A global evidence synthesis of outcomes of urban bird conservation interventions

Aalia I. Khan[1*], Silvia Colucci[1], Trina Rytwinski[1], Edward Cheskey[2], Autumn Jordan[2], Rachel T. Buxton[1]

[1]Department of Biology, Carleton University, Ottawa, Ontario, Canada

[2]Nature Canada, Ottawa, Ontario, Canada

*Corresponding author. Email: akhan550@uottawa.ca

Acknowledgements:

We thank members of the Bird Friendly Cities National Advisory panel, including J Allair, M Mesure, G Rios-Robles, A McKenzie, A-C Olivier, J Kilgour, T Beatley, J Bourque, L Falkiner, M Butler, and G Hvenegaard for providing feedback on search strings and target papers during the conception stages of this project. We extend our gratitude to the broader Bird Friendly Cities Community of Practice for engaging with us and providing feedback on preliminary results of our meta-analyses. We thank librarians S Sunstrum and S Turner from Carleton University, who gave advice on our search strategy, databases, and review software. Finally, we thank C Dennison, J Lee-Yaw, and V Nguyen for graciously providing comments on an earlier version of this manuscript.

Ethics statement: This paper did not collect or use human or animal subjects and therefore did not require ethics review.

Conflicts of interest statement: The authors declare no conflicts of interest.

Funding Statement: This project was supported by the Natural Sciences and Engineering Research Council of Canada (RGPIN 04888).

Author Contributions: AIK, EC, AJ, and RTB conceived the idea (supervised research, formulated question or hypothesis). AIK and SC performed the experiments (collected data, conducted the research). AIK wrote the paper. AIK, SC, TR, and RTB developed or designed methods. AIK analyzed the data. EC, AJ, and RTB contributed substantial materials, resources, or funding.

Data Availability: All primary data and code is available at the Open Science Framework repository for this project: https://osf.io/v6rwz/overview?view_only=8b459b888409479b8077d5ed80cc4ec5

ABSTRACT

Avian populations face high concentrations of threats in urban areas. Understanding the outcomes of urban conservation interventions to tackle these threats could inform more effective evidenced-based approaches. Using an evidence synthesis and meta-analysis of peer-reviewed literature on conservation interventions to tackle four leading causes of urban bird mortality in urban areas (cat predation, bird-window collisions, road mortalities, light pollution, and bird-vehicle collisions), we: 1) summarized the current state of the literature on urban threats and conservation interventions for birds, and 2) evaluated the outcomes of interventions aimed at reducing impacts of major urban threats on birds. Our evidence synthesis found that across all threats, few studies (35 out of 522) explored outcomes of conservation interventions compared to those that determined the establishment, magnitude, and drivers of threats. Our meta-analysis of nine types of collar-based interventions to reduce urban cat predation found that rainbow-colored Birdsbesafe™ collars most consistently demonstrated evidence of reduced numbers of dead birds brought home by cats (pooled reduction of 54% compared to controls). However, these results were drawn from a very small number of studies (n=13). To reduce mortality from bird-window collisions, closely spaced vertical stripes and circular or square decals reduced collisions by 98% (n=6) There were no studies that explored outcomes of interventions to reduce light pollution in urban areas. Two studies explored the use of traffic control measures (speed bumps, chicanes and barrier poles) to reduce bird-vehicle collisions, although we could not draw conclusions on their outcomes. Overall findings suggest there is a need for greater research on the effectiveness of conservation interventions for all urban threats.

Keywords: artificial light at night, bird mortality, bird-vehicle collision, bird-window collision, cat predation, conservation interventions, evidence synthesis, urban birds

LAY SUMMARY

- We reviewed research on four key urban threats facing birds: bird-window collisions, cat predation, light pollution, and bird-vehicle collisions
- We found that very little research is dedicated to understanding outcomes of interventions compared to understanding the magnitude of threats
- Most studies on interventions to reduce cat predation looked at outcomes of cat collars, with Rainbow Birdsbesafe™ collars demonstrating the greatest reduction in bird deaths
- Window treatments with high coverage, such as vertical stripes and circular or square decals resulted in the greatest reduction of bird-window collisions
- More research is needed to understand the outcomes of bird conservation interventions, particularly for light pollution and urban bird-vehicle collisions, as well as on outcomes of feral cat removal and roaming bylaws for owned cats

INTRODUCTION

The rapid expansion of urban landscapes is a major contributor to biodiversity loss worldwide (McKinney, 2006). Urban development typically reduces vegetation, simplifies habitat, and concentrates threats, resulting in the intolerance of many bird species to urbanized landscapes (Marjakangas et al., 2024). Many cities lie along migratory flyways, and habitat for birds at risk of extinction overlap with highly urbanized landscapes (Jokimäki et al., 2018). Given the critical roles birds play in ecosystems (Wenny et al., 2011) along with their value as effective biodiversity indicators (Gregory & Strien, 2010), bird conservation in urban areas can help cities foster broader biodiversity.

Among the most severe anthropogenic threats facing birds in urban areas are predation by cats, collisions with windows, disorientation by light pollution, and bird-vehicle collisions (Marzluff, 2001). It is estimated that feral and owned outdoor cats kill 70-200 million birds annually in Canada alone, making them the leading source of mortality after habitat conversion (Calvert et al., 2013). Collisions with windows kill another estimated 16-42 million birds annually (Calvert et al., 2013). Birds cannot perceive vegetation in clear or reflective glass, resulting in fatal collisions (Klem, 2009). Light pollution causes fewer direct mortalities but influences birds' photoperiod cycles and disorients birds that migrate nocturnally, increasing the risk of window collisions and other urban sources of mortality. As a result, large numbers of birds have been found dead or injured near brightly lit buildings during migration seasons (Van Doren et al., 2021). An estimated 96 million birds are killed by vehicles in the United States (Rabie et al., 2024), where species that forage near roadsides are particularly vulnerable (Orłowski, 2008).

Interventions to tackle these threats have been proposed and, in some cases, tested. For example, the application of decals can result in birds being able to perceive and avoid colliding with windows (Klem, 1990). A study in Delta, British Columbia, found that application of Feather Friendly® dot decals at 2-inch intervals resulted in a 95% reduction in window-collisions post-treatment (De Groot et al., 2022). Other examples include specialized cat collars to reduce cat predation (Willson et al., 2015) and using downward-facing lighting designs and different spectra of light to reduce the effects of light pollution (Poot et al., 2008). However, a comprehensive understanding of the effectiveness of different interventions across different contexts is lacking.

In general, knowledge of the effectiveness and outcomes of proposed conservation interventions remains limited globally across taxa. For example, Binley et al. (2025) found a scarcity of research on outcomes of interventions for species at risk of extinction in Canada. Williams et al. (2020) found a similar pattern in a review of conservation science literature, where nearly half of all studies described the state of nature, 10% linked a mechanism to the driver of change, and very few tested the effectiveness of an intervention.

As global urban land cover is expected to increase threefold from 2000 to 2030 (Fragkias et al., 2013) and continue expanding thereafter, it is essential to understand and implement conservation interventions to reduce bird mortalities in cities. A number of programs address bird conservation in cities, such as the American Bird Conservation and Environment for the Americas' Bird City Network (American Bird Conservancy, 2025) and Nature Canada's Bird Friendly Cities program. These programs encourage cities to implement policies and initiatives that support bird conservation (Nature Canada, 2025). The objectives of these programs are to reduce bird mortalities in cities, towns and villages and build bird conservation awareness by advocating for nature-positive municipal policies, implementing restoration projects of local bird habitat, addressing and mitigating the leading causes of urban bird mortalities, and hosting events that connect and educate community members. Certification criteria are based on how municipalities propose to tackle known major threats to urban birds (Nature Canada, 2025). An evidence-based understanding of the outcomes of conservation interventions for birds could help guide bird friendly city programs in promoting the most effective interventions.

To this end, we conducted an evidence synthesis to explore outcomes of interventions to address the top causes of direct bird mortality of birds in cities: cat predation, bird-window collisions, light pollution, and bird-vehicle collisions. The primary objective of the review was to synthesize available evidence on the outcomes of bird conservation interventions that address key threats in urban areas to provide evidence for bird-friendly city certification programs. Specifically, we: 1) conducted a narrative synthesis of the state of the literature on key urban threats and interventions for birds and 2) conducted a meta-analysis of outcomes of interventions addressing each threat, including reductions in direct bird mortality, improvements to reproductive success, changes in physiological or behavioral stress indicators, or any other bird-related conservation outcomes. We discuss how an understanding of the effectiveness of interventions can inform urban programs that aim to improve bird conservation.

