Dynamics of feedbacks in nonequilibrium biodiversity organizational scale

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[HTTPS://GITHUB.COM/MELIAN009/ECOEVON/TREE/MASTER/CCSS2024](https://github.com/melian009/Ecoevon/tree/master/CCSS2024)

References

Rainey, P., Travisano, M. (1998). Adaptive radiation in a heterogeneous environment. Nature 394:69–72.

Kleidon, A. (2010). Non-equilibrium thermodynamics, maximum entropy production and Earth-system evolution. Philo. Trans. Math., Phys., and Eng. Sciences, 368:181-196.

Melo and Marroig (2015). Directional selection can drive the evolution of modularity in complex traits. PNAS, 112:470-475.

Goswami et al (2015). The fossil record of phenotypic integration and modularity: A deep-time perspective on developmental and evolutionary dynamics. PNAS, 112:4891-4896.

Laughlin D.C., and Messier J. (2015). Fitness of multidimensional phenotypes in dynamic adaptive landscapes. TREE, 30:487-496.

Barros, C. et al. (2016). N-dimensional hypervolumes to study stability of complex ecosystems. Ecol. Lett., 19:729–742.

Boyle et al. (2017). An expanded view of complex traits: From polygenic to omnigenic. Cell. 169:1177-1186.

Melián et al. (2018). Deciphering the interdependence between ecological and evolutionary networks. TREE, 33:504-512.

Andreazzi, C., et al (2024). Biodiversity dynamics with complex genotype-to-phenotype architectures. Submitted to Biol. Rev.

