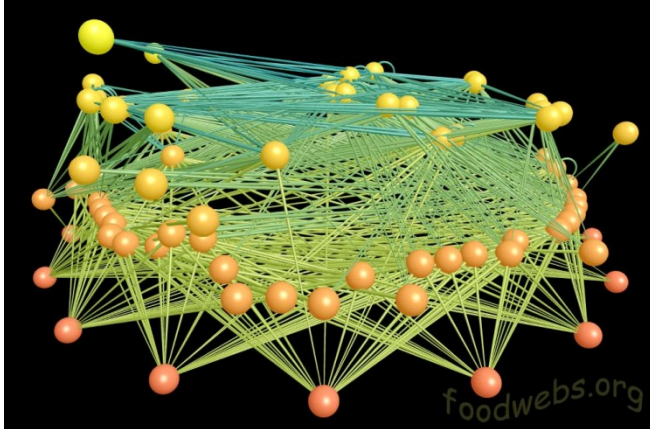


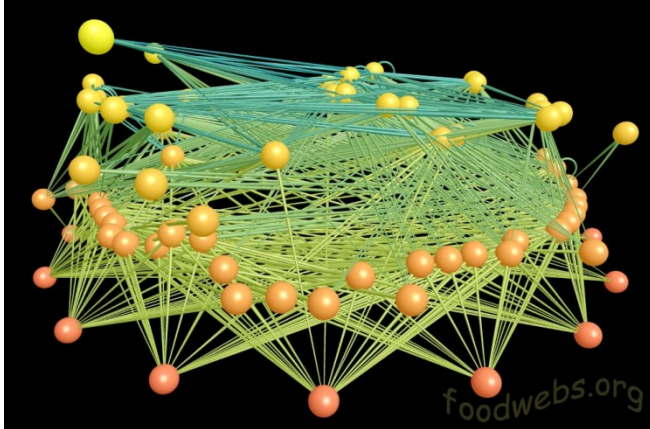
# Interconnexion des interactions mutualistes et antagonistes et stabilité des réseaux écologiques

Elisa Thébault, Alix Sauve et Colin Fontaine

# Réseaux en écologie

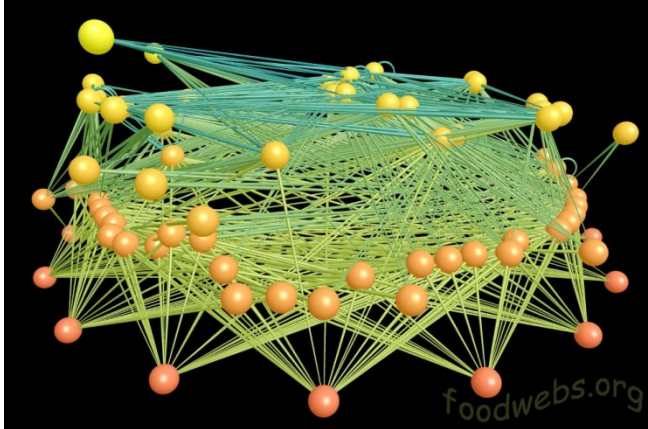


# Réseaux en écologie



community stability

# Réseaux et stabilité en écologie



## Une première formalisation mathématique

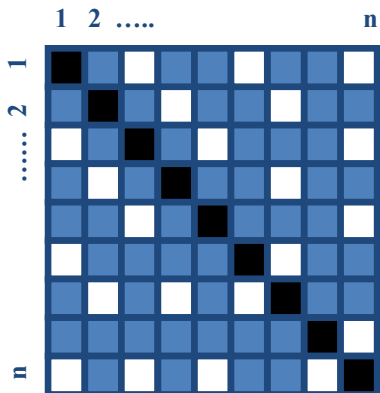
- May (1972)
  - Soit une communauté a  $k$  espèces dont on note les populations  $N_i$
  - Dynamique des populations:

$$\frac{dN_i}{dt} = F_i(N_1, \dots, N_k)$$

- Jacobienne du système à l'équilibre:

$$a_{ij} = \left( \frac{\partial F_i}{\partial N_j} \right)_{eq} \quad \begin{array}{l} A = \text{matrice de} \\ \text{communauté} \\ a_{ij} = \text{force d'interaction} \end{array}$$

community stability

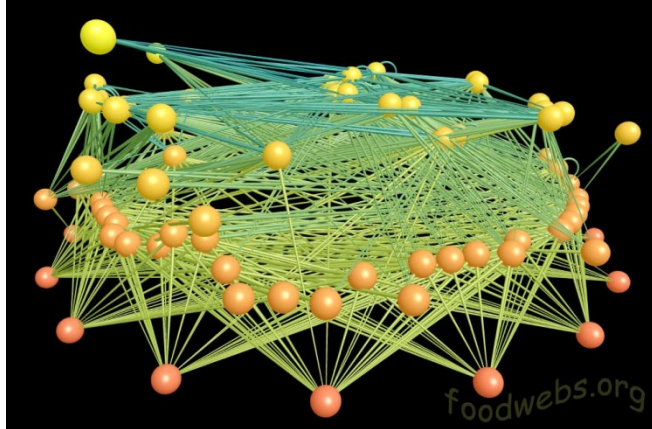


Proportion  $C$  de  $a_{ij}$  est non nulle (connectance)

On tire les valeurs de  $a_{ij}$  au hasard dans l'intervalle  $[-s, s]$

**Condition de stabilité :**  $s\sqrt{kC} < 1$

# Réseaux et stabilité en écologie

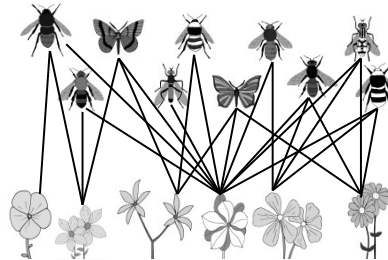


architecture particulière

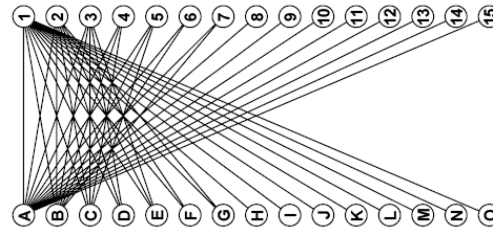
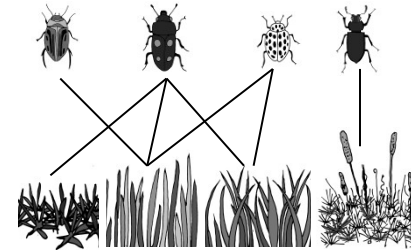


community stability

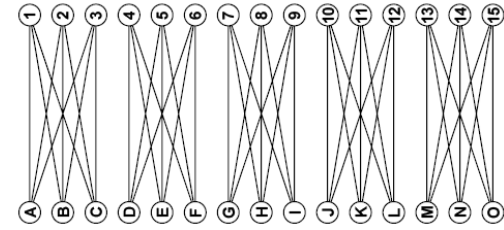
Mutualistic



Trophic



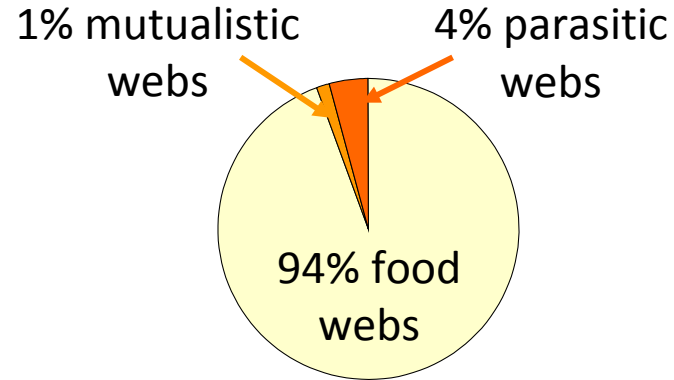
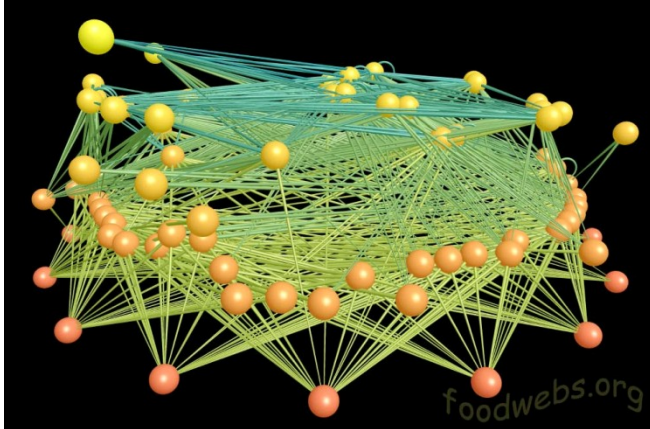
architecture emboîtée



