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Bird deterrent measures at a landfill decreased the productivity of a dependent population of White Stork (*Ciconia ciconia*)

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Landfills provide an abundant and predictable food source for avifauna. The energy and time that are saved because of landfill-foraging have had positive effects on the distribution of bird breeding populations and their reproductive parameters. However, the proliferation of individuals coinciding with the appearance of landfills often increases human–wildlife conflicts and intensifies the contact between waste and the environment. In this context, a landfill in Madrid (Spain) implemented deterrent measures in 2021 aiming to reduce the influx of birds inside its facilities. This study aims to describe the effects that a reduction in the accessibility and availability of landfill food resources may have had on the surrounding breeding populations of White Stork *Ciconia ciconia*. For this purpose, the breeding parameters of three populations with different landfill use indices were analysed before and after the application of bird deterrent measures. The closest population, with the highest landfill use index, suffered a drastic reduction in fledgling productivity during the breeding season with bird deterrent measures. On the other hand, a drought during one of the breeding seasons negatively affected the productivity of the populations that relied partially and completely on natural food resources (located at medium and long distance from the landfill, respectively). Landfill-foraging might have mitigated the consequences of the natural food scarcity caused by this drought, even with the application of bird deterrent measures. Overall, our results show the potential negative impact of bird deterrent measures on populations dependent on landfill food, and highlight the importance of assessing the effect of these techniques beyond the site to determine their appropriateness. Due to the imminent closure of landfills and the expected worsening consequences of climate change, monitoring programmes should be established to determine the long-term effects of bird deterrent measures and unusual environmental conditions on White Stork populations.

Keywords: breeding parameters, food availability, human–wildlife conflict, management, occupation probability.

Over recent decades, human development combined with industrial expansion has led to a global change that involves major climatic and ecological modifications. The changes that have taken place in land and sea use along with direct habitat exploitation are the main drivers of biodiversity loss and alterations in wildlife distribution patterns (Rockström *et al.* 2009, Jaureguiberry *et al.* 2022). Wildlife populations react to these human-induced environmental changes modifying their foraging behaviour and movements at either the individual or population level, sometimes showing remarkable adaptability. Modifications in these traits can negatively impact ecosystems, as they can alter biogeochemical cycles, cause habitat alteration and increase disease transmission (Lowry *et al.* 2013, Wilson *et al.* 2020). For instance, as a result of the urbanization process, the most ‘urban-adaptable’

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individuals or species among native wildlife communities can grow in abundance, as they more easily exploit urban resources (McKinney 2006). Predictable anthropogenic food subsidies are part of the activities that cause modifications in wildlife behaviour, attracting opportunist individuals in high densities and altering population dynamics (Oro *et al.* 2013). Landfills are one of the spatially and temporally predictable anthropogenic food sources that are currently shaping wildlife behaviour.

Landfill-foraging behaviour has been widely studied in bird populations and has been proven to enhance their demographic and breeding parameters, but it is not exempt from costs (Plaza & Lambertucci 2017). Moreover, the remarkable number of birds that feed on landfills has become a human–wildlife conflict, in which the interaction between human activity and biodiversity has resulted in various negative impacts (Abrahms 2021). Bird strike hazard increases when airports are situated in their vicinity (Baxter & Allan 2006) and foraging birds can scatter landfill waste, polluting the surrounding environments and potentially damaging human health when carrying pathogens (Osei *et al.* 2011, Pineda-Pampliega *et al.* 2021). In addition, increasing densities of bird breeding populations in urban areas near landfills can generate a perception of over-abundance and social dislike of the species. As an example, White Stork *Ciconia ciconia*, Linnaeus 1758 nests placed in urban areas near landfills can cause serious damage to buildings that may not support their weight, and when constructed on electricity pylons they can eventually result in power outages that have a multi-level economic impact (Vergara *et al.* 2007, Tryjanowski *et al.* 2009, Moreira *et al.* 2018). Overall, a shift in the social perspective of these species may negatively impact their conservation status, as human–wildlife conflicts are usually understood from the anthropogenic point of view (Abrahms 2021). Because of this perspective, people or administrations implement bird deterrent measures to either reduce or erase these conflicts. Unfortunately, they usually overlook the indirect effects of such measures and underestimate the relevance of properly performed studies to determine their effectiveness, and research regarding landfill management measures is historically scarce (Baxter & Robinson 2007, Cook *et al.* 2008).

