Acclimatisation affects synchrony in space use and the frequentation of multiple colonies in translocated Griffon Vultures (*Gyps fulvus*)

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Abstract Translocations are fundamental for the conservation of large raptors, including Old-World vultures. Different release methods are usually assessed by comparing the movement patterns and survival of released individuals. However, these approaches fail to capture important aspects related to the gregarious behaviour of many vulture species. We compared the effect of long (15 months, n = 7) and short (3 months, n = 16) acclimatisation over the post-release spatial behaviour of 4 cohorts of Griffon Vultures (*Gyps fulvus*) in Sardinia (Italy). Namely, we studied their occurrence distribution at a biweekly resolution and modelled its temporal trends to assess whether long-acclimatised griffons were faster and more prone *i*) to overlap their space use with that of other griffons from the same cohort, *ii*) to restrict their movements around colonies. Although no temporal trend was detected, long-acclimatised griffons had a higher intra-cohort correlation in their occurrence distribution. Long-acclimatised griffons were also faster at moving between the two main colonies than short-acclimatised ones. After 4-5 years, they were also more prone to use both colonies and thus less prone to remain confined into a single colony for 2 weeks, or in moving far away. Long acclimatisation seems to promote group cohesion in released griffons, probably due to the creation of stronger inter-individual bonds at the aviary, which can then facilitate movement at release sites and explain their faster use of a multiple colony system. Long acclimatisation periods (> 12 months) should be preferred for translocations of gregarious birds, such as Griffon Vultures, as they might foster group cohesion and facilitate post-release survival.

keywords: dynamic Brownian Bridge Movement Model; soaring birds; scavengers; Sardinia; Italy; evidence-based conservation

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Introduction

Conservation translocations involve the deliberate movement of organisms from one site to another, to benefit the conservation of one, or more, target species [1]. Conservation projects for large raptors often foresee translocations, since these species are exposed to considerable threats [2][3] have low intrinsic rate of population growth (e.g., late reproduction, low productivity) and often have small and/or fragmented populations.

Old and New World vultures deliver crucial ecosystem services [4], but their conservation status has become in many cases critical [5]. Restocking programs and reintroductions have thus become increasingly important for their conservation [6] (Table S1).

To optimise the outcome of these efforts, research focused on evaluating different translocation strategies, usually by comparing the survival and movements of individuals released by different approaches [7][8][9] or by comparing released individual to wild ones [10][11][12].

Although in conservation translocations both soft and hard release can be used [13], soft release is by far the most common method for vultures. In soft release, translocated individuals are subjected to an acclimatisation, a period when they are temporarily housed in an aviary at the release site, before being released in the wild. The duration of acclimatisation can vary from weeks to more than one year and, in principle, longer acclimatisation periods offer several advantages.

For example, acclimatisation can allow vultures to observe the release site and develop partial cognitive maps [14], which would subsequently facilitate space use [15] and a higher searching efficiency [16]. Available studies highlight that longer acclimatisation increases the post-release survival of gregarious vultures [7][9][17], partially through age-dependent processes [7], while at the same time decreasing the time needed to stabilise their home ranges [8].

For gregarious species, like Griffon Vultures (*Gyps fulvus*, hereinafter "griffons") it is also plausible that acclimatisation could affect space use, and therefore food search and survival by acting on group-level dynamics. In facts, in griffons inter-individual relations are mainly shaped by daily interactions on the ground (e.g roosting)[18], like those that occur at acclimatisation aviaries. Inter-individual relations become important when griffons have to locate food and updrafts [19][20], once released in nature. However, to date no study compared the post-release behaviour of multiple griffons simultaneously to assess the impact of different acclimatisation lengths at the group level.

We addressed this gap by modelling the post-release behaviour of 4 cohorts of griffons, that were translocated in Sardinia (Italy) and were subjected to short (3 months, n = 16) or long (15 months, n = 7) acclimatisation periods. Namely, we studied the bi-weekly occurrence distribution of individuals and modelled its temporal trends in long- and short-acclimatised griffons to test tree hypotheses.

First, we predicted that griffons from long-acclimatised cohorts, by having developed stronger inter-individual bonds, would be systematically more prone to move together, with their occurrence distributions being more correlated than those of griffons from short-acclimatised cohorts (H_1). Moreover, considering that empirical evidence suggests that during the early establishment phase griffons remain around the aviary or engage in individual exploratory forays [21], individuals might need time to start moving together. We expected this time to be shorter in long-acclimatised griffons, due to their stronger inter-individual bonds. Therefore, we predicted long-acclimatised griffons to be faster at attaining a high correlation in their occurrence distributions, compared to short-acclimatised ones (H_2). Finally, as more group cohesion would translate into an increased capacity to locate updrafts, move across the landscape and join colonies, we also predicted long-acclimatised griffons to be faster and more prone to centre their occurrence distribution around the two colonies in northwest Sardinia (H_3).

Materials and methods

Study area and data collection

The study area includes northwest Sardinia (Italy, Fig. 1), the second island in the Mediterranean Sea (Fig. 1).

