Ecological Indicators 178 (2025) 113796

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

A death trap in the nest: anthropogenic nest materials cause high mortality in a terrestrial bird

Ursula M. Heinze[a,*], Marta Acácio[b], Aldina M.A. Franco[a], Inês Catry[c,*]

[a] School of Environmental Sciences, University of East Anglia, Research Park, Norwich NR4 7TJ, UK
[b] MIVEGEC, University of Montpellier, CNRS, IRD, Centre IRD, 34090 Montpellier, France
[c] Centre for Ecology, Evolution and Environmental Changes (CE3C) & CHANGE - Global Change and Sustainability Institute, Faculdade de Ciências da Universidade de Lisboa, 1749-016 Lisbon, Portugal

ARTICLE INFO

Keywords:
Human debris
Waste
Plastic pollution
Baler twine
Entanglement
Breeding success
White stork

ABSTRACT

The impact of anthropogenic debris on wildlife, particularly in marine environments, has garnered significant attention in recent years due to the severity of its effects. In terrestrial environments, the incorporation of human-derived materials into bird nests is well documented, yet most studies primarily focused on quantifying their prevalence rather than systematically examining their direct impacts, particularly on entanglement mortality. This study investigates the use of anthropogenic nest materials (ANMs) by a long-lived bird species and their impact on nestling mortality. Over four years, we photographed 568 white stork (*Ciconia ciconia*) nests to quantify ANMs and nestling mortality, while in 2023, we monitored 93 nests weekly from hatching to fledging to identify vulnerable developmental stages and high-risk materials. Habitat characteristics and proximity to landfill sites were analysed to infer ANM sources. ANMs were present in 91% of nests, with ropes – the main cause of entanglement – found in 42%. Entanglements, often fatal due to injuries such as necrosis and limb loss, were recorded in nearly one-third of the nests, affecting 12% of all nestlings. Most entanglements occurred in early nestling stages (mean age: 2 weeks ± 1.38), highlighting that such fatalities may go undetected without early monitoring of nests. Entanglement risk increased with the number of ropes in the nests which were associated with agricultural areas. Baler twine, a slow degrading polypropylene rope used in agriculture, accounted for 63% of entanglements. This study reveals the widespread use of ANMs, their harmful effects on terrestrial birds, and the urgent need to mitigate baler twine pollution through management actions that minimise the impacts on the species affected by ANMs.

1. Introduction

Global waste production has reached 2126 billion tonnes annually in 2020 and is projected to increase dramatically in the next centuries (UNEP and ISWP, 2024). 38% of it is uncontrolled disposed waste, leading to an accumulation of materials with low decomposition rates in the environment (UNEP and ISWP, 2024). Global reports show this pollution has reached even the most remote ecosystems, with anthropogenic debris found in remote locations such as islands (Tavares et al., 2019), deserts (Zylstra, 2013), and all the way to the deepest point of the sea, the Mariana trench (Chiba et al., 2018). Anthropogenic debris poses various threats to wildlife, including the ingestion of harmful materials by fish (Savoca et al., 2021), mammals (Thrift et al., 2022) and birds (Mee et al., 2007), which can clog up their digestive systems (Wright et al., 2013). Additionally, it also causes entanglement in turtles (Duncan et al., 2017), mammals (Poeta et al., 2017), birds (Ryan, 2018) and fish (Stelfox et al., 2016), further endangering their survival. Plastic is the type of waste most often reported to harm wildlife (Duncan et al., 2017; Malizia and Monmany-Garzia, 2019; Ryan, 2018; Stelfox et al., 2016; Thrift et al., 2022; Wilcox et al., 2016). Each year, more plastic is released into terrestrial ecosystems than marine ecosystems (Lau et al., 2020) but most studies on the effects of anthropogenic debris focus on marine environments (Jagiello et al., 2019; Malizia and Monmany-Garzia, 2019). Thus, there is a significant disparity between the amount of pollution (Hahladakis, 2020; Lau et al., 2020; MacLeod et al., 2021) and the number of studies investigating its impacts in terrestrial environments (Jagiello et al., 2019; Malizia and Monmany-Garzia, 2019).

One often overlooked impact of anthropogenic debris is the incorporation of these materials in nests by birds (Battisti et al, 2019), a

* Corresponding authors.

https://doi.org/10.1016/j.ecolind.2025.113796
Received 7 December 2024; Received in revised form 25 May 2025; Accepted 22 June 2025
Available online 14 July 2025

common behaviour throughout avian phylogeny (Jagiello et al., 2023b), but more frequent in terrestrial species (Jagiello et al., 2019). The reasons for incorporating anthropogenic nesting materials (ANMs) are not yet fully understood, but may be related to the availability of anthropogenic nesting materials and scarcity of natural ones, but also to behavioural imprinting and to signal the fitness of the nest-builder (Jagiello et al., 2023b) and ectoparasite defence (Suárez-Rodríguez et al., 2013). Some materials might also be mistaken for food, being inadvertently incorporated in the nests (Mikula et al., 2024). However, ANMs differ in their properties from natural materials (Blem et al., 2002; Corrales-Moya et al., 2021; Townsend and Barker, 2014), which can change the microclimate of the nest (Corrales-Moya et al., 2021; Veríssimo et al., 2024), promote waste ingestion by the nestlings (Mee et al., 2007) and cause increased visibility and nest predation (Corrales-Moya et al., 2023). In addition, ANMs can cause entanglements, leading to lethal injuries; e.g. necrosis and loss of limbs (Battisti et al., 2019; Townsend and Barker, 2014).

Most studies on ANMs predominantly centre on the assessment of nest contents (Esquivel et al., 2020; Kang et al., 2023) and relating them to the surrounding environment (Blettler et al., 2020; Francila et al., 2023; Hartwig et al., 2007; Jagiello et al., 2023a; Luna et al., 2024). Indeed, nests located in urbanised and more polluted areas show higher frequency of ANMs (Blettler et al., 2020; Francila et al., 2023; Hartwig et al., 2007; Jagiello et al., 2019; Luna et al., 2024; O'Hanlon et al., 2019; Vasquez et al., 2022). However, the fitness consequences of ANMs for nestlings are rarely assessed (Houston and Scott, 2006; Janic et al., 2023; Townsend and Barker, 2014). When such assessments are conducted, they often occur at the end of the nestling period (Blem et al., 2002; Houston and Scott, 2006; Janic et al., 2023) not considering which developmental stages are more vulnerable, potentially biasing survival estimates and underestimating the true impacts of ANMs on nestlings.

White storks are a species known to incorporate ANMs into their nests (Jagiello et al., 2023a; Jagiello et al., 2018; Lasota et al., 2024). Storks frequently nest near or within human settlements and tend to rely on landfills as consistent food sources (Gilbert et al., 2016), and are often used as an environmental indicator (Kronenberg et al., 2017; Tobolka et al., 2012). Studies show that the amount of human-made materials in nests increases in areas with high human activity and proximity to landfills (Jagiello et al., 2023a; Jagiello et al., 2018), which raises concerns on their effects on nestlings. But while the feeding on rubber bands in adult storks has been shown to cause mortality (Henry et al., 2011), the effects of ANMs on fledgling survival rates remain understudied.

