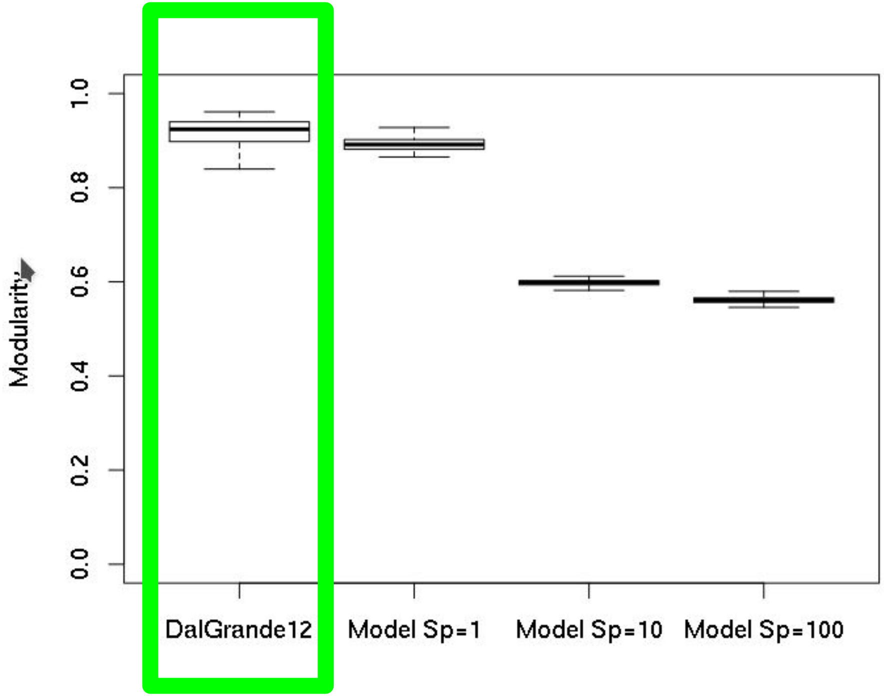



1.0
0.8
0.6
0.4
0.2
0.0
Modularity
DalGrande12
Model Sp=1
Model Sp=10
Model Sp=100


40
30
20
10
0
Number of Modules
DalGrande12
Model Sp=1
Model Sp=10
Model Sp=100

Modularity





Modularity
0.0
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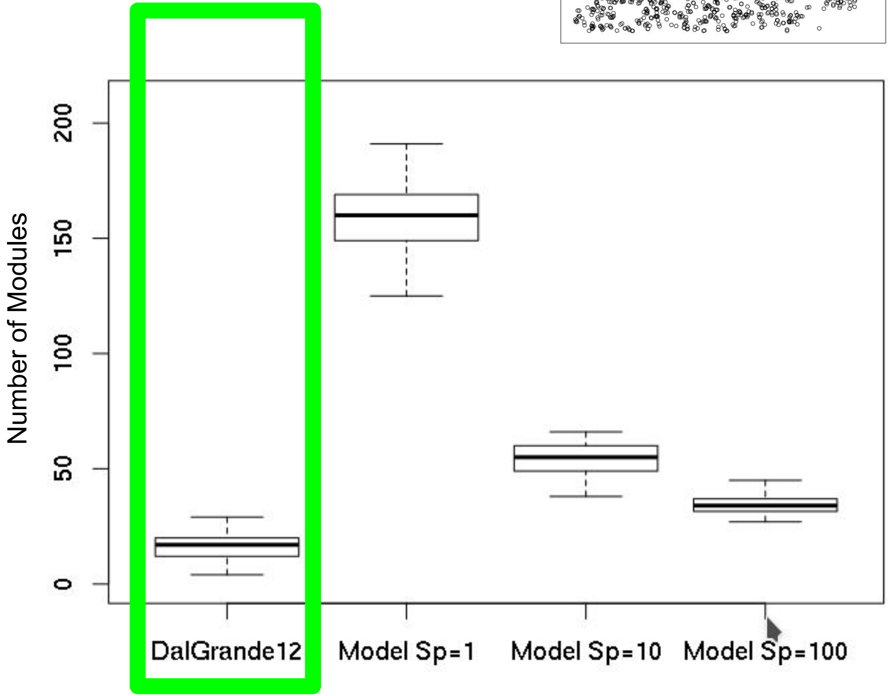

Number of Modules
0
50
100
150
200
DalGrande12
Model Sp=1
Model Sp=10
Model Sp=100

Validation step

More quantitative comparison needed

=> Approximate Bayesian Computation, Beaumont 2010

- Check that the assumptions used to build the model are correct

- Confirm and refine observations made in other studies

Future Experiments

Large scale study,

Speciation,

Emergence of Photobiont mediated guild,

....

Thanks!

