Experimental Assessment of Laser Scarecrows for Reducing Avian Damage to Sweet Corn

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Experimental assessment of laser scarecrows for reducing avian damage to sweet corn

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Abstract

BACKGROUND: Birds damage crops, costing millions of dollars annually, and growers utilize a variety of lethal and nonlethal deterrents in an attempt to reduce crop damage by birds. We experimentally tested laser scarecrows for their effectiveness at reducing sweet corn (*Zea mays*) damage. We presented 18 captive flocks of free-flying European starlings (*Sturnus vulgaris*) with fresh sweet corn ears distributed on two plots where laser and control treatments were alternated each day and allowed each flock to forage over 5 days. In 16 trials, fresh sweet corn ears were mounted on wooden sticks distributed from 0 to 32 m from laser units (Stick Trials), and in two trials birds foraged on ripe corn grown from seed in the flight pen (Natural Trials). We aimed to determine if laser-treated plots had significantly less damage overall and closer to the laser unit, and whether birds became more or less likely to forage in laser-treated plots over time.

RESULTS: Lasers reduced damage overall, marginally in Stick Trials and dramatically in Natural Trials. Damage increased during each week in both trial types. Damage increased significantly with distance from lasers, and significant treatment effects occurred up to ~20 m from lasers.

CONCLUSION: Our results concur with recent field trials demonstrating strong reductions in sweet corn damage when lasers are deployed. This study provides a first look at how birds respond to repeated laser exposure and whether damage increases with distance from lasers. Key differences between pen and field trials are discussed.

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

Keywords: human–wildlife conflict; nonlethal deterrent; pest management; *Sturnus vulgaris*; visual repellent; *Zea mays*

1 INTRODUCTION

1.1 Avian pests

Bird species causing the highest crop damage each year in the United States include red-winged blackbirds (*Agelaius phoeniceus*), brown-headed cowbirds (*Molothrus ater*), Canada geese (*Branta canadensis*), snow geese (*Chen caerulescens*), sandhill cranes (*Grus canadensis*) and European starlings (*Sturnus vulgaris*).[1,2] Grain crops are especially attractive to such species as they ripen during non-breeding and migratory seasons when many bird species aggregate and range widely to forage.[1–3] A variety of deterrents are available to prevent avian pests from damaging grain crops; these can be described as either lethal or nonlethal. Lethal control via guns, traps or chemical avicides is often less preferred because of permit requirements, and declining effectiveness as birds can learn to avoid lethal threats.[4,5] Also, the use of toxic avicides on bait can kill or cause illness in nontarget species.[6] As a result, growers and researchers in agroecosystems frequently turn to nonlethal deterrents to lessen crop consumption by wild birds. Most nonlethal deterrents utilize the threat of predation, including live predators (trained hawks or dogs) and devices that scare or startle birds foraging in fields[7]. Such "scaring" devices include harsh visual or acoustic stimuli (moving objects, flashing lights, popping sounds, or combinations of two or more) that trigger anti-predator escape responses.[8] Acoustic deterrents rely on firecrackers, propane cannons, blank shotgun rounds, recorded predator calls broadcast from loudspeakers, or other types of loud or screeching noises that startle birds and other vertebrates.[8] Nontoxic chemical deterrents, such as nausea-inducing sprays, also can be effective in reducing foraging in a variety of crops.[9,10] Overall, studies of the effectiveness of nonlethal approaches are mixed, and a major problem in some

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situations is a rapid temporal decline in fear response and, in turn, increasing damage during exposure periods.[11] Indeed, despite increasing numbers of nonlethal deterrents on the market today, none appear to provide permanent or singular solutions to bird depredation of crops. Two strategies are emerging, however, to guide effective deployment of nonlethal deterrents: (1) limiting their use to specific temporal windows during which crops are most vulnerable to the target pest(s) and (2) deploying multiple deterrents simultaneously or staggered in time and space.[12–14]

1.2 Laser deterrence in sweet corn

Among the most promising avian deterrent devices are lasers. Visible lasers emit a focused, coherent beam of light at a single wavelength, in contrast to most light sources which emit nonpolarized radiation at multiple wavelengths, with varying intensities.[15] Lasers appear to frighten birds and elicit escape responses similar to other scaring devices,[5] although the exact mechanism is not known. At clinically high exposure levels lasers can damage the eyes of birds.[16] However, lasers deployed in fields to reduce or disrupt avian foraging activity are likely to function by distracting or eliciting discomfort in birds eyes, as occurs in humans.[17] As with other nonlethal deterrents, laser avoidance may decline with repeated exposure, because animals get used to discomfort and distraction if it is not dangerous; this is known as habituation.[18] Sweet corn may be one crop that is especially suitable for laser deterrence because it has a narrow (2 week) temporal window of susceptibility, whilst ears mature into the milking stage when harvest occurs.[19] Because decreased responsiveness is a concern with all nonlethal scaring devices, the short window of sweet corn vulnerability to bird depredation could limit the development of habituation.[20] Levels of protection to sweet corn afforded by lasers are promising based on recent field trials. For example, laser deployment on milking-stage corn in one study caused a 33% reduction in the number of ears damaged by birds.[21]

The purpose of this study was to test the effectiveness of laser scarecrows at reducing damage to milking-stage corn in a controlled experimental setting. We conducted aviary trials with starling flocks foraging on fresh corn presented in two different ways. We planted corn in study plots inside the flight pen and exposed starlings to the mature corn (hereafter Natural Trials) during the 2-week milking stage. We also presented commercially purchased fresh sweet corn on wooden sticks to mimic natural corn stalks (hereafter Stick Trials). Trials with artificially presented corn were used to achieve large sample sizes for analysis. We hypothesized that for our laser scarecrow to be effective, damage by starlings to sweet corn in Natural and Stick Trials should be reduced by ≥20% overall (a margin suggested by growers to R. Brown). Also, because each starling flock foraged for five consecutive days in each trial, we sought to assess whether birds would get used to laser exposure and avoid lasers less over time; indeed, a detectable increase in damage over time on laser plots was expected. We also predicted that ears of corn placed higher aboveground would be attacked more frequently than lower ears. Finally, because laser beam intensity decreases with distance, and bird aversion to exposure should decline at greater distances, we predicted that corn damage by birds would increase with distance from the laser.