The White Stork is known to forage in high numbers at landfills. In central Spain, White Storks began to be recorded at these sites after the population's decline in the 1980s (Lázaro *et al.* 1986, Blanco 1996). After that, the population growth that took place in this area during the following years was associated with the benefits of foraging at landfills (Tortosa *et al.* 2002, López-García *et al.* 2023a). Through this strategy, fledglings receive a more frequent and abundant food intake (Pineda-Pampliega *et al.* 2021) and breeders save time and energy that can be invested in parental care, such as protecting fledglings from climatic events (Gilbert *et al.* 2016, Soriano-Redondo *et al.* 2021). However, the downsides to feeding on human refuse are many: fledglings provided with landfill food have a lower quality diet, are exposed to pollutants and pathogens found in refuse, might ingest non-organic matter (e.g. plastics) and present higher concentrations of contaminants in their blood (Blázquez *et al.* 2006, Plaza & Lambertucci 2017, Pineda-Pampliega *et al.* 2021). Moreover, previous studies indicate that despite increasing hatching success, this phenomenon decreases the future survival of the fledglings, possibly because of this poor-quality diet (López-García *et al.* 2021).

Landfills now have an expiration date as recent European Directives (1999/31/CE and 2018/850/CE) established objectives focused on a reduction in the organic waste that ends up at these sites and their eventual coverage. This phenomenon would eventually make foraging on landfills impossible for White Storks and other wild animals, as the wasted organic matter would become inaccessible or notably reduced. In this context, the Colmenar Viejo landfill located in Madrid (Fig. 1) started to apply bird deterrent measures in September 2021. During the following breeding seasons after the implementation of bird deterrent measures, the individuals that use the Colmenar Viejo landfill might reduce the time spent at this site or the frequency of their visits. These individuals will be flushed from organic waste deposits several times per week using a combination of pyrotechnical and falconry techniques, which have been proven to reduce the probability of habituation (Erickson *et al.* 1990, Cook *et al.* 2008). Considering the improvements in breeding outcomes derived from landfill use, a decrease in the breeding parameters of the more landfill-dependent breeding populations is expected.

