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Structure–stability relationships in networks
combining mutualistic and antagonistic interactions.
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Appendix 1–7

SUPPLEMENTARY MATERIAL

Appendix 1: Analysis of the effect of constant interaction effort hypothesis on our results

We performed additional analyses by adding the assumption that total interaction effort is constant between species (Mougi & Kondoh 2012, Brose 2008). In the differential equation set that models the community dynamics, we added a parameter w_{ij} , the interaction effort of species j for the interaction partner i as follows:

$$\begin{aligned}
 (1) \quad \frac{dH_i}{dt} &= r_{H_i} H_i - I_{H_i} H_i^2 + \sum_{j=1}^{S^p} \frac{w_{ji} c_{ji} H_i P_j}{\alpha_{ji}^{-1} + \sum_{P_k \in \text{prey}(H_i)} w_{ki} P_k} \\
 (2) \quad \frac{dM_i}{dt} &= r_{M_i} M_i - I_{M_i} M_i^2 + \sum_{j=1}^{S^p} \frac{w_{ji} c_{ji} M_i P_j}{\alpha_{ji}^{-1} + \sum_{P_k \in \text{mut}(M_i)} w_{ki} P_k} \\
 (3) \quad \frac{dP_i}{dt} &= r_{P_i} P_i - I_{P_i} P_i^2 + \sum_{j=1}^{S^m} \frac{w_{ji} c_{ij} M_j P_i}{\alpha_{ij}^{-1} + \sum_{M_k \in \text{mut}(P_i)} w_{ki} M_k} - \sum_{j=1}^{S^H} \frac{w_{ij} c_{ij} H_j P_i}{\alpha_{ij}^{-1} + \sum_{P_k \in \text{prey}(H_j)} w_{kj} P_k}
 \end{aligned}$$

When i and j are mutualistic species, A_{ij} is the potential interaction effort of species j for species i :

$$w_{ij} = \frac{A_{ij}}{\sum_{k=1}^{N_j^{\text{mut}}} A_{kj}} \quad \text{with } A_{ij} = A_{ji} \text{ and } N_j^{\text{mut}} \text{ is the generalism degree of species } j.$$

The interaction effort for a given interaction partner is random ($w_{ij} \in [0,1]$). The sum of w_{ij} values for a given species j is 1, so that the overall effort dispensed in interacting with other species is the same whatever the generalism degree of species j (Brose 2008, Mougi & Kondoh 2012). As Mougi and Kondoh (2012), the interaction effort put into mutualism or antagonism is constant regarding separately the mutualistic and the antagonistic generalism degree, and not total generalism degree.

We performed the same analyses as described in Material and Methods section of our manuscript both for interlinked networks and networks with a single type of interaction.

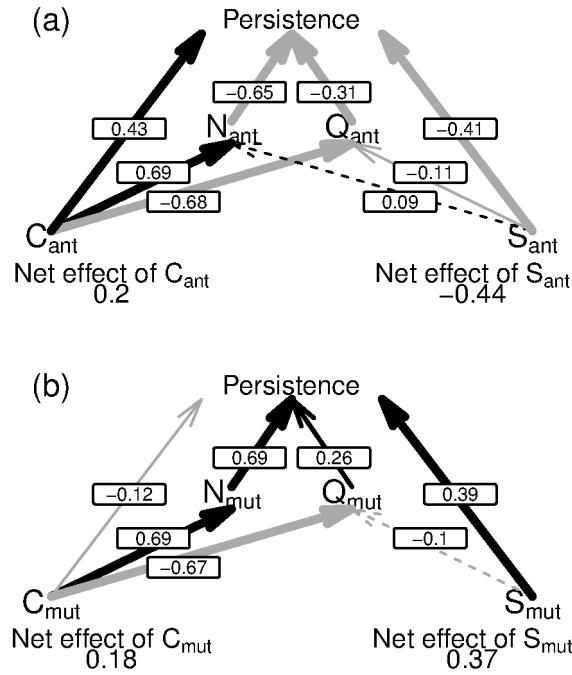


Figure A1: Path diagram of the effects on persistence of the initial structure in antagonistic bipartite networks (a), and in mutualistic bipartite networks (b), under the constant interaction effort hypothesis. Both types of networks are studied in isolation. The effect of a given structural feature on persistence is due to its direct effect, and to its effect mediated through nestedness and modularity. The thickness of the arrows corresponds to the relative strength of the effects. The negative effects are coloured in grey, and the positive ones in black. The path diagram allows considering the direct effects of antagonistic and mutualistic connectance C and diversity S , and their indirect effects through nestedness N and modularity Q . [X_{mut} = mutualistic X ; X_{ant} = antagonistic X . e.g.: C_{mut} = mutualistic connectance].