architecture compartimentée

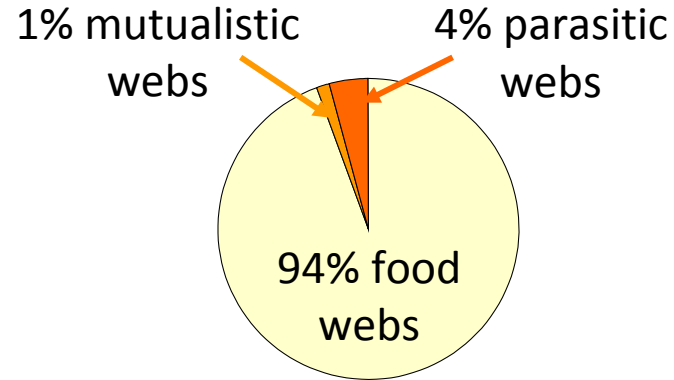
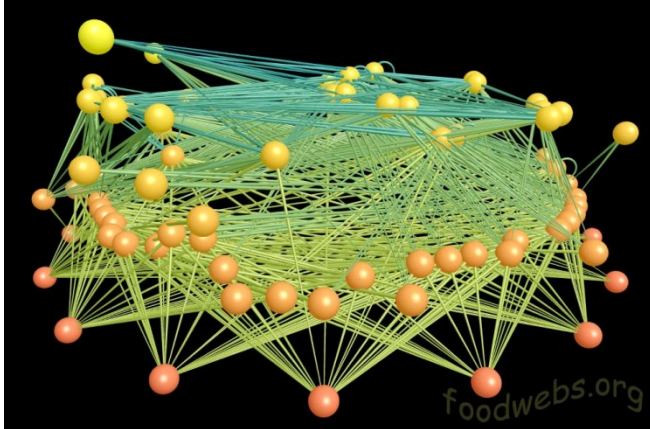
Dans les deux cas, l'architecture particulière de ces types de réseaux favorise la stabilité de la communauté

# Des études focalisées sur un type d'interaction



Proportions of papers on ecological networks published in the last 50 years that were related to food webs, mutualistic webs and parasitic webs

# Des études focalisées sur un type d'interaction

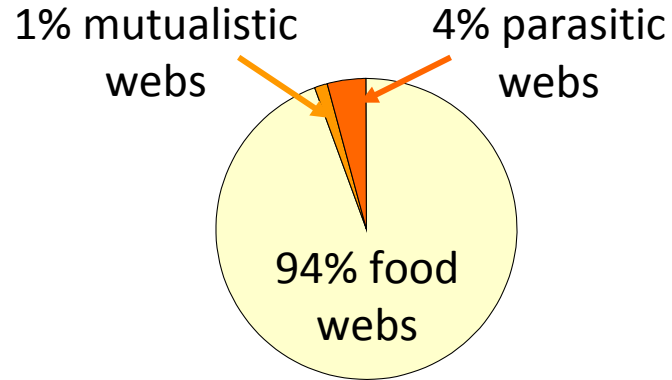
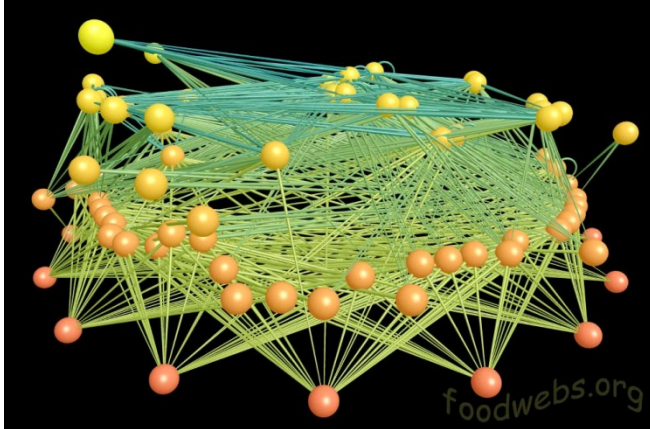


Proportions of papers on ecological networks published in the last 50 years that were related to food webs, mutualistic webs and parasitic webs

Ces différents types d'interactions coexistent dans les communautés



# Des études focalisées sur un type d'interaction



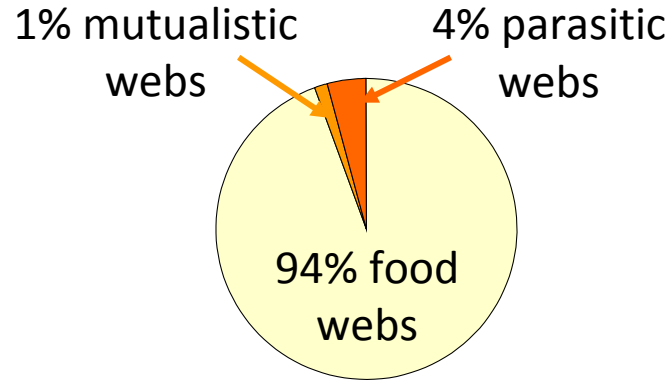
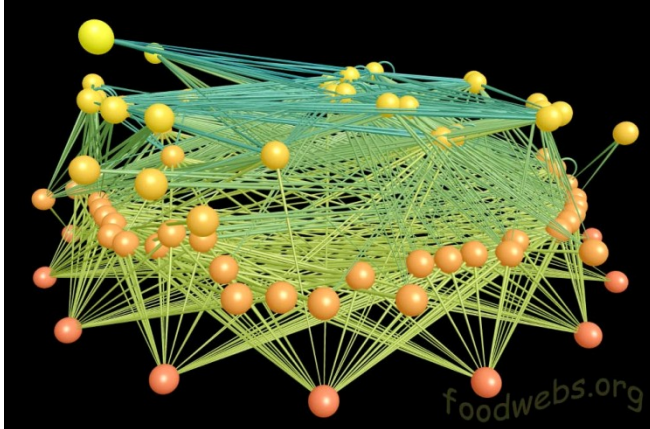
Proportions of papers on ecological networks published in the last 50 years that were related to food webs, mutualistic webs and parasitic webs

Quels sont les effets de ces interconnexions entre différents types de réseaux d'interactions sur la stabilité?





# Des études focalisées sur un type d'interaction



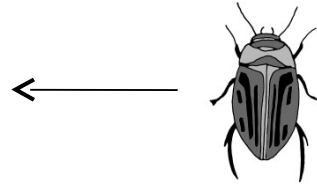
Proportions of papers on ecological networks published in the last 50 years that were related to food webs, mutualistic webs and parasitic webs

Quels sont les effets de ces interconnexions entre différents types de réseaux d'interactions sur la stabilité?

- Cas des réseaux herbivores-plantes-pollinisateurs
- Comment la présence des interactions de pollinisation affecte les effets de l'architecture des réseaux trophiques sur la stabilité?  
Les résultats obtenus dans les réseaux trophiques isolés sont ils robustes?

# Modèle: dynamiques de populations

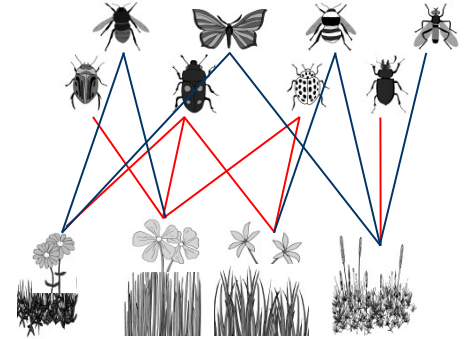
$$\frac{dH_i}{dt} = r_{Hi}H_i - I_{Hi}H_i^2 + \sum_{j=1}^{Np} \frac{c_{ji}H_iP_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{prey}(Hi)} P_k}$$



$$\frac{dM_i}{dt} = r_{Mi}M_i - I_{Mi}M_i^2 + \sum_{j=1}^{Np} \frac{c_{ji}M_iP_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{mut}(Mi)} P_k}$$

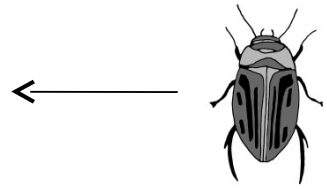


$$\frac{dP_i}{dt} = r_{Pi}P_i - I_{Pi}P_i^2 + \sum_{j=1}^{Nm} \frac{c_{ij}M_jP_i}{\alpha_{ij}^{-1} + \sum_{Mk \in \text{mut}(Pi)} M_k} - \sum_{j=1}^{Na} \frac{c_{ij}H_jP_i}{\alpha_{ij}^{-1} + \sum_{Pk \in \text{prey}(Hj)} P_k}$$

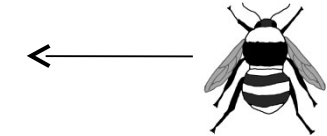


# Modèle: dynamiques de populations

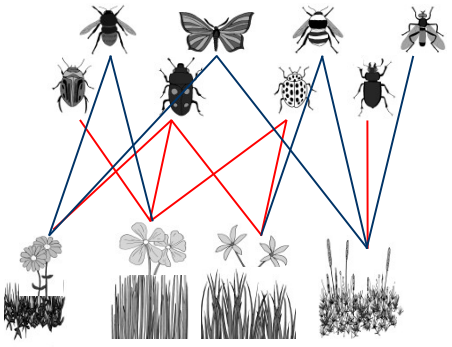
$$\frac{dH_i}{dt} = r_{Hi} H_i - I_{Hi} H_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} H_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{prey}(Hi)} P_k}$$



$$\frac{dM_i}{dt} = r_{Mi} M_i - I_{Mi} M_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} M_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{mut}(Mi)} P_k}$$