2 MATERIALS AND METHODS

Aviaries with space for crop plantings can be pivotal in experimental research testing for deterrent effects, because flight pens prevent free-flying birds from escaping, ensuring bird pressure on the enclosed crop, while also allowing birds to forage much as they would in a natural setting.[22] Thus, experimental pen trials provide conditions closely resembling field situations but with greater control, permitting researchers to refine techniques and designs before conducting major field tests.[23] Here we report on pen trials conducted at the United States Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center (NWRC), Florida Field Station in Gainesville, Florida, USA. Experiments took place inside a 0.2 ha wire mesh flight pen with soil substrate. A small (7 × 5 × 3 m) holding pen within the flight pen was used for overnight retention of test birds between daily trials. This flight pen (Fig. 1) has been used to test a wide range of tools and substances intended for reducing avian depredation of crops.[22,24,25]

Two crop production plots were established inside the pen measuring 18 × 24 m each (Fig. 1). Two laser devices (URI Laser Scarecrow 2020 model; see Supporting Information (SI) Section S1 were installed in plot corners directly in front of an elevated observation blind, one unit per plot, aimed to cover most of each plot without any exposure of observers in the blind (Fig. 1). Two perches were available on the outer edges of each plot with two more perches in the far left and right corners (four total per plot). Additional perching was available in two trees growing in the center of the pen (Fig. 1). To prevent birds from foraging for insects on the ground where grass grew, we covered the exposed ground with landscape cloth. To confine birds to the test plot area of the pen during trial periods, we fashioned a drop-down net between the back edge of the test plots and the rear of the flight pen where the birds roosted in a holding pen overnight.

We conducted a total of 18 1-week trials: six were between 30 August and 9 October 2021 with artificially presented corn only (Stick Trials; see below); the remaining 12 trials occurred between 9 May and 29 July 2022. During this 12-week period we grew sweet corn from seeds planted in the same plot areas. While the natural corn sprouted and matured, we collected damage data from birds foraging on the artificially presented corn (Stick Trials). When the planted corn matured into the milking stage, we removed artificial stalks and assessed bird damage on the live corn ears (Natural Trials). During these 12 weeks, Stick Trials occurred during weeks 1–6 and 8–12, whereas Natural Trials with live corn occurred in weeks 7 and 8. In total, we ran 16 Stick Trials and two Natural Trials.

2.1 Experimental corn presentation

We used wooden stakes to present corn during the Stick Trials. Using wooden dowel pegs, we mounted two ears of corn per stick in offset positions (≥14 cm below the top of each stake). The offset ear presentation mimicked the structure of natural corn, with a top and bottom ear (Fig. 2, left panel). The stakes extended 213 cm aboveground. Five stakes were placed in each of four quadrants per plot for a total of 40 stakes (20 per plot). Stakes ranged from 4 to 27 m from laser units (median distance 17 m). We purchased fresh sweet corn ears for each week of Stick Trials, and all ears presented on sticks had entire, fresh, green husks and silks covering the kernels; the same as naturally growing ears. In Natural Trials (Fig. 2, right panel) with planted rows of corn, each plot had an estimated 1125 live corn plants (140 per quadrant; see SI Section S2 for descriptions of presentation and growing of sweet corn for Natural and Stick Trials).

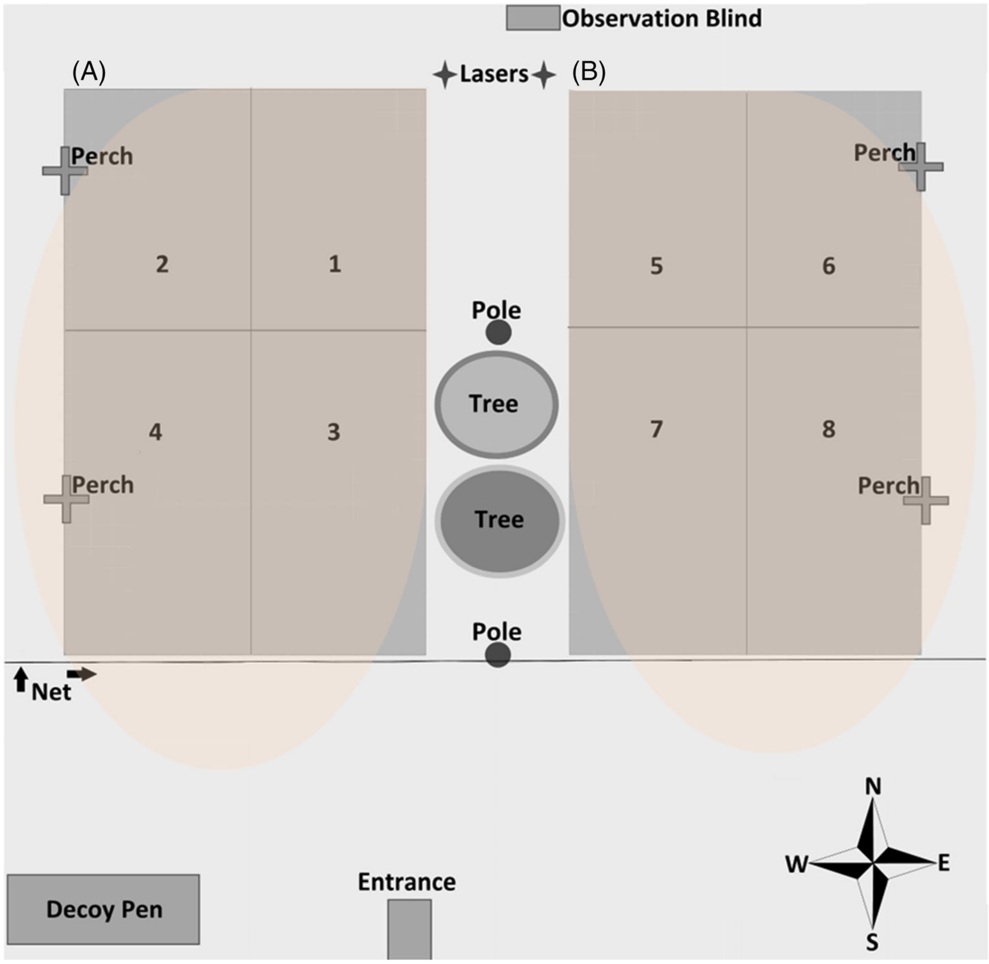

Figure 1. Schematic of the East Flight Pen located at the USDA-Wildlife Services, NWRC Florida Field Station in Gainesville, FL. Foraging was observed from the blind (top) in eight quadrants (1–8) across two test plots (A,B). Perching sites were available on the sides (crosses) and in the central two trees. Birds were kept overnight in the decoy pen (bottom) and confined on plots A and B during the day by dropping a vertical mesh net across the back of the plots prohibiting access to the decoy pen area. Light orange shading indicates approximate laser coverage of the test plots when units were activated.

