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Research Paper

Leakage of plastics and other debris from landfills to a highly protected lake by wintering gulls

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ABSTRACT

General context: Gulls ingest plastic and other litter while foraging in open landfills, because organic matter is mixed with other debris. Therefore, gulls are potential biovectors of plastic pollution into natural habitats, especially when they concentrate in wetlands for roosting.
Novelty: We quantified, for the first time, the flow of plastic and other anthropogenic debris from open landfills to a natural lake via the movement of gulls. We focused on Fuente de Piedra, an inland closed-basin lake in Spain that is internationally important for biodiversity.
Methodology: In 2022, we sampled gull pellets regurgitated in the lake by lesser black-backed gulls *Larus fuscus* that feed on landfills, as well as their faeces, then characterized and quantified debris particles of $\geq$0.5 mm. By combining GPS and census data from 2010 to 2022, together with plastic quantification based on FTIR-ATR analysis, we estimated the average annual deposition of plastic and other debris by the wintering gull population into the lake.
Main results: 86 % of pellets contained plastics, and 94 % contained other debris such as glass and textiles. Polyethylene (54 %), polypropylene (11.5 %) and polystyrene (11.5 %) were the main plastic polymers. An estimated annual mean of 400 kg of plastics were moved by gulls into the lake. Only 1 % of plastic mass was imported in faeces.
Discussion: Incorporating the biovectoring role of birds can provide a more holistic view of the plastic cycle and waste management. Biovectoring is predictable in sites worldwide where gulls and other waterbirds feed in landfills and roost in wetlands. We discuss bird deterrence and other ways of mitigating debris leakage into aquatic ecosystems.

1. Introduction

Plastic and other waste contamination is a major emerging problem, with increasing accumulation in ecosystems (Blettler and Wantzen, 2019). An estimated 9–23 million tons of plastic waste per year are deposited into aquatic ecosystems such as rivers, lakes and oceans derived from waste not properly separated (Macleod et al., 2021; Nava et al., 2023). However, these estimates do not consider the potential role of biovectoring, in which plastic can be carried from land into water by animals (see below). Plastic is a ubiquitous pollutant in the environment around the globe (Cózar et al., 2014, 2017). Aquatic ecosystems are especially susceptible to accumulation of plastic due to the transport of

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land-based mismanaged plastic by surface water runoff (González-Fernández et al., 2021). Oceans are generally the ultimate destination of plastics and other debris (Morales-Caselles et al., 2021). However, inland waters have been largely ignored even though they are highly exposed to plastic derived from industrial and agricultural activities, and evidence of plastic contaminating these ecosystems dates from many years ago (Redford et al., 1997).

Aquatic birds are especially susceptible to the ubiquitous presence of plastic. The overwhelming majority of research to date has been conducted in marine birds, mostly focusing on striking cases concerning entanglements and other injuries. However, a recent review revealed that the most common interaction between aquatic birds and anthropogenic litter is via ingestion (Battisti et al., 2019). While cases of death by massive ingestion are well known because of high visibility and media impact, much less information exists about the frequent ingestion events that do not imply the death of the bird, and their broader ecosystem consequences. In particular, there is a lack of quantitative information about the role of aquatic birds as vectors of plastic transport, and the resulting accumulation of plastic and waste in inland waters. Rivers and particularly lakes can act as sinks for debris transported by birds (Gil-Delgado et al., 2017; Luna et al., 2022), but they are also directly polluted with plastics by human activities (Isobe et al., 2021; Nava et al., 2023). Lakes within the endorheic basins (i.e. in which water has no outflow to the ocean) which cover one-fifth of the Earth's land surface (Wang et al., 2018) can be particularly susceptible to plastic accumulation, which could also be introduced by biovectors such as waterbirds.

More than half of the 300 seabird species have been reported to ingest plastic, including gulls (Laridae) (Battisti et al., 2019; Rivers-Auty et al., 2023). Many gull species extensively use non-marine habitats, roosting in lakes and wetlands outside the breeding period, often in big monospecific flocks, and are thus considered to be waterbirds (Martín-Vélez et al., 2019; Winton and River, 2017). In addition, they have adapted their natural behaviour to take advantage of anthropogenic resources (e.g. at open landfills) (Duhem et al., 2005, 2008; Winton and River, 2017), where the risks of plastic and other debris ingestion are high because unmanaged waste often contains food and other organic matter (Alabi et al., 2019). Gulls are already known to cause extensive lake eutrophication by importing nutrients from landfills in their faeces and regurgitations (Winton and River, 2017, Martín-Vélez et al., 2019). Hence, gulls may also carry out significant plastic biovectoring into inland wetlands via regurgitation and defaecation, that could be especially important in closed basin wetlands. However, no previous studies have categorized and quantified the import of plastics by gulls from waste from open landfills into natural habitats. Quantification of this biovectoring process may help facilitate preventative measures in waste management and landfilling to deter birds from foraging.

Through a combination of spectroscopic techniques for plastic chemistry (e.g. FTIR -ATR; Almeida et al., 2023; Masiá et al., 2019) with bio-logging technology such as GPS tracking (GPS devices; Kays et al., 2015; Nathan et al., 2022) and field observations (count data and diet samples), it is now feasible to make good estimates of the type, amount and origin of plastics transported by birds into aquatic systems. Quantifying plastic loads from gulls could help environmental and landfill managers to implement effective policies to reduce plastic leakage into the natural environment (Coccon and Fano, 2020). GPS data can also facilitate the assessment of how effective deterrence methods (e.g. falconry) can be at open dump sites to reduce plastic ingestion and subsequent deposition in wetlands (Soldatini et al., 2008).

Our main objective was to quantify and characterize plastics and other debris imported by gulls into an endorheic lake, which is one of the most important wetlands in Spain (Batanero et al., 2017). We focused on the lesser black-backed gull (LBBG) *Larus fuscus* at Fuente de Piedra lake (hereafter: FP), which we expected to be the major biovector due to its use of anthropogenic food resources from open landfills and its dominance in the wintering waterbird community (Martín-Vélez et al., 2019). We focused on macro-debris which is more relevant for biovectoring purposes, but also because there is a clear predominance of microplastic studies over macroplastic ones (Blettler et al., 2018). Using GPS data of individual gulls enabled us to identify specific landfills as the sources of contaminants, as well as to estimate rates of biovectoring into FP lake. We used infrared spectroscopy to quantify plastic content per egesta sample, and we used field censuses to extrapolate our plastic load estimation to the LBBG population at FP.