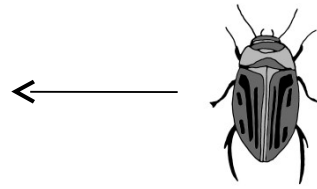
$$\frac{dP_i}{dt} = r_{Pi} P_i - I_{Pi} P_i^2 + \sum_{j=1}^{Nm} \frac{c_{ij} M_j P_i}{\alpha_{ij}^{-1} + \sum_{Mk \in \text{mut}(Pi)} M_k} - \sum_{j=1}^{Na} \frac{c_{ij} H_j P_i}{\alpha_{ij}^{-1} + \sum_{Pk \in \text{prey}(Hj)} P_k}$$



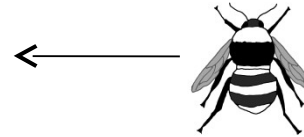
- Taux de croissance intrinsèque :  $r_p > 0$  et  $r_A < 0$ ,
- Compétition intra-spécifique densité-dépendante

# Modèle: dynamiques de populations

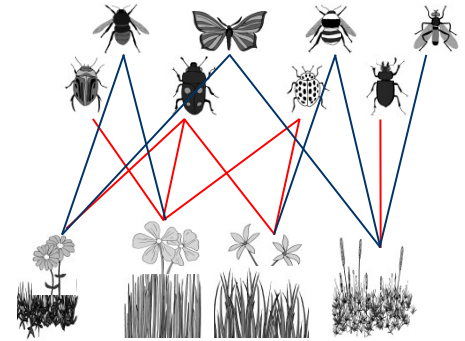
$$\frac{dH_i}{dt} = r_{Hi} H_i - I_{Hi} H_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} H_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{prey}(Hi)} P_k}$$



$$\frac{dM_i}{dt} = r_{Mi} M_i - I_{Mi} M_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} M_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{mut}(Mi)} P_k}$$



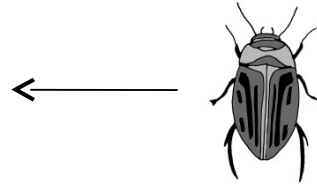
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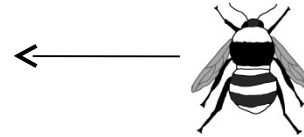
- Taux de croissance intrinsèque :  $r_p > 0$  et  $r_A < 0$ ,
- Compétition intra-spécifique densité-dépendante
- Saturation du terme d'interaction avec la densité de partenaires mutualistes

# Modèle: dynamiques de populations

$$\frac{dH_i}{dt} = r_{Hi} H_i - I_{Hi} H_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} H_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{prey}(Hi)} P_k}$$



$$\frac{dM_i}{dt} = r_{Mi} M_i - I_{Mi} M_i^2 + \sum_{j=1}^{Np} \frac{c_{ji} M_i P_j}{\alpha_{ji}^{-1} + \sum_{Pk \in \text{mut}(Mi)} P_k}$$



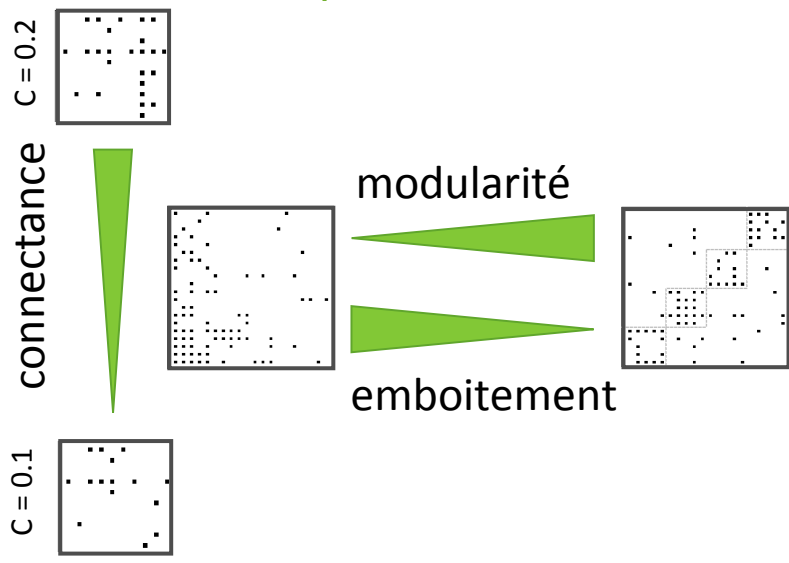
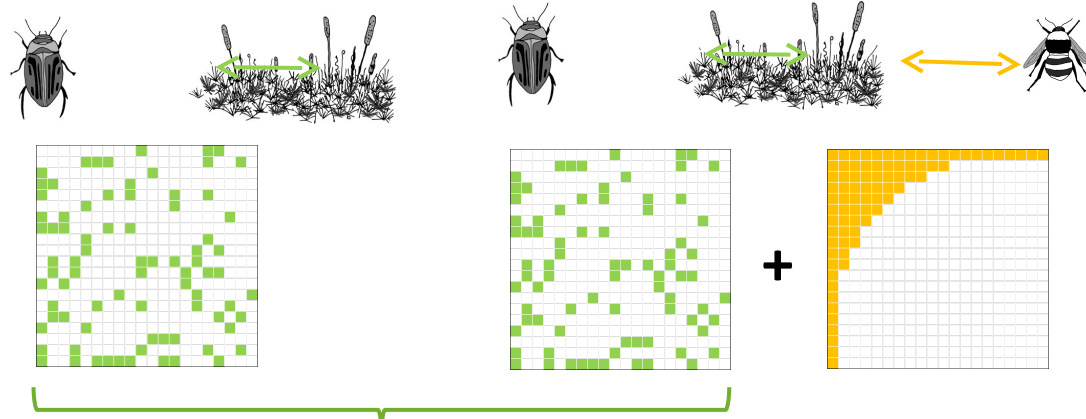
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- Taux de croissance intrinsèque :  $r_p > 0$  et  $r_A < 0$ ,
- Compétition intra-spécifique densité-dépendante
- Saturation du terme d'interaction avec la densité de partenaires mutualistes
- Saturation du terme d'interaction avec la densité des proies

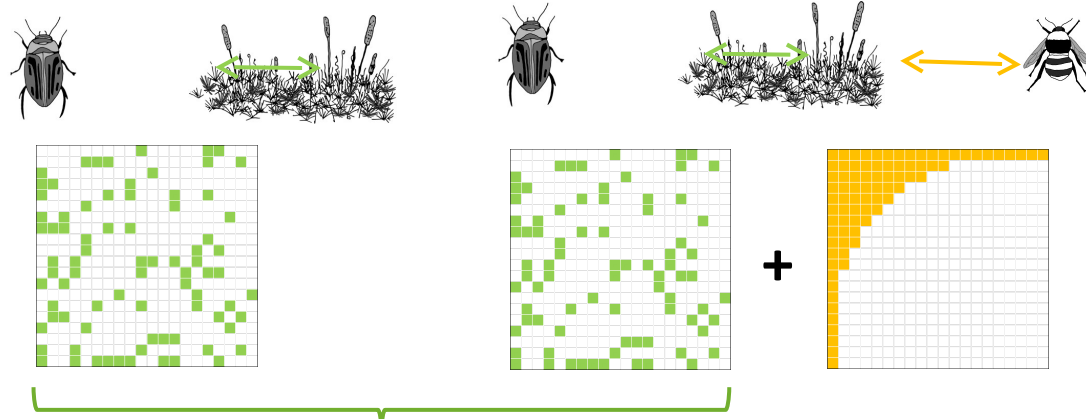
# Simulations

*Effet de l'architecture des réseaux trophiques sur la stabilité ...*

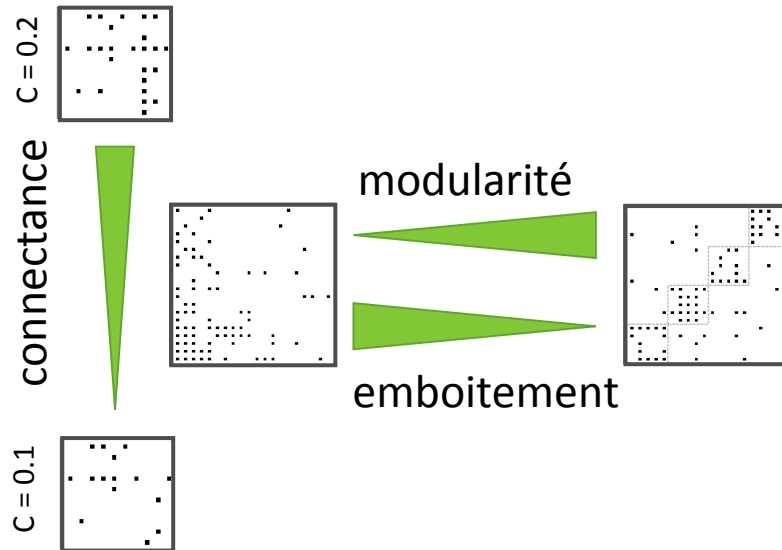


# Simulations

Effet de l'architecture des réseaux trophiques sur la stabilité ...