Where are we now

NONEQUILIBRIUM

Feedbacks

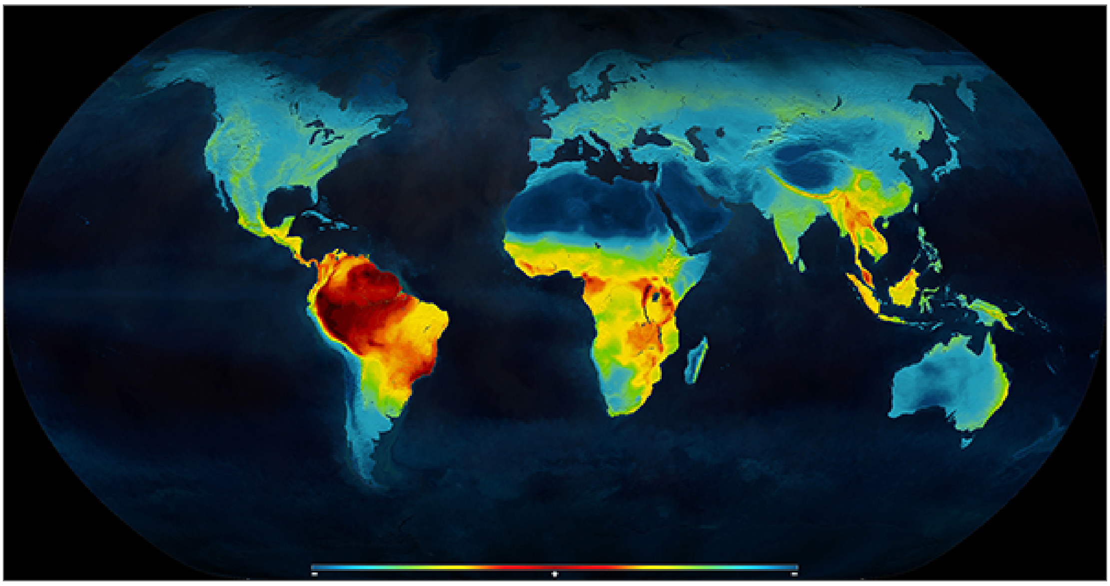
Where are we gonna go

Biodiversity organizational scale

Route to dimensionality

Where are we now

NONEQUILIBRIUM



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In [1]: from IPython.display import Video
        Video("./CCSS2024Fig/ContinentalDrift2.mp4", width=1058, height=508
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Out[1]:
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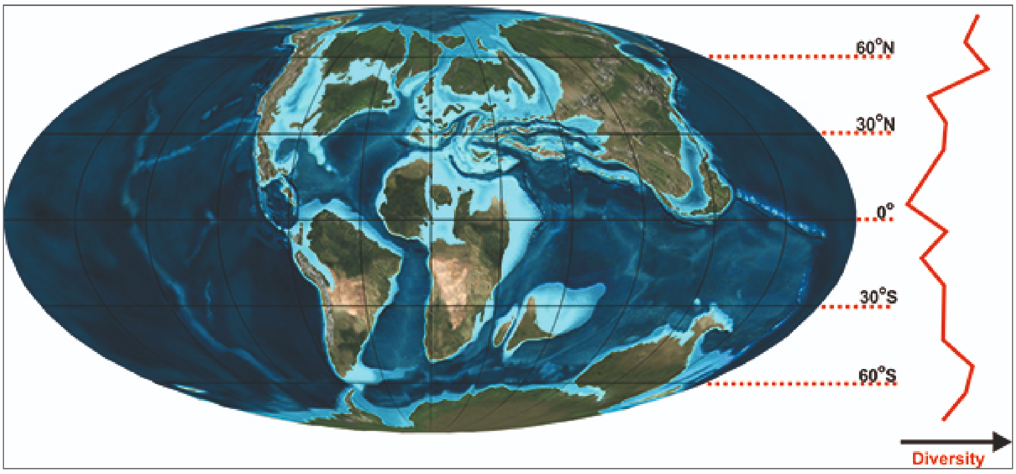
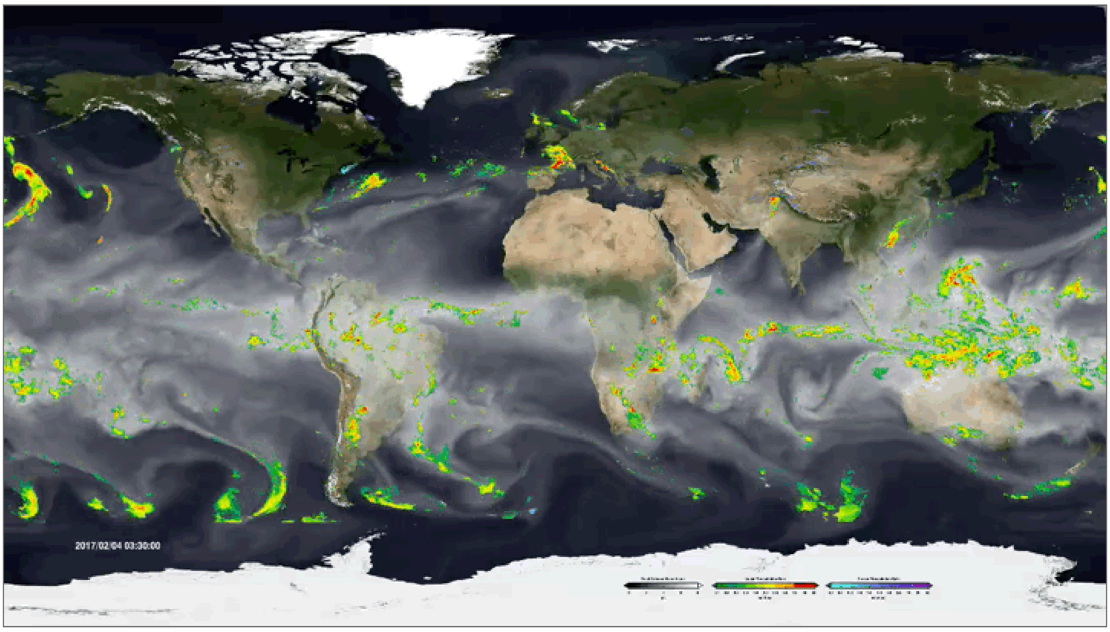
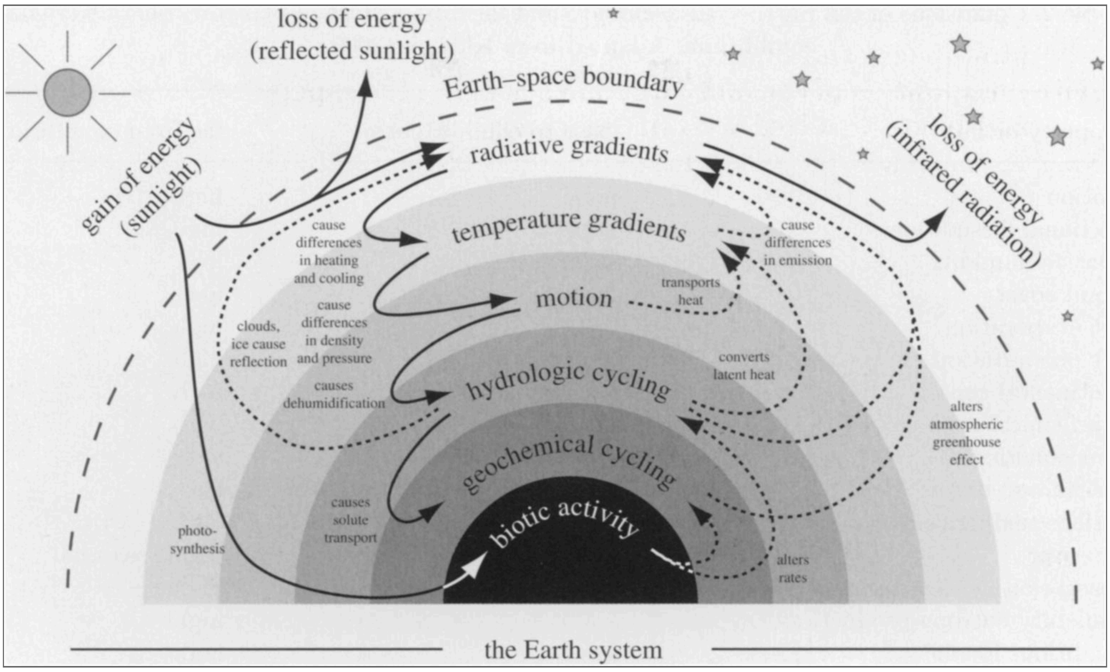
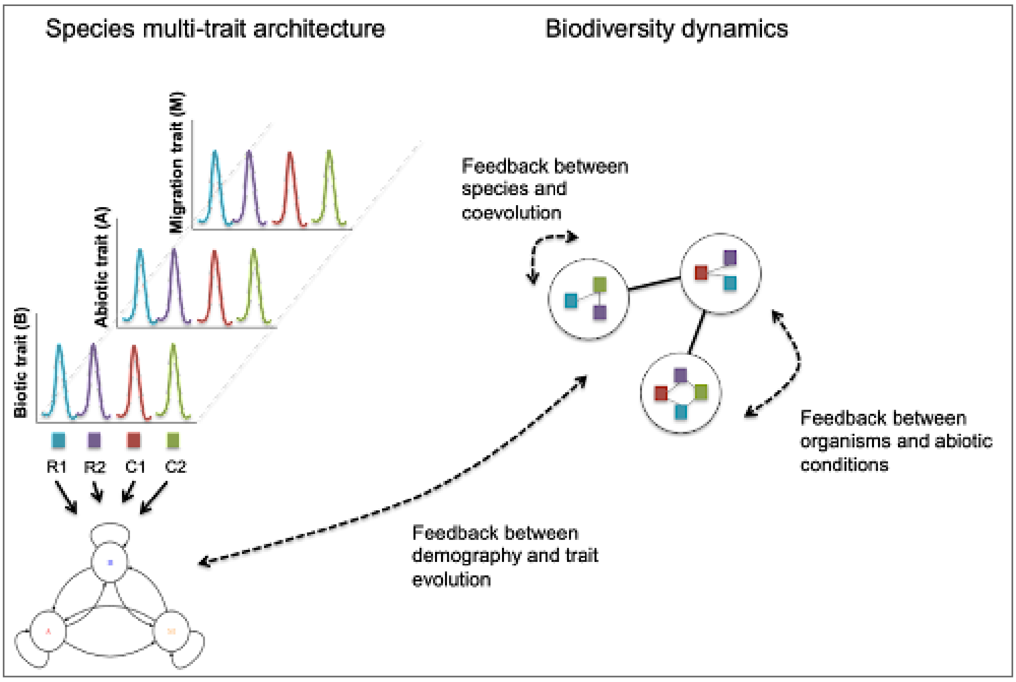