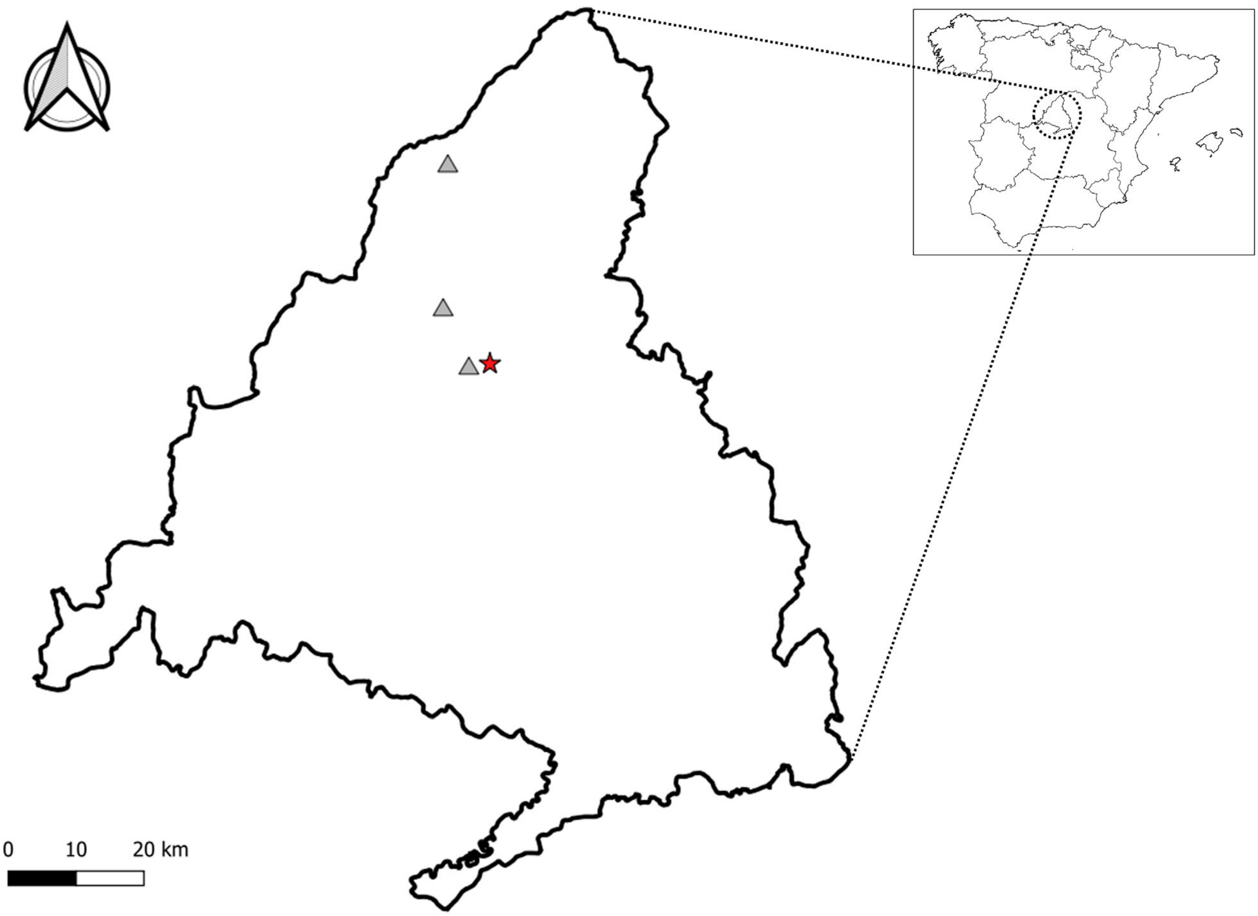

Figure 1. Geographical location of the surveyed White Stork breeding areas (triangles) and the Colmenar Viejo landfill (star) inside Madrid province in Central Spain. From north to south: Lozoya and Pinilla del Valle (long-distance breeding area), Soto del Real (medium-distance breeding area) and Colmenar Viejo (short-distance breeding area).

This study aimed to measure the effects that a reduction in the accessibility and availability of landfill resources derived from the use of bird deterrent measures could have on three surrounding White Stork breeding populations that differed in their use of landfill, because they were located at different distances from the facility (see Fig. S1). To indirectly evaluate the effectiveness of this management measure, the breeding parameters of these populations were recorded by performing a survey during the breeding season before the implementation of bird deterrent measures at the landfill (2021) and during the two consecutive breeding seasons with bird deterrent measures in place (2022 and 2023). Unlike previous studies on the matter, we evaluated the impact of these measures beyond the landfill site and gave a broader insight regarding the effects of these techniques. Previous research has focused mainly on the changes in the number of individuals inside landfills after the use of deterrents and on the impacts of changes in waste management, almost exclusively on gulls (Baxter 2000, Baxter & Allan 2006, Baxter & Robinson 2007, Coccon *et al.* 2022). In this paper, we describe the impact of bird deterrent measures on the breeding parameters of one of the most abundant species at landfills and offer an evaluation of how management measures can be wisely implemented.

Our prediction is that the effects of bird deterrent measures on breeding parameters will be negative and stronger with higher landfill use by breeders and hence with proximity to the landfill. In addition, the beginning of the 2023 breeding season was hit by a drought and afterwards by unusually heavy rainfall coinciding with the early life stages of the fledglings, which is known to negatively affect breeding success in White Storks (Tobolka *et al.* 2015, Bialas *et al.* 2020). These adverse weather conditions are also expected to have an impact overall, but food from landfills might mitigate their consequences on breeding parameters.

METHODS

Study area

The study area covered three White Stork breeding areas in Madrid province (central Spain) that were surveyed in search of occupied nests during the breeding seasons of 2021, 2022 and 2023. These areas are located at different distances from the Colmenar Viejo landfill (40.66407°N, 3.72797°W). The Colmenar Viejo (short-distance), the Soto del Real (medium-distance) and the Lozoya and Pinilla del Valle (long-distance) breeding areas are on average 2.78 km, 11.38 km and 31.18 km away from the landfill, respectively (Fig. 1). According to the literature (Gilbert *et al.* 2016, Soriano-Redondo *et al.* 2021) and our observations (Fig. S1), landfill use decreases with distance. As a result, the breeding pairs in these three populations differed in the use of the landfill as a food source.

Data collection

The survey of each breeding area was carried out through direct observation of nesting sites following the methodology described in López-García and Aguirre (2022). The coordinates of each nest (GPS point) and the breeding area were recorded during fieldwork. To determine whether a nest was occupied or not, we compiled information about the state of the nest (empty or with adults) and the behaviour of the adults (standing on the nest, laying on the nest, or with fledglings).

