Oikos

OIK-06789

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Appendix 1

Table A1. Parameter values (α_1^p, β_1^p, α_2^p, β_2^p) for predation functions (Equation 1). Unlike in Gompert et al. (2011) (see references at the end of the supplementary information), mimicry diversity is not maintained in our simulations with moderately heterogeneous predator micro-habitat use (e.g. (1, 2, 1, 2)) (not shown). This difference lies in the fact that competition for resources, which makes the maintenance of mimicry diversity more difficult, was not accounted in Gompert et al.'s model.

Predator micro-habitat use	**Predators 1**	**Predators 2**	**Predators 3**	**Predators 4**
Homogeneous	$(1, 1, 1, 1)$	$(1, 1, 1, 1)$	$(1, 1, 1, 1)$	$(1, 1, 1, 1)$
Heterogeneous	$(4, 1.5, 4, 1.5)$	$(4, 1.5, 1.5, 4)$	$(1.5, 4, 4, 1.5)$	$(1.5, 4, 1.5, 4)$

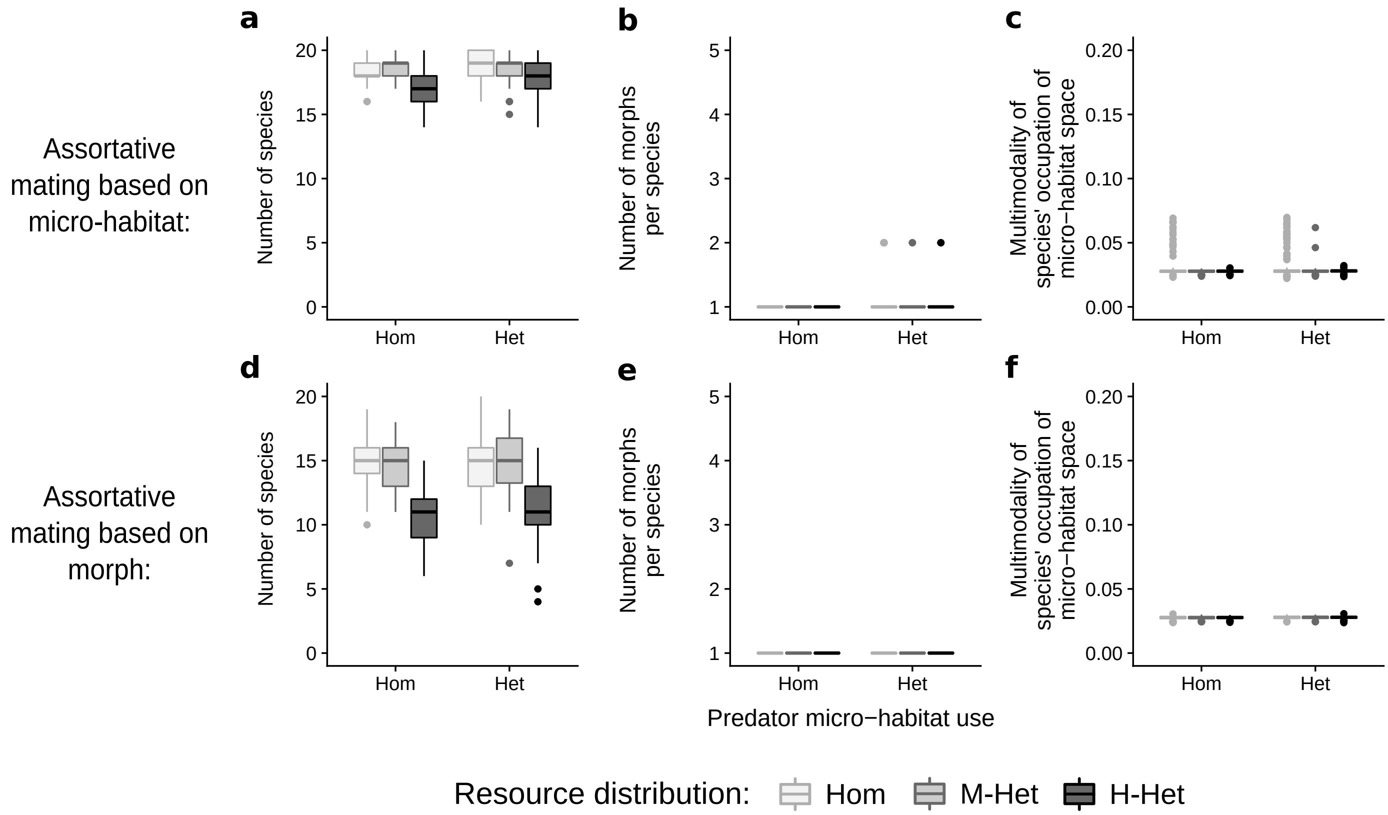

Figure A1. Species diversity and species characteristics. Mating is assortative based either on micro-habitat ($a_{\mathrm{h}} = 5$, $a_{\mathrm{m}} = 0$) (a, b, c) or on morph ($a_{\mathrm{h}} = 0$, $a_{\mathrm{m}} = 0.5$) (d, e, g). After 1,000 generations, we record the number of remaining species (a, d), the number of morphs carried by each species (b, e) and the multimodality of species' occupation of micro-habitat space (c, f). In each species, we count the number of morphs carried by more than 10 individuals (b, e) to increase the likelihood that the morphs observed at the end of the simulation are not transient (morphs generated by recent mutations that would have been eliminated by selection if simulations had continued). To analyze how species use the micro-habitat space, we measure the pairwise Euclidean distances between the individuals position in the two-dimensional micro-habitat space. We then compute the Hartigans' dip statistic (Hartigan and Hartigan, 1985; Freeman and Dale, 2013) to assess the multimodality intensity in the distribution of pairwise micro-habitat distances within species. When species' occupation of the micro-habitat space is unimodal, then the dip statistics of the distribution of the pairwise micro-habitat distances is close to 0. The dip statistic increases when individual distribution throughout the micro-habitat space departs from unimodal expectations, resulting in clustered, multimodal coverage of micro-habitat space. In other words, this statistics is high for species using multiple micro-habitats. In different simulations, predator micro-habitat use is either homogeneous (Hom) or heterogeneous (Het). Resource distribution among micro-habitat is homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). We record some species extinctions in our simulations (a, d). Additionally, almost all species are monomorphic (b, e) and use a restricted micro-habitat (c, f) (except some outlier species). Parameter values: see Table 1.

