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Research Article

Developing best management practices for the invasive monk parakeet (*Myiopsitta monachus*) in urban environments

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Abstract

Managing invasive species has become a major environmental challenge due to their global ecological and socioeconomic impacts. Prioritising effective strategies is essential, especially given the often limited funding. Data from real control programmes are crucial for developing long-term management plans. Between May 2021 and April 2023, the City of Madrid implemented a control plan to reduce its monk parakeet (*Myiopsitta monachus*) population. This study assessed: (1) the plan's efficacy, (2) the impact of removing different age classes on population viability, (3) the capture efficacy and cost-efficiency of various capture methods, (4) the optimal combination of capture methods and (5) the effectiveness of different baits in attracting parakeets. The plan eliminated approximately 87% of the juvenile and adult population present at the plan's onset, reducing total population projections for 2023 and 2031 by 50%. Projections indicated that maintaining the second-year removal intensity for three additional years could have nearly eradicated the species. Removing juveniles and adults proved more than twice as effective at curbing population growth as targeting eggs and nestlings, leading to prioritising juvenile and adult removal year-round. Of the five methods used – shooting, folding net, hand-held net launcher, egg culling and nestling culling – shooting was the most effective in reducing population growth both in and outside spring. Optimisation models suggested prioritising shooting and the combination of folding net and net launcher in spring and exclusively the latter outside spring. We recommend using the shooting method year-round, complemented by the combined use of the folding net and net launcher outside of the spring season. Bread and a mixture of bread, apple and parrot feed were the most effective and cost-efficient baits attracting parakeets, with bread recommended for simplicity. This study enhances understanding of parrot management strategies, offering insights for more effective and cost-efficient control of invasive monk parakeet populations.

Key words: Alien species, bird capture methods, bird control, egg culling, exotic species, feeding preferences, nestling culling, parrots

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Introduction

Biological invasions by Invasive Alien Species (IAS) are considered a major environmental issue due to their significant ecological (Wilcove et al. 1998; Levine et al. 2003) and socioeconomic impacts worldwide (Eiswerth and Johnson 2002; Pimentel et al. 2005; Diagne et al. 2021; Haubrock et al. 2021; IPBES 2023). In the 20^{th} and 21^{st} centuries, the spread of IAS has reached unprecedented levels, facilitated by increasing long-distance trade (Meyerson and Mooney 2007). Although not all introduced alien species become invasive, the rates of invasions are growing and expected to continue accelerating in the coming decades (Seebens et al. 2017, 2021). Consequently, the impacts of IAS are magnified, making their management a major global challenge.

The management of IAS involves a wide range of actions in environmental policy and practice, including preventing introductions, containing or eradicating new spreads and mitigating the impacts of established populations (Simberloff et al. 2013). These actions are essential for biodiversity conservation and protecting economic interests, ecosystem services and human health (Crowley et al. 2017). However, given the high costs of IAS management and often limited funds (Tempel et al. 2004), it is critical to prioritise effective management strategies in IAS control plans. Unfortunately, the results and lessons learned from IAS control programmes are often poorly reported, residing mainly within grey literature and lacking solid statistical analysis to support the conclusions (Martins et al. 2006; Brooke et al. 2007; Holmes et al. 2015; Iacona et al. 2018; Avery and Feare 2020). The lack of adequate evaluation of what works and what does not can prevent managers from effectively implementing control and eradication measures. Moreover, failing to check whether management works weakens the arguments for further investment (Sutherland et al. 2004). Therefore, obtaining data from real control programmes is essential for developing more adaptive and effective long-term management strategies.

Amongst vertebrates, the monk parakeet *Myiopsitta monachus* is one of the most widely distributed and successful IAS worldwide (Calzada Preston and Pruett-Jones 2021). From the 1970s onward, the popularity of this parrot as a pet increased greatly, with millions of individuals captured and exported from South America (its native habitat) to North America and Western Europe (Domènech et al. 2003; Strubbe and Matthysen 2009; Postigo et al. 2017; Souviron-Priego et al. 2018). Deliberate releases and accidental escapes have led to the rapid spread and establishment of increasingly large breeding populations of this species, particularly in urban environments (Da Silva et al. 2010). The monk parakeet has established populations in 26 countries (Calzada Preston et al. 2021), with the highest rates of population growth observed in the USA (Van Bael and Pruett-Jones 1996; Burgio et al. 2016), Mexico (Hobson et al. 2017), Israel (Postigo et al. 2017) and across the United Kingdom, Greece, Italy and Spain (Postigo et al. 2019). Spain currently hosts the largest invasive population of monk parakeets in Europe, estimated at up to 21,000 individuals as of 2015, with 40% residing in Madrid (Molina et al. 2016). In 2013, Spanish legislation classified the monk parakeet as an IAS, which prompted the initiation of prevention measures and the development of strategic management plans, with local and regional governments tasked with implementation.

Between May 2021 to April 2023, the City of Madrid implemented a management plan aimed at reducing its monk parakeet population, acknowledging that complete eradication was unattainable and that a small residual population would likely persist. To carry out this initiative, the Madrid City Council contracted "Mantenimiento de Infraestructuras S.A.U." (hereafter, MATINSA), which employed five common bird control methods to capture parakeets: shooting, folding nets, hand-held net launchers, egg culling and nestling culling. The capture efficacy and cost-efficiency of these capture methods were evaluated through a collaborative study between Universidad Rey Juan Carlos and MATINSA. The specific objectives of the study were to: (1) assess the impact of the management plan on the population viability of the monk parakeet; (2) examine whether the removal of individuals from different age classes has differential effects on population viability; (3) identify the most effective capture method (i.e. highest capture rate per hour) and the most cost-efficient one (i.e. lowest cost per parakeet captured), while considering seasonal variation; (4) determine the combination of control methods that maximise effectiveness and cost-efficiency; and (5) determine which bait type attracts the highest number of parakeets per hour and offers the best cost-efficiency (i.e. lowest cost per parakeet attracted). This study aims to enhance understanding of the effectiveness of current management tools to facilitate more effective and cost-efficient management of this species in the future.

Methods

Study species

The monk parakeet (*Myiopsitta monachus*) belongs to the order Psittaciformes (commonly known as parrots) and is native to temperate and subtropical South America. Monk parakeets are unique amongst Psittaciformes for building nests rather than nesting in cavities. They often build communal nests, where multiple pairs collaborate in constructing and using the nest year-round for roosting and breeding (Bucher et al. 1991). They can live up to 15 years, though this lifespan applies to captive birds (Burgio et al. 2020). In the wild, their lifespan is estimated to be around 13 years (Senar et al. 2021). Reproductive efficiency of monk parakeets in their invasive range is higher than in their native range: in the invasive range, 55% of first-year parakeets breed compared with almost zero in South America (Bucher et al. 1991; Martín and Bucher 1993; Senar et al. 2019). Fledging success during the first brood is double in the invasive range (3.3 ± 1.08 vs. 1.6 ± 0.53) (Navarro et al. 1992; Peris and Aramburú 1995; Senar et al. 2019) and the percentage of pairs attempting second broods is three times higher compared to the native range (56 ± 9.93% vs. 15%) (Navarro et al. 1992; Senar et al. 2019). Invasive monk parakeet populations exhibit exponential growth rates, with populations in Mediterranean countries experiencing higher exponential growth, greater spread rates and more rapid colonisation than those in the Atlantic Region (Postigo et al. 2019). Population growth rate estimations in Spain ranges from 0.15 to 0.31 depending on the area studied and the year, with a population doubling time of 4.8 to 2.3 years (Muñoz 2003; Molina et al. 2016; Postigo and Senar 2017; Postigo et al. 2019; Senar et al. 2021).

Various negative impacts of the monk parakeet have been reported throughout both its invasive and native range, including damage to crops (Batllori and Nos 1985; Tillman et al. 2000; Conroy and Senar 2009; Senar et al. 2016; Muñoz-Jiménez and Alcántara-Carbajal 2017; Battisti 2019; Battisti and Fanelli 2022; Castro et al. 2022) and vegetation (Shields et al. 1974; Batllori and Nos 1985; Menchetti and Mori 2014), risk of nest fall (Esteban 2016), interspecific aggression (Batllori and Nos 1985; Weiserbs and Jacob 1999; García and Bonfil 2007; Dangoisse 2009; Briceño et al. 2019), spreading of exotic plants (Blanco et al. 2015, 2016, 2018; Tella et al. 2015; Hernández-Brito et al. 2021a), facilitation of the establishment of introduced and invasive birds (Briceño et al. 2019; Hernández-Brito et al. 2021b, 2022) and the introduction and spread of parasites and pathogens (Aramburú et al. 2003; Mori et al. 2015, 2018, 2019; Briceño et al. 2017, 2023; Ancillotto et al. 2018; Martínez-de la Puente et al. 2020; Morinha et al. 2020; Sandoval-Rodríguez et al. 2021; Blanco-González et al. 2024).

Study area

The City of Madrid covers an area of 604 km^2 and is home to 3,332,000 inhabitants, with a population density of 5,300 inhabitants/km^2. The city has an average altitude of 657 metres and a continental Mediterranean climate, characterised by mild, wet winters and warm, dry summers. Madrid boasts approximately 6,400 hectares of publicly-owned municipal green areas and an estimated total of 16,700 cedars (Morcillo San Juan 2015), including both Himalayan cedars (*Cedrus deodora* Roxb. ex D.Don) and Atlas cedars (*Cedrus atlantica* Endl.). These trees are the most favoured by monk parakeets for nest construction in Madrid (Martín-Pajares 2006; Molina et al. 2016). Most parakeet capture efforts were conducted on public land, except for shooting, which was primarily carried out on private land due to regulatory restrictions and where conditions allowed. Nest removals were also performed, mainly on public land, but occasionally on private property when there was an imminent risk of nest collapse.