The visits took place from April to June (the surveyed months hereinafter will be referred to as the breeding season unless specified otherwise) of the years 2021, 2022 and 2023. The first studied breeding season was characterized by no bird deterrent measures at the landfill (NDM breeding season, 2021), followed by a season when bird deterrent measures were applied (DM breeding season, 2022), and one last season with bird deterrent measures at the landfill and a strong drought in the study area (DM + D breeding season, 2023). The climatic data regarding the unusual environmental conditions of the DM + D breeding season were reported by the State Meteorological Agency's website.

The breeding parameters measured in this study were the occupation probability of the nests and the productivity of fledglings. The frequency of visits to determine the occupation probability and productivity of each population was based on the previous methodology of European White Stork censuses (Schulz 1999, Molina & Carlos del Moral 2005). The productivity data were defined in this study as the mean number of fledglings per breeding pair with known breeding success (i.e. breeding pairs whose fledglings could be counted accurately) within each population. The number of fledglings was considered the number of nestlings older than 30 days of life, as they suffer from age-related mortality during their early development (Jovani & Tella 2004). The occupation probability data referred to the percentage of occupied nests in relation to the total surveyed nesting sites in the breeding area. Nests were visited at least three times during the breeding season to detect breeding pairs and fledglings following the method of Aguirre and Vergara (2009): a first visit during April, a second visit during late May and a last visit in the first 2 weeks of June; the timing of visits was adjusted following the particular breeding areas' phenologies. Occupation is best detected during April, when all pairs have arrived in the breeding zone, whereas productivity of fledglings is efficiently surveyed from late May into the first 15 days of June, when fledglings are big enough to be counted reliably (Aguirre & Vergara 2009). This research was carried out with permits from the Madrid Community (Ref: 10/274200.9/23 and 10/375506.9/23).

PVC-ringed adults were identified as breeders whenever feasible, using camera traps at nests or a telescope. At the same time, the Colmenar Viejo landfill was visited regularly (at least once a week) from 2021 to collect data on marked White Storks found foraging at this site. The surveys were carried out during the afternoon and before sunset for 2–3 h coinciding with the time at which bigger flocks of storks aggregated in the landfill and when the rubbish truck activities were minimal according to Blanco (1996) and López-García *et al.* (2021). A Landfill Use Index developed by López-García *et al.* (2021) was used to study the number of observations of each marked individual within the total number of visits to the landfill. The period of observations covered from February, which is when nest occupation starts, until June, when fledglings achieve their full development and leave the nest (Bernis 1981).

Statistical analyses

The studied variables known to be affected by changes in landfill use by White Storks were occupation probability (López-García & Aguirre 2023) and productivity (Tortosa *et al.* 2002, López-García *et al.* 2021), studied as response variables. The breeding area was included as a fixed factor with three levels (short-distance, medium-distance and long-distance) and the breeding season was included as another fixed factor divided into three categories (NDM, DM and DM + D). The nest variable was included as a random intercept to avoid pseudoreplication due to the use of different data from the same nest and the high probability of re-occupation by the same breeding pair during different breeding seasons (Barbraud *et al.* 1999, Vergara *et al.* 2006).

To test whether the occupation probability and productivity had changed between the different breeding seasons in each breeding area, we constructed several generalized linear mixed-effects (GLME) models using the lme4 package as validated by Bates *et al.* (2023) (see Table 1). The effect of the fixed factors breeding season and breeding area considering the nest as a random intercept was studied on the occupation probability as a binomial variable using '1' for occupied nests and '0' for unoccupied nests with a binomial error structure and a logit link function. Using the same package, various GLME models were developed to study the effect of the above-mentioned predictor variables on productivity with a Poisson error structure and a log link function. The GLME models tested for each breeding parameter (the response variables) were constructed from the null model (model 1) going through different combinations of the factors being studied until the model that described an interaction between the two fixed factors (model 5) as listed below, resulting in 10 models in total (five models with occupation probability and five models with productivity as a response variable):

1 Occupation probability/productivity ~ 1 + (1|nest).
2 Occupation probability/productivity ~ breeding area + (1|nest).
3 Occupation probability/productivity ~ breeding season + (1|nest).
4 Occupation probability/productivity ~ breeding area + breeding season + (1|nest).
5 Occupation probability/productivity ~ breeding area*breeding season + (1|nest).

Model selection used Akaike's Information Criterion (AIC) and was performed using the Multi-Model Inference package as described in Barton (2023). Models were ranked according to their ΔAICc, which represents the difference between the best model's AICc and the AICc of the model being compared, with AICc corresponding to the AIC corrected for small sample sizes (Burnham & Anderson 2004). Post-hoc tests were performed for the results of the selected models to detect statistically significant differences. All statistical analyses were performed using R Statistical Software (Version 4.3.0; R Core Team 2023).