2.2 Trial protocol

For this study, we tested the effectiveness of an experimental laser device developed by D. and R. Brown at the University of Rhode Island (URI) and known as the URI Laser Scarecrow (see SI Section S1). Laser units were mounted on poles with adjustable clamps. To create the deterrent effect, we aimed lasers at or just above the top of the ears/plants, forming a horizontal "lid" over the corn plots. In Stick Trials, the laser was set at 1.75 m above-ground, and the laser beam hit the sticks just above the top ear (see Fig. 2, left panel). In Natural Trials, the mature sweet corn ears were closer to the ground and more variable in height. The lasers were aimed at the tops of the corn plants each day (≈1 m above-ground on average) to create the lid effect just above the ears.

We conducted 5-day trials with each cohort, and birds were allowed to forage on corn between 08:00 and 10:00 h (weather-dependent; see SI Section S3 for animal use and care). After birds were moved out of the test plot area each day, we conducted a corn damage assessment. On Day (D)1 of all trials, no laser was turned on to allow birds to explore both test plots freely. On trial D2–D5, one laser scarecrow unit was activated on plot A (plot B laser was off) and the next day, plot B's laser was switched on (and plot A's was off). Over the next 2 days, the same pattern was repeated. Each plot received control and treatment twice each per cohort. This insured that any plot effects could be separated from treatment effects in analyses.

2.3 Corn damage assessment

We assessed damage on all ears each day of a trial regardless of whether it was artificially presented or naturally grown, although differences had to be accommodated. In all cases, the percentage of kernels eaten per ear was typically <10% and nearly all occurred at the silk end; thus, we defaulted to a 0 (no damage) or a 1 (damaged) binomial metric to quantify damage. For fresh market sweet corn, any damage at all renders an ear unmarketable, so the binomial metric does not overestimate crop loss to growers. In Stick Trials, all damaged and undamaged ears were removed at the end of each day of a trial, and fresh ears were put in place to maintain equal crop attractiveness to the birds each day. In Natural Trials, any damaged ears detected were removed so they would not be counted on subsequent days, and we relied on natural ripening processes to generate fresh ears for the birds to eat each day. We carefully crafted our damage assessment for both trial types to obtain comparable measures of damage rates and distributions in both trial types where each distance measure recorded was associated with either a true positive (1) or

Figure 2. (Left) Two stick stalks with fresh commercial sweet corn mounted on dowels are shown with a starling foraging on a lower ear. (Right) Planted corn rows in one of the test plots showing that the drip tape runs parallel with corn. Corn rows were planted using twin row spacing. Observation blind visible at left (Right).

true negative (0) measure of damage (see SI Section S4 for details regarding ear damage estimation).

2.4 Data analysis

We used multilevel mixed-effects models with a logit link function to test for laser effects on ear damage. The two types of trials (Stick, Natural) were analyzed with different models owing to slightly different combinations of predictor variables (Table 1). Damage to corn was expressed as a binary variable, damage present (1) or absent (0; Table 1). Birds foraged on both plots on their first trial day with no laser activated, to habituate them to the plot layout and foraging conditions. Analyses only included D2 to D5 of each trial when a laser unit was activated on one or the other plot. In both analyses, cohort identity was used as a random effect to avoid pseudoreplication of observations in each day of a trial week (the same 10 birds in each cohort were used 4 days in a row). We did not use Ear Code (top or bottom ear) variables in analysis of Natural Trials (Table 1) because top and bottom ears overlapped as a consequence of variation in corn stalk heights and tilting. Distance from laser (0–32 m) is a continuous variable, but our measures associated with stakes were integers. Therefore, we centered and scaled the distance measures [(meters–mean)/1SD] to enhance numerical stability of the models. We conducted an *a priori* power analysis suggesting that 20 trials would be needed to detect a conservative 20% change at 95% power.

In order to parameterize models for both trial types we started with all main effects and two-way interactions. To obtain the best-fit model, we removed nonsignificant interaction terms one-by-one until remaining interaction terms had $P < 0.05$. We did not remove any main effects terms, whether significant or

Table 1. All variables used in statistical analyses, their abbreviations, names, role in analysis, and descriptions.

Variable code	Variable name	Type of variable (role)	Metric
DamCD	Damage code	Categorical (response)	Ear damaged (1) or not (0)
TreatCD	Treatment code	Categorical (fixed effect)	Laser (L) or Control (C) treatment
EarCD*	Ear code	Categorical (fixed effect)	Upper (U) or lower (L) ears
TrialDay	Trial day	Ordinal (fixed effect)	Trial day (D2 to D5)
LaserDist†	Laser distance	Continuous (covariate)	Distance between active laser and ear (m)
PlotCD‡	Plot code	Categorical (fixed or random effect)	Two plots (A or B)
Cohort	Cohort ID	Nominal (random effect)	A flock of 10 birds

Note: All variables listed are main effects in the analyses for Stick Trials.

not, because each variable represented designed hypothesized effects on damage rates suggested by previous research. A minimum of a two-point reduction in Akaike's Information Criterion (AIC) was used to gauge model improvement. If dropping a term did not reduce the AIC sufficiently, then we added it back in and dropped another. The AIC metric we used accounts for parsimony, or reduction in the number of terms, represented by $AIC = -2 \times LL + 2 \times k = -2(LL - k)$ where LL is model log-likelihood and k is the number of predictors ($2 \times k$ is a penalty term).[26]

If a model term had $P \leq 0.2$, then we plotted the marginal means to see if the chi-square (χ^2) associated with any marginal contrasts was significant; if so, we presented these effects in plots.[26] We report the odds ratios (OR) in model output, rather than coefficients, to aid in interpreting experimental outcomes.[27] For a given factor in the model, an OR = 1.0 indicates that there is no difference in likelihood of an ear being damaged in a laser or control plot; ORs>1 or <1 indicate different odds of damage in the context of reference categories stipulated in the output. Finally, we detected a very strong effect of plot (A or B) on bird foraging activity and needed to address this in analyses (see SI Section S5 for how plot effects were handled in analysis). All analyses were conducted in STATA/BE v17.0 (Copyright 1985–2021 StataCorp LLC), and datasets and model codes are permanently archived here https://zenodo.org/record/8287630.