Censused population of the monk parakeet in Madrid

At the outset of the management plan, the most recent census of monk parakeets in Madrid, conducted in 2019, estimated a population of 11,156–12,967 reproductive individuals distributed across 4,418 nests and 9,402 chambers (Nebreda et al. 2019). This indicated a population doubling time of approximately 4.4 years compared to the 2015 census, which recorded 6,291–7,113 individuals, 2,198 nests and 4,945 chambers (Molina et al. 2016). Both censuses used consistent methodology, counting nests and chambers and estimating occupancy rates based on the average number of resident individuals per chamber, with data collected from the ground using binoculars. These surveys were conducted at the same time of year, largely by volunteers.

Based on the 4.4-year doubling time, the monk parakeet population in Madrid at the start of the control plan in spring 2021 was estimated at 15,360 –17,855. This closely aligns with MATINSA's estimate of 15,177 – 17,580 individuals across 4,667 nests and 12,645 chambers at the plan's outset (MATINSA unpublished data) (Fig. 1A). MATINSA retrospectively calculated these figures in August 2022, following the removal of 2,040 nests and a total count of 5,538 chambers. MATINSA's calculated chamber-to-nest ratio was 2.71, compared to 2.13 from the 2019 census (Nebreda et al. 2019). An advantage of MATINSA's census was its direct chamber counts at the nests using aerial platforms, likely providing a more accurate estimate than previous ground-level surveys (Molina et al. 2016; Nebreda et al. 2019). However, MATINSA did not independently estimate the average occupancy per chamber, instead applying the occupancy rate from Nebreda et al. (2019), which ranged from 1.2 to 1.39 individuals per chamber.

It is important to highlight that a post-control census was not conducted at the conclusion of the management plan. As a result, the population size at the end of the management plan was estimated using demographic projections.

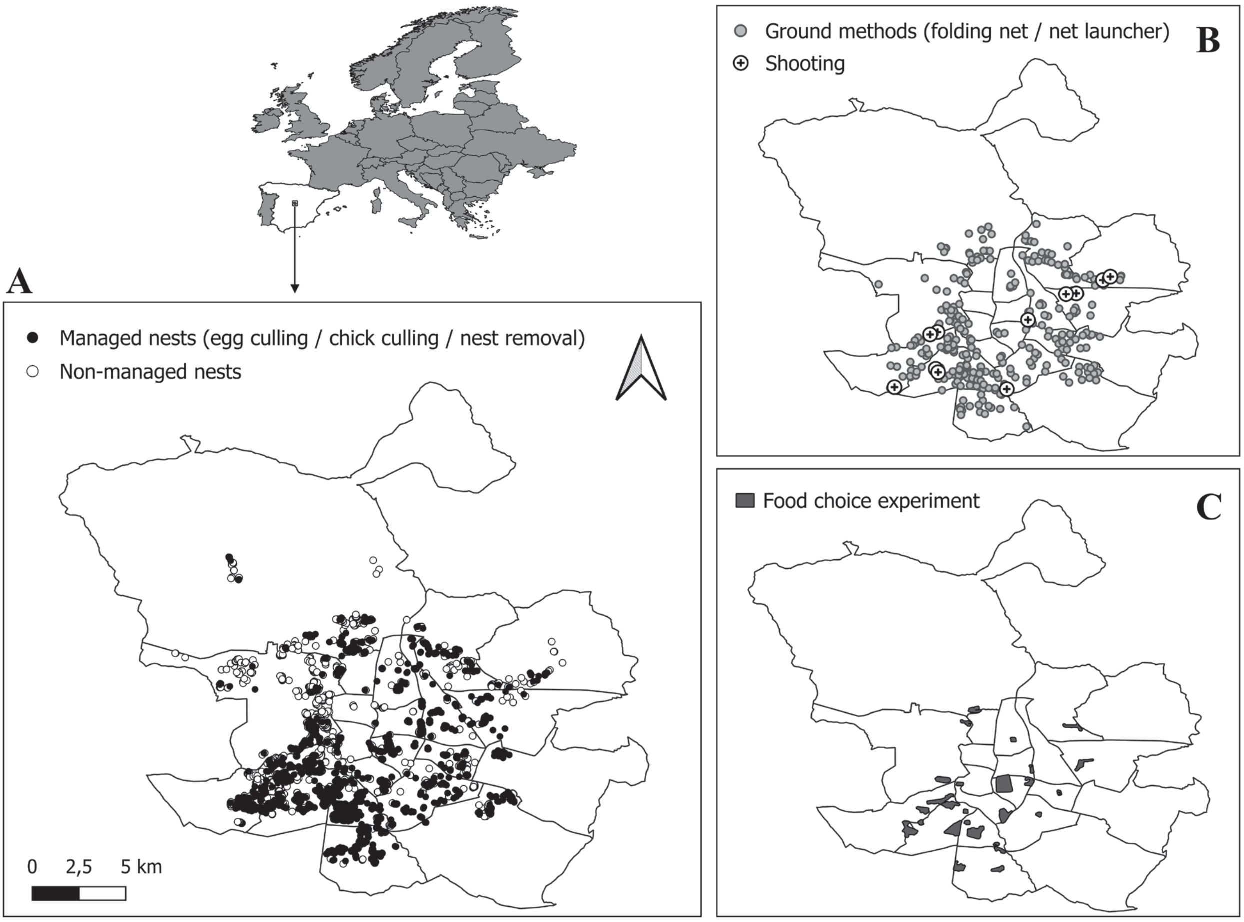

Figure 1. Map showing the location of the City of Madrid in Spain. **A** Ahows the location of the monk parakeet nests surveyed by MATINSA, distinguishing between nests managed during the control plan and those that were not managed **B** shows the sites where captures were made using ground methods and shooting **C** shows the parks where the food choice experiment was conducted.

Capture methods and lethal control

Captures were performed by 10 capture teams, each typically composed of two individuals, working Monday to Friday from 7:00 to 15:00 h. Different capture methods were employed, categorised into three main groups: shooting (aimed at birds perched on high branches, never on the ground), ground methods (conducted at ground level using net capture techniques) and aerial methods (accessing the nests using an aerial work platform). Below, we provided detailed information on each capture method:

Shooting: Skilled shooters employed pre-charged pneumatics (PCP) air rifles (5.5 mm diameter) equipped with telescopic scopes. The rifles fired a single round-tipped projectile per shot aimed to eliminate the targeted individual. The rifle's usage was confined to specific parks with restricted access and to private areas (Fig. 1B).

Ground methods: 1) Folding nets: Nets were discreetly installed at ground level to avoid detection by parakeets. Parakeets were attracted by bait placed on the net. Upon landing, the net was remotely activated, effectively immobilising the parakeets on the ground. Successful execution of this method required both the rotation of capture sites and pre-baiting the area for several days (on average 8.0 days ± 2.5), allowing the parakeets to become familiar with the location and thereby enhancing the potential for capturing multiple birds in each operation; 2) Hand-held net launcher (hereafter, “net launcher”): This portable CO_2-powered net launcher features a net size of 1 m × 1 m and was capable of capturing a few individuals at most (average: 1.5; range: 1–6), but its discretion and quick setup allowed for multiple attempts per day (Fig. 1B).

Aerial methods: 1) Egg culling: Since nest removals were also performed as part of the control plan, eggs were removed when the nests were being taken down. In cases where the nests were not being taken down, the eggs were pricked to interrupt the asepsis inside and to fatally damage the embryos (Smith et al. 1999). This strategy seeks to deceive the parents into maintaining incubation, thereby preventing them from laying replacement eggs; 2) Nestling culling: Parakeet nestlings were removed regardless of whether the nest was meant for removal or not. Since there were few days when only nestlings were culled, this method has been analysed in conjunction with egg culling, as it was common to combine both egg and nestling culling on the same day (Fig. 1A).

All parakeets captured alive, either by ground or aerial methods, were transported to an authorised veterinary clinic for lethal control. Birds were individually euthanised by a veterinarian on the same day of capture. At the time of euthanisation, birds were under anaesthesia (Isoflurane 100%; 2 l/min-5%). An injection of 2 ml of pentobarbital sodium (200 mg/ml) was administered at the base of the neck between the insertion of the pectoralis and supracoracoideus muscles. Verification of the cessation of respiratory signs and the disappearance of reflexes confirmed successful euthanasia. In accordance with the law, the carcasses of all parakeets (both captured-euthanised and shot) were cremated.

Notably, the capture of monk parakeets faced public opposition at various stages, particularly in the initial phases. However, these events did not significantly disrupt the management plan (Appendix 1).

Food choice experiment

The success of capturing monk parakeets with nets improves when baits are used to attract them to the ground. During the management plan for the monk parakeet in Madrid, four different baits were used interchangeably: stale bread (hereafter, “bread”), apple, commercial parrot feed (Pilesan® brand; hereafter, “parrot feed”) and a mixture of all these foods (hereafter, “mixture”). To determine which type of bait attracts the most parakeets to the ground, we conducted a food choice experiment in 27 parks in Madrid City where parakeets were present (Fig. 1C). In three parks, we performed the experiment twice, separated in time by a minimum of 12 days to prevent learning by parakeets, adding a total of 120 observations (n = 30 replicates × 4 baits per replicate).