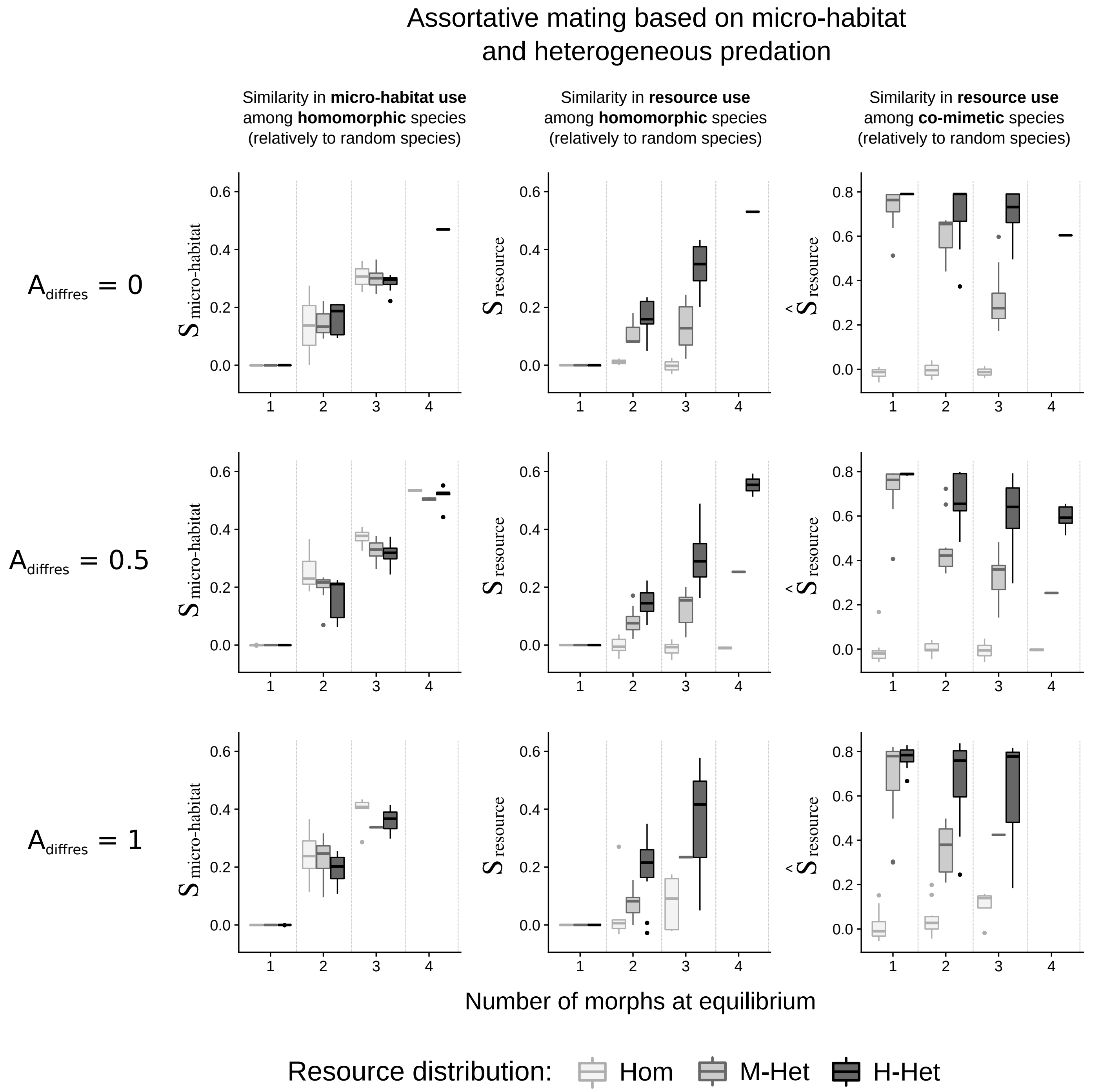

Figure A2. Ecological similarity among homomorphic or co-mimetic species under heterogeneous predation for different values of the resource-based competition parameter A_{diffres}. Mating is assortative based on micro-habitat ($a_{\text{h}} = 5$, $a_{\text{m}} = 0$). Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). See caption of Fig. 3 for details. For $A_{\text{diffres}} = 1$, competition between species using the same or different resources is even. Note that, among the 40 runs performed per combination of parameters, we do not observe the maintenance of high mimicry diversity (number of morph at equilibrium = 4) for some combinations of parameters. For all conditions tested, similarity in resource use among co-mimetic species occur if resources are heterogeneously distributed (because it promotes co-occurrence among co-mimetic species). Parameter values: see Table 1.