3 RESULTS

Stick Trials included 16 cohorts of birds and 4800 observations of corn ears for damage, and for the Natural Trials, two cohorts of birds allowed for ≤256 observations of damage. One early Stick Trial cohort was dropped from analysis because no birds touched the corn. The best models for Stick and Natural Trials (Tables 2 and 3, respectively) showed a marginal (Stick) or highly significant (Natural) overall effect of laser treatment on reducing corn damage (Fig. 3). In both trial types, birds generally increased corn damage as trial days progressed (Fig. 4) and with distance from laser (Fig. 5). Birds attacked top ears more often than bottom ears in Stick Trials (see SI Fig. S1, left panel). Because we included plot as a fixed effect in analyses of Natural Trial damage (Table 3), we can see that birds habitually foraged in plot A more often than B (Fig. S1, right panel), and this was true in Stick Trials as well (note the large OR for plot random effect; bottom of Table 2). Analyses of Stick Trial data revealed significant interactions between treatment and trial day (see SI Fig. S2) and treatment with distance to laser (Fig. 6).

4 DISCUSSION

We observed consistently lower damage overall in laser-treated plots, and this effect was striking in Natural Trials. Our results support the growing perception that lasers can effectively deter crop depredating birds.[21,28] This is the first controlled pen study of free-flying birds with access to fresh sweet corn where individuals could choose to feed in laser-treated and control plots. Tests of diverse nonlethal bird deterrents (e.g. lasers, poppers, animated tubes)[14,29,30] at field scales are accumulating fast. Thus, it is early to generalize about the overall impact(s) of nonlethal deterrents on crop damage reduction, even though the technologies are promising.

4.1 Overall laser deterrence

We initially considered that there might be greater overall damage in Natural than Stick Trial laser treatments simply because we thought the birds would be able to use the foliage of the planted corn to block the laser beams from hitting their eyes.[31] One potential reason for the increased effectiveness of lasers in Natural Trials could be a consequence of the lack of sturdy perching substrates there, compared to the sticks. In the Stick Trials, birds could perch on sturdy wooden dowels that did not move under their weight, whereas natural stalks were too weak to support the birds fully. As a result, birds foraging on natural corn ears are likely to have bobbed in and out of the laser layer, experiencing more laser scatter and distraction[32] as the beams bounced off vegetation. In Stick Trials, by contrast, birds could probably see and avoid the static laser "lid."[16] We could only test two cohorts on naturally growing corn owing to the short period of ear vulnerability to starling foraging during the milking stage. This provided only 8 days of damage assessment across the 32 subquadrants ($N = 256$). Moreover, the first of the two cohorts (7) foraged less often on corn than the second (Cohort 8; see the large OR for

Table 2. Generalized linear mixed model results for Stick Trials

Predictor variables	Odds ratio	Standard error	Z	$P > \lvert z \rvert$
TreatCD (C)	1.58	0.50	1.45	0.15
TrialDay 3 (2)	1.86	0.59	1.96	0.05
TrialDay 4 (2)	1.91	0.32	3.87	0.00
TrialDay 5 (2)	1.98	0.62	2.17	0.03
EarCD (L)	1.47	0.11	5.15	0.00
LaserDist	1.20	0.06	3.50	0.00
TreatCD#TrialDay (L, D3 *versus* C, D2)	0.36	0.21	−1.73	0.08
TreatCD#TrialDay (L, D4 *versus* C, D2)	0.52	0.11	−2.98	0.00
TreatCD#TrialDay (L, D5 *versus* C, D2)	0.48	0.28	−1.25	0.21
TreatCD#LaserDist (C)	1.23	0.09	2.76	0.01
Constant	0.29	0.13	−2.69	0.01
Cohort	1.82	0.70	–	–
PlotCD	2.10	0.69	–	–

Note: Response variable used is DamCD (binomial; see Table 1) and the model used a logit link function. Symbols in () signify reference levels for contrasts applied to categorical variables. Italics = random effects.

Table 3. Generalized linear mixed model results for Natural (corn) Trials

Predictor variables	Odds Ratio	Standard Error	*Z*	*P* > |z|
TreatCD (C)	0.08	0.04	−4.90	0.00
TrialDay 3 (2)	0.37	0.25	−1.46	0.14
TrialDay 4 (2)	2.44	1.21	1.80	0.07
TrialDay 5 (2)	1.82	1.09	0.99	0.32
PlotCD (A)	0.16	0.08	−3.69	0.00
LaserDist	1.58	0.31	2.35	0.02
Constant	0.92	1.05	−0.07	0.94
Cohort	1.97	2.09	–	–

Note: Response variable used is DamCD (Table 1) and the model used a logit link function. Symbols in () signify reference levels for contrasts applied to categorical variables. Italics = random effects.

Cohort at the bottom of Table 3; see SI Fig. S3). Thus, while we do not doubt that birds (especially in Cohort 8) were strongly avoiding laser-treated corn, the magnitude of effect of lasers in Natural Trials would be more trustworthy if replicated/confirmed in future trials of similar design.[33]

Two contrasting explanations are possible for the weak treatment effect that we observed in Stick Trials. Either the birds' eyes were damaged and they became insensitive to laser exposure, or birds were able to avoid lasers more easily while foraging in Stick than Natural Corn presentations. First, without foliage to block lasers in Stick Trials, birds' eyes may have been damaged to a degree that they could not be distracted or discouraged from foraging on laser plots. If lasers caused eye damage, then the resulting behaviors arising from physical insensitivity to laser detection would mimic tolerance or avoidance.[34] Birds did prefer top ears on the sticks (Fig. S1), and this preference located them just under the laser "lid" where laser exposure should be likely. In humans at least, eye damage can occur from temporary laser exposures at distances of several meters or more, but few such damages appear to last.[17] In a recent study, starlings' eyes were exposed to lasers more powerful than ours, and a variety of serious eye damage occurred. Researchers observed corneal edema,

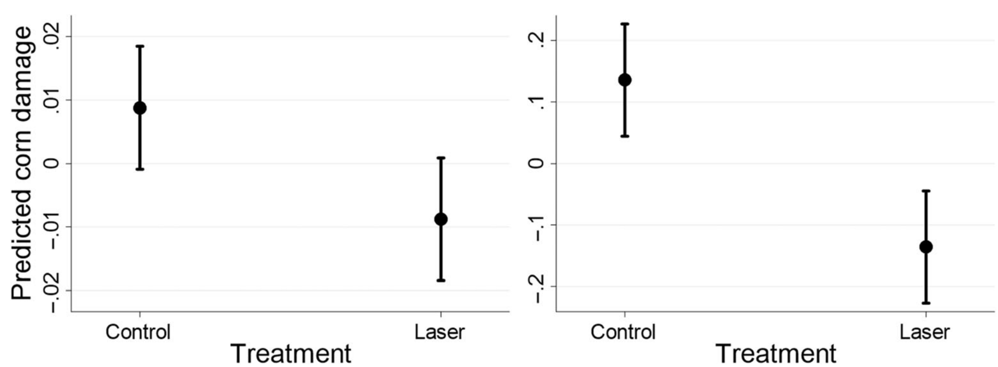

Figure 3. Marginal predicted mean ear damage (centered on the mean) on laser *versus* control plots in (left) Stick Trials (marginal contrast: $\chi^2 = 3.16$, $P = 0.07$) and (right) Natural Trials (marginal contrast: $\chi^2 = 8.53$, $P = 0.00$). Error bars = 95% CI.