The experiment was conducted from late January to mid-March 2023, between 7:00 and 10:00 h. In each park, a 1 m x 1 m area was selected to place the baits on the ground (hereafter, “feeder”), ensuring that all feeders were similar in terms of spatial structure (e.g. presence of trees and paths). Each feeder contained a single type of bait (bread/apple/parrot feed/mixture). The food in each feeder was spread out evenly to facilitate parakeet detection, with larger portions of bread and apple used to deter parakeets from carrying them away. Each feeder was supplied with one kilogram of food (the mixture bait contained approximately 0.3 kg of bread, 0.3 kg of apple and 0.3 kg of parrot feed). Baits were not replenished during the experiment. Each feeder was placed approximately 20 m from the observers, with an angle of 45° between adjacent feeders, forming a cross (Appendix 2). The relative positioning of the feeders was randomised daily. Observations were made by two observers stationed at the centre of the cross, starting from the arrival of the first parakeet at any of the four feeders. From that moment onwards, each observer recorded the number of parakeets entering two adjacent feeders at 5-minute intervals over a two-hour period. Every 5 minutes, observers would alternate between their feeders to avoid biases. Each parakeet entering the feeder was counted, regardless of whether it had previously visited that feeder or not. After the experiment concluded, any remaining food was saved for reuse or properly disposed of.

Data analyses

To assess the impact of the management plan and the removal of individuals from different age classes on the population viability of the monk parakeet, we conducted demographic projections incorporating both demographic and environmental stochasticity using the “Rramas” package (De la Cruz Rot 2019). We defined ten age classes: nestling, first-year juvenile and eight adult classes ranging from second-year birds to individuals over eight years old. Mean reproduction and survival parameters, along with standard deviations for each age class, were obtained from Senar et al. (2019, 2021) to construct two transition matrices: one with average values and another incorporating standard deviations to account for environmental stochasticity (Appendix 3). The egg stage was excluded from the model, as age transitions were equated to calendar years, omitting intra-annual transitions such as the shift from egg to nestling. Consequently, the nestling age class included both eggs and recently-hatched chicks.

Using these parameters, we evaluated the impact of MATINSA’s management plan on population viability (Objective 1) by estimating the effect on population size following the removal of individuals during the first and second years of the control plan (12 months each). These results were compared against two scenarios: (1) no management actions and (2) a continuation of management beyond the two years of the actual plan, assuming the removal of individuals at the same rate as in the second year until virtual eradication was achieved.

All projections were modelled over a 10-year timeframe. The baseline scenario (no management) was compared with the results obtained from the demographic analysis of Senar et al. (2021) to validate the accuracy of the population modelling.

To assess whether the removal of individuals from different age classes had differential effects on population viability (Objective 2), we estimated the impact of annually removing a fixed number of either eggs and nestlings or juveniles and adults on the annual population growth rate over a 10-year period. Population growth rate was calculated as:

$$\text{Population growth rate}(\%) = \left(\left(\frac{N_{t10}}{N_{t0}} \right)^{\frac{1}{t_{10}}} - 1 \right) \times 100$$

where N_{t10} is the population size at the end of the 10-year period, N_{t0} is the initial population size at the beginning of the study and t_{10} represents the duration of the period in years (10 years in this case).

The “Rramas” package used for Objectives 1–2 allowed for the direct inclusion of the number of eggs, juveniles and adults removed annually.

We then analysed whether capture methods differed in terms of: (1) capture efficacy, measured as the number of parakeets captured per hour (referred to as "birds/h"); and (2) cost-efficiency, measured as the cost per parakeet captured (referred to as "€/bird") (Objective 3). We assessed these measures during two different seasons: the "spring" (21 March – 21 June) and the "non-spring" period (rest of the year; 22 June – 20 March). This division reflects the primary nesting season occurring during spring, allowing us to evaluate method performance both within and outside of this period. This division also provides an intuitive calendar for the implementation of control methods in future management plans.

For hourly parameterisation, we defined a standard working day as 8 hours. Typically, each team consisted of two individuals, though sometimes they could be formed by only one person. Therefore, we set the working days for two-person teams at 16 hours and for one-person teams at 8 hours. On certain days, capture techniques were combined with non-capture activities, such as nest removal and baiting of feeders. Consequently, we also included the time invested on these extra activities when calculating the total time needed for each capture method. Additionally, we computed costs associated with personnel, vehicle rental and petrol, incineration of corpses and material used for capture activities and at the veterinary clinic. Detailed explanations of these calculations can be found in Appendix 5.

For Objective 3, we compared the capture methods (shooting, folding net, net launcher, egg culling, nestling culling) including two combinations of methods frequently used: the combination of folding net and net launcher and the combination of egg and nestling culling.

To test whether the capture method and the season influenced capture efficacy, we fitted a generalised linear mixed model (GLMM) with a negative binomial error distribution (nbinom1) and a logarithmic link function. The response variable was the number of captured parakeets. We included the interaction between method and season as fixed factors and team as a random factor. The capture effort, measured as the number of hours dedicated to a specific capture method, was adjusted using the "offset" argument, as the time allocated by different teams to each capture method varied daily.

To test whether the capture method and the season influenced cost-efficiency, we fitted a GLMM with a Gaussian error distribution and a logarithmic link function. The response variable was the cost of capturing a single parakeet. We included the interaction between method and season as fixed factors and team as a random factor. In both models, we incorporated a temporal autocorrelation using the Ornstein-Uhlenbeck covariance structure and corrected the heteroscedasticity within factor levels using the "dispformula" argument. However, we were unable to fully correct the heteroscedasticity issue, likely due to lack of orthogonality in the data since the design was not fully crossed (i.e. not all teams conducted all control methods in each season).

To determine the optimal combination of capture methods that maximise effectiveness and cost-efficiency (Objective 4), we utilised the population dynamics and decision-making model developed by Senar et al. (2021). First, we evaluated the individual impact of each control method on population growth rate based on their capture efficacy. For this analysis, all control methods were considered, with an annual effort of 2,000 hours per method, a feasible number of hours as determined by the control plan. Second, we identified the combination of methods and effort levels that maximised population reduction, while minimising associated costs. For computational efficiency, only the three most effective methods were included: shooting, the combination of egg and nestling culling and the combination of folding net and net launcher. The maximum annual effort for each method was capped at 2,000 hours. Analyses were conducted separately for spring and non-spring periods.

To investigate the influence of bait type on the number of attracted parakeets (objective 5), we fitted a GLMM with a negative binomial error distribution (nbinom1) and a logarithmic link function. The response variable was the number of parakeets attracted per hour, with the type of bait as a fixed factor and park as a random factor. To determine the most cost-effective bait (lowest investment per attracted parakeet), we fitted a GLMM with a Gaussian error distribution and a logarithmic link function. The response variable was the cost of attracting a single parakeet, with the type of bait as a fixed factor and park as a random factor. In both models, we incorporated a temporal autocorrelation using the Ornstein-Uhlenbeck covariance structure.

Models for objectives 3 and 5 were fitted using the “glmmTMB” package (Brooks et al. 2017). Model selection followed the recommendations of Zuur et al. (2009), with the suitability of different models evaluated, based on the Akaike Information Criterion (AIC). Models with a difference in AIC > 2 indicated that the worst model had virtually no support and could be omitted. If there were more than one best model (difference in AIC ≤ 2), we selected the simplest model (Wagenmakers and Farrell 2004). Collinearity between predictors was assessed using the “performance” package (Lüdecke et al. 2021) and model assumptions were checked using the “DHARMa” package (Hartig 2022). To test for significant differences amongst the levels of predictor variables (i.e. either capture methods or types of baits), we conducted Tukey’s and Sidaks’s *post-hoc* pairwise comparisons tests from the “emmeans” (Lenth 2024) package. We used Tukey’s test when comparing all pairs of predictors with equal sample sizes and Sidak’s test when comparing specific pairs of predictors with unequal sample sizes. Goodness-of-fit of the models was assessed using Efron’s pseudo-R^2 from the “performance” package. All statistical analyses were performed using R Statistical Software v. 4.2.2 (R Core Team 2022).

Results

Effects of management on population viability

A total of 14,321 adult individuals (including both adults and juveniles, as distinguishing between them was not possible), 2,822 nestlings and 2,062 eggs were eliminated over the two years of the management plan. During the first year, MATINSA culled 1,560 eggs and nestlings and 4,535 juveniles and adults. In the second year, 3,324 eggs and nestlings and 9,786 juveniles and adults were removed (see Table A3 in Appendix 4 for monthly capture numbers).

The population viability analysis projected that, by the end of 2023 and following the two-year management plant, the monk parakeet population would consist of 18,153 individuals, including nestlings, juveniles and adults. In the absence of management, however, the population would have reached 36,138 individuals by 2023, 99% greater than under the management scenario. By 2031, ten years after the plan’s initiation, projections estimated the managed population at 71,636 individuals, compared to 155,534 individuals without intervention, 117% greater