Our specific objectives were: (1) determine the amounts of plastic and other debris in gull egesta samples from FP lake; (2) categorize and characterize plastic and other debris; (3) estimate the total plastic loading to FP lake by gulls based on egesta samples content, censuses and GPS data; (4) identify the sources of plastic using GPS data, and to explore the role of individual landfills for feeding; and (5) study the effects of deterrence methods in landfills to reduce plastic ingestion from gulls. The paper is organized as follows. Section 2 describes the methodology, presenting the study area, model species and the five steps for analysis. Section 3 shows the results associated with plastic characterization, plastic and other debris quantification, and landfill use. Finally, Section 4 discusses the implications of our analysis in a broader context, including waste management.

2. Methods

2.1. Study area

This study was performed in Fuente de Piedra (FP), a hypersaline endorheic inland shallow lake located in southern Spain (37.11°N, 4.77°W, Fig. 1). It is the largest natural lake in Andalusia, covering an area of 1,350 ha (6.8 km long and 2.5 km wide, Batanero et al., 2017) within a watershed of 15,000 ha (Rodríguez-Rodríguez et al., 2016). Fuente de Piedra lake is the main breeding site for greater flamingos *Phoenicopterus roseus* within Spain). The lake is protected at different levels: (1) regional (Natural Reserve of the Andalusian government), (2) European (Special Protection Area under the EU Birds Directive), and (3) global as an Internationally Important Wetland (Ramsar site). Inputs of water come from rainfall, ground water and two intermittent streams, whereas output is limited to evaporation (Rodríguez-Rodríguez et al., 2005, 2016).

Fuente de Piedra seasonally fluctuates in water level, salinity and nutrient concentrations, tending to increase in depth during the course of the winter but to dry out in late summer, except in the wettest years (Batanero et al., 2017). Apart from birds, there is no obvious source of large plastic particles, although wind-blown pollution from surrounding agricultural and urban areas is likely. Microplastics may enter via discharge from a Waste Water Treatment Plant (de-los-Ríos-Mérida et al., 2021). Therefore, gulls may be important vectors for plastic deposition, whose origin is likely waste from open landfills within flight distance (Martín-Vélez et al., 2019).

2.2. Study species

The lesser black-backed gull (LBBG) *Larus fuscus* is one of the most abundant wintering waterbirds in Andalusia (e.g. average 68,000 birds counted in censuses from 2010 to 2017), taking advantage of anthropogenic habitats such as ricefields (Rendón et al., 2008) and open landfills (Martín-Vélez et al., 2019, 2020). This behaviour, along with the abundance and availability of GPS-tracking data (Bouten et al., 2013), makes the LBBG an ideal study model for avian inputs of plastics and other debris into FP. The LBBG is the most abundant wintering species at FP lake, representing on average 56 % of all waterbirds, and is the only numerous large gull (Martí and del Moral, 2003). In addition to faeces, gulls regurgitate indigestible items in pellets (Provencher et al., 2019), that can provide a major pathway for biovectoring of plastic and other debris. Analysis of pellets is a non-invasive method that provides information about the source of plastics ingested, especially given the

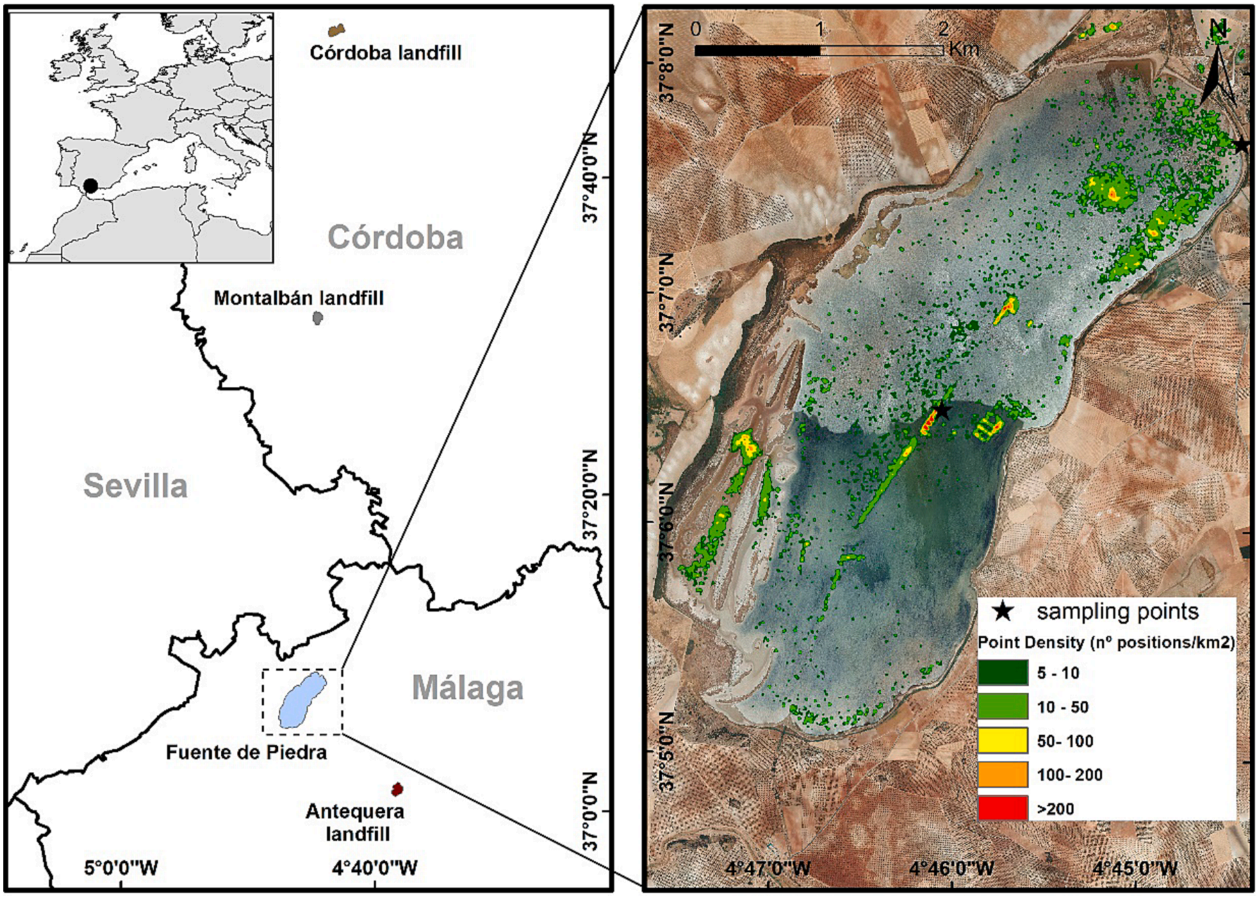

Fig. 1. **Left figure:** Location of Fuente de Piedra in Europe and the Iberian Peninsula. Location of Fuente de Piedra and the three landfills (Antequera, Montalban and Cordoba) used by tagged gulls. **Right figure:** Point density heat map for the 45 LBBG gull-years with GPS data (speed < 2.7 m/s) using Fuente de Piedra lake from 2010 to 2022.

large size of items found (Stewart et al., 2020; Bond et al., 2021; Almeida et al., 2023). Although bird faeces often contain microfibers and other small plastic fragments, large particles cannot pass from the gizzard into the intestines (Martín-Vélez et al., 2021a).

