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Assessing the effectiveness of intensive conservation actions: Does guarding and feeding increase productivity and survival of Egyptian Vultures in the Balkans?

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ABSTRACT

Assessing the effectiveness of conservation measures to reverse population declines is essential to evaluate management strategies. Management solutions such as direct protection or supplementary feeding typically aim at reducing mortality or increasing productivity, but demonstrating such demographic consequences of adopted management is often difficult. Here we assess the effectiveness of large-scale management actions aimed at the conservation of an endangered vulture on the Balkan Peninsula by extending a novel analysis to estimate seasonal adult survival from observations of unmarked individuals. We monitored Egyptian Vulture *Neophron percnopterus* breeding success and territory occupancy over 11 years in three countries during which both nest guarding and supplementary feeding were carried out. We found little evidence that nest guarding and supplementary feeding increased breeding propensity (mean $= 0.88 \pm 0.32$ standard deviation, $n = 463$), breeding success (0.82 ± 0.39), or the number of fledglings raised by successful pairs (1.3 ± 0.74). We estimated adult survival during the 23-week breeding season (mean = 0.936, 95% credible interval 0.889–0.968) and found no significant increase due to management. In the last 13 years 43 dead adult birds have been found during the breeding season, and 77% of confirmed mortalities were due to poisoning. Overall, the current management measures may have so far failed to halt ongoing population declines because the beneficial effects are insufficient to offset the loss of adult birds for example due to poisoning. We suggest that additional measures to slow the decline of Egyptian Vultures in the Balkans are required. In the short term, we urge governments to enforce anti-poison regulations that already exist. In the medium term, alternative approaches need to be developed that reduce the use of poisons and the associated accidental mortality of vultures and other wildlife species.

1. Introduction

Ongoing increases in the number of species threatened with extinction require the development and implementation of conservation management strategies to halt or reverse population declines. Despite the adoption of many well-intended management approaches, conservation management frequently lacks the resources or the capacity to properly evaluate the effectiveness of management actions taken, and academic research into effectiveness often lacks the link to practical implementation on the ground (Arlettaz et al., 2010; Gibbons et al., 2011). Adaptive management, where active management and research into underlying mechanisms occur simultaneously, has been highlighted as a useful strategy to maximise management efficiency (Nichols et al., 2007). Adaptive management is especially useful for the conservation of long-lived species with slow life-histories, where a focus on research without any intervention could cause temporal delays during which a population would continue to decline. Implementing management and research simultaneously offers a useful approach to test the effectiveness of practically implemented management activities, which is critical to avoid further expenditure on management actions that do not deliver intended outcomes (Martínez-Abraín and Oro, 2013; Schaub et al., 2009).

Conservation management is most frequently applied to large and charismatic species (Sitas et al., 2009). One group of animals that receives considerable management attention are long-lived bird

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species, such as seabirds and raptors, partly because they exhibit strong population declines due to direct persecution, accidental mortality due to human activities, and loss of suitable habitat (Croxall et al., 2012; Ogada et al., 2012; Virani et al., 2011). Many raptor populations globally have been assisted by conservation management such as the provision of safe nesting sites (Altwegg et al., 2014; Demerdzhiev et al., 2014), supplementary food (Cortés-Avizanda et al., 2010; González et al., 2006; Oro et al., 2008), reduction of disturbance (Liberatori and Penteriani, 2001; Zuberogoitia et al., 2014), and guarding and protection of nests to reduce poaching and persecution (Demerdzhiev et al., 2014; Lindsey, 1992; Vaughan et al., 2005). While these widespread management activities have resulted in successful conservation or recovery of several species, they are often cost- and labour-intensive, and can occasionally have unintended outcomes (Carrete et al., 2006; Ferrer and Hiraldo, 1991). For example, the provision of supplementary food at central feeding stations may attract non-breeding birds or other facultative scavengers resulting in increased interference and a reduction of productivity (Carrete et al., 2006; Cortés-Avizanda et al., 2010; Lieury et al., 2015). Testing the effectiveness of any large-scale population management is therefore essential to avoid negative outcomes and to ensure that the investment in these approaches benefits the target population (Ewen et al., 2015; Lieury et al., 2015; López-López et al., 2014).

Assessing the effectiveness of management requires the examination of effects on reproductive output and survival. Estimates of adult survival are especially important for long-lived species, because population growth rates of these species are expected to be highly sensitive to adult survival (Saether and Bakke, 2000). The need to estimate management effects on survival is a trade-off, because the most common approach to obtain robust estimates of survival are capture–mark–recapture techniques (Lebreton et al., 1992; Williams et al., 2002), which require a labour-intensive research programme that can incur large costs (Oro et al., 2008; Schaub et al., 2009). Alternative approaches to estimate survival from simpler monitoring data have recently been developed (Dail and Madsen, 2011; Hernández-Matías et al., 2011; Roth and Amrhein, 2010), and adopting such approaches to assess the effectiveness of management on long-lived species would increase the efficient use of sparse conservation resources.