60°N
30°N
0°
30°S
60°S
Diversity

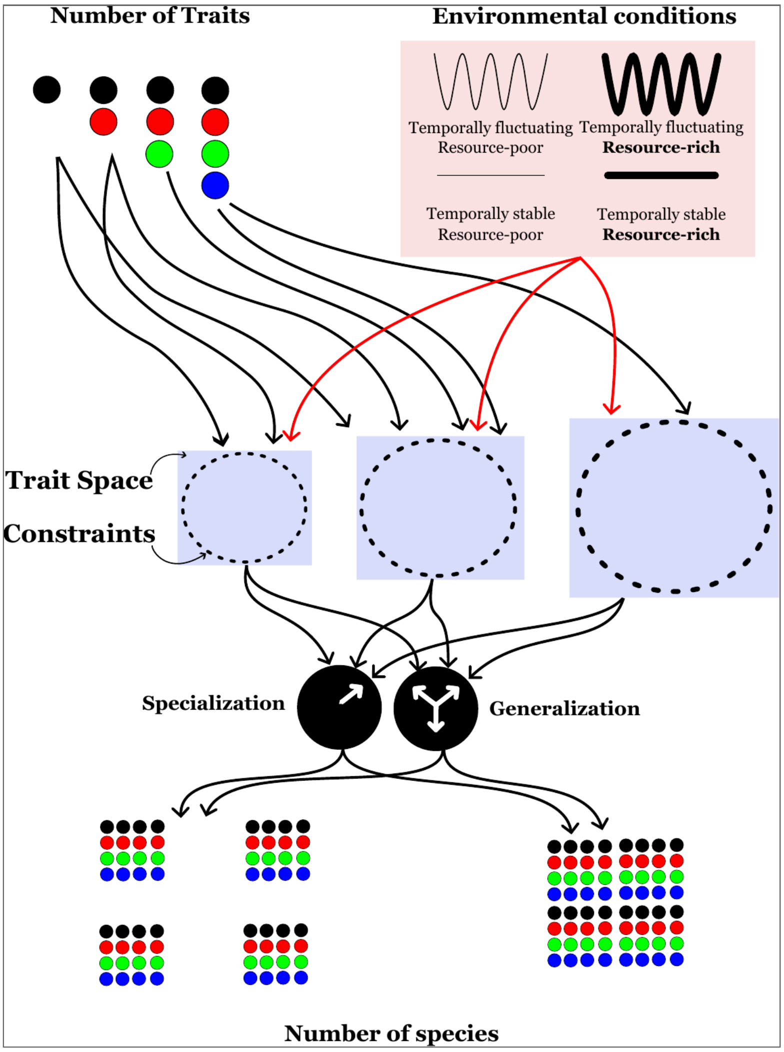

2017/02/04 03:30:00

Feedback


loss of energy
(reflected sunlight)
Earth–space boundary
gain of energy
(sunlight)
loss of energy
(infrared radiation)
radiative gradients
temperature gradients
motion
hydrologic cycling
geochemical cycling
biotic activity
cause differences in heating and cooling
cause differences in density and pressure
clouds, ice cause reflection
causes dehumidification
causes solute transport
photo-synthesis
cause differences in emission
transports heat
converts latent heat
alters atmospheric greenhouse effect
alters rates
the Earth system


Species multi-trait architecture
Biodiversity dynamics
Migration trait (M)
Abiotic trait (A)
Biotic trait (B)
R1
R2
C1
C2
Feedback between species and coevolution
Feedback between organisms and abiotic conditions
Feedback between demography and trait evolution