2.3. *Sample collection and laboratory processing*

We collected samples during January, coinciding with the highest peak of individuals at the lake and allowing us to optimize fieldwork as 40 % of gull-days at the lake occur in January. A total of 35 pellets and 47 faeces were collected in zip bags on the 18th January 2022 (Fig. 2A). We did not address seasonal changes in pellet or faecal contents, but

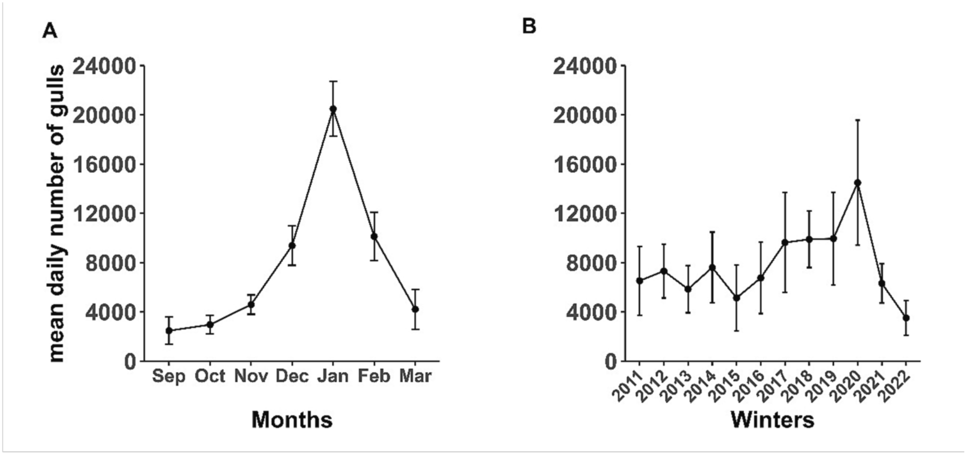

Fig. 2. A) Mean counts for LBBG with standard errors for winter months (from September to March) at Fuente de Piedra lake, during 12 study winters. B) Mean counts with standard errors for the 12 study winters (from September to March, e.g. “winter 2011” refers to September 2010 to March 2011). Missing data were interpolated using the *imputeTS* R package.

there were no seasonal changes in the importance of landfills as feeding sites for gulls in previous studies (Stewart et al., 2020). Similarly, Cano-Povedano et al. (2023) found no seasonal change in the plastic content of pellets from white storks *Ciconia Ciconia* feeding at a landfill in southwest Spain. However, we evaluated the changes in landfill use over the winter season (see below). We collected fresh faeces and pellets, ensuring that there was at least one-meter separation between samples to avoid collecting samples from the same individual. Samples were frozen until processing. Samples were dried in the oven at 50–80 °C during 3–24 h (until constant weight), then kept in a desiccator for 3 h before being weighed on a balance (OHAUS Voyage Pro Analytical VP214C). They were then rehydrated with tap water and their contents washed over a 500 μm mesh sieve to retain larger debris particles. Thus, macroplastics (>2.5 cm), mesoplastics (0.5–2.5 cm) and some microplastics (0.5–5 mm) were retained on the mesh (following size classes by Andrady, 2017; Frias and Nash, 2019).

The resulting sieved material was poured over petri dishes and inspected under a Zeiss Stemi 2000-C Stereo Microscope 6.5×–50×. The observer picked out and classified debris into three different categories based on colour, hardness and malleability: Highly Probable Plastic (HPP), Possible Plastic (PP), and Other Debris (OD) such as glass, textiles, porcelain and metal (Table S1). This classification allowed for a more targeted validation. Each category was then weighed separately.

2.4. Plastic identification

To identify debris composition, we chose representative items from categories HPP and PP. The characterization of these particles was carried out by Fourier-Transform InfraRed spectroscopy using the Attenuated Total Reflectance technique (FTIR-ATR). Only items larger than 4 mm^2 were analysed by FTIR-ATR spectroscopy, as required by our lab equipment (INVENIO X FTIR Research Spectrometry). The software used was OPUS 8.5 and the FTIR-ATR analysis was performed with an INVENIO X FTIR Research Spectrometer, using the MIR-ATR-MCA 400-4000-32 XPM method to obtain spectra. This consists of a multichannel analyser (MCA) performing 32 spectra in a wavelength range from 400 to 4000 cm^{-1}. Blank measures were made in air approximately every 10 samples to obtain background data.

Raw infrared spectra were treated using the *OpenSpecy* library (Cowger and Steinmetz, 2022) in R version 4.2.2. We followed the guidelines in Cowger and Steinmetz (2022), using function parameters that fitted best to our items. We took a threshold value of ≥0.8 for the Hit Quality Index (HQI), in order to identify the smoothed spectra of a given item. HQI measures the closeness of fit between the spectrum of the item under analysis and each reference spectrum (the higher the HQI value, the closer the obtained spectrum is to the reference spectrum). If the result obtained was not coherent with the nature of the analyzed item, we chose the next congruent result with a similar spectrum. In total, 101 items were successfully identified, 79 in the HPP and 22 in the PP category. Of the HPP category, 63 % of items were identified as plastics, compared to 50 % of PP items. No FTIR-ATR analysis was conducted for OD items. We multiplied the weights obtained for HPP and PP categories in each pellet by 63 % and 50 % respectively to obtain a total weight of plastic found per pellet. The proportion of non-plastic synthetic debris identified by FTIR-ATR in HPP and PP was 20 % and 18 % respectively, and the remaining 17 % and 32 % were natural items (e.g. chitin or cellulose) excluded from further calculations of debris loading. The proportions of plastic and natural items in the OD category were assumed to be zero.

2.5. Count data and GPS tracking

We used monthly LBBG censuses (from September to March) during twelve “winters” from September 2010 to March 2022 (e.g. “winter 2011” was from September 2010 to March 2011) provided by the Andalusian Government. Missing counts (25 out of 84 months; 29 %) were imputed based on linear interpolation from *imputeTS* package in R (Moritz and Bartz-Beielstein, 2017).