Here we extend one approach to estimate adult survival from simple monitoring data (Roth and Amrhein, 2010) to assess the effectiveness of large-scale management actions aimed at the conservation of a globally threatened scavenger species, the Egyptian Vulture *Neophron percnopterus* on the Balkan Peninsula. We compiled territory monitoring data from three countries over the past ten years, and examine the effectiveness of conservation measures on productivity and adult survival during the breeding season. Specifically, our objectives were to assess whether central feeding stations, nest guarding and individual supplementary feeding increased (1) breeding propensity, breeding success, or the proportion of pairs raising two fledglings; and (2) the survival of territorial adult birds during the breeding season. This work critically examines the demographic consequences of widely used management actions, and provides an example of how the effectiveness of such management can be evaluated with basic monitoring data.

2. Methods

2.1. Study species and area

The Balkan Peninsula is situated in south-eastern Europe, and harbours a population of <100 pairs of the globally threatened Egyptian Vulture, which is declining more rapidly than populations in western Europe or India (Galligan et al., in press; Velevski et al., 2015). The decline of the Egyptian Vulture is likely caused by a combination of several known threats such as poisoning, electrocution, landscape changes and direct persecution (Mateo-Tomás and Olea, 2010; Sanz-Aguilar et al., 2015; Velevski et al., 2015). Since the late 1980s, centralised supplementary feeding stations (also known as 'vulture restaurants') have been operating in areas with high vulture density in Bulgaria and Greece, and since 2003 in vulture regions in the Former Yugoslav Republic of Macedonia (hereafter the FYR of Macedonia). Since 2009, nest guarding and the provision of supplementary food at individual, low intensity feeding places have been implemented as additional management actions in Bulgaria and Greece, but not in the FYR of Macedonia (Fig. 1). These activities were intended to increase the productivity of vultures and reduce mortality from accidental ingestion of poison (Blanco et al., 2009; Oro et al., 2008), which is illegally used for various purposes especially in Greece (Kalpakis et al., 2009; Mazaris et al., 2008; Skartsi et al., 2014). Because the large-scale adoption of these conservation measures has so far not reversed the population decline (Velevski et al., 2015), the effectiveness of the management needs to be objectively evaluated.

2.2. Field data collection and management activities

Between 2005 and 2015, we monitored Egyptian Vulture territories in Bulgaria ($n = 233$), Greece ($n = 44$), and the FYR of Macedonia ($n = 186$), and during that time period the population size decreased from 114 to 55 adult birds in Bulgaria, from roughly 60 to 18 in Greece, and from 72 to 42 in the FYR of Macedonia (Grubač et al., 2014; Velevski et al., 2015). Nests were discovered in April by searching known territories, and monitored regularly to assess whether adults were still incubating or chicks were still alive. During these monitoring visits, we counted the number of adult birds observed, and recorded the amount of time spent by an observer in the territory as an index of observation effort for a particular survey (Olea and Mateo-Tomás, 2011). At the end of the breeding season (August), we counted the number of fledglings produced by observing dependent young being fed by adults in the vicinity of the nest.

The conservation measures were applied in Bulgaria and Greece in an adaptive management framework: based on monitoring of breeding success from 2005 to 2010, territories that were situated in areas with high poisoning or poaching risk and away from established feeding stations were chosen for nest guarding and individual supplementary feeding. For Bulgaria, the territories included in our analysis are therefore only a subset of the overall Egyptian Vulture population, and include mostly territories where conservation management was deemed necessary. No individual territory-level management was carried out in the FYR of Macedonia.

Between 2009 and 2015, the territories in Bulgaria and Greece received conservation management at two levels of intensity: nest guarding mostly to prevent disturbance and poaching, and nest guarding plus individual supplementary feeding with a mixture of common livestock carcasses such as cattle, donkey, goat and sheep to facilitate successful breeding and divert adults from consuming poisoned carcasses in the landscape (Fig. 1). The supplementary food consisted of a piece of meat (1–3 kg) provided two or three times per week between 06:00 and 08:00 h in the morning on an open rock 100–1500 m from the nest. For each nest we recorded the total guarding effort (in hours), and the total amount of supplementary food provided (in kg). In addition, some territories including some in the FYR of Macedonia were located near a centrally located vulture feeding station (Fig. 1), a third type of management that operated independently of nest guarding and supplementary feeding at the territory level. These 'vulture restaurants' provide a large amount of common livestock carcasses on a regular basis (up to three times per week), which may benefit breeding vultures. If a central feeding station was operational within 10 km of the nest, we considered this station to be within the normal foraging radius and therefore easily accessible for breeding Egyptian Vultures (López-López et al., 2014).