METHODS

Our evidence synthesis followed, as closely as possible, the Collaboration for Environmental Evidence's (CEE) standardized guidelines for systematic maps (CEE, 2022). All full-text screening and data extraction were conducted by two reviewers following a double-blind process (i.e., reviewers did not see each other's responses until a conflict arose), with conflicts resolved by discussion and consultation with the principal investigator. We used separate search strings and conducted independent screenings for each threat category: cat predation, bird-window collisions, light pollution, and bird-vehicle collisions.

Search for articles

Search sources

The Bird Friendly Cities program National Advisory Panel (NAP), made up of 10 experts in bird conservation from across Canada, were consulted early in the review process (Nature Canada, 2025). The NAP helped to identify target studies (i.e., De Groot et al., 2022; Gordon et al., 2010; Hall et al., 2015; Klem, 1990; Poot et al., 2008; Zuberogoitia et al., 2015) and provided recommendations for keywords used in search strings. Following consultation with librarians at Carleton University, we selected Web of Science Core Collections and Scopus as relevant databases for our literature search, as they are more repeatable databases. Moreover, we ran a preliminary test on 250 studies in Google Scholar and found that including Google Scholar citations in the review search stage did not produce any additional relevant citations. Using citations of excluded review articles (see "Eligibility Criteria"), we performed supplemental searching to capture studies that did not come up in our initial search.

Search strings

For each threat category, we used search strings that targeted the title, abstract and keywords within relevant studies ("Topic" in Web of Science, or "TITLE-ABS-KEY" in Scopus; Supplementary Material Table S1). A list of target studies was used to develop and test the comprehensiveness of the search strings (listed here: Barton et al., 2017; Geiger et al., 2022; Groot et al., 2022; Poot et al., 2008; Willson et al., 2015; Zuberogoitia et al., 2015) and respective population, intervention, comparator, and outcome (PE/ICO) elements (see Supplementary Material Table S2 for full search strings). Search string elements were further refined through multiple rounds of preliminary abstract screening under each threat category. Search strings did not necessarily contain all PE/ICO elements to remain inclusive of all relevant studies. For example, under the cat predation threat topic, it may have been relevant to include the term "urban" or related keywords to keep the studies within an urban setting, or "predation" or "mortality" to specify exposure or outcome. However, as the target studies did not include the words "urban", "predation", or "mortality" within their title, abstract, or keywords, specifying these terms in the search string would have excluded target studies. We instead used the terms "domestic", "pet", "feral" and "*Felis catus*". We also excluded the terms "influenza" or "virus" or "disease" or "flu", as these studies fell out of the scope of our objectives. Similarly, the term "aircraft" was excluded from window collisions studies to focus on building collisions and "poultry" was excluded from light pollution studies to focus on the effects of artificial light on wild birds.

Article screening

For eligibility screening, studies were uploaded from Web of Science and Scopus onto Covidence (Veritas Health Innovation, Melbourne, Australia), a web-based systematic review software. Duplicates between databases were removed automatically by the software; missed duplicates were removed manually during the screening process. Each of the four threat categories was screened in Covidence as an independent review. For abstract screening, a kappa test was performed in which both reviewers each completed the same 30% (a random subset) of abstracts under each threat category and achieved a score representing a good strength of agreement ($\kappa = 0.7$, where $\kappa > 0.6$ is considered good strength of agreement) (Sim & Wright, 2005). Following the kappa test, abstracts were screened independently. Each article was judged for eligibility based on its abstract, and when reviewers were uncertain, articles were included for full-text screening.

Eligibility criteria

Following abstract screening, the full-text screening stage was completed in full by two review authors (double-blind screening). All conflicts were resolved by discussion, with unsolved conflicts resolved by the principal investigator. During both screening stages (abstract and full-text), studies were excluded if they were not peer reviewed, not available in English (as it was beyond project capacity to review studies not in English), or not related to the (PE/ICO) elements defined for each topic (Supplementary Material Table S2 & S3). No studies were excluded based on the presence or absence of a comparator. Present, historical, and even archaeological evidence (e.g., Onar et al., 2021) were all considered eligible, provided that they presented new data or findings not previously published in peer-reviewed literature. Otherwise, they were excluded as “non-primary research” and used for supplemental searching. These were typically review papers and perspective pieces. There were no geographical or time-based limits on publications for the review. We reached out to the corresponding author for studies we could not access. Studies were excluded as “inaccessible” if we did not hear from the author within 14 days. See Supplementary Material Table S3 for detailed exclusion criteria.

Eligible setting

To date, there is no well-established global standard definition for the term “urban”. Thus, we followed the definition for “urban” outlined by the country in which each study occurred, using the most up-to-date list collated by the United Nations Statistics Division (United Nations Statistics Division, 2005). University campuses were considered eligible even when outside of strict urban boundaries, as they typically emulate an urban environment. We also included experiments completed in controlled or non-urban settings if the goal of the study was to understand outcomes in an urban environment (particularly important for studies on light pollution). Studies that contained a gradient or interface between urban, rural, and natural habitats were included.

Data extraction

Defining threat and intervention categories

Following full-text screening, we separated studies into threat and intervention studies. Drawing from the framework created by (Williams et al., 2020), threat studies were assigned three categories: a) studies that incidentally discover or establish the presence of a threat (i.e., studies in which the threat is discovered as a by-product of the study rather than its main goal, such as reports on wildlife rehabilitation center admission records), b) studies whose primary objective is to assess the magnitude of the threat, and c) studies that explore drivers that influence how the threat impacts birds. We defined intervention studies as those that assess the outcome of an implemented conservation intervention on bird populations. Studies that explored the design and implementation of a proposed intervention, but did not explore outcomes, or studies that included surgical or care-related treatments of birds, were not considered for further data extraction.

Data extraction from threat studies

From both threat and intervention-based studies we extracted: bibliometric information, geographic location of the study, bird species or community studied, and conservation status of each species. We also collected information on whether the study targeted a specific individual bird species. Furthermore, we collected information on whether the study was conducted in a controlled setting (i.e., in a lab or field setting in which the environment and population were strictly controlled) or was observational in a less strictly controlled, usually field-based, setting. Data extraction was completed in full (i.e., double-blind data extraction and conflict resolution) by two reviewers. The full data extraction template can be found in the Open Science Framework page for this project **(link to be provided upon acceptance)**.

Data extraction for meta-analysis of intervention studies

For intervention studies only, we collected additional information for quality assessment and meta-analyses. This included information on the study design, type of intervention, sample sizes and more specific data according to the type of effect size used (see information on meta-analyses below). Due to the limited number of intervention studies in the light pollution and vehicle collision threat categories, we only extracted further information for meta-analysis in the cat predation and bird-window collisions categories. A list of all included studies and their data can be found in the Open Science Framework page for this project. These data were extracted by the lead author.

We assessed intervention studies for the quality of their methodological approach and potential for risk of bias. One author (AK) assessed study quality based on modified CEE-based study validity assessments of two previous systematic reviews (Harper et al., 2022; Rytwinski et al., 2023). Our rubric (Supplementary Material Table S4) defined and assessed selection bias (i.e., whether the study was appropriately controlled, whether there was true replication, and whether replicates were well matched); assessment bias (i.e., consistency in sampling methods and whether a quantitative outcome was provided); performance bias (i.e., whether the study was free of extenuating circumstances and whether study settings were consistent); and attrition bias (i.e., whether units of replication were removed from the study, leading to sampling differences between the control and intervention groups – particularly applicable to cat predation studies).

To determine relevant confounding factors to assess selection and performance bias (Supplementary Material Table S4), we used information from threat studies. The full quality assessment rubric with results can be found in in the Open Science Framework page for this project.

Statistical analysis

All analyses were conducted using R statistical software version 4.4.3 (R core team, 2024). To retrieve the conservation status of each species studied, we used the “rredlist” package (Gearty & Chamberlain, 2025) to extract information directly from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species Version 2025-1 (API v4) (International Union for Conservation of Nature, 2025).