We used GPS tracking data (UvA-BiTS; https://www.uva-bits.nl) collected during long-term studies of several LBBG populations breeding in Northern Europe (Bouten et al., 2013; Thaxter et al., 2015; Shamoun-Baranes et al., 2017; Baert et al., 2018) in order to identify agricultural and landfill foraging sites used by gulls roosting at FP lake. We first selected those GPS data points that fall spatially within the boundary of FP (from the polygon delimited by Corine Land Cover 2012, see below) from September through March (i.e. the wintering period) in 2010–2022. We then selected all points outside FP from the same individuals within this time period. The resulting tracking dataset included 45 individuals. However, the distribution of individuals at FP between winters is unequal as tagging campaigns started in different years (Fig. S1). GPS fixes were recorded at intervals of 10–30 min.

We calculated the number of visits to landfills, the time spent there, and the total number of GPS-tagged individuals per ordinal date (merging all 12 study winters; ordinal day *1* is 1st September and ordinal day *212* is 31th March). For each ordinal date, we created a ratio (n° of tagged gulls visiting landfills/total n° of tagged gulls) to correct census data in FP based on the proportion of individuals per day that are feeding at landfills, in order to estimate plastic loading. We also generated a heat map in FP based on a density map of non-flying birds (number of GPS points with 2D speed < 2.7 m/s), considering a 50 m neighbouring area of influence. We used the Point Density estimation tool from QGIS 3.26.1 with a final spatial resolution of 10 m. The final visualization output was carried out in ArcMap 10.8.

2.6. Plastic and other debris input estimation

We estimated the total loading of plastics in pellets per winter (Equation (1). The same procedure was used to estimate the number of plastic and OD particles deposited. Pellet egestion rate was assumed to be 1 pellet produced per day (Lovas-Kiss et al., 2018; see also Cano-Povedano et al., 2023 for storks), and we assumed that all pellets were deposited at the roosting site (i.e. in FP lake). Consequently, we considered a random mass of plastic (so called “RPA_i”) taken from our empirical data (a pool of 35 pellet samples) to be the hypothetical pellet deposited in FP lake by a given wintering gull during a given ordinal day. Randomization was carried out once for each bird in the wintering population, based on census values (corrected based on the number of daily visits to landfills).

$$\mathrm{PL} = \sum_{i=1}^{NBc} \mathrm{ERpellets}^{*}\, R\mathrm{PA}_i, \tag{1}$$

where PL = Plastic Load per winter; ER = Egestion Rate in pellets as 1 per day; NB_c = Number of Birds corrected using GPS data to exclude those not visiting landfills; RPA_i = Random Plastic Amount (in grams) taken by resampling from 35 pellets.

We also estimated the much smaller quantity of debris deposited in faeces following a similar procedure as for pellets, but incorporating time spent at the lake from the GPS data and a fixed excretion rate of 8 faeces/day as reported in previous studies (Hahn et al., 2007; Martín-Vélez et al., 2019). We assumed that the percentage of time spent at FP determined the proportion of faeces egested there.

2.7. Sources of plastics and other debris

To locate the main sources of plastic and OD, we identified the main foraging sites used by gulls roosting at FP. We identified three main landfills: Valsequillo Environmental Complex (in Antequera municipality), Cordoba Environmental Complex (in Cordoba municipality) and Montalban Environmental Complex (in Cordoba de Montalban municipality) (Fig. 1). All three lie outside the hydrological catchment of FP. We extracted the boundaries of each landfill from CORINE Land Cover

2018 (Coordination of Information on the Environment, CLC; https://land.copernicus.eu/) and added a buffer of 200 m around the perimeter to account for gulls that may be resting around the site (typically waiting for garbage trucks) before foraging. To quantify landfill use, we determined the dates on which each individual gull roosted at the lake and identified foraging behaviour at landfills by daylight GPS fixes where gulls were considered to be stationary or walking (instantaneous GPS 2D speed < 2.7 m/s), based on histograms of speed data and previous literature (Shamoun-Baranes et al., 2017; Martín-Vélez et al., 2020).

In Andalusia, LBBG also exploit agricultural habitats (Martín-Vélez et al., 2020; Martín-Vélez et al., 2021a). Therefore, we also extracted agricultural land-use by gulls from CORINE land cover 2018 and determined whether it was an "olive plantation" or "other agricultural", and associated this to GPS fixes as above. We thus calculated the accumulated time spent (when gulls were not flying) by each tagged individual each single day per winter in each landfill, and in agricultural land. We calculated the mean percentage of time spent at each landfill and agricultural habitat in relation to the total amount of time spent in all these foraging sites for each winter (percentage habitat use during potential foraging).

We studied whether there were differences in the use of landfills (time spent) by individual gulls between landfills and winter months to test for seasonal differences by using Generalized Linear Mixed-effects Models. We controlled for individual and individual nested within winter as a random factor. We also investigated whether the use of landfills (time spent and number of visits) varied over time (between years) because of deterrence techniques (e.g. falconry). From 2017 onwards, deterrence techniques (e.g. intense falconry with Harris Hawk *Parabuteo unicinctus* and goshawk *Accipiter gentilis*) were implemented at Antequera landfill to prevent gulls from feeding there (Complejo Medioambiental de Valsequillo/Antequera manager pers. comm.). We calculated the mean number of visits to each of the three landfills per individual gull per winter. To investigate any changes in the use of all landfills by gulls after the introduction of falconry to Antequera (from 2017 onwards), we tested whether there were differences in the number of visits per winter across different landfills, the effect of the introduction of falconry, and their interaction (with "individuals" and "winters" included as a random intercept) with a Linear Mixed-effect Model (LMM).

3. Results

3.1. Census data and use of Fuente de Piedra lake by tagged gulls

Based on census data, the numbers of LBBG gulls counted in FP lake varied among years and months (Fig. 2). Numbers peaked strongly in midwinter (January, Fig. 2A), and reached a maximum in winter 2020 with a mean count of almost 16,000 birds (maximum of 33,000 in January 2020). There was a strong decrease in census numbers for winters 2021 and 2022 (Fig. 2B). The use of FP by tracked gulls (and hence the expected density of debris egestion) varied spatially, with high concentrations of points ($>$200 positions per km^2) in the centre, west and northeast (Fig. 1).

3.2. Plastic characterization

Mean dry weight of gull pellets was 4.54 g $\pm$ 2.33 (mean $\pm$ SD, range 0.97–8.05 g; see Fig. S2). On average, 0.29 g of this was made up of plastic (after confirmation with FTIR-ATR), 1.55 g of other anthropogenic debris, and the remainder of organic waste items (including human food from landfills). Of 35 pellet samples, 30 (86 %) contained plastic items and 34 (94 %) other debris (e.g. glass, ropes, aluminium, textiles, porcelain; Table S1). Only 4 % of 47 faecal samples showed plastic presence $>$0.5 mm. A total of 485 debris particles were found in pellets. After correction with FTIR-ATR, on average 7.69 plastic items of $\geq$0.5 mm (25, 50 and 75 % quantiles: 2, 7, 10.5 respectively) and 5.4 particles classified as other debris (25, 50 and 75 % quantiles: 2, 5, 8 respectively) were found per pellet. Among plastic items (Fig. S3), the majority (54.1 %) were composed of polyethylene (PE). Polypropylene (PP) and polysterene (PS) were the next most common types of plastics, each representing 11.5 % of items. Other materials (e.g. polyamide, PVC, PVCD, styrene allyl alcohol, PET, Vinylidene chloride acrylonitrile) were found in smaller proportions (Fig. 3).

