

RESEARCH ARTICLE

Exposure to a raptor-like robot induces collective escape responses in two avian species and can trigger massive and persistent displacements

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Abstract

1. Bird flocks frequently generate human–wildlife conflicts, resulting in safety and health hazards, and economic losses. Remotely controlled, raptor-like robots have recently emerged as potentially effective deterrence tools, exploiting the innate collective escape response of birds to their predators and hence avoiding the emergence of habituation, but field tests are still scanty.
2. We tested the effectiveness of a robotic falcon (RobotFalcon [RF]) as a deterrence tool for feral pigeons *Columba livia* breeding and feeding in a cattle farm (~500 individuals) and black-headed gulls *Chroicocephalus ridibundus* night-roosting in a wastewater treatment plant (~8000 individuals). We analysed collective behavioural responses during 10-min RF exposure trials mimicking natural predator attacks and assessed deterrence effectiveness (change in the number of birds) at different temporal scales (immediate response—within-trials and returning post-trials; short-term response—across 5–8 successive daily exposures). We also evaluated medium-term deterrence effectiveness by quantifying gull flight activity using a marine radar for ~10 days after RF exposure trials.
3. The RF induced consistent collective behavioural responses, similar to real avian predators. The frequency of collective behaviours decreased both within- and across trials, mainly because flocks rapidly abandoned the target sites.
4. Pigeons decreased both during and increasingly across trials, abandoning the target site soon after trial onset. However, most pigeons returned within 30 min after the end of trials, and individuals returning post-trials decreased only slightly (13%) across trials. The RF triggered massive gull displacements during trials, with a faster reaction in the last trial days compared to initial ones, and individuals returning post-trials decreased markedly (94%) across trials. Night flight activity

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showed a large (40%) decrease post- compared to pre-trial days, suggesting persistent deterrence effects.

5. *Practical implication.* The RF is a valuable tool to deter birds from gathering in flocks in contexts where human–wildlife conflict may arise, based on robust evidence and field tests under different conditions. Yet, its effectiveness may depend on the importance of resources used by the target flocking species at the exposure site. Predator-like robots provide unique advantages related to animal welfare, consistency of deterrence protocols and effective management of human–wildlife conflicts.

KEYWORDS

anti-predator response, birds, collective behaviour, deterrence, ethorobotics, human–wildlife conflict, landscape of fear

1 | INTRODUCTION

Animals often form aggregations (e.g. bird flocks, fish schools and insect swarms) that may considerably vary in size, composition, temporal persistence and extent of inter-individual distancing (Krause & Ruxton, 2002; Sumpter, 2011). Such aggregations express collective behaviours (Beauchamp, 2002; Lack, 1968; Shaw, 1978) providing benefits unattainable individually (Morand-Ferron & Quinn, 2011). In birds, flocking is frequent across life stages and contexts, including migration, foraging and roosting. Predation risk is a key evolutionary driver of flocking, as grouping reduces individual predation risk through information sharing, confusion effects via self-organizing collective behaviours and dilution effects (Beauchamp, 2002; Carere et al., 2009; Landeau & Terborgh, 1986; Ling et al., 2019; Magurran, 1990; Olson et al., 2013; Storms et al., 2019; Wood & Ackland, 2007; Zoratto et al., 2010).

Large bird aggregations at specific sites can lead to conflicts with human activities, generating economic losses and safety hazards (Conover, 2001). For instance, bird flocks may damage crops and consume livestock feed (Anderson et al., 2013). Such aggregations could facilitate the spread of zoonotic and epizootic diseases through their faeces (Belant, 1997) and may cause considerable damage to buildings and infrastructure when birds perch or nest (e.g. when they settle breeding colonies) on them by releasing abundant droppings that may chemically alter surfaces (Spennemann et al., 2017) and/or by accumulating nest building material (Liu & Li, 2024). Furthermore, large bird flocks gathering near airfields may pose serious risks for aviation safety, with bird strikes being a major cause of aviation incidents and, occasionally, accidents (Dolbeer et al., 2014).

Several tools have been devised to disperse bird flocks from target sites or prevent their gathering, including visual, acoustic or chemical deterrents (e.g. flashlights, laser beams, broadcasted distress/predator calls, loud blasts and repellents), physical barriers (e.g. nets and spikes) or scaring through trained birds of prey (Blackwell et al., 2002; Gagliardo et al., 2020; Harris & Davis, 1998). Such tools, if effective, may reduce reliance on lethal methods (e.g.

culling), limiting ethical/legal issues associated with bird control (McManus et al., 2015; Shvrik, 2004) and may alleviate human–wildlife conflicts when lethal methods are restricted or inappropriate. Their effectiveness, defined as the ability to drive bird flocks away persistently from a specific target area, varies widely. Unfortunately, many deterrence tools are prone to habituation, a process where birds become less responsive to non-lethal stimuli upon repeated exposures (Blumstein, 2016). A desirable deterrent tool would thus prevent habituation or even induce sensitization, that is, an increased responsiveness to a repeated stimulus (Blumstein, 2016). Yet, lack of habituation to a specific stimulus is essential but not sufficient for assessing deterrence effectiveness, since the latter may involve evaluating the persistence of the deterrence effect through time, which would limit the need for continuous deployment of a specific deterrence tool (or alternation of different deterrence tool; see Storms et al., 2022).

Remotely controlled, predator-like robots offer a promising alternative to traditional bird deterrents, addressing many of their limitations (Polverino et al., 2019; Storms et al., 2022; Wandrie et al., 2019). Predator-like aircrafts have proven to be more effective than drones or standard aircrafts in eliciting strong anti-predator collective responses in bird flocks (Egan et al., 2020; Storms et al., 2022, 2024). For instance, Egan et al. (2020) showed that under controlled conditions birds perceived drones with predatory characteristics as riskier than normal drones (i.e. fixed-wing and multirotor platforms), suggesting that flight type but also features like silhouette, shape or colour contribute to the deterrence effectiveness of predator-like robots. Furthermore, the fact that raptor-like robots trigger the innate collective escape responses of birds to their natural aerial predators (Emlen, 1952) could minimize the risk of habituation to the artificial threat after repeated exposures. Finally, predator-like robots allow operators to avoid the many challenges associated with deploying real predators such as trained raptors, including addressing animal welfare issues (of both predator and prey), high maintenance and training costs and inconsistent deployment protocols (Storms et al., 2022).

We performed a test of the effectiveness of a remotely controlled predator-like robot, the RobotFalcon (RF hereafter), as a tool for the deterrence of bird flocks from target sites. The RF mimics a peregrine falcon *Falco peregrinus* (see [Supporting Information](#) for more details; [Figure S1](#)), a cosmopolitan raptor that preys on medium to large bird species (White et al., 2024), and has recently emerged as an effective tool for experimentally studying predator–prey interactions and collective avian escape responses (Cerritelli et al., 2025; Papadopoulou et al., 2022a, 2022b, 2023; Sankey et al., 2021; Storms et al., 2024). So far, its deterrence potential has been explored by a single study, where opportunistically detected small flocks of several bird species (corvids *Corvus monedula*, *C. frugilegus*, *C. corone*; black-headed gull *Chroicocephalus ridibundus* and common gull *Larus canus*; northern lapwing *Vanellus vanellus*; starling *Sturnus vulgaris*) foraging in farmland areas rapidly flew away once chased by the RF, and birds (not necessarily the chased ones) took several hours (3–4) to show up again at a field where chasing took place (Storms et al., 2022). However, testing RF deterrence efficiency across different contexts and evaluating the potential for habituation/sensitization (by deploying repeatedly and consistently the RF at the same target sites) is required for a proper assessment of its effectiveness as a bird flock deterrence tool.