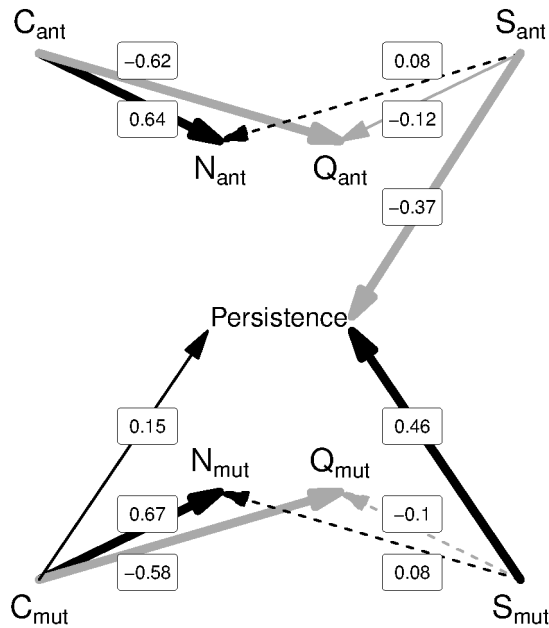


Figure A2: Path diagram of the effects on persistence of the initial structure of the mutualistic sub-network and the antagonistic sub-network of an interlinked network, under the constant interaction effort hypothesis. Same legend as Figure A1.

The effects of connectance and diversity on persistence are qualitatively the same whether considering the diversity of interaction types or not. The net effects of mutualistic and antagonistic connectances and diversities on persistence are mostly mediated through changes in nestedness and modularity when considering a single interaction type. But when mutualistic and antagonistic networks are merged, nestedness and modularity effects are lost. Including a constant interaction effort hypothesis (which could be related to a trade-off between interaction strength and generalism degree) does not affect qualitatively our conclusions despite some changes in the nature of complexity-stability relationship.

Appendix 2: Network simulation design

Table A1: Symbols, definitions, and range of values of model parameters used in the simulations.

Parameter values were chosen to allow comparison with previous studies (Okuyama and Holland 2008, Thébault and Fontaine 2010).

Symbol	Definition	Range values
r_{Pi}	Intrinsic growth rate of plant species i	[0.1,0.2]
r_{Mi} / r_{Hi}	Intrinsic growth rate of insect species (pollinator or herbivore)	[-0.2,-0.001]
$I_{Pi} / I_{Mi} / I_{Hi}$	Density-dependent self-limitation of species i (plant, pollinator or herbivore)	[1,2]
c_{ij}	Maximum rate of antagonistic consumption or mutualism benefit for the interaction between plant i and insect species j	See Table A2
α_{ij}	Half saturation of antagonistic consumption or mutualism benefit for the interaction between plant species i and insect species j	[0.1,1]

Table A2: Set of simulations performed with the initial complexity for each sub-network.

Simulation type	Antagonistic complexity $\{S_h ; C_{ant}\}$	Maximum rate of herbivory	Mutualistic complexity $\{S_m ; C_{mut}\}$	Maximum rate of pollination
Antagonistic sub-network centred simulations	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{40 ; 0.25\}$	[2;3]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{16 ; 0.10\}$	[2;3]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{16 ; 0.25\}$	[2;3]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{40 ; 0.10\}$	[2;3]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{40 ; 0.25\}$	[1,1.5]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{16 ; 0.10\}$	[1,1.5]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{16 ; 0.25\}$	[1,1.5]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{40 ; 0.10\}$	[1,1.5]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{40 ; 0.25\}$	[4,6]
	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	$\{16 ; 0.10\}$	[4,6]
Mutualistic sub-network centred simulations	$\{40 ; 0.25\}$	[2;3]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{16 ; 0.10\}$	[2;3]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{16 ; 0.25\}$	[2;3]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{40 ; 0.10\}$	[2;3]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{40 ; 0.25\}$	[1,1.5]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{16 ; 0.10\}$	[1,1.5]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{16 ; 0.25\}$	[1,1.5]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{40 ; 0.10\}$	[1,1.5]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{40 ; 0.25\}$	[4,6]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
	$\{16 ; 0.10\}$	[4,6]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]
$\{16 ; 0.25\}$	[4,6]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	
$\{40 ; 0.10\}$	[4,6]	$\{[16,40] ; [0.07,0.25]\}$	[2;3]	

Appendix 3: Sensitivity analysis to relative interaction strengths in mutualistic and antagonistic sub-networks

We performed supplementary simulations to test the effect of mutualistic to antagonistic interaction strength ratio on our results. The results remain qualitatively the same whether mutualism is stronger than antagonism or not.