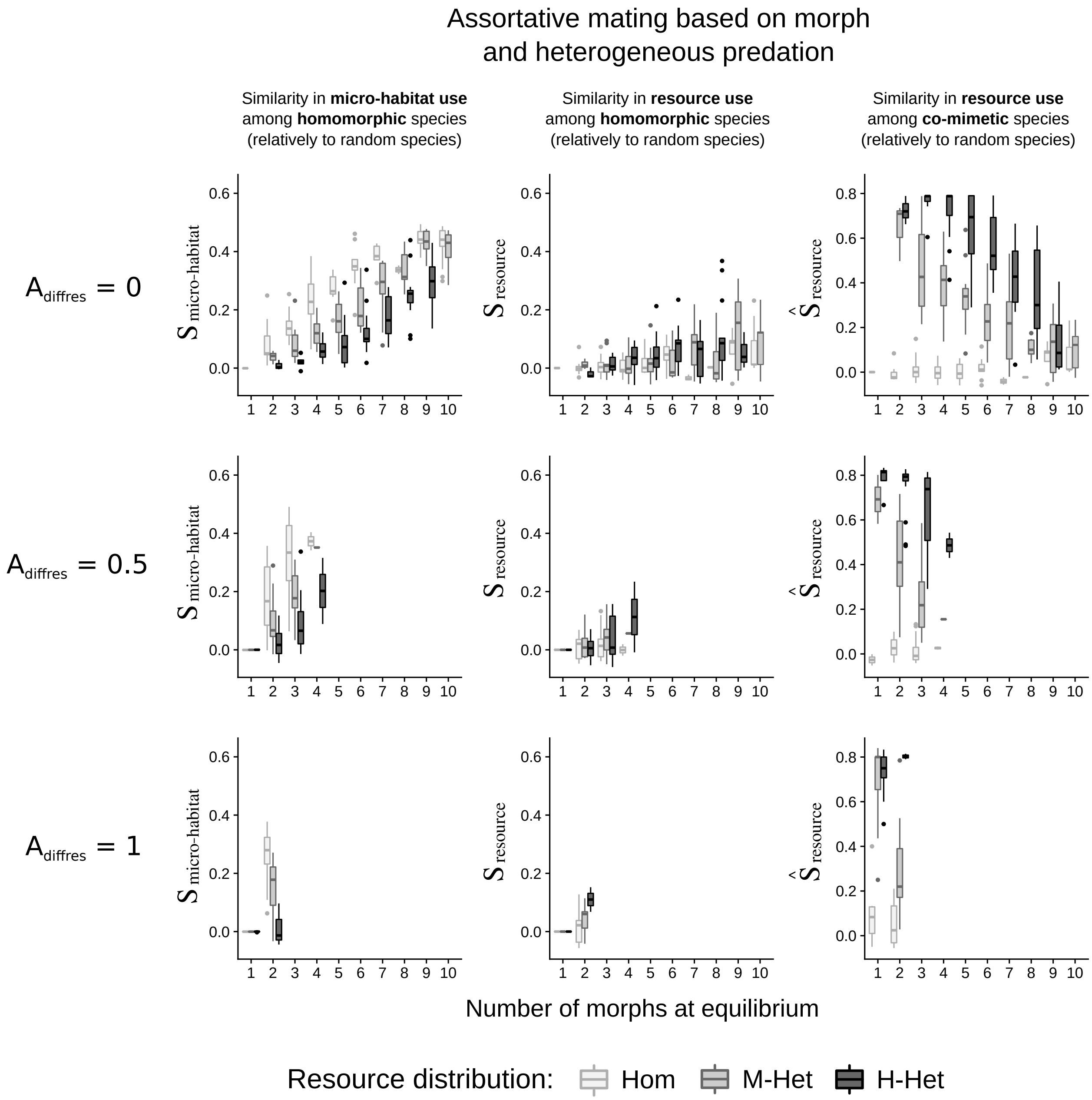

Figure A3. Ecological similarity among homomorphic or co-mimetic species under heterogeneous predation for different values of the resource-based competition parameter A_{diffres}. Mating is assortative based on morph ($a_{\text{h}} = 0$, $a_{\text{m}} = 0.5$). Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). See caption of Fig. 3 for details. For $A_{\text{diffres}} = 1$, competition between species using the same or different resources is even. When low mimicry diversity is maintained (number of morphs at equilibrium < 4), similarity in resource use among co-mimetic species occur if resources are heterogeneously distributed (because it promotes co-occurrence among co-mimetic species). When high mimicry diversity is maintained (number of morph at equilibrium > 4), species that are not co-mimetic are faced to the same predator community, weakening the effects of positive interactions on ecological similarity in resource use ($\hat{S}_{\text{resource}}$ decreases with mimicry diversity at equilibrium). For all values of A_{diffres} tested, similarity in micro-habitat ($S_{\text{micro-habitat}}$) or resource use (S_{resource}) among homomorphic species do not reflect the importance of positive interactions in structuring Müllerian mimetic communities. Overall, however, co-mimetic species use more similar micro-habitats than random pairs of species ($S_{\text{micro-habitat}} > 0$, left column) and use more similar resources than random pairs of species if resource distribution is heterogeneous ($\hat{S}_{\text{resource}} > 0$, right column). Parameter values: see Table 1.

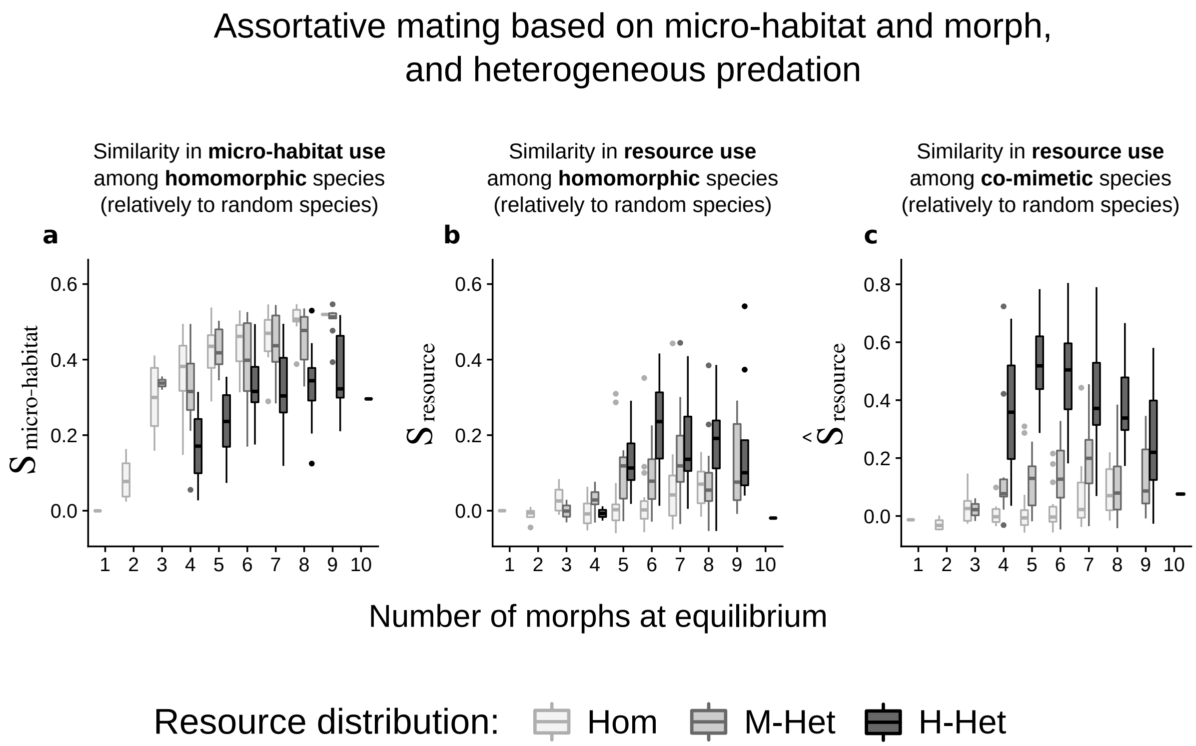

Figure A4. Ecological similarity among homomorphic or co-mimetic species under heterogeneous predation when mating is assortative based on micro-habitat and morph ($a_{\mathrm{h}} = 5$, $a_{\mathrm{m}} = 0.5$). Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). See caption of Fig. 3 for details. For $A_{\mathrm{diffres}} = 1$, competition between species using the same or different resources is even. Here, assortative mating based on morph favours the maintenance of multiple morphs despite positive frequency-dependent predation. When high mimicry diversity is maintained (number of morphs at equilibrium > 4), species that are not co-mimetic are faced to the same predator community, weakening the effects of positive interactions on ecological similarity in resource use ($\hat{S}_{\mathrm{resource}}$ decreases with mimicry diversity at equilibrium, c). Moreover, similarity in resource use (S_{resource}, b) among homomorphic species weakly reflects the importance of positive interactions in structuring Müllerian mimetic communities. Overall, however, co-mimetic species use more similar micro-habitats than random pairs of species ($S_{\text{micro-habitat}} > 0$, a) and use more similar resources than random pairs of species if resource distribution is heterogeneous ($\hat{S}_{\mathrm{resource}} > 0$, c). Parameter values: see Table 1.

