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Appendix 1. Null model analysis of species co-occurrence by geographic locality

Pooling localities in our null model analyses could have biased our results by eliminating possible effects of spatial heterogeneity in the observed levels of co-occurrence. This has the potential to hide patterns of aggregation or segregation, which might be found if the analyses were run at the geographic locality level. To assess this possibility, we ran our null model analyses independently for each locality, and interpreted the results using a meta-analysis.

Methods

For each locality, we ran the same null model analyses as we did for the pooled data: we used four different null model algorithms and analyses were carried out in two scenarios: including or excluding non-infested hosts. However, we could not run all possible null models in all localities. One of the localities incorporated in the pooled analyses was excluded from the single locality analyses because it had only three hosts; in all other localities at least nine hosts were captured, and consequently had enough individuals to run the null models. In two localities 100% of the bats were parasitized, consequently null models including empty host could not be run. Also, the number of individuals was so small in two localities that the fixed-fixed algorithm could not randomize the observed matrix (this is caused because this algorithm sets many constraints on how the observations must be reshuffled). In the end, we were able to run a total of 29 analyses by combinations of the scenario in which the algorithms were carried out (excluding or including empty hosts), the null model algorithm (fixed-equiprobable, fixed-fixed, fixed-proportional and fixed- by host body weight), and the locality (six localities).

From each of the previously described analyses, we were able to calculate one-tailed probabilities for aggregation ($p[C_{obs} \leq C_{exp}]$) and for segregation ($p[C_{obs} \geq C_{exp}]$), as well as a measure of standardized effect size

$$SES=(C_{obs}-C_{exp})/S_{sim}$$

as used by Gotelli and Rhode 2002, where C_{obs} is the C-score calculated from the empirical matrix, C_{exp} is the mean C-score from the simulated matrices and S_{sim} is the standard deviation of the null distribution.

Exploring the effect of number of individuals on null model analysis results

All null models used a total of 10 000 randomizations. However, the number of individuals that are included in each randomization process could influence the results produced by the null models and the power of the tests. To understand these effects, we conducted linear regressions of the number of individuals included in the randomization (n) on: 1) the standard deviation of the randomized distribution, 2) the standardized effect size, 3) and 4) both one tail probability values. To control for non-independence of the observations, we modified the number of degrees of freedom in the denominator for the F-tests to be equal to the number of localities; this implied a reduction from 27 to 6 degrees of freedom. It is difficult to determine exact degrees of freedom for the 29 points used in the regressions; however, we think that this reduction is sufficient for the purpose of controlling for most non-independence.

Testing standardized effect sizes against the zero null hypothesis

To test whether the observed levels of co-occurrence differed significantly from random assembly, we compared the standardized effect size against the null hypothesis of no difference from zero. We did this by using a one-sample t-test for each combination of algorithm and scenario, and also for each algorithm irrespective of the scenario, and for each scenario irrespective of the algorithm used.

Testing for differences among algorithms and scenarios

To test if there are any trends or differences among the algorithms or between the scenarios in which the null models were ran, we conducted three independent General linear models using as dependent variables: 1) the standardized effect size, 2) the probability of aggregation, and 3) the probability of segregation. In these analyses, algorithms and scenarios were included as independent variables, while locality was included as a random factor.

Results

In Fig. A1, we observe that the number of individuals had a significant impact on the null model outcomes. A greater number of individuals increases the possibility of more configurations for the randomized matrices, and consequently increases the variability in the null distribution (Fig. A1a). Similarly, the number of individuals has a significant association with the SES and the probability values (Fig. A1b–d). Increases in the number of individuals also increase the power of the null model analysis (Fig. A1c–d), by increasing the SES (Fig. A1b).

Table A1 shows the results from the null model analyses run independently per locality, algorithm and scenario. Most single null model analyses did not show a pattern that could be distinguished from random assembly. As suggested by the previous correlation analyses, this could result from a lack of statistical power. However, if we look at the locality that had the largest number of individuals (locality 3), we can see that all null model algorithms that excluded empty hosts were clearly not statistically significant, while the null models that included empty hosts show evidence of interspecific aggregation, being the only statistically significant results at an alpha of 0.05. The results at this locality, where presumably we have enough statistical power, showed perfect concordance with the analyses that pooled all individuals together. On the other hand, at locality 5, three of the four null models that exclude empty hosts show marginally significant support for the idea of segregation.

Figure A2 and Table A2 show the results from the one-sample t-test of the standardized effect sizes with respect to the null expectation of zero. Only one of the groups seems to be different from zero: in the case of the null models that included empty hosts (irrespectively of the null model algorithm), the one-sample t-test showed marginally significant results.