The goals of this study are to (1) assess the prevalence of ANMs in white stork nests, (2) identify potentially hazardous materials and evaluate their impact on nestling mortality rates, and (3) determine the origin of hazardous ANMs, by correlating their occurrence with the surrounding habitat of the nests. Our main goal is to identify the ANMs that may pose significant risks to terrestrial bird species and pinpoint

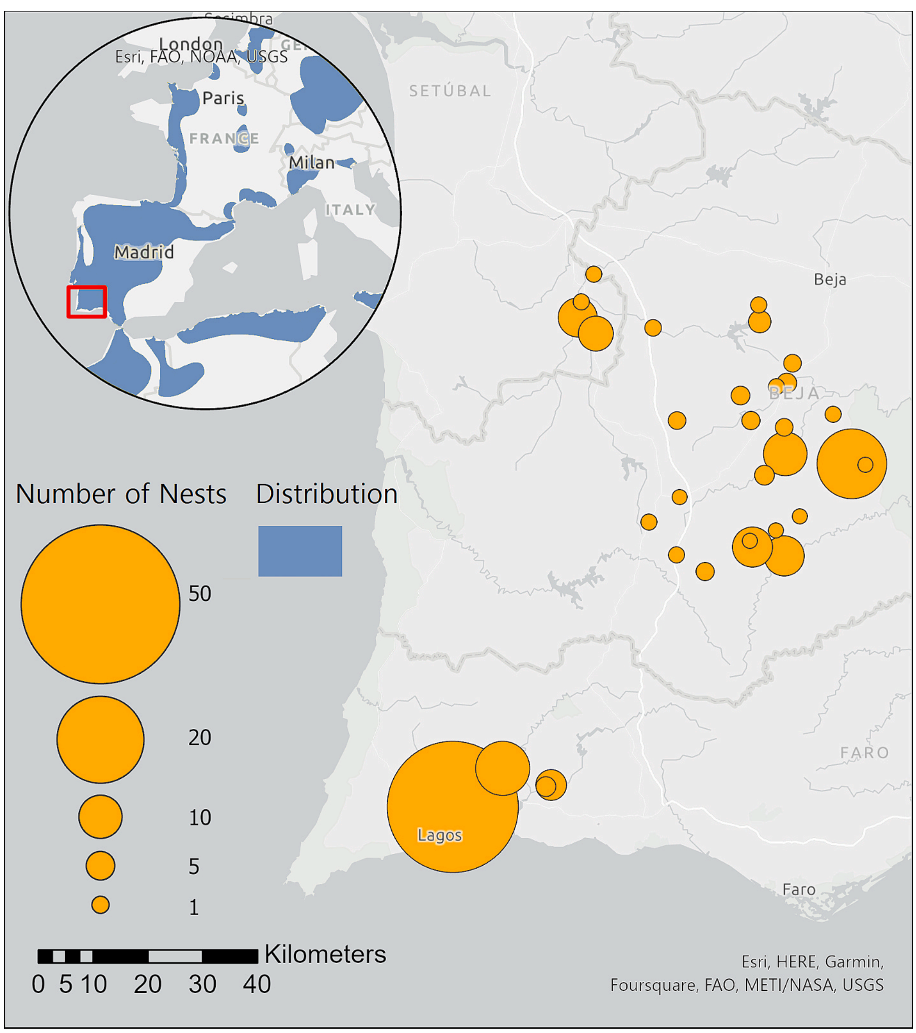

Fig. 1. Location of the 32 monitored white stork colonies in Southern Portugal. The size of the circles indicates the number of nests per colony averaged over the four study years. The inset shows the location of the study area in Western Europe.

their origins, in order to develop effective strategies to mitigate these risks to wildlife.

2. Methods

2.1. Study area and study system

Between 2018 and 2023, we monitored 32 white stork colonies and 568 nests (mean 142 ± 36 nests/year) in southern Portugal (Alentejo and Algarve, Fig. 1). Colony size ranged from one to 63 breeding pairs (mean 17.8 ± 31.9). The habitat surrounding the colonies was highly variable: some colonies were within urban settlements or near urbanised areas and landfills, while others were surrounded by *montado*, a traditional Mediterranean agro-silvo pastoral system, characterised by the co-existence of open woodland, dominated by cork oaks (*Quercus suber*) and holm oaks (*Quercus ilex*), with extensive grasslands and agricultural land (Pinto-Correia et al., 2011). Nests were mostly located on trees (pines, olive trees, and holm and cork oaks) and in some cases on artificial structures, such as telephone and electricity poles and buildings.

2.2. Nest monitoring and breeding parameters

Between 2018 and 2023, we monitored over 100 white stork nests/year: 100 in 2018, 173 in 2019, 170 in 2020 and 125 in 2023. The nests were photographed on a weekly basis from March until July using a small camera (GoPro Hero session 5) attached to a 10 m telescopic pole, or, on rare occasions, using a drone. These photographs allowed us to estimate the breeding parameters (laying and hatching dates, clutch size, brood size, and number of fledglings).

2.3. Nestling examination and entanglements

In addition to the regular monitoring, in 2023 we also physically examined the nestlings of 93 nests on a weekly basis, to assess the threats posed by exposure to anthropogenic materials. Entanglements were the most common threat; we quantified how many nestlings were entangled and identified the materials causing the entanglements. We accessed the nests that were accessible with a ladder, freed the entangled nestlings and removed the material that had caused the entanglement. We did not determine causes of death, since most dead nestlings are removed from the nests by the parents and are often quickly predated, making it impossible to perform necropsies.

All fieldwork was carried out in agreement with the recommendations of Instituto da Conservação da Natureza e das Florestas (ICNF) under the licenses 549/2018/CAPT, 248/2019/CAPT, 365/2020/CAPT, 199/2021/CAPT, 542/2022/CAPT and 505/2023/CAPT.

2.4. Assessment of nest contents

ANMs were assessed by a single observer from photos of the nests. During weekly visits over four years, we collected more than 6000 nest images. From this extensive dataset, we selected two images per nest: one taken during incubation (i.e., with eggs) and another when the nestlings were less than two weeks old, prioritising the images with most visible ANMs. We focused on the early breeding period to ensure clear visibility of nest contents, as nestlings grow quickly but cover only a small portion of the nest when younger than 2 weeks (see Fig. 2a). To verify the accuracy of ANM identification from the photos, we compared them with visual inspections conducted in 2023, when the nests were examined for chick entanglements.

ANMs were categorised according to the type of material or their function (e.g., ropes, fabric, paper, etc. see Table 1 for a full list of

Fig. 2. Nests with ANMs and examples of injuries caused by anthropogenic materials in white stork nestlings**.** Two nests showing the typical construction of a stork nest, built out of sticks and lined with grass; both contain a large number of ANMs in the lining. One with soft plastic and paper (a) and other with many ropes (blue areas, b). Entanglement in rope (c, d), leading to lacerations (d), necrosis and amputations (e). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Anthropogenic nesting materials found in white stork nests. Frequency of occurrence, mean number of ANM items (n = 568 nests) and number of nestlings entangled (n = 93).