Meta-analysis of intervention studies

Meta-analysis was conducted using the “metafor” package (Viechtbauer, 2010). We built a multi-level mixed-effects model using the *rma.mv* function with intervention type as a moderator. Several studies included multiple interventions; in these cases, each intervention was independently assessed for quality, and separate effect sizes were calculated. To account for multiple study comparisons, study ID was included as a random factor in the model. Due to the small number of studies, we opted to fit the model without an intercept (i.e., without a reference) to summarize the average effects of each intervention rather than compare their relative effectiveness (Viechtbauer, 2010).

For both meta-analyses, we assessed heterogeneity using tests for τ^2 (between-study variance and within-study variance) and I^2 (proportion of variability due to true differences among effect estimates) (Viechtbauer, 2010). Residual heterogeneity was evaluated using QE, which tests whether unexplained variation remained after accounting for moderators (i.e., intervention type) and the random effects (i.e., study ID). Moderator effects were tested using QM, which evaluates whether intervention type significantly explains variation in effect estimates (results in Table S9, Table S10, Table S11, and Table S12).

Publication bias was also assessed by using two complementary approaches (Figure S3 and Figure S4). First, funnel plot asymmetry was evaluated using Egger's regression test (Egger et al., 1997). However, these results should be interpreted with caution as this test suffers from poor power when the number of effect sizes is low (Simmonds, 2015). We also used Rosenberg's fail-safe number N (Rosenberg, 2005), which is commonly used for random effects models and estimates the number of additional studies with an average effect size of zero that would be required to make an outcome not significant. We considered the meta-analysis robust against publication bias if the failsafe number was greater than $5k + 10$, where k is the number of effect sizes in the analysis.

For cat predation studies, our meta-analysis evaluated the reduction in birds brought home by cats from collar-based interventions. We used the standardized mean difference (SMD) (otherwise known as Hedges' g, which includes a correction for smaller sample sizes) as our effect size measure, calculated manually using the steps in Koricheva et al., (2013):

$$g = \frac{\bar{X}_{G1} - \bar{X}_{G2}}{S_{pooled}} \cdot J$$

where $\bar{X}_{G1}$ is the mean of group 1, or the control group (i.e., the average number of birds brought home per cat with no intervention collar), and $\bar{X}_{G2}$ is the mean of group 2, or the intervention group (i.e., the average number of birds brought home per cat wearing the intervention collar). S_{pooled} is the pooled standard deviation between the two groups. J is a correction applied to remove small sample bias:

$$J = \left[1 - \frac{3}{4(n_1 + n_2) - 1}\right]$$

where n_1 is the sample size of group 1 and n_2 is the sample size of group 2. A positive Hedges' *g* indicates that the average number of birds brought home per cat was lower when cats wore an intervention collar than cats with no intervention collars, while a negative Hedges' *g* corresponds with an increase in birds brought home by cats with intervention collars compared to controls. We also calculated sampling variance to build confidence intervals around the effect size, defined as:

$$v_i = \frac{n_1 + n_2}{n_1 n_2} + \frac{g^2}{2(n_1 + n_2)}$$

Mean, standard deviation, and sample size were collected from all studies where possible, where mean was the average number of birds killed per cat and the sample size was the number of cats. For some studies, we used PlotDigitizer (PORBITAL, 2025) to extract mean and standard error values from figures, which were then converted to Hedges' *g* and variance values. For one study reporting confidence intervals, we manually calculated standard error, assuming a normal distribution.

For bird-window collision studies, we examined log odds ratios for each intervention using the *escalc* function (Viechtbauer, 2010). The simplified equation (Koricheva et al., 2013) is:

$$logOR = ln\left(\frac{a_i \cdot d_i}{b_i \cdot c_i}\right)$$

where a_i is the number of times a bird collides with a treated window, b_i is the number of times a bird avoids a collision with treated window, c_i is the number of times a bird collides with an untreated window, and d_i is the number of times a bird avoids a collision with an untreated window. Negative log-odds ratios indicate a reduction in window collisions following the intervention.

Separate effect sizes between the two meta-analyses were used due to the differences in how outcomes were reported in studies for each threat category. For the cat predation studies, outcomes were continuous, making Hedges' *g* an appropriate effect size to compare mean values between groups (i.e., before vs. after intervention). In contrast, bird–window collision studies reported binary outcomes (collision vs. no collision), making a log odds ratio more appropriate.

We could not extract and calculate effect estimates from all studies, as some lacked replication, some did not maintain consistent controls, and some did not present the results in a way that allowed effect sizes to be calculated. For this reason, we also conducted and compared results from a vote-count for each threat category, in which the number of significant results for each intervention was tallied across studies (Koricheva et al., 2013).

RESULTS

Literature search and screening

Our review retrieved a total of 522 articles (Figure 1), including 118 on cat predation of birds, 93 on bird-window collisions, 221 on light pollution, and 101 on bird-vehicle collisions. The United States of America was the most common country in which studies were located, comprising 26.6% of all studies, followed by the United Kingdom (6.5%), Canada (6.1%) and Australia (6.1%; Supplementary Material Figure S1).

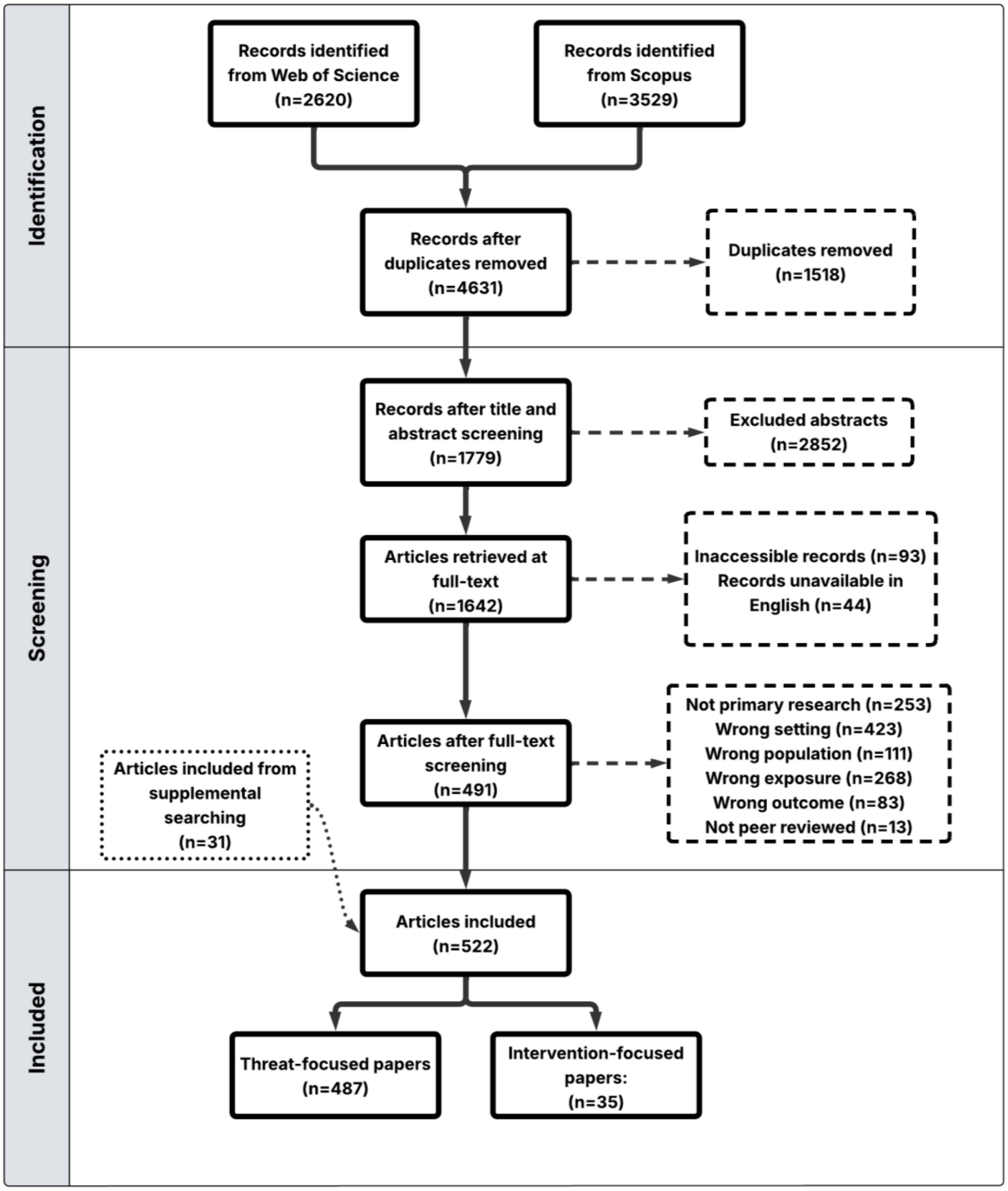


Figure 1. ROSES flow diagram (modified from Haddaway et al., 2018) showing literature sources and inclusion/exclusion process with criteria for combined evidence syntheses on cat predation, bird-window collisions, light pollution, and bird-vehicle collisions.