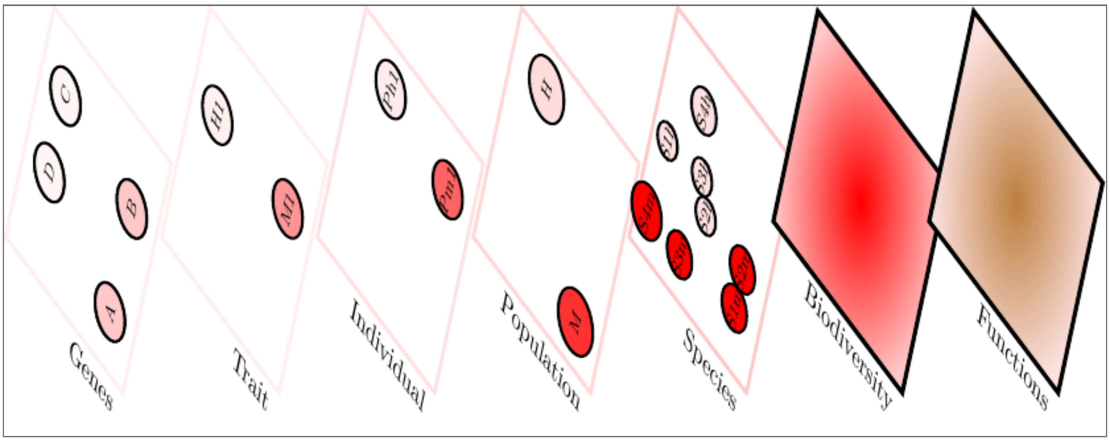
Where are we gonna go

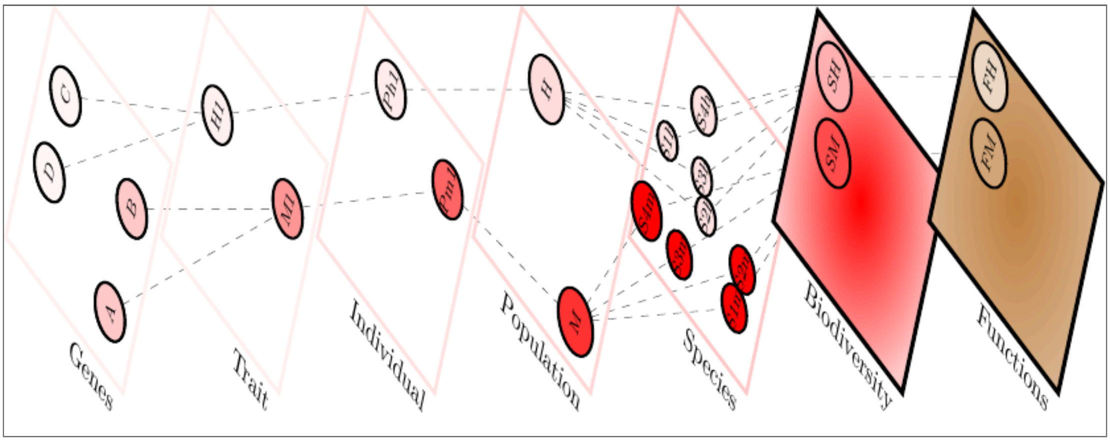

Number of Traits
Environmental conditions
Temporally fluctuating
Resource-poor
Temporally fluctuating
Resource-rich
Temporally stable
Resource-poor
Temporally stable
Resource-rich
Trait Space
Constraints
Specialization
Generalization
Number of species

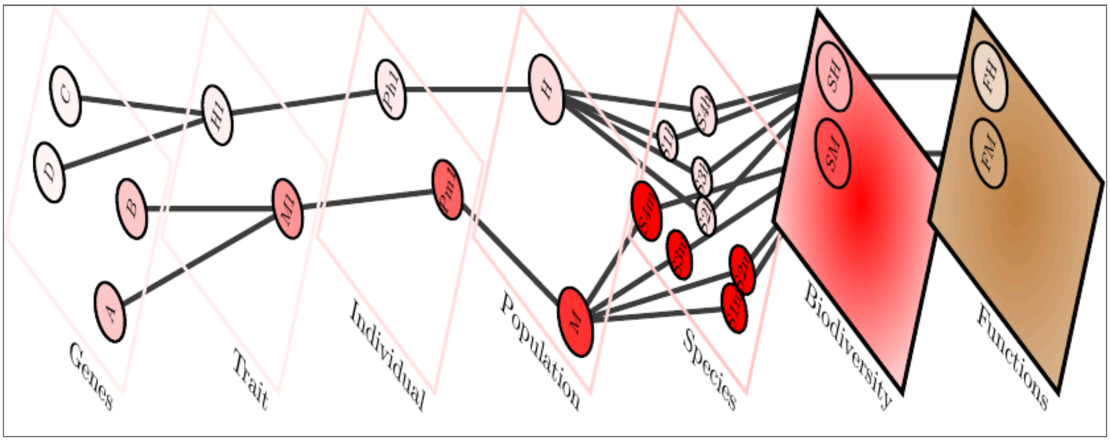
$$\mathbf{\Omega_{BAM}} = \begin{bmatrix} V_B & C_{BA} & C_{BM} \\ C_{AB} & V_A & C_{AM} \\ C_{MB} & C_{MA} & V_M \end{bmatrix}$$

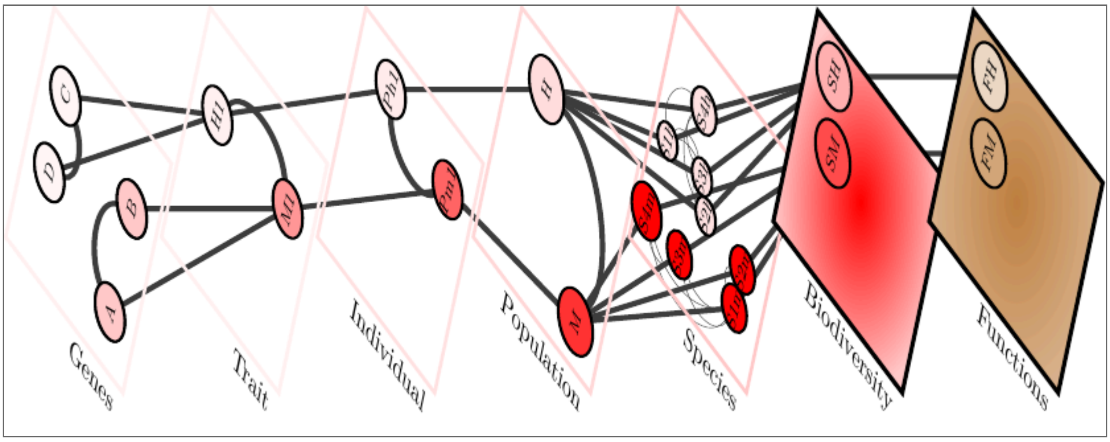
$$\mathbf{W}(\mathbf{z})^t_{ix} = exp[-\gamma([\mathbf{z}^t_{ix} - \theta^{\mathbf{t}}{}_{ix}]^T \mathbf{\Omega_{BAM}}^{-1}[\mathbf{z}^t_{ix} - \theta^{\mathbf{t}}{}_{ix}])]$$

$$\underbrace{\begin{bmatrix} W(\mathbf{z_B}{}^t_{ix}) \\ W(\mathbf{z_A}{}^t_{ix}) \\ \vdots \\ W(\mathbf{z_M}{}^t_{ix}) \end{bmatrix}}_{\mathbf{W}} = \underbrace{\begin{bmatrix} W(B^t_{ix})^* \\ W(A^t_{ix})^* \\ \vdots \\ W(M^t_{ix})^* \end{bmatrix}^T}_{\mathbf{W}} \underbrace{\begin{bmatrix} V_B & C_{BA} & \dots & C_{BM} \\ C_{AB} & V_A & \dots & C_{AM} \\ \vdots & \vdots & \vdots & \vdots \\ C_{MB} & C_{MA} & \dots & V_M \end{bmatrix}^{-1}}_{\mathbf{\Omega_{BAM}}} \underbrace{\begin{bmatrix} W(B^t_{ix})^* \\ W(A^t_{ix})^* \\ \vdots \\ W(M^t_{ix})^* \end{bmatrix}}_{\mathbf{W}}$$


