Research Article

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# Peck or pass? Individual-level testing of a bird-repellent seed coating

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## Abstract

**Background: Carrion crows (*Corvus corone*) are a major depredating species of spring crops across European agroecosystems, especially during sowing, but limited effective non-lethal repellents are currently available.**

**Results: We assessed the deterrent effect of a bird-repellent seed coating, based on black pepper oleoresin (BPO) and applied to maize seeds, on free-ranging carrion crows. Using a standardized unique-choice test design in an urban context, we recorded the behavior of 45 ringed individuals exposed to natural, purple-dyed and purple BPO-coated maize seeds. Although color alone had no deterrent effect, BPO-coated seeds were largely avoided. Age-related differences in habituation emerged: younger birds (≤2 years) habituated to color cues over time, unlike older birds (≥3 years); all age groups maintained an aversion to BPO-treated seeds.**

**Conclusion: Our results underscore the relevance of chemosensory repellents for persistent deterrence and offer a novel and replicable framework for pre-field testing of avian repellents.**

*Supporting information may be found in the online version of this article.*

**Keywords:** bird repellents; black pepper oleoresin; carrion crows; crops; maize

## 1 INTRODUCTION

Conflicts between human activity and wildlife continue to pose significant conservation challenges,[1,2] in urban as in rural landscapes.[3,4] Among these conflicts, bird crop damage stands out as a globally prevalent issue, resulting in considerable economic losses and complicating efforts to balance agricultural productivity with biodiversity conservation.[5,6] Birds, especially granivorous and omnivorous species, exploit cultivated landscapes for high-energy food sources, frequently targeting the sowing and ripening phases of crop production.[7–9] These interactions not only compromise yields, but also raise ethical and practical management challenges, particularly regarding the use of lethal control methods.[3]

In Europe, corvids, including carrion crows (*Corvus corone*), have emerged as significant agricultural pests.[10,11] Their high cognitive abilities, generalist diets and large home ranges allow them to thrive in peri-urban agricultural zones, exploiting predictable sowing schedules while facing minimal predator pressure.[12,13] In France and Switzerland, carrion crows are responsible for widespread damage in early crop stages, particularly in maize and sunflower fields,[14,15] and are consistently cited by farmers among the most problematic avian species, especially during sowing.[3]

Traditional deterrent techniques such as auditory cannons, reflective tape and predator decoys have shown variable and often short-lived effectiveness,[16] particularly against corvids known for their rapid learning and advanced problem-solving skills.[17,18] Increasingly, research has shifted toward non-lethal chemical repellents, particularly seed coatings, as an ethically viable alternative.[19–21] These deterrents operate through one or more of three mechanisms: pre-ingestive aversion via color, odor or taste; post-ingestive malaise; and negative aversive conditioning.[22–24] Among these, anthraquinone (AQ) and methyl anthranilate have shown efficacy in reducing avian seed predation through gastrointestinal feedback and trigeminal irritation, respectively.[25,26] However, despite behavioral results in species such as red-winged blackbirds (*Agelaius phoeniceus*) and common grackles (*Quiscalus quiscula*),[27–29] neither compound is currently approved for use as an avian repellent in the European Union (EU). This is due to insufficient data on environmental exposure and non-target effects.[30,31] This caution is consistent with the EU's broader decision to ban other bird-repellent seed treatments, such as thiram and methiocarb, because of their high ecotoxicological risks.[32–35] Following these withdrawals, Ziram-based formulations have remained among the few authorized seed treatments for maize in certain European countries, including

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Switzerland.[36] Yet concerns persist regarding Ziram's toxicity to aquatic organisms and granivorous birds through seed ingestion or environmental contamination.[37]

Anticipating further regulatory restrictions, there is growing interest in seed-coating repellents based on natural compounds that offer lower ecological and ecotoxicological risk,[38] such as pulegone, caffeine and garlic oil, with studies reporting reduced feeding in blackbirds and starlings under laboratory conditions.[20,39–41] Nonetheless, the effects of these compounds are often species-specific, with limited studies evaluating their deterrent potential in corvids, despite being frequently associated with crop depredation. Recent findings have shown that carrion crows initially avoid colored or flavored seeds but quickly habituate, underscoring the challenge of developing repellents that remain effective under natural foraging conditions.[14] Furthermore, field evaluations are hindered by fluctuating bird pressure, crop phenology, weather conditions and landscape heterogeneity, which complicate replication and interpretation of deterrence results.[11,20,42]

To address these limitations, our study adopted a controlled urban setting to evaluate the short-term deterrent effects of a commercial seed treatment that is currently authorized in Switzerland and designed to function via chemosensory aversion using black pepper oleoresin (BPO). We built on earlier research,[43] involving a marked population of urban carrion crows at Jardin des Plantes, Paris—a site where birds regularly forage near humans and exhibit predictable daily activity patterns.

We conducted a series of sequential unique-choice tests using maize seeds under three treatment conditions: control (no treatment), purple-colored (food dye) and BPO-treated (which is purple-colored). This design allowed us to isolate the effects of color and BPO cues and evaluate the potential of the repellent coating to reduce seed consumption by crows. We expect wild crows that forage on maize to consume or to get used to consuming colored seeds,[43] but to avoid BPO-coated seeds if the coating is effective as a repellent. Our findings, from repeated observations of marked individuals, should offer preliminary insights into the potential of BPO seed treatment as a non-lethal bird deterrent.