BSC Barcelona Supercomputing Center
Centro Nacional de Supercomputación

British Lichen Society

SANTA FE INSTITUTE

iBE CSIC UPF INSTITUT de BIOLOGIA EVOLUTIVA

upf. Universitat Pompeu Fabra Barcelona

EP NET
ECONOMIC & POLITICAL NETWORK

erc European Research Council
Established by the European Commission

BRITISH ECOLOGICAL SOCIETY

Population Structure

Nodes Properties vs Spatial Structure:

Betweenness centrality

Betweenness centrality (Martín González A, Dalsgaard, Olesen JM. 2010. Centrality measures and the importance of generalist species in pollination networks. Ecological Complexity 7, 36-43)

is the importance of a node as a connector between different parts of the network. Nodes with BC>0 connect areas of the network that would otherwise be sparsely or not connected at all. Species which are important to the cohesiveness of the network will have a positive BC.

$$BC_i = 2 \sum_{j<k;i\neq j} \frac{g_{jk}(i)/g_{jk}}{(n-1)(n-2)}$$

n, number of species

$g_{jk}(i)$, number of shortest paths between j and k going through i

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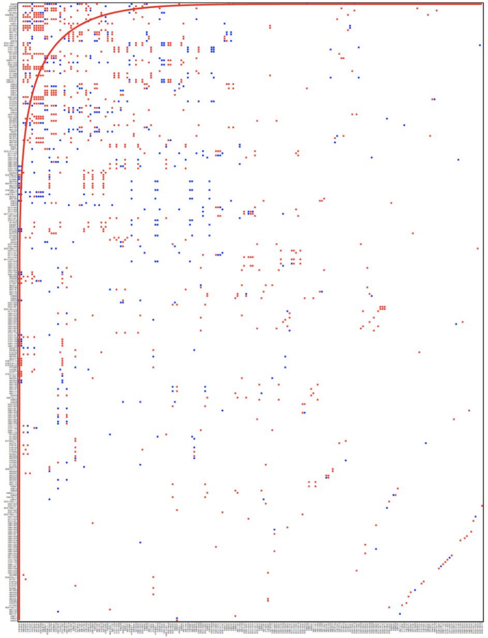
Network metrics



Nestedness

$$N_{NODF} = \frac{\sum_{ij} M_{ij}^{row} + \sum_{ij} M_{ij}^{col}}{[\frac{m(m-1)}{2}] + [\frac{n(n-1)}{2}]}$$

$$M_{ij}^{row} = \begin{cases} 0 & \text{if } k_i \leq k_j \\ n_{ij}/\min(k_i, k_j) & \text{otherwise} \end{cases}$$

m, n, n° of rows and columns

k_i, n° of interactions in row i

k_j, n° of interactions in row j

n_{ij}, n° of shared interactions between rows i and j

Almeida-Neto M, Guimaraes P, Guimaraes PR Jr, Loyola RD, Ulrich W. 2008. A consistent metric for nestedness analysis in ecological systems: reconciling concept and measurement Oikos, 117: 1227 1239

Flores C, Poisot T, Valverde S Weitz J. 2016. BiMat: a MATLAB package to facilitate the analysis of bipartite networks. Methods in Ecology and Evolution, 7:127–132.

Network metrics

Assortative/Disassortative mixing

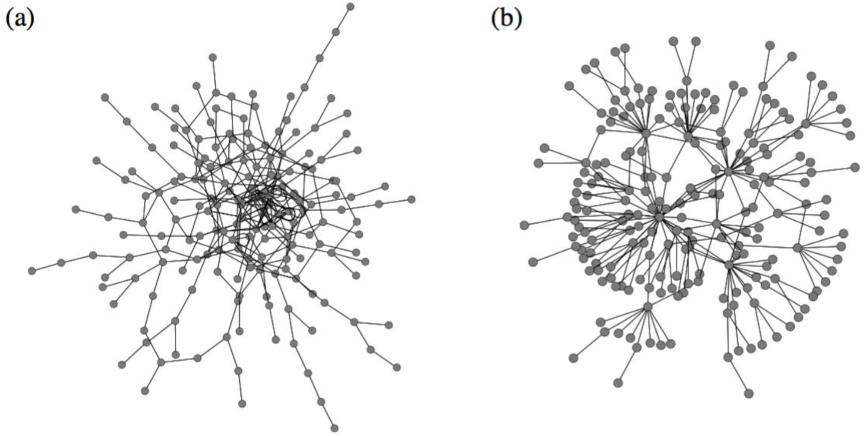
$$r = \frac{M^{-1}\sum_i j_i k_i - [M^{-1}\sum_i \frac{1}{2}(j_i + k_i)]^2}{M^{-1}\sum_i \frac{1}{2}(j_i^2 + k_i^2) - [M^{-1}\sum_i \frac{1}{2}(j_i + k_i)]^2}$$

j_i, k_i degrees of the vertices at the ends of ith edge, with $i = 1, ..., M$

Newman M.E.J. 2002. Assortative Mixing in Networks. Phys. Rev. Lett. 89, 208701

Network metrics

Assortative/Disassortative mixing



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Newman, M.E.J and Girvan M. Mixing patterns and community structure in networks. Statistical Mechanics of Complex Networks, nº 625 Lecture Notes in Physics, pp. 66-87, Springer, Berlin (2003)

Network metrics

Asymmetry metrics

$$d_{ij}^F = \frac{w_{ij}}{\sum_j w_{ij}}$$

$$d_{ji}^A = \frac{w_{ji}}{\sum_i w_{ji}}$$

$$AS(i,j) = \frac{d_{ij}^F - d_{ji}^A}{max(d_{ij}^F, d_{ji}^A)}$$

d_{ij}^F, dependence of fungi species i on algae species j

d_{ji}^A, dependence of algae species j on fungi species i

Bascompte J, Jordano P, Olesen J. 2006. Asymmetric Coevolutionary Networks Facilitate Biodiversity Maintenance. Science, 312 (5772), 431-433.