Item category	Frequency of occurrence	Mean number of items per nest [range]	Number of nestlings entangled	Description
Rope	42%	0.9 [0–22]	22	Rope (in most cases baler twine)
Baler wrap	13%	0.1 [0–2.5]	6	Plastic mesh, used to cover hay balers
Soft plastic	65%	1.5 [0–14]	2	Bendable plastic (e.g., plastic bags)
Cover	32%	0.3 [0–7]	2	Plastic sheets created from woven plastic threads, used as a protection from weeds in agriculture
Paper	25%	0.4 [0–10]	0	Any paper or cardboard
Sponge	9%	0.1 [0–2]	0	Sponge (any material)
Fabrics	18%	0.2 [0–5]	0	Fabrics (any material, e.g., clothing)
Hard plastic	9%	0.1 [0–2]	0	Not bendable plastic (e.g., milk containers)
Unidentified	59%	1.0 [0–10]	3	Not identifiable or other material
ANMs (total)	91%	4.6 [0–31]	35	

categories). We manually counted and categorised the items in the nests using the program ImageJ (Schneider et al., 2012), and averaged the number of items in each category between the two selected images.

2.5. *Origin of anthropogenic nest materials (ANM)*

To determine the origin of materials prone to cause entanglements we analysed the habitat surrounding the white stork colonies. We extracted the land use from the CORINE land cover 2018 layer (mapping unit: 25 ha) (Copernicus Land Monitoring, 2018) in a 3.5 km radius around the central coordinate of each colony, which is the average foraging range of storks during breeding (Gilbert et al., 2016). After extraction, we merged some of the land use categories and grouped the land uses that are unsuitable for white storks, hence we reduced the 30 land uses to nine classes (Appendix A Table S1).

As indicators for human influence, we extracted the mean population density from the GHSL population density layer (mapping unit: 9 arc seconds, population per grid cell) (JRC, 2021) and measured the geodesic distance in kilometres to main roads, settlements and landfills. For the distance to roads, we used a layer depicting only the main roads (EuroGeographics, 2016) and for the distance to settlements and landfills, satellite images of the Esri World imagery (Esri, 2023). All data extractions and measurements were conducted with ArcGIS Pro (ESRI Inc., 2023).

2.6. *Statistical analysis*

Using a generalised linear model (GLM) with a binomial distribution and a logit link function, we related the presence (1) or absence (0) of chick entanglements within a nest, with the average number of hazardous items (materials known to have caused an entanglement during this study, (Table 1) and the number of ropes (that caused most entanglements) (n = 93 nests). In addition, we built a model in the same way, but specifically relating the number of entanglements in ropes to the average number of ropes present in the nest. Only hazardous materials were considered in the models as we did not expect significant results with materials that were not involved in entanglements which were the only cause of mortality observed (Table 1).

To investigate the impact of ANMs on nestling mortality rates, we modelled the proportion of nestlings that died in each nest (i.e., dead/fledged) using two generalised linear mixed models (GLMM), with a binomial distribution and a logit link function. In the first model, the predictors included the average number of hazardous items per nest (including ropes), while the second model considered only the impact of ropes. Laying date as Julian week was included in both models, to account for a negative impact of a later laying date on nestling survival (Soriano-Redondo et al., 2023). Colony ID and year were fitted as random intercepts. For this analysis we excluded the nests in which we had no data on nestling survival and the 93 nests in which we freed nestlings from entanglements, as this affected their likelihood of survival (n = 455 nests). We used Akaike's Information criterion to select the model with the best fit. (Akaike, 1974).

Finally, we used a GLMM with binomial distribution and a logit link function, to evaluate if the presence (1) or absence (0) of ropes in the nests was correlated with selected habitat variables, accounting for colony and year as random intercepts (n = 568 nests). Considering the large number of land use categories and habitat variables surrounding the colonies (13), we pre-selected the variables to be included in the main multivariate model. To do so, we built a series of univariate models, testing the relationship between the presence/absence of ropes and each variable, and included in the multivariate model only the variables with a p-value < 0.25. Consequently, the multivariate model included distance to landfill (categorical in 5 km intervals), the relative cover of agro-forestry areas, non-irrigated arable land and permanently irrigated arable land. We then used dredge (MuMIn R package, (Barton, 2023) to identify the combination of variables that produced the optimal models based on the Akaike's information criterion modified for small sample size (AICc).

For all models, we analysed the residuals using DHARMa R package (Hartig, 2022). All analyses were performed in R Core Team version 4.3.0 (R Core Team, 2023).

3. Results

The majority of nests (91%) contained ANMs, with soft plastic being the most prevalent category, found in 65% of all nests. This was followed by rope, which was present in 42% of nests, with an average of 0.9 ± 1.88 ropes per nest. In 2023, 12% of the nestlings became entangled in ANMs, with entanglement occurring in 27% of the nests (n = 93 nests, n = 290 nestlings, Table 1, Fig. 2). In 63% of cases, entanglements were caused by ropes (Table 1). The number of ropes per nest was highly variable with nests having up to 22 ropes (Table 1).

3.1. *Nestling entanglement and mortality*

The majority of the entanglements, affecting 12% of nestlings (Table 1), occurred early in their life (mean age at entanglement = 2.09 weeks ± 1.38). Only in one case the entangled nestlings were older than 4 weeks (7 weeks). We found multiple entanglements in the same nest; in six cases, siblings were entangled at the same time, and two nestlings became entangled more than once (one nestling twice and another three times) despite the fact that the original entanglement materials were removed from the nests.

Most entanglements were caused by ropes, accounting for 22 out of the total 35 (63%) incidents. Among these, 17 nestlings (49%) were entangled with baler twine, a polypropylene rope commonly used in agriculture (Table 1; examples shown in Fig. 2). While the first model was non-significant, we found a positive and significant correlation between the number of ropes in a nest and the probability of becoming entangled in them (Table 2, Fig. 3a).

Table 2
Summary statistics of the binomial GLMM predicting nestling rope entanglement in white storks (n = 93). Model estimates, standard errors (SE) and measures of significance as p- and z-values are presented.