Because the cumulative guarding effort and the amount of supplementary food increased the longer a nest was active (guarding and feeding were discontinued when nests failed), we scaled the guarding and

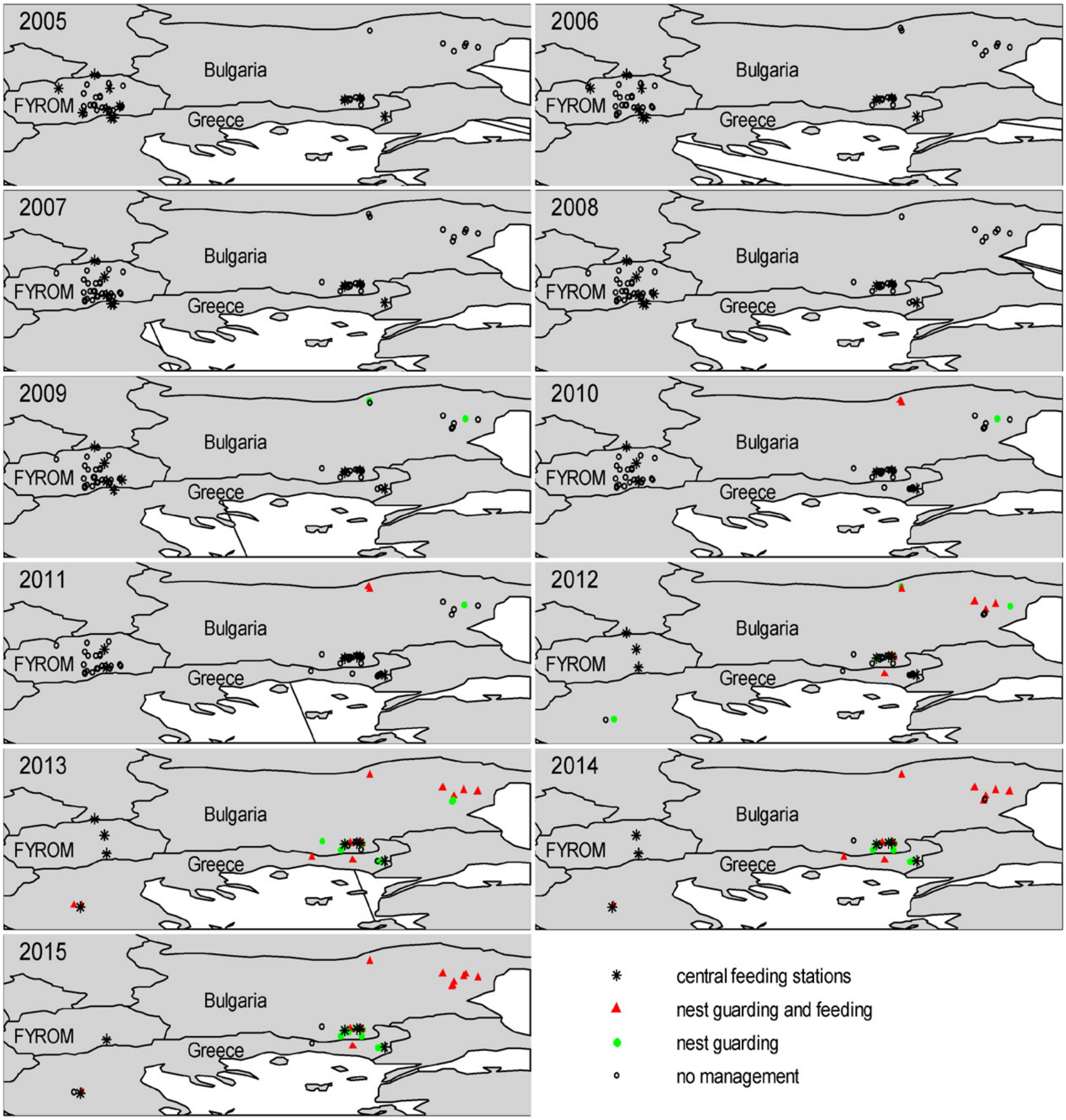

Fig. 1. Study area and distribution of Egyptian Vulture nest sites for which adequate monitoring data exist between 2005 and 2015. For each year, monitored nests are displayed according to the different levels of management, and active central feeding stations are displayed at their respective location.

feeding effort to daily values by dividing the total guarding effort and total amount of food provided by the number of days a nest was active, and used this average daily guarding and feeding effort as continuous variables in our analysis.