3.3. Loading of plastic and other debris into Fuente de Piedra lake

As expected from variation in numbers of LBBG counted at the lake, there was strong annual variation in estimated loading of plastic into FP (Fig. 4). On average, 1888 g of plastic were estimated to be deposited per day into the lake, and 77 % of GPS tracked individuals visited at least one of the three landfills on a given day. The peak of plastic input was estimated for winter 2020, with 798 kg of plastic transported into FP that winter (Fig. 4). A mean of 400 kg of plastic was predicted to be deposited each winter into FP lake, with only 4.9 kg in faeces (1.2 %). On average, 8.1 million plastic and 5.3 million other debris particles of $\geq$0.5 mm were estimated to be deposited by gulls each winter in FP (Fig. S4).

3.4. Habitat use while foraging

During the day, LBBG spent time in agricultural habitats and at three main landfills: Montalbán, Antequera and Cordoba (Figs. 1 and 5). All these were foraging sites, but the proportion of time spent actually feeding while there is unknown. LBBG spent more time on average in agricultural habitats (88 %) than at landfills (12 %) (Fig. 5A). Montalban (44.9 km distance) was the landfill most used in terms of time spent by LBBG that roost at FP (Fig. 5A), despite being farther away than Antequera landfill (14.9 km distance). Cordoba landfill was much farther away than the other landfills (80 km distance), and was the least used (Fig. 5). There were no seasonal differences over the winter in the percentage of daily time spent by an individual gull at landfills ($F_{6,1331} = 1.67$, $p = 0.38$). However, there were significant differences in the number of visits across landfills (Fig. 5B, Table S2) with Antequera landfill receiving most of the visits from 2014 to 2017 (Fig. 5B). The presence of falcons at Antequera reduced the number of visits to landfills in general (see main effects from Table S2). More precisely, the use of falconry increased the number of visits to Cordoba landfill, while reducing the number of visits in Antequera and Montalban (Table S2). However, although the number of visits to Montalban declined after falconry was introduced to Antequera in 2017, the time spent at Montalban actually increased, as did the time spent in "other crops" (Fig. 5A).

4. Discussion

The present study demonstrates the importance that gulls can have for transporting plastics and other debris from open landfills, where they commonly feed (Martín-Vélez et al., 2021b; Van Rees et al., 2021; Winton and River, 2017), into natural inland waters, where they roost. Lesser black-backed gulls feeding at landfills loaded important quantities of plastics and other debris (e.g. glass and textiles) while roosting at FP, a highly protected shallow lake. Many other waterbirds also feed on landfills (see Arnold et al., 2021 for review) and can ingest and transport plastics to aquatic environments, suggesting that our study is representative of a widespread biovectoring process. However, at FP, LBBG are undoubtedly the most important waterbird contributing to plastic transport into the lake. Due to the endorheic nature of FP (with no outlet to the ocean), imported anthropogenic debris is likely to permanently accumulate in the lake (although some export of low-density particles may occur by wind dispersal). All open landfills visited by gulls based on movement data lie beyond the lake's watershed, so that debris from

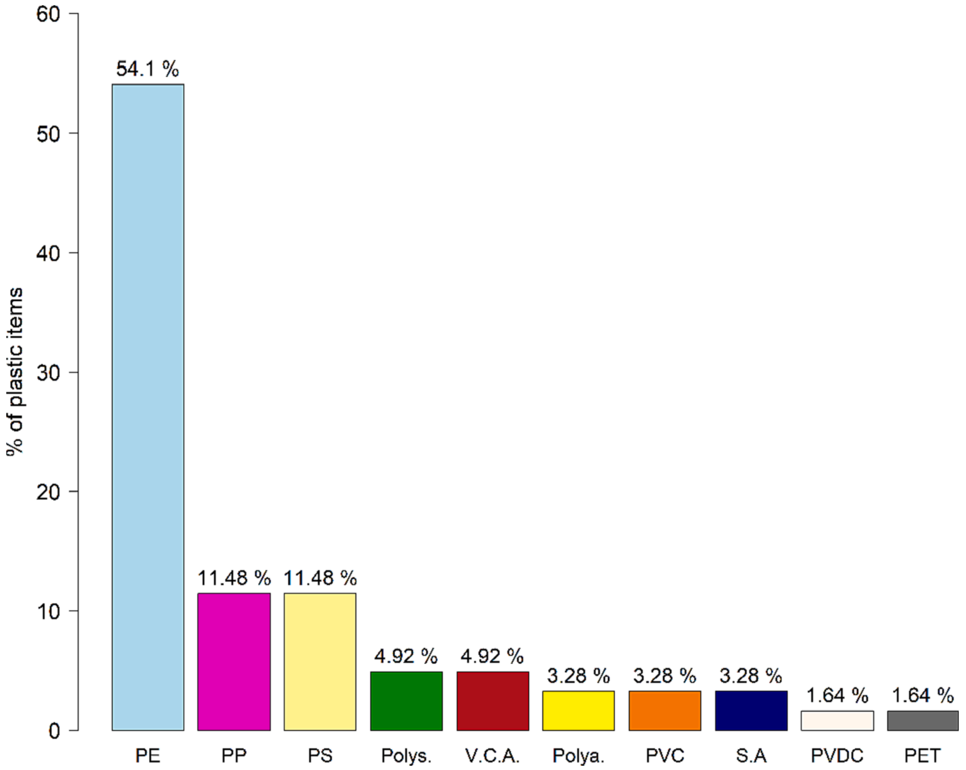

Fig. 3. Percentages of the types of plastics recorded (N = 61 items). PE = Polyethylene, PP = Polypropylene, PS = Polystyrene, Polys. = Polyester, V.C.A. = Vinylidene chloride acrylonitrile, Polya. = Polyamide, PVC = Polyvinyl chloride, S.A. = Styrene allyl alcohol, PVDC = Polyvinylidene dichloride, PET = Polyethylene terephthalate.

there could not otherwise enter the lake via streams or flooding events. GPS tracking data also allowed us to identify the relative importance of different landfills as sources of plastics imported to the lake, and the proportion of gulls feeding in other habitats, so allowing us to estimate plastic loading effectively. On the other hand, the use of FTIR techniques allowed us to correct for mis-identified plastics, and characterize the polymer composition of waste imported to the lake.

