*Ecology*

# Appendix S1

# Using the multivariate Hawkes process to study interactions between multiple species from camera trap data

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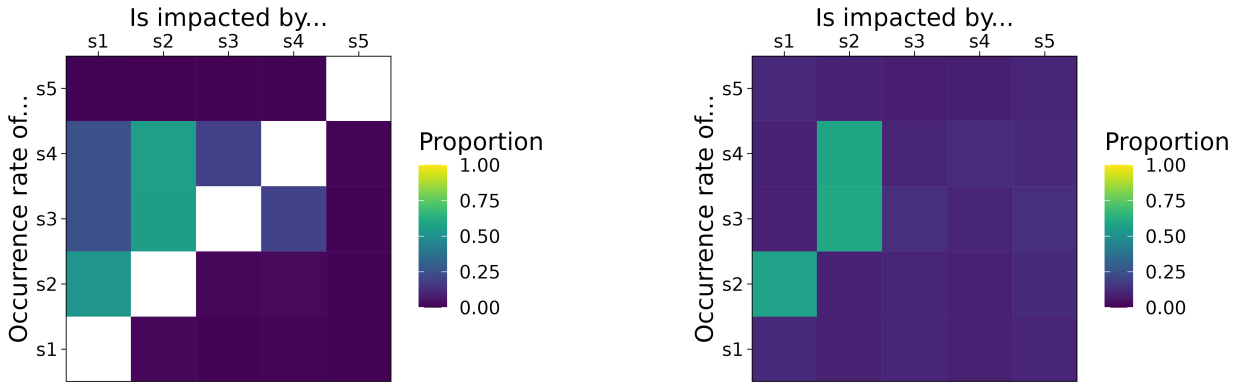
This PDF includes Section S1 to Section S4 from Appendix S1.

# Section S1 Bias in the inference methods

We are interested in knowing whether spurious interactions are more likely to be inferred between species which are part of an interaction chain. To investigate this question, we analyze the inferences performed with the inter-event times method of Murphy et al. (2021) and with the Hawkes method (respectively sections 3.1.2 and 3.1.1 in the main text). The true interaction graph used for these simulations is depicted in Figure 1a in the main text ($s_1$ attracts $s_2$, and $s_2$ attracts $s_3$ and $s_4$). The total number of repetitions over all conditions were respectively $N = 750$ for the inter-event times method (Figure S1a) (5 durations $\times$ 5 strengths $\times$ 30 datasets) and $N = 2250$ for the Hawkes model (Figure S1b) (5 durations $\times$ 5 strengths $\times$ 30 datasets $\times$ 3 penalizations). With the inter-events times method, the model is biased towards inferring more often the indirect interactions $s_1 \to s_3$, $s_1 \to s_4$, $s_3 \to s_4$ and $s_4 \to s_3$. This is not the case with the Hawkes model.




**(a)** Inter-event times

**(b)** Hawkes model

**Figure S1: Bias in the inference.** These graphs show the proportion of times an interaction was inferred over all simulated data in different conditions for (a) the inter-event times method of Murphy et al. (2021) and (b) the Hawkes model. The true interactions are $s_1 \to s_2$, $s_2 \to s_3$ and $s_2 \to s_4$.

# Section S2 Background rates inferred for real data

The figure below shows the background rates inferred for each species in the application example. These background rates are closely linked to the species abundances observed on camera traps, with impala being by far the most abundant species (50 803 occurrences), followed by zebra (9 843), then wildebeest and kudu (respectively 5910 and 5560) and lion being far more rare (587).