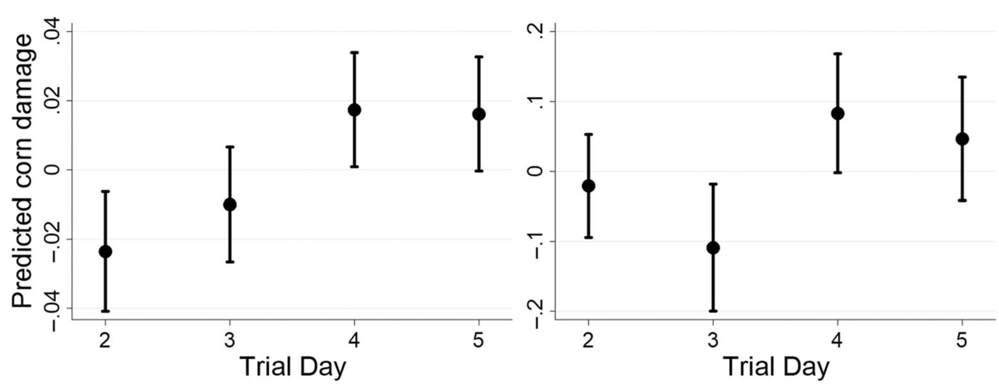

Figure 4. Marginal predicted mean ear damage (centered on the mean) by trial day (D) in (left) Stick and (right) Natural Trials. Significant marginal contrasts for Stick Trials: D2 (*versus* the mean), $\chi^2 = 7.11$, $P < 0.01$; D4, $\chi^2 = 4.27$, $P = 0.04$; D5, $\chi^2 = 3.68$, $P = 0.05$; joint $\chi^2 = 11.41$, $P < 0.01$. Significant marginal contrasts for Natural Trials: D3 (*versus* the mean), $\chi^2 = 5.53$, $P < 0.02$; D4, $\chi^2 = 3.68$, $P = 0.05$; joint $\chi^2 = 11.41$, $P < 0.01$. Error bars = 95% CI.

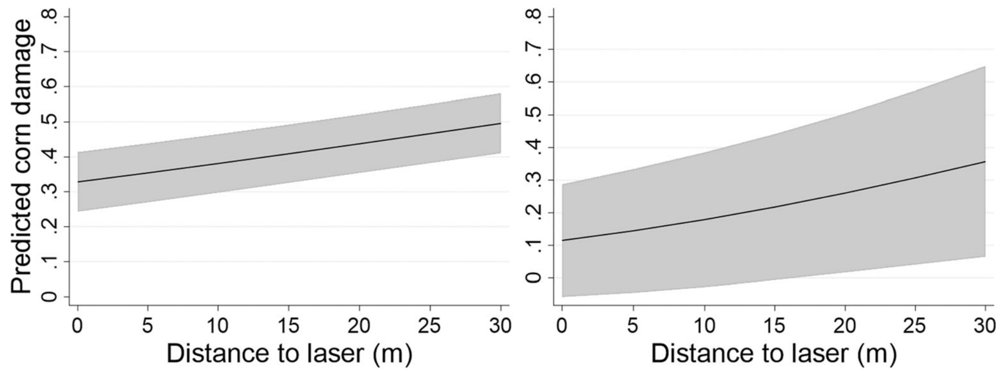

Figure 5. Marginal predicted effect of distance to laser on ear damage in (left) Stick and (right) Natural Trials. Shading = 95% CI.

cataracts and retinal atrophy; all of which can reduce the ability of eyes to detect visual signals.[16] We note that birds were restrained in this study and the laser source was <5 m from the birds' eyes, whereas birds in our pens were freely moving with large areas unexposed to lasers available to them. Thus, we suggest that eye damage causing insensitivity to lasers was less likely in Stick Trials than the real possibility that birds simply learned to avoid lasers while foraging. Indeed, if birds' eyes were so damaged by laser exposure that they were insensitive to it, then they should have foraged more often than they did within 10 m of the laser units, and we would not expect such a strong treatment-by-distance interaction (Fig. 6). It is more likely that birds could see the lasers, especially without occluding foliage, and therefore might easily have dodged exposure during Stick Trials by keeping their heads below the laser layer even when foraging on upper ears. Birds were unwilling to forage close to the laser units in Stick Trials, suggesting that they remained highly sensitive to laser exposure even if they could minimize it with behavioral accommodation. This is the most parsimonious explanation for the small treatment effect in Stick Trials.

In Natural Trials, however, behavioral avoidance of laser exposure would be much harder for the birds to achieve than in Stick Trials, and this could readily explain why the treatment effects were so strong. Birds foraging in natural corn must descend into foliage, perch on wobbly corn stalks and peck at floppy corn ears with restricted visibility of their surroundings and other birds. The lack of visibility of surroundings, and of potential predators, would elevate starlings' perceptions of predation risk, making them more flighty.[35] In addition, the combined movement of the foliage and of the birds during foraging could cause the birds to bounce in and out of the laser layer, exposing them to laser reflections off foliar surfaces as well as unpredictable direct flashes in their eyes. With nuisance noise and light, intermittent signals cause more avoidance, annoyance and stress in wildlife and humans than constant high levels of noise or light.[36,37] This same effect may have elevated the laser deterrent effect for birds in Natural Trials. Birds also may have been able to see the laser beams more clearly in the lower light conditions caused by foliage occlusion in natural corn[38], allowing them to quickly detect the lasers and move to the other plot. In both types of trials, 5 days is sufficient time for birds to learn where to forage.[39] In sum, we conclude that while eye damage remains as a possible mechanism underlying a weak laser effect in Stick Trials, the more parsimonious explanation is simply that in Stick Trials birds could see and avoid the beams, but that in naturally growing corn they were deterred by lasers to a greater degree.