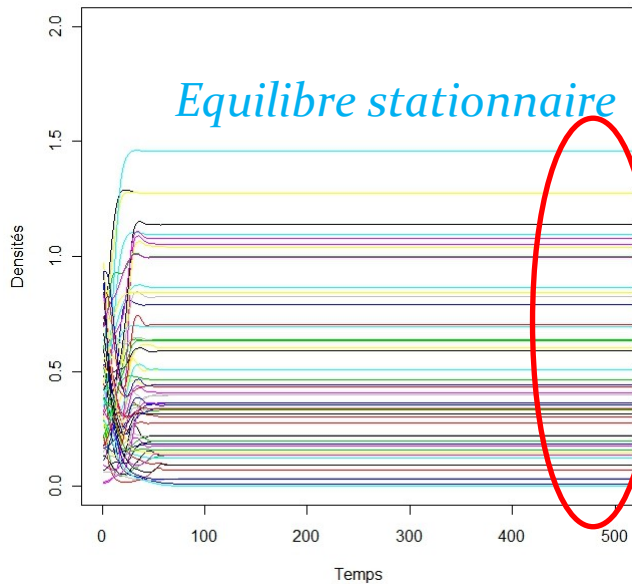
... en absence ou en présence d'un réseau mutualiste emboîté



Deux cas :  $c_{ijmut}$  moyen  
 $c_{ijmut}$  fort

$$\frac{dM_i}{dt} = r_{Mi}M_i - I_{Mi}M_i^2 + \sum_{j=1}^{Np} \frac{c_{ji}M_iP_j}{\alpha_{ji}^{-1} + \sum_{Pk \in mut(Mi)} P_k}$$

# Mesures de stabilité



$J =$

plantes			pollinisateurs			herbivores			
$\frac{\partial f_{P_1}}{\partial P_1}$	...	$\frac{\partial f_{P_1}}{\partial P_n}$	$\frac{\partial f_{P_1}}{\partial M_1}$	...	$\frac{\partial f_{P_1}}{\partial M_n}$	$\frac{\partial f_{P_1}}{\partial H_1}$	...	$\frac{\partial f_{P_1}}{\partial H_n}$	plantes
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	
$\frac{\partial f_{P_n}}{\partial P_1}$	...	$\frac{\partial f_{P_n}}{\partial P_n}$	$\frac{\partial f_{P_n}}{\partial M_1}$	...	$\frac{\partial f_{P_n}}{\partial M_n}$	$\frac{\partial f_{P_n}}{\partial H_1}$	...	$\frac{\partial f_{P_n}}{\partial H_n}$	
$\frac{\partial f_{M_1}}{\partial P_1}$	...	$\frac{\partial f_{M_1}}{\partial P_n}$	$\frac{\partial f_{M_1}}{\partial M_1}$	...	$\frac{\partial f_{M_1}}{\partial M_n}$	0	...	0	pollinisateurs
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	
$\frac{\partial f_{M_n}}{\partial P_1}$	...	$\frac{\partial f_{M_n}}{\partial P_n}$	$\frac{\partial f_{M_n}}{\partial M_1}$	...	$\frac{\partial f_{M_n}}{\partial M_n}$	0	...	0	
$\frac{\partial f_{H_1}}{\partial P_1}$	...	$\frac{\partial f_{H_1}}{\partial P_n}$	0	...	0	$\frac{\partial f_{H_1}}{\partial H_1}$	...	$\frac{\partial f_{H_1}}{\partial H_n}$	herbivores
$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	
$\frac{\partial f_{H_n}}{\partial P_1}$	...	$\frac{\partial f_{H_n}}{\partial P_n}$	0	...	0	$\frac{\partial f_{H_n}}{\partial H_1}$	...	$\frac{\partial f_{H_n}}{\partial H_n}$	

## Persistence

Proportion d'espèces qui persistent à l'équilibre.

## Architectures des réseaux à l'équilibre

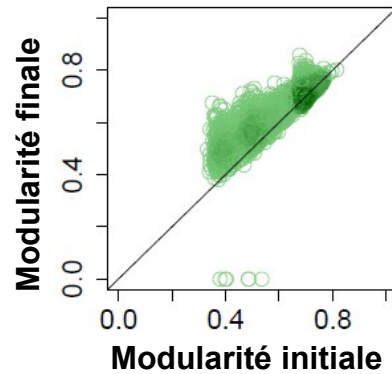
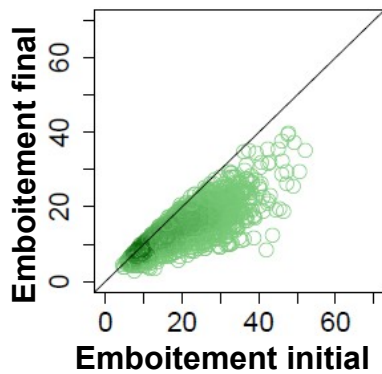
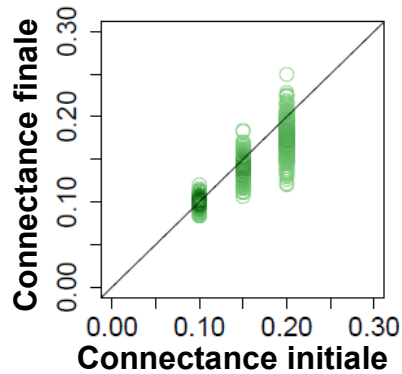
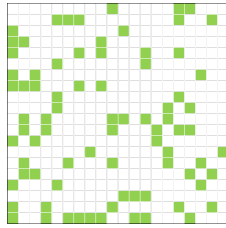
## Résilience

Mesure la capacité d'un système à retourner à l'équilibre après une perturbation.

$$resilience = |\max(\text{Re}(\lambda))|$$

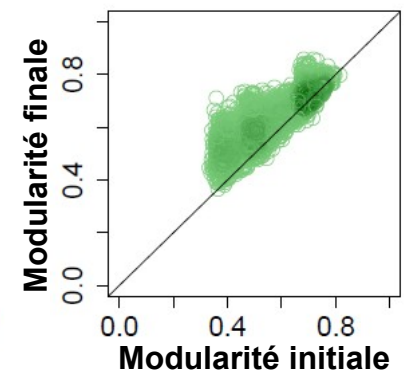
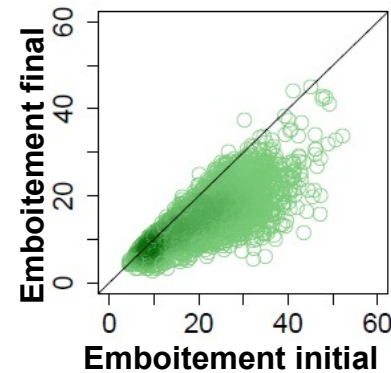
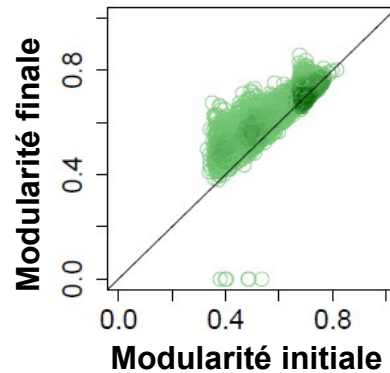
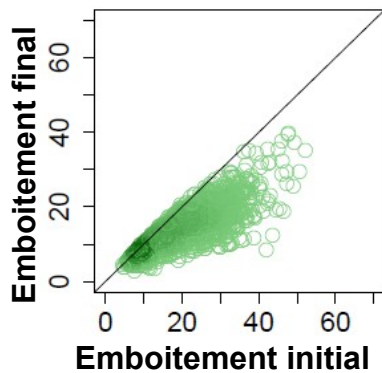
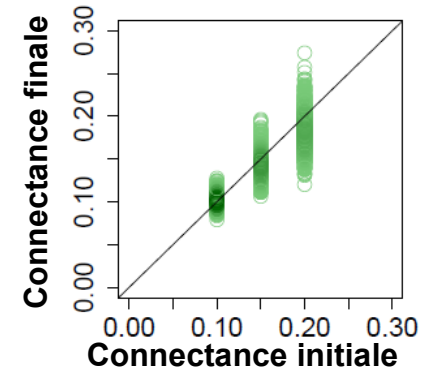
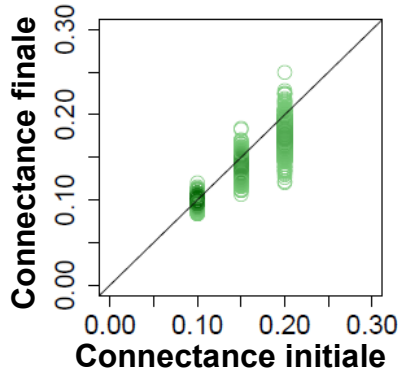
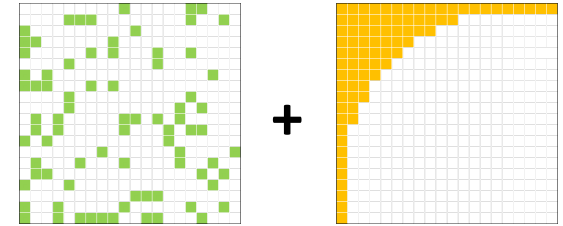
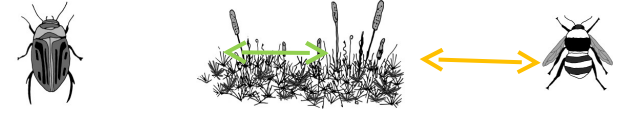
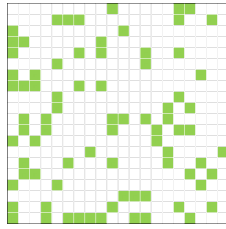