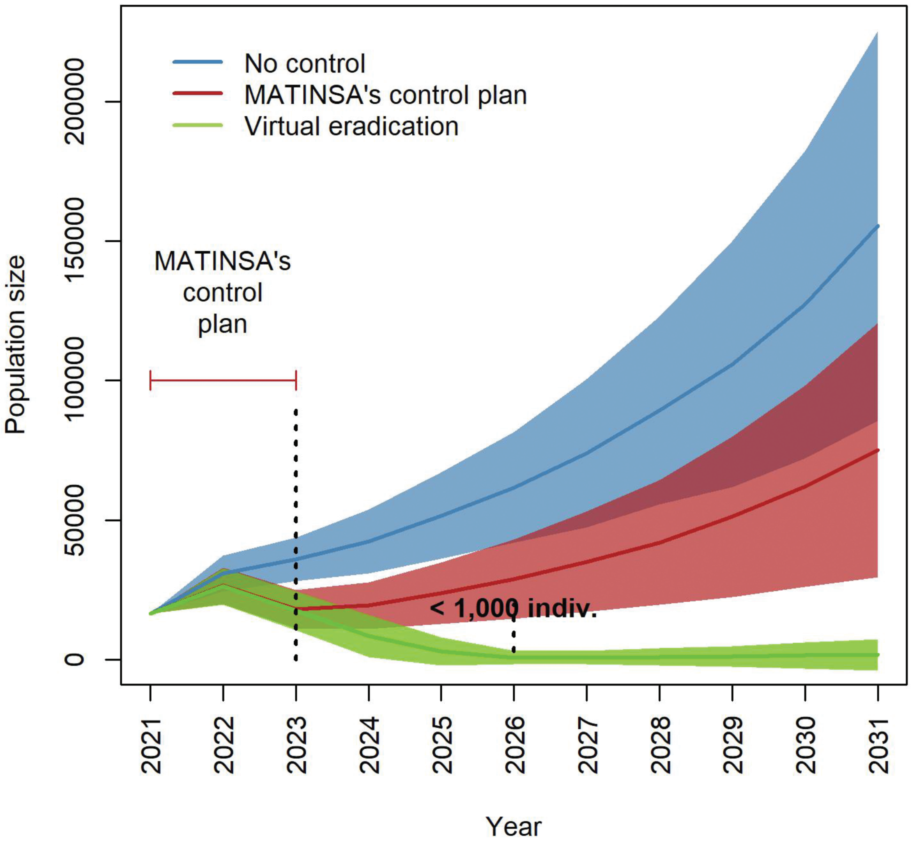

Figure 2. Projected monk parakeet population dynamics in Madrid over a 10-year period. The red line represents the population trajectory under the management plan implemented from 2021 to 2023, while the blue line shows the projected population trajectory without management intervention. The green line depicts a management scenario targeting a reduction of the adult population to fewer than 1,000 individuals. Shaded areas represent the (demographic and environmental) uncertainty range around each projection. The dashed vertical line marks the population size at the end of the management plan. Population size is measured as the combined total of nestlings, juveniles and adults. Models do not assume a carrying capacity, which would otherwise result in predictions reaching an asymptote as the population growths.

than under the management scenario (Fig. 2). The growth rate (r) between 2023 and 2031 was estimated as 0.16 for the managed scenario and 0.25 for the unmanaged scenario, corresponding to population doubling times of 4.33 and 2.77 years, respectively. To reduce the adult population to fewer than 1,000 individuals, an additional three years of management would have been required, assuming the removal rates achieved in the second year were sustained annually. This reduction would likely have been accomplished by 2026.

Examining the hypothetical impact of management strategies, based on age class, our models indicated that removing 1,000 eggs and nestlings annually over a 10-year period would reduce the annual population growth rate by approximately 2.1%, compared to the scenario without management. In contrast, removing 1,000 juveniles and adults annually over the same period resulted in a more substantial reduction of 7.4%. To achieve a neutral annual growth rate (0%) over 10 years, the model suggests removing either 4,800 juveniles and adults or 11,000 eggs and nestlings (Fig. 3). Sustained removal of more individuals than the indicated thresholds annually over 10 years would result in a negative growth rate, leading to a gradual population decline.

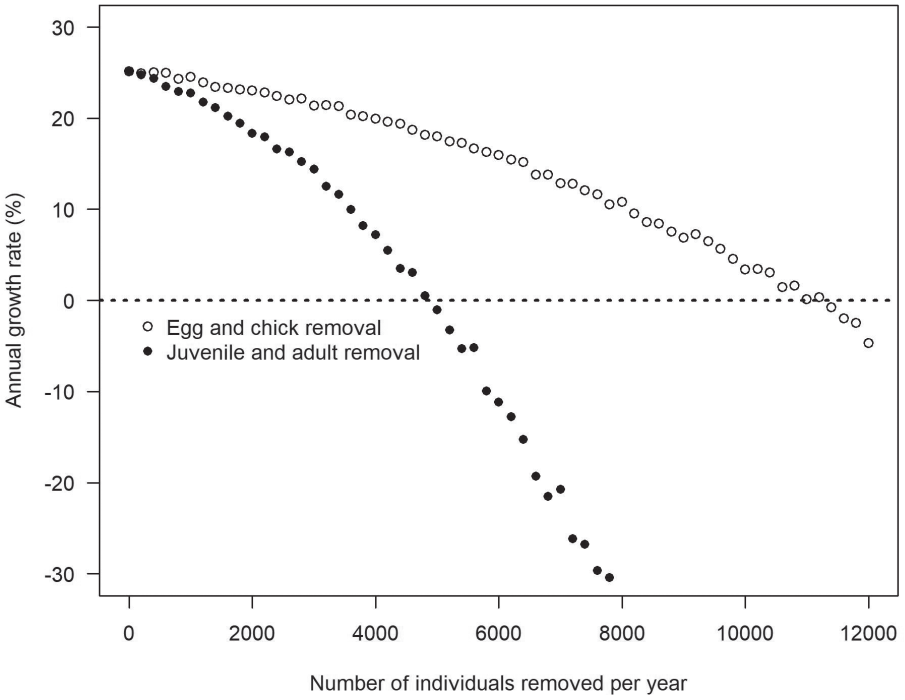

Figure 3. Relationship between the number of individuals removed per year and the annual population growth rate (%) of the monk parakeet after 10 years of simulation. Two management scenarios are compared: egg and nestling removal (open circles) and juvenile and adult removal (closed circles). A positive growth rate indicates population increase, a negative rate indicates decline and a neutral rate (0%) reflects no net change in population size.

Effectiveness and cost-efficiency of capture methods

The different capture methods were implemented a total of 1,859 times over 448 days, with the folding net being the most frequently employed method (n = 882), followed by the combination of egg and nestling culling (n = 365), the combination of folding net and net launcher (n = 301), net launcher on its own (n = 142), shooting (n = 92) and lastly egg culling on its own (n = 77) (Table 1).

The analysis of capture efficacies revealed that the capture method used, the period of the year and the interaction between these two variables significantly influenced capture efficacy (Appendix 6: Table A4). Efron's pseudo-R^2 coefficient for this model was 0.53. Pairwise comparisons using Sidak's test identified differences in the performance of the methods. During spring, the combination of egg and nestling culling was the most effective method, while folding net was the least effective. The rest of the methods performed similarly and lay in between in terms of capture efficacy. Outside of spring, the combination of folding net and net launcher was the most effective method, while folding net and net launcher, when used separately, were the least effective. The rest of the methods were not statistically significant from either the most or the least effective ones (Fig. 4A).

Results from the analysis of cost-efficiencies showed that the capture method used, the period of the year and the interaction between these two variables significantly influenced cost-efficiency (Appendix 6: Table A4). Efron's pseudo-R^2 coefficient for this model was 0.48. As with capture efficacies, there were methods that could not be exclusively assigned to one group. During spring, the combination of egg and nestling culling was the most cost-efficient method, while folding net

Table 1. Capture efficacy (number of parakeets captured per hour), cost-efficiency (cost per parakeet captured) and cost per hour of the capture methods used to manage the monk parakeet population in Madrid between 2021 and 2023. Sample sizes (n), mean values and standard deviation are shown for each capture method.

Season	Capture method	n	Birds/h	Cost/bird (€)	Cost/hour (€)
Spring	Shooting	22	1.4 ± 1.2	137 ± 76	192 ± 196
	Folding net	157	0.3 ± 0.5	212 ± 134	64 ± 113
	Net launcher	50	0.9 ± 0.8	76 ± 63	68 ± 83
	Egg culling	61	1.4 ± 1.6	215 ± 246	301 ± 487
	Folding net + net launcher	26	0.6 ± 0.5	83 ± 64	50 ± 56
	Egg + nestling culling	203	2.4 ± 1.7	134 ± 221	321 ± 577
Non-spring	Shooting	70	2.2 ± 1.5	102 ± 92	224 ± 254
	Folding net	725	1.2 ± 1.4	124 ± 148	149 ± 248
	Net launcher	92	1.2 ± 1.0	52 ± 37	62 ± 68
	Egg culling	16	0.8 ± 0.8	239 ± 233	191 ± 267
	Folding net + net launcher	275	1.7 ± 1.5	57 ± 86	97 ± 169
	Egg + nestling culling	162	2.1 ± 5.1	289 ± 235	607 ± 1554

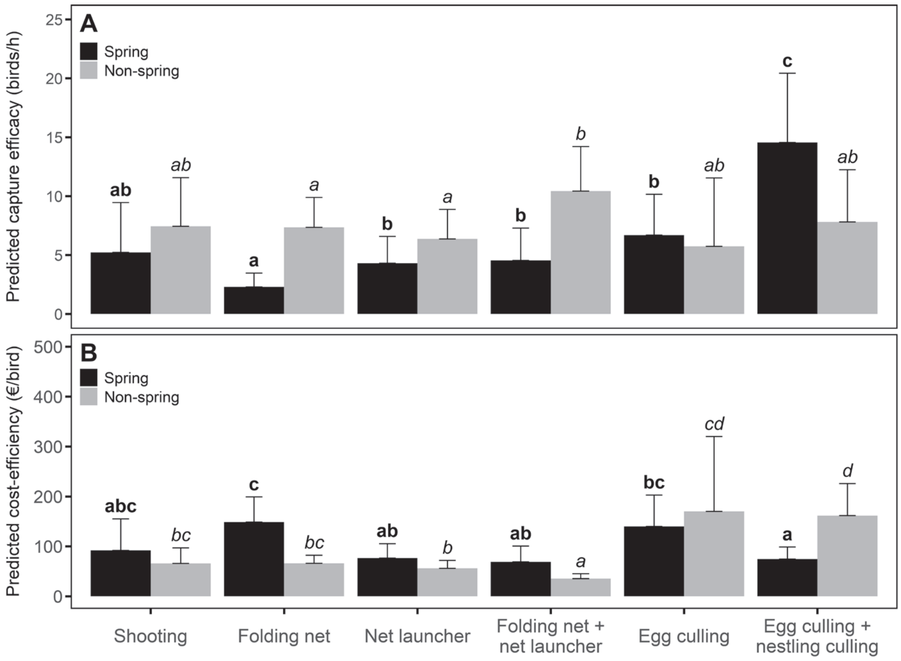

Figure 4. Results of the models for capture efficacies (**A**) and cost-efficiencies (**B**) across different capture methods. Bars represent least-square means, with 95% confidence intervals shown as error bars. Letters above the error bars indicate groups, based on Sidak's *post-hoc* test; bold letters denote spring values and italicised letters denote non-spring values. Methods without shared letters differ significantly, while those sharing at least one letter do not. Note that in panel **A**, higher capture efficacy indicates better performance, whereas in panel **B**, lower cost-efficiency values indicate better performance.

was the least cost-efficient. The remaining methods showed intermediate levels of cost-efficiency. Outside of spring, the combination of folding net and net launcher was the most cost-efficient method, while both aerial methods were the least cost-efficient. The rest of the methods performed similarly and lay in between in terms of cost-efficiency (Fig. 4B).