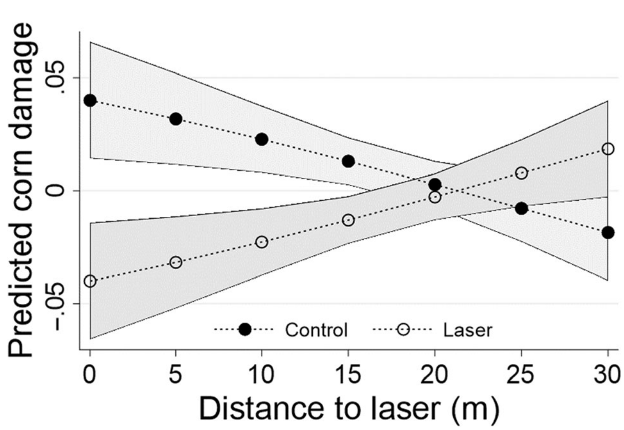

Figure 6. Marginal predicted mean ear damage for the interaction between treatment (control *versus* laser) and distance to laser for Stick Trials. Selected marginal contrasts for treatment effects: at −100, $\chi^2 = 9.27$, $P < 0.00$; at 0, $\chi^2 = 3.36$, $P = 0.07$; and at 100, $\chi^2 = 3.48$, $P = 0.06$; joint $\chi^2 = 10.19$, $P = 0.07$). Shading = 95% CI.

4.2 Spatial effects

In both trial types, starlings much preferred plot A over B (Fig. S1, Tables 2 and 3, bottom, see OR for plot as random effect) regardless of which laser was activated. However, such behavioral biases in foraging site choices are often observed at field scales in corn (R. Brown, personal observation) and in other crops.[40] Free-living birds may head for the field nearest their perching or loafing sites at much higher frequencies than sites further away, demonstrating the well-known phenomenon of "central place foraging," the tendency of animals to forage close to home.[41] Limiting travel time to feed is especially important for maximizing caloric surpluses in birds because flight is energetically expensive. We did not quantify the perching tendencies of birds in our pen, but we expect that the birds may have preferred resting on the west side of the pen (Fig. 1) simply because their overnight holding pen (with *ad libitum* food) also is on the west side. Despite this behavioral bias leading to consistently higher damage on plot A, the overall effect of lasers was to suppress corn damage. Regarding vertical spatial bias, birds in Stick Trials habitually chose top cobs over bottom cobs (see SI Fig. S1). This is apparently typical of corn depredating birds,[2,9] and is likely to be a result of predation risk sensitivity where higher foraging sites offer better escape positions from attacking predators.

When birds foraged in a laser-treated plot, distance to the laser had a significant effect on all cohorts of birds (Figs 5 and 6), with higher overall damage further from the laser unit; this is likely to have been caused by the loss of laser intensity with distance from source.[42] There was a very strong laser deterrence effect up to ~20 m, but none by 30 m, from scarecrow units in Stick Trials, which is most likely because laser power drops off rapidly owing to the beam divergence of our units (see SI Fig. S1). While this result suggests that in natural cornfields, birds should be able to settle and feed undisturbed >20 m away from laser units, field tests of the same type of scarecrow unit that we used did not detect this pattern owing to an essential difference between our pens and open fields from the birds' perspective. Field tests of lasers in sweet corn typically deploy a single laser unit in each large corn field, and this reduces damage significantly across the entire field (R. Brown, unpublished data).[21] Why this occurs relates to wild flock behaviors. Growers in field studies note that a common response to the presence of a laser in a field is that entire flocks will simply not settle in the field after a laser is detected, and instead move—sometimes large distances—to untreated fields.[1,5,21,43] Therefore, it is important to understand not only the differences in the bird–corn interactions between the Stick and Natural Trials that we conducted, but also how the foraging behaviors of the birds in our small-scale pen study may differ from those of free-flying bird flocks with access to large, sweet corn fields. Birds in our study were confined and essentially forced to forage repeatedly in or adjacent to laser-treated areas more often than they would have in a field setting.

4.3 Temporal effects

In both trial types, birds were eating more corn overall by D5 than they were on D2 (Fig. 4). The simplest interpretation is that birds were learning to find corn ears and utilize them more effectively as the week progressed wherever they foraged. It is possible that their tolerance of laser discomforts increased with day of exposure, but we have no direct evidence of this. Tolerance is defined as acceptance of discomfort or perceived risk to fulfill a need such as foraging.[18] For example, some wildlife species strongly avoid humans but will tolerate them nearby to feed on human garbage. Tolerant behavior toward uncomfortable stimuli also can develop via habituation-like processes, but identifying either process requires confirming that specific individuals withstood increasing direct exposure over time, data that we did not collect.

Given only two Natural Trials, we could not examine interactions in the statistical model. To gain some insight into how birds foraging in Natural Trials responded over time in treatment and controls, we plotted the raw numbers of ears damaged (range 0–8) in the 32 subquadrants during Natural Trials (see SI Fig. S3). These few data suggest the possibility that aversion to lasers may have intensified over time in Cohort 8; damage increased markedly on control plots and decreased slightly on laser-treated plots, suggesting that birds rapidly increased utilization of control plots and may have decreased activity on laser-treated plots while clearly avoiding them. True sensitization (the inverse of habituation) would require that individuals become increasingly avoidant of a repeated stimulus because they perceive real danger to themselves.[18,44] We did not assess individual changes in behavior here, but if some individuals in Cohort 8 became more reactive to lasers, others may have become more avoidant through social learning.

4.4 Pen *versus* field scale

The scale of this study was smaller than field plots; nonetheless, we detected all major effects of lasers noted in field-scale studies. We caution that the interactions between birds, lasers and sweet corn in our pen study will not scale directly to fields with free-flying flocks. In open fields, flocks of starlings and blackbirds move freely among fields and a single field may attract many different individuals each day.[45] Also, wild flocks are much larger than 10 birds and birds can choose how to associate with each other, whereas we formed artificial social groups that may have lacked coherence. For example, wild starlings rely on sentinels (nonforaging birds perched nearby) to look for predators (which we did not assess). If pen flocks did not have sentinels, then this and the small flock size could have elevated the birds' perceptions of risk that, in turn, may have influenced behavioral patterns while foraging.[46,47] Finally, a common behavior of starling, blackbird and grackle flocks in fields with nonlethal deterrents (lasers, audio devices, robot predators, drones) is that when startled, flocks will rise and leave the affected field entirely in order to settle in untreated fields (R. Brown, personal observations), an option unavailable to birds in the pen study.[48]