We focused on two bird species that frequently cause human–wildlife conflicts when they congregate near human settlements and infrastructure (Burger et al., 2020; Lowther & Johnston, 2020), namely feral pigeons *Columba livia* (hereafter, pigeons) breeding and feeding in a cattle farm (~500 individuals) and black-headed gulls (hereafter, gulls) night roosting in a wastewater treatment plant (~8000 individuals). Both species may transmit pathogens to humans and livestock, including bacteria, viruses, fungi, arthropods and allergenic proteins (Caserta et al., 2024; Hatch, 1996; Kozdrun et al., 2015; Li et al., 2024; Mia et al., 2022; Shwiff et al., 2012). Their droppings may cause chemical alterations to buildings and infrastructure, as is the case with large pigeon colonies (Belant, 1997; Giunchi et al., 2012). Additionally, pigeons and gulls are among the species most frequently involved in bird strikes (El-Sayed, 2019; ENAC, 2023). Pigeons also induce substantial damage to crops and extensively forage on livestock feeds (Giunchi et al., 2012; Sausse et al., 2021).

We aimed at: (1) characterizing the collective escape response of the target species to RF repeated exposures; (2) assessing the effectiveness of deterrence (change in numbers) induced by RF deployment at different temporal scales. We mostly not only focused on the immediate (during RF exposure trials and immediately post-trials) and short-term responses (across successive daily RF exposure trials), but also evaluated medium-term deterrence effectiveness in gulls. We expected the RF to: (a) elicit strong collective behavioural escape responses, similar to those triggered by real avian predators; (b) effectively chase away birds from the target sites during the exposure period (immediate effects; Storms et al., 2022), an effect that should persist across repeated RF exposures (i.e. with no or minimal habituation). No general prediction could be formulated for the medium- or long-term deterrence effects of the RF due to the lack of previous data (Storms et al., 2022). However, repeated exposure

to a robotic predator may persistently shape the 'landscape of fear' (Gaynor et al., 2019), leading flocks to avoid sites perceived as too risky due to frequent encounters with a potential threat.

2 | MATERIALS AND METHODS

2.1 | Study sites and target species

This study was conducted at two sites in northern Italy. The first, a cattle farm in San Zenone al Lambro (SZ; 45°19'34" N, 9°21'41" E), hosts ~500 pigeons year-round, perching and breeding on rooftops and feeding on silage, which causes conflicts with farmers and exposes livestock to avian-borne pathogens. To reduce such conflicts, regular (1–2 times/year) culling of hundreds of individuals is carried out at the site (pers. obs.). The second site, Nosedo wastewater treatment plant (NO; 45°25'34" N, 9°13'11" E), serves as a winter night-roost for ~8000 black-headed gulls. Between October and March, gulls gather at the site at dusk (Bonomelli, 2021), probably attracted by the warm temperature (~10°C) of the denitrification tanks and leave the area at dawn. Their regular night presence at the site leads to guano accumulation, which may impair water treatment, increase equipment corrosion and expose workers to wildlife diseases like avian influenza (Alexander, 2000). No previous attempt to drive gulls away from the site by local managers (i.e. deployment of static raptor decoys, predator calls, falconry; C. Brioschi, pers. comm.) was successful.

The study did not require ethical approval as it involved only non-invasive deterrence of target non-protected species, which were never harmed or restricted in movement during deterrence activities. Furthermore, the study was conducted on very large monospecific aggregations of the two species, implying that negative effects of the RF on non-target bird species were negligible.

2.2 | RF exposure trials

The RF was launched near the concentrations of birds (within 50–100m) and flown on sight by R.J.M. (developer and certified RF operator), implying that it mostly remained within 200m of the target site. It mimicked peregrine falcon flight and hunting behaviour, circling over the site while scanning for prey (Herbert & Herbert, 1965). Stoops (i.e. sudden dives simulating attacks; Alerstam, 1987) were performed to target pigeons but avoided with gulls to prevent them from fleeing to the water treatment tanks of the plant, a described response to aerial threats in this waterbird species involving perching on water, where they are safe from falcon attacks (Cramp, 1985), which may hinder deterrence from the target site. We set exposure timing and duration to maximize the number of birds encountering the RF while minimizing other disturbances and simulating natural predator presence, also accounting for RF battery duration (~15min). We performed RF flights under licence from the local authority (Prefettura di Milano—Ufficio Territoriale del Governo, Prot. 12B2/2015-017578), in compliance with Italian regulations (ENAC ATM-05 circular).

In SZ, we performed 10 RF exposure trials (i.e. deterrence flights) over 5 days in mid-February 2023 (two flights per day). Trials lasted 10.20 ± 1.14 min (mean $\pm$ SD; range: 8–12 min), with the first one starting around midday (11:50 AM–12:30 PM) and the second one between 12:40 PM and 1:15 PM, the quietest period of the day at the farm, when pigeons were foraging on cattle feeders and were little disturbed by farming activities.

In NO, we exposed black-headed gulls to the RF eight times during 8 non-consecutive days (over a 10-day sampling period, due to conditions preventing RF flight, such as fog or rain). Flights began between 5:15 PM and 5:30 PM and lasted 9.50 ± 1.77 min (mean $\pm$ SD; range: 8–13 min). The timing was selected to coincide with the peak presence of gulls, according to previous knowledge of gull behaviour at the site (Bonomelli, 2021), while ensuring sufficient daylight for RF flights.

Because the size and appearance of predators can affect the response of potential prey, we used two RF models differing in size, a smaller (male-like) model and a larger (female-like) model, reflecting peregrine falcon sexual dimorphism (White et al., 2024) (see [Supporting Information](#) for details). We performed an equal number of trials for each RF model at both sites, using a balanced randomization scheme.

2.3 | Characterizing and quantifying collective escape and numerical responses to the RF

We video-recorded flock reactions (1080p HD, 30 fps, Samsung Galaxy S22 Ultra) during all RF exposure trials from launch to

landing from a single vantage point allowing a good view of target sites (~500 m radius). After each trial, two observers monitored both sites for about 30 min in SZ and 1 h in NO (the difference was due to time constraints imposed by the sampling protocol at SZ), noting return times (time from trial end to consistent return of birds at the site) and estimating the maximum number of individuals returning.