Finally, the results of the General linear models can be found in Table A3 and Fig. A2 and A3. In general, the analyses that include and exclude empty hosts seem to provide significantly different results, suggesting that when empty hosts are included, the levels of co-occurrence are suggestive of patterns of aggregation, and when these hosts are not used in the analyses, the patterns seem to be mostly random. This is supported by the statistical analyses which show that the categories of scenario are significantly different for all three dependent variables. There also seems to be significant variation in the results among the null model algorithms and localities, indicated by the significance of the algorithm term and the interaction terms with locality. However, some of the observed interactions with locality can result from differences in the statistical power across sites which will show significant results in some, while no statistical support in others.

Conclusions

Overall, these results show support for our pooled-sites null model analyses. When the null models are run separately for each locality, there is little evidence of segregation patterns hidden in the analyses in which we pooled together hosts across localities. Moreover, when we conduct meta-analyses on the single locality results, they point to the same conclusions obtained from the pooled data in that there is a clear difference between the results of the null models when empty hosts are included versus when empty hosts are excluded. It seems that when we consider the entire host population, these parasites are markedly aggregated; conversely, the parasites seem to be distributed randomly in the part of the population that is infested. This suggests that competition is not a strong force shaping the distribution and infracommunity assembly of these parasite species.

Table A1. Results from the single-locality null model analyses. For each combination of Locality, Scenario and Algorithm, for which we ran null model analyses of co-occurrence, we report the total number of individuals used in the randomization (n), the observed C-score (C_{obs}), the expected C-score (C_{exp}, which is the mean of the C-scores of the null matrices), the standard deviation of the null distribution (S_{sim}), the one-tailed probability for aggregation ($p[C_{obs} \leq C_{exp}]$), the one-tailed probability for segregation ($p[C_{obs} \geq C_{exp}]$), and a measure of standardized size effect, as defined by Gotelli and Rhode 2002 (SES). The p-values that were statistically significant ($p \leq 0.05$) and marginally significant ($0.05 \leq p \leq 0.10$) are highlighted in bold letters.

Locality	Scenario	Algorithm	n	C_{obs}	C_{exp}	S_{sim}	$p(C_{obs} \leq C_{exp})$	$p(C_{obs} \geq C_{exp})$	SES ($[C_{obs} - C_{exp}]/S_{sim}$)
1	Excluding empty hosts	Fixed-ByHostWeight	5	1.00	0.40	0.49	1.000	0.401	1.221
1	Excluding empty hosts	Fixed-Equiprobable	5	1.00	0.39	0.49	1.000	0.392	1.244
1	Excluding empty hosts	Fixed-Proportional	5	1.00	0.39	0.49	1.000	0.387	1.257
1	Including empty hosts	Fixed-ByHostWeight	9	1.00	3.10	1.56	0.172	0.959	–1.343
1	Including empty hosts	Fixed-Equiprobable	9	1.00	3.07	1.52	0.168	0.960	–1.365
2	Excluding empty hosts	Fixed-ByHostWeight	16	8.33	10.03	3.17	0.445	0.641	–0.537
2	Excluding empty hosts	Fixed-Equiprobable	16	8.33	10.38	3.94	0.402	0.679	–0.521
2	Excluding empty hosts	Fixed-Fixed	16	8.33	9.07	0.82	0.410	1.000	–0.902
2	Excluding empty hosts	Fixed-Proportional	16	8.33	8.13	3.88	0.645	0.446	0.053
3	Excluding empty hosts	Fixed-ByHostWeight	25	12.67	12.99	5.31	0.514	0.528	–0.061
3	Excluding empty hosts	Fixed-Equiprobable	25	12.67	13.11	5.29	0.505	0.539	–0.084
3	Excluding empty hosts	Fixed-Fixed	25	12.67	13.02	1.20	0.831	0.557	–0.298
3	Excluding empty hosts	Fixed-Proportional	25	12.67	11.13	5.06	0.657	0.389	0.304
3	Including empty hosts	Fixed-ByHostWeight	33	12.67	37.16	11.27	**0.014**	0.990	–2.173
3	Including empty hosts	Fixed-Equiprobable	33	12.67	37.51	11.41	**0.013**	0.991	–2.177
4	Excluding empty hosts	Fixed-ByHostWeight	9	1.67	2.99	1.66	0.203	0.802	–0.798
4	Excluding empty hosts	Fixed-Equiprobable	9	1.67	3.10	1.67	0.187	0.819	–0.858
4	Excluding empty hosts	Fixed-Proportional	9	1.67	2.35	1.62	0.341	0.669	–0.423
5	Excluding empty hosts	Fixed-ByHostWeight	7	5.33	2.98	1.40	0.973	**0.078**	1.680
5	Excluding empty hosts	Fixed-Equiprobable	7	5.33	3.05	1.38	0.972	**0.085**	1.646
5	Excluding empty hosts	Fixed-Fixed	7	5.33	5.35	0.39	0.756	0.630	–0.052
5	Excluding empty hosts	Fixed-Proportional	7	5.33	2.81	1.39	0.980	**0.063**	1.822
5	Including empty hosts	Fixed-ByHostWeight	8	5.33	3.54	1.52	0.919	0.177	1.178
5	Including empty hosts	Fixed-Equiprobable	8	5.33	3.70	1.51	0.908	0.203	1.076
6	Excluding empty hosts	Fixed-ByHostWeight	12	2.00	2.13	1.78	0.768	0.730	–0.073
6	Excluding empty hosts	Fixed-Equiprobable	12	2.00	2.17	1.81	0.762	0.736	–0.093
6	Excluding empty hosts	Fixed-Proportional	12	2.00	1.90	1.75	0.813	0.678	0.055
6	Including empty hosts	Fixed-ByHostWeight	14	2.00	6.40	3.17	0.134	0.919	–1.388
6	Including empty hosts	Fixed-Equiprobable	14	2.00	6.47	3.12	0.127	0.922	–1.431