Genes
Trait
Individual
Population
Species
Biodiversity
Functions

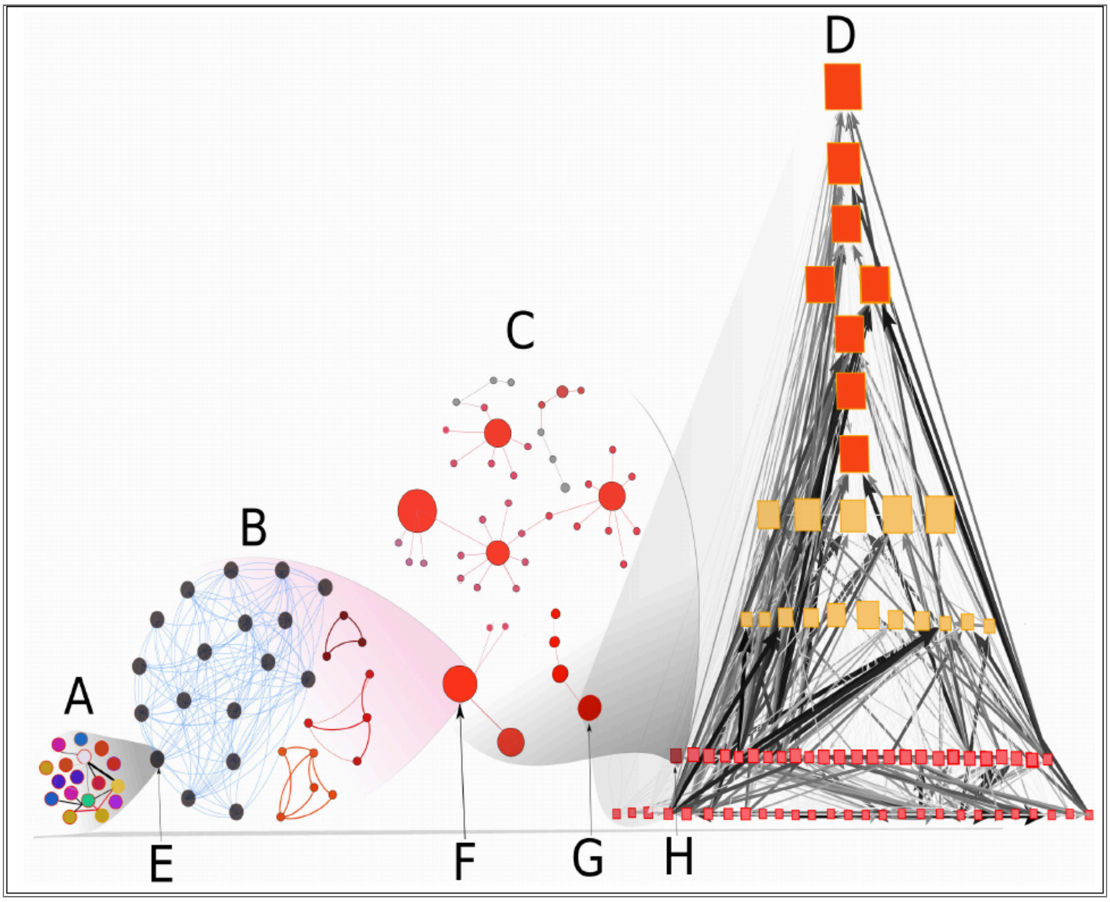

Genes
Trait
Individual
Population
Species
Biodiversity
Functions
C
D
B
A
H1
M1
Ph1
Pm1
H
M
SH
SM
FH
FM