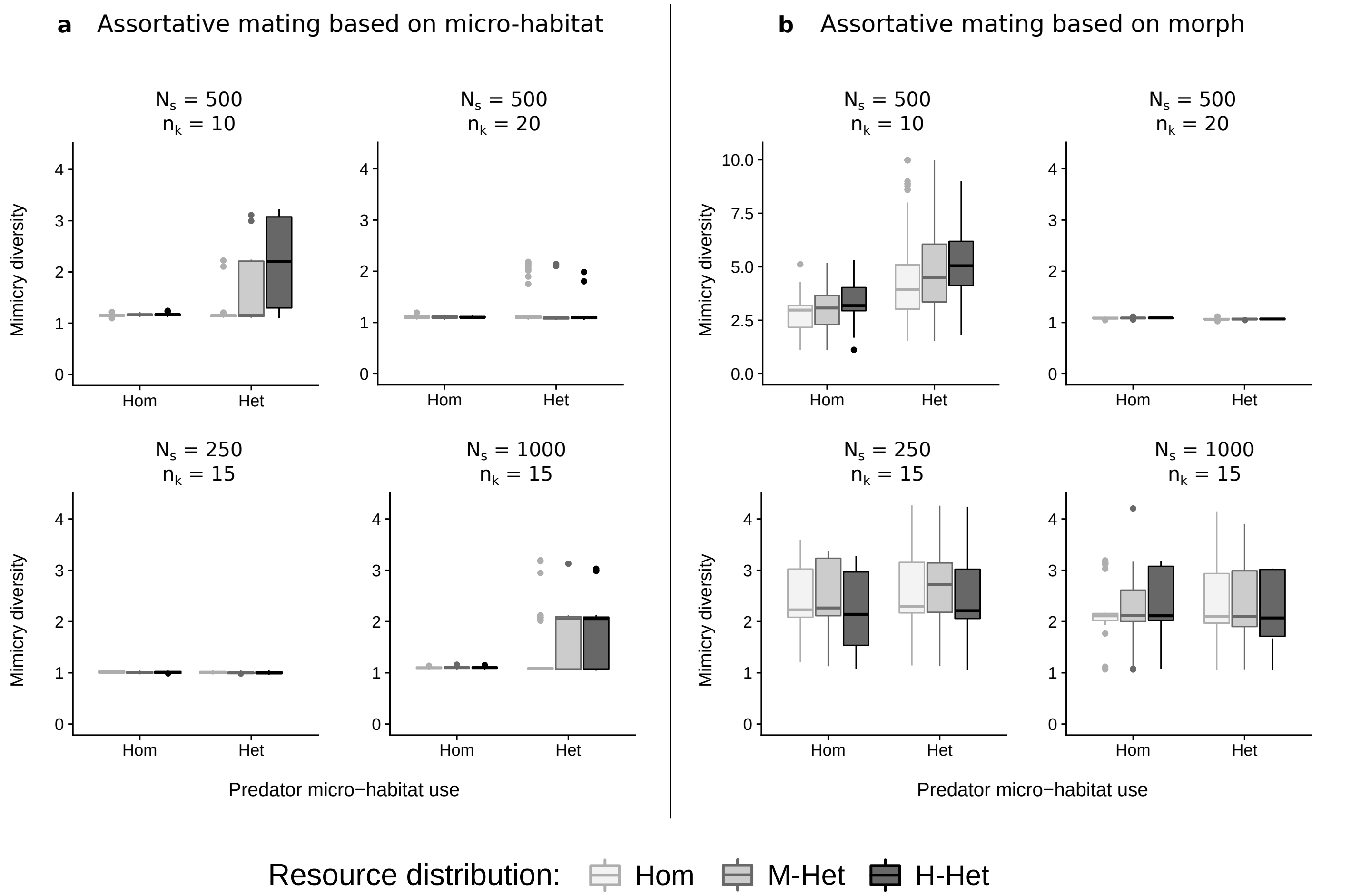

Figure A5. Maintenance of mimicry diversity and sensitivity to (N_{s}, n_{k}). After 1,000 generations, we measure the remaining mimicry diversity. Mating is assortative based on micro-habitat ($a_{\mathrm{h}} = 5$, $a_{\mathrm{m}} = 0$) (a) or morph ($a_{\mathrm{h}} = 0$, $a_{\mathrm{m}} = 0.5$) (b). In different simulations, predator micro-habitat use is either homogeneous (Hom) or heterogeneous (Het). Resource distribution among micro-habitat is homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). The conditions favouring the maintenance of mimicry are very limited. In the main analysis, we therefore implement parameters favouring the maintenance of mimicry diversity ($N_{\mathrm{s}} = 500$, $n_k = 15$). As long as mimicry diversity is maintained, we get qualitatively the same results concerning the structure of ecological communities (Fig. A6). Other parameter values: see Table 1.