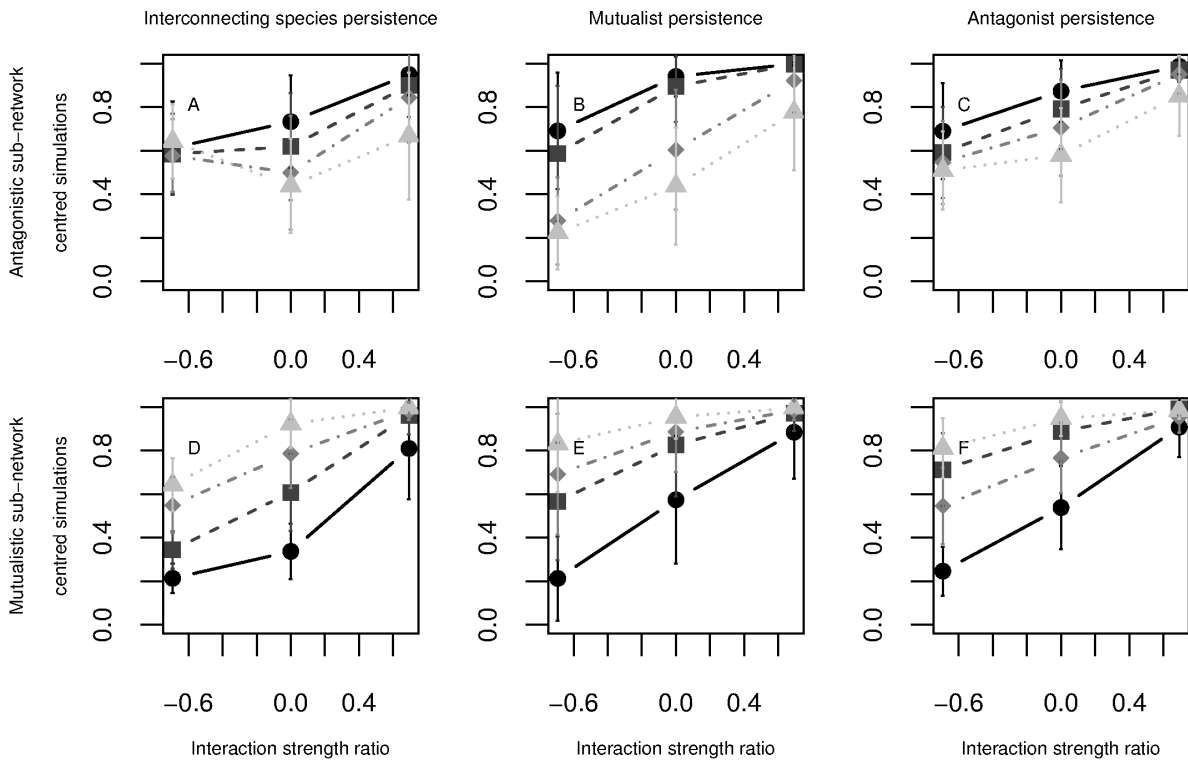


Figure A3: (a), (b) and (c) effects of antagonistic complexity and mutualistic to antagonistic interaction strength ratio ($\log[\bar{c}^{(mut)}/\bar{c}^{(ant)}]$) on persistence (mean \pm sd) for the mutualistic sub-network centred simulations; (d), (e) and (f) effects of mutualistic complexity and mutualistic to antagonistic interaction strength ratio on persistence (mean \pm sd) for the antagonistic sub-network centred simulations. Solid and black lines correspond to complexity $S_{(ant, mut)}C_{(ant, mut)}=16$, dark grey and dashed lines to $S_{(ant, mut)}C_{(ant, mut)}=10$, grey and dot-dashed lines to $S_{(ant, mut)}C_{(ant, mut)}=6.4$, light grey and

dotted lines to $S_{(ant, mut)}C_{(ant, mut)}=4$.