Narrative synthesis of threats and intervention studies

Across threat categories, we found 6.7% of studies (n=35 of 522) explored outcomes of conservation interventions (Figure 2). The majority (68.7%, n=359) of all studies were focused on understanding the magnitude of each threat. 16.5% of studies incidentally explored threats, typically examining and reporting on causes of admittance of birds to wildlife rehabilitation centers. 9% of studies specifically explored drivers that influence the effects of the threat on birds, such as studies exploring effects of different wavelengths of light on birds' sleep cycles (Liu et al., 2019). The bird-window collisions threat category had the greatest number (n=20) and proportion of intervention studies, where 21.5% of all window collisions studies explored outcomes of interventions, comprising over half (54%**)** of intervention studies across all categories. Cat predation had the second greatest number of intervention studies (n=13), comprising 11% of all studies in cat predation and 35.1% of all intervention studies. The light pollution category had no intervention studies, but it had the greatest proportions of studies assessing drivers of threats, comprising 12.7% of studies in the light pollution threat category and 59.3% of all studies on drivers. Only two studies were found on interventions for bird-vehicle collisions.

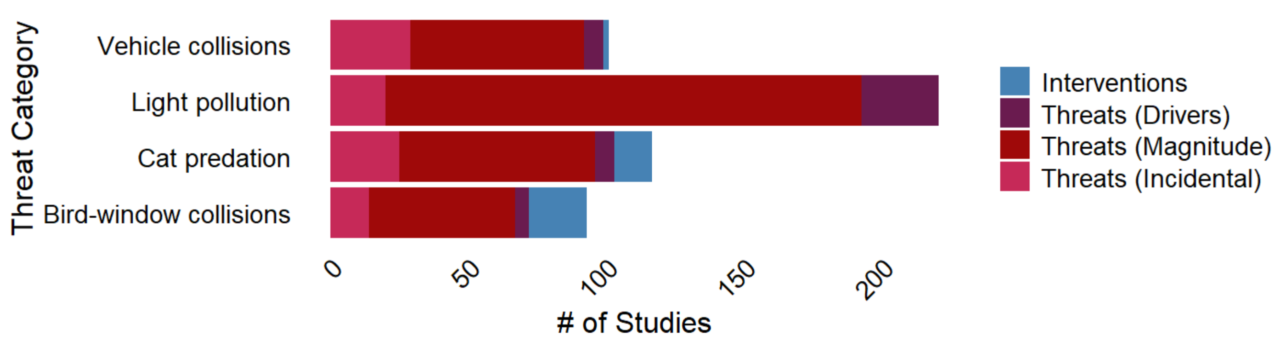


Figure 2. The number of studies extracted for the narrative synthesis on each key urban threat to bird populations. Colors represent studies that incidentally establish the presence of a threat

(incidental), assess the magnitude of a threat (magnitude), explore drivers of the threat (drivers), or assess outcomes of interventions addressing the threat (interventions).

Studies were published from 1971 to 2024 (Figure 3). 96.6% studies were published on or after the year 2000. The first paper in 1971 provided records of ringing recovery and established the first incidental findings of bird-window collisions, bird-vehicle collisions, and cat predation (Glue, 1971). Studies assessing the magnitude of threats were published almost three decades later in 1989, when experiments were conducted to determine whether birds can see glass (Klem, 1989). Intervention studies across all threat categories began to appear in the 1990s with experiments on window treatments that prevent bird-window collisions (Klem, 1990), but did not pick up in frequency until after 2000.

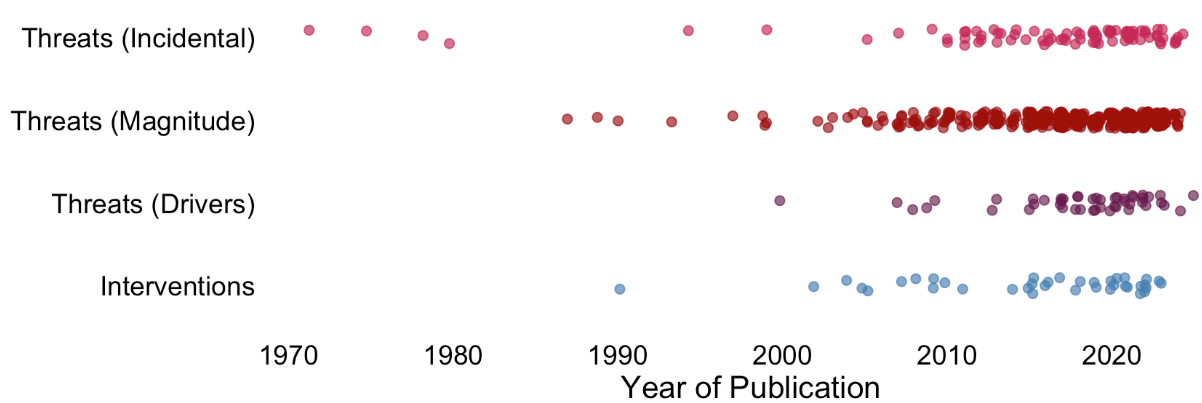


Figure 3. Densities of studies on cat predation, bird-window collisions, light pollution and bird-vehicle collisions over time from an evidence synthesis aiming to explore the outcomes of conservation interventions for major urban threats. Each point represents one paper. Colors represent studies that incidentally establish the presence of a threat (incidental), assess the magnitude of a threat (magnitude), explore drivers of the threat (drivers), or assess outcomes of interventions addressing the threat (interventions).

Most studies (81.1%) were natural experiments which did not control the setting. Light pollution studies had the greatest number (n=62) and proportion (32.8%) of studies in controlled settings, the majority of which were indoor avian experiments to examine the effects of different wavelengths and intensities of artificial light on bird health and behaviour. A little under half of studies targeted individual taxa (47.9%) (Supplementary Material Figure S2). Light pollution had the highest number of such studies (n=170), comprising 66.7% of all studies targeting individual taxa. We were able to retrieve data on individual species from 60.4% of studies for a total of 646 unique bird species from 97 families. Of these, 579 were Least Concern, 27 were Near Threatened, 22 were Vulnerable, 11 were Endangered, five were Critically Endangered, and two were Data Deficient. In most threat categories, very few birds targeted were red-listed birds (10.1%) (Figure 4). Light pollution was an exception, in which 20.6% of birds targeted for research were listed. Intervention studies almost exclusively reported on species listed as Least Concern except for a single Near Threatened species mentioned in an intervention study for bird-window collisions.

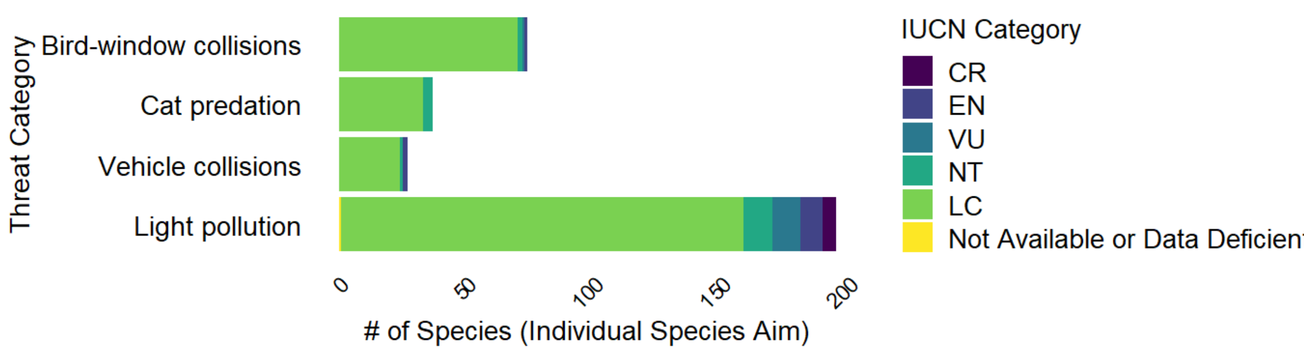


Figure 4. Proportions of 260 species extracted from studies targeting individual species under each threat category. Bars are stacked by the International Union for Conservation of Nature's (IUCN) Red List category.