There are no storks at FP (Martí and Del Moral, 2003), where the only other wintering bird that sometimes feeds at landfills is the smaller black-headed gull *Chroicocephalus ridibundus*, which rarely produces pellets and has much less capacity to transport plastics of ≥5 mm than LBBG (authors, unpublished data). Most other waterbird species feed in FP lake itself, so will only recycle plastic particles within the ecosystem, without importing more. An exception is the flamingo during the breeding season, when most adults fly to other (mainly coastal) wetlands to feed and then regurgitate food to their chicks in the FP colony (Batanero et al., 2017). Given the increasing abundance of microplastics in the invertebrates and sediments of coastal wetlands (Kumar et al., 2021), flamingos may therefore import microplastics with their food to FP.

4.1. Plastic in pellets

In our study, 86 % of the pellet samples presented plastics. This prevalence is similar to previous findings in other species of gulls feeding at landfills (Almeida et al., 2023; Stewart et al., 2020). Almeida et al. (2023) found presence of plastic in 83 % of gull pellets of yellow-legged gulls *Larus michahellis* and, likewise, Cano-Povedano et al. (2023) found that 98 % of pellets of storks feeding at landfills contained plastics. Although we only analysed pellets from one single day in January, we observed no seasonal variation in the proportion of LBBG that were feeding at landfills. Therefore, we assumed that our single sampling event was representative of the biovectoring phenomemon at FP. Future studies should study variation in biovectored wastes using larger sample sizes and repeated sampling.

The use of pellets to determine plastics is a non-invasive sampling technique widely used in waterbirds (Provencher et al., 2019). The plastics in pellets released to the environment by gulls have been partially degraded by gull digestion, which possibly facilitates their integration into the food chain in and around the lake, especially as they are broken into smaller particles (Provencher et al., 2018). However, here we disregarded microplastics of <0.5 mm, and only smaller sized items are abundant in faeces from gulls, explaining the low prevalence of plastics we found in faeces in this study (Senes et al., 2023). Microplastic particles are the most commonly studied size of plastic items in freshwater ecosystems (76 %), in comparison with macroplastics (19 %) (Blettler et al., 2018). Microplastics result from the degradation of large plastics and can be integrated into aquatic food chains, especially the smallest sizes (Kumar et al., 2021). Our study focuses on particle sizes ≥ 0.5 mm that account for the great majority of the overall weight of plastic egested by gulls, but perhaps not the majority of plastic particles. To our knowledge, apart from biovectoring by waterbirds, there are no other major sources of plastics of ≥0.5 mm to FP lake, and none were apparent during visits to the lake for previous studies (Batanero et al., 2017, Martín-Vélez et al., 2019). Indeed, our study was initiated because of long-term concern from managers about the obvious accumulation of debris in those parts of the lake where gulls roost.

4.2. Composition of plastics and other debris transported by gulls

The main non-plastic items were glass and textiles, as recorded in other gull studies (Lopes et al., 2021). Glass, metal or porcelain items represented the majority of imported debris by mass, and may have been ingested because they were coated with food at open landfills, but possibly some were mistaken by gull individuals as large items of grit that are used to help digestion (Stewart et al., 2020). These dense items

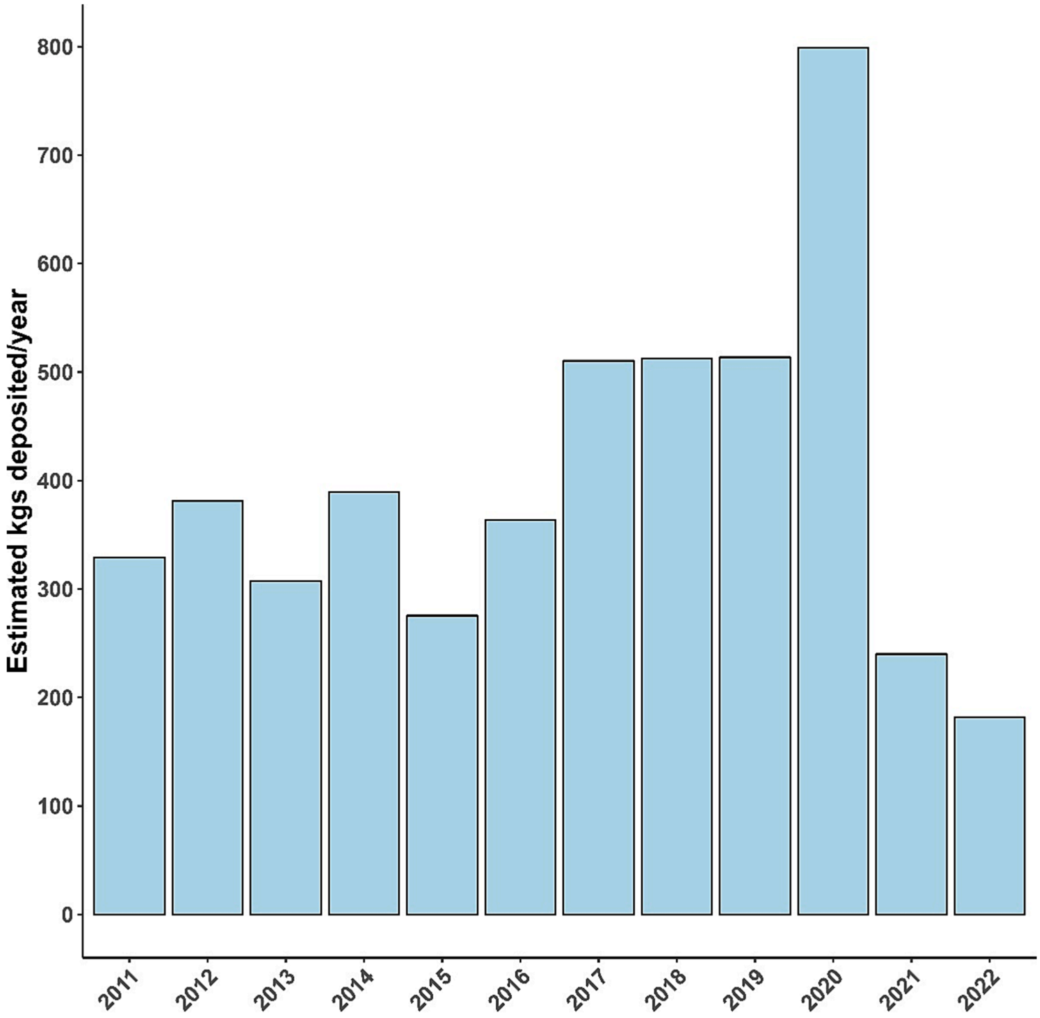

Fig. 4. Estimated annual loading of plastic deposited in Fuente de Piedra lake (with GPS correction based on the number of visits to landfills, and confirmation of synthetic nature with FTIR-ATR techniques) per winter season based on LBBG census data and plastic content in egesta.

could not be expected to exit the lake via wind action after their arrival, but are likely to have less impact on flora and fauna than the plastic pollution.