RESULTS

A total of 1974 nesting locations were analysed in this study: 326 nests each breeding season in the short-distance breeding area, 258 in the medium-distance area and 74 in the long-distance area. Table S1 shows the number of occupied nests and mean number of fledglings in each breeding area and season. The two selected models that best predicted occupation probability and productivity contained an interaction between breeding area and breeding season (see Tables 1 & 2). After selecting the best models, post-hoc tests were performed to study the differences between all the combinations of breeding seasons and areas for each breeding parameter.

According to the post-hoc tests, occupation probability remained constant at the short- and medium-distance breeding areas during the three studied breeding seasons, although a non-significant increase in the short-distance population during the DM + D breeding season in comparison to the previous one was found (Fig. 2; estimate ± standard error (se) −0.232 ± 0.188, Wald = −1.233, $P = 0.949$). This was not the case for the long-distance population, where a decrease in occupation probability took place between the NDM and DM breeding seasons (Fig. 2; estimate ± se 1.207 ± 0.372, Wald = 3.249, $P = 0.032$),

M	Effects	*K*	LogLik	AICc	ΔAICc	*w*
Occupation probability						
5	**Breeding area*breeding season**	**10**	**−1071.5**	**2163.11**	**0**	**0.791**
2	Breeding area	4	−1079.1	2166.21	3.109	0.167
4	Breeding area + breeding season	6	−1078.47	2168.98	5.872	0.042
1	Null	2	−1114.94	2233.88	70.78	0
3	Breeding season	4	−1114.31	2236.65	73.54	0
Productivity						
5	**Breeding area*breeding season**	**10**	**−1731.9**	**3483.99**	**0**	**0.980**
4	Breeding area + breeding season	6	−1739.86	3491.79	7.796	0.020
3	Breeding season	4	−1763.38	3534.79	50.80	0
2	Breeding area	4	−1774.92	3557.87	73.88	0
1	Null	2	−1800.81	3605.63	121.64	0

Table 1. Model selection table for the response variables in relation to the breeding area and/or the breeding season, including interactions (*) between the two factors. The selected models are represented in bold type. Note: terms are AICc, Akaike information criterion corrected for small sample size; *K*, number of parameters; logLik, log-likelihood value; *M*, model abbreviation; *w*, Akaike weights; ΔAICc, the AICc difference between the current model and the one with the lowest AICc value.

Response variable	Explanatory variables	Estimate	se	*Z* value	*P* value
Occupation probability	Short-distance	0.059	0.095	0.623	0.533
	Medium-distance	**0.848**	**0.109**	**7.796**	**< 0.001**
	NDM	**0.229**	**0.093**	**2.447**	**0.014**
	DM	−0.150	0.092	−1.627	0.104
	Short-distance*NDM	**−0.289**	**0.112**	**−2.575**	**0.010**
	Medium-distance*NDM	**−0.256**	**0.125**	**−2.056**	**0.040**
	Short-distance**DM*	0.064	0.111	0.580	0.562
	Medium-distance**DM*	0.219	0.124	1.760	0.078
Productivity	**Short-distance**	**0.276**	**0.052**	**5.337**	**< 0.001**
	Medium-distance	**0.310**	**0.054**	**5.783**	**< 0.001**
	NDM	**0.226**	**0.067**	**3.366**	**0.001**
	DM	**0.184**	**0.061**	**3.007**	**0.003**
	Short-distance**NDM*	0.009	0.071	0.125	0.900
	Medium-distance**NDM*	−0.078	0.073	−1.073	0.283
	Short-distance*DM	**−0.233**	**0.066**	**−3.530**	**< 0.001**
	Medium-distance**DM*	−0.028	0.070	−0.406	0.685

Table 2. Output of the generalized linear mixed-effects models selected for Occupation probability and Productivity as response variables. Interactions between factors are represented with an asterisk. The variables with a significant effect on the response variable are shown in bold type. Note: terms are standard error (se) and standard deviation (*Z* value); DM, deterrent measures in place; NDM, no bird deterrent measures in place.

maintaining this trend during the DM + D breeding season (Fig. 2; estimate ± se −0.093 ± 0.359, Wald = −0.258, $P = 1.000$).