# Architecture des réseaux et persistance



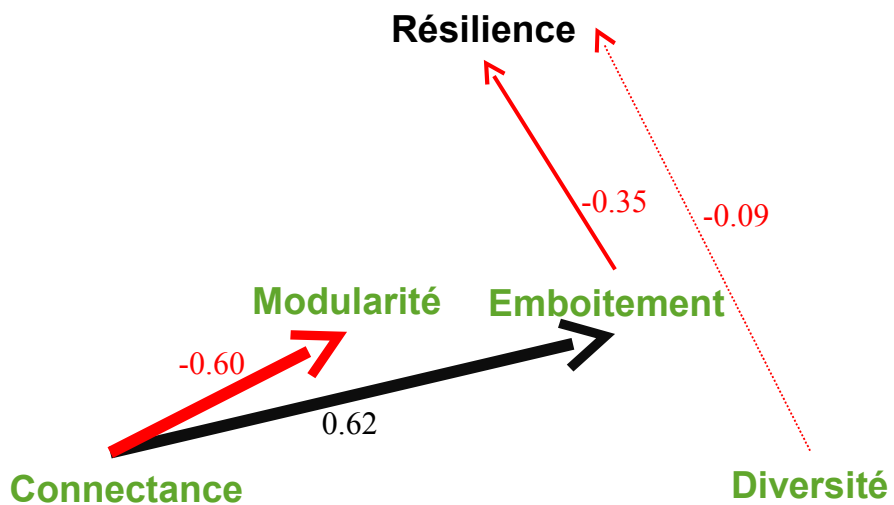
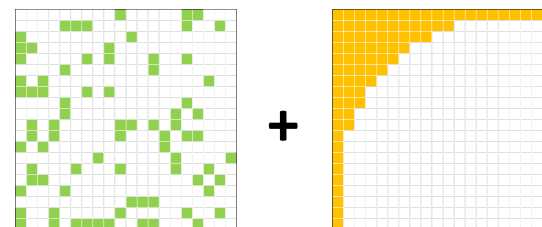
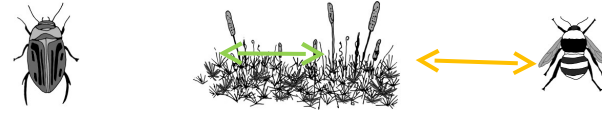
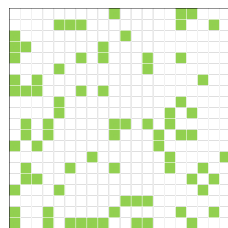
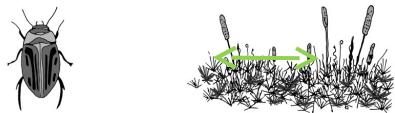
# Architecture des réseaux et persistance

Cas  $c_{ijmut}$  moyen



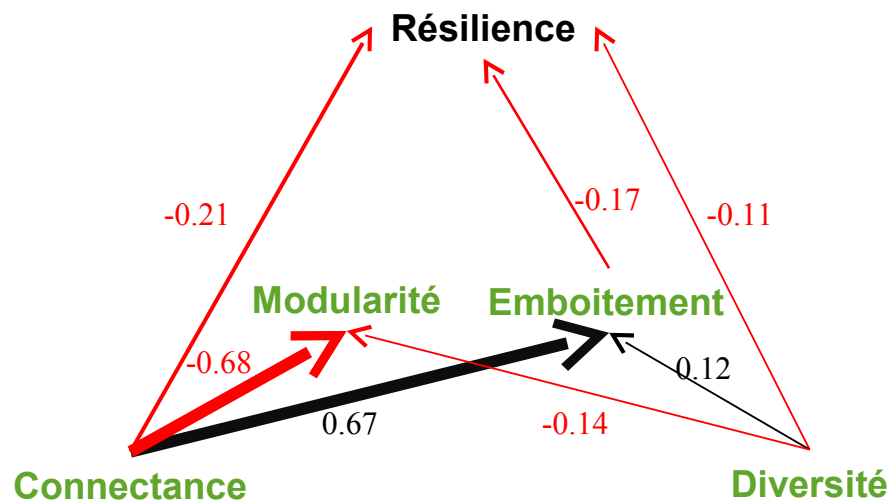
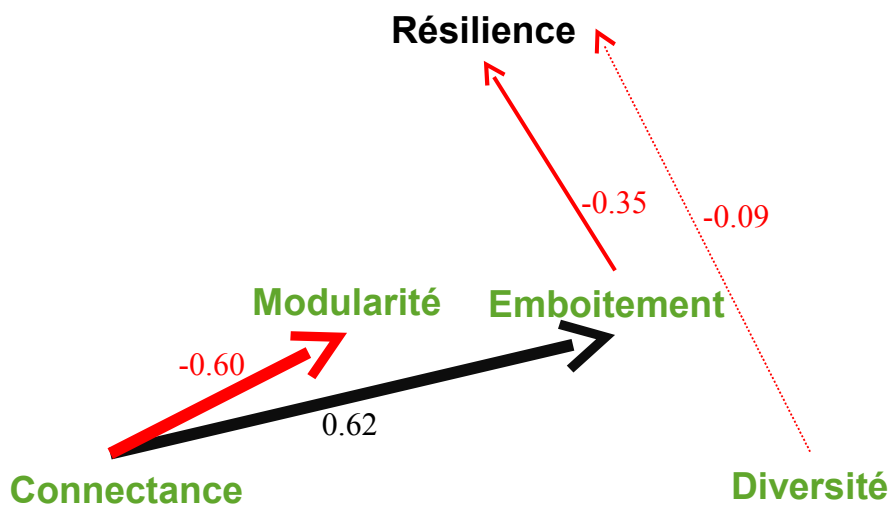
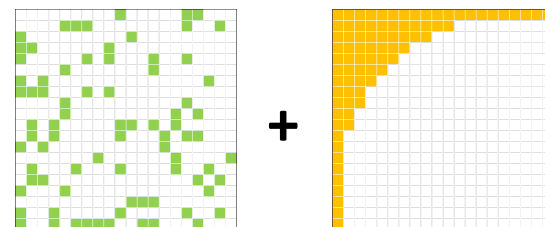
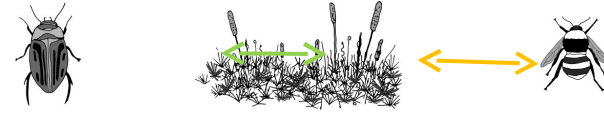
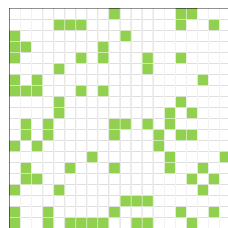
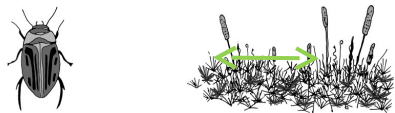
# Architecture des réseaux et résilience

Cas  $c_{ijmut}$  moyen



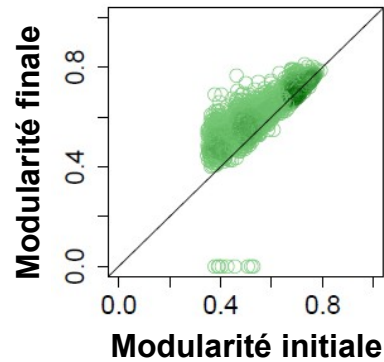
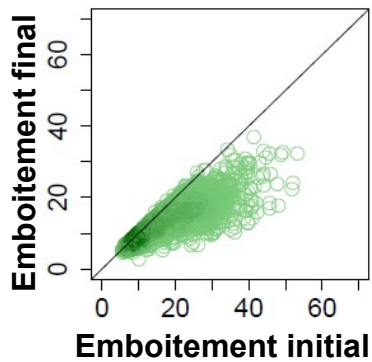
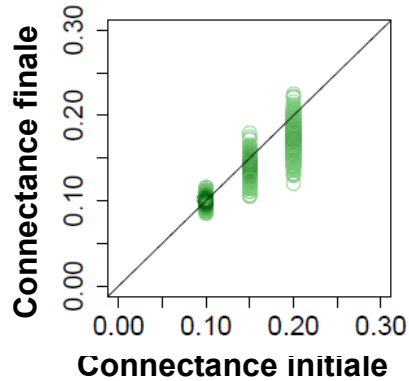
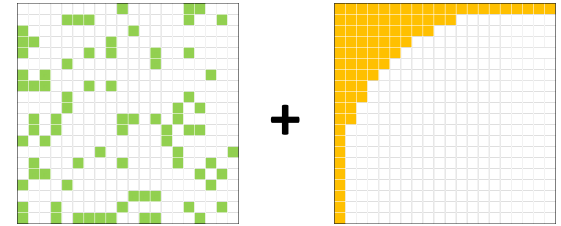
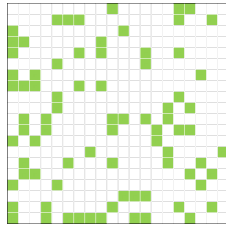
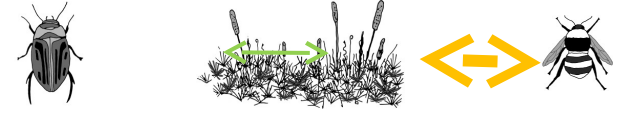
# Architecture des réseaux et résilience