We analysed video recordings using BORIS, a software developed for coding behavioural data obtained from video/audio observations (Friard & Gamba, 2016). To minimize bias, two observers scored flock responses together at a slow speed ($\times 0.3$ speed for pigeons and $\times 0.5$ for gulls). Scored events included: (1) time from RF launch to first bird take-off; (2) flock absence (i.e. no visible flocks); (3) collective behaviours performed by flocks. We referred to the collective behaviour categories described in Storms et al. (2019) and Papadopoulou et al. (2022a; Table 1). We scored only clearly recognizable collective behaviours from our video recordings, so these categories may not be exhaustive.

During trials, pigeons formed small distinct flocks consisting of three or more birds displaying coordinated movements. We estimated both the number/presence of flocks and of individuals in the video recordings every min after the first bird took off.

Gulls reacted to the RF often forming a single large flock of thousands of individuals, sometimes splitting into a few relatively smaller flocks, consisting of hundreds of individuals. Flocks were sometimes too distant from the observers, preventing the accurate scoring of collective turns. We scored behaviours only for large flocks of gulls

TABLE 1 List of collective behaviours involved in collective escape responses, as described in Storms et al. (2019) and Papadopoulou et al. (2022a), scored for feral pigeon and black-headed gull flocks.

Behaviour	Description
Behaviours observed in both species	
First take off	The first bird taking flight once the RobotFalcon has taken off
Dive	The flock flies downwards
Split	A single flock split into one or multiple sub-flocks
Merge	Multiple sub-flocks merge together
Flash expansion	Birds suddenly move radially outward from a certain location in the flock
Behaviours observed in pigeons	
Collective turn	The flock, or a large part of it, changes direction with a minimum of 90°
Compacting	The whole flock darkens indicating smaller inter-individual distances
Flock dilution	After compacting, the flock expands, increasing inter-individual distances
Behaviours observed in gulls	
Blackening	Part of the flock darkens indicating smaller inter-individual distances
Wave event	Pulse(s) of optically darkened bands propagating along a direction across flock
Cordon	Two parts of the flock are interconnected by a thin string of individuals

(≥ 100 individuals) and estimated the number of individuals at the site at 1, 5 and 10 min of each trial.

2.4 | Analyses of behavioural and numerical responses to the RF

2.4.1 | Variation in collective escape responses

We extracted visible collective escape behaviour events per frame from BORIS and summed frames to calculate behavioural rates per minute (i.e. number of frames/min where a given collective behaviour occurred) during the entire exposure trial (10 min). Collective behavioural rates (behaviours/min) were calculated only when at least one flock was visible in the video recordings. Because of the small frequency of occurrence of most collective behaviours, they were pooled into a variable called 'collective escape behaviour rate' (frames with collective behaviours/min), except for 'collective turn rate', which was analysed also separately following the same procedure. We fitted a binomial generalized mixed model (GLMM) with collective escape behaviours rate as the dependent variable, including as predictors minute of trial (continuous covariate; reflecting immediate response; except for the number of individual gulls, where it was considered as a three-level factor, that is, 1, 5 and 10 min; see Section 2.3), trial day (continuous covariate; pigeons: 1–5; gulls: 1–8; reflecting short-term response), RF model (large vs. small) and for pigeons only, trial order (first vs. second daily exposure). Trial day was also included as a random intercept effect given the hierarchical nature of the experimental design. All numeric covariates were mean-centred. The interaction between minute of trial and trial day was included in initial models and removed if non-significant ($p > 0.05$). If overdispersion was detected, we accounted for it by fitting a beta-binomial GLMM.

2.4.2 | Variation in flock absence rate, number of flocks and individuals present, and number of returning individuals

We computed flock absence rates (frames without flocks/min) following the same steps described above for collective behaviours rates and fitted mixed binomial models (or beta-binomial in case of overdispersion) with the same parametrization described in Section 2.4.1. For pigeons, minute of trial was also included as a quadratic term to account for non-linear variation in flock absence detected in exploratory analyses.

We fitted Poisson GLMMs to analyse variation in the number of flocks (for pigeons) and individuals (as defined for pigeons and gulls) within and across RF exposure trials (i.e. immediate and short-term numerical responses). Predictors and random effects matched those described in Section 2.4.1. If overdispersion occurred, we fitted negative binomial or generalized Poisson GLMMs, using model diagnostics to choose the best one.

The number of individuals returning after each trial was modelled, separately for each species, using Poisson general linear models (GLMs), including trial day, RF model and trial order (only for pigeons) as predictors.

GLMMs were fitted using the *glmmTMB* 1.1.7 package (Brooks et al., 2017) in R (version 4.3.0, R Core Team, 2023). Since some of our dependent variables were collected at relatively short consecutive time intervals (i.e. minutes), before fitting GLMMs including minute of trial as a predictor, we performed exploratory analyses to check whether accounting for temporal autocorrelation improved model fit by adding an *ar1* autocorrelation structure (Zuur et al., 2009). In all cases, accounting for temporal autocorrelation did not improve model fit based on AIC comparison (AIC values were higher or < 2.0 units compared to the models without *ar1*). We therefore concluded that temporal autocorrelation did not bias our model, and we did not consider it further.

2.5 | Assessing medium-term persistence of RF deterrence effects on gulls

To assess medium-term RF deterrence effects on gulls, we used a marine radar (GEM Elettronica, San Benedetto del Tronto, Italy; 12-kW, x-band 9.1 GHz, 38 RPM rotation and 2.1 m horizontal antenna) to monitor bird activity around NO. We positioned the radar on a rooftop facing the sewage treatment tanks. It operated within a 2 km radius, covering the 105° sector where gulls gather (Figure 1), continuously recording movements of targets during 12 days before RF trials (PRE), during the 8 trial days (TR) and during 11 days post-trials (POST).

We used R4B software (www.radar4birds.com) to record 2D movement paths of airborne targets, including target position at each rotation (see Beason et al., 2013). Each track (identified by an ID) represents the path (i.e. serial steps) of an individual or a flock, as radar consolidates lightly packed groups of birds into single targets (Beason et al., 2013). Hence, the radar provides a bird flight activity index, reflecting relative gull flight activity, but does not allow assessing actual bird abundance. However, we assumed that higher flight activity is associated with a greater presence of gulls at the site. Since the presence of other large bird species at the target site was negligible (pers. obs.), we attributed all tracks to gulls.

We filtered radar data based on weather, distance from radar and track step count. Weather, particularly rain, can introduce noise, as each raindrop can reflect radar signals and appear as moving elements (Nilsson et al., 2018). Hence, we exclude data recorded 2 h before and after rain events logged by the two nearby ARPA weather stations (Rodano, 45°28'21" N - 9°21'13" E; and Corsico, 45°26'10" N - 9°05'51" E; 11.6 and 9.9 km from NO, respectively). We limited track steps to a 1500 m radius from the radar (fixing steps sequence and track IDs of tracks that crossed the threshold), that is, targeting only tracks near the wastewater plant. Finally, we discarded tracks with fewer than five steps to minimize environmental clutter (long tracks were maintained given their scarcity).