Table 2. Variation in population increase rate (r), based on different capture methods depending on the season. The model assumes an initial population size of 16,500 birds, an effort of 2000 hours annually and a period of control of 10 years.

Season	Capture method	R	Final population size (10 years)
Spring	Shooting	0.03	24,768
	Folding net	0.14	67,813
	Net launcher	0.10	46,237
	Egg culling	0.11	48,561
	Folding net + net launcher	0.13	57,449
	Egg culling + nestling culling	0.03	25,715
Non-spring	Shooting	-1.06	1,053
	Folding net	0.07	33,671
	Net launcher	0.07	33,975
	Egg culling	0.14	63,746
	Folding net + net launcher	-0.14	11,711
	Egg culling + nestling culling	0.06	33,014

Regarding the impact of individual capture methods on population growth rate, the models indicated that, during spring, shooting and the combination of egg and nestling culling were the most effective in reducing population growth rate. Outside of spring, however, shooting and the combination of folding net with net launcher were the most effective in reducing population growth rate (Table 2).

Decision-making models analysing the optimal combination of methods and effort levels revealed that, starting with a population of 10,000 individuals, the optimal strategy in spring was to allocate the maximum effort to both shooting and the combination of folding net and net launcher. This approach would eradicate the population within three years at a cost of €1,452,000. Outside of spring, the optimal strategy was to dedicate the maximum annual effort exclusively to the combination of folding net and net launcher, achieving eradication within three years at a cost of €582,000.

Food choice experiment

The different baits were tested a total of 30 times each in 27 different parks (Table 3). There were significant differences in the number of parakeets attracted by different types of bait (Appendix 6: Table A5). Efron's pseudo-R^2 coefficient for this model was 0.66. Pairwise comparisons revealed two groups of responses: one comprising the parrot feed and apple (Tukey's *post-hoc* test: $Z = -1.88$, $P = 0.24$) and the other one consisting of bread and the mixture of foods (Tukey's *post-hoc* test: $Z = 0.70$, $P = 0.90$). However, there were significant differences in the attractiveness between these two groups (Tukey's *post-hoc* test: $Z = -5.68$, $P < 0.001$), with bread and the mixture of foods attracting, on average, between two and six times more parakeets than the parrot feed and apple (Fig. 5A).

There were significant differences in the cost-efficiencies of attracting parakeets amongst different types of bait. Efron's pseudo-R^2 coefficient for this model was 0.73. Pairwise comparisons revealed that bread and the mixture of foods were the most cost-efficient baits, with no significant differences between them (Tukey's *post-hoc* test: $Z = 1.18$, $P = 0.64$). The apple bait was intermediate and the parrot feed was the least cost-efficient (Fig. 5B).

Table 3. Parakeets attracted per hour and cost-efficiency (cost per parakeet attracted) of the different baits used. Letter n represents the sample size and the rest of the values represent the mean, followed by the standard deviation.

Bait type	n	Parakeets attracted (birds/h)	Bait cost (€/kg)	Cost/bird (€)
Bread	30	27 ± 36	0.75	0.1 ± 0.2
Apple	30	13 ± 26	1.50	0.4 ± 0.3
Parrot feed	30	3 ± 8	2.05	0.8 ± 0.4
Mixture of the three baits	30	34 ± 44	1.43	0.2 ± 0.3

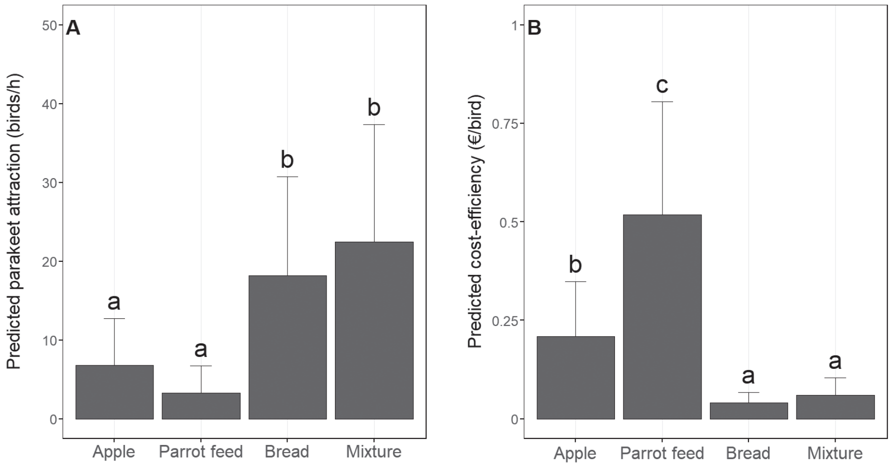

Figure 5. Results of the models for attraction efficacies (**A**) and cost-efficiencies (**B**) across different types of bait. Bars represent least-square means, with 95% confidence intervals shown as error bars. Letters above the error bars indicate groups, based on Tukey's *post-hoc* test. Methods without shared letters differ significantly, while those sharing at least one letter do not. Note that, in panel **A,** higher parakeet attraction indicates better performance, whereas, in panel **B,** lower cost-efficiency values indicate better performance.

Discussion

The monk parakeet management plan in Madrid, conducted from May 2021 to April 2023, aimed to minimise the city's population of this invasive species. As a result, the intervention reduced the projected total population (including nestlings, juveniles and adults) for 2023 and 2031 by approximately 50% compared to projections without management efforts. Notably, projections indicated that extending removal efforts at the intensity of the plan's second year for three additional years could have achieved near-total eradication of the species. The study showed that removing juveniles and adults was more than twice as effective in reducing population growth as removing eggs and nestlings, leading us to recommend prioritising the removal of juveniles and adults year-round rather than targeting eggs and nestlings. The plan employed various control methods, including shooting adults and juveniles perched on high branches, capturing them on the ground with folding nets and hand-held net launchers and culling eggs and nestlings. Capture efficacies and cost-efficiencies of these methods varied seasonally. In spring, shooting and the combination of egg and nestling culling were the most effective methods for reducing population growth rates; however, we do not recommend the latter due to evidence gathered against its use and its high associated costs. Outside spring, shooting and the combination of folding net and net launcher were most effective. When incorporating cost-efficiency into optimisation models, these indicated that, in spring, maximum effort should be allocated to both shooting and the combination of folding nets and net launchers. Outside of spring, the optimal strategy was to allocate maximum effort exclusively to the combination of folding nets and net launchers. These findings differ slightly from those derived using mixed models of capture efficacy and cost-efficiency, which are discussed later. Finally, two bait types – bread alone and a combination of bread, apple and parrot feed – were found to be most effective and cost-efficient for attracting parakeets to the ground.

The division into seasons allows for analysis of two biologically distinct periods for the monk parakeet: spring, when most of nesting occurs and the rest of the year, when reproductive activity decreases significantly (Senar et al. 2019). In spring, the method with the highest number of captures per hour was the combination of egg and nestling culling, which was expected given that most clutches occur during this season (Senar et al. 2019).

This high capture efficacy likely explains why, in our analyses, the combination of egg and nestling culling, along with shooting, were the two methods that most effectively reduced the population growth rate in spring. However, in parallel analyses, we concluded that culling eggs and nestlings is half as effective for population reduction as culling juveniles and adults. This, combined with several studies discrediting the effectiveness of egg culling, leads us to recommend against its use. Amongst these studies, some indicate that egg culling requires treating a large proportion of clutches to achieve a meaningful population impact (Coluccy et al. 2004; Baxter et al. 2010; Beston et al. 2016). Other research suggests that egg culling alone typically does not substantially reduce population size (Martínez-Abraín et al. 2004; Conroy and Senar 2009; Sanz-Aguilar et al. 2009; Esteban 2016), although it has proven effective for some species, such as the Canada goose *Branta canadiensis*, mute swans *Cygnus olor* and common ravens *Corvus corax* (Hindman et al. 2014; Beaumont et al. 2018; Brussee and Coates 2018). Additionally, parakeets may quickly detect culled eggs (whether oiled, punctured or replaced with dummies) and replace them, as observed in the U.K. (Animal and Plant Health Agency, unpublished data). Regarding nestling culling, no studies have assessed its effectiveness, likely due to welfare concerns and public opposition (Carrete et al. 2022). Nestling culling may be more effective than egg culling since nestlings have a higher probability of survival to reproductive maturity than unhatched eggs (Navarro et al. 1992; Ackerman et al. 2014). Furthermore, it may result in smaller replacement clutches or more frequent reproductive delays compared to egg culling, as seen in the red-backed shrike *Lanius collurio* (Antczak et al. 2009). Nevertheless, nestling culling is still less effective than methods targeting adults for several reasons: i) nestlings and juveniles have high natural mortality rates, meaning many would not survive to contribute to the population regardless of culling efforts (Bucher et al. 1991; Senar et al. 2019); ii) the method is restricted to a short window during the breeding season, whereas adult-focused methods can be applied year-round; and iii) synchronised reproduction requires significant, simultaneous effort, adding logistical challenges. These limitations reinforce our conclusion that egg and nestling culling is less effective and less practical than approaches focused on removing juveniles and adults.