Cas  $c_{ijmut}$  moyen



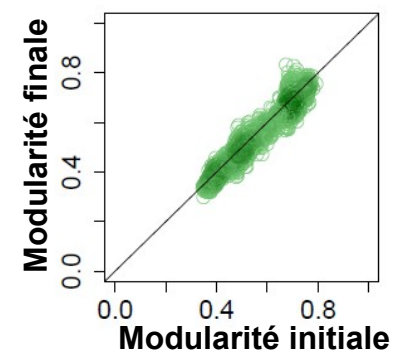
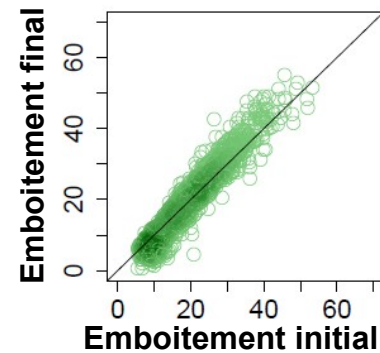
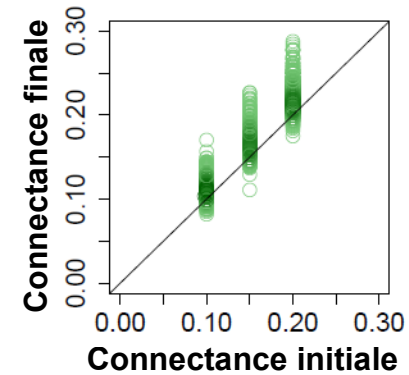
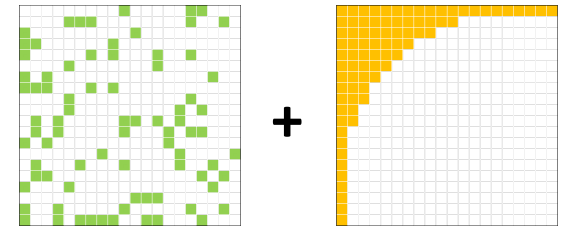
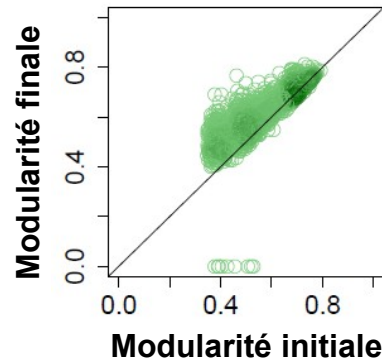
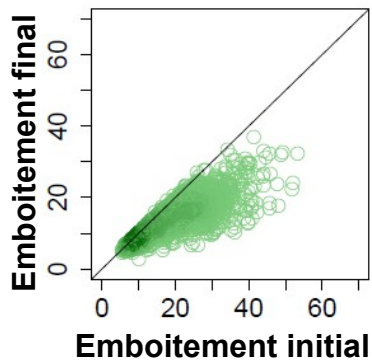
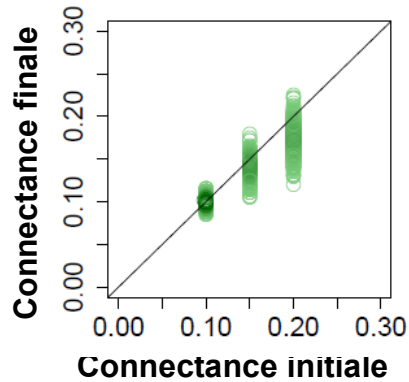
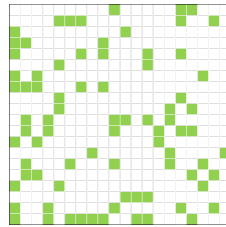
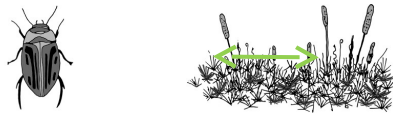
# Architecture des réseaux et persistance

Cas  $c_{ijmut}$  fort



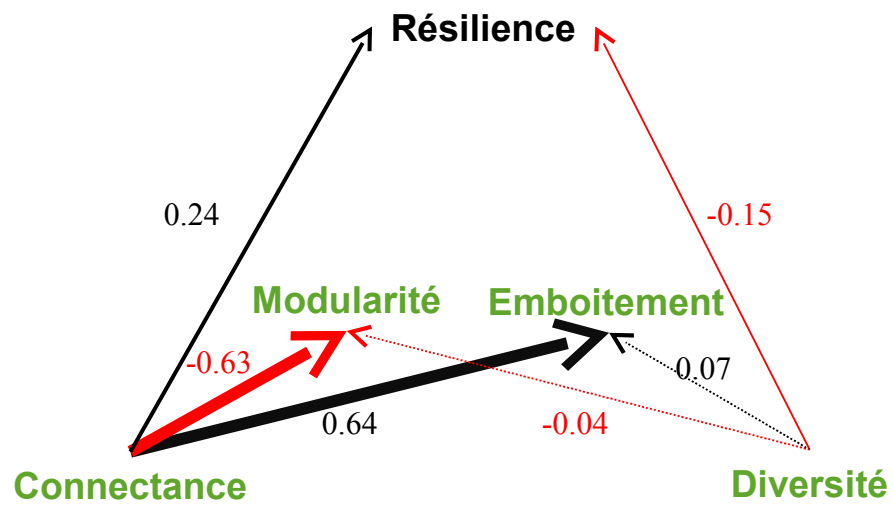
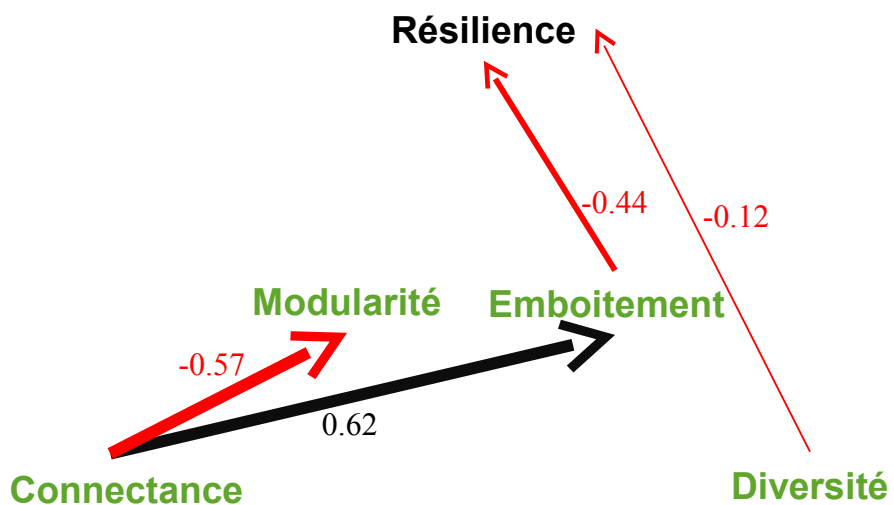
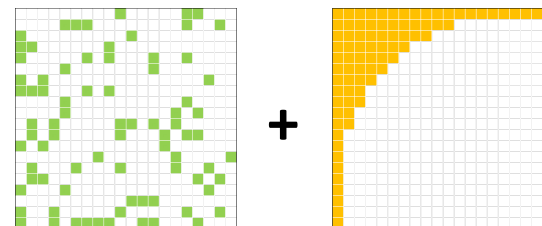
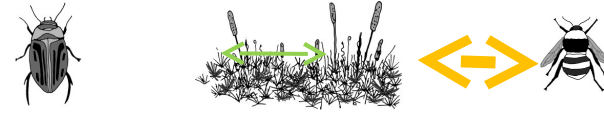
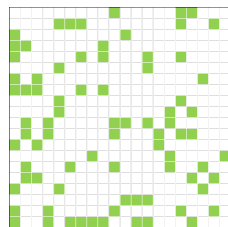
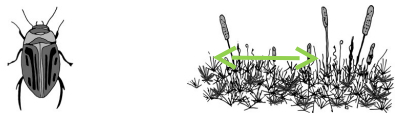
# Architecture des réseaux et persistance