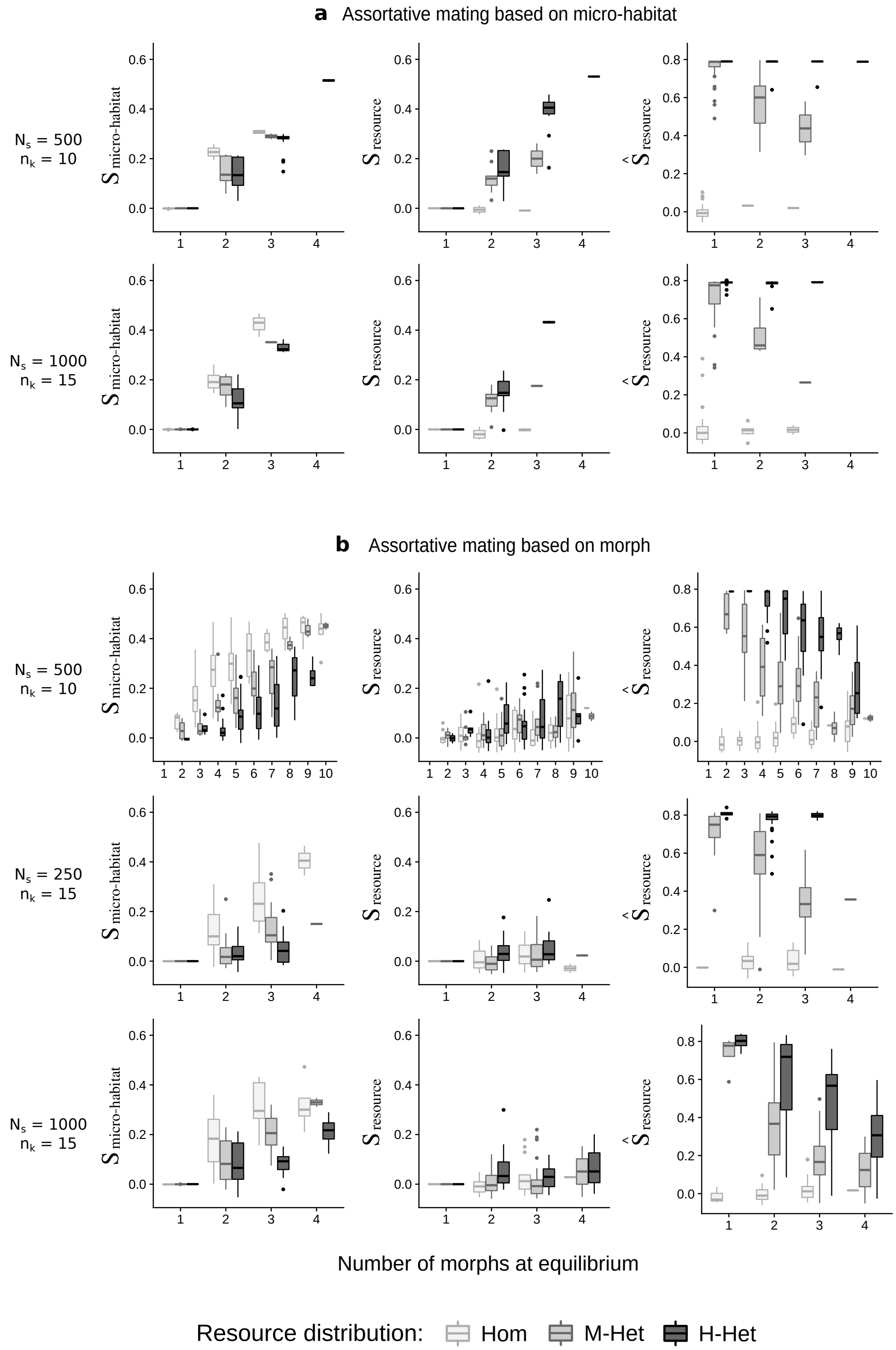

Figure A6. Ecological similarity among homomorphic or co-mimetic species under heterogeneous predation, and sensitivity to (N_s, n_k). After 1000 generations, we assess the level of similarity in micro-habitat use ($S_\text{micro-habitat}$) and in resource use (S_resource) among homomorphic species compared to random pairs of species. We also assess the level of similarity in resource use among co-mimetic species compared to random pairs of species ($\hat{S}_\text{resource}$). For each combination of parameters, simulations are classified according to the number of morphs that remain in the community. Here we implement combinations of parameters (N_s, n_k) that lead to the maintenance of mimicry diversity (Fig. A5). We get qualitatively the same results concerning the structure of ecological communities (shown in Fig. 3). Other parameter values: see Table 1.

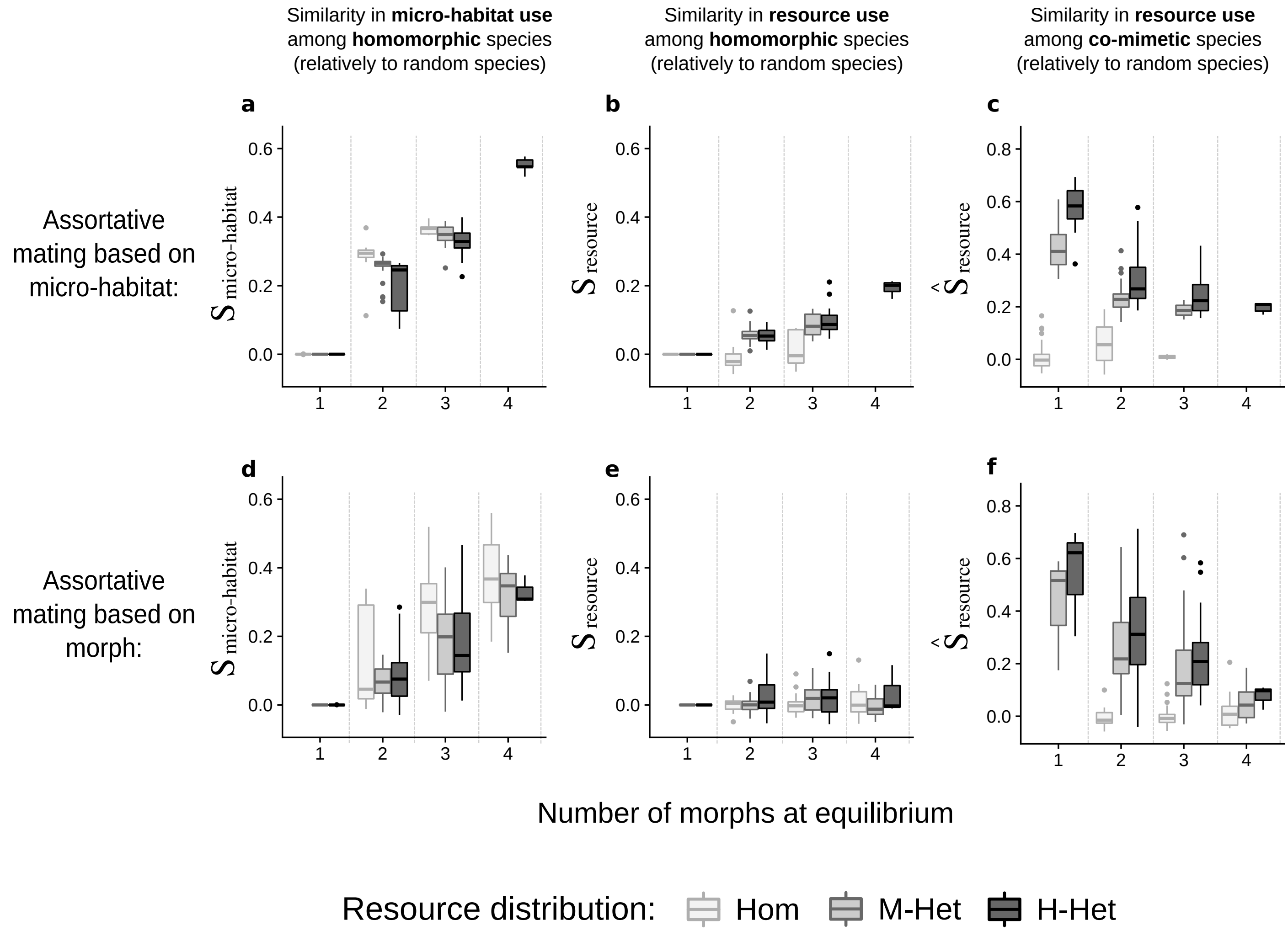

Figure A7. Ecological similarity among homomorphic or co-mimetic species under heterogeneous predation within a three-dimensional niche space (with $N_{\mathrm{resource}} = 8$ and $N_{\mathrm{predator}} = 8$ organized as in the two-dimensional case, i.e. as in Fig. 1b-c). Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). Mating is assortative based either on micro-habitat ($a_{\mathrm{h}} = 5$, $a_{\mathrm{m}} = 0$) (a, b, c) or on morph ($a_{\mathrm{h}} = 0$, $a_{\mathrm{m}} = 0.5$) (d, e, g). See caption of Fig. 3 for details. Parameter values: see Table 1.