## 2 MATERIAL AND METHODS

### 2.1 Study sites and population

This study was conducted in Paris, France (48.84° N, 2.36° E), in urban parks and places where there is a continual human presence throughout the day because of recreational, transit and educational activities. The city supports a long-term monitored population of carrion crows (*Corvus corone*), habituated to humans and frequently observed foraging in open areas. Since 2015, more than 1500 individuals have been ringed at the site as part of a long-term monitoring program led by Parisian environmental services, aimed at assessing survival rates and movement patterns.[4] There are several crow roosts across the city, where crows move between foraging and roosting sites in fission–fusion dynamics.[44]

The sites are the Jardin des Plantes (48.84° N, 2.36° E), a 23.5-ha botanical garden managed by the National Museum of Natural History, Gare de Lyon train station (48.84° N, 2.37° E) and the esplanade Les Halles (48.86° N, 2.34° E). Ringed carrion crows are frequently observed there exploiting food waste and urban structures for foraging and perching. Repeated field observations confirmed the consistent presence of individually marked birds from the same monitored population.

### 2.2 Seed treatments

We tested a BPO seed coating, marketed commercially as Ibisio®,[45] which was pre-colored in purple (variety DKC 3434). To approximate this appearance in the color-avoidance experiment, natural untreated maize seeds (variety LG 31272) were manually coated with food dyes. Both maize varieties were dent-flint with similar maturity, minimizing varietal confounding. We prepared three dye formulations: purple #1 was mixed as 8 mL of red dye (E124 Ponceau 4R, E104 Quinoline) and 6 mL of purple dye (E122 Carmoisine, E133 Blue FCF) per 100 g of maize seeds. Purple #2 used 4 mL of red dye and 2 mL of purple dye with 6 mL of $H_2O$, and purple #3 used 14 mL of red dye and 6 mL of purple dye with 20 mL of $H_2O$ (per 100 g of seeds) (Supporting Information, Fig. S1).

A post-treatment investigation of seed color-coat reflectance (350–700 nm) was performed using a PSR spectroradiometer (Spectral Evolution, Haverhill, Massachusetts). Spectra were converted to violet-sensitive avian cone catches (D65, von Kries adaptation), and chromatic distances to BPO were computed with the receptor-noise-limited model ($\Delta S$, JND units) using *pavo* R package.[46] Purple #1 was closest to BPO ($\Delta S = 1.18$; purple #2 = 1.43, purple #3 = 1.73), so we used purple #1 subsequently (Supporting Information, Fig. S2).

### 2.3 Experimental design

Prior to testing, we implemented a habituation phase to identify ringed individuals from the local population that consistently consumed untreated maize seeds. During this period, maize seeds were provided *ad libitum* at fixed feeding spots. Only individuals that consistently consumed offered seeds (≥20 natural maize seeds) were further included in deterrence tests to ensure reliable behavioral responses.

#### 2.3.1 Color-avoidance tests

From 18 November 2024 to 27 March 2025, we conducted a color-avoidance experiment using small pools of ringed individuals simultaneously (pre-selected during habituation). Each bird received a single seed, either natural (N, uncolored) or artificially colored purple (P). No minimum number of seeds per individual bird was required. Each interaction was considered as an independent test and assigned to the corresponding bird based on its unique ring code.

This experiment aimed to account for potential color-driven biases, given that BPO-treated seeds are purple. By isolating the effect of coloration, we ensure that any potential avoidance observed in later tests is attributable to the treatment itself.

#### 2.3.2 BPO avoidance tests

To assess the deterrent effect of the BPO seed coating, we conducted a second experimental series (27 March to 13 June 2025) using the same protocol described above. This time, we compared uncolored untreated maize (N) with maize seeds coated in a purple BPO formulation (P). Unique-choice tests were performed in the same population of ringed crows; each test offered one seed per trial (N or P) (Fig. 1). Each consumption event was attributed to the corresponding individual using ring identification and each interaction was treated as an independent observation.

During both experimental phases, we recorded a consumption score on a binary scale, classifying seeds as either unconsumed (0) or consumed (1). We also documented the study site (Jardin des Plantes, Les Halles or Gare de Lyon), the date and start time,

**Figure 1.** Ringed carrion crow (G516) during a unique-choice test with natural maize at Jardin des Plantes, Paris. Photograph: M.L. Pamart.

detailed consumption scores for each seed presented, along with its type (N/P) and experimental phase (color/BPO). Ring codes of participating individuals were noted, and their original ringing dates were retrieved to determine age classes. The age of the ringed crows was determined at ringing based on palate color and molt stage, classifying birds as 1 year old (1Y), 2 years old (2Y) or 3 or more years old (≥3Y) and allowing us to know or estimate the age of the individuals involved in the experiment.

We included in the analysis only individuals that interacted with all three seed types—natural, purple untreated and purple BPO-treated (with a minimum of one seed in each category).