Sardinia hosts a population of approximately 332-378 griffons (103 territorial couples in 2024, Berlinguer et al., in prep.), which concentrate their movements between two colonies in the northwestern part of the island, where they feed on livestock carrion [22]. Since 2015 this population has been subjected to different conservation interventions, funded by the European Commission through the LIFE program. These included anti-poisoning campaigns, power lines retrofitting and the creation of supplementary feeding stations [23]. A restocking program also led to the translocation of 79 individuals between 2016 and 2020, within the LIFE Under Griffon Wings project (LIFE14/NAT/IT/000484). The program was
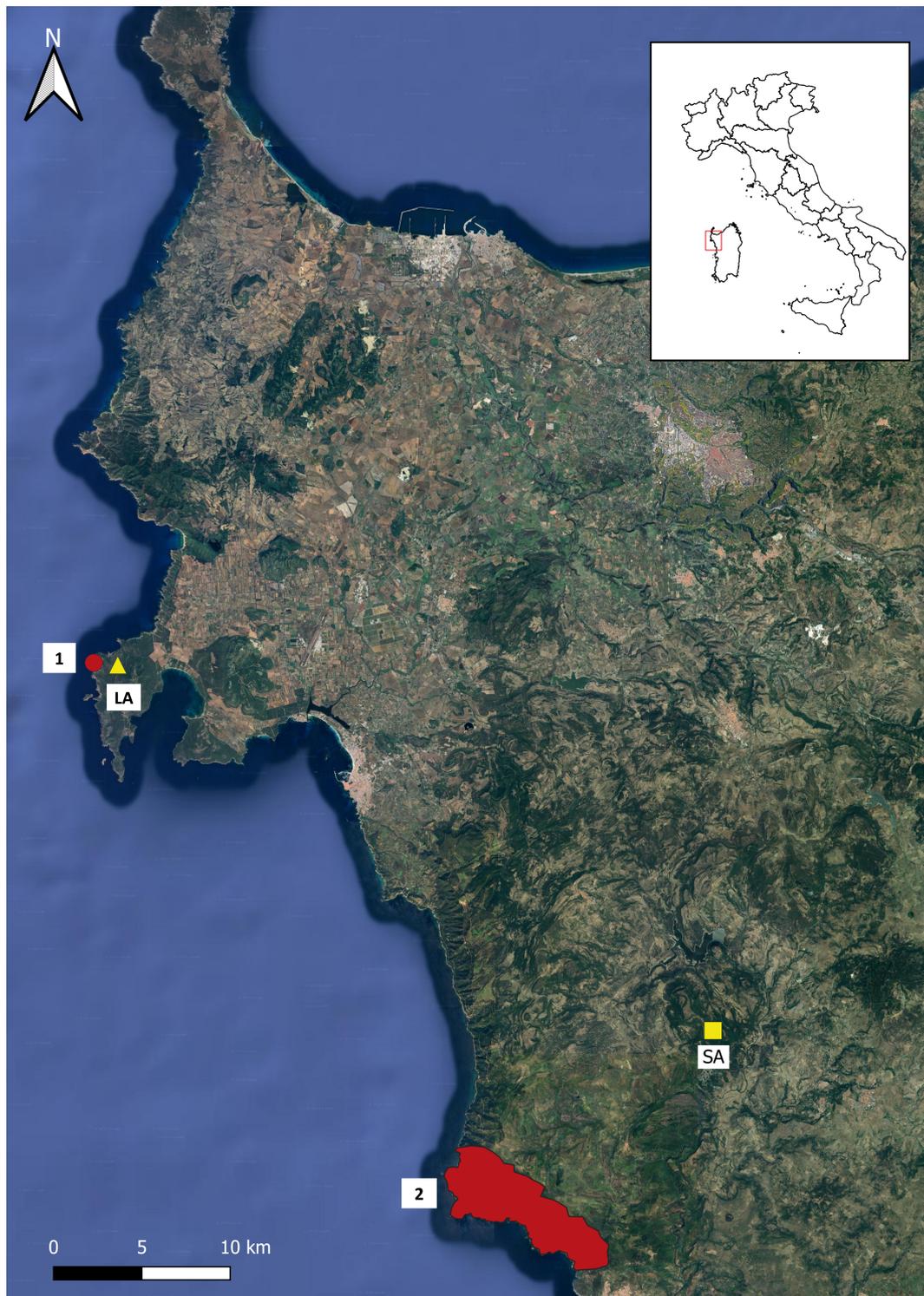
Figure 1: Map of the study area, representing the acclimatisation aviaries in Porto Conte (yellow triangle) and Bosa (yellow square) and the two colonies of Porto Conte (red circle) and Bosa (red polygon).

Table 1: Table. 1. Characteristics of the released griffons

Name	Cohort	Period	N.fix	Release	Data up to
Artis1	1	15 months	5,485	2018-04-14	2020-01-14
Artis2	1	15 months	2,810	2018-04-14	2019-02-15
Artis3	3	3 months	19,278	2019-06-24	2023-02-11
Artis4	3	3 months	9,309	2019-06-24	2021-03-11
Artis5	3	3 months	2,384	2019-06-24	2020-08-18
Barca	1	15 months	15,784	2018-04-14	2022-12-07
Bulga	1	15 months	4,618	2018-04-14	2019-07-30
Calmedia	4	3 months	2,816	2019-10-17	2020-10-13
Caniga	4	3 months	8,960	2019-10-17	2023-02-08
Cannisone	2	3 months	2,237	2018-12-11	2019-09-25
Corte	4	3 months	4,890	2019-10-17	2021-09-24
Cristallo	1	15 months	13,505	2018-04-14	2023-02-07
Cuada	2	3 months	12,861	2018-12-11	2022-12-17
Doglia	4	3 months	18,090	2019-10-17	2023-02-19
Fenuggiu	1	15 months	10,255	2018-04-14	2021-09-12
Idile	2	3 months	9,431	2018-12-11	2022-12-22
Macomer	3	3 months	8,012	2019-06-24	2021-12-15
Meilogu	4	3 months	2,484	2019-10-17	2020-08-14
Pabelanasa	2	3 months	10,526	2018-12-11	2023-02-06
Pituabile	2	3 months	10,526	2018-12-11	2021-01-31
Pozzomaggi	3	3 months	6,574	2019-06-24	2021-11-18
Timidone	1	15 months	8,451	2018-04-14	2021-02-22
Tottubella	4	3 months	7,740	2019-10-17	2022-09-10

authorized by the National Institute for Environmental Protection and Research (ISPRA, representing the Ministry for the Environment) and the Sardinian Regional Department for the Environment.

Before being released, translocated individuals were acclimatised in two aviaries located in the backcountry of the two colonies, named Bosa and Porto Conte (Fig. 1). We refer to these sites as colonies since they are used for breeding by adults, while non-breeding individuals, as the ones tagged in the present study, use them as communal roosts. Namely, three cohorts of griffons in the Bosa aviary (n. individuals = 16) had an acclimatisation of 3 months, while a cohort of griffon in the Porto Conte aviary (n. individuals = 7) had an acclimatisation of 15 months (see Fozzi et al. [8] for a description of acclimatisation).

Before being released, griffons were tagged with a subcutaneous RFID tag and leg rings, and their remiges or rectrices were bleached with individual patterns. Griffons were also equipped with GPS/GSM transmitters. These were attached with a Teflon leg-loop harness made of three assembled strings (round silicone cord 2mm + tubular teflon ribbon 0.2500 and 0.4400) following Hegglin et al. [24]. Transmitters and rings did not exceed 3% of body mass [25]. GPS tags were fitted by following the best practice in animal welfare - the heads of the birds were covered to guarantee minimal stress, and the transmitter placement time was reduced to less than ten minutes. GPS tags were programmed to record 1 GPS location every hour, from 06:00 GMT to 18:00 GMT. Due to their duty cycle and solar-powered batteries, tags did not collect the location of griffons during the night, and data acquisition was sometimes irregular due to reduced solar radiation (e.g. cloud cover) and/or short daylength. A complete overview of tagged animals used in this study is available in Table 1 at the end of the article.