Predictors	Estimate (± SE)	z-value	p
(Intercept)	−1.93 ± 0.35	−5.48	<0.001
Number of ropes	0.29 ± 0.13	2.28	0.023

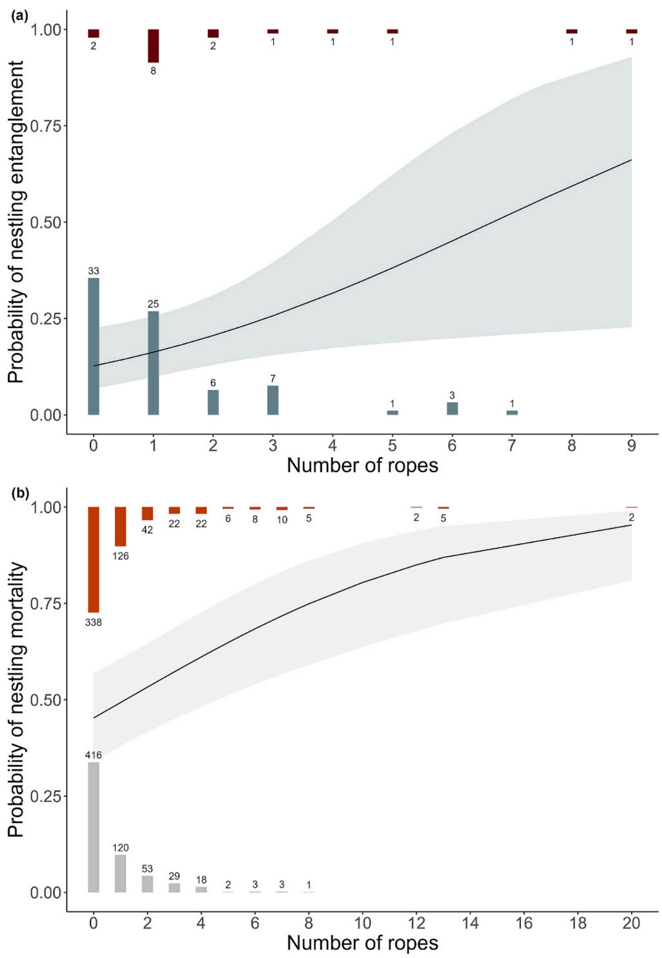

Fig. 3. Predicted probabilities of nestling (a) entanglement (n = 93) and (b) mortality (n = 455) in relation to the number of ropes in the nest. The black lines show the predicted model probability, and the shaded area the 95% confidence interval. (a) The number of nests is displayed in the bars; nests with (red, top) and without (grey, bottom) entanglements. (b) The bars represent observations of nestlings that died (red, top) and nestlings that fledged (grey, bottom). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Additionally, we found that the probability of nestling mortality increased with both the number of materials known to cause entanglements and the number of ropes found in a nest (Table 3). While both models were significant, the AIC value was considerably lower for the model with ropes (Table 4). For every additional rope in the nest, the mortality probability increased by a factor of 1.17 (estimate = 0.16, SE = 0.04, p < 0.001) (Table 3, Fig. 3b).

3.2. Rope origin and nest surroundings

Colonies had heterogeneous surroundings, with some nests being almost entirely surrounded by agriculture and others within or near

Table 3
Summary statistics of the binomial GLMMs predicting nestling mortality (n = 455). Model estimates, standard errors (SE), measures of significance as p- and z-values and AIC values are presented.

Model	Predictors	Estimate (± SE)	z-value	p	AIC
1. probability of nestling mortality ~ number of ropes + laying date	(Intercept)	−2.71 ± 0.51	−5.31	<0.001	1075.38
	Number of ropes	0.16 ± 0.04	4.02	<0.001	
	Laying date	0.23 ± 0.04	5.47	<0.001	
2 probability of nestling mortality ~ number of hazardous items + laying date	(Intercept)	−2.83 ± 0.51	−5.50	<0.001	1088.00
	Number of hazardous items	0.06 ± 0.02	2.56	0.010	
	Laying date	0.24 ± 0.04	5.73	<0.001	

settlements or close to landfills (Appendix A Table S2, Fig. S1). We performed a series of GLMs to determine the variables associated with the number of ropes in the nests, including landfill distance, relative cover of permanently irrigated land, non-irrigated arable land and agro-forestry areas. However, only the two latter variables remained significant after testing the models separately and using the dredge function (ΔAICc < 2, Table 4). The probability of finding ropes in white stork nests increased in areas with higher relative cover of non-irrigated arable land (estimate = 1.03, SE = 0.30, p < 0.001) and agro-forestry areas (estimate = 0.92; SE = 0.30; p = 0.002) around the nests (Table 4, Fig. 4).

4. Discussion

In this study, we conducted the first comprehensive survey of nestling entanglements in a terrestrial bird species by systematically monitoring nests throughout the entire nestling developmental period. Our findings offer new insights into the extent of nestling mortality caused by entanglement in anthropogenic nesting materials (ANMs).

White stork chicks in nests containing a higher number of ropes were more likely to become entangled and exhibited lower survival rates. We found that 12% of nestlings became entangled, with baler twine accounting for more than half of the incidents. Ropes, including baler twines, were present in nearly half of the nests, particularly in colonies surrounded by agricultural areas. This study highlights the urgent need to remove polypropylene baler twine from both agricultural use and the environment, given its detrimental impacts on nestlings.

4.1. ANMs and entanglement-related mortality

The use of ANMs was pervasive across the studied white stork population, more than 90% of the nests visited across a range of habitats and distances to landfill sites had ANMs. This is not unusual; many other studies of terrestrial (Antczak et al., 2010; Blettler et al., 2020; Corrales-Moya et al., 2021; Kang et al., 2023) and marine bird species (Montevecchi, 1991; O'Hanlon et al., 2019) have reported ANMs in over 90% of the nests surveyed. Yet, in contrast to other studies, which report entanglement rates mostly ranging from 0.34% to 5.6%, we found a high percentage of nestlings entangled (12%) (Janic et al., 2023; Mallet et al., 2020; Restani, 2023; Seacor et al., 2014; Townsend and Barker, 2014; Votier et al., 2011). Only one study reported similar entanglement rates

Table 4
Models predicting probability of rope occurrence in white stork nests in relation to habitat surrounding the colonies (n = 568). Three best generalised linear mixed models (ΔAICc < 2) and their coefficients (SD = standard deviation), with Log-likelihood function (logLik), Akaike information criteria with correction for small sample sizes (AICc), AICc differences (Δi) and Akaike weights.

Model	(Intercept)	Landfill distance (categorical) ± SD	Agro-forestry areas (scaled) ± SD	Non-irrigated arable land (scaled) ± SD	Permanently irrigated land (scaled) ± SD	logLik	AICc	Δi	Akaike weight
1	−0.91 ± 0.55	–	0.92 ± 0.30	1.03 ± 0.30	–	−312.33	634.65	0.00	0.44
2	−0.79 ± 0.65	<5km 0.79 ± 1.13 >5 km 0.90 ± 0.96	0.87 ± 0.33	0.96 ± 0.37	–	−311.25	636.49	1.84	0.18
3	−0.90 ± 0.55	–	0.91 ± 0.32	1.02 ± 0.31	−0.04 ± 0.32	−312.32	636.64	1.99	0.16