Network metrics

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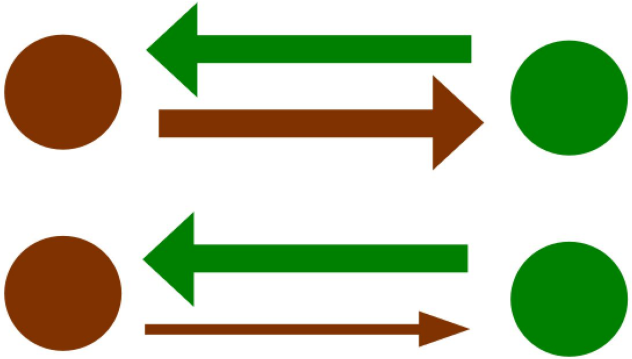

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Network metrics

Modularity (Barber MJ. 2007. Modularity and community detection in bipartite networks. Physical Review E, 76: 066102)

MODULARITY:

Modularity indicates the presence of dense clusters of nodes with many overlapping interactions embedded within the net- work.
Clusters are considered dense when they have high internal edge density relative to the expected edge density in the null model. These dense clusters are termed modules. Identifying modules and estimating the associated modularity require a partitioning of the network

Network metrics

Modularity

$$Q_R = \frac{W}{E}$$

E, edges in a network

W, n° of edges established between members of the same module

Poisot T. 2013. An a posteriori measure of network modularity. F1000 Research, 2:130

Flores C, Poisot T, Valverde S Weitz J. 2016. BiMat: a MATLAB package to facilitate the analysis of bipartite networks. Methods in Ecology and Evolution, 7:127–132.

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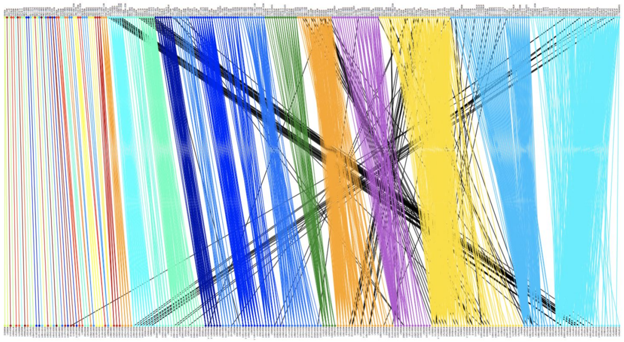

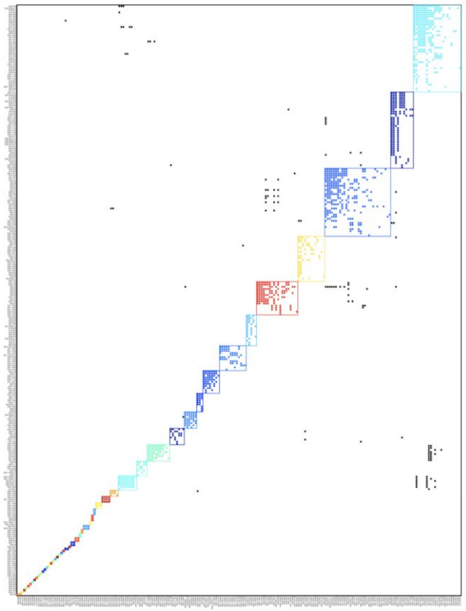

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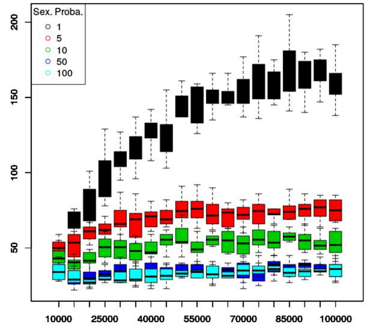
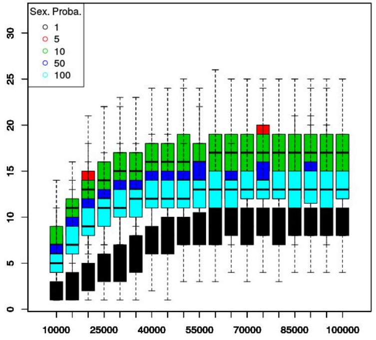
Exploration of the model dynamics

Number of Modules





Modularity