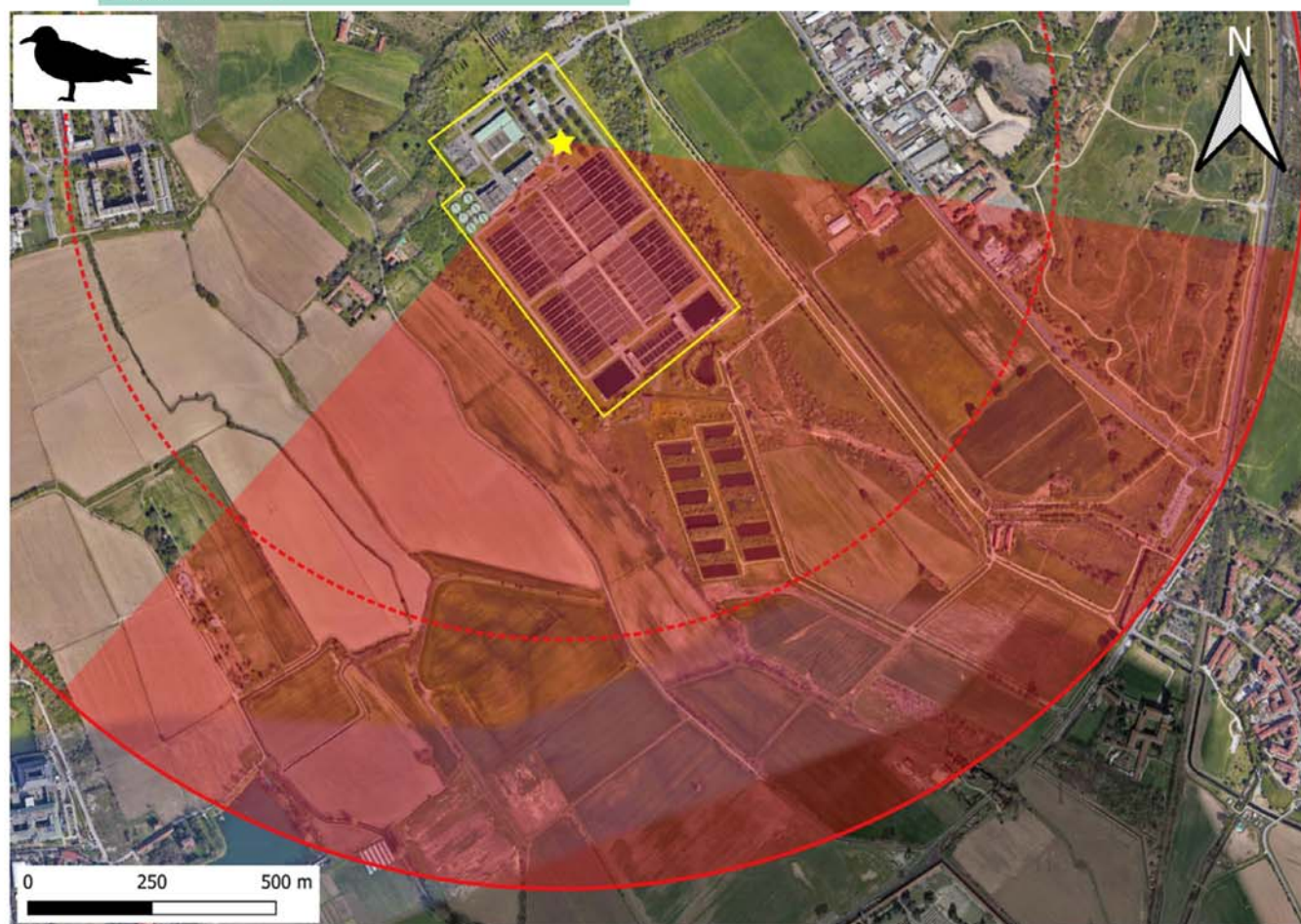


FIGURE 1 Nosedo wastewater treatment plant (NO, yellow line) and surrounding area. The yellow star marks the videorecording and marine radar location. The solid red line marks radar's detection range (1500m radius), the dashed red line marks the boundary for calculating the net incoming flow of tracks (1000m radius) and the shaded red semi-circle the monitored area (105° angle).

The filtered dataset consisted of approximately 1,200,000 tracks (PRE=601,124; TR=250,926; POST=330,208).

We quantified gulls' activity in NO as tracks/min during radar operating time. We used a 10min moving average for smoothing and visualizing daily flight activity averages across PRE, TR and POST periods with a line plot. To investigate gull direction, we calculated the net bird flow/min as the average number of tracks/min entering minus those exiting a 1000m radius around the radar (chosen as the limit between entering and exiting the plant area; data were previously smoothed with a 30min daily moving average; [Figure 1](#)). Radar data were analysed using R version 4.3.0 (R Core Team, 2023).

3 | RESULTS

3.1 | Pigeon behavioural and numerical responses to the RF

Collective turns were the most frequent collective escape response displayed by flocking pigeons across all RF exposure trials ([Table 2](#)). Collective behaviour rates decreased over the course of each trial,

TABLE 2 Frequency of occurrence (%) of collective behaviours observed in pigeon and gull flocks during RobotFalcon exposure trials. It is computed as the fraction of time during which a given behaviour was observed across all trials divided by the time during which at least one flock was visible. The remaining percentage refers to the fraction of time when individuals were flocking but not performing collective behaviours (62% of time for pigeons, 93% for gulls). Values are omitted if a given behaviour was not observed/ scored for a given species.

Behaviour	Pigeons (%)	Gulls (%)
Collective turn	35.74	-
Compacting	0.54	0.04
Relaxing	0.39	0.04
Dive	1.13	1.04
Merge	0.10	0.01
Split	0.14	0.01
Flash expansion	<0.01	<0.01
Blackening	-	3.98
Wave event	-	1.23
Cordon	-	0.17