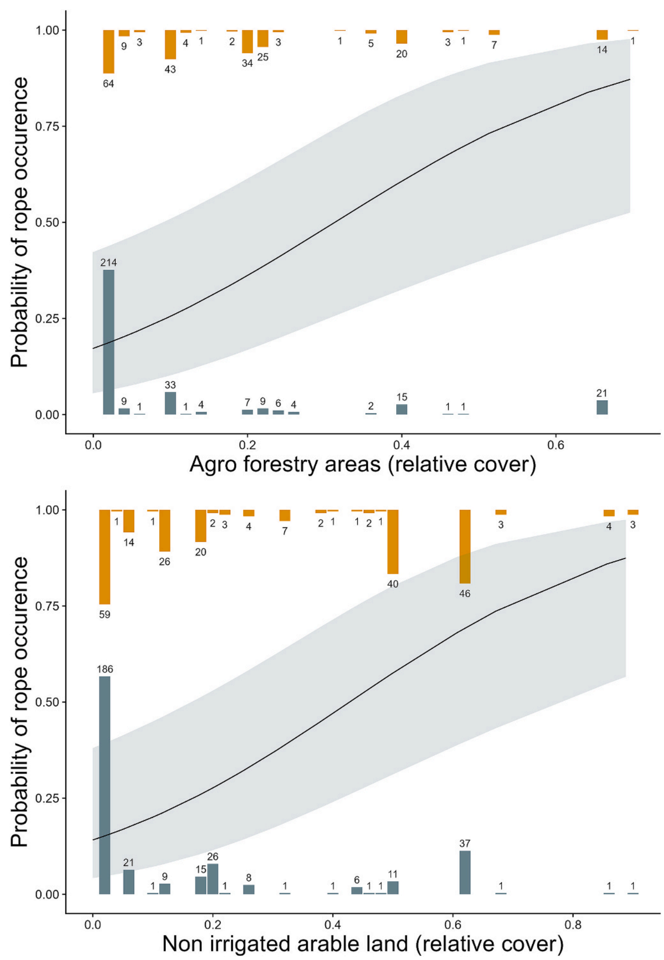

Fig. 4. Probability of rope occurrence in white stork nests (n = 568) in relation to the surrounding habitats: (a) relative agro-forestry cover and (b) relative cover of non-irrigated arable land. The black line shows the predicted model probability, and the shaded area the 95% confidence interval. The number of nests are displayed in the bars; nests with ropes (yellow, top) and without (grey, bottom). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(11.7%) in ospreys (*Pandion haliaetus*) (Houston and Scott 2006).

The low entanglement rates found for species with similar high occurrence rates of ANMs (Restani, 2023; Seacor et al., 2014; Townsend and Barker, 2014), might be explained due to the low number of nest visits, particularly during the early nestling stages. Indeed, most studies calculate entanglement rates based on a single or a few visits, often performed close to the age of fledging, when the chicks are ringed (Janic et al., 2023; Mallet et al., 2020; Restani, 2023; Seacor et al., 2014). Given our observations and results showing that most entanglements occur within the first couple of weeks after hatching, a single visit in the fledging stage is likely to underestimate the true entanglement rates.

Overall, our findings suggest that the threat posed by ANMs and specifically baler twine to terrestrial birds may be far more severe than previously recognised. Especially, as the external assessment of nestlings only accounts for ANM-related entanglement and does not consider other ANM-driven mortality risks such as ingestion (Henry et al., 2011; Lopes et al., 2021) or changes in nest microclimate (Corrales-Moya et al., 2021). Although ropes were not the most common ANM, this material—and especially baler twine—was responsible for the highest number of entanglements, suggesting it is the most significant cause mortality through entanglements. The reason it is so dangerous to nestlings may lie in its properties. It is a long, flexible material made up of many strong polypropylene strands (Townsend and Sette, 2016), which breaks up into individual strands in nests, increasing the risk of entanglement.

As a common indicator species (Kronenberg et al., 2017; Tobolka et al., 2012), the entanglements of white storks in baler twine reported in this study, highlights a broader environmental issue not limited to white storks or Portugal. This material is used in agriculture worldwide and entanglements have been reported in ospreys in North America (Blem et al., 2002; Houston and Scott, 2006), caracaras (*Caracara plancus*) in Argentina (Mallet et al., 2020), and black storks (*Ciconia nigra*) in Poland (Janic et al., 2023). In our study area, there are records of baler twine entanglements in two endangered species, the lesser kestrel (*Falco naumanni*) and jackdaw (*Corvus monedula*) (Almeida et al., 2022).

As entanglements are poorly understood, and in marine birds a review found reports of entanglement in over 36% of species (Ryan, 2018) we predict that future research will reveal also a higher number of terrestrial species affected.

In addition to the obvious animal welfare concerns, baler twine entanglement is also a concern for conservation, as the presence and effects baler twine has on white storks is a robust indicator for a high probability that vulnerable conservation species may also be affected, as shown by the observations in our study area. Further work to identify the high-risk materials is therefore crucial, and future policy action needs to be prioritised.

4.2. Origin of baler twine pollution

Baler twine has a very specific agricultural purpose, to tie hay or straw balers. Nonetheless, due to its flexibility and strength, this thread is quite versatile, making it a common resource in rural areas, where it is reused by the population for various daily tasks. Across Europe, 80 thousands tones (kt) of twine are used every year (EIP-AGRI, 2021) and agricultural waste such as twine are often not disposed properly, but often buried in the fields (Briassoulis et al., 2010). As baler twine has very long decomposition rates (~30 years), it accumulates and remains highly available in agricultural areas (Alsabri et al., 2022).

Areas used for grazing and feeding livestock (non-irrigated arable land and agroforestry areas) are more affected by its contamination than other areas with more diverse and concentrated waste, such as landfills. This hazardous and long-lasting contamination of natural and semi-natural habitats highlights the need for policy actions that limit the use of these materials.

4.3. Implications and recommendations

Policies addressing materials hazardous to wildlife can be legislated where there is sufficient political will, as demonstrated by past initiatives such as the ban on non-degradable six-pack holders in Vermont (NEPIS, 1993), the prohibition of single-use plastics in the European Union (Directive (EU) 2019/904) and Canada (GoC, 2022) and the ban of single-use polythene materials in East African Community member states (EAC, 2016). But none of these address baler twine and progress in reducing baler twine pollution has been limited. Only a few local initiatives exist, such as an awareness campaign in Portugal (Projecto - SISAL, 2025) and a tech company developing biodegradable alternatives (Cordex, 2023). Elsewhere in Europe, initiatives often fall short —for example, in Germany, a system that should have made recycling possible (baler twine cannot enter the usual recycling facilities, as it blocks the machines), requires farmers to often travel over 50 km to specialised recycling centres and pay for the disposal (ERDE, 2025).

This study adds to the growing body of reports and studies showing that baler twine is a widespread problem, causing avoidable mortality in wildlife (Blem et al., 2002; Janic et al., 2023; Restani, 2023). Thus, we argue that polypropylene baler twine should also be considered a hazardous material and removed from use. Sisal has only been replaced by plastic in the last 38 years (Townsend and Sette 2016), the switch to this previously used, more biodegradable material might be an option. In addition to the transition from plastic-based baler twine, which persists in the environment for centuries (Alsabri et al., 2022), environmental remediation may be required to prevent the prolonged presence of strands and avoid their detrimental impacts.

Similarly to what has been established in the marine environment, this study contributes to the recognition that plastic materials are also dangerous in terrestrial environments and can be used as anthropogenic nesting materials that pose a serious entanglement threat to nestlings (Battisti et al., 2019; Ryan, 2018; Votier et al., 2011). This study highlights that terrestrial bird entanglements require implementation of new policies to reduce the prevalence of dangerous materials in terrestrial environments.