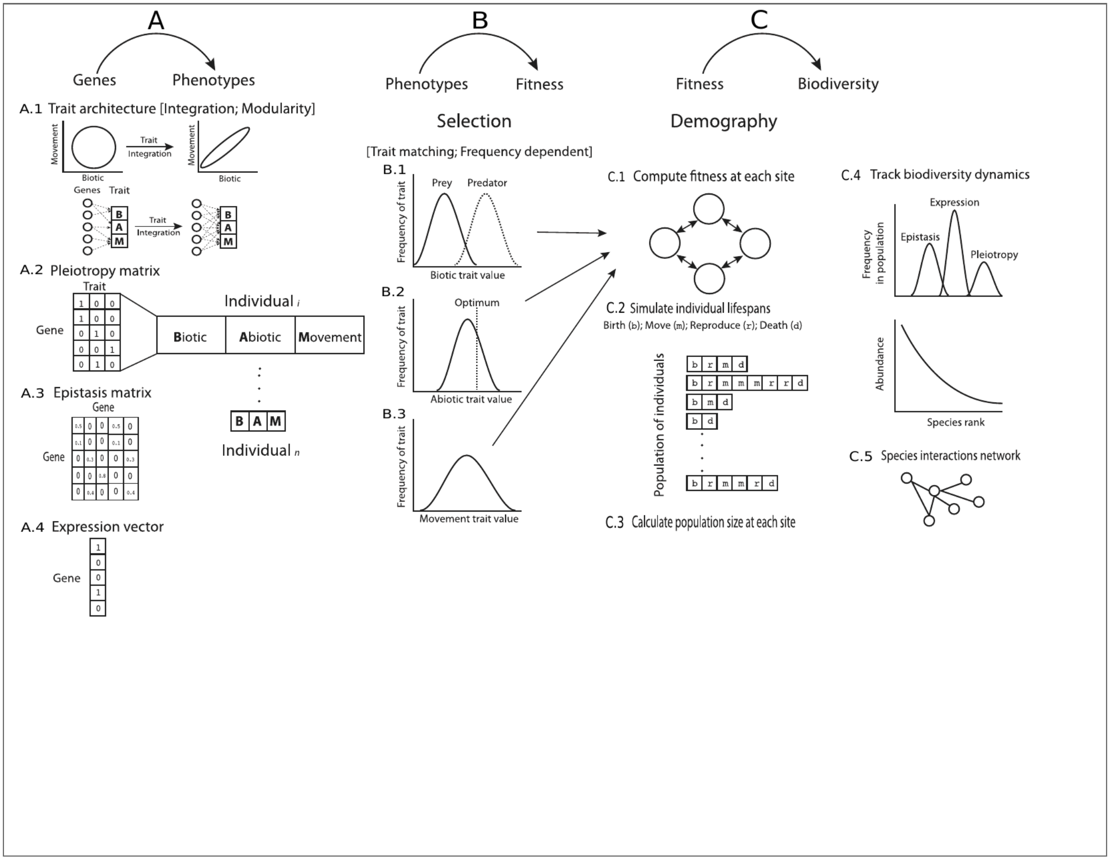

Genes
Trait
Individual
Population
Species
Biodiversity
Functions


Genes
Trait
Individual
Population
Species
Biodiversity
Functions

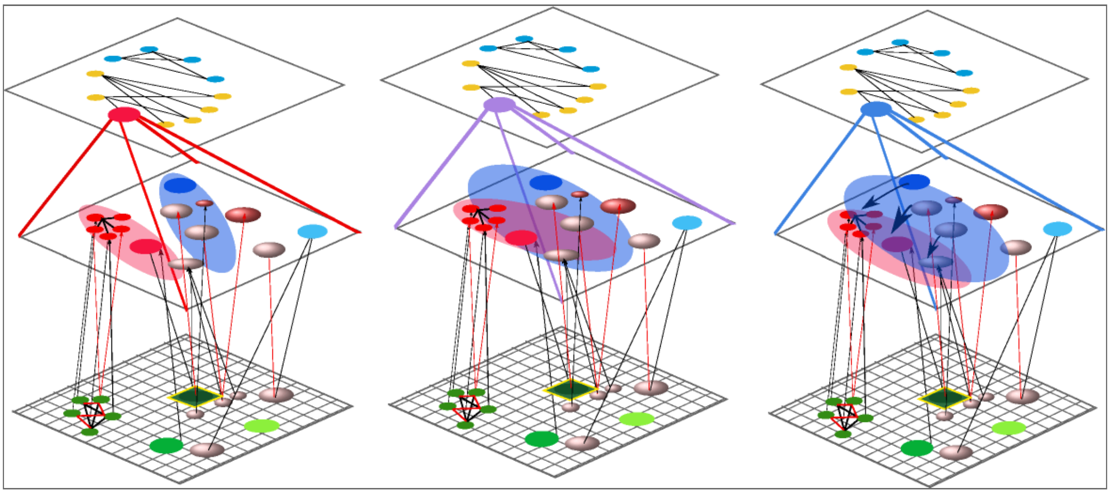
$$\partial_t \rho(\mathbf{z}, \mathbf{t}) = -\nabla_{\mathbf{z}} \left[\nabla_{\mathbf{z}} \mathbf{F}(\mathbf{z}, \mathbf{y_t}) \rho(\mathbf{z}, \mathbf{t}) \right] - r(\mathbf{z}, \mathbf{y_t}) \rho(\mathbf{z}, \mathbf{t})$$
$$+ \int_\Omega \int_\Omega M(\mathbf{z}|\mathbf{z}', \mathbf{z}'') \mathbf{B}(\mathbf{z}', \mathbf{z}'') \rho(\mathbf{z}', \mathbf{t}) \rho(\mathbf{z}'', \mathbf{t}) \mathbf{d^d z' d^d z''}$$