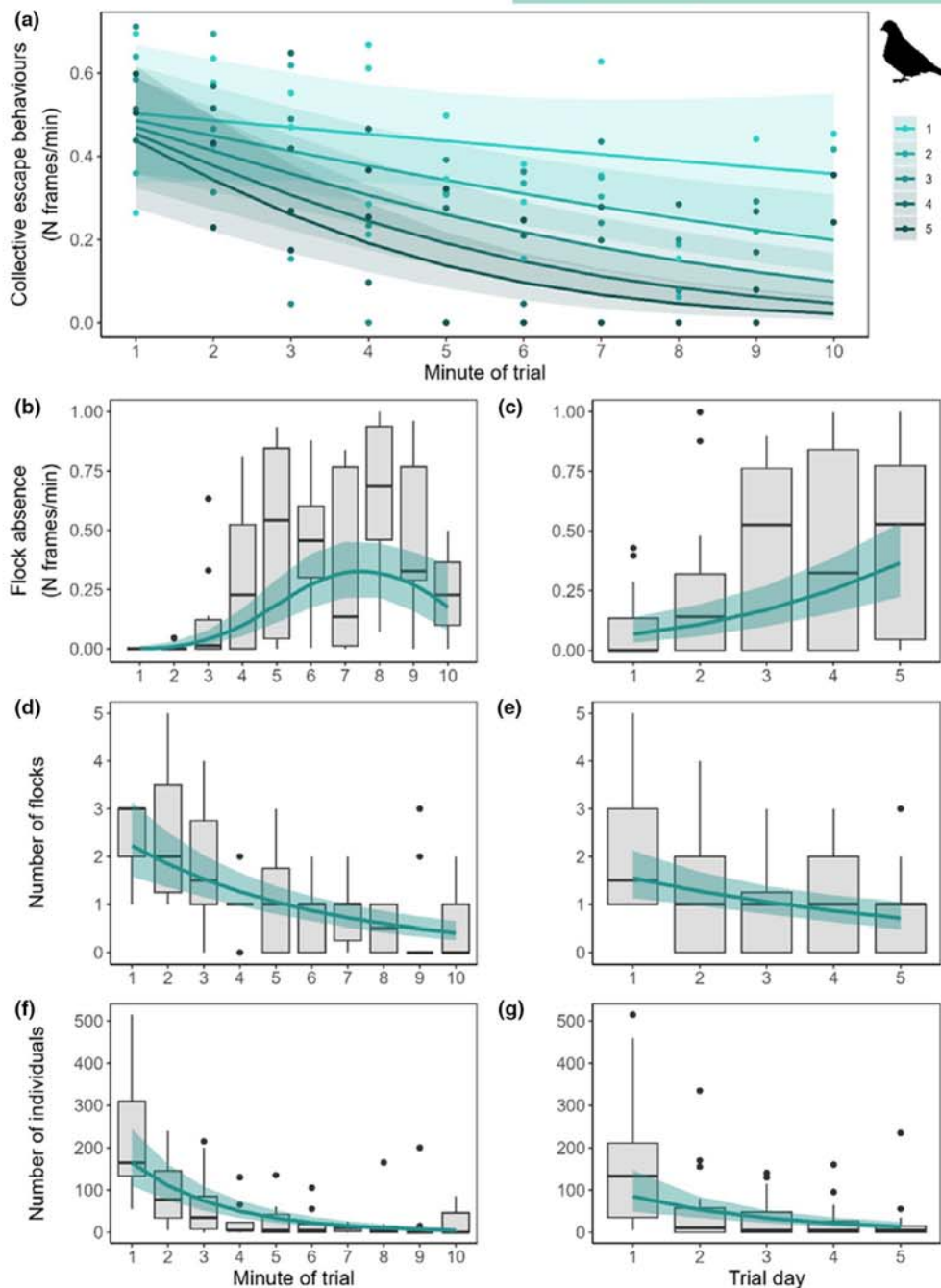


FIGURE 2 Behavioural and numerical responses of feral pigeons to RobotFalcon exposure. (a) Combined effect of minute of trial and trial day (from 1 to 5) on overall collective behaviour rate and (b, c) independent effects of both variables on flock absence rate, (d, e) on number of flocks and (f, g) on number of individuals counted during trials. Points and boxplots represent raw data; lines indicate predictions from fitted models and their 95% confidence bands (model detail in Table 3).

the decrease being faster across subsequent trial days (significant minute of trial $\times$ trial day interaction) (Figure 2; Table 3). No significant effects of trial order or RF model on collective behaviour rates emerged (Table 3). Similar trends were observed for collective turn rates (Table S1; Figure S2).

Pigeon flocks were absent from video recordings 30% of the time. Flock absence increased progressively both within and across trials, peaking at about mid-trial before declining slightly (quadratic effect of

minute of trial) (Figure 2; Table 3). Furthermore, flock absence significantly increased from the first (25% of trial duration) to the second (34%) daily RF exposure (Table 3). Both the number of flocks and individuals decreased with trial sequence and minute of trial (Figure 2; Table 3). Trial order did not significantly affect the number of flocks present, while the number of individuals significantly declined from the first to the second daily exposure (Table 3). No significant effect of RF model on pigeon numerical responses emerged (Table 3).

TABLE 3 Behavioural and numerical responses of feral pigeons and black-headed gulls to RobotFalcon (RF) exposure. Model estimates are derived from mean-centred predictors. See Section 2.4 for details of model fitting.

Dependent variables	Predictors	Estimate (SE)	Z	p
Pigeons				
Collective escape behaviour rate ^a	Minute of trial	-0.769 (0.134)	-5.740	<0.001
	Trial day	-0.646 (0.140)	-4.612	<0.001
	Trial order	-0.119 (0.199)	-0.596	0.551
	RF model	0.101 (0.200)	0.506	0.613
	Minute of trial × trial day	-0.357 (0.133)	-2.691	0.007
Flock absence rate ^a	Minute of trial	14.607 (2.208)	6.616	<0.001
	Minute of trial ²	-8.134 (1.887)	-4.310	<0.001
	Trial day	0.816 (0.165)	4.931	<0.001
	Trial order	1.064 (0.339)	3.137	0.002
	RF model	-0.131 (0.339)	-0.385	0.700
Number of flocks ^b	Minute of trial	-0.592 (0.104)	-5.674	<0.001
	Trial day	-0.281 (0.083)	-3.365	<0.001
	Trial order	-0.184 (0.170)	-1.078	0.281
	RF model	0.202 (0.168)	1.204	0.229
Number of individuals ^d	Minute of trial	-1.243 (0.148)	-8.381	<0.001
	Trial day	-0.666 (0.148)	-4.489	<0.001
	Trial order	-0.585 (0.194)	-3.051	0.003
	RF model	0.182 (0.191)	0.953	0.341
Individuals returning post-trial ^c	Trial day	-0.052 (0.015)	-3.50	<0.001
	Trial order	-0.099 (0.029)	-2.44	<0.001
	RF model	0.052 (0.029)	1.82	0.069
Gulls				
Collective escape behaviour rate ^a	Minute of trial	-0.973 (0.225)	-4.335	<0.001
	Trial day	-0.640 (0.201)	-3.184	0.001
	RF model	-0.150 (0.378)	-0.398	0.691
Flock absence rate ^a	Minute of trial	1.848 (0.364)	5.073	<0.001
	Trial day	1.927 (0.477)	4.044	<0.001
	RF model	1.322 (0.900)	1.470	0.142
Number of individuals ^d	Minute of trial (min 5)	-1.121 (0.293)	-3.821	<0.001
	Minute of trial (min 10)	-5.533 (1.264)	-4.379	<0.001
	Trial day	-0.250 (0.159)	-1.580	0.115
	RF model	0.120 (0.287)	-0.419	0.675
	Minute of trial (min 5) × trial day	-0.967 (0.258)	-3.750	<0.001
	Minute of trial (min 10) × trial day	-3.903 (0.921)	-4.237	<0.001
Individuals returning post-trial ^c	Trial day	-0.960 (0.291)	-3.304	<0.001
	RF model	0.395 (0.569)	0.693	0.489

^aBeta-binomial GLMM.

^bPoisson GLMM.

^cPoisson GLM.

^dNegative binomial GLMM.

^eNegative binomial GLM.