Data analyses

We used a dynamic Brownian Bridge Movement Model (hereinafter "dBBMM")[26] to quantify the occurrence distribution of griffons. We used dBBMMs as they identify barriers to animal movement (e.g., the sea)[27] and because kernels estimate the range distribution, which depicts the long-term space utilisation by individuals [28], and it is suboptimal for comparing fine-scale temporal shifts in space use.

Occurrence distribution was estimated in a temporal window of 14 days, as this was the minimum

time scale allowing for its estimation, based on our data. As GPS acquisition was sometimes irregular, we optimised the estimation of dBBMMs by discarding values of the Brownian motion variance associated with irregular sampling. Overall, we estimated 864 biweekly occurrence distributions for griffons with 3 months acclimatisation (hereinafter referred to as "short-acclimatised griffons") and 413 for griffons with 15 months acclimatisation (hereinafter referred to as "long-acclimatised griffons").

Similarity in the biweekly space use of a single cohort of griffons was estimated as the median of the pairwise Pearson's correlations between the occurrence distributions of griffons from a certain cohort. Then, to test for H_1 and H_2 we fitted a Bayesian Generalized Linear Model (GLM) with a Skewed Normal distribution to model the temporal evolution of space use overlap between the four cohorts (n = 370). Covariates included the number of days since the release date, and an ordered variable with four levels, representing the four cohorts. As only one cohort of griffons (n = 7) was subjected to long acclimatisation, it was chosen as a reference level, to estimate cohort-specific differences. We also used an interaction term to test for different temporal trends between the four cohorts.

To quantify colony use and test for H_3, we overlapped the biweekly occurrence distribution of griffons with the two colonies of Bosa and Porto Conte. Then we classified each temporal window as a categorical variable indicating whether the occurrence distribution overlapped with *i*) both colonies, *ii*) only the colony of Bosa, *iii*) only the colony of Porto Conte or *iv*) none of the two colonies. We used a Bayesian categorical Generalized Linear Mixed Model (GLMM) to predict the overlapping according to the sex, the time since release and the acclimatisation of each griffon (long and short). We also fit a random intercept model, to account for differences between individuals, as well as a random-and-intercept model to account for individual differences in the effect of time since release over colony use.

Statistical analyses were carried out with the software R [29] and with Stan [30]. Namely, dBBMMs were fitted with the "move" package [31], and Bayesian GLMs were implemented in STAN through the "brms" package [32]. Model selection followed a forward approach, based on leave-one-out cross validation [33]. An overview of model selection is available in Fig. S2 and Fig. S5. Candidate models for both overlap in space use and colony use, showed a good fit to the data (Fig. S1 and Fig. S4).

Results

Bayesian GLMs revealed that long-acclimatised griffons had a higher median correlation in their occurrence distribution than short-acclimatised ones (Fig. 2).

Model selection, however, did not highlight any particular temporal trend, with both groups being rather fast at synchronizing their occurrence distributions (Fig. S3).

The best candidate model for colony use included the sex of released griffons, time and its interaction with acclimatisation period, as well as a random intercept between individuals (Fig. S5).

The best candidate GLMM highlighted that the occurrence distribution of long-acclimatised griffons had a higher overall probability of overlapping with both colonies, during biweekly temporal windows. They were also faster in doing so, after being released, then individuals subjected to short acclimatisation. Moreover, birds subjected to long acclimatisation had a lower probability, throughout the entire post-release period, to move away from colonies (Fig. 3).

With respect to using single colonies, both groups of griffons used mostly the colony in Bosa. However, birds subjected to short acclimatisation, after approx. 3 years from their release slightly were more prone to remain at the colony of Porto Conte for a biweekly period, although effect size were lower and credibility intervals larger for this latter colony (Fig. S6). Overall, the sex of released griffons had little impact over their probability of using one or multiple colonies (Fig. 4).

Discussion

Although some studies quantified the effect of acclimatisation over the post-release spatial behaviour of vultures [8][10][11], to the best of our knowledge this is the first study that explicitly considered the simultaneous space use by multiple individuals. We believe that our findings can be potentially important to study and improve translocation strategies in griffons and other gregarious vultures from the genus Gyps (e.g. *G. bengalensis*)[12].

Our results confirm our hypothesis (H_1) that the correlation in the biweekly occurrence distribution is systematically higher in long-acclimatised griffons compared to short-acclimatised ones. Long-acclimatisation period may increase on-the-ground interactions, which are considered important for the creation of inter-individual bonds [18], also affecting in turn group foraging and in the detection of updrafts [20]. Increased gregarious movements, which improve the energetic efficiency of griffons'
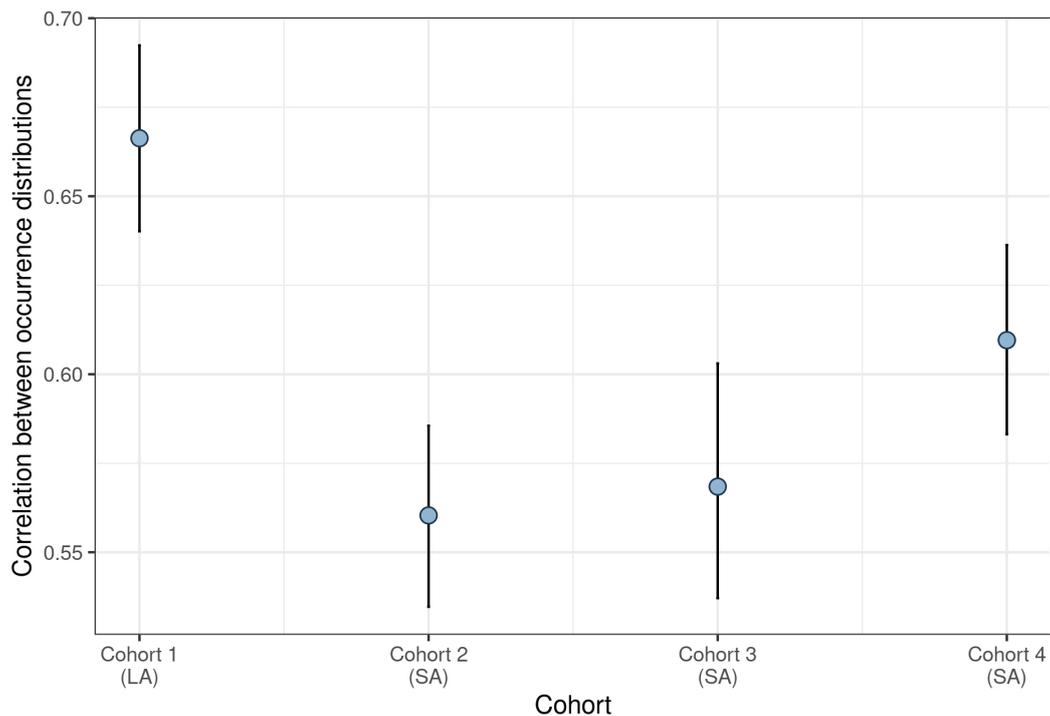
Figure 2: Conditional effect plot representing the estimated median Pearson's correlation between the occurrence distributions of the four cohorts of released griffons, altogether with their acclimatisation (LA - Long Acclimatisation, SA - Short Acclimatisation). Occurrence distributions were estimated with a dynamic Brownian Bridge Movement Model.