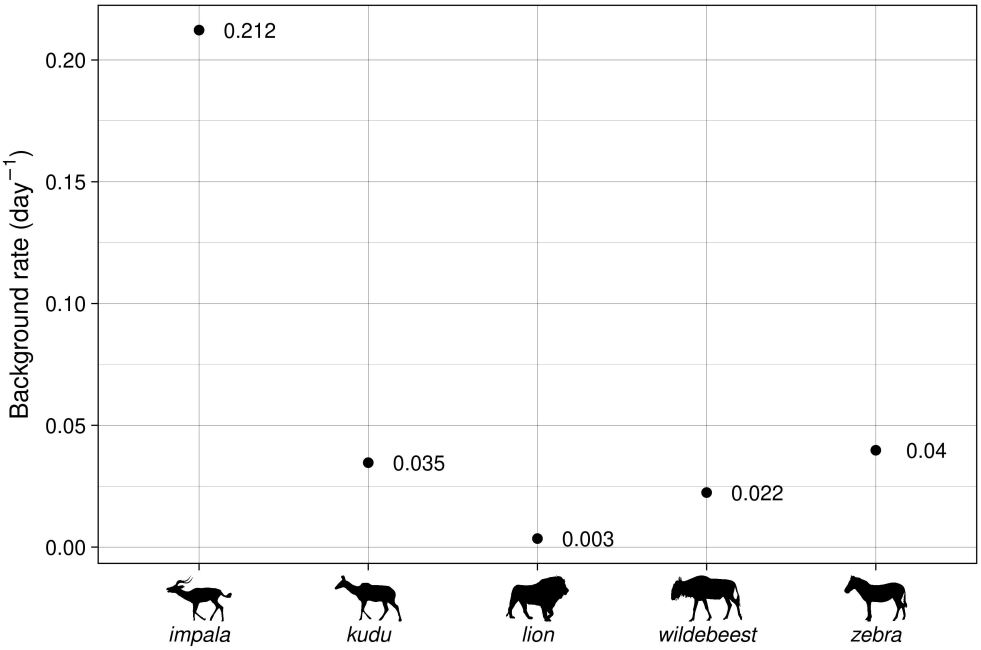
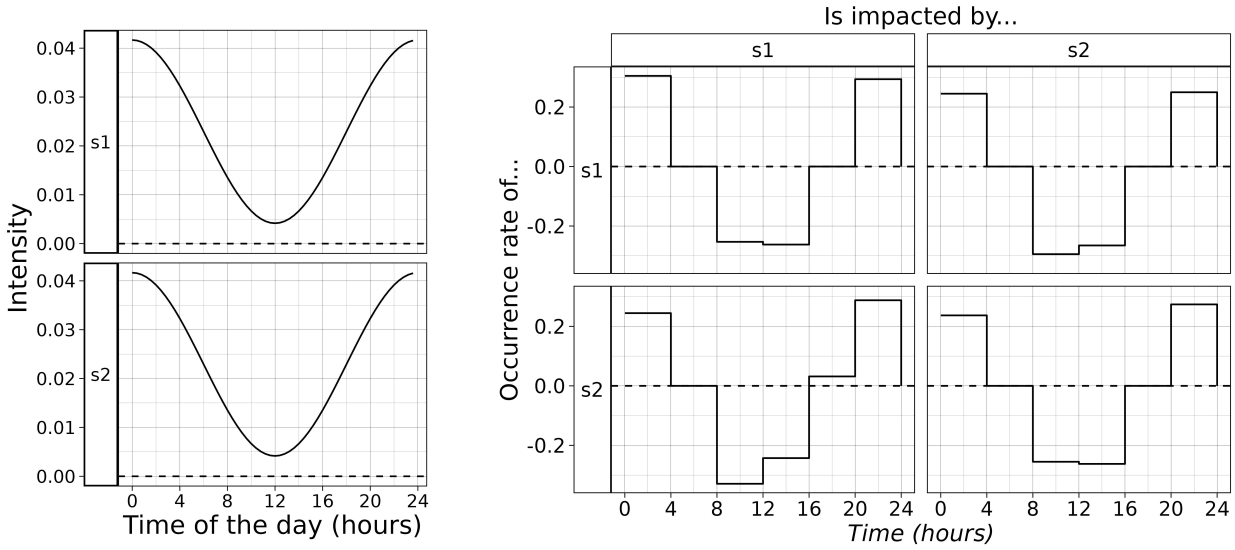



**Figure S2: Background rates inferred with the Hawkes process for each species.** The background rates values are written besides the points.
Silhouette images from PhyloPic by Lukasiniho (wildebeest), Margot Michaud (lion), Robert Hering (kudu), Zimices (zebra) and an unknown author (impala).

# Section S3 Influence of circadian rhythms

We simulated two species occurrences with cyclic rates in order to mimic circadian rhythms. We simulated occurrences over 1000 days on a single camera. For that, we used an inhomogeneous Poisson process for which species intensities varied periodically over 24 hours, with the Poisson non-homogeneous intensity defined with a cosine function with a period of 24 hours. Even though species occurrences were independent, the Hawkes process inferred a periodic attraction/repulsion pattern between and within species.




**(a)** Inhomogeneous Poisson intensity

**(b)** Inferred interactions with the Hawkes process

**Figure S3: Inference of spurious interactions when circadian rhythms are present.** (a) shows the non-homogeneous Poisson intensities for the two species. (b) shows the interaction functions inferred with a multivariate Hawkes process from the data simulated with two non-homogeneous Poisson process for which the intensities are shown in (a).