The first pigeon flock returned to the target site 11.4 ± 4.3 min (mean $\pm$ SD; $N = 10$ trials) after RF landing. An average of 506 ± 44 pigeons returned within 30 min of termination of RF flights (mean $\pm$ SD; $N = 10$ trials), with a statistically significant but limited (13%)

estimated decrease over trial days (Figure 4; Table 3). Intriguingly, with the exception of trial day 1, the estimated number of pigeons returning to the target site within 30 min of the termination of the RF exposure trials was often considerably larger (up to eight times)

than the numbers estimated at the beginning of the trials (Figures 2 and 4).

3.2 | Gull behavioural and numerical responses to the RF

Blackening was the most frequent collective behavioural response displayed by gull flocks during RF exposure (Table 2). Gull flocks displayed significantly fewer collective behaviours with the progress of trials and over trial days (Figure 3; Table 3). There was no significant effect of RF model on behavioural responses (Table 3).

Gulls rapidly abandoned NO upon repeated RF deployment. Flocks were absent 16% of the time, a value increasing significantly with trial progression and over trial days (Figure 3; Table 3). Starting from trial day 3, the site was nearly completely cleared of gulls at the end of trials (significant minute of trial $\times$ trial day interaction) (Figure 3; Table 3). The RF model showed no significant effect on numerical responses (Table 3).

The first gull flock returned to the site 30.1 ± 5.1 min (mean $\pm$ SD; $N=8$ trials) after RF landing. Post-trial monitoring revealed a sharp decline in the number of gulls returning over trial days, with nearly no birds returning after the last RF exposure, resulting in a 94% decrease across the trial period (Figure 4; Table 3).

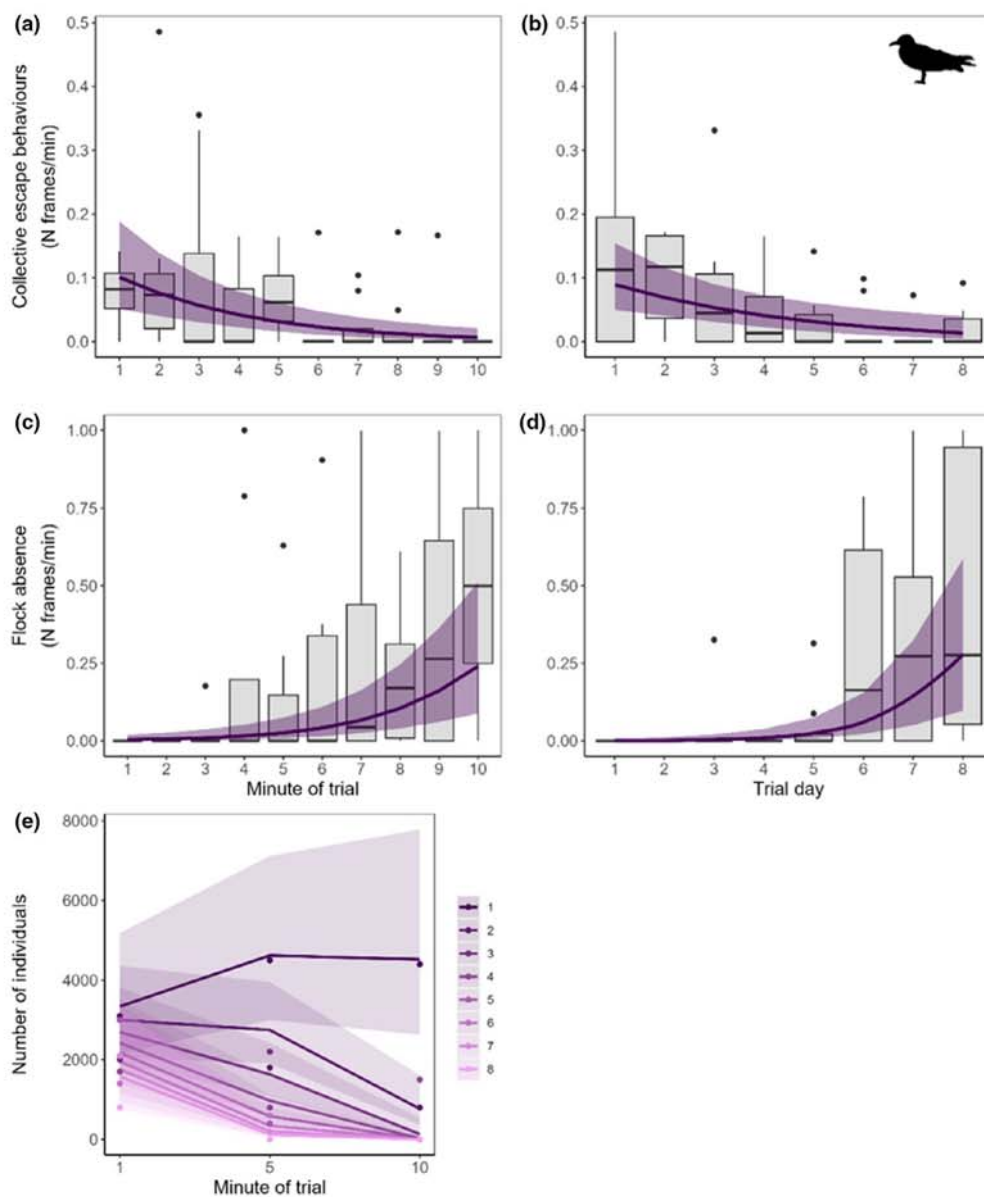


FIGURE 3 Behavioural and numerical responses of black-headed gulls to RobotFalcon exposure. (a, b) Effect of minute of trial and trial day on overall collective behaviour rate, (c, d) on flock absence rate and (e) combined effect of minute of trial and trial day on number of individuals counted during trials (trial days from 1 to 8). Points and boxplots represent raw data; lines indicate predictions from fitted models and their 95% confidence bands (model detail in Table 3).

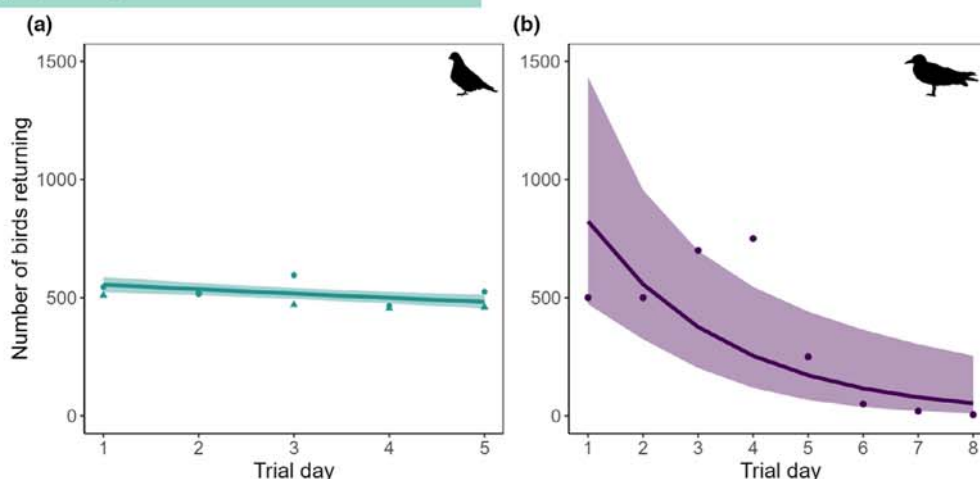


FIGURE 4 (a) Number of feral pigeons and (b) black-headed gulls returning to the study site as a function of trial day.