We ensured that the findings were not sensitive to this minimal threshold by testing stricter inclusion criteria (minimum of two or three seeds per type) (Supporting Information, Table S1).

### 2.4 Statistical analyses

To analyze seed consumption, we used a generalized linear mixed model (GLMM) with a binomial error structure using the *glmer* function from the *lme4* package.[47] The binary response variable was the consumption score (0 = unconsumed, 1 = consumed). To track the individual exposure for each seed type, we generated a variable called *test_number*. This index reflected the cumulative number of times an individual bird was presented with a given seed type (N/P), regardless of the experimental phase. For each bird (*ID_individu*), trials were ordered chronologically by date within each seed type and numbered sequentially starting from 1. We assumed that purple seeds used in color and BPO experimental phases were visually equivalent and thus represented the same stimulus across treatments.

Fixed effects included seed type (Control or Treated), experimental phase (color or BPO phase), referred to as 'treatment', test number (scaled) and age class of the individuals. Interaction terms were included to examine whether the effects of seed type and exposure differed across treatments or age groups. To account for pseudo-replication (due to repeated observations on the same individuals), bird ring code (*ID_individu*) was included as a random effect. This also ensures that inferences are made at the population level rather than being driven by individual preferences.

The explanatory variables included in the model were selected with a forward stepwise procedure. Model assumptions were checked visually using the R package *DHARMa*.[48] All statistical analyses were performed in R v.4.3.3 (R Core Team 2024) and the significance level considered was 0.05.

## 3 RESULTS

We retained 45 individuals of the 166 tested, with age at testing ranging from 1 to 12 years old. Individuals were further grouped into two age classes for modeling purposes: a 'young' group (≤2Y, $n = 29$) and an 'old' group (≥3Y, $n = 16$). Within this monitored population, birds moved between sites: individuals from Les Halles ($n = 3$) were also tested at the main site (Jardin des Plantes), and only two birds were tested exclusively at Gare de Lyon.

### 3.1 Treatment-dependent seed selection

The GLMM revealed significant main effects of seed type ($\chi^2_1=44.14$, $P<0.001$), treatment ($\chi^2_1=69.59$, $P<0.001$) and their interaction ($\chi^2_1=52.41$, $P<0.001$) on the probability of maize seed consumption by carrion crows. Under the color treatment, crows consumed natural and purple maize at comparable rates [N: 94.5% ± 1.7% standard error (SE); 95% confidence interval (CI) 0.9–0.97 *versus* P: 93.1% ± 1.9% SE; 95% CI 0.88 to 0.96, $P=0.78$], indicating no color-based avoidance. By contrast, under the BPO treatment, purple treated seeds were consumed at significantly lower rates (29.5% ± 5.17% SE; 95% CI 0.2 to 0.4) than natural maize (89.3% ± 2.98% SE; 95% CI 0.81 to 0.94, $P<0.001$) and untreated purple maize (93.1% ± 1.9% SE; 95% CI 0.88 to 0.96, $P<0.001$). These results confirm a marked—although not complete—aversion to BPO-coated seeds, independent of seed color (Fig. 2).

### 3.2 Learning trends across age

A significant interaction between age class and test number ($\chi^2_1=8.69$, $P<0.01$) revealed age-specific learning dynamics. Younger individuals (≤2Y) displayed a positive consumption trend over repeated trials (0.051 ± 0.01 SE; 95% CI 0.02 to 0.07), whereas older individuals (≥3Y) showed no significant learning slope (−0.001 ± 0.01 SE; 95% CI −0.03 to 0.03). The slope contrast was significant ($z=2.95$, $P=0.003$), suggesting lower behavioral plasticity in older birds (Fig. 3).

### 3.3 Learning trends across treatments

Maize seed consumption patterns over time differed significantly between treatments ($\chi^2_1=13.35$, $P<0.001$). Whereas seed consumption increased with repeated exposure under the color treatment (0.060 ± 0.02 SE; 95% CI 0.02 to 0.09), no such trend was detected under the BPO treatment (−0.010 ± 0.01 SE; 95% CI −0.031 to 0.011). This difference in learning slopes was statistically significant ($z=3.65$, $P=0.0003$), and consistent across seed types (Control/Treated), as the three-way interaction was not significant ($\chi^2_1=0.15$, $P=0.69$) (Fig. 4).

## 4 DISCUSSION

Our experimental design revealed a clear deterrent effect of the BPO seed coating on carrion crows, whereas seed color alone (purple dye) had no deterrent effect. In addition, habituation dynamics were shaped by age, with younger birds showing greater behavioral flexibility and learning over repeated trials.