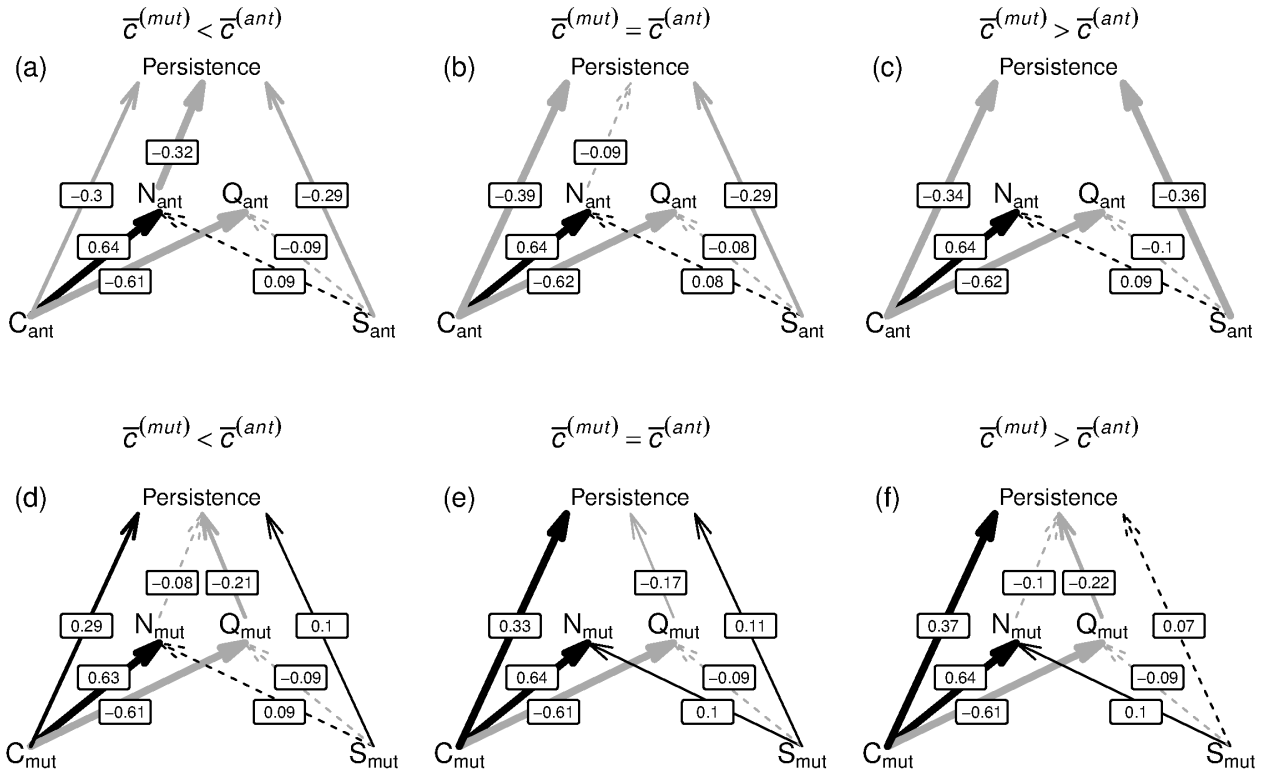


Figure A4: (a), (b) and (c) Path diagrams of the effects on persistence of the initial structure of the antagonistic sub-network; (d), (e) and (f) Path diagrams of the effects on persistence of the mutualistic sub-network in the merged network, for different ratios of interaction strength: (a) and (d) for $\bar{c}^{(mut)} < \bar{c}^{(ant)}$; (b) and (e) for $\bar{c}^{(mut)} = \bar{c}^{(ant)}$; (c) and (f) for $\bar{c}^{(mut)} > \bar{c}^{(ant)}$. The thickness of the arrows corresponds to the relative strength of the effects. The negative effects are coloured in grey, and the positive ones in black. The path diagram allows considering the direct effects of antagonistic and mutualistic connectance C and diversity S, and their indirect effects through nestedness N and modularity Q. [X_{mut} = mutualistic X; X_{ant} = antagonistic X. e.g.: C_{mut} = mutualistic connectance].

Appendix 4: Sensitivity analysis of the effect of a given sub-network structure on persistence to the structure of the other sub-network

We tested the robustness of the effect of one given sub-structure on persistence to the structure of the other sub-network. Our results remain qualitatively the same whatever the sub-structures are.