Synthesis and meta-analysis of evidence from intervention studies

Cat predation

Effectiveness of interventions

Of the 13 intervention studies, we found eight studies on Birdsbesafe™ (BBS) cat collars, five on belled collars, two on other sonar devices, two studies on CatBibs™ (Calver et al., 2007), one study on feral cat removal (Meckstroth & Miles, 2005) and three studies on behavioural or diet-based interventions including using a puzzle feeder, increased play with wands and other toys, and a higher protein diet (Cecchetti et al., 2021) (vote count results are in Supplementary Material Table S5). Three studies tested outcomes of combined interventions: one tested outcomes of Rainbow-coloured BBS collars combined with bells (Geiger et al., 2022), and two tested outcomes of the CatBib™ with a bell (Calver et al., 2007). For the one study on outcomes of predator removal in an urban area we were unable to isolate the specific effects of cat removal from the effects of removing all predators (Meckstroth & Miles, 2005).

For our multi-level mixed-effects model, we extracted 13 standardized mean differences from seven different studies (Figure 5; Supplementary Material Table S6). Of the six studies we could not include, three did not separate the bird-based outcomes from other taxa and three lacked sufficient data to calculate a Hedges' *g* effect size. Consistent with our vote count results (Supplementary Material Table S5), the Rainbow BBS collar had the greatest effect estimate supported by the largest number of studies (0.46 ± 0.13, $p < 0.05$; $n=4$). In magnitude, the weighted mean percent reduction in birds brought home by cats with collars was 53%. The effect for mounted sonar devices was also significantly positive (0.40 ± 0.20, $p < 0.05$). We were able to include three out of five studies on belled collars in our multi-level model, which had a significant positive pooled effect (0.41 ± 0.15, $p < 0.05$, $n = 3$). The two studies from which we could not extract a Hedges' *g* effect size did not find a significant effect of bells; however, both had low quality assessment scores for study design, selection bias and performance bias (see quality assessment below). The combination of the CatBib™ with the bell had a significantly positive effect (0.72 ± 0.23, $p<0.05$). However, the combination of the Rainbow BBS and bell was not significant (0.19 ± 0.37, $p = 0.61$) nor were red and yellow BBS collars (0.15 ± 0.26, $p=0.58$; –0.13 ± 0.34, 0.69, respectively).

Our test for heterogeneity found that intervention type significantly explained the variation in effect estimates (QM = 32.39, df = 7, $p < 0.001$) (Table S9). Within-intervention tests found moderate inconsistency in results among studies within the “bell” intervention category (I = 46.26%), and high consistency within the “rainbow BBS” category ($I^2 = 0.01\%$) (Table S10). The Rosenburg’s fail safe number N was 130, suggesting that the meta-analysis is robust against publication bias. The funnel plot and Egger’s test results for publication bias can be found in the Supplementary Materials (Figure S3).

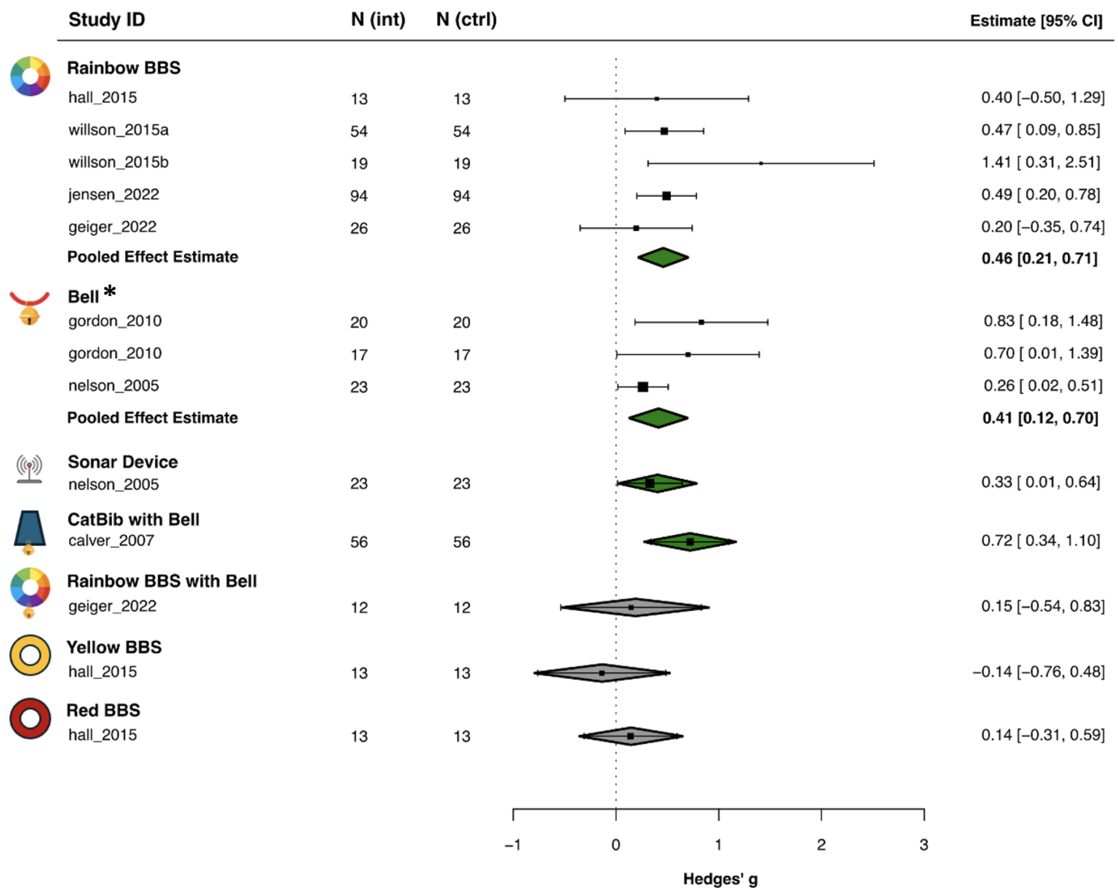


Figure 5. Standardized mean different effect size (Hedges' *g*) of collar-based interventions on rates of birds brought home by pet cats. The columns "N (int)" and "N (ctrl)" refer to the sample sizes of cats tested with the interventions on, compared to cats tested during the control. Interventions are pooled into seven different types, with the diamond depicting pooled effects (i.e., for intervention types with >1 effect size comparison). Error bars indicate 95% confidence intervals. A positive mean value (right of dashed zero line) indicates that the number of birds brought home by cats with interventions was less than control groups (no intervention) (i.e., a significant positive reduction in birds brought home). Sizes of squares depict relative weight on pooled effect size. Multiple trials within the same study are included as separate effect sizes. *We could only draw effect sizes from studies that found a significant positive effect for belled

collars. Two studies which could not be included did not find a significant positive effect for belled collars.

Quality assessment

Intervention assessments from every article except for two had a repeated-measures crossover design (the exceptions being a correlative study and a BACI design) and true replication, resulting in a low risk of selection and assessment bias. However, none of the studies recorded the relative lengths of time each cat was let out during the day, resulting in a moderate risk of performance bias. Many studies were at moderate or high risk of attrition bias as they did not specify exactly when cats were removed during the trials and how the removals affected their final sample sizes and resulting analyses (see OSF data repository for full assessments).