Unlike traditional field trials, where repellent efficacy can be confounded by factors such as weather, fluctuating bird pressure and landscape structure,[11,19,49] our experimental design offers a controlled, individual-level approach. By using ringed individuals, we ensured repeated measures and age tracking, while minimizing variance from unknown individuals and social foraging

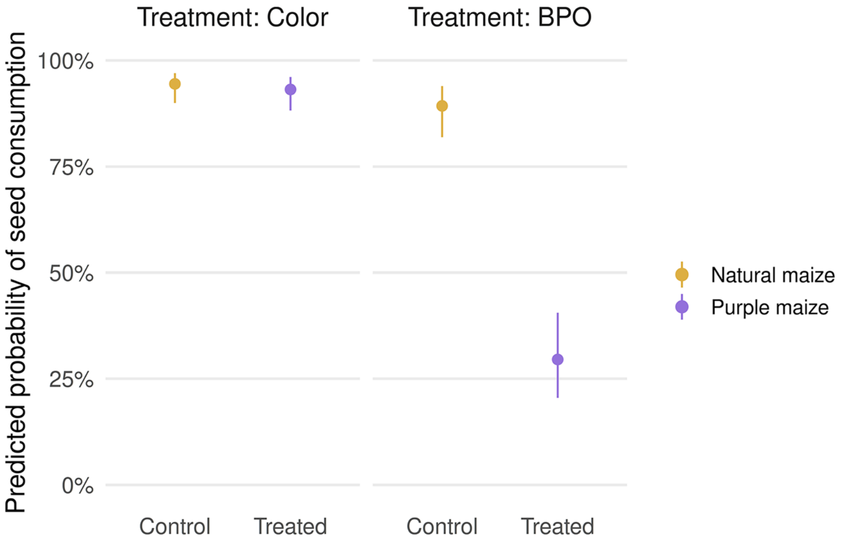

**Figure 2.** Predicted probability of maize seed consumption across treatments (color/BPO) and seed types (Natural = Control/Purple = Treated), as predicted by the binomial generalized linear mixed model. Error bars represent 95% confidence intervals.

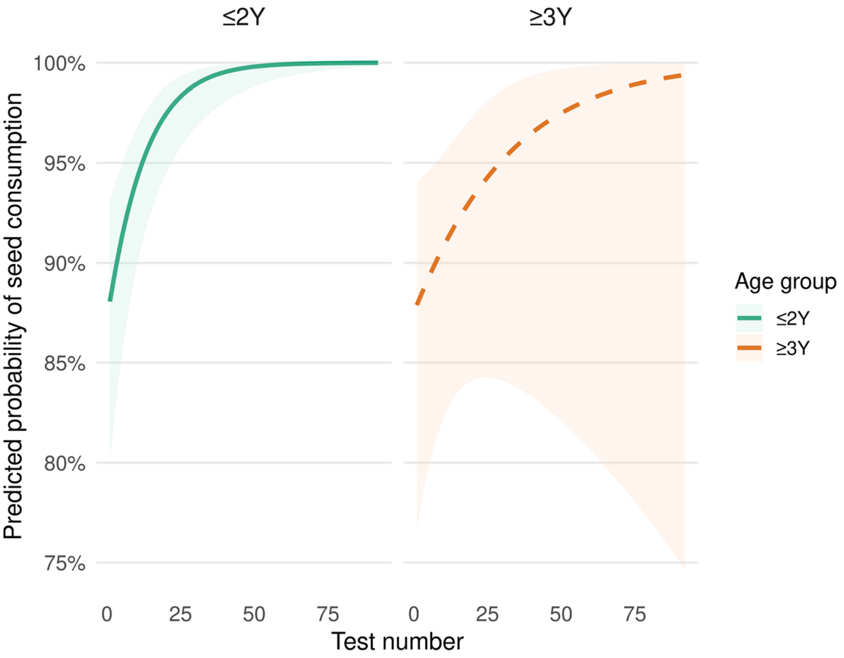

**Figure 3.** Predicted probability of maize seed consumption across repeated trials (test number), by age group (≤2Y *versus* ≥3Y). Predictions and 95% confidence intervals are derived from the binomial generalized linear mixed model. Line type encodes the estimated learning slope significance within each age group (solid: $P < 0.05$; dashed: $P \geq 0.05$).

(dominant individuals may access seeds first or more frequently, affecting consumption patterns).[50] In contrast to feeding experiments with captive birds,[51,52] this approach enhances interpretability by using free-ranging individuals under semi-natural foraging conditions.

Within this framework, color cues alone (purple dye) were ineffective in deterring carrion crows, supporting previous research in which visual cues alone proved ineffective.[43] The here-tested BPO coating, however, clearly drove aversion to maize seeds, highlighting the importance of chemosensory-induced avoidance over visual stimuli.[53] Moreover, aversive effects of BPO persisted over time, possibly due to sensory irritation, preventing habituation. Similar dynamics have been described in conditioning studies.[27,39,54]

Furthermore, our results revealed age-related differences in carrion crows' learning patterns with exposure. Younger individuals (≤2Y) displayed an increasing willingness to forage across repeated trials, whereas older birds (≥3Y) showed no such trend. This pattern is consistent with earlier findings in corvids, where neophilia and exploration decrease with age (Heinrich 1995; Miller *et al*. 2015).[55,56] In crows, juveniles experience a period of environmental exploration as they disperse from their parents' territory and integrate into non-breeder flocks.[57] During this stage, increased openness to novelty likely facilitates the