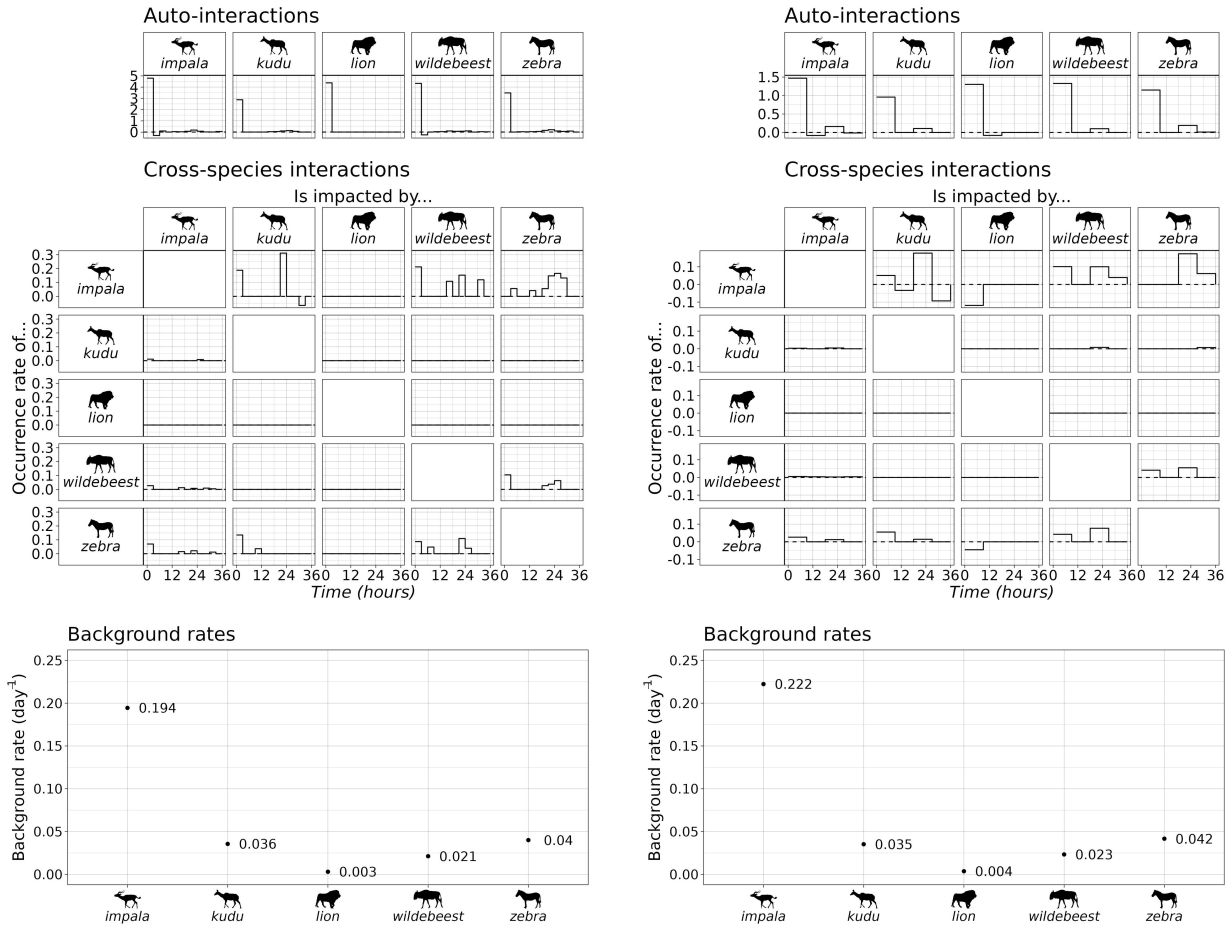
## Section S4 Influence of bin width

In order to check if bin width influences the inferred interaction functions, we changed the bin width used for the inference on the real data. Here, we inferred a Hawkes process with bins widths $\delta$ of 3 and 9 hours (compared to $\delta = 6$ hours in the main text).

Results are shown in Figure S4. Overall, the parameters are similar between 3, 6 and 9 hour bins. Regarding the 3 hours bins, the nonzero interactions are the same than with 6 hours bins and they have the same direction. Only the negative interactions (lion-impala and lion-zebra) are missed, possibly due to low power. The inferred background rates are similar to the rates inferred with 6 hours bins, except for impala which has a smaller background rate (0.194 compared to 0.212 occurrences day$^{-1}$ in the main text).

Regarding the 9 hours bins, all nonzero interactions are the same and they have the same direction as in the 6 hours bins version. The inferred background rates are similar to those inferred with 6 hours bins as well.

Finally, we can note that the values of the interaction functions are smaller when the bins widths are larger. This is expected because the average number of occurrences gained or suppressed during a given interval is the integral of the function over this interval.




**(a)** Bin width: 3 hours

**(b)** Bin width: 9 hours

**Figure S4: Inference of a multivariate Hawkes process with different bin widths.** (a) shows the parameters inferred with 3 hours bins and (b) the parameters inferred with 9 hours bins.
Silhouette images from PhyloPic by Lukasiniho (wildebeest), Margot Michaud (lion), Robert Hering (kudu), Zimices (zebra) and an unknown author (impala).

# References

Murphy, A., D. R. Diefenbach, M. Ternent, M. Lovallo, and D. Miller. 2021. Threading the needle: How humans influence predator–prey spatiotemporal interactions in a multiple-predator system. Journal of Animal Ecology **90**:2377–2390.