We found that occupation probability was significantly higher in the medium-distance population compared with the short-distance one for the NDM breeding season (estimate ± se −0.821 ± 0.234, Wald = −3.509, $P = 0.013$) and the DM breeding season (estimate ± se −0.943 ± 0.238, Wald = −3.968, $P = 0.002$), but not for the DM + D breeding season (estimate ± se −0.601 ± 0.235, Wald = −2.553, $P = 0.207$). The long-distance population showed the lowest occupation probability during the DM and DM + D breeding seasons in comparison with both the medium-distance population (for DM breeding season: estimate ± se 2.257 ± 0.343, Wald = 6.577, $P < 0.0001$; for DM + D breeding season:

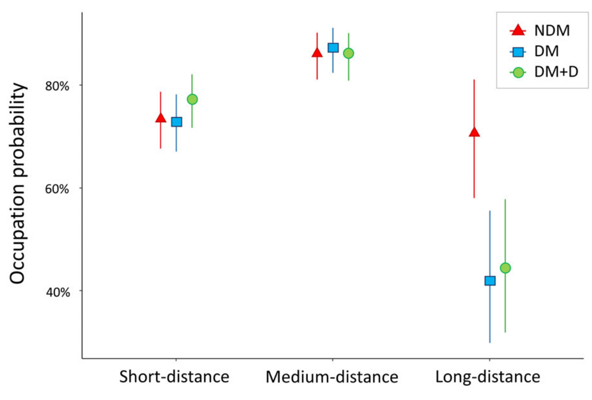

Figure 2. Occupation probability of the populations at the different breeding areas (short-distance, medium-distance, long-distance) during each breeding season (triangles for NDM, squares for DM, circles for DM + D). Whiskers represent the 95% confidence intervals. D, drought; DM, deterrent measures; NDM, no deterrent measures.

estimate ± se 2.054 ± 0.338, Wald = 6.069, $P < 0.0001$) and the short-distance population (for DM breeding season: estimate ± se 1.314 ± 0.312, Wald = 4.204, $P = 0.0009$; for DM + D breeding season: estimate ± se 1.453 ± 0.314, Wald = 4.620, $P = 0.0001$).

According to the multiple comparison tests on productivity, this parameter decreased significantly in the short-distance population during the DM breeding season (estimate ± se 0.284 ± 0.069, Wald = 4.098, $P = 0.001$) but not at the further distances (Fig. 3). The short- and medium-distance populations started from similar productivity values during the NDM breeding season (all $P > 0.05$), both significantly higher than the long-distance population (compared with the short-distance population: estimate ± se 0.802 ± 0.234, Wald = 3.43, $P = 0.018$; compared with the medium-distance population: estimate ± se 0.749 ± 0.236, Wald = 3.18, $P = 0.04$). However, as previously mentioned, productivity in the medium- and long-distance populations only declined during the DM + D breeding season (for the medium-distance population: estimate ± se 0.459 ± 0.103, Wald = 4.434, $P = 0.0003$; for the long-distance population: estimate ± se 1.186 ± 0.345, Wald = 3.441, $P = 0.017$).

DISCUSSION

An association between the use of bird deterrent measures at a landfill site and a decrease in the productivity of a short-distance White Stork breeding population was found in this study. The two studied populations breeding further away (i.e. the medium- and long-distance populations) showed no changes in their productivity values when bird deterrent measures were used at the landfill and, as a result, food availability changed. However, when a severe drought combined with late and abundant rainfall took place during the last studied breeding season, these populations suffered a reduction in this breeding parameter. Occupation probability did not show differences between breeding seasons within the short- and medium-distance breeding areas and was only drastically reduced at the long-distance population during the second studied breeding season.

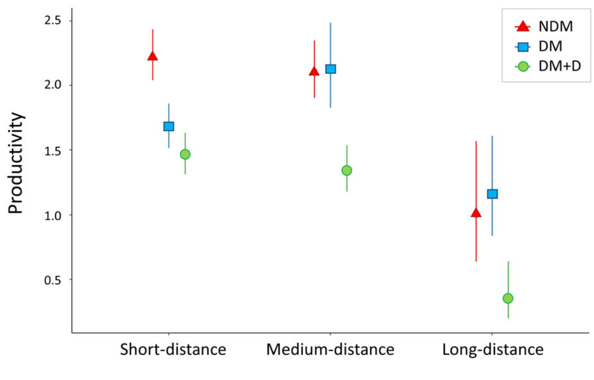

Figure 3. Productivity (mean number of fledglings per breeding pair with known breeding success) of the populations in each breeding area (short-distance, medium-distance, long-distance) during breeding seasons with no deterrent measures (NDM), deterrent measures (DM) or deterrent measures and drought (DM + D). Whiskers represent the 95% confidence intervals.