Our FTIR-ATR technique identified 63 % of the visually assigned plastics (HPP category) as genuine plastics based on HQI ≥ 0.8 (a conservative approach). This highlights the limitations of visual identification of plastic items and the importance of using analytical methods such as FTIR-ATR. However, the percentage of plastics in HPP and PP categories was likely underestimated by the FTIR-ATR analysis. This is because plastics found in pellets were often covered with dirt or visibly degraded, which could have altered their spectral signature and led to misidentification as either natural or anthropogenic materials, or prevent their classification (Xu et al., 2019; Dimassi et al., 2023). There are several analytical methods to identify plastic polymers, but vibrational spectroscopy techniques (FTIR or Raman) have several advantages over other instrumental analysis methods (e.g. they are non-destructive) and are widely used in plastic research. Both FTIR and RAMAN have advantages and limitations, depending on the characteristics of the samples (Käppler et al., 2016; Xu et al., 2019), but for the type of samples used in this study (mainly coloured macroplastics), FTIR is a highly suitable and rapid method.

Identification of polymers ingested by birds is not only important for their intrinsic associated toxicity, but also because of their physical and chemical interaction with the environment when they are egested (fragmentation, migration, etc; Sridharan et al., 2022). We found the most common plastic polymer to be polyethylene (PE) (54.1 % in abundance), related to sheet plastics. This relative abundance of PE in pellet samples is similar to previous studies of gulls (Lindborg et al., 2012; Almeida et al., 2023) and also of storks (Cano-Povedano et al., 2023). This plastic is commonly found in food packaging, agricultural plastic mulching, and plastic bags (Almeida et al., 2023). Due to the growing use of polyethylene in daily life (it constitutes 64 % of all synthetic plastic), the extremely high durability (up to 1000 years for natural degradation), the low recycling rate, and the high mobility of products made with it, it is one of the most widely distributed plastics in natural environments (Sangale et al., 2012). While it has been recognised as a major threat for marine life, reports in inland waterbodies are much rarer (Blettler and Mitchell, 2021; Bobori et al., 2022). Our study illustrates how wildlife can be an important vector for polyethylene into inland waterbodies.

Other plastics (e.g. polypropylene, polystyrene) were also abundant in LBBG pellets. Polystyrene is often related with foamed plastic packaging, and gulls may sometimes confuse it with natural items (Battisti, 2020). The main polymers identified in gull pellets are highly toxic for biota, with neurotoxic, reproductive and behavioural effects. Even when are egested in pellets, the time they remain in the highly acidic gut of gulls may be enough for the release of harmful chemicals (Mak et al., 2019).

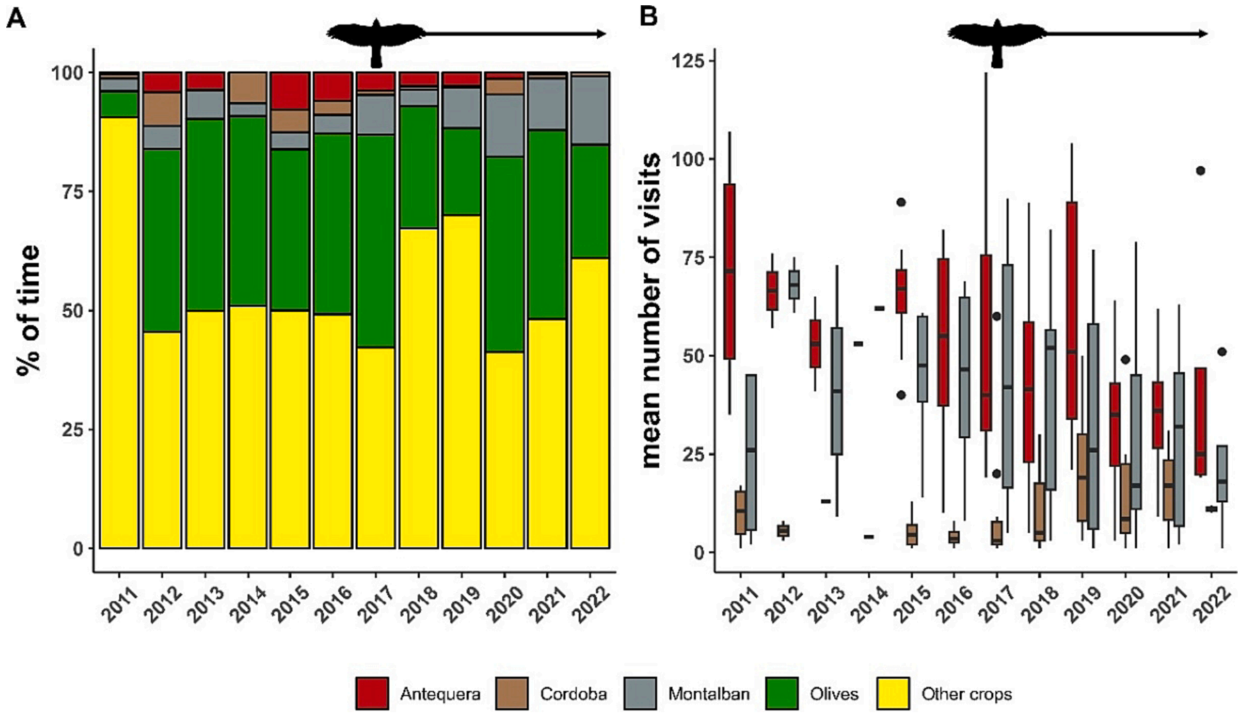

Fig. 5. (A) Percentage of time spent in each landfill site (Antequera, Montalban and Cordoba) and different crops (olives and others) by birds roosting at Fuente de Piedra lake, in relation to the total amount of time spent away from the lake. (B) Mean number of visits per individual per winter to each landfill. Falconry activities in Antequera started in 2017.

4.3. Plastic and other debris loading to Fuente de Piedra Lake by LBBG

By using a combination of GPS movement data, census data from 12 winters, and plastic data from egesta (corrected by FTIR-ATR techniques), we estimated the amount of plastic biovectored to FP lake. Similar methods should be used to quantify the biovectoring impacts of waterbirds in wetlands elsewhere, particularly those using open landfills that feed on organic matter mixed with waste (e.g. white storks, López-Calderón et al., 2023; Cano-Povedano et al., 2023). Based on GPS data, Martín-Vélez et al. (2020) already identified a further 12 landfills connected with 23 wetlands of particular importance for LBBG wintering elsewhere in Andalusia.