2.3. Estimating the effect of management on productivity

The territories in Bulgaria and Greece were chosen for management based on the recorded breeding performance. In those two countries we therefore only considered territories in the analysis for which data were available from years when no conservation management was applied ($n = 34$ territories; 39% of those occupied in 2003). Our test of the effectiveness of conservation management is thus based on both a longitudinal comparison of the same territories over time, combined with a spatial comparison of territories with (Bulgaria, Greece) and without management (the FYR of Macedonia; Fig. 1). Although our analysis may be confounded by temporal changes in territory quality, we found no major changes in diet composition of Egyptian Vultures over time (Dobrev et al., in press), observed no major habitat conversions in these territories, and therefore assumed that temporal changes in territory quality were negligible for the duration of our study.

We considered three biological processes on which management may have had an influence: whether territorial pairs initiated a breeding attempt (breeding propensity), whether pairs that did initiate a breeding attempt raised any fledglings (breeding success), and whether successfully breeding pairs managed to raise two rather than just one fledgling (fledging rate). These three processes together are the key components of annual productivity, which we define as the number of fledglings raised by a territorial pair.

To test whether any of the conservation interventions were effective in increasing any of the three reproductive processes, we constructed a series of multivariate models to examine specific hypotheses. We constructed six competing models that reflected the main hypotheses of management interest, and used an information-theoretic approach by evaluating support for each model using AIC_c (Burnham and Anderson, 2002; Galipaud et al., 2014). The six models considered (1) constant productivity (no effect of conservation management); productivity to increase with either (2) nest guarding, or (3) the presence of a central feeding station, (4) productivity to increase with nest guarding and individual supplementary feeding; (5) productivity to increase with nest guarding and the presence of a central feeding station; and (6) productivity to benefit from nest guarding, individual supplementary feeding, and the presence of a central feeding station. For the analysis of breeding propensity we evaluated only four models, because nest guarding only occurred after a nest had been initiated, and models 2 and 5 were therefore redundant. In this analysis we only used the amount of supplementary food provided prior to the actual or mean nest initiation date, because food provided after nest initiation was no longer relevant for breeding propensity.

We used generalised linear mixed models with a binomial error distribution to assess the effect of conservation management on the three different components of productivity (breeding propensity, breeding success, fledging rate) while accounting for variation between years and territories by including these factors as random intercepts in each model (Bolker et al., 2009; Gillies et al., 2006). We fitted all models using the Laplace approximation in R 3.1.1 (R Development Core Team, 2014) with the package 'lme4' (Bates et al., 2014), using the following generic formula: glmer(productivity component ~ management variables + (1|territory ID) + (1|year)).

2.4. Estimating the effect of management on survival

Because none of the Egyptian Vultures were individually marked, we were unable to estimate seasonal survival using traditional mark-recapture approaches (Williams et al., 2002). We therefore assumed that during the breeding season individual breeders would generally remain within their breeding territory (López-López et al., 2013, 2014), and used the temporal sequence of observations to estimate the persistence probability of each territorial bird while accounting for imperfect detection.

Survival of unmarked individuals has been estimated using either individual replacement (Hernández-Matías et al., 2011) or a dynamic occupancy model framework (Roth and Amrhein, 2010), which can estimate the probability that an individual survives at a certain site if repeated observations for each primary time period exist to account for imperfect detection (Kéry and Schaub, 2012; MacKenzie et al., 2003). Because vulture territories are usually occupied by two breeding adults, and adult Egyptian Vultures are not sexually dimorphic and cannot be reliably distinguished, we extended the dynamic occupancy model formulation of Roth and Amrhein (2010) to a binomial model for the ecological state (Appendix 1), and estimated survival following approaches adapted from abundance estimation in open populations (Chandler et al., 2011; Dail and Madsen, 2011). Specifically, we allowed the response variable (number of observed adults) to be either 0, 1, or 2, and used a binomial distribution with the number of adults instead of a Bernoulli distribution with a trial size of 1 in an occupancy model framework (Kéry and Schaub, 2012; Roth and Amrhein, 2010). These models assumed that there was no individual replacement of territorial adults during the breeding season, and that there were no age and sex differences in seasonal survival probability. We consider these assumptions realistic, because in our declining population the pool of potential floaters to replace lost territorial adults is likely negligible, and other studies of Egyptian Vultures have so far not shown sex differences in survival probability (Grande et al., 2009; Lieury et al., 2015). Although annual survival probability varies by age, low survival was mostly associated with obtaining a territory (Grande et al., 2009), and for our suite of territorial breeders we consider it realistic that age-related differences in seasonal survival probability are negligible.