Bird-window collisions

Effectiveness of Interventions

We included 8 out of 20 studies in our odds ratio analysis –four field studies and four tunnel experiments – for a total of 36 effect sizes (Figure 6). Studies were included if they had an adequate control, replication, and results presented in a way that would allow odds ratio values to be extracted. Field studies applied interventions in real-world settings under natural conditions, typically on pre-existing buildings. Tunnel experiments were randomized controlled trials in which birds were released into an enclosed tunnel containing constructed window surfaces to assess collision risk in response to different window treatments. As with our vote-count results (Supplementary Material Table S7), our meta-analysis found that vertical stripes had the greatest effect size (-3.92 ± 0.57, $p<0.05$), resulting in a pooled reduction in window collisions of 98%. The only study that found vertical strips to be ineffective had the strips greater than 10 cm apart (Klem, 2009). Circular or square decals had almost as large an effect size as vertical stripes (-

3.80 ± 0.60, $p<0.05$), with circular decals also being the most frequently studied intervention (n=9). UV reflective coatings or films were also widely studied and found to reduce the number of birds colliding with windows (-1.35 ± 0.56, $p<0.05$), except where the film was applied to the interior rather than the exterior surface of the window (Swaddle et al., 2023). Fritted glass (-1.38 ± 0.59, $p<0.05$) and horizontal stripes (-2.15 ± 0.56, $p<0.05$) also reduced collisions but had fewer studies (n=3 and n=4, respectively). Pooled results for the "other" category (coral, maple leaf, and feather designs) had a relatively large and statistically significant effect size (-2.04 ± 0.63, $p<0.05$); however, of these studies, only the effect size of the coral design was significant. Studies on bird-of-prey decals, which could not be included in the meta-analysis, were the only intervention found to be consistently ineffective in preventing window collisions based on our vote-count.

Our test for heterogeneity found that intervention type significantly explained the variation in effect estimates (QM = 255.77, df = 8, $p < 0.001$) (Table S11). Tests for within-intervention heterogeneity found that vertical stripes showed high heterogeneity (QE = 87.82, $p < 0.001$; $\tau^2 = 4.341$; $I^2 = 94.31\%$) as well as circle or square decals (QE = 37.70, $p < 0.001$; $\tau^2 = 6.141$; $I^2 = 84.08\%$), and horizontal stripes (QE = 20.58, $p < 0.001$; $\tau^2 = 1.759$; $I^2 = 85.42\%$) (Table S12). The Rosenburg's fail safe number N was 8161, suggesting that the meta-analysis is robust against publication bias. The funnel plot and Egger's test results for publication bias can be found in the Supplementary Materials (Figure S4).

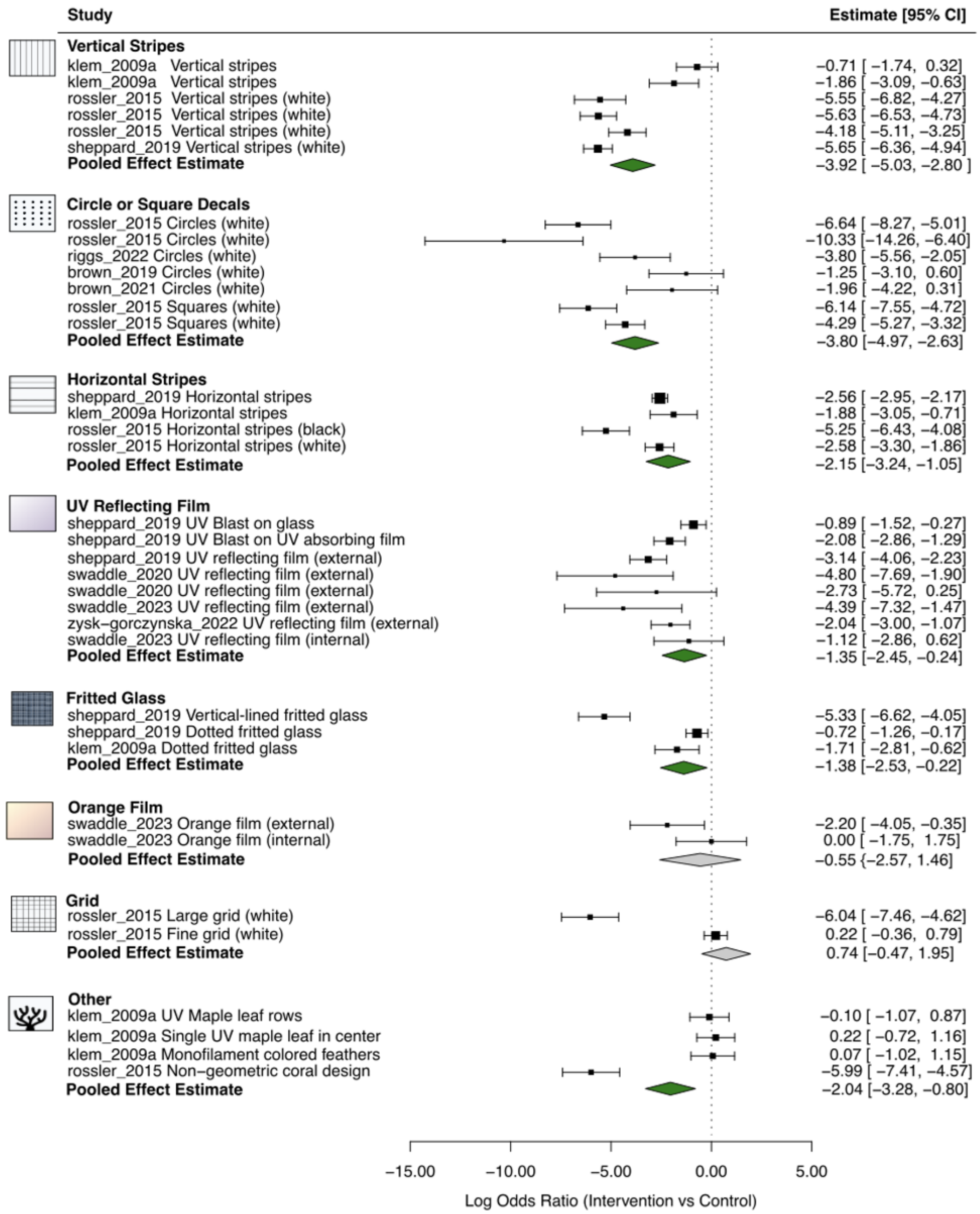


Figure 6. Log-odds ratio of 36 effect sizes for 21 specific interventions from 8 studies on outcomes of window treatments on bird-window collisions. Interventions are pooled into eight different intervention types, with the diamond depicting the pooled effects. Horizontal bars depict the effect size and 95% confidence intervals. Negative log-odds ratios indicate a reduction in window collisions following intervention. Effect sizes whose confidence intervals do not

overlap the dotted line of no effect are statistically significant. Sizes of squares depict the relative weight on pooled effect size.

Quality assessment

Two BACI field studies had perfect quality scores (Riggs et al., 2023; Zyśk-Gorczyńska & Żmihorski, 2022). Of the remaining field studies, 10 of 13 did not have true replication, eight did not report potential environmental confounding factors, and only four adequately described confounding factors between the units of replication (i.e., the window area, angling and specific color/tinting, if applicable). All tunnel test experiments were randomized controlled trials in strictly controlled settings which accounted for potential confounders; thus, almost all received perfect scores through our quality assessment rubric. The exception was a tunnel test study which was not transparent about its statistical methodology for determining significance (Klem, 1990).

Bird-vehicle collisions

Only two studies tested outcomes of interventions for bird-vehicle collisions. The first paper comprised three experimental studies involving different bird taxa that found vertical pole barriers were successful at altering the flight paths of birds, which could result in avoidance of bird-vehicle collisions (Zuberogoitia et al., 2015). All three experiments received perfect quality scores for assessment and performance biases but lacked true replication and independent control sites.

The second paper compared road-kill rates before and after the installation of a series of traffic calming devices, such as chicanes and speed bumps, finding that road mortality rates were lower in forested areas where the road calming devices were installed (Jones et al., 2014). This study lacked replication, had a high risk of performance bias as it did not account for related confounding factors, and outcomes for birds and other taxa were pooled, making it impossible to discern the effects of the intervention on birds independently.

Discussion

In synthesizing the literature on the effectiveness of conservation interventions to tackle urban threats, we found a dearth of literature on outcomes for birds, supporting results from other reviews in conservation science (e.g., Binley et al., 2025; Esler et al., 2010; Williams et al., 2020). While research on threats has greatly increased in volume, those exploring outcomes of interventions have not seen the same growth, remaining infrequent in urban bird research. Most studies (93.3%) presented the prevalence, magnitude, or drivers of threats. Of these, studies exploring drivers, which are critical for informing intervention research and practice, were also proportionately few (9% of all studies).