We found an increase in plastic deposition by LBBG to FP from 2017 to 2020, mainly due to higher numbers of wintering gulls reported those years. However, after 2020, there was a decrease in gull numbers the following two winters, reducing their debris deposition. According to census data, the LBBG population suffered a reduction of 40 % between the midwinter periods 2020 to 2021 across the whole Andalusian territory. However, these censuses underestimate the number of gulls using FP, because many birds depart for landfills at first light before the censuses are carried out (Martín-Vélez et al., 2019). Therefore, our calculations of debris loading are also likely to be conservative. Islands within the lake where gulls rest are the areas where debris deposition is concentrated (Fig. 1), and this is supporting by direct observation (personal observations). Plastics deposited are also expected to accumulate in sediments, causing potential impacts in soil (Sun et al., 2022) and to be incorporated into food webs of the water column (Sendra et al., 2020) when lake levels rise. On the other hand, this concentration of plastic and other debris may facilitate any cleaning efforts by managers to reduce the amount of external debris in the lake. Furthermore, cleaning efforts are made more feasible by the regular drying out of FP in summer (Fig. S5).

The presence of biovectored plastics *per se* is not the only potential impact to the FP ecosystem. This material is also combined with other contaminants like plasticizers or flame retardants than can affect the health of both the biovector itself (Charlton-Howard et al., 2023) and the ecosystem, potentially affecting other biota that do not directly forage in landfills (Sendra et al., 2020). Plastics are also vectors of transport for several abiotic (e.g. heavy metals, Borges-Ramírez et al., 2021) and biotic (e.g. antibiotic resistant bacteria; Liang et al., 2023) contaminants. Nevertheless, there is a lack of knowledge in the behaviour of plastics in hypersaline habitats like FP, and the degradation and fate of these materials in these extreme conditions needs investigating (Da Costa et al., 2018; Abbasi and Turner, 2022). For example, how are plastic-degrading bacteria and algae are affected by salinity? (Hadiyanto et al., 2022; Dong et al., 2023).

Although the presence of plastic has previously been reported in gulls (Seif et al., 2018; Almeida et al., 2023; Lopes et al., 2021), their role as vectors for plastic loading has not been studied in depth, with only a few examples over the world. These examples show that gulls and other seabirds can act as plastic vectors even in remote ecosystems (Provencher et al., 2018; Grant et al., 2021; Ballejo et al., 2021). Ours is the first study to quantify plastic loading by gulls into a particular endorheic wetland, where this may be the main source of plastics. Given the amount of plastic imported by birds, preventative measures can be implemented to deter them from feeding in open-sky landfills (see below). This case study suggests that similar leakage from landfills by gulls into wetlands is likely to be occurring elsewhere in Andalusia (Martín-Vélez et al., 2020), as well as at landfills used by white storks across Spain and Morocco (López-Calderón et al., 2023, Cano-Povedano et al., 2023), and probably at landfills worldwide (Nava et al., 2023). Some indication of the scale of this leakage can be provided from Winton and River (2017), who estimated that >5 million gulls used landfills throughout North America. Based on this estimation and results from our study, if each gull carried out of landfills 0.29 g of plastic every day, this would amount to a daily leakage of approximately 1.5 tonnes of plastic (in addition to 7 tonnes of other anthropogenic waste). Unfortunately, there are no estimates for the total numbers of gulls feeding at landfills in Europe.

4.4. Landfill use by LBBG and implications for management

There was a decrease in recent years in the use of Antequera landfill despite its close distance to FP, and this was probably a consequence of bird deterrence by falconers. However, deterrence techniques have been shown to be inefficient at preventing gulls from feed at open landfills in other study areas and with different gull species, where only an intensive combination of techniques (with high economical costs) were shown to be efficient (Baxter and Robinson, 2007).

Around 40 % of plastic waste generated by urban populations in Europe is accumulated in landfills as the final destination due to the low efficiency in waste separation (PlasticsEurope, 2021). The closure of open landfills is a first step to reduce the visits of scavenging birds like gulls (Langley et al., 2021), thus limiting their role as plastic biovectors. An integrated waste management approach to reduce waste, but also to improve plastic and other debris separation from organic waste, would likely reduce the amount of plastic ingested by gulls while foraging. Furthermore, specific measures to prevent birds from feeding at open landfills should be implemented. A reduction in the amount of time that the waste is exposed in the open air would reduce the food availability for birds, as indicated in the new EU waste management directive (Belant, 1997; Vaverková, 2019). Such measures could potentially reduce the number of gulls foraging at landfills, and hence the plastic deposition into aquatic ecosystems.

The use of bioplastics, especially those that use biowaste, has been proposed as a method to diminish the impact of plastic pollution, especially polylactic acid (Morone et al., 2015; D'Adamo et al., 2020). This could also help to develop a circular economy by reducing the amount of waste that ends up accumulated in landfills (D'Adamo et al., 2020). Nevertheless, bioplastics are not harmless and more research is needed to consider the impact of bioplastics and its additives, especially in aquatic ecosystems (Qin et al., 2021; Feng et al., 2023).

4.5. Conclusions

This study highlights the importance that gulls can have for leakage of plastic and other debris from landfills into inland waters. Plastic accumulation is particularly likely in closed-basin lakes such as Fuente de Piedra. The combination of waterbird counts, GPS tracking and egesta analysis allows the quantification of plastic and other debris loading, and identifies a clear need to improve policy legislation to improve waste separation and plastic reduction. Changes in food packaging to bio-based solutions (D'Adamo et al., 2020), or development of biodegradable plastic residues (bioplastic; Morone et al., 2015) would reduce the amount of plastic that enters landfills. Long-term studies over several years (12 in our case) also allow evaluation of deterrence techniques and other methods to reduce landfill use by gulls or other biovectors. Given the widespread concentrations of gulls on inland waters and landfills worldwide, our study highlights an important issue, and provides a useful model for future work elsewhere.

CRediT authorship contribution statement

Víctor Martín-Vélez: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Julián Cano-Povedano:** Writing – review & editing, Resources, Methodology, Formal analysis. **Belén Cañuelo-Jurado:** Resources, Methodology, Investigation. **Cosme López-Calderón:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Vanessa Céspedes:** Writing – review & editing, Resources, Investigation. **Macarena Ros:** Writing – review & editing, Methodology. **Marta I. Sánchez:** Writing – review & editing, Investigation. **Judy Shamoun-Baranes:** Writing – review & editing, Resources. **Wendt Müller:** Writing – review & editing, Resources. **Chris B. Thaxter:** Resources, Writing – review & editing. **Cornelis J. Camphuysen:** Writing – review & editing, Resources. **Andrés Cózar:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Andy J. Green:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.01.034.

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