flight [34], would also explain why long-acclimatised birds were faster at moving between the two colonies and less prone to move away from them (H$_3$). This finding aligns with previous findings reporting that long-acclimatised griffons stabilise their home-range size faster and have a higher survival [8].

Considering that movement costs and gains are crucial for soaring birds [35], understanding the nexus between acclimatisation length, synchronicity in space use, carrion detection and fitness [36], would be crucial to optimise translocation strategies for gregarious vultures. This is particularly important when translocated birds are young individuals that typically have poorer flight performances than adults [37]. This research gap should be addressed through high-resolution telemetry and biologging [38], as they would allow to monitor individual behaviour at fine spatio-temporal scales [39], thus quantifying the selection of thermals [40] and feeding events [41], as well as to obtain reliable data about individual survival [42][43]. The use of high-resolution telemetry would also allow to replicate our findings with a greater level of accuracy, by exploring synchronicity between griffons through network analysis [44][18], and by classifying their behaviour [45].

Indeed, we did not find any difference in the temporal evolution of occurrence distribution overlapping (H$_2$), as the four cohorts of griffons were all quite fast in synchronising their space use. This could have depended upon data resolution and the relatively short distance between the two colonies. We quantified occurrence distribution in a biweekly temporal window, as this was the smallest one that we could achieve with our sampling rate, without having computational issues in dBBMMs. However, by doing so, we had a low granularity on vulture movements in the 3-4 weeks in the aftermath of the release. This time window is usually when released griffons adapt to live in the wild [7]. Future studies, adopting high-resolution GPS data and trajectory interpolation [46] to compute the distance between individuals, might indeed detect differences in the synchronisation between individuals subjected to different acclimatisation, during the first 3-4 weeks after the release.

Moreover, another limit of our study lies in the fact that the two colonies in Sardinia are at only 30 km of distance and the population has less than 400 individuals. In many areas of Europe (e.g. Iberian Peninsula) colonies are much larger and encompass a higher number of sites. Moreover, griffons often move between different colonies during their large-scale movements [47][48], and group foraging involves a much higher number of individuals. Future studies should replicate our findings in these contexts, where spatial scales are significantly larger and group dynamics certainly stronger [49].
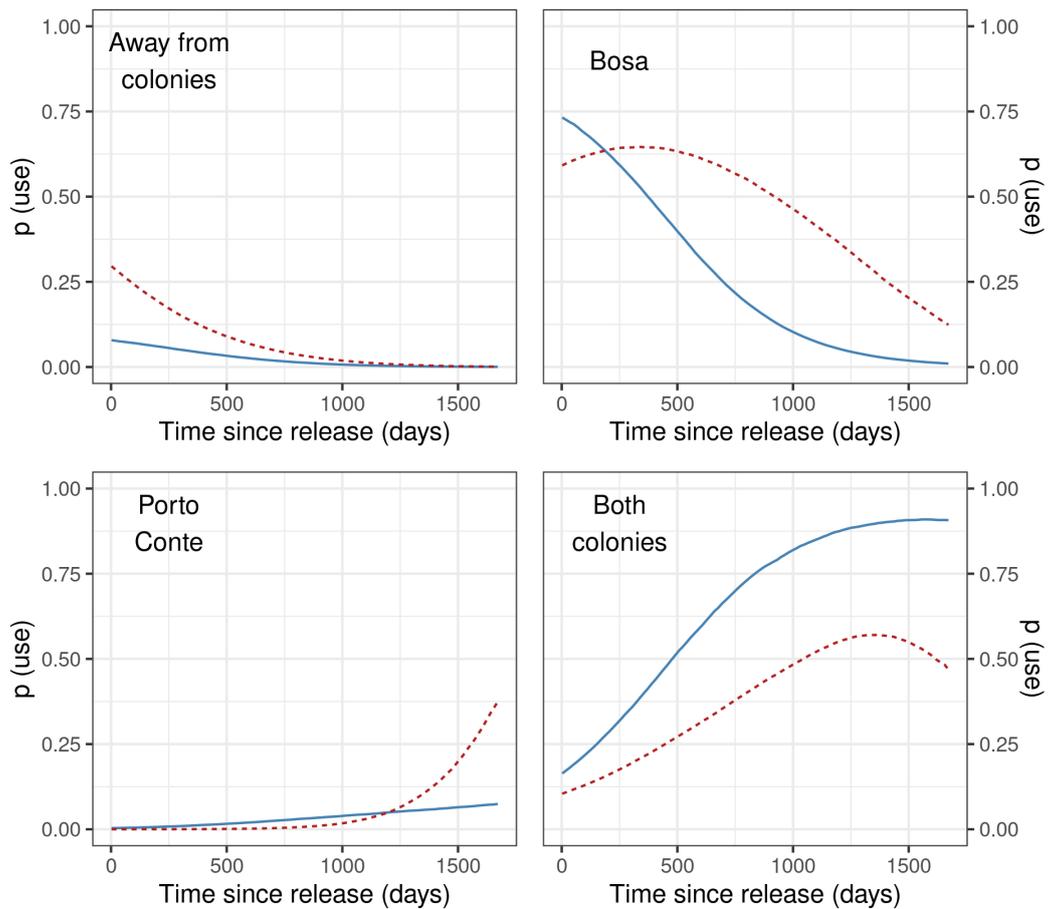
Figure 3: Conditional effect plot representing the temporal evolution of the probability that griffons stayed away from colonies, used the colony of Bosa or Porto Conte, or used both colonies, over a 14 days period. Credibility intervals have been removed to facilitate plot interpretation. However, the same plot with credibility intervals is in Fig. S6.
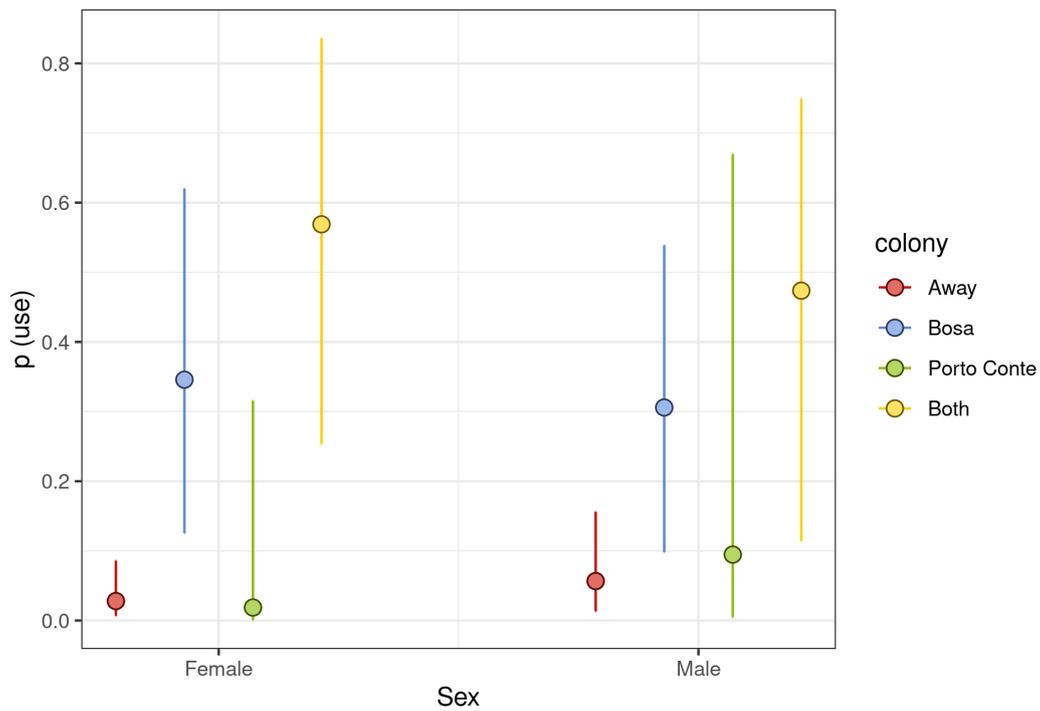
Figure 4: Conditional effect plot representing the effect of sex over the probability that griffons stayed away from colonies, used the colony of Bosa or Porto Conte, or used both colonies, over a 14 days period.