Table A2. Results from one-sample t-tests to compare the values of standardized effect size to the null hypothesis of zero. See also Fig. A2. The p-values that were statistically significant ($p \leq 0.05$) and marginally significant ($0.05 \leq p \leq 0.10$) are highlighted in bold letters.

Scenario	Algorithm	t_{stat}	DF	p (two-tailed)	Mean difference
Excluding empty hosts	Fixed-Equiprobable	0.545	5	0.609	0.222
Excluding empty hosts	Fixed-Fixed	–1.652	2	0.240	–0.418
Excluding empty hosts	Fixed-Proportional	1.474	5	0.200	0.511
Excluding empty hosts	Fixed-ByHostWeight	0.591	5	0.580	0.239
Including empty hosts	Fixed-Equiprobable	–1.376	3	0.262	–0.974
Including empty hosts	Fixed-ByHostWeight	–1.278	3	0.291	–0.931
All	Fixed-Equiprobable	–0.640	9	0.538	–0.256
All	Fixed-Fixed	–1.652	2	0.240	–0.418
All	Fixed-Proportional	1.474	5	0.200	0.511
All	Fixed-ByHostWeight	–0.570	9	0.583	–0.229
Excluding empty hosts	All	1.132	20	0.271	0.218
Including empty hosts	All	–2.026	7	**0.082**	–0.953

Table A3. Results from the GLM analyses for the standardized effect size (SES), the probability of aggregation ($p[C_{obs} \leq C_{exp}]$) and the probability of segregation ($p[C_{obs} \geq C_{exp}]$). See also Figs. A2 and A3. The p-values that were statistically significant ($p \leq 0.05$) and marginally significant ($0.05 < p \leq 0.10$) are highlighted in bold letters.

	SES ($[C_{obs}–C_{exp}]/S_{sim}$)			$p(C_{obs} \leq C_{exp})$			$p(C_{obs} \geq C_{exp})$		
	F	DF	p	F	DF	p	F	DF	p
Scenario	13.268	1	**0.036**	9.497	1	**0.054**	9.334	1	**0.055**
Algorithm	8.659	3	**0.002**	1.235	3	0.340	11.076	3	**0.001**
Locality	3.365	5	0.151	2.261	5	0.246	4.021	5	0.102
Scenario-Algorithm interaction	2.404	1	0.219	0.358	1	0.592	0.440	1	0.555
Scenario- Locality interaction	2300.598	3	**<0.001**	8308.128	3	**<0.001**	1054.024	3	**<0.001**
Algorithm- Locality interaction	242.049	12	**<0.001**	804.206	12	**<0.001**	218.883	12	**<0.001**