CRediT authorship contribution statement

Ursula M. Heinze: Writing – original draft, Investigation, Methodology, Formal analysis. **Marta Acácio:** Supervision, Investigation, Data curation, Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Aldina M.A. Franco:** Supervision, Investigation, Conceptualization, Writing – review & editing, Methodology, Funding acquisition. **Inês Catry:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization, Supervision, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are grateful to Joana Marcelino and Katy Mitchell for their contributions during fieldwork in 2023, and to Claudia Sans Gómez for creating the white stork graphic. This work was financed by the British Ecological Society (Large Grant LRB22/1006), by the FEDER Funds through the Operational Competitiveness Factors Program - COMPETE and by National Funds through FCT - Foundation for Science and Technology within the scope of the project "POCI-01-0145-FEDER-028176 and UID/00329/2025. " MA was supported by the Natural Environment Research Council (NE/N012070/1) and by Campus France with a MOPGA Fellowship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113796.

Data availability

Data will be made available on request.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Autom. Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705.

Almeida, J., Godinho, C., Leitão, D., Lopes, R.J., 2022. Lista Vermelha das Aves de Portugal Continental. SPEA, ICNF, LabOR/UÉ, CIBIO/BIOPOLIS. https://www.listavermelhadasaves.pt/lista-vermelha/ (accessed 24 October 2024).

Alsabri, A., Tahir, F., Al-Ghamdi, S.G., 2022. Environmental impacts of polypropylene (PP) production and prospects of its recycling in the GCC region. Mater. Today 56, 2245–2251. https://doi.org/10.1016/j.matpr.2021.11.574.

Antczak, M., Hromada, M., Czechowski, P., Tabor, J., Zabłocki, P., Grzybek, J., Tryjanowski, P., 2010. A new material for old solutions—the case of plastic string used in Great Grey Shrike nests. Act. Ethol. 13, 87–91. https://doi.org/10.1007/s10211-010-0077-2.

Barton, K., 2023. MuMIn: Multi-Model Inference. Comprehensive R Archive Network (CRAN). https://cran.r-project.org/web/packages/MuMIn/index.html (accessed 2 August 2023).

Battisti, C., Staffieri, E., Poeta, G., Sorace, A., Luiselli, L., Amori, G., 2019. Interactions between anthropogenic litter and birds: a global review with a 'black-list' of species. Mar. Pollut. Bull. 138, 93–114. https://doi.org/10.1016/j.marpolbul.2018.11.017.

Blem, C., Blem, L., Harmata, P., 2002. Twine causes significant mortality in nestling Ospreys. Wilson Bull. 114, 528–529. https://doi.org/10.1676/0043-5643(2002)114[0528:TCSMIN]2.0.CO;2.

Blettler, M., Gauna, L., Andréault, A., Abrial, E., Lorenzón, R., Espínola, L.A., Wantzen, K., 2020. The use of anthropogenic debris as nesting material by the greater thornbird, an inland–wetland-associated bird of South America. Environ. Sci. Pollut. Res. 27, 41647–41655. https://doi.org/10.1007/s11356-020-10124-4.

Briassoulis, D., Hiskakis, M., Scarascia, G., Picuno, P., Delgado, C., Dejean, C., 2010. Labeling scheme for agricultural plastic wastes in Europe. Qual. Assur. Saf. Crops Food 2, 93–104. https://doi.org/10.1111/j.1757-837X.2010.00061.x.

Chiba, S., Saito, H., Fletcher, R., Yogi, T., Kayo, M., Miyagi, S., Ogido, M., Fujikura, K., 2018. Human footprint in the abyss: 30 year records of deep-sea plastic debris. Mar. Policy 96, 204–212. https://doi.org/10.1016/j.marpol.2018.03.022.

Copernicus Land Monitoring, 2018. CORINE LAND COVER 2018. EEA.

Cordex, 2023. Cordex - Biocord. https://cordex.com/biocord/ (accessed 17 February 2025).

Corrales-Moya, J., Barrantes, G., Chacón-Madrigal, E., Sandoval, L., 2021. Human waste used as nesting material affects nest cooling in the clay-colored thrush. Environ. Pollut. 284, 117539. https://doi.org/10.1016/j.envpol.2021.117539.

Corrales-Moya, J., Barrantes, G., Chacón-Madrigal, E., Sandoval, L., 2023. A potential consequence for urban birds' fitness: Exposed anthropogenic nest materials reduce nest survival in the clay-colored thrush. Environ. Pollut. 326, 121456. https://doi.org/10.1016/j.envpol.2023.121456.

Directive (EU) 2019/904. of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment. https://eur-lex.europa.eu/eli/dir/2019/904/oj (accessed 5 August 2023).

Duncan, E.M., Botterell, Z.L., Broderick, A.C., Galloway, T.S., Lindeque, P.K., Nuno, A., Godley, B.J., 2017. A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action. Endanger. Species Res. 34, 431–448. https://doi.org/10.3354/esr00865.

EAC, 2016. East African Community Polythene Materials Control Bill, 2016. https://kenyalaw.org/kl/fileadmin/pdfdownloads/EALA_Legislation/EASTAFRICANCOMMUNITYPOLYTHENEMATERIALSCONTROLBILL2016.pdf (accessed 24 October 2024).

EIP-AGRI, 2021. EIP-AGRI Focus Group. Reducing the plastic footprint of agriculture. European Comission. https://ec.europa.eu/eip/agriculture/sites/default/files/eip-agri_fg_plastic_footprint_final_report_2021_en.pdf (accessed 10 December 2023).

ERDE, 2025. ERDE Sammelstellen und Termine. https://www.erde-recycling.de/erntekunststoffe-abgeben/sammelstelle-finden/?tx_rigkcollectionpoints_collectionpointmap%5Baction%5D=showCollectionPointMap&tx_rigkcollectionpoints_collectionpointmap%5Bcontroller%5D=CollectionPoint&cHash=ae6291f1f1ef91d7654c01d55d3a346b#collectionpoints (accessed 17 February 2025).

Esquivel, C., La O, J.M. de, Sánchez Vargas, S., Paniagua, S., Esquivel Cambronero, A., Núñez, D., Quesada Ávila, G., 2020. Anthropogenic materials used by birds to nest in an urban landscape of Costa Rica. UNED Res. j. 12. Doi: 10.22458/urj.v12i2.3124.

Esri, 2023. World Imagery. https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9 (accessed 2 August 2023).

ESRI Inc., 2023. ArcGIS Pro. CA: Environmental Systems Research Institute., Redlands California, Redlands California.

EuroGeographics, 2016. Europe - Road. https://public.opendatasoft.com/explore/dataset/europe-road/information/?refine.icc=PT&location=6,37.37278,-10.94604&basemap=jawg.light (accessed 18 July 2023).

Francila, F.A., Prasanna, N., Shrotri, S., Nawge, V., Gowda, V., 2023. Life amidst debris: urban waste management affects the utilization of anthropogenic waste materials in avian nest construction. Trop. Ecol. 2023. https://doi.org/10.1007/s42965-023-00302-z.