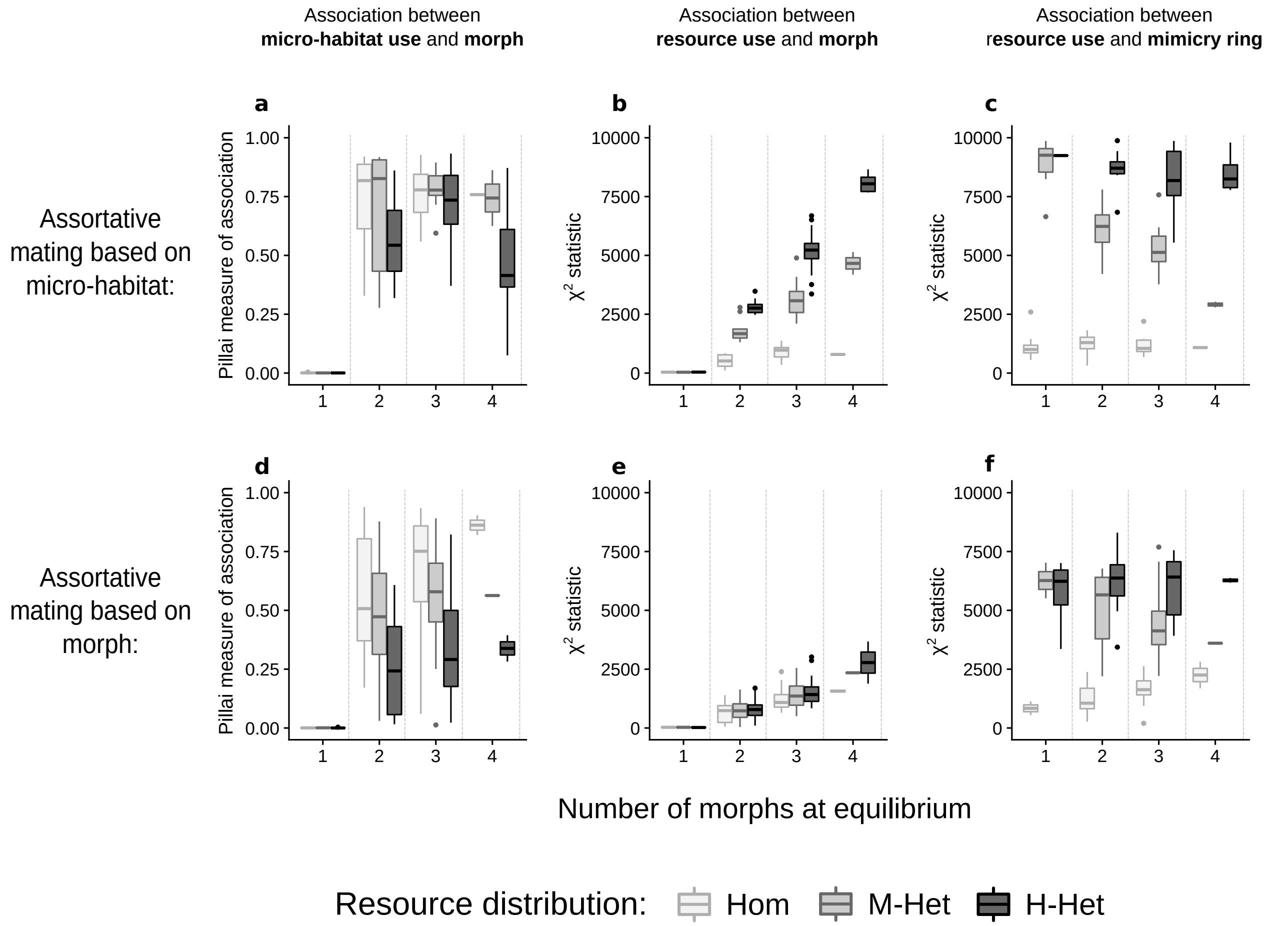

Figure A8. Ecological similarity among homomorphic or co-mimetic individuals under heterogeneous predation using statistics measuring strength of association within population. Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). Mating is assortative based either on micro-habitat ($a_{\mathrm{h}} = 5$, $a_{\mathrm{m}} = 0$) (a, b, c) or on morph ($a_{\mathrm{h}} = 0$, $a_{\mathrm{m}} = 0.5$) (d, e, g). Mimicry ring is here defined using the co-mimicry criterion: individuals belonging to the same mimicry ring have the same morph and occupy the same micro-habitat (descretized as in Fig. 1a). We measured the association between morph/mimicry group and the two niche scores of each individual by calculating Pillai's trace statistic in a multivariate analysis of variance framework. Pillai's trace is analogous to the coefficient of determination. We measured the association between morph/mimicry group and the resource use of each individual by calculating the χ^2 statistic (i.e. a measures of goodness of fit). Using those statistics accounting for the variance within population lead to qualitatively similar results than with our measures of similarity ($S_{\text{micro-habitat}}$, S_{resource}, $\hat{S}_{\text{resource}}$) at the species level (Fig. 3). See caption of Fig. 3 for other details. Parameter values: see Table 1.