3.3 | Medium-term persistence of RF deterrence effects on gulls

During the PRE period, gull flight activity peaked at around 4:00–5:00PM, the time of bulk arrival of gulls at the site, declined afterwards and remained low during night-time, when birds rested in water tanks or on plant structures (Figure 5). A second peak occurred around 7:00AM as birds left the plant to forage in the surrounding farmland. The track flow analysis confirmed the occurrence of prevailing movements towards NO during the evening and of prevailing outward movements in the morning, with limited movements to and from the plant during the rest of the day and night (Figure S4). Flight activity was intermediate during daytime (Figure 5), when few gulls are present at NO (Bonomelli, 2021). RF exposure altered this baseline activity: during the TR period, activity spiked sharply soon after RF deployment, rapidly dropping afterwards and remaining markedly lower during the night compared to the PRE period (on average 42% reduction between 6:00PM and 6:00AM). The morning peak remained unchanged, while daytime activity was slightly lower than baseline (9% reduction between 9:00AM and 4:00PM; Figure 5). Furthermore, during the TR period, activity noticeably decreased about 1h before RF trial onset (Figure 5), suggesting that immediately after the first exposure trial, the abundance of incoming birds decreased as they likely reacted to predation threat by avoiding gathering in NO in subsequent days (Figure S3). This aligns with the massive reduction of the number of birds counted at the site by the end of the RF exposure trials occurring from trial day 3 (Figure 3). Importantly, during the POST period, reduced gull flight activity persisted (40% lower night-time and 11% lower daytime activity compared to PRE) and was similar to that observed during TR, suggesting that deterrence effects were detectable in the medium term, well beyond the completion of RF exposure trials (Figure 5).

4 | DISCUSSION

We investigated the behavioural and numerical responses of feral pigeon and black-headed gull flocks when repeatedly exposed to

the RF, a biomimetic robot designed to simulate an avian predator, and evaluated the effectiveness of this innovative tool in deterring flocks of these two species from critical areas at different temporal scales (immediate to medium term). Both species showed consistent collective behavioural responses, but these behaviours decreased in frequency both immediately (within exposure trials) and in the short term (across trial days). Concomitantly, the RF elicited a strong numerical response, with the number of birds/flocks at each site decreasing rapidly both within trials and across trial days, and fewer individuals returning after successive exposures, especially in the case of night-roosting gulls. For the latter species, the RF was able to induce massive displacements, involving thousands of individuals, within minutes of deployment and after only a few exposures. Such a strong deterrence effect persisted in the medium term and lasted for up to 10 days upon termination of RF exposure trials, as gauged through reduced flight activity levels automatically recorded by a marine radar.

The collective behaviours exhibited by both species in response to the RF closely resembled those displayed by group-living birds interacting with real avian predators (Beauchamp, 2002; Dekker, 2022; Lima, 1993), including frequent turning (likely predator evasion manoeuvres) and compacting/blackening (decreasing inter-individual distances and likely representing predator confusion manoeuvres) (Cresswell, 1994; Landeau & Terborgh, 1986; Magurran, 1990; Olson et al., 2013). This confirms previous evidence that the RF effectively increases predation risk perception.

Across successive RF exposures, both species showed a tendency to perform fewer collective behaviours. This reduction is explained by a faster abandonment of study sites across successive trials as soon as the RF appeared. Such a progressively faster abandonment of study sites, most evident in gulls, is a previously undocumented biological effect of the RF. It suggests that persistently exposing flocks to predation threat may trigger faster displacements to nearby areas perceived as less prone to predation risk. This pattern is coherent with sensitization, with the fleeing response from a potentially dangerous stimulus being prioritized compared to collective aerial displays after repeated exposures to that stimulus. Our results

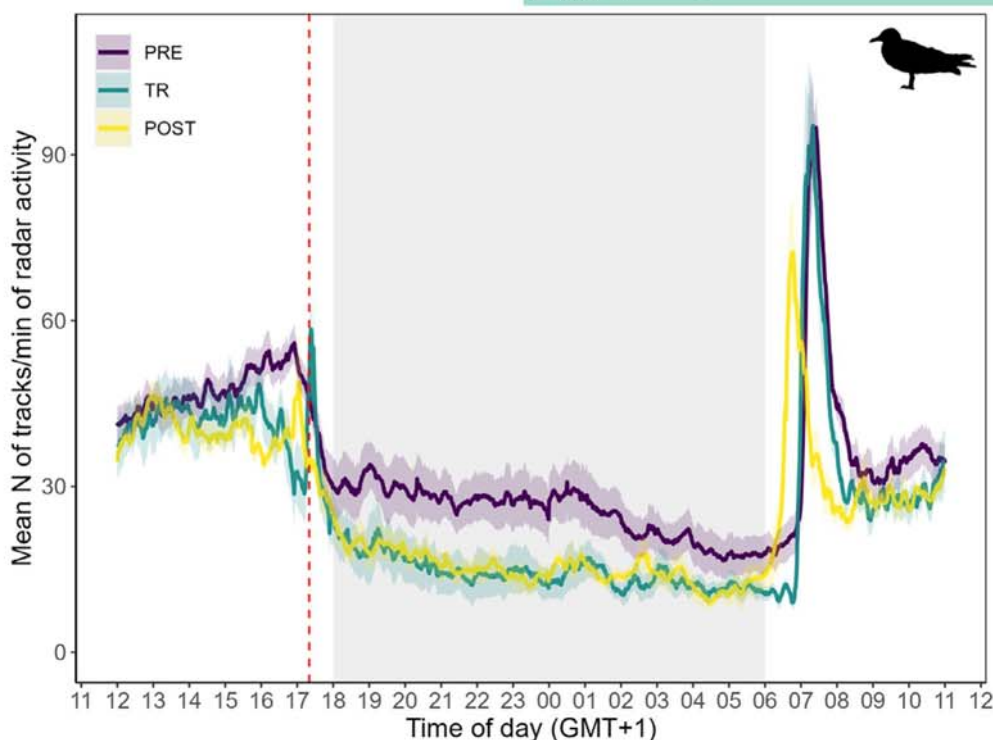


FIGURE 5 Medium-term persistence of deterrence effects in gulls from marine radar data. Mean number of tracks per minute (10-min moving average within each day) ($\pm$ SE), according to time of day (GMT + 1) recorded during 12 days before RobotFalcon exposure (PRE), during exposure (TR), and during 11 days post-exposure (POST). The grey panel represents night-time. The red dashed line indicates the approximate start of RobotFalcon exposure trials.

thus not only confirm previous suggestions that the RF should not be prone to habituation (Storms et al., 2022, 2024), but also highlight that the RF may induce sensitization (Blumstein, 2016; Mohring et al., 2025), which may possibly be one of the key advantages in using the RF compared to other bird deterrence tools (Baxter, 2000; Klug et al., 2023; York et al., 2000).