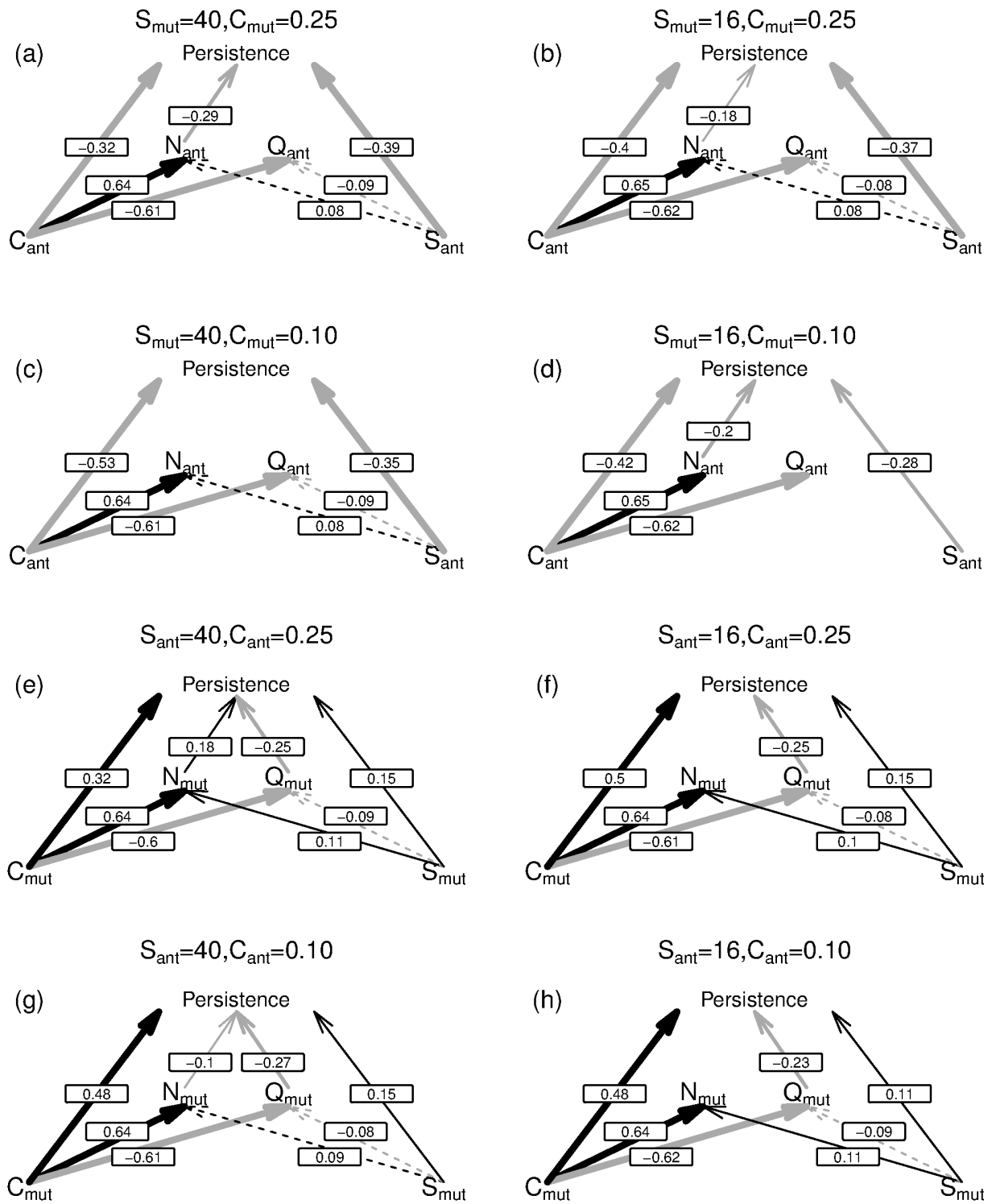


Figure A5: (a), (b), (c) and (d) Path diagrams of the effects on persistence of the initial structure of the antagonistic sub-network in the merged network, for different cases of diversity S_{mut} and connectance C_{mut} of the mutualistic sub-network; (e), (f), (g), and (h) Path diagrams of the effects on persistence of the initial structure of the mutualistic sub-network in the merged network, for

different cases of diversity S_{ant} and connectance C_{ant} of the antagonistic sub-network. The thickness of the arrows corresponds to the relative strength of the effects. The negative effects are coloured in grey, and the positive ones in black. The path diagram allows considering the direct effects of antagonistic and mutualistic connectance C and diversity S , and their indirect effects through nestedness N and modularity Q . [X_{mut} = mutualistic X; X_{ant} = antagonistic X. e.g.: C_{mut} = mutualistic connectance].

Appendix 5: Changes in nestedness and modularity in mutualistic and antagonistic sub-networks, embedded in a network combining mutualistic and antagonistic interactions

We compare initial and final structures of both mutualistic and antagonistic sub-networks. To assess whether observed changes were related to changes in sub-network diversity and connectance, we compare the values of nestedness and modularity in the observed sub-networks with the ones expected in random networks of same diversity, connectance and link distribution (Bascompte *et al.* 2003; Fortuna *et al.* 2010). To do so, we use the null model developed by Bascompte *et al.* (2003). This null model keeps the bipartite structure, the observed species richness and the number of links, and it further takes into account the original distribution of links by defining probabilities of interactions in the random network (Bascompte *et al.* 2003; Fortuna *et al.* 2010; Thébault & Fontaine 2010). The probability of an interaction between a given plant and a given insect is the mean of the proportion of observed links of the plant and the proportion of observed links of the insect relative to the overall number of links in the network (Bascompte *et al.* 2003; Fortuna *et al.* 2010). For each sub-network, we create 50 random networks based on our null model, and we calculate relative nestedness and relative modularity as follows:

$$(4) N = \frac{N_{obs} - \bar{N}_r}{\bar{N}_r}$$

$$(5) Q = \frac{Q_{obs} - \bar{Q}_r}{\bar{Q}_r}$$

N_{obs} and Q_{obs} are the observed nestedness and modularity, and N_r and Q_r are the averaged nestedness and modularity of random replicates. Variations in relative nestedness and modularity between final (*i.e.* at equilibrium after species extinctions) and initial (*i.e.* before species extinctions) sub-networks indicate that the observed variations in nestedness and modularity are not only due to variations in connectance and diversity (Thébault & Fontaine 2010).