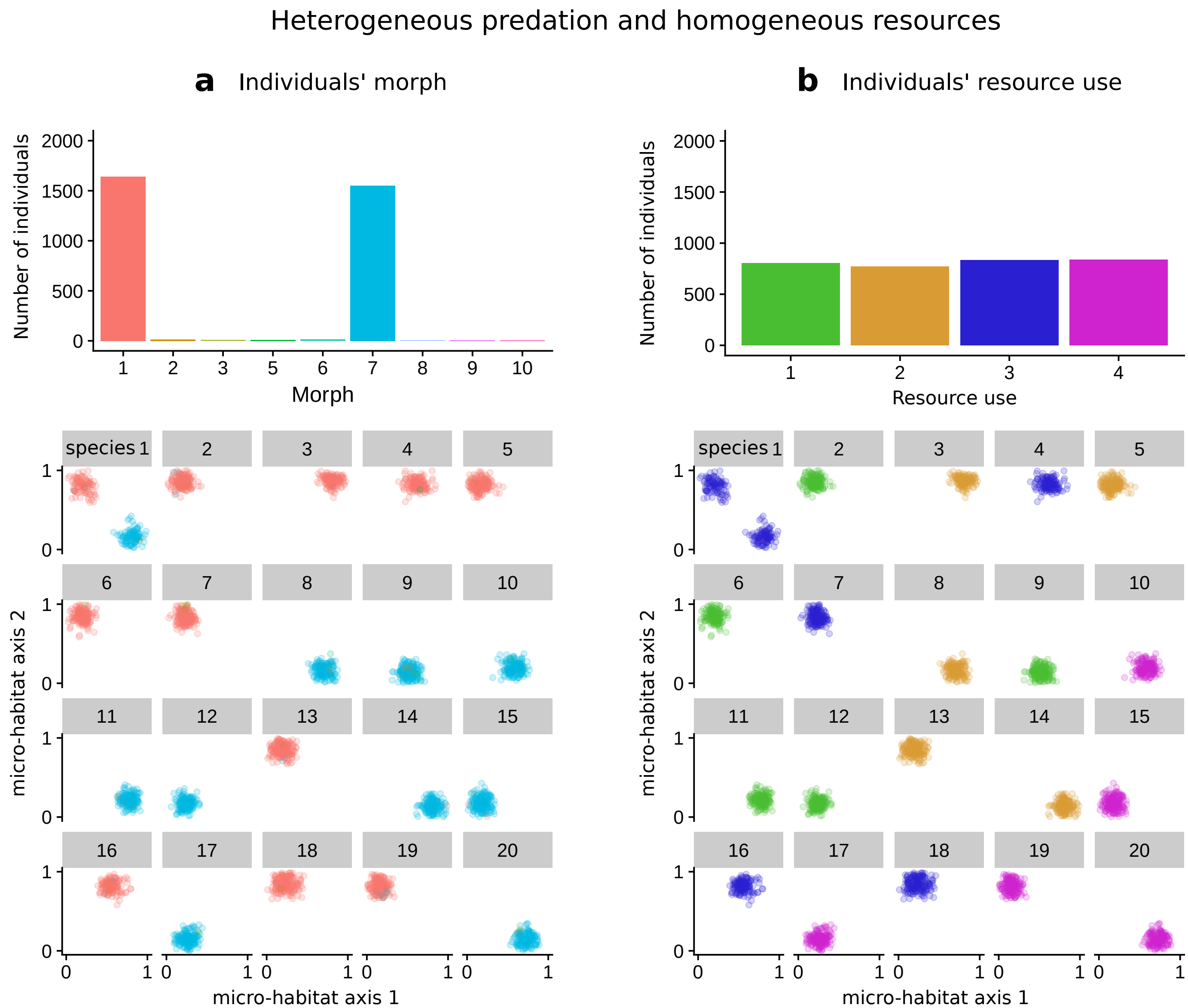

Figure A9. Example of ecological community with heterogeneous predator micro-habitat use and homogeneous resources after 1000 generations. Individuals' morph (a) and resource use (b) are shown. We represent the number of individuals with each trait value (graphs at the top), as well as the micro-habitat use of each individual from all 20 remaining species (graphs at the bottom). Each colour corresponds to a morph value or a resource use value. Here, mimicry diversity is maintained via heterogeneous predator micro-habitat use. Homomorphic species often use similar micro-habitats (a), but may differ in their resource use (b). Mimicry is linked to ecological similarity along the micro-habitat axis, but not along the resource axis. Parameter values: see Table 1.

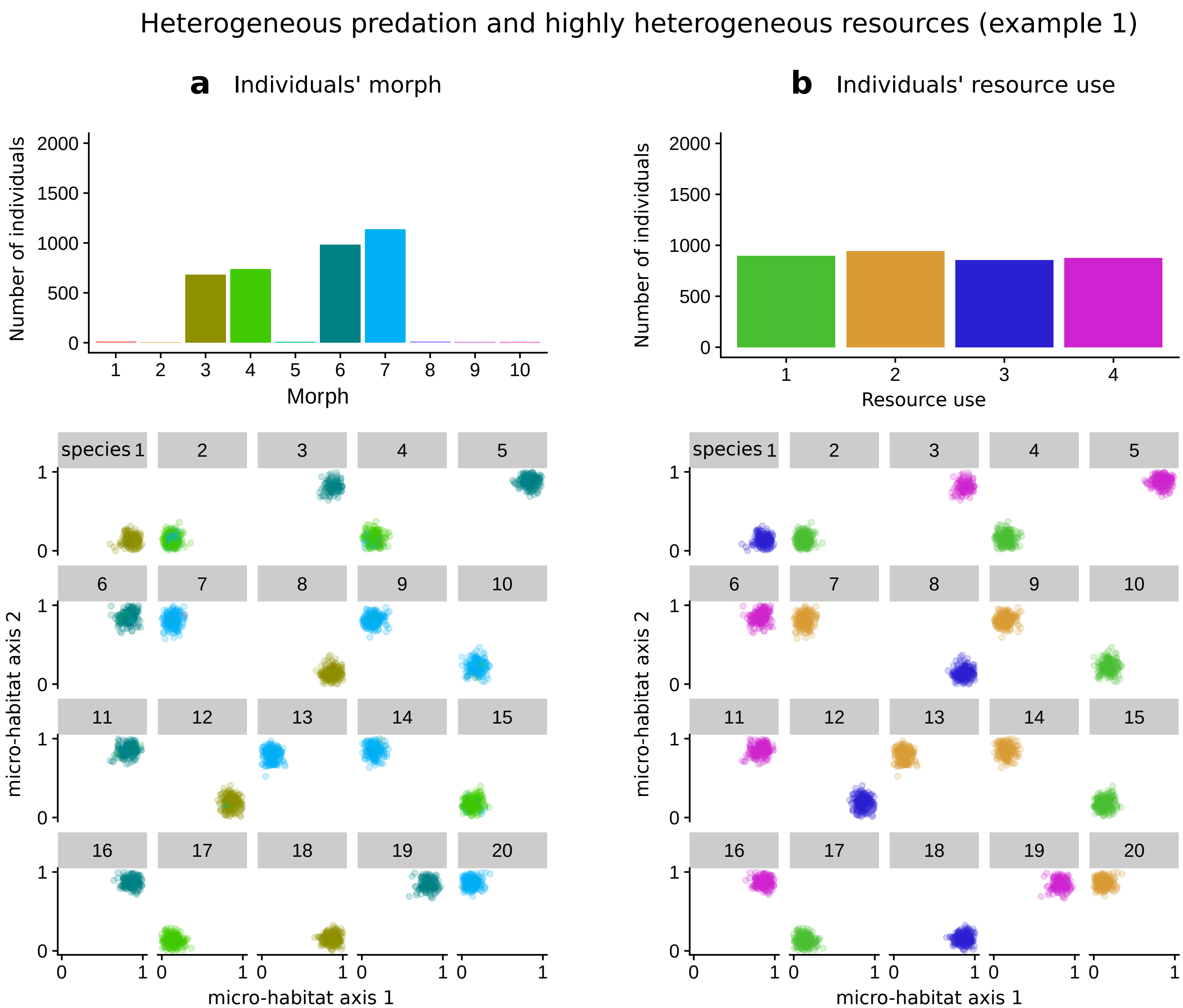

Figure A10. Example of ecological community with heterogeneous predator micro-habitat use and highly heterogeneous resources after 1000 generations. See caption of Fig. A9 for details. Again, mimicry diversity is maintained via heterogeneous predator micro-habitat use. Homomorphic species often use similar micro-habitats (a), and the same resource (e.g. species 1, 8, 12 and 18) (b). Mimicry is linked to ecological similarity along the micro-habitat and resource axes. Parameter values: see Table 1.