5 CONCLUSION

Lasers are proving to be effective bird deterrents in sweet corn. The damage reduction that we detected in Natural Trials was similar in magnitude with field studies, at far more than 20%.[21] In addition to lasers, other types of nonlethal deterrents are proven to be effective at field scales.[49] Moreover, when lasers are paired with other devices (e.g. acoustic), damage to sweet corn fields is reduced more than when lasers are used alone.[50] In this study, the scale was confined to laser effects within 30 m. In general, however, field trials with lasers show that far larger distances between deterrent devices, even in problem areas near roosting sites, can work very well.[21,51]

The controlled experimental setting allowed us to detect significant effects of distance to laser and temporal patterns in damage, and the comparison of two trial types (artificial and natural corn) yielded important insights into how lasers may function. For example, we suggest that in cropping situations with little foliage, it may be best to program laser units to sweep up and down; this probably would have enhanced treatment effects in Stick Trials by directly hitting the birds as they foraged. However, it also is clear from our Natural Trials and field trials that it is better to project a stationary laser layer over sweet corn tops, because sweeping the laser up and down in dense corn foliage would be ineffective past a very short distance (R. Brown, personal observations).

Finally, the development of avoidance or tolerance by birds and, in turn, temporal declines in laser deterrence, is probably unimportant in sweet corn simply because the vulnerable period is brief; typically less than a week between the onset of milking stage and harvest.[52] However, if lasers are used to deter birds from crops with long vulnerable periods, such as fruits and berries, then identifying the likelihood of laser avoidance or tolerance will be important.[53,54] Many birds that attack fruit crops are year-round residents; individual responses to repeated laser exposure could, therefore, determine efficacy.[55,56] We would encourage studies of marked individuals in pen and field settings to deepen understanding of the likelihood of laser tolerance or avoidance via habituation and sensitization.[18]

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CONFLICT OF INTEREST

All authors reported there were no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available via Zenodo at https://zenodo.org/record/8287630.

SUPPORTING INFORMATION

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

REFERENCES

1 Linz GM and Klug PE, Strategies for evading blackbird damage, in *Ecology and Management of Blackbirds (Icteridae) in North America*, ed. by Linz GM, Avery ML and Dolbeer R. CRC Press/Taylor & Francis, Boca Raton, FL, pp. 175–190 (2017).
2 Linz GM, Johnson RJ and Thiele JR, European starlings, European starlings, in *Ecology and Management of Terrestrial Vertebrate Invasive Species in the United States*, ed. by Pitt W, Beasley J and Witmer G. CRC Press, Taylor and Francis Group, New York, New York, USA, pp. 337–357 (2018).
3 Klug PE and Homan HJ, Movement behavior of radio-tagged European starlings in urban, rural, and exurban landscapes. *Human-Wildlife Interactions* **14**:398–408 (2020).
4 Linz GM, Bucher EH, Canavelli SB, Rodriguez E and Avery ML, Limitations of population suppression for protecting crops from bird depredation: a review. *Crop Prot* **76**:46–52 (2015).
5 Klug PE, Shiels AB, Kluever BM, Anderson CJ, Hess SC, Ruell EW *et al*., A review of nonlethal and lethal control tools for managing the damage of invasive birds to human assets and economic activities. *Manag Biol Invasions* **14**:1–44 (2023).
6 Coleman J and Spurr EB, Farmer perceptions of bird damage and control in arable crops. *N Z Plant Protect* **54**:184–187 (2001).
7 Egan CC, Blackwell BF, Fernández-Juricic E and Klug PE, Testing a key assumption of using drones as frightening devices: do birds perceive drones as risky? *Condor* **122**:1–15 (2020).
8 Seamans TW and Gosser A, Bird Dispersal Techniques, in *Wildlife Damage Management Technical Series*. USDA, APHIS, WS National Wildlife Research Center. Ft. Collins CO USA (2016).
9 Carlson JC, Tupper SK, Werner SJ, Pettit SE, Santer MM and Linz GM, Laboratory efficacy of an anthraquinone-based repellent for reducing bird damage to ripening corn. *Appl Anim Behav Sci* **145**:26–31 (2013).
10 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).
11 Bomford M and O'Brien PH, Sonic deterrents in animal damage control: a review of device tests and effectiveness. *Wildl Soc Bull* **18**:411–422 (1990).
12 Clapperton BK, Porter RE, Day TD, Waas JR and Matthews LR, Designer repellents: combining olfactory, visual or taste cues with a secondary repellent to deter free-ranging house sparrows from feeding. *Pest Manag Sci* **68**:870–877 (2012).
13 Blackwell BF and Fernandez-Juricic E, Behavior and physiology in the development and application of visual deterrents at airports, in *Wildlife in Airport Environments: Preventing Animal-Aircraft Collisions through Science-Based Management*, ed. by DeVault TL, Blackwell BF and Belant JL. The Johns Hopkins University Press, Baltimore, MD; in association with The Wildlife Society, pp. 11–22 (2013).
14 Blackwell BF, Bernhardt GE and Dolbeer RA, Lasers as nonlethal avian repellents. *J Wildl Manag* **66**:250–258 (2002).
15 Schawlow AL, Principles of lasers. *J Clin Laser Med Surg* **13**:127–130 (1995).
16 Harris DL, *Effects of Laser Power and Exposure Time on the Avian Eye: Implications for the Use of Bird Deterrent*. Doctoral dissertation. Purdue University, West Lafayette, IN (2021).
17 Sethi CS, Grey RH and Hart CD, Laser pointers revisited: a survey of 14 patients attending casualty at the Bristol eye hospital. *Br J Ophthalmol* **83**:1164–1167 (1999).
18 Blumstein DT, Habituation and sensitization: new thoughts about old ideas. *Anim Behav* **120**:255–262 (2016).
19 Nisbet I, Disturbance, habituation, and Management of Waterbird Colonies. *Waterbirds* **23**:312–332 (2000).
20 Baxter AT and Allan JR, Use of lethal control to reduce habituation to blank rounds by scavenging birds. *J Wildl Manag* **72**:1653–1657 (2008).
21 Brown RN and Brown DH, Robotic laser scarecrows: a tool for controlling bird damage in sweet corn. *Crop Prot* **146**:105652 (2021).
22 Daneke DE and Avery ML, Effective plot sizes for testing red-winged blackbird repellents in a large flight pen, in *Vertebrate Pest Control and Management Materials*, 6th Volume. ASTM International, West Conshohocken PA USA, pp. 19–27 (1989).
23 Avery ML, Whisson DA and Marcum DB, Responses of blackbirds to mature wild rice treated with flight control bird repellent, in *Proceedings of the Vertebrate Pest Conference*, University of California, Davis CA USA. Vol. **19**, pp. 26–30 (2000).
24 Avery ML, Experimental evaluation of partial repellent treatment for reducing bird damage to crops. *J Appl Ecol* **26**:433–439 (1989).
25 Avery ML, Finding good food and avoiding bad food: does it help to associate with experienced flockmates? *Anim Behav* **48**:1371–1378 (1994).
26 StataCorp, *Stata Statistical Software: Release 17*. StataCorp LLC, College Station, TX (2021).
27 Gallis JA and Turner EL, Relative measures of association for binary outcomes: challenges and recommendations for the global health researcher. *Ann Glob Health* **85**:137 (2019).
28 Rivadeneira P, Kross S, Navarro-Gonzalez N and Jay-Russell M, A review of bird deterrents used in agriculture. *Vertebrate Pest Conference* **28**: 218–223 (2018).
29 Werner SJ and Clark L, Effectiveness of a motion-activated laser hazing system for repelling captive Canada geese. *Wildl Soc Bull* **34**:2–7 (2006).
30 Brown R, *Laser Scarecrows: Gimmick or Solution? University of Rhode Island Vegetable Production Research Reports,* Kingston RI USA (2017) https://digitalcommons.uri.edu/riaes_bulletin/25.
31 Coveney S and Fotheringham AS, Terrestrial laser scan error in the presence of dense ground vegetation. *Photogrammetr Rec* **135**: 307–324 (2011).
32 Liang Y and Lee JD, Combining cognitive and visual distraction: less than the sum of its parts. *Accident Anal Prevent* **42**:881–890 (2010).
33 Schoeneberger JA, The impact of sample size and other factors when estimating multilevel logistic models. *J Exp Educ* **84**:373–397 (2016).
34 Belda X, Fuentes S, Daviu N, Nadal R and Armario A, Stress-induced sensitization: the hypothalamic–pituitary–adrenal axis and beyond. *Stress* **18**:269–279 (2015).
35 Gaynor KM, Brown JS, Middleton AD, Power ME and Brashares JS, Landscapes of fear: spatial patterns of risk perception and response. *Trends Ecol Evol* **34**:355–368 (2019).
36 Francis CD and Barber JR, A framework for understanding noise impacts on wildlife: an urgent conservation priority. *Front Ecol Environ* **11**:305–313 (2013).
37 Inger R, Bennie J, Davies TW and Gaston KJ, Potential biological and ecological effects of flickering artificial light. *PLoS ONE* **9**:e98631 (2014).
38 Briot JL and Bataille P, *A new laser equipment designed for avian dispersal in airport environment*. International Birdstrike Committee, Warsaw, PL, pp. 5–9 (2003).