Conclusions

Our findings confirm that the length of the acclimatisation period before release affects the post-release behaviour of griffons. Long-acclimatised vultures from the same cohort showed a higher synchronisation in their space as their occurrence distribution overlapped more than in short-acclimatised cohorts. Long-acclimatisation also favoured the frequentation of the two colonies in the study area. Due to increased synchronicity in their movements and a higher frequentation of the colonies, long-acclimatised griffons might be better at locating updrafts and detect carrions. Therefore, they might also have a higher survival and fitness, in line with evidence from previous studies [7].

Translocation strategies for gregarious vultures should therefore encourage long acclimatisation over short acclimatisation or hard release, as it probably fosters stronger bonds between individuals, which in turn may improve their post-release navigation, space use and survival.

Table 2: Table. 1. Characteristics of the released griffons

Name	Cohort	Period	N.fix	Release	Data up to
Artis1	1	15 months	5,485	2018-04-14	2020-01-14
Artis2	1	15 months	2,810	2018-04-14	2019-02-15
Artis3	3	3 months	19,278	2019-06-24	2023-02-11
Artis4	3	3 months	9,309	2019-06-24	2021-03-11
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Pituabile	2	3 months	10,526	2018-12-11	2021-01-31
Pozzomaggi	3	3 months	6,574	2019-06-24	2021-11-18
Timidone	1	15 months	8,451	2018-04-14	2021-02-22
Tottubella	4	3 months	7,740	2019-10-17	2022-09-10

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Data availability statement

The reproducible data and software code are available at: https://osf.io/ea9zq/

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CRediT authorship contribution statement

Conceptualization: DS, FB, JC, MA Methodology: CB, CC, FB, IF, JC Software: CC, CB, IF, JC Validation: CB, CC, DAB, DDR, DS, IF, JC, JE, LP, MA, MM Formal analysis: CB, JC Investigation: CB, CC, DAB, DDR, DS, FB, IF, JE, LP, JC, MA, MM Resources: DS, FB, MA, MM Data curation: CC, DAB, DDR, IF, JE, LP, MA Writing - original draft: CC, CB, DDR, IF, FB, JC Writing- review and editing: DDR, IF, FB, JC, MA Visualization: DDR, IF, JC, FB Supervision: DDR, DS, FB, MA, MM Project administration: FB, JC Funding Acquisition: FB, DS

Conflict of interest

The authors declare no conflict of interest.