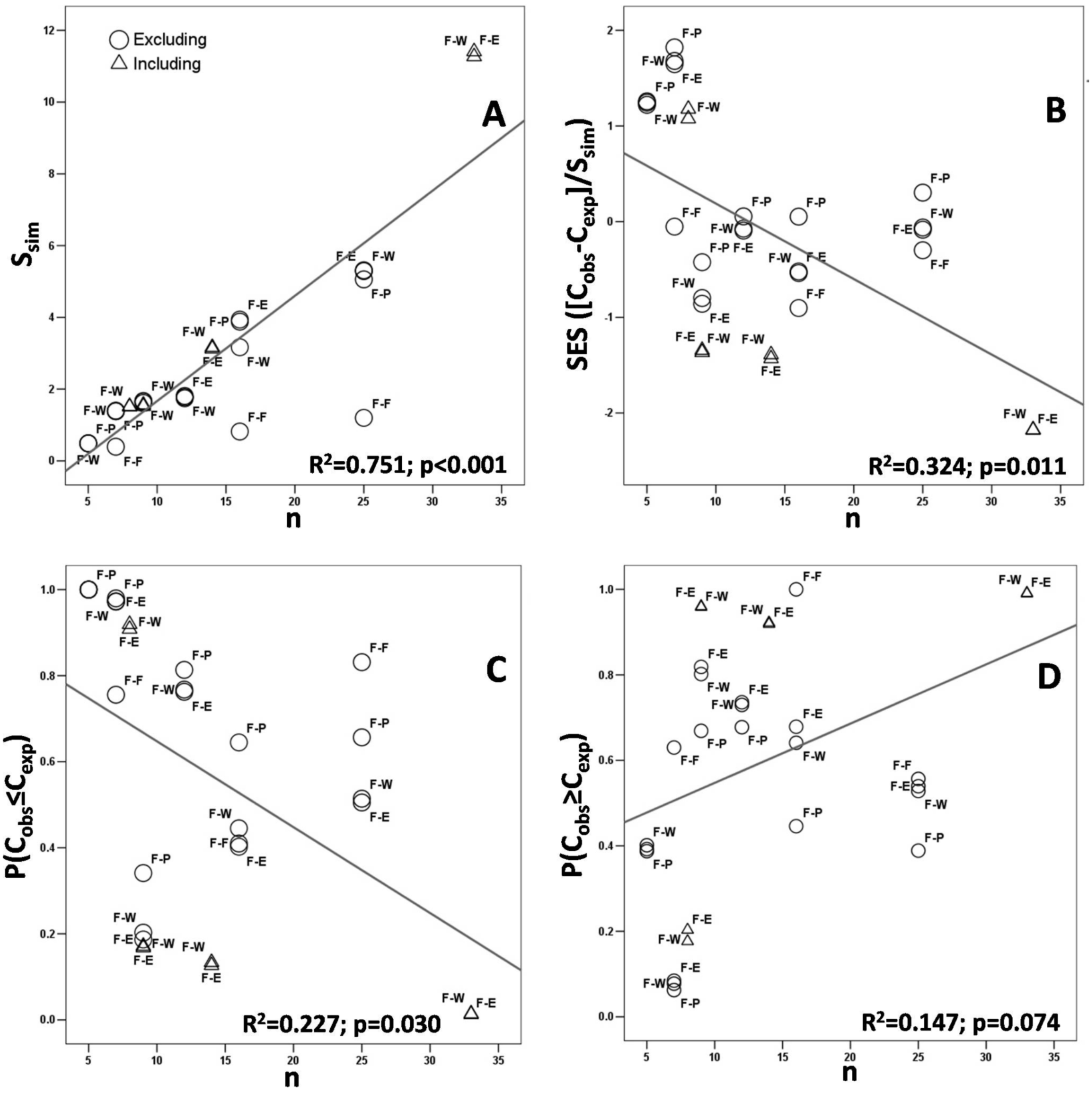

Fig. A1. Relationships among the number of individuals per locality (n) and (A) the variation in the null distribution of C-scores (S_{sim}), (B) the standardized effect size (SES), (C) the probability of aggregation ($p[C_{obs} \leq C_{exp}]$), and (D) the probability of segregation ($p[C_{obs} \geq C_{exp}]$). For each relationship the p-value has been adjusted for non-independence among points (see text for details). Algorithms: F-E: fixed-equiprobable, F-F: fixed-fixed, F-P: fixed-proportional, and F-W: fixed-probability by host weight.