Gilbert, N.I., Correia, R.A., Silva, J.P., Pacheco, C., Catry, I., Atkinson, P.W., Gill, J.A., Franco, A.M.A., 2016. Are white storks addicted to junk food? Impacts of landfill use on the movement and behaviour of resident white storks (Ciconia ciconia) from a partially migratory population. Mov. Ecol. 4, 1–7. https://doi.org/10.1186/s40462-016-0070-0.

GoC, 2022. Single-use Plastics Prohibition Regulations: Canadian environmental protection act 1999. https://laws-lois.justice.gc.ca/eng/regulations/SOR-2022-138/page-1.html (accessed 5 August 2023).

Hahladakis, J.N., 2020. Delineating and preventing plastic waste leakage in the marine and terrestrial environment. Environ. Sci. Pollut. Res. 27, 12830–12837. https://doi.org/10.1007/s11356-020-08139-y.

Hartig, F., 2022. DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html (accessed 2 August 2023).

Hartwig, E., Clemens, T., Heckroth, M., 2007. Plastic debris as nesting material in a Kittiwake-(Rissa tridactyla)-colony at the Jammerbugt, Northwest Denmark. Mar. Pollut. Bull. 54 (5), 595–597. https://doi.org/10.1016/J.MARPOLBUL.2007.01.027.

Henry, P.-Y., Wey, G., Balança, G., 2011. Rubber Band Ingestion by a Rubbish Dump Dweller, the White Stork (Ciconia ciconia). Waterbirds: Int J. Waterbird Biol. 34, 504–508. https://doi.org/10.1675/063.034.0414.

Houston, C.S., Scott, F., 2006. Entanglement threatens ospreys at saskatchewan nests. J. Raptor Res. 40, 226–228. https://doi.org/10.3356/0892-1016(2006)40[226:ETOASN]2.0.CO;2.

Jagiello, Z., Dylewski, Ł., Aguirre, J.I., Białas, J.T., Dylik, A., López-García, A., Kaługa, I., Olszewski, A., Siekiera, J., Tobółka, M., 2023a. The prevalence of anthropogenic nest materials differs between two distinct populations of migratory birds in Europe. Environ. Sci. Pollut. Res. 30, 69703–69710. https://doi.org/10.1007/s11356-023-27156-1.

Jagiello, Z., Dylewski, Ł., Tobółka, M., Aguirre, J.I., 2019. Life in a polluted world: a global review of anthropogenic materials in bird nests. Environ. Pollut. 251, 717–722. https://doi.org/10.1016/j.envpol.2019.05.028.

Jagiello, Z., Dylewski, Ł., Winiarska, D., Żołnierowicz, K.M., Tobółka, M., 2018. Factors determining the occurrence of anthropogenic materials in nests of the white stork Ciconia ciconia. Environ. Sci. Pollut. Res. Int. 25, 14726–14733. https://doi.org/10.1007/s11356-018-1626-x.

Jagiello, Z., Reynolds, S.J., Nagy, J., Mainwaring, M.C., Ibáñez-Álamo, J.D., 2023b. Why do some bird species incorporate more anthropogenic materials into their nests than others? Philos. Trans. r. Soc. London, Ser. B 378, 20220156. https://doi.org/10.1098/rstb.2022.0156.

Janic, B., Bańbura, J., Glądalski, M., Kaliński, A., Kamiński, M., Marszał, L., Pieniak, D., Wawrzyniak, J., Zieliński, P., 2023. Plastic occurrence in nests of a large forest bird. Ecol. Indic. 153, 110470. https://doi.org/10.1016/j.ecolind.2023.110470.

JRC, 2021. Global Human Settlement Layer: Population and Built-Up Estimates, and Degree of Urbanization Settlement Model Grid. Joint Research Centre - JRC - European Commission; Center for International Earth Science. https://sedac.ciesin.columbia.edu/data/set/ghsl-population-built-up-estimates-degree-urban-smod (accessed 10.12.23).

Kang, K.-H., Nam, K.-B., Jeong, B.-S., Kim, J.-S., Yoo, J.-C., 2023. The use of plastic litter as nesting material by the azure-winged magpie Cyanopica cyanus in an agricultural environment of South Korea. Environ. Sci. Pollut. Res. Int. 30, 84814–84821. https://doi.org/10.1007/s11356-023-28409-9.

Kronenberg, J., Andersson, E., Tryjanowski, P., 2017. Connecting the social and the ecological in the focal species concept: case study of White Stork. Nature Conservation 22, 79–105. https://doi.org/10.3897/natureconservation.22.12055.

Lasota, J., Błońska, E., Zbyryt, A., Ciach, M., 2024. Microplastics characteristics and environmental correlates of their presence in the nests of white stork: an evidence for biotransfer and biocirculation in the ecosystem. Ecol. Indic. 162, 112005. https://doi.org/10.1016/j.ecolind.2024.112005.

Lau, W.W.Y., Shiran, Y., Bailey, R.M., Cook, E., Stuchtey, M.R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B., Thompson, R.C., Jankowska, E., Castillo Castillo, A., Pilditch, T.D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., Baulch, S., Atreya, M.E., Fischer, D., He, K.K., Petit, M.M., Sumaila, U. R., Neil, E., Bernhofen, M.V., Lawrence, K., Palardy, J.E., 2020. Evaluating scenarios toward zero plastic pollution. Science 369, 1455–1461. https://doi.org/10.1126/science.aba9475.

Lopes, C.S., Paiva, V., Vaz, P.T., Faria, J.P.d., Calado, J.G., Pereira, J.M., Ramos, J., 2021. Ingestion of anthropogenic materials by yellow-legged gulls (Larus michahellis) in natural, urban, and landfill sites along Portugal in relation to diet composition. Environ. Sci. Pollut. Res. 1–18. https://doi.org/10.1007/s11356-020-12161-5.

Luna, Á., Moreno, E., Pinzolas, J.A., Oliver, S., Meyer, S., Brodermann, O., Merino, C., Karaardıç, H., Da Silva, L.P., Chatton, C., Laesser, J., Meier, C.M., Gutiérrez, J.S., Masero, J.A., Pérez, J., Kullberg, C., Pérez-Gómez, Á., Mateos-González, F., Tigges, U., Toledo, B., Rausell-Moreno, A., 2024. Anthropogenic debris as nest material in three swift species: New insights into the interactions of atmospheric pollution with wildlife. Sci. Total Environ. 949, 175171. https://doi.org/10.1016/j.scitotenv.2024.175171.

MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic pollution. Science 373, 61–65. https://doi.org/10.1126/science.abg5433.

Malizia, A., Monmany-Garzia, A.C., 2019. Terrestrial ecologists should stop ignoring plastic pollution in the Anthropocene time. Sci. Total Environ. 668, 1025–1029. https://doi.org/10.1016/j.scitotenv.2019.03.044.

Mallet, J., Liébana, M.S., Santillán, M.Á., Grande, J.M., 2020. Raptor Entanglement with Human Debris at Nests: a Patchy and Species-specific Problem. J. Raptor Res. 54, 316–318. https://doi.org/10.3356/0892-1016-54.3.316.

Mee, A., Rideout, B.A., Hamber, J.A., Todd, J.N., Austin, G., Clark, M., Wallace, M.P., 2007. Junk ingestion and nestling mortality in a reintroduced population of California Condors Gymnogyps californianus. Bird Conserv. Int. 17, 119–130. https://doi.org/10.1017/S095927090700069X.