We structured our data to assess weekly persistence of territorial adults from April to the end of August to avoid early departure on migration (in September, Oppel et al., 2015) to bias survival estimates. Egyptian Vultures generally remain in their territories even after breeding failure, and we assumed that the disappearance of an adult from a breeding territory was indicative of mortality. For each territory ($n = 78$) and year ($n = 10$), we used the recorded number of observed adults during each territory survey to account for imperfect detection. For each week during the breeding season ($n = 23$ weeks, the primary time period over which we assessed survival), up to seven daily observations of adult Egyptian Vultures were possible, and these observations were used as the repeat surveys to estimate detection probability. We considered that detection probability would vary with the duration of each survey and guarding effort, as more intensive monitoring would generally result in better detectability of birds (Olea and Mateo-Tomás, 2011).

We implemented the survival model in a Bayesian framework using Markov chain Monte Carlo methods in JAGS 3.3 (Plummer, 2012) via the R2jags library (Su and Yajima, 2012) in R 3.1.1 (R Development Core Team, 2014). We ran three Markov chains each with 45,000 iterations and discarded the first 5000 iterations to ensure that the models converged. Convergence was tested using the Gelman–Rubin diagnostic (Brooks and Gelman, 1998), and all parameters had values of R-hat < 1.02.

Analogous to the models used to assess management effectiveness on productivity (see above), we evaluated which of the management actions best explained variation in seasonal survival of territorial birds over the 23-week breeding season. Because multi-model inference is complicated for hierarchical models fit in a Bayesian framework, we used a Gibbs variable selection procedure by introducing additional parameters to estimate the inclusion probability of all regression parameters in the ecological state model (Hooten and Hobbs, 2015; O'Hara and Sillanpaa, 2009; Tenan et al., 2014). We report the inclusion probability of each management parameter in the survival model, estimates of seasonal survival probability and detection probability as the posterior mean and 95% credible intervals.

3. Results

3.1. Effectiveness of management on productivity

Overall productivity of 463 monitored breeding attempts was 0.94 (±0.86) fledglings per occupied territory (Table 1). Nest guarding ranged from 6 to 182 days (mean = 61 days) with an average effort of 8.0 h/day (range 2–13 h/day). Nests provided with supplementary food near the nest received on average 62 kg of supplementary food (range 6–180 kg) spread over 33 delivery days (range 3–107 days). The total guarding effort of 50.108 h between 2009 and 2015 prevented six nest disturbances by confronting and averting human threats that would have led to nest loss, and also rehabilitated 10 chicks that had fallen from the nest. The guarding increased the overall productivity in Bulgaria and Greece by 6.3% from 158 to 168 fledglings and the overall proportion of pairs raising at least one fledgling by 3.5% from 0.69 to 0.71.

At the population level, however, there was no evidence that either of the management actions improved breeding propensity, breeding success, or fledging rate, and the null model received the most support from the data for all three productivity components (Table 2). There was some support for central feeding stations to have increased breeding propensity ($b = 0.564 \pm 0.518$ standard error), and nest guarding to have affected breeding success ($b = -0.06 \pm 0.037$), but the estimated effect size for nest guarding was very small.

3.2. Effectiveness of management on survival

Since 2002, the loss of 45 adult Egyptian Vultures was recorded during the breeding season in Bulgaria (21), Greece (18), and the FYR of Macedonia (6). Of the 35 mortality events where the cause of death could be ascertained with confidence, 27 (77%) had died from poisoning,

Table 1
Summary of productivity of Egyptian Vultures on the Balkan Peninsula under different management regimes between 2005 and 2015. Breeding propensity is the proportion of pairs that initiated a breeding attempt; breeding success is the proportion of breeding pairs that raises at least one fledgling; fledging rate is the average number of fledglings produced by successfully breeding pairs.

Management activity	Presence of central feeding station	Breeding propensity			Breeding success			Fledging rate		
		n	Mean	sd	*n*	Mean	sd	*n*	Mean	sd
None	No	212	0.88	0.33	186	0.82	0.39	152	1.32	0.98
None	Yes	153	0.86	0.35	131	0.84	0.37	110	1.26	0.44
Nest guarding	No	13	1.00[a]		13	0.92	0.28	12	1.42	0.51
Nest guarding	Yes	32	1.00[a]		32	0.72	0.46	23	1.35	0.49
Nest guarding and supplementary feeding	No	25	0.84	0.37	21	0.76	0.44	16	1.31	0.48
Nest guarding and supplementary feeding	Yes	28	0.89	0.31	25	0.80	0.41	20	1.25	0.44

[a] Nest guarding was only implemented once a breeding attempt had been initiated.