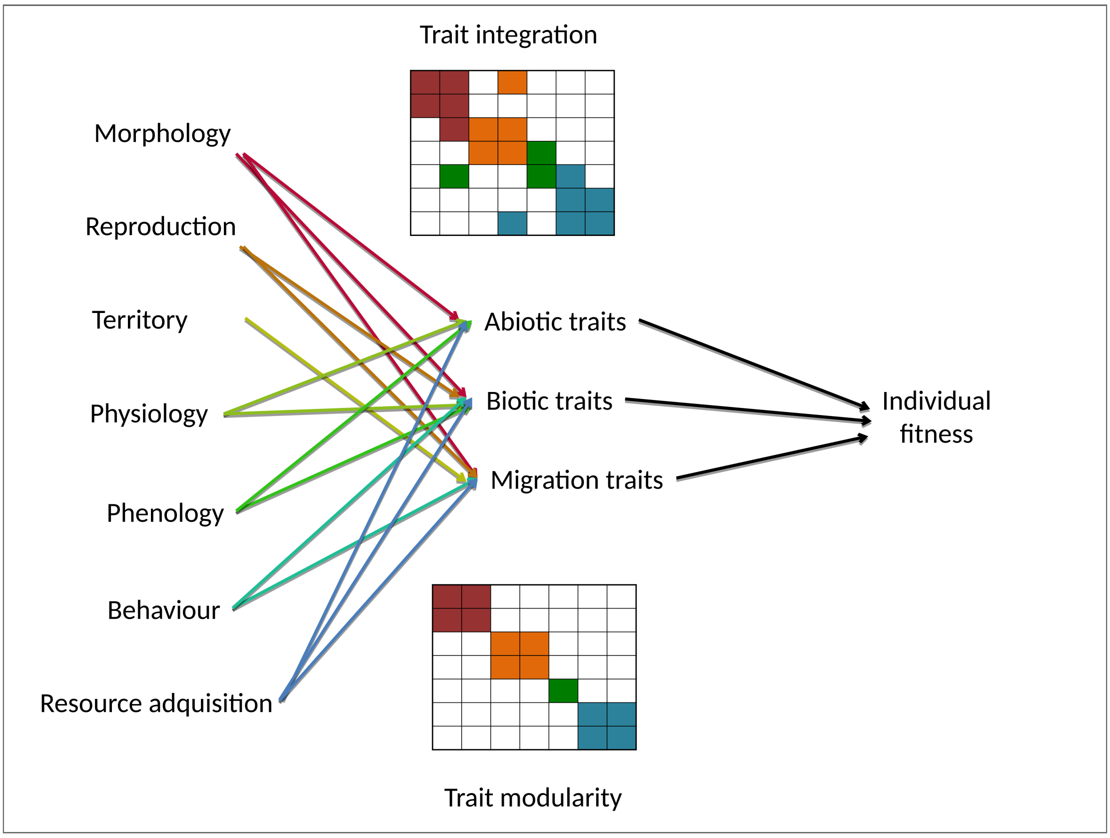
Biodiversity organizational scale


D
C
B
A
E
F
G
H


A
Genes
Phenotypes
A.1 Trait architecture [Integration; Modularity]
A.2 Pleiotropy matrix
Individual i
Biotic
Abiotic
Movement
A.3 Epistasis matrix
Individual n
A.4 Expression vector
B
Phenotypes
Fitness
Selection
[Trait matching; Frequency dependent]
Prey
Predator
Biotic trait value
Optimum
Abiotic trait value
Movement trait value
C
Fitness
Biodiversity
Demography
C.1 Compute fitness at each site
C.2 Simulate individual lifespans
Birth (b); Move (m); Reproduce (r); Death (d)
Population of individuals
C.3 Calculate population size at each site
C.4 Track biodiversity dynamics
Expression
Epistasis
Pleiotropy
Abundance
Species rank
C.5 Species interactions network

Route to Dimensionality




Trait integration
Morphology
Reproduction
Territory
Physiology
Phenology
Behaviour
Resource adquisition
Abiotic traits
Biotic traits
Migration traits
Individual fitness
Trait modularity

Complex traits: GPA

$$z_j^i(x,t) = \boldsymbol{f(\mathbf{L})}(x,t), \boldsymbol{f} : \mathbb{R}^m \rightarrow \mathbb{R}^z \tag{1}$$

In this formulation, an individual's i phenotype in site x and time t is given by

$$\mathbf{Z^i}_{(x,t)} = f(\mathbf{L}) = \mathbf{D}[\mathbf{f(L)}] = \mathbf{BY}, \tag{2}$$

$$\mathbf{Z^i}_{(x,t)} = \mathbf{B^T EY} \tag{3}$$

Abiotic trait

$$D(z_a^i)_{(x,t)} = |0.5 - cdf(\mathcal{N}(\theta_a, \sigma^2), z_a^i)|, \tag{4}$$

where $D(z_a^i)$ is the distance of abiotic trait of individual i to its optimum, θ_a is the optimal value used as the mean of a normal distribution, σ^2 is the variance of the normal distribution, and z_a^i is the value of the abiotic trait i and cdf is cumulative distribution function. The fitness of the abiotic trait of individual i is then given by

$$W(z_a^i)_{(x,t)} = 1 - D(z_a^i)_{(x,t)} \tag{5}$$

Biotic trait

$$D(z_b^i z_b^j)(x,t) = |0.5 - cdf(\mathcal{N}(z_b^i, \sigma^2), z_b^j)|. \tag{6}$$

The strength of an interaction is a function of species-species coefficient and the phenotypic distance between the two individuals

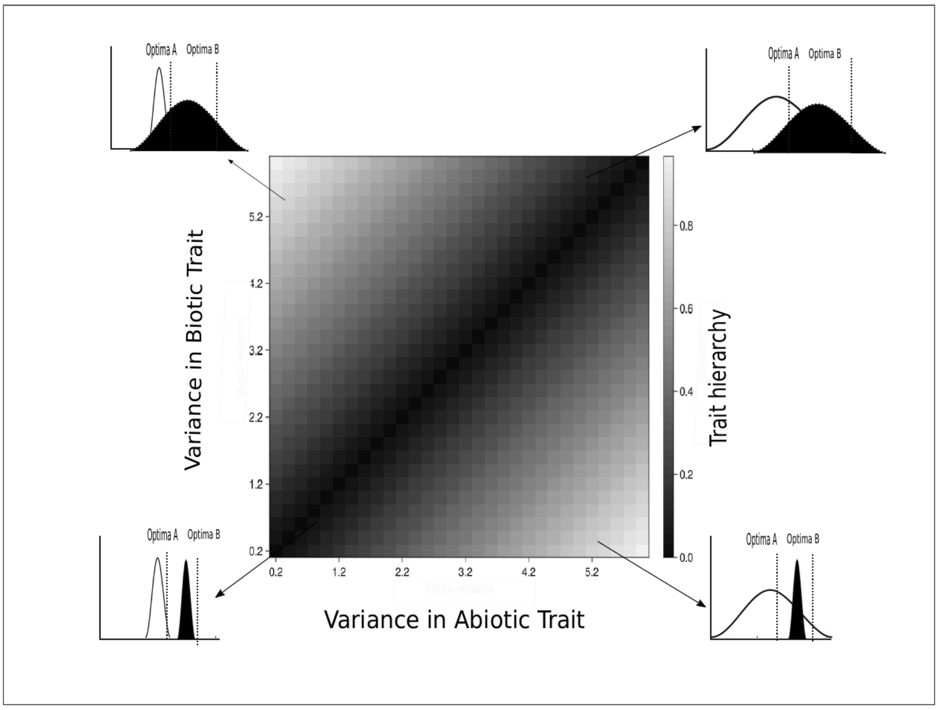
$$s_{z_b^i z_b^j}(x,t) = (1 - D(z_b^i z_b^j)(x,t)) \times |c_{z_b^A z_b^B}| \times sign(c_{z_b^A z_b^B}) \tag{7}$$