Mikula, P., Karg, J., Jerzak, L., Walasz, K., Siekiera, J., Czyż, S., Mikicińska, K., Pietkiewicz, M., Sztwiertnia, H., Wyka, J., Tryjanowski, P., 2024. Diet analysis and the assessment of plastic and other indigestible anthropogenic litter in the white stork pellets. Environ. Sci. Pollut. Res. Int. 31, 6922–6928. https://doi.org/10.1007/s11356-023-31710-2.

Montevecchi, W.A., 1991. Incidence and types of plastic in gannets' nests in the northwest Atlantic. Can. J. Zool. 69, 295–297. https://doi.org/10.1139/z91-047.

NEPIS, 1993. Federal Register: April 7, 1993, 40 CFR Parts 238. Degradable Ring Rule. Environmental Protection Agency, US (accessed 29 July 2023).

O'Hanlon, N.J., Bond, A.L., Lavers, J.L., Masden, E.A., James, N.A., 2019. Monitoring nest incorporation of anthropogenic debris by Northern Gannets across their range. Environ. Pollut. 255, 113152. https://doi.org/10.1016/j.envpol.2019.113152.

Pinto-Correia, T., Ribeiro, N., Sá-Sousa, P., 2011. Introducing the montado, the cork and holm oak agroforestry system of Southern Portugal. Agroforest Syst. 82, 99–104. https://doi.org/10.1007/s10457-011-9388-1.

Poeta, G., Staffieri, E., Acosta, A.T., Battisti, C., 2017. Ecological effects of anthropogenic litter on marine mammals: a global review with a "black-list" of impacted taxa. Hystrix It. J. Mamm. 28, 253–264. https://doi.org/10.4404/hystrix-00003-2017.

Projecto - SISAL, 2025. Enfardar Naturalmente apoiado pelo Fundo Ambiental. http://transicaoagriculturaecologica.aepga.pt/pt/projecto/ (accessed 17 February 2025).

R Core Team, 2023. R: The R Project for Statistical Computing. https://www.r-project.org/ (accessed 2 August 2023).

Restani, M., 2023. Individual and population effects of entanglement mortality on ospreys from plastic baling twine in nests. Global Ecol. Conserv. 44, e02496. https://doi.org/10.1016/j.gecco.2023.e02496.

Ryan, P.G., 2018. Entanglement of birds in plastics and other synthetic materials. Mar. Pollut. Bull. 135, 159–164. https://doi.org/10.1016/j.marpolbul.2018.06.057.

Savoca, M.S., McInturf, A.G., Hazen, E.L., 2021. Plastic ingestion by marine fish is widespread and increasing. Glob. Chang. Biol. 27, 2188–2199. https://doi.org/10.1111/gcb.15533.

Schneider, C.A., Rasband, W.S., Eliceiri, K.W., 2012. NIH image to ImageJ: 25 years of image analysis. Nat. Methods 9, 671–675. https://doi.org/10.1038/nmeth.2089.

Seacor, R., Ostovar, K., Restani, M., 2014. Distribution and abundance of baling twine in the landscape near Osprey (*Pandion haliaetus*) nests: implications for nestling entanglement. Can Field Nat 128, 173. https://doi.org/10.22621/cfn.v128i2.1582.

Soriano-Redondo, A., Franco, A.M.A., Acácio, M., Payo-Payo, A., Martins, B.H., Moreira, F., Catry, I., 2023. Fitness, behavioral, and energetic trade-offs of different migratory strategies in a partially migratory species. Ecology 104, e4151.

Stelfox, M., Hudgins, J., Sweet, M., 2016. A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. Mar. Pollut. Bull. 111, 6–17. https://doi.org/10.1016/j.marpolbul.2016.06.034.

Suárez-Rodríguez, M., López-Rull, I., Garcia, C.M., 2013. Incorporation of cigarette butts into nests reduces nest ectoparasite load in urban birds: new ingredients for an old recipe? Biol. Lett. 9, 20120931. https://doi.org/10.1098/rsbl.2012.0931.

Tavares, D., Moura, J.F., Merico, A., 2019. Anthropogenic debris accumulated in nests of seabirds in an uninhabited island in West Africa. Biol. Conserv. 2019, 586–592. https://doi.org/10.1016/J.BIOCON.2019.05.043.

Thrift, E., Porter, A., Galloway, T.S., Coomber, F.G., Mathews, F., 2022. Ingestion of plastics by terrestrial small mammals. Sci. Total Environ. 842, 156679. https://doi.org/10.1016/j.scitotenv.2022.156679.

Tobolka, M., Sparks, T.H., Tryjanowski, P., 2012. Does the White Stork Ciconia ciconia reflect farmland bird diversity? Ornis Fenn 89, 222–228-222–228. Doi: 10.51812/of.133809.

Townsend, A.K., Barker, C.M., 2014. Plastic and the nest entanglement of urban and agricultural crows. PloS One 9, e88006. https://doi.org/10.1371/journal.pone.0088006.

Townsend, T., Sette, J., 2016. Natural Fibres and the World Economy, in: Natural Fibres: Advances in Science and Technology Towards Industrial Applications. Springer, Dordrecht, pp. 381–390.

UNEP, ISWP, 2024. United Nations Environment Programme and International Solid Waste Association: Global Waste Management Outlook 2024 - Beyond an age of waste: Turning rubbish into a resource. Doi: 10.59117/20.500.11822/44939.

Vasquez, M.P., Rylander, R.J., Tleimat, J.M., Fritts, S.R., 2022. Use of Anthropogenic Nest Materials by Black-Crested Titmice along an Urban Gradient. J. Fish Wildl. Manage. 13, 236–242. https://doi.org/10.3996/JFWM-21-058.

Veríssimo, S.N., Veloso, F., Neves, F., Ramos, J.A., Paiva, V.H., Norte, A.C., 2024. Plastic use as nesting material can alter incubation temperature and behaviour but does not affect yellow-legged gull chicks. J. Therm. Biol. 125, 104005. https://doi.org/10.1016/j.jtherbio.2024.104005.

Votier, S.C., Archibald, K., Morgan, G., Morgan, L., 2011. The use of plastic debris as nesting material by a colonial seabird and associated entanglement mortality. Mar. Pollut. Bull. 62, 168–172. https://doi.org/10.1016/j.marpolbul.2010.11.009.

Wilcox, C., Mallos, N.J., Leonard, G.H., Rodriguez, A., Hardesty, B.D., 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. Mar. Policy 65, 107–114. https://doi.org/10.1016/j.marpol.2015.10.014.

Wright, S.L., Thompson, R.C., Galloway, T.S., 2013. The physical impacts of microplastics on marine organisms: a review. Environ. Pollut. 178, 483–492. https://doi.org/10.1016/j.envpol.2013.02.031.

Zylstra, E.R., 2013. Accumulation of wind-dispersed trash in desert environments. J. Arid. Environ. 89, 13–15. https://doi.org/10.1016/j.jaridenv.2012.10.004.