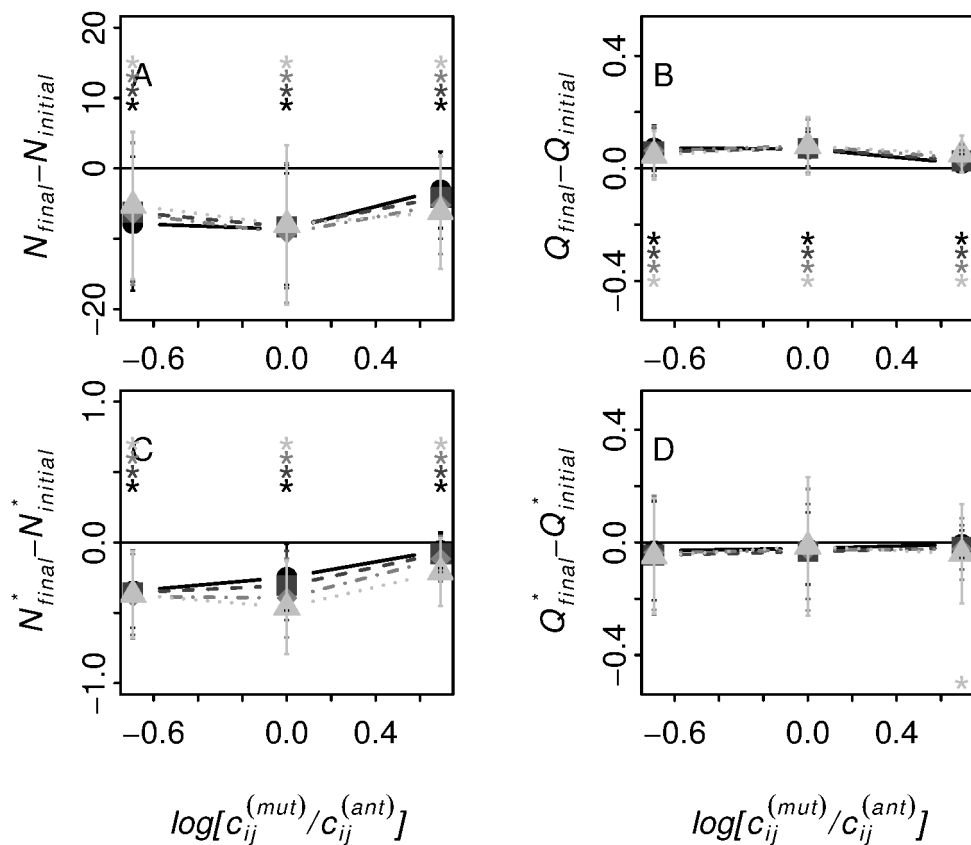


Figure A6: Difference between final and initial structure of antagonistic sub-networks against mutualistic to antagonistic interaction strength ratio ($\log[\bar{c}^{(mut)}/\bar{c}^{(ant)}]$), for different cases of mutualistic complexity ($\text{mean}\pm\text{sd}$). (A) difference between final nestedness and initial nestedness, (B) difference between final modularity and initial modularity, (C) difference between final relative nestedness and initial relative nestedness, (D) difference between final relative modularity and initial relative modularity. Solid and black lines correspond to complexity $S_{mut} * C_{mut}=16$, dark grey and dashed lines to $S_{mut} * C_{mut}=10$, grey and dot-dashed lines to $S_{mut} * C_{mut}=6.4$, light grey and dotted lines to $S_{mut} * C_{mut}=4$. Stars indicate significant difference ($p\text{-value}<0.05$) with zero according to Wilcoxon rank test performed for each case of mutualistic complexity for a given value of mutualistic to antagonistic interaction strength ratio. Star colour corresponds to the case of mutualistic complexity, as described above.

In merged networks, final antagonistic sub-networks tend to be significantly less nested (Figure A6 A) and more modular (Figure A6 B) than initially. According to the null model defined above, the changes in modularity are only due to changes in connectance and diversity (Figure A6 D) whereas it is not the case for nestedness (Figure A6 C). At higher mutualistic to antagonistic interaction strength ratio, the changes in structure are weaker because of high persistence of species (see Figure A3).