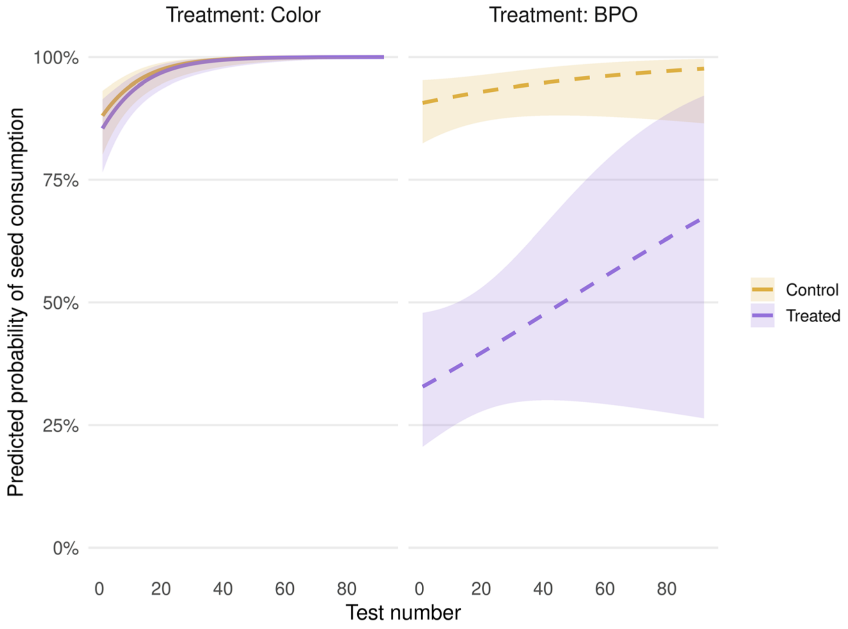

**Figure 4.** Predicted probability of maize seed consumption over repeated trials (test number) across treatments (color *versus* BPO), shown separately for natural (Control) and purple (Treated) maize. Predictions and 95% confidence intervals are derived from the binomial generalized linear mixed model. Lines are dashed in the BPO treatment to indicate a near-zero, non-significant slope.

discovery of new foraging and roosting sites.[58] By contrast, older territorial adults exhibit less behavioral flexibility and tend to operate within familiar areas, thereby reducing the need for frequent exploratory behavior.[59]

Although our findings showed no deterrent effect from seed coloration alone, it is important to note that the purple dye applied to untreated seeds was not chemically identical to BPO's coloring. Because BPO formulations include integrated coloration, exact replication of the reflectance was not feasible. Moreover, expanding trials to a broader range of depredating species including other corvids, such as rooks (*Corvus frugilegus*) and jackdaws (*Corvus monedula*) would strengthen ecological relevance.

Although field trials are a key test of repellent efficacy, our approach offers a valuable pre-field tool for assessing behavioral responses before large-scale testing. The strong and consistent avoidance of BPO-coated seeds across age groups and sessions underscores its potential as a bird repellent, particularly for carrion crows. However, future research must address several practical questions. Key considerations include the short- and long-term avian safety of BPO and its persistence under field conditions, including rainfall, soil moisture and seed germination. Previous studies have shown that similar chemical repellents, such as anthraquinone, may wash off under environmental stressors, limiting their field efficacy.[52,60] Moreover, our experiment took place in an urban foraging context; thus, validating results in agricultural landscapes with broader food availability is crucial. We also excluded birds below a minimum seed consumption threshold (≥20 natural maize seeds), which may bias the sample toward more responsive feeders and should be kept in mind when generalizing the results.

Overall, this approach addresses key limitations commonly associated with traditional field trials. By implementing controlled unique-choice tests on individually identified, free-ranging birds, we offer a replicable framework for evaluating the efficacy of avian repellents under semi-natural conditions.

## AUTHOR CONTRIBUTIONS

AC: conceptualization (equal), data curation (lead), formal analysis (lead), methodology (equal), visualization (lead), writing – original draft (lead), writing – review & editing (equal). AB: conceptualization (supporting), funding acquisition (lead), supervision (supporting), writing – review & editing (equal). FJ: conceptualization (equal), formal analysis (supporting), investigation (lead), methodology (equal), supervision (lead), writing – review & editing (equal).

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## DATA AVAILABILITY STATEMENT

The data, script and main figures are available at Zenodo:

Chantoufi, A., Baux, A., & Jiguet, F. (2025). Code and data for: Peck or pass? Individual-level testing of a bird repellent seed coating [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17208640.

## ETHICS STATEMENT

For trials involving BPO-treated seeds, the experimental protocol was submitted to the Cuvier Ethics Committee (MNHN) and received a favorable decision (Reference 2025–68-135). Authorization to capture and mark carrion crows was granted by the CRBPO (Muséum National d'Histoire naturelle), as the official national licensing authority for bird ringing, under permit reference PP883.

## CONFLICT OF INTEREST

The authors declare no conflicts of interest.

## SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

## REFERENCES

1 Mekonen S, Coexistence between human and wildlife: the nature, causes and mitigations of human wildlife conflict around Bale Mountains National Park, Southeast Ethiopia. *BMC Ecol* **20**:51 (2020). https://doi.org/10.1186/s12898-020-00319-1.

2 Redpath SM, Young J, Evely A, Adams WM, Sutherland WJ, Whitehouse A *et al*., Understanding and managing conservation conflicts. *Trends Ecol Evol* **28**:100–109 (2013). https://doi.org/10.1016/j.tree.2012.08.021.