4 (11.4%) from direct persecution, and 3 (8.6%) from collision or electrocution with electricity infrastructure. For 357 territory monitoring years we had observation records to estimate detection probability and assess the influence of management activities on adult survival probability during the breeding season. There was no support for any of the management variables to have significantly influenced seasonal survival probability, and the most likely model included no effects of management (Table 3). This model estimated the survival probability of territorial adults over the 23-week breeding season as 0.936 (0.889–0.968), and weekly survival probability as 0.997 (0.995–0.999). The average detection probability across all sites and occasions was 0.637 (0.632–0.642).

4. Discussion

This study provides evidence that management actions that have benefitted other raptor populations elsewhere did not lead to marked increases of productivity and seasonal survival probability of adult Egyptian Vultures in Bulgaria and Greece. Despite observed individual successes, such as the prevention of fatal nest disturbances or the rescue of fallen chicks, the population-level effectiveness of the adopted management activities was likely insufficient because monitoring data show an ongoing population decline of the Egyptian Vulture that is of similar magnitude in countries with intensive (Bulgaria, Greece) and with minimal (the FYR of Macedonia) management (Velevski et al., 2015). While some of the threats for this population may operate outside the breeding season during migration and on wintering grounds in Africa (Angelov et al., 2013; Arkumarev et al., 2014; Oppel et al., 2015), alternative and more efficient design of management needs to be found during the breeding season to slow the decline of Egyptian Vultures on the Balkan Peninsula.

Management that affects survival will have a proportionally stronger effect on population trends than management that affects only productivity in long-lived species like large raptors (García-Ripollés and López-López, 2011; Soutullo et al., 2008; Velevski et al., 2014). Supplementary feeding has been projected to facilitate a reversal of negative population trends, but these projections were based on the assumption that adult and juvenile survival would be increased by 10–30% (García-Ripollés and López-López, 2011). Such an increase in survival probability has been found for Egyptian Vultures after the establishment of central feeding stations in France (Lieury et al., 2015). Our study did not find a significant beneficial effect of current conservation management on seasonal adult survival, and the current implementation of supplementary feeding may not lead to a stabilisation of the population (Bretagnolle et al., 2004; Oro et al., 2008; Velevski et al., 2014).

Estimating adult survival from unmarked individuals is challenging, and requires adequate models accounting for imperfect detection and sufficient sample sizes to estimate parameters (Hernández-Matías et al., 2011; Roth and Amrhein, 2010). Our approach extending previous occupancy-based frameworks provided realistic estimates of seasonal survival probability of adult birds: if we assume that weekly survival probability of Egyptian Vultures was constant throughout the year, annual survival probability of breeding adult Egyptian Vultures would be 0.86 (95% CI 0.77–0.93), which is consistent with previous estimates of adult survival in this species derived from mark-recapture analyses (Grande et al., 2009; Lieury et al., 2015). Thus, while our approach succeeded in retrieving plausible estimates of adult survival probability from territory monitoring of unmarked birds, it may not have been

Table 2
Model selection table evaluating the effect of conservation management on three processes of productivity (breeding propensity, breeding success and fledging rate) of Egyptian Vultures in the Balkans between 2005 and 2015. See text for description of models. k = number of estimable parameters, AIC_c = Akaike's information criterion, ΔAIC_c = difference in AIC_c units to the most parsimonious model, ωAIC_c = relative weight of evidence for each model.

Productivity component	Model	k	AIC_c	ΔAIC_c	ωAIC_c	Deviance
Breeding propensity	No management	3	327.59	0.00	0.38	321.54
	Central feeding station	4	328.29	0.69	0.27	320.20
	Feeding	4	328.75	1.15	0.21	320.66
	Feeding + central feeding station	5	329.56	1.96	0.14	319.43
Breeding success	No management	3	391.77	0.00	0.38	385.71
	Guarding	4	392.64	0.87	0.25	384.54
	Central feeding station	4	393.81	2.04	0.14	385.71
	Guarding + feeding	5	394.42	2.64	0.10	384.27
	Guarding + central feeding station	5	394.69	2.91	0.09	384.54
	Guarding + feeding + central feeding station	6	396.48	4.70	0.04	384.27
Fledging rate	No management	3	376.28	0.00	0.38	370.21
	Guarding	4	377.51	1.22	0.20	369.38
	Central feeding station	4	377.55	1.26	0.20	369.42
	Guarding + central feeding station	5	378.78	2.50	0.11	368.60
	Guarding + feeding	5	379.52	3.24	0.07	369.34
	Guarding + feeding + central feeding station	6	380.79	4.50	0.04	368.53

Table 3
Posterior model probabilities derived from a Gibbs variable selection approach of candidate models evaluating the effect of conservation management on the probability of survival of adult Egyptian Vultures in a territory during the breeding season in Bulgaria and Greece between 2005 and 2015. Each model included parameters to adjust for varying detection probability among birds and with observation effort; see text for description of models.