39 Pleskacheva MG, Behavior and spatial learning in radial mazes in birds. *Neurosci Behav Physiol* **39**:725–739 (2009).
40 Guyot C, Arlettaz R, Korner P and Jacot A, Temporal and spatial scales matter: circannual habitat selection by bird communities in vineyards. *PLoS ONE* **12**:e0170176 (2017).
41 Callaghan CJ, Daneshfar B and Thompson DJ, Modeling waterfowl damage to crops surrounding the Quill lakes in Saskatchewan. *Human Wildlife Interactions* **9**:87–100 (2015).
42 Wawrzyński W, Zieja M, Tomaszewska J, Michalski M, Kamiński G and Wabik D, The potential impact of laser pointers on aviation safety. *Energies* **15**:6226 (2022).
43 Hagy HM, Linz GM and Bleier WJ, Optimizing the use of decoy plots for blackbird control in commercial sunflower. *Crop Prot* **27**:1442–1447 (2008).
44 Magrath RD, Haff TM, McLachlan JR and Igic B, Wild birds learn to eavesdrop on heterospecific alarm calls. *Curr Biol* **25**:2047–2050 (2015).
45 Fischl J and Caccamise DF, Influence of habitat and season on foraging flock composition in the European Starling (*Sturnus vulgaris*). *Oecologia* **67**:532–539 (1985).
46 Conner RN, Prather ID and Adkisson CS, Common raven and starling reliance on sentinel common crows. *Condor* **77**:517 (1975).
47 Keys GC and Dugatkin LA, Flock size and position effects on vigilance, aggression, and prey capture in the European starling. *Condor* **92**: 151–159 (1990).
48 Storms RF, Carere C, Musters R, van Gasteren H, Verhulst S and Hemelrijk CK, Deterrence of birds with an artificial predator, the RobotFalcon. *J R Soc Interface* **19**:20220497 (2022).
49 Wang Z, Griffin AS, Lucas A and Wong KC, Psychological warfare in vineyard: using drones and bird psychology to control bird damage to wine grapes. *Crop Prot* **120**:163–170 (2019).
50 Boycott TJ, Mullis SM, Jackson BE and Swaddle JP, Field testing an acoustic lighthouse: combined acoustic and visual cues provide a multimodal solution that reduces avian collision risk with tall human-made structures. *PLoS ONE* **16**:e0249826 (2021).
51 Whitehead SC, Wright J and Cotton PA, Winter field use by the European starling *Sturnus vulgaris*: habitat preferences and the availability of prey. *J Avian Biol* **26**:193–202 (1995).
52 Agackesen MN, Oktem AG and Oktem A, Effect of harvest at different maturation stages on fresh ear yield and ear characteristics of sweet corn (*Zea mays* L. saccharata) genotypes. *Appl Ecol Environ Res* **20**: 3335–3351 (2022).
53 Anderson A, Lindell CA, Moxcey KM, Siemer WF, Linz GM, Curtis PD *et al.*, Bird damage to select fruit crops: the cost of damage and the benefits of control in five states. *Crop Prot* **52**:103–109 (2013).
54 Gebhardt K, Anderson AM, Kirkpatrick KN and Shwiff SA, A review and synthesis of bird and rodent damage estimates to select California crops. *Crop Prot* **30**:1109–1116 (2011).
55 Jubb GL and Cunningham HN, Birds associated with grapes in Erie County, Pennsylvania. *Am J Enol Vitic* **27**:161–162 (1976).
56 Brady ML, *Birds and Berries: The Costs and Benefits of Birds in Agricultural Ecosystems*. Doctoral dissertation. Michigan State University, East Lansing, MI (2022) https://d.lib.msu.edu/etd/50436.