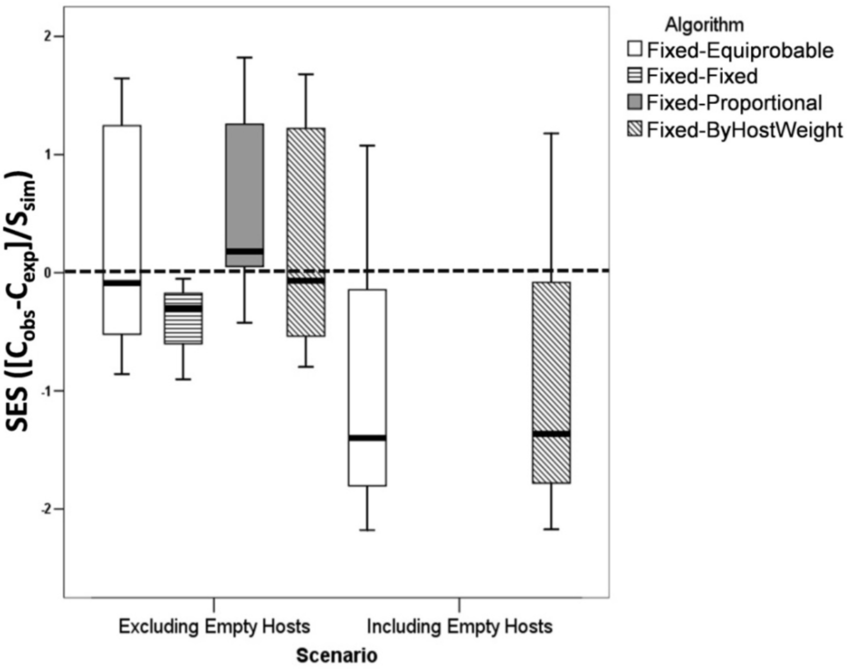

Fig. A2. Comparison of the standardized effect size values per Scenario and Algorithm categories. The dashed line across the figure represents the value expected under the null hypothesis of random assembly. For each case: the box represent the 25 to 75 percentiles of the distribution, the bold horizontal line in the box represent the median, and the top and bottom lines represent the maximum and minimum values respectively.

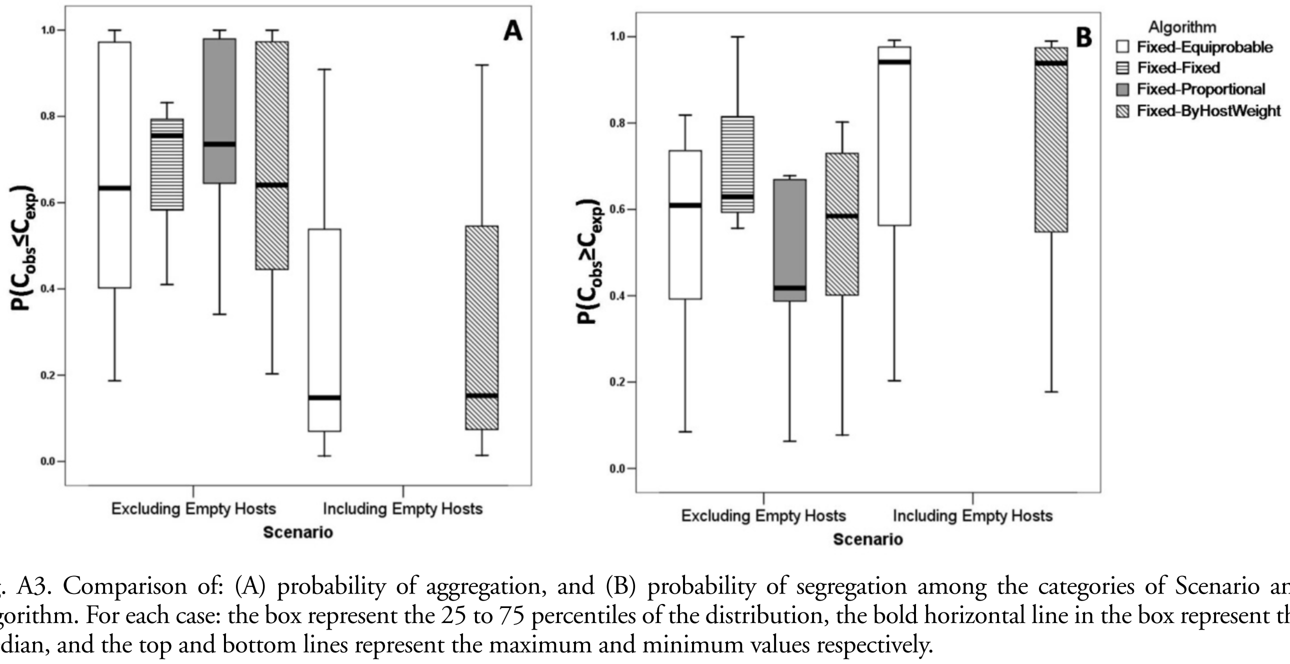

Fig. A3. Comparison of: (A) probability of aggregation, and (B) probability of segregation among the categories of Scenario and Algorithm. For each case: the box represent the 25 to 75 percentiles of the distribution, the bold horizontal line in the box represent the median, and the top and bottom lines represent the maximum and minimum values respectively.