Model	Model probability	Mean parameter estimate	95% credible interval	
No management	0.935			
Central feeding station	0.031	−0.30	−2.45	1.85
Guarding	0.022	0.46	−0.24	1.15
Feeding	0.011	−0.09	−0.88	0.70
Guarding + central feeding station	0.001			
Guarding + feeding	0.000			
Guarding + feeding + central feeding station	0.000			

sufficiently powerful to estimate the effects of management if these effects are relatively small. However, given the declining population size and the relative rarity of adult mortality events, it is unlikely that additional monitoring and data collection or extensive ringing programmes could lead to much more powerful inference.

While intensive mark-recapture programmes will likely lead to more precise estimates of survival probability, untangling the effects of age, sex, experience and estimating the effects of management will likely always be challenging in small populations where the available sample sizes would render multiple parameters non-identifiable (Bailey et al., 2010). A potential solution to increase the confidence in demographic parameter estimates would be to incorporate multiple sources of information in an integrated population model (Abadi et al., 2010; Besbeas et al., 2005; Schaub et al., 2007). The formulation of our survival model in a Bayesian framework facilitates the easy incorporation of this model into existing integrated population models for raptors (Altwegg et al., 2014; Demerdzhiev et al., 2015; Lieury et al., 2015), which might increase the precision of parameter estimates and might allow the estimation of parameters for which few field data exist.

4.1. Possible reasons why management appeared to be ineffective

Egyptian Vultures require annual adult survival of ~90% or higher to maintain stable populations (García-Ripollés and López-López, 2011; Velevski et al., 2014). We estimated adult survival probability during the breeding season, which may be higher than survival during migration (Klaassen et al., 2014; Oppel et al., 2015), and the annual adult survival on the Balkan Peninsula is therefore likely too low, which may explain ongoing population declines despite management (Velevski et al., 2015). Incidental mortality of even a small number of adult birds can have severe effects on small populations of long-lived species (Carrete et al., 2009). We witnessed numerous incidents of adult mortality during the breeding season that were mostly caused by poisoning, which is illegal in all three countries. The use of poison is a complex response to human–wildlife and human–human conflicts: livestock breeders and hunters use poison to reduce loss of livestock or game animals to natural predators and feral dogs, hunters use poison to prevent or avenge the loss of skilled hunting dogs to more powerful shepherd dogs, and shepherds use poison to kill hunting dogs (Skartsi et al., 2014). Similar illegal poisoning has been shown to limit population recovery of other raptors (Margalida et al., 2014b; Smart et al., 2010), and is considered a serious threat that has caused major population declines of avian scavengers worldwide (Margalida, 2012; Margalida et al., 2013; Mateo-Tomás et al., 2012; Ogada et al., in press). In the Balkans, most current conservation management is conducted by non-governmental organisations which do not have the authority to enforce existing legislation that prohibits the use of poison to kill wild animals. Because these non-governmental organisations do not have the authority to enforce the law, they can only implement 'band-aid' solutions like supplementary feeding that do not remove the actual source of the problem. The risk to consume poisoned bait in the landscape may not be amalgamated by supplementary feeding (similar to other diversionary feeding applications, Kubasiewicz et al., 2016), and we therefore encourage the authorities in the Balkans to take appropriate action and reduce the illegal but widespread use of poison baits in rural landscapes to increase the survival probability of Egyptian Vultures (Margalida et al., 2013; Skartsi et al., 2014).