Cas  $c_{ijmut}$  fort



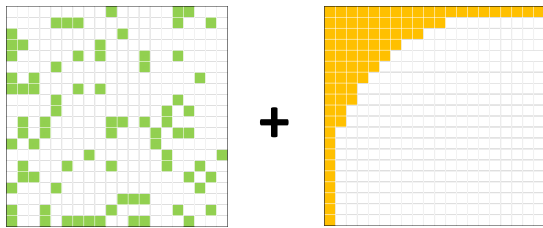
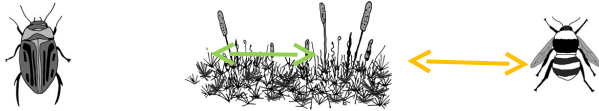
# Architecture des réseaux et résilience

Cas  $c_{ijmut}$  fort



# Forces d'interactions et résilience

Cas  $c_{ijmut}$  moyen

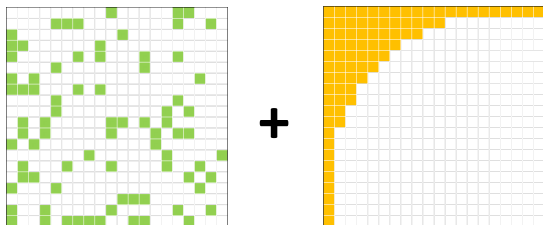
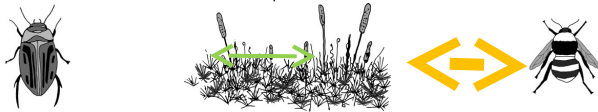


$\neq ?$

$Max(\text{Re}(\lambda))$

$J =$

		plantes		pollinisateurs		herbivores			
$\left[ \begin{array}{l} \text{plantes} \\ \text{pollinisateurs} \\ \text{herbivores} \end{array} \right.$	$\frac{\partial f_{P_1}}{\partial P_1}$	...	$\frac{\partial f_{P_1}}{\partial P_n}$	$\frac{\partial f_{P_1}}{\partial M_1}$	...	$\frac{\partial f_{P_1}}{\partial M_n}$	$\frac{\partial f_{P_1}}{\partial H_1}$	...	$\frac{\partial f_{P_1}}{\partial H_n}$
	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	$\frac{\partial f_{P_n}}{\partial P_1}$	...	$\frac{\partial f_{P_n}}{\partial P_n}$	$\frac{\partial f_{P_n}}{\partial M_1}$	...	$\frac{\partial f_{P_n}}{\partial M_n}$	$\frac{\partial f_{P_n}}{\partial H_1}$	...	$\frac{\partial f_{P_n}}{\partial H_n}$
	$\frac{\partial f_{M_1}}{\partial P_1}$	...	$\frac{\partial f_{M_1}}{\partial P_n}$	$\frac{\partial f_{M_1}}{\partial M_1}$	...	$\frac{\partial f_{M_1}}{\partial M_n}$	0	...	0
	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	$\frac{\partial f_{M_n}}{\partial P_1}$	...	$\frac{\partial f_{M_n}}{\partial P_n}$	$\frac{\partial f_{M_n}}{\partial M_1}$	...	$\frac{\partial f_{M_n}}{\partial M_n}$	0	...	0
	$\frac{\partial f_{H_1}}{\partial P_1}$	...	$\frac{\partial f_{H_1}}{\partial P_n}$	0	...	0	$\frac{\partial f_{H_1}}{\partial H_1}$	...	$\frac{\partial f_{H_1}}{\partial H_n}$
	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	$\frac{\partial f_{H_n}}{\partial P_1}$	...	$\frac{\partial f_{H_n}}{\partial P_n}$	0	...	0	$\frac{\partial f_{H_n}}{\partial H_1}$	...	$\frac{\partial f_{H_n}}{\partial H_n}$
	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$



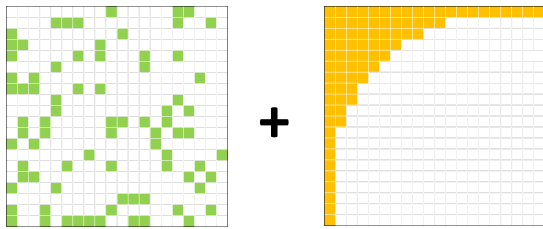
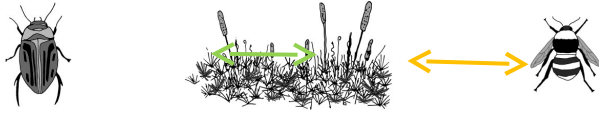
Cas  $c_{ijmut}$  fort



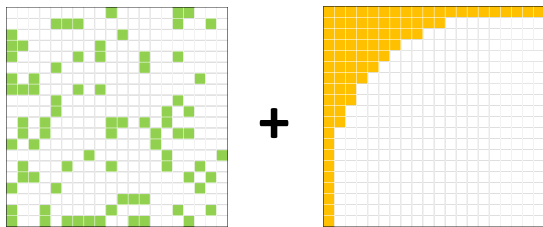
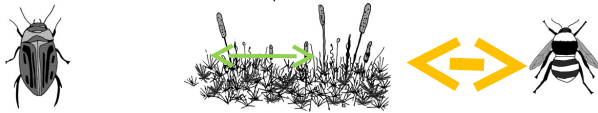


# Forces d'interactions et résilience

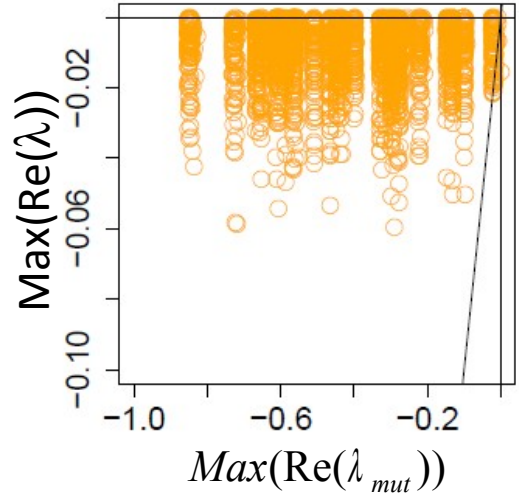
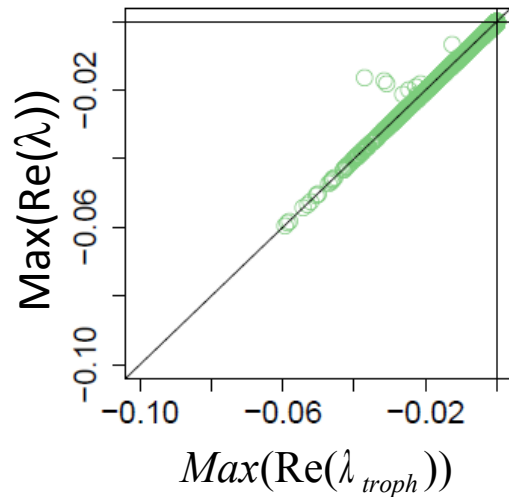
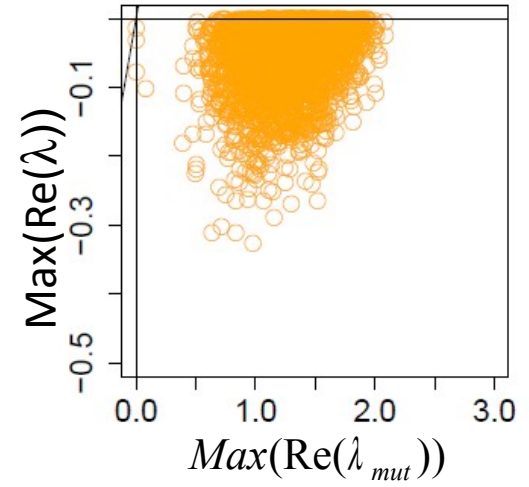
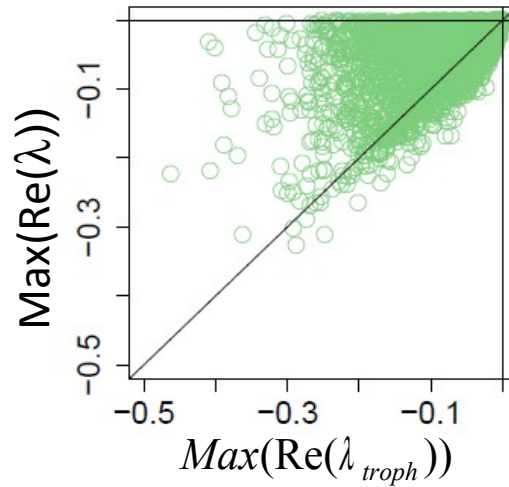
Cas  $c_{ijmut}$  moyen



$\neq$  ?