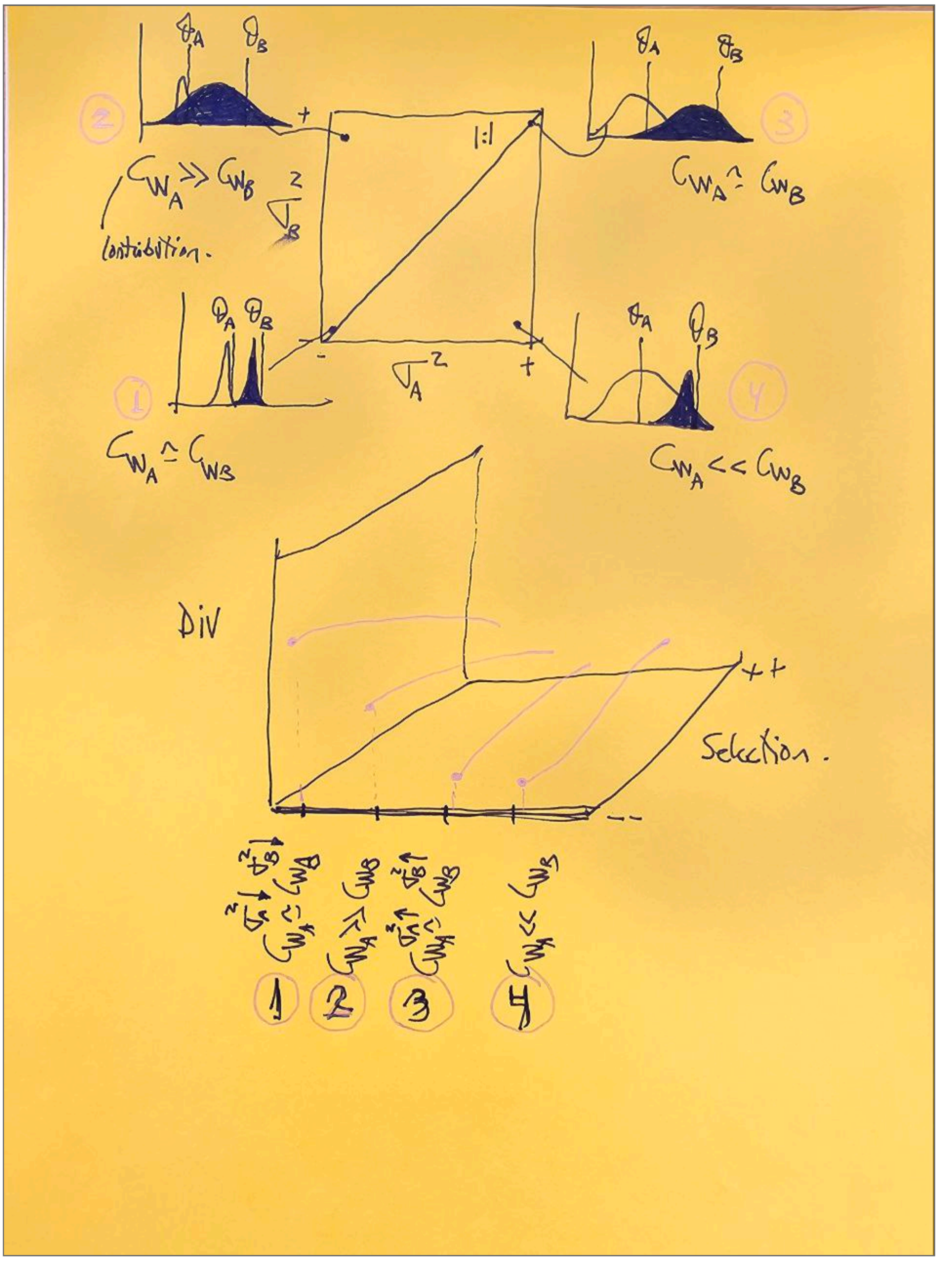
Fitness

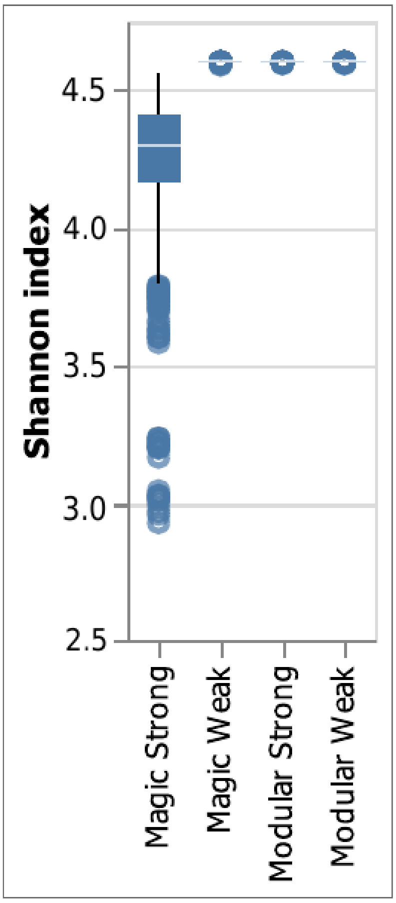
$$W(Z^i)_{(x,t)} = W(z_a^i)_{(x,t)} + s_{z_b^i z_b^j}(x,t), \tag{8}$$

and the fitness function takes into account the selection coefficient as

$$W(Z^i)_{(x,t)} = 1 - ((1 - W(Z^i)(x,t)) \times s_A) \tag{9}$$


Optima A
Optima B
Variance in Biotic Trait
Variance in Abiotic Trait
Trait hierarchy
0.2
1.2
2.2
3.2
4.2
5.2
0.0
0.2
0.4
0.6
0.8


1:1
contribution.
Div
Selection.
1
2
3
4


Shannon index
4.5
4.0
3.5
3.0
2.5
Magic Strong
Magic Weak
Modular Strong
Modular Weak

Take home message

Where are we now

- gap in understanding bb-ba-ab-aa-interactions accounting for nonequilibrium and feedbacks at many spatiotemporal scales

Where are we gonna go

- GPA connecting complex traits to biotic-abiotic feedbacks and diversity patterns
- The route to dimensionality integrating BOS to feedbacks