Shooting was equally good as the combination of egg and nestling culling in reducing the population increase rate in spring and the best method in doing so outside of spring. This was expected because it has been the main control method deployed in most successful parakeet management programmes (Zaragoza, Spain: Esteban (2016); Balearic Islands, Spain: Orueta (2007), Molina et al. (2016); Uruguay: Bruggers et al. (1998), Linz et al. (2015); US: Neidermyer and Hickey (1977), Avery and Shiels (2017); but see the following for cases where shooting proved ineffective: Godoy (1963); Morgan and McNee (2000); Petersen and Grasso (2010)). Senar et al. (2021) estimated the capture efficacy and the cost of shooting for Zaragoza (Spain) and their results were much better than ours. However, there are factors with the shooting method in Madrid that could explain these discrepancies: unlike in Zaragoza, where shooting was allowed throughout the entire city, in Madrid, shooting was restricted to specific locations closed to the public. This may have limited the number of parakeets captured because shooting did not always take place in areas with high parakeet nest densities. Additionally, shooting was the only method with inactive periods, as it was decided to shoot at dawn and dusk when parakeet activity is highest in order to maximise captures, resulting in a period of inactivity between these shooting windows. These two factors may have led to an underestimation of the method's capture efficacy. Regarding cost-efficiency, the shooting team was the only subcontracted team, resulting in a proportionally higher salary compared to other teams hired by the company, thereby inflating the cost-efficiency estimates for this method. Additionally, it is important to note that, since there was only one shooting team, there is a high degree of collinearity between the team and the shooting method. This complicates the identification of the true predictor – whether it is the shooting method itself or the specific team – affecting the response variable (see Appendix 7). Despite these limitations, the shooting method performed quite well and we consider it a viable option for serious consideration both in spring and, particularly, outside of the spring season. Indeed, shooting could be particularly useful for targeting adults, the age class most likely to survive into the next breeding season, compared to eggs, nestlings and juveniles (Bucher et al. 1991; Conroy and Senar 2009). This is because adults seem less likely to fall into folding nets compared to juveniles, who are more naïve (Senar, pers. comm.). Therefore, shooting could be effective in targeting localised populations where adult birds no longer fall into capture nets, thereby facilitating subsequent nest removal with guarantees of not being rebuilt. Moreover, shooting can be an effective method for quickly eliminating incipient monk parakeet populations and preventing their dispersal and proliferation. Finally, we believe that shooting can also be considered one of the most ethical capture methods, as it is intended to cause immediate death to the animal and to avoid prolonged stress. However, for this method to be truly ethical and ensure immediate death, it must be carried out by expert shooters with animal welfare training.

Outside of spring, the second best method in reducing population increase rate was the combination of folding net and net launcher. The reason for the high effectiveness of the method is that, during summer, autumn and winter, parakeets descend to the ground to feed, relying on herbaceous vegetation and human-provided food, which facilitates their capture with nets. In contrast, during spring, parakeets have more food available in trees (e.g. new shoots and flowers) and do not need to come down to the ground (Postigo et al. 2021). Although there is not much precedent for these methods in managing monk parakeets, similar systems have been used successfully elsewhere (Florida: Avery et al. (2002); Barcelona: Senar et al. (2021)). While the folding net can go more unnoticed than other types of traps, repeated captures can make birds cautious, reducing long-term effectiveness. To prevent this, rotating capture sites regularly can help maintain effectiveness by keeping parakeets from learning patterns. Additionally, it is highly recommended to pre-bait the capture area with bread to attract parakeets to the area and potentially achieve more numerous captures.

The analysis of capture efficacy and cost-efficiency using mixed models aligns with the findings from the population growth rate reduction analysis and the optimisation model for method selection, with one notable exception: the shooting method. In the mixed model analysis, the efficacy of shooting appears to be underestimated, likely due to heteroscedasticity introduced by the lack of orthogonality in the control plan design. This limitation stems from the plan being tailored for technical rather than scientific purposes. However, when the random factor "team" is removed (Appendix 7), the mixed model results converge with those obtained from the demographic and optimisation models of Senar et al. (2021).

The food choice experiment was conducted to determine the most effective bait to use in order to increase the capture success of the folding net method. The baits that attracted the most parakeets were bread and the mixture bait composed of bread, apple and parrot feed. Our findings align with those of Postigo et al. (2021), who found that bread provided by humans ranked as the second most consumed food by monk parakeets in urban settings, just after grass (Poaceae family). Moreover, anthropogenic food has been identified as a key factor influencing the distribution of monk parakeets in Barcelona (Rodríguez-Pastor et al. 2012) and contributing to their breeding success and survival (Chamberlain et al. 2009). Since the bread and the mixture bait are equally cost-efficient, we recommend using only bread to simplify the food supply.

Conclusions and further prospects

This study evaluates the impact of the monk parakeet management plan implemented in Madrid from 2021 to 2023 on the population viability of the species. It also assesses the capture efficacy and cost-efficiency of different capture methods according to the season, concluding that the removal of juveniles and adults is more than twice as effective as the removal of eggs and nestlings in reducing population growth. For this reason, despite the superior capture efficacy of egg and nestling removal in spring, we recommend the use of the shooting method year-around, along with the combined use of the folding net and the net launcher outside of the spring season. The folding net allows for bulk captures, although it may have a bias towards naïve juveniles and requires pre-baiting to attract parakeets. In contrast, shooting is effective for targeting individuals, mainly adults, who have become wary of capture nets.

Additionally, the study tested different types of bait to determine the most effective option for attracting parakeets to the folding net, with bread being exclusively recommended.

It is also crucial to emphasise the importance of territorial coordination, as parakeets can easily move between neighbouring municipalities (Borray-Escalante et al. 2023). A lack of synchronised management across regions can lead to parakeets shifting to areas where previous control measures have created new, unoccupied niches, reducing the effectiveness of localised efforts. Therefore, a coordinated approach involving all affected municipalities is essential. This could include regular meetings to align strategies, share data and monitor parakeet movements across borders. Such collaboration can ensure a more comprehensive and effective control effort, minimising the risk of parakeets exploiting management gaps.

Additionally, management efforts must be sustained over time to prevent population recovery. Parakeets are highly adaptable and resilient birds, capable of quickly re-establishing populations if control measures are paused or halted. Continuous monitoring and control activities are essential to maintain the progress made in reducing parakeet numbers. This long-term commitment should involve regular assessments to adjust strategies based on updated data and research.

Sustainable funding and resources are also critical for maintaining ongoing efforts. Municipalities should seek to secure long-term financial support, possibly through partnerships with governmental and non-governmental organisations, to ensure that control measures can be sustained over time. Public education and community involvement are also crucial; raising awareness about the impact of invasive parakeets and encouraging public participation in reporting sightings can enhance the effectiveness of the management programme. Madrid's control plan included talks at academic institutions and for professionals in the field, along with the distribution of information leaflets. Looking ahead, we recommend also involving public administrators and educational institutions.

In summary, this study highlights the importance of rigorously testing management tools for invasive species, such as the monk parakeet, to ensure more effective and cost-efficient management of the species in the future. Coordinated, long-term efforts across municipalities are key to achieving lasting population reductions and ongoing collaboration between management teams and the scientific community is crucial for developing scientifically validated strategies.

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Additional information

Conflict of interest

Co-authors JB-G, FE and IA are employees contracted by MATINSA, the company awarded the contract by the Madrid City Council to control the monk parakeet population in Madrid from May 2021 to April 2023. One piece of information that we have omitted in the text due to financial considerations relates to how food was distributed in the feeders used to capture parakeets with folding nets. Knowledge gained from this trial-and-error process would have been beneficial for other companies in the event of a hypothetical future tender to continue controlling the parakeet population in Madrid.

Ethical statement

The monk parakeet (*Myiopsitta monachus*) is classified as an invasive exotic species in Spain under Royal Decree 630/2013, dated 2 August 2013. This Decree mandates that competent authorities control and manage the species in accordance with current animal welfare laws. The management carried out by MATINSA adhered to this regulation.

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Author contributions

All authors contributed to the conception and design of the study. The design, implementation and monitoring of the control plan were performed by FE, IA and JCO. Food choice experiment was performed by JB-G. Data analysis was performed by JB-G, IL-R and LC. The first draft of the manuscript was written by JB-G, IL-R and LC and all authors commented on other versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

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Appendix 1

Public opposition

The management plan encountered public opposition at various stages, particularly at the beginning. This reaction was expected due to three main factors: the monk parakeet's perception as charismatic that many residents had adopted and normalised; legal requirements mandating the culling of captured individuals; and the high population density of Madrid, which increased the likelihood of public resistance.

The most notable public backlash occurred early on, when three individuals illegally entered a closed public park where shooting was underway. They filmed the operators and took a parakeet that had been shot, leading to widespread, often sensationalist, media coverage. In response, the plan prioritised using parks and green spaces that could be securely closed to prevent unauthorised access during shooting operations. These areas were mostly private, though certain public parks that met safety requirements were also utilised.

In addition to this widely-publicised event, operators occasionally faced verbal confrontations from the public while capturing parakeets using both ground and aerial methods and two minor protests occurred outside MATINSA's offices. These events, however, did not significantly disrupt the management plan. Importantly, strong support from the city council - especially in deploying police to de-escalate conflicts between operators and residents - was critical in maintaining operational continuity.