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Supplementary Tables and Figures

Table 3: Table S1. Overview of the main translocations and reintroductions involving Old World vultures

Species	Country	Action	Method	Source	
Cape vulture (*Gyps coprotheres*)	South Africa	Restocking	Captive-bred or rehabilitated individuals	Soft release	https://doi.org/10.1017/S0030605319000814
Griffon vulture (*Gyps fulvus*)	Bulgaria	Reintroduction	Captive-bred or rehabilitated individuals	Soft release	https://doi.org/10.3897%2FBDJ.9.e663634
Griffon vulture (*Gyps fulvus*)	Cyprus	Restocking	Rehabilitated individuals	Soft release	https://4vultures.org/our-work/reintroduction-and-restocking/griffon-vulture-cyprus/
Griffon vulture (*Gyps fulvus*)	France	Reintroduction	Captive-bred or rehabilitated individuals	Soft release	https://doi.org/10.1890/07-0854.1
Griffon vulture (*Gyps fulvus*)	Israel	Restocking	Captive-bred individuals	Soft release	https://doi.org/10.1111/csp2.308
Griffon vulture (*Gyps fulvus*)	Italy (mainland)	Reintroduction	Captive bred or rehabilitated individuals	Soft release	https://doi.org/10.1017/S0959270923000199
Griffon vulture (*Gyps fulvus*)	Italy (Sardinia)	Restocking	Captive bred or rehabilitated individuals	Soft release	https://doi.org/10.1016/j.isci.2023.106699
Bearded vulture (*Gypaetus barbatus*)	Alps	Reintroduction	Captive bred individuals	Hacking	https://doi.org/10.1002/2688-8319.12347
Bearded vulture (*Gypaetus barbatus*)	France (mainland)	Reintroduction	Captive bred individuals	Hacking	https://doi.org/10.1002/ecs2.4856
Bearded vulture (*Gypaetus barbatus*)	France (Corse)	Restocking	Captive bred individuals	Hacking	https://www.gypaetecorse.com/en/life-gyprescue/
Bearded vulture (*Gypaetus barbatus*)	Spain	Reintroduction	Captive bred individuals	Hacking	https://doi.org/10.1002/ecm.1414