Of the literature on outcomes of interventions, over half (57.1%) explored outcomes of window treatments to reduce bird-window collisions. These studies found that most window treatments, except for bird of prey decals and other films or decals with low area coverage or placed on the inside of the window, reduced bird-window collisions by 98%. Out of collar-based interventions to reduce the number of birds killed by cats, Rainbow Birdsbesafe™ collars showed the greatest reduction in the number of birds cats brought home. However, cats wearing these collars still brought home some birds, whereas hypothetically none would be brought home if cats were kept indoors. The quality of intervention studies was found to be particularly poor for bird-window collision field studies, requiring greater true replication and accounting for confounders at the level of replication and between treatment and control environments.

For cat predation, existing intervention studies were high in quality but were primarily focused on collar-based or behavioural interventions for owned cats that were still let outdoors, rather than interventions that keep owned cats indoors or reduce feral cat populations. While we found proportionately more studies for window collision interventions, many of the field tests suffered from significant quality issues, making it difficult to conduct statistical analyses on most studies. We found no urban research on the effectiveness of proposed conservation interventions for light pollution. Conclusions from the two studies for bird-vehicle collisions were also limited by quality.

A very small proportion of studies tested outcomes on or detected red-listed species (International Union for Conservation of Nature, 2025). Species at risk of extinction may not be detected in studies of urban threats as they may be more uncommon in urban areas. However, it is likely that they are still vulnerable to these threats. For instance, many species at risk of extinction are migratory, and light pollution is specifically more concentrated along migratory hotspots (Cabrera-Cruz et al., 2018). Among the threat categories, light pollution had the greatest proportion of research involving red-listed species (20.6%), possibly due to existing knowledge on the impacts on migratory birds (Cabrera-Cruz et al., 2018; Van Doren et al., 2021).

Research on interventions

Cat Predation

We found that existing research on interventions addressing cat predation in cities focused predominantly on collar-based devices that work to mitigate predation by owned outdoor cats. The Rainbow Birdsbesafe™ collar, a brightly rainbow-colored fabric tube worn over a breakaway collar which makes the cats highly visible to birds (Hall et al., 2015; Willson et al., 2015), was studied most widely and had consistently demonstrated reductions in the number of birds brought home, with a pooled reduction of 53%. Studies on belled collars had mixed results, although the two studies that found bells did not significantly reduce bird catch had lower scores for quality – one was a correlative study (Morgan et al., 2009), and the other had a medium risk of selection and performance bias (Cecchetti et al., 2021). Bells are intended to deter birds by making a sound, but it is possible they may be less effective in urban areas where the sound could be masked by anthropogenic noise (Damsky & Gall, 2016). Other interventions, such as the CatBib™ (another visibility-based collar) (Calver et al., 2007) and various mounted sonic devices (Calver & Thomas, 2010; Nelson et al., 2005), were each found to significantly reduce rates of birds brought home, but research remains too limited to draw definitive conclusions. Cats are known to be particular and vary greatly in their individual tolerances of different collar types (Harrod et al., 2016). Therefore, continued research would benefit from testing a variety of potential interventions and cats' relative tolerance alongside the outcomes for birds. However, it is important to note that even the Rainbow Birdsbesafe™ collar only reduced the number of birds brought home by just over half (54%), whereas keeping cats indoors would reduce prey brought home entirely.

With this in mind, we recommend continued prioritization of education and research on the efficacy of other interventions for keeping cats indoors. We found there is still little research on outcomes of other interventions for owned cats, such as restricting cat movement using leashes and catios, or the introduction of roaming bylaws. One study found that areas where cats were not allowed or cats faced strict curfews resulted in no significant outcomes for local small mammal diversity and abundance, although factors such as vegetation characteristics may have also played a role (Lilith et al., 2010). Another study that correlated cat density with bird abundance and diversity within different neighbourhoods in the City of Ottawa, Canada, found that the two variables were only weakly related (Perkins et al., 2021). Although threat studies demonstrate that unowned cats have high predation rates of birds in urban areas (Loss et al., 2013), we found limited research on potential interventions for unowned cats. While many studies exist on outcomes of cat eradication for island birds (Nogales et al., 2004), we found only one study that explored the outcomes of predator removal on birds in San Francisco (Meckstroth & Miles, 2005). However, cats were only one predator removed, and the presence of other more common predator species confounded results (Meckstroth & Miles, 2005). Several studies suggest that ongoing and comprehensive trap-and-neuter programs are the most effective way to lower urban cat populations (Luzardo et al., 2025; Spehar & Wolf, 2018); however, more research is needed on whether these programs result in reduced predation rates of birds in cities.

A common source of bias across most cat intervention studies was attrition bias, which can be particularly impactful where sample sizes are already quite small. Clearer reporting of how this bias may have affected the final treatment group sizes would improve transparency and allow for more accurate interpretation of results. Additionally, none of the studies recorded the relative lengths of time each cat was let out during the day, and whether these lengths may have been different between the treatment and control periods. A significant driver of predation rates is the amount of time a cat has spent outside, since this correlates with the amount of territory they cover and gives them more opportunity to catch prey (Cordonnier et al., 2022). Additionally, a single cat may exhibit significant variation in the time it spends outside on a given day, depending on season or weather (Dunford et al., 2024; Jensen et al., 2022).

Cat predation is a major threat faced by many other taxa, and conservation interventions applied to reduce harm to birds may have variable outcomes for other animals. For example, Cecchetti et al. (2021) discovered that puzzle feeders made cats bring home proportionally fewer birds but greater amounts of prey overall. The same study also found that playing with toys at home made cats bring home less prey overall, but proportionally more birds.

Bird-window collisions

Interventions that most consistently reduced bird-window collisions were circular decals and vertical stripes on windows spaced less than 10 cm apart. Other interventions were found to reduce collisions but were only tested in single studies, such as white sheets, square decals, UV-reflective films, or full-window white films. Interventions such as bird-of-prey decals or artwork that only covered small parts of a window did not significantly reduce bird-window collisions. Our findings are comparable to meta-analyses found in grey literature from recent years (Colbaugh, 2023; Samuels, 2025), which have similarly emphasized the importance of window treatments with minimal gaps for the most effective outcomes.

There were significant quality issues with the field studies in bird-window collisions. Many studies did not have true replication or did not control for or report confounders which are known to influence collision risk such as the sizes or angles of the windows, nearby vegetation, or placement of bird feeders (Brown et al., 2019; Klem et al., 2004). While field studies can be limited in their ability to control for covariates and confounders, some confounders such as window area can be statistically accounted for post hoc (De Groot et al., 2022). With this in mind, we recommend that future studies aim to improve replication and at least report confounders where possible.

All tunnel test studies received perfect scores in all categories of the quality assessment, except for one that did not clearly describe the statistical tests used to determine significance (Klem, 1990). Tunnel tests can be highly useful as they can control for all potential confounders. However, this also limits their applicability in real-world settings (Samuels, 2025). In addition, tunnel test studies use specific bird taxa, and responses to window treatments may differ across different species (Klem, 1989; Ocampo-Peñuela et al., 2016); thus, results from tests may not be representative of responses by bird communities in the real world. Therefore, we recommend prioritizing well-designed field studies that can complement tunnel experiments and better assess outcomes of proposed interventions in real-world settings.

Light pollution

We did not find any studies on outcomes of interventions to reduce light pollution on birds in urban areas. Proposed interventions include lights-out events, switching to warm lighting, and employing downward-facing lighting (e.g., FLAP Canada, 2023; Audubon, 2025). However, due to the spatially pervasive nature of light pollution (e.g., skyglow or diffuse luminance of the night sky by artificial lights) compared to other threats in our review, it can be difficult to clearly assess spatially controlled outcomes of these interventions (Seymoure et al., 2025).

While we did not find any intervention studies, light pollution had the greatest proportion of studies on drivers of threats. These studies were typically experiments exploring the effects of different wavelengths and intensities of light. High intensity white and broad spectrum light had the largest effect on sleep quality and immune functioning of birds (Kernbach et al., 2020; Ouyang et al., 2017). However, based on the species and setting, sleep quality could also be affected by green light (Ulgezen et al., 2019), orange light (Liu et al., 2019), and violet light (Ren et al., 2021). Additionally, blue and green light were found to be more likely to result in fatal light attraction (Rebke et al., 2019; Zhao et al., 2020). However, one intervention study, which was excluded because it was not in an urban environment, found that green lighting was the least disorienting for birds, whereas red and white lights were the most disorienting (Poot et al., 2008). We recommend future research testing outcomes of interventions that reduce outdoor light intensity and scatter in real-world settings.