Appendix 2

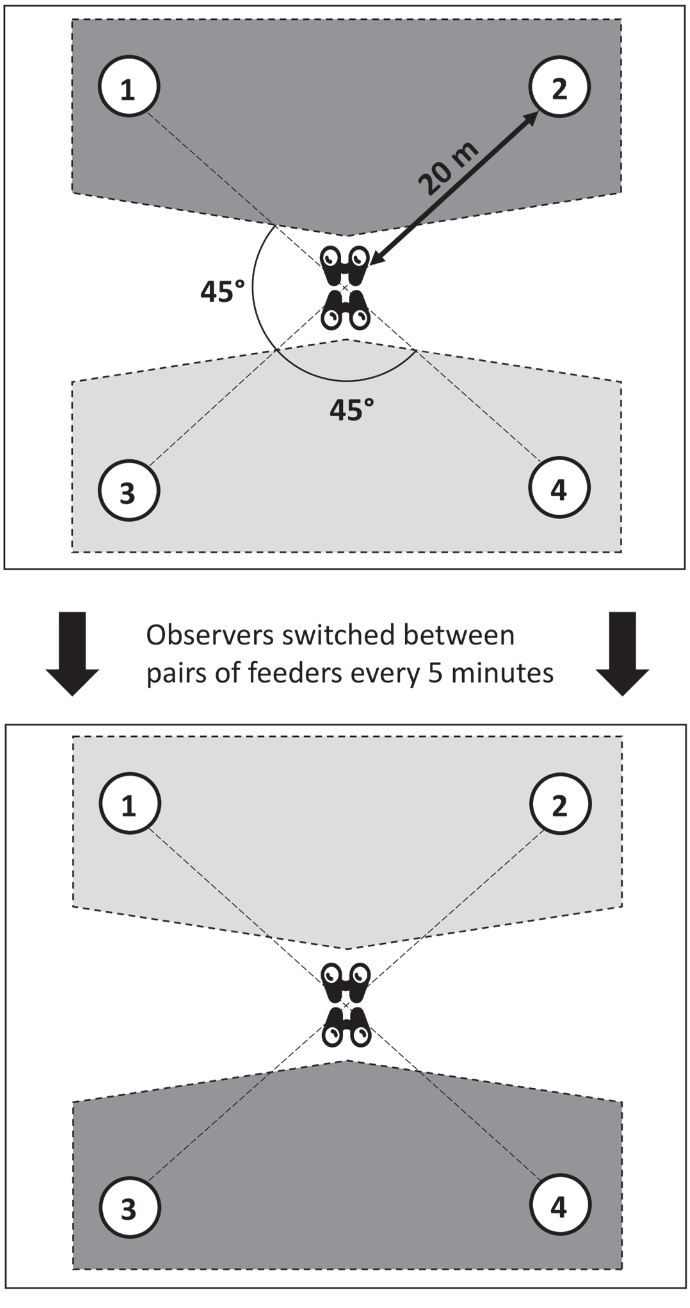

Figure A1. Diagram illustrating the positions of the two observers relative to the feeders, which are labelled with numbers from 1 to 4. Each feeder was placed approximately 20 m from the observers. Feeders observed by Observer 1 are shown in dark grey and those observed by Observer 2 are shown in pale grey.

Appendix 3

The population viability analysis was based on two transition matrices that modelled reproduction and survival rates across age classes. The first matrix contained the average values (Table A1), while the second included standard deviations to incorporate environmental stochasticity (Table A2). Most values were sourced from Senar (2021), with two exceptions: the nestling-to-juvenile survival probability, derived from Senar et al. (2019), and the uncertainty associated with survival rates, estimated by assuming a 10% standard deviation relative to the average. Reproduction rates indicate the number of nestlings produced annually by each individual based on age class; first-year juveniles were assigned a single clutch per year, while adults were assumed to produce two clutches annually.

Table A1. Average transition rates for the monk parakeet population in Madrid. The first row shows fecundity rates, expressed as the annual number of nestlings produced per individual in each age class. Subsequent rows represent age-class transition probabilities, indicating the likelihood of advancing to the next age class within a year.

Age class	Nestling	Juvenile 1st year	Adult 2nd year	Adult 3rd	Adult 4th	Adult 5th	Adult 6th	Adult 7th	Adult 8th	Adult +8th
Nestling	0	0.75	1.386	1.431	1.431	1.431	1.431	1.431	1.431	0
Juvenile 1st year	0.524	0	0	0	0	0	0	0	0	0
Adult 2nd year	0	0.61	0	0	0	0	0	0	0	0
Adult 3rd	0	0	0.81	0	0	0	0	0	0	0
Adult 4th	0	0	0	0.81	0	0	0	0	0	0
Adult 5th	0	0	0	0	0.81	0	0	0	0	0
Adult 6th	0	0	0	0	0	0.81	0	0	0	0
Adult 7th	0	0	0	0	0	0	0.81	0	0	0
Adult 8th	0	0	0	0	0	0	0	0.81	0	0
Adult +8th	0	0	0	0	0	0	0	0	0.81	0.81

Table A2. Standard deviations for transition rates in the monk parakeet population matrix, representing the variability incorporated into the population viability model to account for environmental stochasticity.

Age class	Nestling	Juvenile 1st year	Adult 2nd year	Adult 3rd	Adult 4th	Adult 5th	Adult 6th	Adult 7th	Adult 8th	Adult +8th
Nestling	0	0.32	0.456	0.475	0.475	0.475	0.475	0.475	0.475	0
Juvenile 1st year	0.0524	0	0	0	0	0	0	0	0	0
Adult 2nd year	0	0.061	0	0	0	0	0	0	0	0
Adult 3rd	0	0	0.081	0	0	0	0	0	0	0
Adult 4th	0	0	0	0.081	0	0	0	0	0	0
Adult 5th	0	0	0	0	0.081	0	0	0	0	0
Adult 6th	0	0	0	0	0	0.081	0	0	0	0
Adult 7th	0	0	0	0	0	0	0.081	0	0	0
Adult 8th	0	0	0	0	0	0	0	0.081	0	0
Adult +8th	0	0	0	0	0	0	0	0	0.081	0.081

Appendix 4

Table A3. Total and monthly removal of monk parakeets by age class from May 2021 to April 2023. Parakeets are categorized into three age classes: adults and juveniles, nestlings, and eggs. Data from 2021 cover the months of May to December, data from 2022 cover January to December, and data from 2023 cover January to April.

		2021								2022											2023			
	Total	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**
Adults + juveniles	14,321	2	0	9	267	466	320	591	657	941	409	276	210	342	555	522	1,07	1,260	1,674	959	1,166	1,241	767	24
Nestlings	2,822	178	18	9	9	1	0	0	0	0	0	277	1,569	571	103	61	23	3	0	0	0	0	0	0
Eggs	2,062	19	37	6	15	13	1	1	0	0	92	884	471	330	93	33	32	4	0	0	0	0	16	15

Appendix 5

Time dedication to each capture method

During the control plan, up to 10 teams were working simultaneously to reduce the monk parakeet population. Nine teams were consistently composed of two people (hereafter referred to as "standard teams"), while one team consisted of 1 or 2 people depending on the capture method and the day (hereafter referred to as the "shooting team"). This last team was the only one authorised to use an air rifle. Each worker's workday lasted 8 hours. To standardise calculations for both the time dedicated to capture methods and the associated costs, the workday for teams of two was set at 16 hours. An exception was made for the shooting team: when using the folding net or net launcher, only one person was involved, so the workday was 8 hours. On days when air rifle shooting was employed, either one or two people were involved, depending on the expected number of parakeets, so the time dedicated to air rifle shooting was standardised to 12 hours – the average of 8 hours (one person) and 16 hours (two people).

Additionally, two auxiliary activities were conducted during the management plan that, although not capture methods per se, had to be factored into calculations because they were often combined with parakeet capture: nest removal and baiting of feeders. In the case of nest removal, the time dedicated to this activity was subtracted from the corresponding workday to accurately assess the time dedicated to capturing parakeets. Regarding baiting of feeders, we categorised this activity in two ways: "average baiting", which is the average time taken to bait an area before the capture day and which was always added to the associated folding net activity; and "day baiting", which refers to daily baiting carried out by the teams to maintain an effective rotation of capture sites. The time spent on "day baiting" was subtracted from the workday, while it was added to all instances of capture with the folding net. Additionally, on days when nest removal or "day baiting" occurred, the proportional travel time associated with these two auxiliary activities was also subtracted from the workday.

Below, we outline how we calculated the time dedicated to each capture method, depending on the team performing it and any other methods being used simultaneously. We will separate the explanations for the shooting team and the standard team, as well as by the number of methods used per day. The time for average baiting is not specified because it varied for each of the 10 teams. Combinations not explained did not occur.

Shooting team

One method per day

- Shooting: 12 h.
- Folding net: 8 h + average baiting.
- Net launcher: 8 h.

Two methods per day

- Shooting and day baiting: 12 h – 2 h (day baiting) – 1 h (commute).
- Folding net and day baiting: 8 h – 1.25 h (day baiting) – 40 min (commute) + average baiting.

Standard teams

One method per day

- Folding net: 16 h + average baiting × 2.
- Net launcher: 16 h.
- Egg culling: 16 h.

Two methods per day

- Folding net and day baiting: 16 h – 3 h × 2 (day baiting) – 1 h 20 min (commute) + average baiting × 2.
- Folding net and net launcher: 16 h + average baiting × 2.
- Net launcher and pre-baiting: 16 h – 3 h × 2 (day baiting) – 1 h 20 min (commute).
- Egg culling and nestling culling: 16 h.
- Egg culling and nest removal: 16 h – (1 h 20 min × n° of nests removed) – 1 h 20 min (commute).

Three methods per day

- Folding net and net launcher and day baiting: 16 h – 3 h × 2 (day baiting) – 53 min (commute) + average baiting × 2.
- Egg culling and nestling culling and nest removal: 16 h – (1 h 20 min × n° of nests removed) – 53 min (commute).

Cost per capture method

After calculating the daily time dedicated to each capture method, we determined the cost of implementing these methods in order to subsequently calculate cost-efficiency values. The following associated costs were considered:

Salaries

- Shooting team: 92.6 € / h × day.
- Standard teams: 11.9 € / h × person.
- Manager: 12.5 € / h × person.
- Veterinarian: 32 € / h × person.