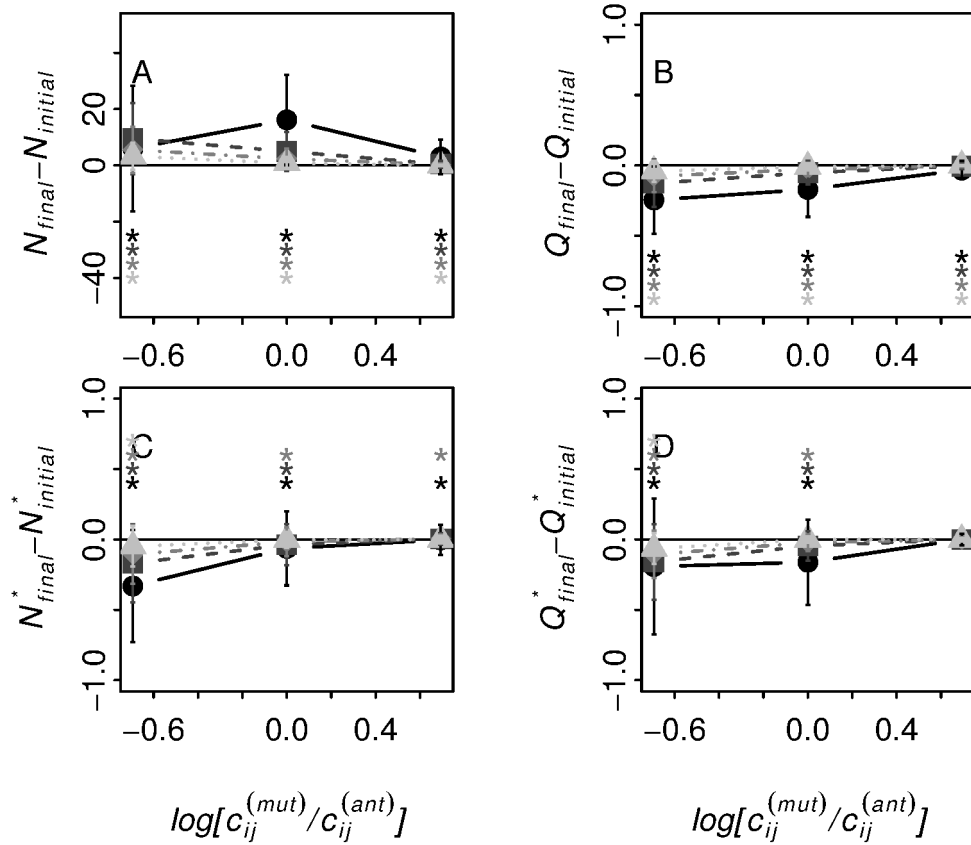


Figure A7: Difference between final and initial structure of mutualistic sub-networks against mutualistic to antagonistic interaction strength ratio ($\log[\bar{c}^{(mut)}/\bar{c}^{(ant)}]$), for different cases of antagonistic complexity (mean±sd). (A) Difference between final nestedness and initial nestedness, (B) difference between final modularity and initial modularity, (C) difference between final relative nestedness and initial relative nestedness, (D) difference between final relative modularity and initial relative modularity. Solid and black lines correspond to complexity $S_{ant} * C_{ant}=16$, dark grey and dashed lines to $S_{ant} * C_{ant}=10$, grey and dot-dashed lines to $S_{ant} * C_{ant}=6.4$, light grey and dotted lines to $S_{ant} * C_{ant}=4$. Stars indicate significant difference (p-value<0.05) with zero according to Wilcoxon rank test performed for each case of mutualistic complexity for a given value of mutualistic to antagonistic interaction strength ratio. Star colour corresponds to the case of antagonistic complexity, as described above.

In merged networks, final mutualistic sub-networks tend to be more nested (Figure A7 A) and less modular (Figure A7 B) than initially. At low mutualistic to antagonistic interaction strength ratio, modularity is confirmed to decrease when taking into account changes in connectance and diversity (Figure A7 D). To the contrary, relative nestedness tends to decrease over the dynamics, but this trend is not always significant and depends on antagonistic complexity (Figure A7 C). At high mutualistic to antagonistic interaction strength ratio, the changes in structure are weak or null because of high persistence of species (see Figure A3).

Appendix 6: Structure-stability relationships in networks with a single interaction type

We performed numerical simulations of bipartite networks with a single interaction type, either mutualistic (with a guild of species P interacting with a guild of species M) or antagonistic (with a guild of species P consumed by a guild of species H), as in Thébault and Fontaine (2010). The dynamical model and the range of parameter values are the same than the one used in their study (and ours). However, the simulation design is slightly different from Thébault and Fontaine (2010) so that initial network structures correspond to the range of values used in our simulation sets for merged networks. Initial S_p is always 24, while S_M and S_H belong to the following range: {16; 20; 28; 36; 40}. Connectance belongs to the following range: {0.07, 0.15, 0.2, 0.25, 0.3}.

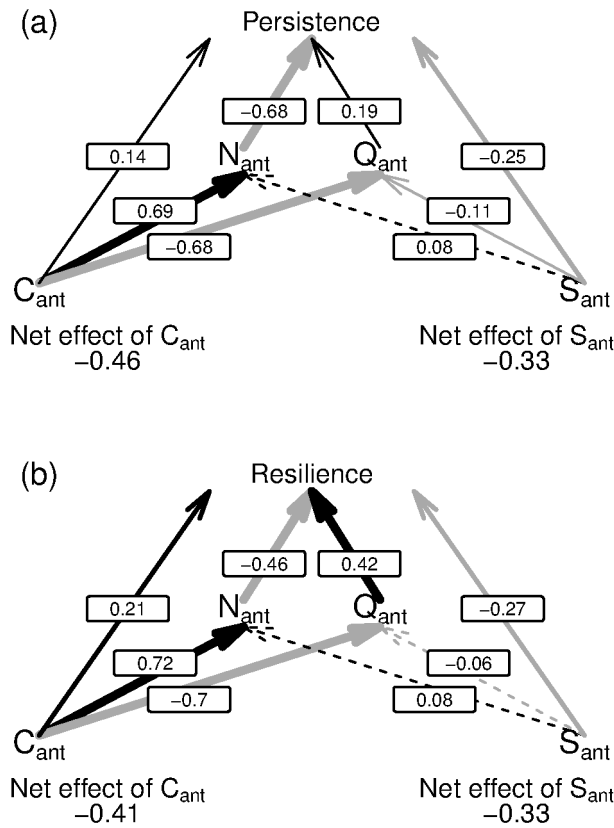


Figure A8: Path diagram of effects of initial structure of antagonistic networks on persistence (a), and of effects of final structure of antagonistic networks on resilience (b). The thickness of the arrows corresponds to the relative strength of the effects. The negative effects are coloured in grey, and the positive ones in black. The path diagram allows considering the direct effects of antagonistic connectance C and diversity S , and their indirect effects through nestedness N and modularity Q . [X_{ant} = antagonistic X . e.g.: C_{ant} = antagonistic connectance].