Besides the lack of a positive effect of management on survival, our results are also inconsistent with the hypothesis that feeding and guarding increases the key components of productivity. Raptor management can have mixed success; for example, various measures to prevent disturbance or to increase breeding success were unsuccessful in Spanish Imperial Eagles (*Aquila adalberti*), and supplementary feeding during the chick rearing period did not increase breeding success of Bearded Vultures (*Gypaetus barbatus*) (Ferrer and Hiraldo, 1991; Margalida, 2010). However, preventing human disturbance was found to be important for Egyptian Vultures in Spain and Italy (Liberatori and Penteriani, 2001; Zuberogoitia et al., 2014), yet nest guarding did not lead to an increase in productivity in the Balkans. One possible reason for this discrepancy is that some of the nests that were selected for nest guarding were considered highly 'valuable': territories with consistently high productivity (e.g. in Northern Bulgaria) but exposed to the risk of poaching and persecution. Because these nests had high productivity, it was unlikely that management would increase productivity, and the fact that productivity did not decrease in those areas could be considered a success of the nest guarding. In addition, nest guarding provides useful opportunities to engage with local stakeholders, increase awareness of conservation problems, include local communities in conservation and create a positive attitude towards the species. The rescue of some chicks, combined with the positive effect on public attitude, may therefore lead to larger benefits than is suggested by our analysis of reproductive parameters.

Feeding stations have been very successful to increase productivity in Spain (Cortés-Avizanda et al., 2010; López-López et al., 2014; Margalida et al., 2010), but central feeding stations in southern France led to a 26% reduction of the number of fledglings produced per pair (Lieury et al., 2015). We found some evidence for a positive effect of central feeding stations on breeding propensity, but no negative or strong positive effect of either individual supplementary feeding in territories or of central feeding stations on other components of productivity. While the central feeding stations in Bulgaria, Greece and the FYR of Macedonia may differ from similar feeding stations in other countries by their distance to Egyptian Vulture nests, accessibility, or frequency and type of supplementation, one possible reason for the lack of a positive effect is that food availability may not have been limiting (Margalida, 2010): Egyptian Vultures have an extremely broad and opportunistic diet, and we found no changes in diet composition over the past 10 years and no relationship between dietary diversity and productivity, indicating that dietary constraints may not be the most important threat to Egyptian Vultures (Dobrev et al., in press). Further support for this interpretation comes from the fact that several pairs that were individually fed did not consume any of the provided food, and we suggest that altering the type and the timing of supplementary food based on individual pairs' preferences might increase uptake (Cortés-Avizanda et al., 2010). Besides the potential increase in breeding propensity, central feeding stations may provide other beneficial effects that we could not quantify in our analysis. For example, supplementary feeding might increase the body condition of nestlings and increase juvenile survival (Lieury et al., 2015; Margalida et al., 2014b; Oro et al., 2008). In addition, feeding stations provide a great opportunity to watch vultures, can have a positive effect on rural economies by attracting tourists and increase awareness of avian scavengers, and such feeding stations therefore remain an important conservation tool.

4.2. Additional options to slow the decline of Egyptian Vultures in the Balkans

Many threats are known to influence the declining population of Egyptian Vultures, but the relative importance of these threats is still unclear and multiple conservation measures may have to be implemented simultaneously at large scales to halt and reverse population declines (Sanz-Aguilar et al., 2015; Velevski et al., 2015). Here we focus only on breeding grounds, where the loss of adult birds due to illegal poisoning is a threat that could potentially explain the observed population declines due to the strong influence of adult survival probability on population dynamics (García-Ripollés and López-López, 2011; Smart et al., 2010; Velevski et al., 2014). Because the current management might not have sufficiently increased adult survival probability in our study, we recommend three additional actions to address the problem of illegal poisoning in the short and medium term: (1) Firmer law enforcement has been found to be an effective strategy in other raptor populations (Smart et al., 2010), and we urge governments to take action on enforcing regulations that prohibit the use of poison baits and regulate the use of other hazardous substances (e.g. pharmaceuticals, pesticides) to reduce the continued harm to vultures and other wildlife on the Balkan Peninsula (Margalida et al., 2013, 2014a); (2) Until law enforcement takes effect, canine poison detection units can be used to detect and eliminate poison baits and carcasses containing toxic substances. Such units have been in operation since 2014 in Greece and managed to remove around 10 kg of poison baits and 65 dead animals laced with cyanide, phorate, endosulfan, carbofuran and methomyl (Kret et al., 2015); (3) In the medium term, the ultimate causes that lead to illegal poisoning should be addressed and removed. For instance, developing effective strategies to help farmers and hunters to prevent or cope with losses of animals might reduce their incentive to use poison baits and thereby reduce the risk for vultures and other wildlife. Poisoning is a complex response to economic and societal tensions, and vultures are unfortunate collateral damage in this conflict (Skartsi et al., 2014). The approaches needed to address the poisoning problem will require substantial financial and logistical commitment from governments which cannot be provided by charitable conservation organisations, and all approaches must be accompanied by robust research to estimate survival probabilities both during the breeding season but also throughout the remainder of the year.

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Appendix A. Supplementary data

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