Vehicle rental

- Aerial work platform: 79 € / h.
- Light vehicle: 8.5 € / h.
- Gasoline: 5 € / car × day.

Other Costs

- Bait: 4.7 € / baiting event.
- Clinical equipment: 49 € / any capture method used × day.
- Consumables: 12.7 € / any capture method used × day.
- Incineration of carcasses: 4.7 € / any capture method used × day.
- Signals and markings: 27.7 € / any capture method used × day.

Price calculation

Shooting team

- Shooting: salary × h + incineration + veterinarian × 0.7.
- Folding net: salary × h + clinical equipment + consumables + incineration + veterinarian.
- Net launcher: salary × h + clinical equipment + consumables + incineration + veterinarian.
- Folding net and net launcher: salary × h + clinical equipment + consumables + incineration + veterinarian.

Standard teams

- Folding net: salary × h + bait + clinical equipment + consumables + incineration + veterinarian + gasoline.
- Net launcher: salary × h + clinical equipment + consumables + incineration + veterinarian + gasoline.
- Folding net and net launcher: salary × h + bait + clinical equipment + consumables + incineration + veterinarian + gasoline.
- Egg culling: salary × h + aerial work platform × h + light vehicle × h + signals and markings + gasoline.
- Egg culling and nestling culling: salary × h + aerial work platform × h + light vehicle × h + signals and markings + clinical equipment + consumables + incineration + veterinarian + gasoline.

Appendix 6

Table A4. AIC and Efron's pseudo-R^2 values for the selection of the best model for capture efficacy and cost-efficiency of the capture methods. Following the order of the best model selection process, the selection of random factors is presented first, where a full model is fitted and different random structures are compared. Once the random structure is chosen, the selection of fixed effects is performed, where different fixed structures are compared while keeping the previously-selected random structure fixed. The best model (lowest AIC) is indicated in boldface type.

	Capture efficacy		**Cost-efficiency**	
Random factors selection	**AIC**	**Efron's pseudo-R^2**	**AIC**	**Efron's pseudo-R^2**
No random factors	11906	0.16	5526	0.19
(1 | date)	11879	0.28	5519	0.27
ou[1] (time[2] + 0 | season)	11845	0.26	5488	0.26
ou (time + 0 | covariate[3])	11843	0.26	5487	0.27
(1 | team)	11817	0.21	5453	0.24
ou (time + 0 | method)	11792	0.33	5444	0.36
(1 | team) + (1 | date)	11777	0.37	5441	0.33
(1 | team) + ou (time + 0 | season)	11739	0.35	5414	0.31
(1 | team) + ou (time + 0 | covariate)	11737	0.35	5413	0.32
ou (time + 0 | team)	11710	0.44	5375	0.44
(1 | team) + ou (time + 0 | method)	11694	0.41	5370	0.40
(1 | team) + ou (time + 0 | team)	**11684**	**0.50**	**5368**	**0.47**
Fixed factors selection				
Null model	11781	0.481	5454	0.429
Season	11781	0.48	5450	0.427
Method	11714	0.456	5391	0.443
Method: Season	11684	0.499	5368	0.471
Method: Season + method	11684	0.499	5368	0.471
Method: Season + season	11684	0.499	5368	0.471
Method*Season	**11684**	**0.499**	**5368**	**0.471**

[1] The Ornstein-Uhlenbeck (OU) covariance structure models temporal autocorrelation.
[2] Numerical factor used to model temporal autocorrelation.
[3] Factor with a single level, used to specify that the temporal autocorrelation applies to all observations.

Table A5. AIC and Efron's pseudo-R^2 values for the selection of the best model for attraction efficacy and cost-efficiency of the bait types. See Table A4 for more information on the best model selection process. The best model (lowest AIC) is indicated in boldface type.

	Attraction efficacy		**Cost-efficiency**	
Random factors selection	**AIC**	**Efron's pseudo-R^2**	**AIC**	**Efron's pseudo-R^2**
No random factors	963	0.171	476	0.354
(1 | park) + (1 | date)	961	0.496	476	0.538
(1 | date)	959	0.496	473	0.538
(1 | park)	**959**	**0.496**	**473**	**0.538**
Fixed factors selection				
Null model	985	0.237	520	0.246
Bait type	**951**	**0.495**	**468**	**0.538**

Appendix 7

Due to the high collinearity between the shooting method and the team responsible for conducting the shooting (correlation coefficient of 0.86), it is unclear which of these factors is influencing the response variable. To assess whether the "team" factor was masking the performance of the shooting method, we adjusted the models for capture efficacy and cost-efficiency without including the team factor as random factor. In this way, it can be observed that the capture efficacy of the shooting method shows a significant increase both during and outside of spring (Fig. A2B), being amongst the most effective methods in both seasons, compared to the model including the team factor (Fig. A2A). Regarding cost-efficiency, an improvement can be observed in spring when the team factor is not included (Fig. A3B). However, the mixed model selection, based on AIC and Efron's pseudo-R^2, indicated that the team factor should be included in the model. Therefore, we have included the model with the team factor in the main text and placed the model without it in the Appendices.

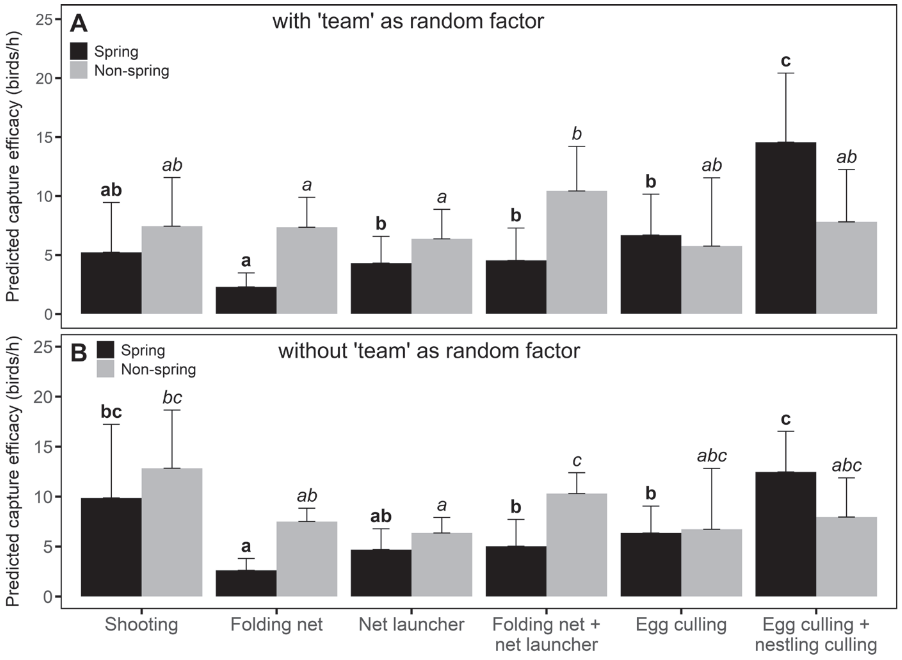

Figure A2. Results of the models for capture efficacies when the "team" factor is included as random factor (**A**) and when it is not (**B**). Bars represent least-square means, with 95% confidence intervals shown as error bars. Letters above the error bars indicate groups based on Sidak's *post-hoc* test; bold letters denote spring values and italicised letters denote non-spring values. Methods without shared letters differ significantly, while those sharing at least one letter do not. Note that a method performs better, the higher its capture efficacy.

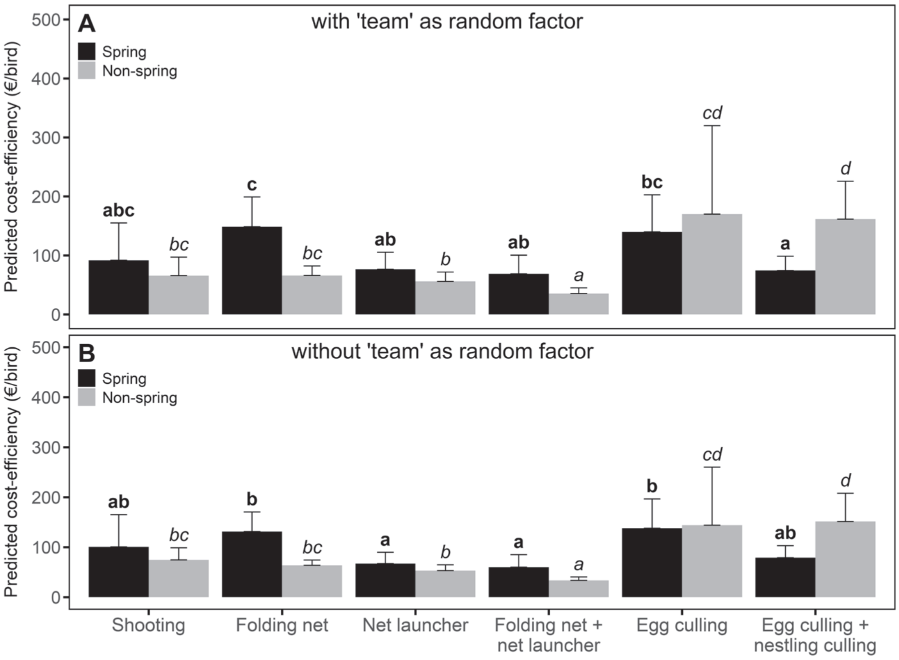

Figure A3. Results of the models for cost-efficiencies when the "team" factor is included as random factor (**A**) and when it is not (**B**). Bars represent least-square means, with 95% confidence intervals shown as error bars. Letters above the error bars indicate groups based on Sidak's *post-hoc* test; bold letters denote spring values and italicised letters denote non-spring values. Methods without shared letters differ significantly, while those sharing at least one letter do not. Note that a method performs better, the lower its cost-efficiency.