3 Craplet J, Chantoufi A, Laurent E-A, Compagnone C and Baux A, Why do we keep killing crows? Farmers' attachment to a controversial method in an attempt to protect their crops. *J Rural Stud* **119**: 103707 (2025). https://doi.org/10.1016/j.jrurstud.2025.103707.

4 Lequitte-Charransol P and Jiguet F, Restricted mowing reduces grass uprooting by urban crows. *Eur J Wildl Res* **67**:59 (2021). https://doi.org/10.1007/s10344-021-01504-3.

5 Linz GM, Homan HJ, Werner SJ, Hagy HM and Bleier WJ, Assessment of bird-management strategies to protect sunflowers. *Bioscience* **61**: 960–970 (2011). https://doi.org/10.1525/bio.2011.61.12.6.

6 Nilsson L, Bunnefeld N, Persson J, Žydelis R and Månsson J, Conservation success or increased crop damage risk? The Natura 2000 network for a thriving migratory and protected bird. *Biol Conserv* **236**: 1–7 (2019). https://doi.org/10.1016/j.biocon.2019.05.006.

7 Ernst K, Elser J, Linz G, Kandel H, Holderieath J, DeGroot S *et al*., The economic impacts of blackbird (*Icteridae*) damage to sunflower in the USA. *Pest Manag Sci* **75**:2910–2915 (2019). https://doi.org/10.1002/ps.5486.

8 Kasprzykowski Z, Habitat preferences of foraging rooks Corvus frugilegus during the breeding period in the agricultural landscape of eastern Poland. *Acta Ornithol* **38**:27–31 (2003). https://doi.org/10.3161/068.038.0107.

9 Klosterman ME, Linz GM, Slowik AA and Homan HJ, Comparisons between blackbird damage to corn and sunflower in North Dakota. *Crop Prot* **53**:1–5 (2013). https://doi.org/10.1016/j.cropro.2013.06.004.

10 Furlan L, Contiero B, Chiarini F, Bottazzo M and Milosavljević I, Risk factors and strategies for integrated management of bird pests affecting maize establishment. *Crop Prot* **148**:105744 (2021). https://doi.org/10.1016/j.cropro.2021.105744.

11 Sausse C and Lévy M, Bird damage to sunflower: international situation and prospects. *OCL* **28**:34 (2021). https://doi.org/10.1051/ocl/2021020.

12 Chiarati E, Canestrari D, Vera R and Baglione V, Subordinates benefit from exploratory dominants: response to novel food in cooperatively breeding carrion crows. *Anim Behav* **83**:103–109 (2012). https://doi.org/10.1016/j.anbehav.2011.10.012.

13 Marzluff JM and Angell T, *In the Company of Crows and Ravens*. Yale University Press, New Haven, CT (2007).

14 Destrez A, Sausse C, Aublet V, Lanthony M, Schaal B and Costes-Thiré M, Colouration and flavouring of sunflower seeds affect feeding behaviour in urban carrion crows (Corvus corone): a preliminary study. *Appl Anim Behav Sci* **251**:105642 (2022). https://doi.org/10.1016/j.applanim.2022.105642.

15 Sausse C, Baux A, Bertrand M, Bonnaud E, Canavelli S, Destrez A *et al*., Contemporary challenges and opportunities for the management of bird damage at field crop establishment. *Crop Prot* **148**:105736 (2021). https://doi.org/10.1016/j.cropro.2021.105736.

16 Gilsdorf JM, Hygnstrom SE and VerCauteren KC, Use of frightening devices in wildlife damage management. *Integr Pest Manag Rev* **7**: 29–45 (2002). https://doi.org/10.1023/A:1025760032566.

17 Balakhonov D and Rose J, Crows rival monkeys in cognitive capacity. *Sci Rep* **7**:8809 (2017). https://doi.org/10.1038/s41598-017-09400-0.

18 Seed AM, Clayton NS and Emery NJ, Cooperative problem solving in rooks (*Corvus frugilegus*). *Proc R Soc Lond B Biol Sci* **275**:1421–1429 (2008). https://doi.org/10.1098/rspb.2008.0111.

19 Avery M, AVIAN REPELLENTS. United States Department of Agriculture Wildlife Services: Staff Publications (2002). https://digitalcommons.unl.edu/icwdm_usdanwrc/462.

20 Avery ML, Werner SJ, Cummings JL, Humphrey JS, Milleson MP, Carlson JC *et al*., Caffeine for reducing bird damage to newly seeded rice. *Crop Prot* **24**:651–657 (2005). https://doi.org/10.1016/j.cropro.2004.11.009.

21 Watkins RW, Cowan DP and Gill EL, Plant secondary chemicals as nonlethal vertebrate repellents. Proceedings of the Vertebrate Pest Conference (1996). https://escholarship.org/uc/item/5132n4f9.

22 Gill EL, Watkins RW, Gurney JE, Bishop JD, Feare CJ, Scanlon CB *et al*., Cinnamamide: a nonlethal chemical repellent for birds and mammals. In *National Wildlife Research Center Repellents Conference*, pp. 43-51 (1995) https://digitalcommons.unl.edu/nwrcrepellants/19.