| Species	Country	Action	Method	Source	
Bearded vulture (*Gypaetus barbatus*)	South Africa	Reintroduction/restocking	Captive breeding of chicks collected from the wild	Not yet released	https://4vultures.org/blog/saving-bearded-vultures-in-southern-africa-through-a-captive-breeding-programme/
Cinereous vulture (*Aegypius monachus*)	Bulgaria	Reintroduction	Captive-bred or rehabilitated individuals	Soft release or hacking	https://doi.org/10.3897%2FBDJ.11.e100521
Cinereous vulture (*Aegypius monachus*)	France	Reintroduction	Captive-bred or rehabilitated individuals	Soft release or hacking	https://doi.org/10.1002/ecs2.3862
Cinereous vulture (*Aegypius monachus*)	Portugal	Restocking	Rehabilitated individuals	Soft release	https://4vultures.org/life-aegypius-return/
Egyptian vulture (*Neophron percnopterus*)	Israel	Reintroduction	Captive breeding	Soft release	https://doi.org/10.1093/ornithapp/duab065
Egyptian vulture (*Neophron percnopterus*)	Italy	Restocking	Captive breeding	Soft release + hacking	https://www.lifegyptianvulture.it/news/il-progetto-life-egyptian-vulture-disponibile-un-report-divulgativo-su-azioni-e-risultati/
White-rumped vulture (*Gyps bengalensis*)	India	Reintroduction	Captive-bred individuals	Soft release	https://roundglasssustain.com/conservation/vultures-reintroduction-tadoba
White-rumped vulture (*Gyps bengalensis*)	Nepal	Reintroduction	Captive-bred individuals	Soft release	https://doi.org/10.1111/ibi.13303
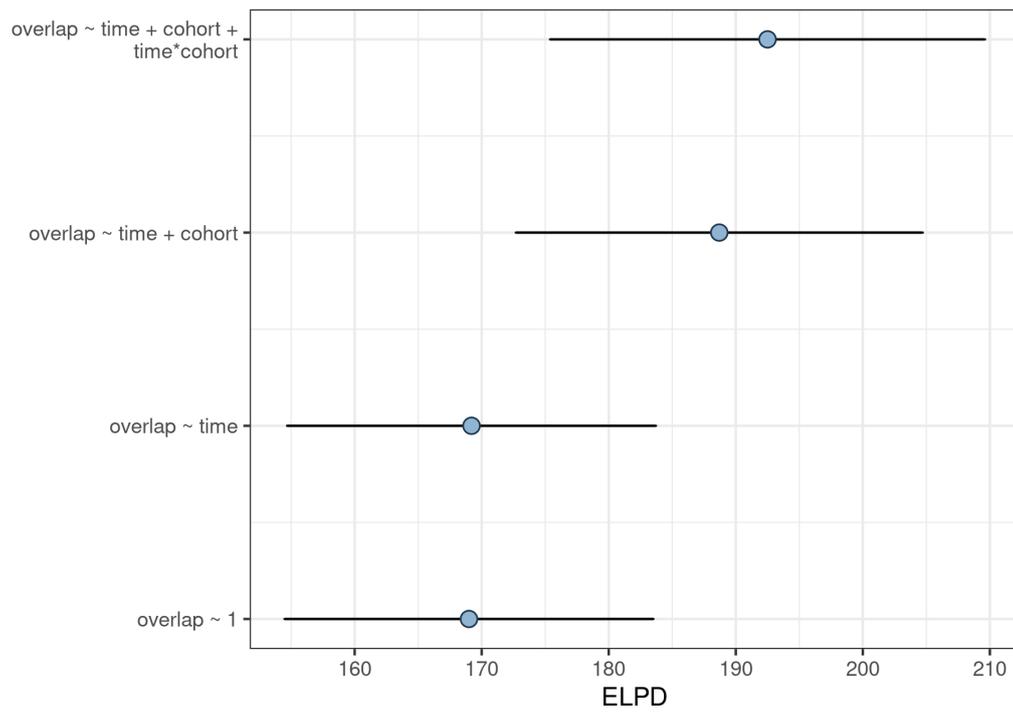
Figure S1: Expected Log-Pointwise Density (ELPD) of the different GLMs for overlap in the occurrence distributions of griffons from the same cohort. The higher the ELPD score, the better the model.
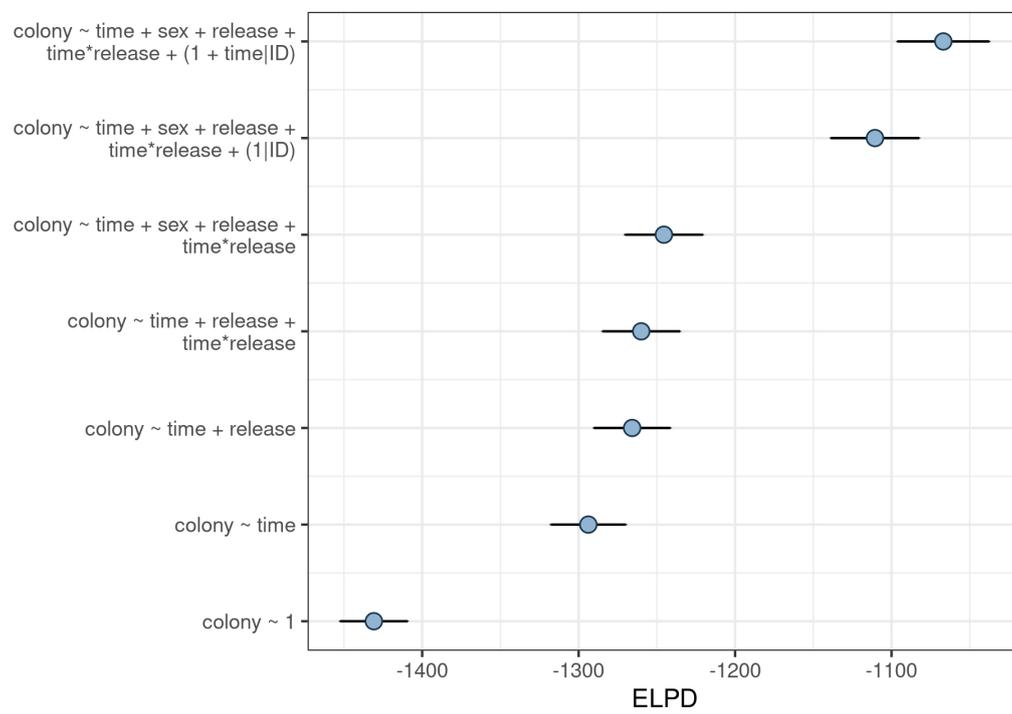
Figure S1: Expected Log-Pointwise Density (ELPD) of the different GLMMs for colony use. The higher the ELPD score, the better the model.
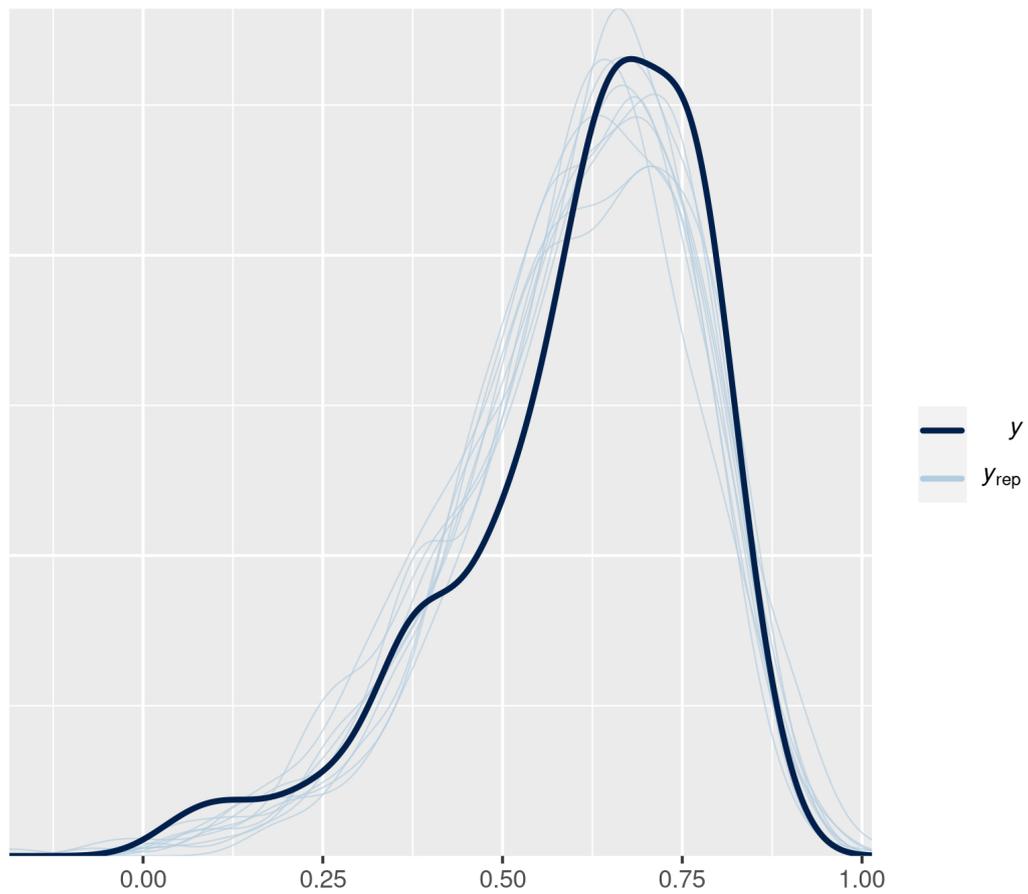
Figure S3: Comparison between the posterior predictive distribution of the best candidate model for overlap in space use and observed data. For further information see: https://mc-stan.org/bayesplot/reference/bayesplot-package.html
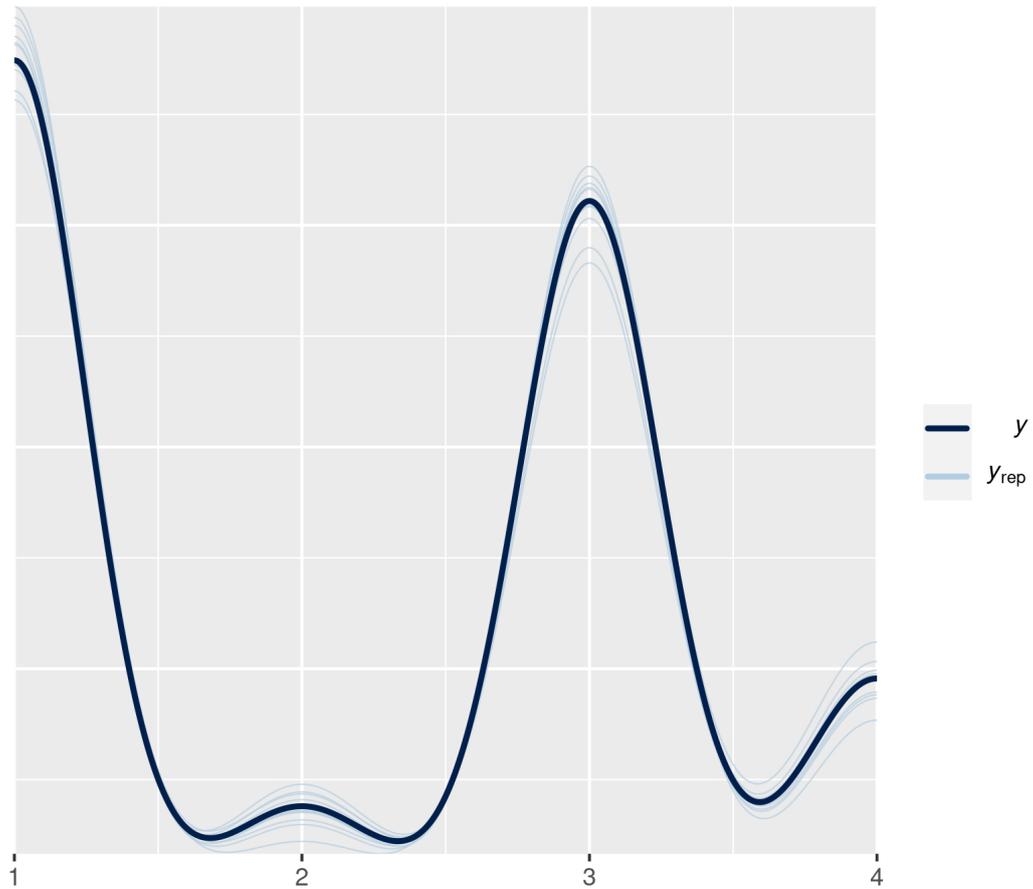
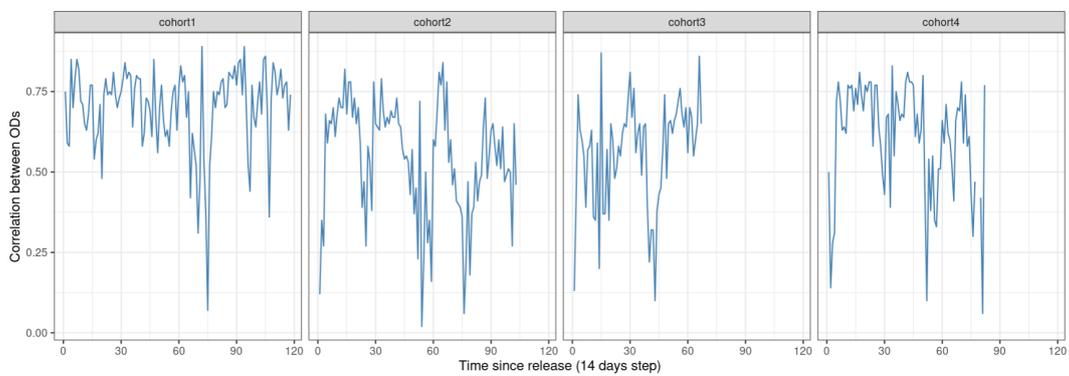**Figure S4:** Comparison between the posterior predictive distribution of the best candidate model for colony use and observed data. For further information see: https://mc-stan.org/bayesplot/reference/bayesplot-package.html