The occupation probability values in the short-distance population remained stable throughout the three studied breeding seasons, being unaffected by the use of bird deterrent measures at the landfill. Considering that productivity strongly decreased at this breeding area during the DM breeding season (Fig. 3) and that pairs tend to change their nesting site after breeding failure in the previous season (Vergara *et al.* 2006) a decrease in occupation probability was expected at least in the DM + D breeding season, but was not apparent in this study. This probably indicates that the bird deterrent measures' effect on the nest-site selection of breeding pairs takes longer to show than the impact on productivity. The philopatric and semi-colonial behaviour of the White Stork might be causing this delay as the colonization of other suitable breeding areas can take time (Moreira *et al.* 2018).

The long-distance population suffered a drastic reduction in occupation probability between the NDM and the DM breeding seasons. We consider that this is not a consequence of bird deterrent measures as this population did not rely on landfill food during the breeding season (Fig. S1). The DM breeding season was characterized by a severe fire episode near the long-distance breeding area, which might have caused the movement of breeding pairs away from the region. In addition, most of the trees in this area have become unusable as a nesting surface since the cessation of certain agricultural practices, such as ash lopping (Vergara *et al.* 2007), possibly causing breeding pairs to gradually colonize other sites with more nesting options and high food availability, such as urban or semi-natural habitats from which landfill sites are easily accessible (López-García & Aguirre 2023).

The highest occupation probability was found in the medium-distance population, which follows previous findings in which a combination of medium to low landfill use was found to be the best strategy (López-García *et al.* 2021). A higher occupation probability occurred in the medium-distance population in comparison with the short-distance one in the absence of drought, possibly because nest-site selection has been influenced by landfill location (Gilbert *et al.* 2016, López-García *et al.* 2023b) with individuals in the short-distance breeding area changing nests more frequently to be closer to the landfill than in the medium-distance breeding area. A combination of high-quality habitat for nesting and foraging, lower anthropogenic disturbance and the possibility of visiting landfills as an extra food supply when natural resources are scarce might be the optimal conditions for breeding White Storks in the study area.

Regarding productivity, our results showed that the short-distance population suffered a significant reduction in the number of fledglings between the breeding season with no deterrent measures and the breeding season with them being applied. In studies on vultures and gulls, reduced food availability mediated by the closure of predictable anthropogenic food sources pushed individuals to search for new food sources, which impacted the number of breeding pairs, breeding parameters and survival (Pons 1992, Martínez-Abraín *et al.* 2012, Steigerwald *et al.* 2015). Like these previous studies, we found that a reduction in the time and/or frequency of foraging behaviour at the landfill caused by the application of bird deterrent measures at this site diminished the productivity of a dependent White Stork breeding population. This result, together with the absence of changes in productivity at the medium- and long-distance breeding areas, supports that dependence on supplementary feeding increases with proximity to the food supply origin (Hilgartner *et al.* 2014, Soriano-Redondo *et al.* 2021). The predicted lack of impact on the medium- and long-distance populations' productivity found during the DM breeding season shows the broader food source possibilities that these populations can access and proves the capacity of the medium-distance population to quickly adapt to a higher rate of natural food foraging, which has already been shown in gull populations after landfill closure (Zorrozua *et al.* 2020).

Overall, the energy that foraging storks may be spending on vigilance and escape makes foraging at the landfill less efficient since the DM breeding season. If breeders cannot spend the same amount of time foraging at the landfill as during the NDM breeding season or they visit it less frequently, then they could be feeding their brood at a lower rate or in less abundance, and be searching for natural prey further than in the previous breeding seasons. Foraging further than usual from the nesting site in search of natural food resources can involve time and energy costs, which are accentuated by the fact that high-quality habitats might be located far from the nesting location because of a nest-site selection based on the presence of the landfill when the population was initially established (Gilbert *et al.* 2016, Soriano-Redondo *et al.* 2021).

While medium- and long-distance populations were not affected by the diminished accessibility to the landfill, they were more vulnerable to weather conditions, as this directly affects natural food availability. The last studied breeding season (DM + D) was characterized by extreme weather scenarios in the study area, which are known to affect breeding success in White Storks (Tobolka *et al.* 2015). In the NDM and DM breeding seasons high precipitation occurred in April, but during the DM + D breeding season a severe drought took place in April, followed by abundant rainfall in May compared with the other studied seasons (Fig. S2). When this happened, productivity in the medium- and long-distance populations decreased, but not in the short-distance population, bringing to light the mitigation effect of landfill resources for wildlife when natural food availability is low (Evans & Gawlik 2020).