Cas  $c_{ijmut}$  fort

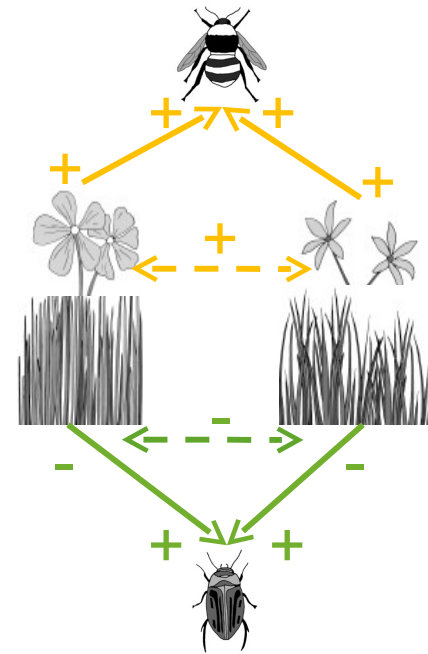


# Conclusions et perspectives

- les effets de l'architecture des réseaux trophiques sur la stabilité dépendent de leur association avec un réseau mutualiste
  - effets conservés quand les interactions trophiques et mutualistes sont d'intensités comparables
  - effets opposés de la connectance du réseau trophique quand les interactions mutualistes sont plus fortes
- les effets de l'architecture des réseaux mutualistes sur la stabilité dépendent aussi de leur association avec un réseau trophique

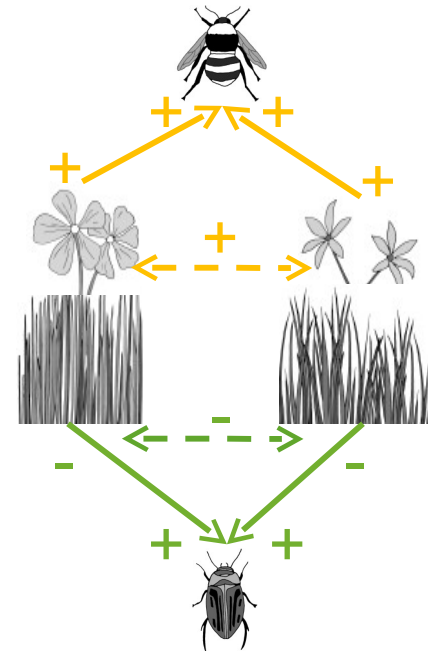
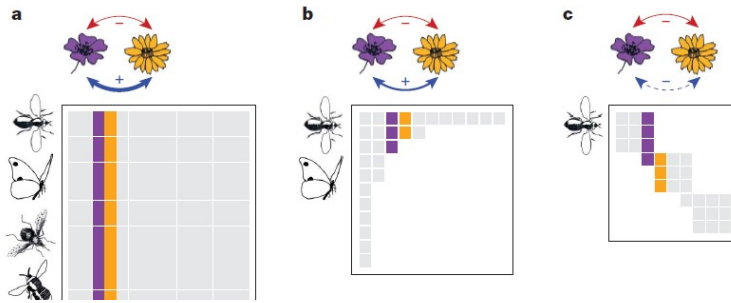
# Conclusions et perspectives

- Importance des effets indirects pour comprendre les conséquences de l'architecture des réseaux sur la stabilité ?



# Conclusions et perspectives

- Importance des effets indirects pour comprendre les conséquences de l'architecture des réseaux sur la stabilité ?



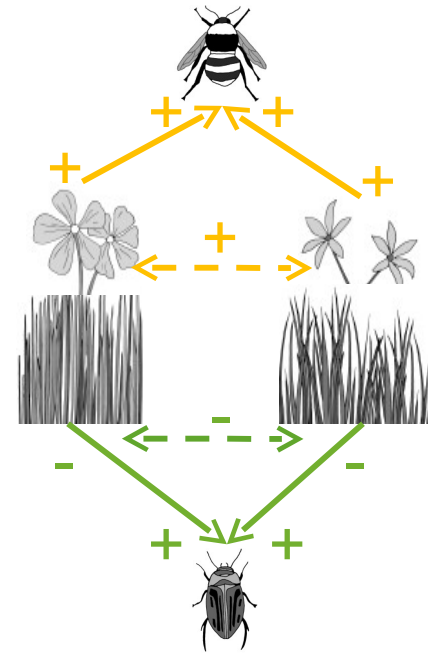
$$\frac{1}{N_i^{(P)}} \frac{dN_i^{(P)}}{dt} = \alpha_i^{(P)} - \sum_{j \in P} \beta_{ij}^{(P)} N_j^{(P)} + \sum_{k \in A} \frac{\gamma_{ik}^{(P)} N_k^{(A)}}{1 + h^{(P)} \sum_{l \in A} \gamma_{il}^{(P)} N_l^{(A)}}$$

$$\left. \frac{1}{\bar{S}^{(P)}} \frac{\partial \bar{S}_{\text{mut}}^{(P)}}{\partial R} \right|_{R=0} = \left( 1 + \frac{1}{\bar{S}^{(P)}} \right) \langle n^{(P)} \rangle \left[ \bar{S}^{(P)} \left( \hat{\eta}^{(P)} - \frac{\langle n^{(P)} \rangle}{S^{(A)} + \bar{S}^{(A)}} \right) - (1 - \hat{\eta}^{(P)}) + \frac{\langle (n^{(P)})^2 \rangle - \langle n^{(P)} \rangle^2}{\langle n^{(P)} \rangle (S^{(A)} + \bar{S}^{(A)})} \frac{S^{(P)} + \bar{S}^{(P)}}{S^{(P)} - 1} \right]$$

Augmente avec  $\hat{\eta}^{(P)} = \sum_{i \neq j} n_{ij}^{(P)} / \left( (S^{(P)} - 1) \sum_k n_k^{(P)} \right)$

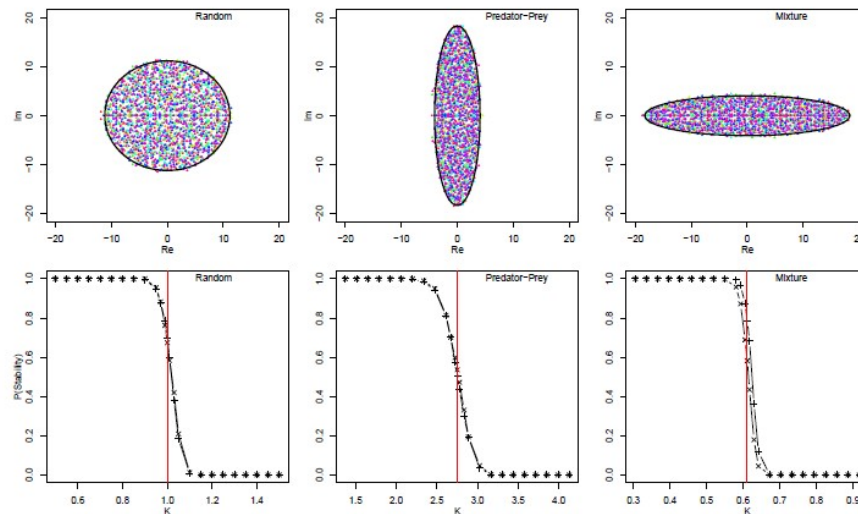
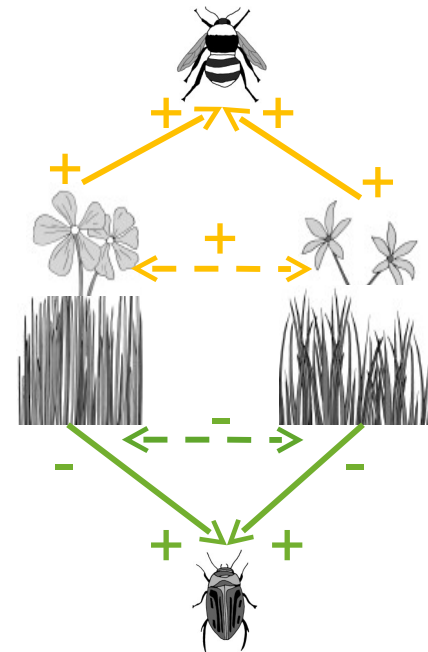
# Conclusions et perspectives

- Importance des effets indirects pour comprendre les conséquences de l'architecture des réseaux sur la stabilité ?
- Nécessité d'une étude analytique pour comprendre les effets de l'architecture dans ces réseaux complexes sur la persistance et la résilience



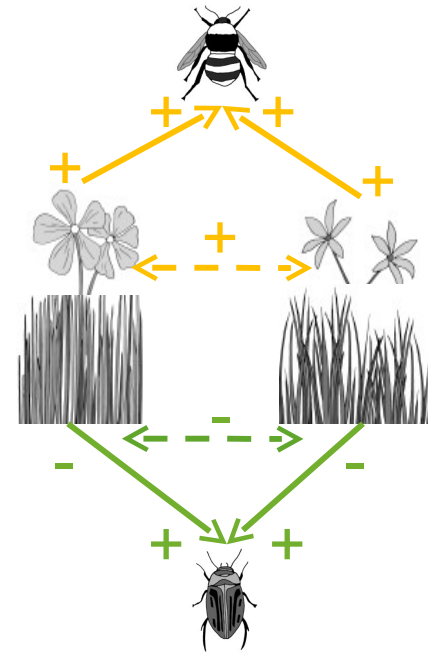
# Conclusions et perspectives

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# Conclusions et perspectives

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- Autres mesures de stabilité ?
- Définir de nouveaux indices d'architecture de réseaux





***Merci de votre  
attention***