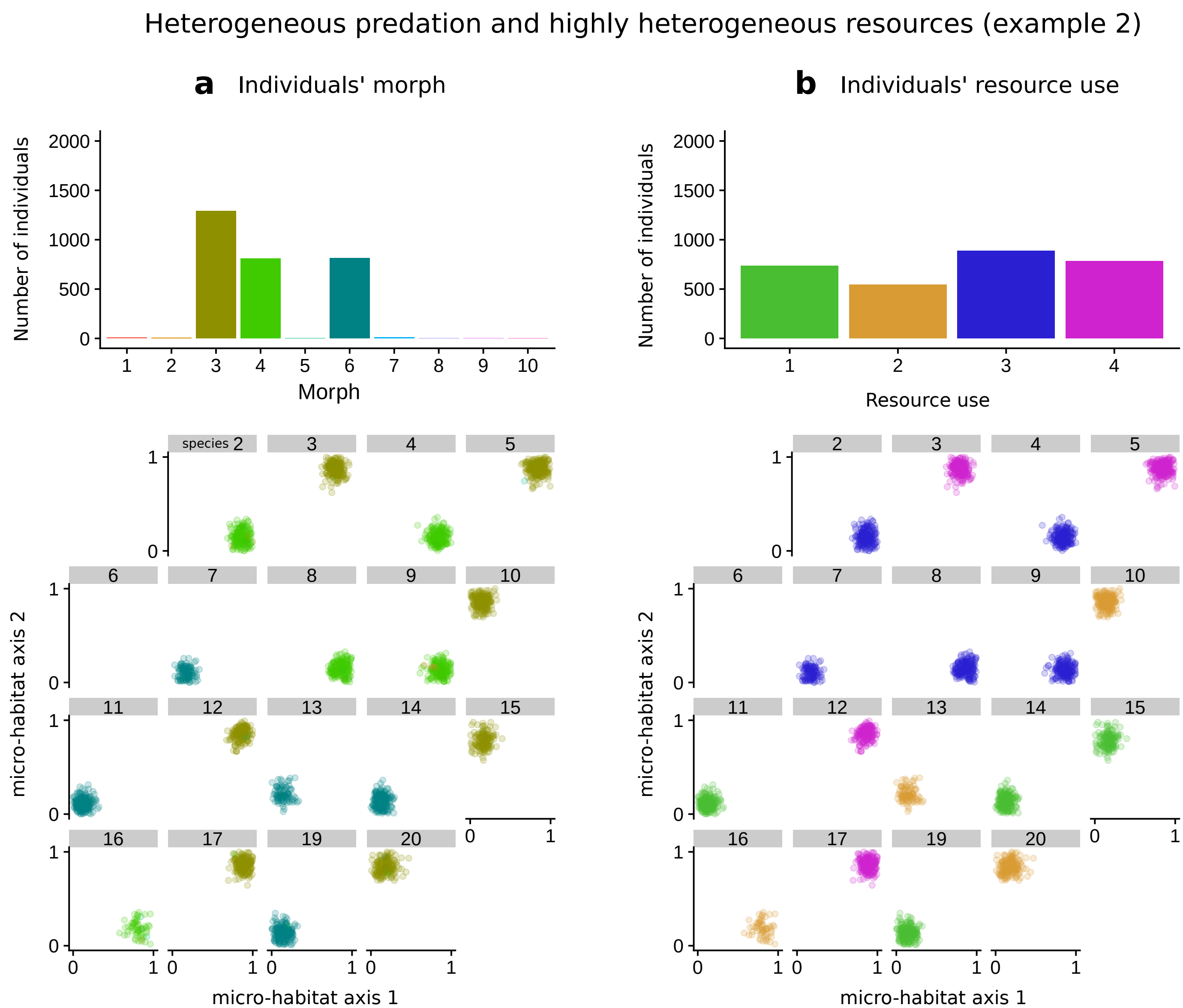

Figure A11. Same conditions than in Fig. A10, but this time with the maintenance of only three morphs at equilibrium. Note that individuals carrying morph 3 use both the top-left and top-right corners of the niche space. Homomorphic species are not all co-mimetic species facing the same predator community.

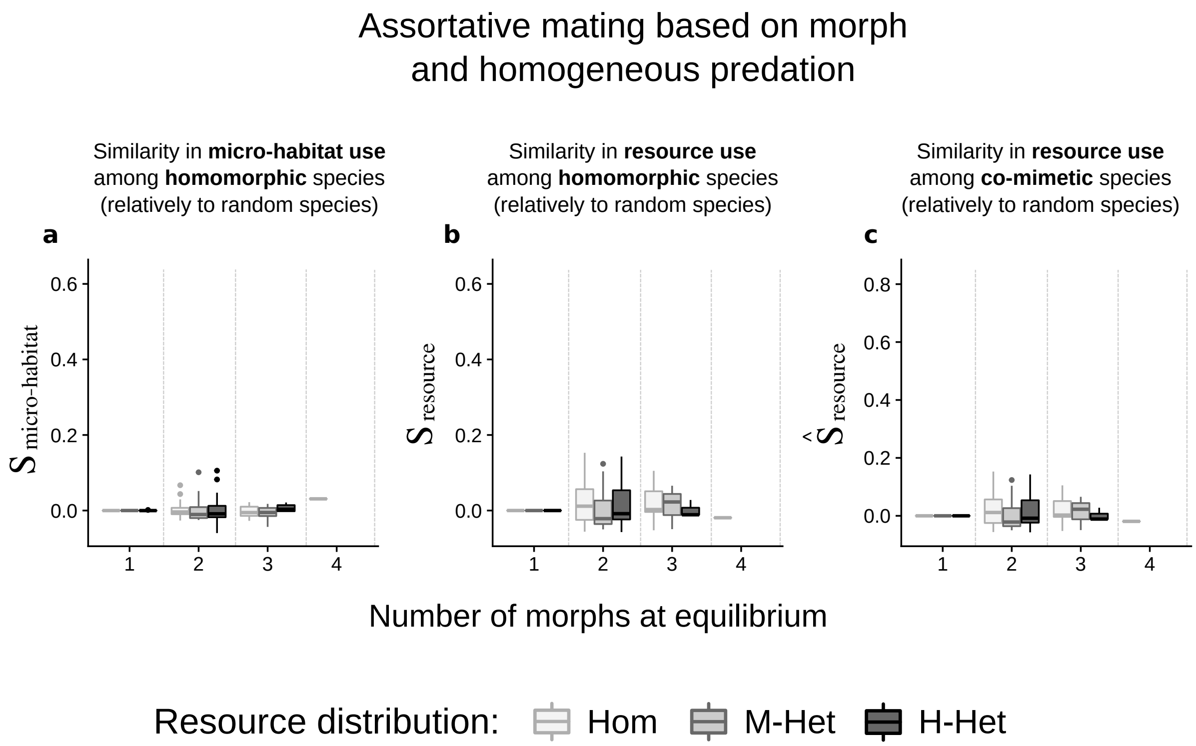

Figure A12. Ecological similarity among homomorphic or co-mimetic species under homogeneous predation. Mating is assortative based on micro-habitat ($a_\text{h} = 5$, $a_\text{m} = 0$). Resource distribution among micro-habitat can be homogeneous (Hom), moderately heterogeneous (M-Het) or highly heterogeneous (H-Het). See caption of Fig. 3 for details. For $A_\text{diffres} = 1$, competition between species using the same or different resources is even. Here, all species are faced to the same community of predators (homomorphic species are necessarily co-mimetic) and assortative mating based on morph favours the maintenance of multiple morphs despite positive frequency-dependent predation. Compared to the case with heterogeneous predation (Fig. 3d-f), there is little ecological similarity in micro-habitat use or resource use among co-mimetic species (statistics $S_\text{micro-habitat}$, S_resource and $\hat{S}_\text{micro-habitat} \simeq 0$) when predation is homogeneous. Parameter values: see Table 1.

References

Freeman, J. B. and Dale, R. 2013. Assessing bimodality to detect the presence of a dual cognitive process. *Behavior Research Methods*, 45(1):83–97.

Gompert, Z., Willmott, K., and Elias, M. 2011. Heterogeneity in predator micro-habitat use and the maintenance of Müllerian mimetic diversity. *Journal of theoretical biology*, 281(1):39–46.

Hartigan, J. A. and Hartigan, P. M. 1985. The dip test of unimodality. *The Annals of Statistics*, 13(1):70–84.