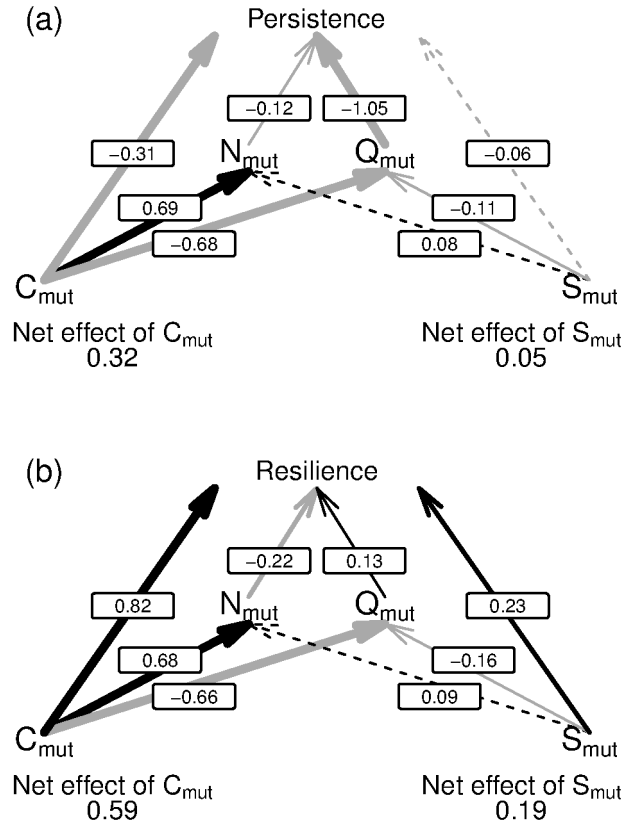


Figure A9: Path diagram of effects of initial structure of mutualistic networks on persistence (a), and of effects of final structure of mutualistic networks on resilience (b). Same legend as Figure A8.

Appendix 7: Analysis of the effect of total connectance on persistence in the merged network combining mutualistic and antagonistic sub-networks

Here, we consider the total connectance in a network combining two types of networks: a mutualistic sub-network and an antagonistic one. Total connectance C_{tot} is calculated as follows:

$$C_{tot} = \frac{L_{tot}}{S_P S_M + S_P S_H}$$

Where L_{tot} is the number of realized interactions in the whole network, S_P the number of species with both mutualistic and antagonistic interactions, S_M the number of mutualistic species, and S_H the number of antagonistic species.

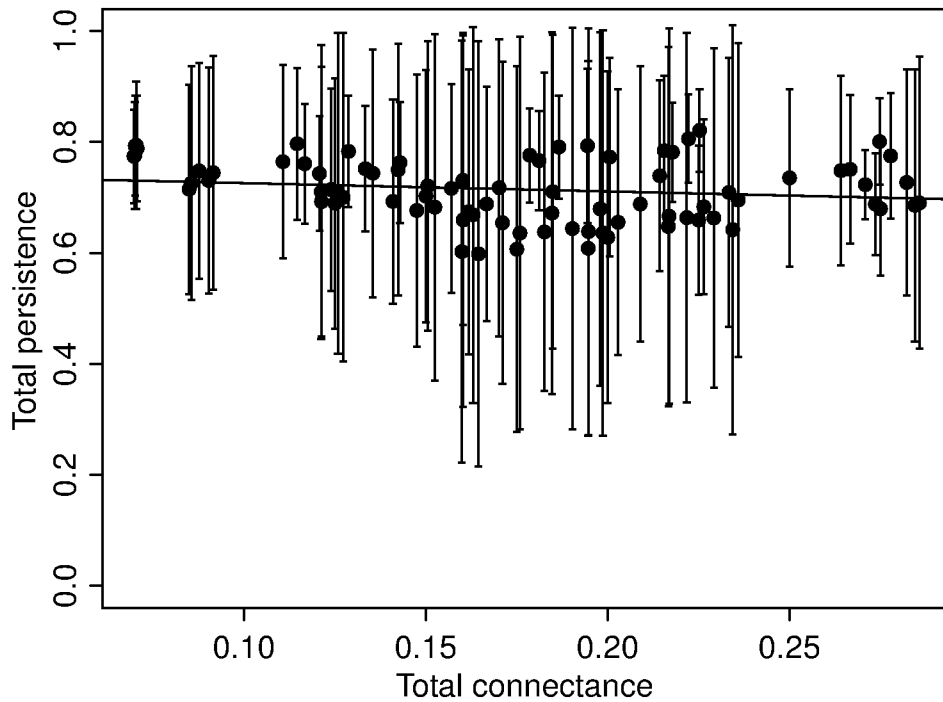


Figure A10: Effects of total connectance on total persistence (mean \pm sd), when mutualism is as strong as antagonism ($c^{(mut)}=c^{(ant)}$).

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