23 Werner S and Clark L, Understanding Blackbird Sensory Systems and How Repellent Applications Work. United States Department of Agriculture Wildlife Services: Staff Publications (2003). https://digitalcommons.unl.edu/icwdm_usdanwrc/287.

24 Werner SJ, Kimball BA and Provenza FD, Food color, flavor, and conditioned avoidance among red-winged blackbirds. *Physiol Behav* **93**: 110–117 (2008). https://doi.org/10.1016/j.physbeh.2007.08.002.

25 Avery ML, Decker DG, Humphrey JS, Aronov E, Linscombe SD and Way MO, Methyl anthranilate as a Rice Seed treatment to deter birds. *J Wildl Manag* **59**:50 (1995). https://doi.org/10.2307/3809115.

26 DeLiberto ST and Werner SJ, Review of anthraquinone applications for pest management and agricultural crop protection. *Pest Manag Sci* **72**:1813–1825 (2016). https://doi.org/10.1002/ps.4330.

27 Avery ML and Mason JR, Feeding responses of red-winged blackbirds to multisensory repellents. *Crop Prot* **16**:159–164 (1997). https://doi.org/10.1016/S0261-2194(96)00076-2.

28 Werner SJ, Carlson JC, Tupper SK, Santer MM and Linz GM, Threshold concentrations of an anthraquinone-based repellent for Canada geese, red-winged blackbirds, and ring-necked pheasants. *Appl Anim Behav Sci* **121**:190–196 (2009). https://doi.org/10.1016/j.applanim.2009.09.016.

29 Werner SJ, Linz GM, Carlson JC, Pettit SE, Tupper SK and Santer MM, Anthraquinone-based bird repellent for sunflower crops. *Appl Anim Behav Sci* **129**:162–169 (2011). https://doi.org/10.1016/j.applanim.2010.11.010.

30 EFSA Panel on Additives and Products or Substances used in Animal Feed (FEEDAP), Scientific opinion on the safety and efficacy of anthranilate derivatives (chemical group 27) when used as flavourings for all animal species. *EFSA J* **9**: 2441 (2011).

31 European Food Safety Authority, Reasoned opinion on the review of the existing maximum residue levels (MRLs) for anthraquinone according to article 12 of regulation (EC) No 396/2005. *EFSA J* **10**: 2761 (2012). https://doi.org/10.2903/j.efsa.2012.2761.

32 European Food Safety Authority (EFSA), Arena M, Auteri D, Barmaz S, Brancato A, Brocca D *et al*., Peer review of the pesticide risk assessment of the active substance methiocarb. *EFSA J* **16**:5429 (2018). https://doi.org/10.2903/j.efsa.2018.5429.

33 Kennedy TF and Connery J, An investigation of seed treatments for the control of crow damage to newly-sown wheat. *Ir J Agric Food Res* **47**: 79–91 (2008).

34 Commission Implementing Regulation, Commission Implementing Regulation (EU) 2018/1500 of 9 October 2018 Concerning the Nonrenewal of Approval of the Active Substance Thiram, and Prohibiting the Use and Sale of Seeds Treated with Plant Protection Products Containing Thiram, in Accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council Concerning the Placing of Plant Protection Products on the Market, and Amending Commission Implementing Regulation (EU) No 540/2011. ELI (2018) (2018). p. 1. http://data.europa.eu/eli/reg_impl/2018/1500/oj.

35 Commission Implementing Regulation, Commission Implementing Regulation (EU) 2019/1606 of 27 September 2019 Concerning the Non-renewal of the Approval of the Active Substance Methiocarb, in Accordance with Regulation (EC) No 1107/2009 of the European Parliament and of the Council Concerning the Placing of Plant Protection Products on the Market, and Amending the Annex to Commission Implementing Regulation (EU) No 540/2011. ELI (2019). p. 53 (2019). http://data.europa.eu/eli/reg_impl/2019/1606/oj.

36 Swiss Federal Office for Agriculture (FOAG), Korit 420 FS – product information. Swiss pesticide database [Online] Available at: https://www.psm.admin.ch/fr/produkte/6679 Accessed 16th Jun 2025.

37 ANSES, *KORIT 420 FS* [product page]. *E-phy* (n.d.). Retrieved September 26, 2025, from: https://ephy.anses.fr/ppp/korit-420-fs.

38 Klug P, Shiels A, Kluever B, Anderson J, Hess S, Ruell E *et al*., A review of nonlethal and lethal control tools for managing the damage of invasive birds to human assets and economic activities. *Management of Biological Invasions* **14**:1–44 (2023). https://doi.org/10.3391/mbi.2023.14.1.01.

39 Avery ML, Decker DG, Humphrey JS and Laukert CC, Mint plant derivatives as blackbird feeding deterrents. *Crop Prot* **15**:461–464 (1996). https://doi.org/10.1016/0261-2194(96)00010-5.

40 Hile AG, Shan Z, Zhang S-Z and Block E, Aversion of European starlings (*Sturnus vulgaris*) to garlic oil treated granules: garlic oil as an avian repellent. Garlic oil analysis by nuclear magnetic resonance spectroscopy. *J Agric Food Chem* **52**:2192–2196 (2004). https://doi.org/10.1021/jf035181d.