Figure S5: Fig. S5. Temporal evolution of overlap, since release, in the four cohorts of griffons.
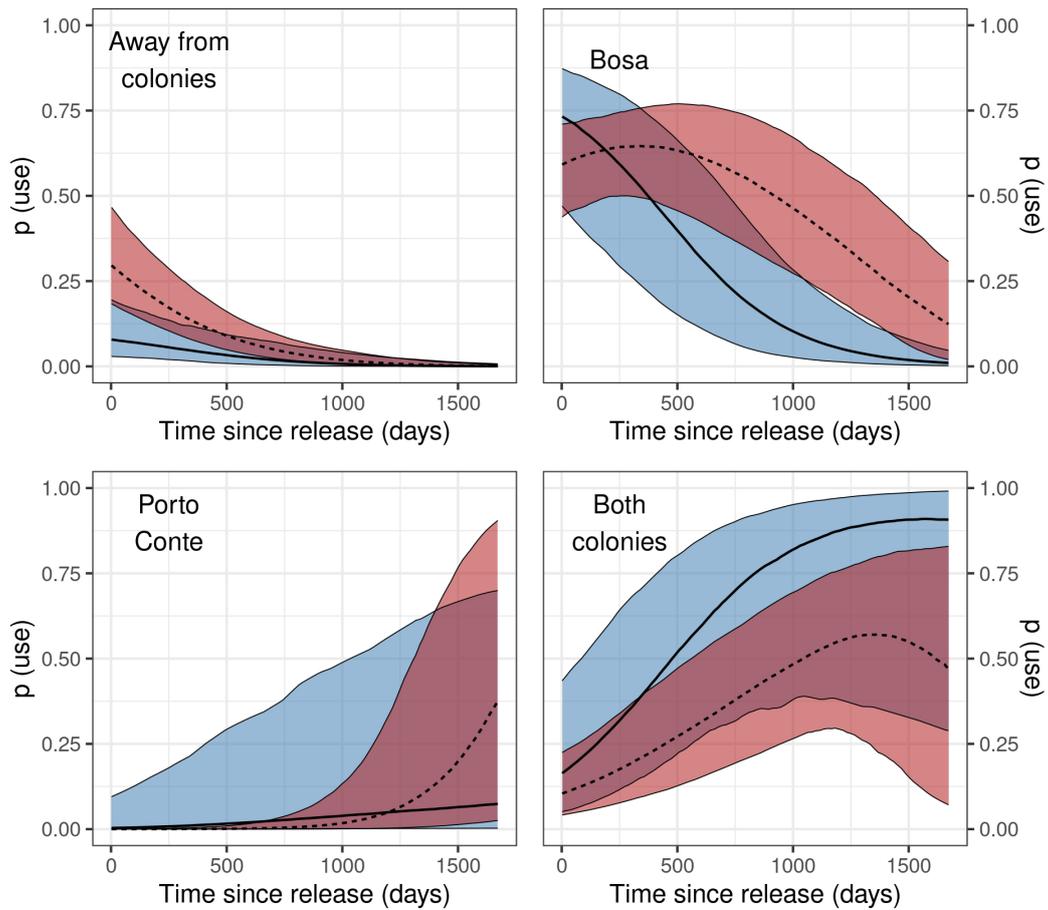
Figure S6: Fig. S6. Conditional effect plot representing the temporal evolution of the probability that griffons resided in the Porto Conte colony (a), in the Bosa colony (b), in both colonies (c) or stayed away from colonies (d), in a 14 days period. Credibility intervals are reported.