Yet, the deterrence effectiveness markedly differed between the two species. Pigeons rapidly left the site upon RF exposure, but their overall number at the site did not decrease noticeably throughout the exposure period, with birds rapidly returning to the site after exposure. We could only detect a mere 13% decline in the number of returning individuals at the end of the trials. Oddly, with the exception of trial day 1, the number of pigeons returning after trials was sometimes considerably larger (up to 5–8 times) than individuals counted at the beginning of trials. This could be the case because pigeons at the site may have rapidly associated (from the third trial) the arrival of operators at the farm with a potential threat induced by deploying the RF, and hence may have abandoned the site even before the onset of trials. Pigeons leaving the site mostly moved to a nearby (<1 km) town (church tower), from which they could likely witness when the threat induced by the RF ceased, rapidly returning afterwards. In the end, the number of pigeons at the very beginning of the first trial (515 individuals) was very similar to the number counted returning after the last trial (465 individuals), indicating considerable stability of population size during the experimental period. Pigeons were year-round residents at the cattle farm, using the site

both for breeding and foraging, which may explain their strong ties to it. As one of the main factors regulating population dynamics of pigeons is the availability of nesting sites (Giunchi et al., 2012), the target livestock farm likely represented an irreplaceable and/or essential resource for them. Although the RF was successful in rapidly displacing birds for a short time, such numerical response was only temporary and the decline in returning numbers after RF deployment was limited. This may suggest that only a few non-territorial individuals occasionally frequenting the site underwent higher deterrence/sensitization, whereas the bulk of individuals rapidly returned to their breeding duties after the potential threat vanished. In contrast, gulls were rapidly massively displaced, took longer than pigeons to return to the plant and the numbers returning markedly decreased across successive exposures, with almost none returning after the final trial. Gulls were using the NO site only during winter, likely to exploit the considerably mild microclimatic conditions determined by water treatment procedures at the site, and to drink freshwater. Hence, although they are strongly attracted by the favourable ecological conditions in NO, they did not become strongly tied to it, and if the site is perceived as unsafe, they may rapidly disperse to nearby water bodies or agricultural fields for roosting. The persistent medium-term deterrence effect highlighted by the analysis of radar data may involve an alteration of the so-called 'landscape of fear' (Gaynor et al., 2019) which may greatly enhance deterrence effectiveness and prevent bird flocks from frequenting potentially unsafe site in terms of perceived predation risk. Overall, such massive displacements are intriguing

and future studies involving individuals marked with satellite transmitters (e.g. GPS-GSM transmitters) may better clarify the extent of the movements in response to RF exposure and how persistent such deterrence effects are, including the characterization of 'landscape of fear' alterations.

To conclude, collective behaviours and numerical responses displayed by the target species during RF exposure indicate that this artificial stimulus elicited a strong antipredator response, corroborating preliminary field evidence (Storms et al., 2022, 2024) with data from two specific contexts where effective deterrence was the desired outcome. There was no evidence for habituation upon repeated RF trials and we highlighted novel evidence for sensitization in the numerical response, despite the overall effectiveness of the RF as a deterrence tool markedly differed between species. The medium-term persistence of deterrence effectiveness towards gulls suggests that it may even at least temporarily alter the 'landscape of fear' of some avian prey in specific contexts, creating novel opportunities for the analysis of spatial, landscape-level aspects of collective responses of birds to predation risk. Whether the RF also induces negative but non-lethal fitness effects on target species, for instance, by impairing reproduction, time activity budgets, as well as space use, is a promising and little explored topic in the study of avian predator-prey interactions. The idea that species differences in RF effectiveness are explained by the strength of their reliance on specific resources at the target sites could be further explored by studying the same species across contexts differing in the availability of such resources (e.g. comparing RF responses of pigeons when foraging on crops vs. breeding/feeding in farms). If this is the case, the effectiveness of the RF as a deterrence tool should increase when resources for the target species can be easily replaced by alternative ones. On the applied side, future studies may explore the use of different robotic-raptor models (e.g. eagles or large hawks) tailored to specific contexts and targeting larger conflict-prone species, such as cormorants and herons in fishing ponds/farms or geese foraging in croplands, exclusively where coexistence measures have failed and economic losses outweigh biodiversity and welfare concerns. Yet, our findings underscore the need for a careful use of predator-like robots, and of drones in general, to study wildlife, because these devices may severely disrupt the fitness of non-target species besides that of target ones (Brisson-Curadeau et al., 2025; Schad & Fischer, 2023). These tools should only be used when there is sufficient confidence that they will only affect the target species and no protected or ecologically important species are present at the target sites (Mulero-Pázmány et al., 2017). Taken together, our results convincingly show that deterrence of monospecific bird flocks from specific areas by the RF is highly feasible, opening new, ethically acceptable avenues for the effective management of human-wildlife conflicts.

AUTHOR CONTRIBUTIONS

Irene Vertua, Clémence Menand, Robert J. Musters, Valeria Jennings, Giulia Cerritelli, Anna Gagliardo, Dimitri Giunchi, Claudio Carere and Diego Rubolini conceived the ideas and designed methodology. Irene Vertua and Clémence Menand collected and analysed the data. Irene

Vertua led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest. Robert J. Musters agreed to publish results (regardless of the findings) before the study took place.

PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70078>.

DATA AVAILABILITY STATEMENT

The dataset and R code used for the analyses are available at Dataverse via the following link: https://doi.org/10.13130/RD_UNIMI/NGJN3W (Vertua, 2025).

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SUPPORTING INFORMATION

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

Figure S1. The two RobotFalcon models we have been using in this study: male model (left) and female model (right).

Figure S2. Effect of interaction between trial day (from 1 to 5) and minute of trial on collective turn rate of feral pigeon. Points represents raw data; lines indicate the predictions made by the best-fitting regression model and their 95% confidence bands (from ggeffects 1.2.2 and sjPlot 2.8.14 R packages).

Figure S3. Number of tracks per hour, normalized per minute of radar activity, according to time of day (GMT + 1) during 12 PRE exposure days (a, from -12 to -1) 8 trial days (b, from 1 to 8) and 11 POST exposure days (c, from +1 to +11). Time of day is centred on midnight for ease of representation; grey panel represents night-time. The red dashed line indicates the approximate trial time.

Figure S4. Net incoming flow of tracks ($\pm$ SE, calculated as the square root of the sum of the squared SEs for the number of entering and exiting tracks), normalized per minute of radar activity, from the 1000m circumference, according to time of day (GMT + 1) before (PRE), during (TR) and after (POST) RobotFalcon exposure. Time of

day is centred on midnight for ease of representation; grey panel represents night-time. The red dashed line indicates the approximate trial time.

Table S1. Effects of RobotFalcon (RF) exposure on feral pigeon collective turn at the exposure site. Z-value is reported as test statistic. See 'Statistical analyses of collective escape responses' for details.

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