41 Linz G, Homan HJ, Penry LB, Primus TM and Goodall MJ, Evaluation of Caffeine and Garlic Oil as Bird Repellents. United States Department of Agriculture Wildlife Services: Staff Publications (2007). https://digitalcommons.unl.edu/icwdm_usdanwrc/706.

42 Tracey J, Bomford M, Hart Q, Saunders G and Sinclair R, *Managing Bird Damage to Fruit and Other Horticultural Crops*. Bureau of Rural Sciences, Canberra (2007).

43 Chantoufi A, Canário AM, Baud T, Vallé C, Baux A and Jiguet F, Seed and color preferences of wild carrion crows from cafeteria experiments. *Ecol Evol* **15**:e70944 (2025). https://doi.org/10.1002/ece3.70944.

44 Jiguet F and Gantin C, Fission–fusion dynamics and spring movements in first-year carrion crows Corvus corone challenge the efficiency of culling strategies. *Sci Rep* **15**:31068 (2025). https://doi.org/10.1038/s41598-025-17175-y.

45 Bayer CropScience, Biological bird repellent Ibisio® showcases the power of innovation. Bayer SeedGrowth (2024). https://www.seedgrowth.bayer.com/en-us/news-stories/biological-bird-repellent-ibisio-showcases-the-power-of-innovation.html.

46 Maia R, Eliason CM, Bitton P, Doucet SM and Shawkey MD, Pavo: an R package for the analysis, visualization and organization of spectral data. *Methods Ecol Evol* **4**:906–913 (2013). https://doi.org/10.1111/2041-210X.12069.

47 Bates D, Mächler M, Bolker B and Walker S, Fitting linear mixed-effects models using lme4. *J Stat Softw* **67**:1–48 (2015). https://doi.org/10.18637/jss.v067.i01.

48 Hartig F, DHARMa: Residual Diagnostics for Hierarchical (Multi-Level/-Mixed) Regression Models (2016). https://doi.org/10.32614/CRAN.package.DHARMa.

49 Kaiser BA, Johnson BL, Ostlie MH, Werner SJ and Klug PE, Inefficiency of anthraquinone-based avian repellents when applied to sunflower: the importance of crop vegetative and floral characteristics in field applications. *Pest Manag Sci* **77**:1502–1511 (2021). https://doi.org/10.1002/ps.6171.

50 Richner H, Phenotypic correlates of dominance in carrion crows and their effects on access to food. *Anim Behav* **38**:606–612 (1989). https://doi.org/10.1016/S0003-3472(89)80005-3.

51 Avery M and Cummings JL, Chemical Repellents For Reducing Crop Damage By Blackbirds. United States Department of Agriculture Wildlife Services: Staff Publications (2003). https://digitalcommons.unl.edu/icwdm_usdanwrc/199.

52 Esther A, Tilcher R and Jacob J, Assessing the effects of three potential chemical repellents to prevent bird damage to corn seeds and seedlings. *Pest Manag Sci* **69**:425–430 (2013). https://doi.org/10.1002/ps.3288.

53 DeLiberto ST and Werner SJ, Applications of chemical bird repellents for crop and resource protection: a review and synthesis. *Wildl Res* **51**:WR23062 (2024). https://doi.org/10.1071/WR23062.

54 Werner SJ and Provenza FD, Reconciling sensory cues and varied consequences of avian repellents. *Physiol Behav* **102**:158–163 (2011). https://doi.org/10.1016/j.physbeh.2010.10.012.

55 Miller R, Bugnyar T, Pölzl K, and Schwab C, Differences in exploration behaviour in common ravens and carrion crows during development and across social context. *Behavioral Ecology and Sociobiology*, **69**:1209–1220 (2015). https://doi.org/10.1007/s00265-015-1935-8

56 Heinrich B. Neophilia and exploration in juvenile common ravens, Corvus corax. *Animal Behaviour*, **50**:695–704 (2019). https://doi.org/10.1016/0003-3472(95)80130-8

57 Cramp S, Perrins CM and Brooks DJ, *Handbook of the Birds of the Western Palearctic Vol. VIII: Crows to Finches*. Oxford University Press, Oxford (1994).

58 Greenberg R and Mettke-hofmann C, Ecological aspects of neophobia and neophilia in birds, in *Current Ornithology*, ed. by Nolan V and Thompson CF. Springer US, Boston, MA, pp. 119–178 (2001). https://doi.org/10.1007/978-1-4615-1211-0_3.

59 Sih A and Del Giudice M, Linking behavioural syndromes and cognition: a behavioural ecology perspective. *Philos Trans R Soc Lond Ser B Biol Sci* **367**:2762–2772 (2012). https://doi.org/10.1098/rstb.2012.0216.

60 UK Department for Environment, Food & Rural Affairs, Annex 2: Review of alternative non-lethal methods for mitigating damage by avian species (Wild Bird General Licence Review) (2021). https://assets.publishing.service.gov.uk/media/6048ed94d3bf7f1d12811526/annex-2-non-lethal-alternatives-report.pdf.