White Stork fledglings are strongly dependent on abundant invertebrate prey in their early development stage, when natural food ingestion along with overall food availability is critical for their survival, and the food found at landfills is usually too big for them to handle (Gilbert *et al.* 2016, Bialas *et al.* 2021). Some of the fledglings that hatched in April during the DM + D breeding season might have died due to inanition or hypothermia because of a low-quality food intake, as prey abundance (i.e. natural food availability) at water-dependent habitats was lower than usual (Pinowski *et al.* 1991, Djerdali *et al.* 2016, Bialas *et al.* 2020). Moreover, April's drought during the DM + D breeding season was followed by strong precipitation in May, in comparison with the NDM and DM breeding seasons (Fig. S2) forcing fledglings hatched in May to endure the heavy rainfall without having yet acquired their thermoregulatory capacity (Tortosa & Castro 2003, Jovani & Tella 2004).

In summary, our results show the effectiveness of the bird deterrent measures used at the Colmenar Viejo landfill as a management tool to control the breeding populations that are dependent on anthropogenic food sources. Their appropriateness is also manifested in the fact that these management measures would not influence populations that feed on natural resources, ensuring their conservation. This study offered an opportunity to show the impact of measures that reduce food availability at landfills, in particular bird deterrents, proving that it harms the productivity of the most dependent populations in the White Stork. Eventually, the occupied nest densities in the surrounding area of landfills will reduce due to displacement to other breeding areas or by consecutive breeding failure events, which may mitigate potential human–wildlife conflicts.

Nonetheless, the latest EU Directives (1999/31/CEE and 2018/850/CE) established aims for more efficient and environmentally respectful waste management, substantially reducing the amount of organic waste in these facilities. A drastic change in landfill refuse management in a short period, together with climate change, may pose a risk for the persistence of the populations (López-García *et al.* 2023a). To detect a critical reduction in recruitment and a possible future population crash, careful long-term monitoring of the surrounding populations is needed. Synergy with landfill management authorities is of vital importance for both reducing human–wildlife conflicts and allowing a gradual departure of White Stork breeding pairs from these sites' close surroundings.

Longer study periods could solve unanswered questions in this study according to the occupation probability variable and confirm the trends that were detected. It would be necessary to collect information from a higher number of breeding areas with a broader range of distances to landfills in other countries to confirm our conclusions in other regions. However, our study case clearly reflected the effects of bird deterrent measures on breeding populations that usually forage at landfills.

Further research could focus on studying the impacts of bird deterrent measures on different species and regions beyond landfill boundaries to provide more data on our inferences and enrich bird population management near these facilities. In addition, individual monitoring of White Storks with a known landfill use index after changes in landfill food availability would provide knowledge of this species' adaptability and habitat selection in the future.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Laura Osorio: Investigation; formal analysis; visualization; writing – original draft. **Alejandro López-García:** Conceptualization; writing – review and editing; methodology; formal analysis; supervision; investigation. **Irene Colino-Freire:** Writing – review and editing; investigation. **Elena Ramos-Elvira:** Writing – review and editing; investigation. **José I. Aguirre:** Conceptualization; methodology; supervision; funding acquisition; writing – review and editing; investigation; resources.

ETHICAL NOTE

No animals experienced any harm during the activities described in this paper, and all procedures were conducted in compliance with state and provincial permit.

Data Availability Statement

The data used in this study are available in Data S1.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Mean Landfill Use Index (LUI) of the identified breeding White Storks in each breeding area during the totality of the surveyed breeding seasons (short-distance: n = 36, medium-distance: n = 181; long-distance: n = 3). The whiskers represent the standard errors. These data include young breeders (1st to 6th calendar year) and adult breeders (after the 6th calendar year).

Figure S2. Mean precipitation (L/m^2) during the surveyed months of the NDM (triangles), DM (squares) and DM + D (circles) breeding seasons at the study area (Madrid, Spain). Silhouettes represent the species' general breeding phenology in the Iberian Peninsula: incubation in April, hatching in May and grown-up fledglings in June (Bernis 1981). Data were reported by the State Meteorological Agency's website and are a result of the average between the community's meteorological stations. Normal values are the average data on a period from 1982 to 2010 (*).

Table S1. Number of nesting sites, occupied nests (Nests; with the number of nests with known breeding success in brackets) and mean number of fledglings ± the standard error (Productivity) according to the breeding area and breeding season.