Light pollution also influences bird-window collisions. An intervention study we included in our the bird-window collisions threat category found that lowered interior lighting during midday, when reflectivity is the highest, significantly reduced bird-window collisions (Emerson et al., 2022). Although most window collisions occur during the day, modelled estimates suggest that reducing light pollution can reduce collisions at night during peak migration periods by 53-59% (Van Doren et al., 2021). However, models have not been empirically tested, so actual outcomes of these programs remain unknown.

Vehicle collisions

We found very little research on interventions for urban bird-vehicle collisions. This is surprising given that road mortalities are a widely studied phenomenon globally and many interventions have been proposed for other taxa including mammals, reptiles, and amphibians, such as overpasses, underpasses, and road barriers, which have been reviewed elsewhere (Glista et al., 2009; Rytwinski et al., 2016). The two intervention studies we found had positive results. The study on pole barriers found that they were effective in circumventing flight paths for tamed raptors, waterbirds, and griffon vultures. However, all experiments in this paper lacked true replication and were conducted in open fields rather than the roads upon which they would be applied (Zuberogoitia et al., 2015). The study on traffic calming devices found reductions in road mortalities in areas where the devices were installed. However, this study was at high risk of selection and performance bias. In addition, while results were provided on specifically bird-related mortality accidents prior to the upgrade, results following the upgrade and installation of calming devices were pooled for all wildlife, so the effectiveness on birds alone could not be determined.

A few threat-based studies in this category (7.1%) explored drivers of bird-vehicle mortalities and could be used as a starting point for future intervention research. For example, Husby (2016) found that species that were lighter in weight and were attracted to roads for foraging opportunities were more likely to be hit by vehicles. Other studies have found that the height of the embankment and presence of hedgerows or other vegetation nearby also influence bird-vehicle collisions (Husby, 2016; Orłowski, 2008; Pons, 2000). Based on these findings, future interventions could target known hotspots and employ strategies such as removing food attractants like roadkill, applying structural deterrents such as fences, or moving vegetation farther away from the road (Orłowski, 2008).

Future directions and conclusions

The available evidence base for conservation intervention studies for urban birds was relatively small and unevenly distributed across intervention types, which limited the strength of conclusions drawn from the meta-analyses, including our ability to assess heterogeneity and publication bias. While some interventions, such as the Rainbow Birdsbesafe™ collars, showed consistent effects across studies, the overall number of studies was still low (e.g., n=4). In addition, several intervention studies in the bird-window collisions threat category lacked the appropriate controls and replication to be included in the meta-analysis. Furthermore, as is the case for many global reviews, a major limitation of our study was that studies had to be restricted to English, potentially missing key studies published in other languages which is reported to bias outcomes of ecological meta-analyses (Konno et al., 2020). Our review also only examined peer-reviewed studies, thus missing key results from grey literature (Jacobson, 2022; Samuels, 2025). Finally, while the focus of our study was on urban settings, it is important to consider that studies occurring in non-urban settings can still influence our knowledge on overall threats and interventions. Future meta-analyses could expand their scope to include non-English and grey literature to add strength to their conclusions.

While our review explored outcomes of interventions for bird populations once applied, the success of the application of these interventions relies on the awareness and uptake by people. Some of the intervention studies for cat predation also included questionnaires for owners to understand owner preferences and collar uptake by the cats (Calver et al., 2007; Hall et al., 2015). These questionnaires found that people's preferences for aesthetics and cats' attitudes around wearing the collar influenced whether an owner was likely to keep the collar on the cat. For application of window collision interventions, a study by Lysyk & Khan et al. (2025) found that barriers such as time, cost, and aesthetic preferences may prevent people from applying window collision stickers to individual homes. In summary, understanding the biological outcomes of bird conservation interventions is important, and understanding the potential social, economic, and political barriers to uptake is equally important for successful implementation.

References

American Bird Conservancy. (2025). Conservation Advocacy Archives. *American Bird Conservancy*. https://abcbirds.org/program-division/conservation-advocacy/

Audubon. (n.d.). *Lights Out Program | Audubon*. Retrieved July 28, 2025, from https://www.audubon.org/our-work/cities-and-towns/lights-out

Barton, C. M., Riding, C. S., & Loss, S. R. (2017). Magnitude and correlates of bird collisions at glass bus shelters in an urban landscape. *PLOS ONE*, *12*(6), e0178667. https://doi.org/10.1371/journal.pone.0178667

Binley, A. D., Haddaway, L., Buxton, R., Lalla, K. M., Lesbarreres, D., Smith, P. A., & Bennett, J. R. (2025). Endangered species lack research on the outcomes of conservation action. *Conservation Science and Practice*, *7*(2), e13304. https://doi.org/10.1111/csp2.13304

Brown, B. B., Kusakabe, E., Antonopoulos, A., Siddoway, S., & Thompson, L. (2019). Winter bird-window collisions: Mitigation success, risk factors, and implementation challenges. *PeerJ*, *7*, e7620. https://doi.org/10.7717/peerj.7620

Cabrera-Cruz, S. A., Smolinsky, J. A., & Buler, J. J. (2018). Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world. *Scientific Reports*, *8*(1), 3261. https://doi.org/10.1038/s41598-018-21577-6

Calver, M. C., & Thomas, S. R. (2010). Effectiveness of the Liberator? In reducing predation on wildlife by domestic cats. *Pacific Conservation Biology*, *16*(4), 244–250. https://doi.org/10.1071/pc110244

Calver, M., Thomas, S., Bradley, S., & McCutcheon, H. (2007). Reducing the rate of predation on wildlife by pet cats: The efficacy and practicability of collar-mounted pounce protectors. *Biological Conservation*, *137*(3), 341–348. https://doi.org/10.1016/j.biocon.2007.02.015

Calvert, A., Bishop, C., Elliot, R., Krebs, E., Kydd, T., Machtans, C., & Robertson, G. (2013). A Synthesis of Human-related Avian Mortality in Canada. *Avian Conservation and Ecology*, *8*(2). https://doi.org/10.5751/ACE-00581-080211

Cecchetti, M., Crowley, S. L., Goodwin, C. E. D., & McDonald, R. A. (2021). Provision of High Meat Content Food and Object Play Reduce Predation of Wild Animals by Domestic Cats Felis catus. *Current Biology*, *31*(5), 1107-1111.e5. https://doi.org/10.1016/j.cub.2020.12.044

Colbaugh, J. (2023). *A Meta-Analysis of Bird-Window Collision Solutions* [Auburn University]. https://www.proquest.com/docview/3169936480?%20Theses&accountid=9894&fromopenview=true&parentSessionId=eW9yYhvaaRGolNgNjx25sqwSBm0eON%2B0JjYUqP4Oq3A%3D&parentSessionId=l663t01ohcIxzq311b2S9QoiUHZTsTRLSynuEB1ak9s%3D&pq-origsite=gscholar&sourcetype=Dissertations%20

Collaboration for Environmental Evidence. (2022). *Guidelines and Standards for Evidence synthesis in Environmental Management. Version 5.0 (A. S. Pullin, G. K. Frampton, B. Livoreil, & G. Petrokofsky, Eds.)*. https://environmentalevidence.org/information-for-authors/

Cordonnier, M., Ferry, N., Renaud, E., Maurice, A.-C., Bonnaud, E., & Baudry, E. (2022). Drivers of predation by pet cats: Environment overcomes predator’s intrinsic characteristics. *Urban Ecosystems*, *25*(4), 1327–1337. https://doi.org/10.1007/s11252-022-01231-w

Damsky, J., & Gall, M. D. (2016). Anthropogenic noise reduces approach of Black-capped Chickadee (Poecile atricapillus) and Tufted Titmouse (Baeolophus bicolor) to Tufted Titmouse mobbing calls. *The Condor*, *119*(1), 26–33. https://doi.org/10.1650/CONDOR-16-146.1

De Groot, K. L., Wilson, A. G., McKibbin, R., Hudson, S. A., Dohms, K. M., Norris, A. R., Huang, A. C., Whitehorne, I. B. J., Fort, K. T., Roy, C., Bourque, J., & Wilson, S. (2022). Bird protection treatments reduce bird-window collision risk at low-rise buildings within a Pacific coastal protected area. *PeerJ*, *10*, 13142.

Dunford, C. E., Loca, S., Marks, N. J., & Scantlebury, M. (2024). Seasonal habitat selection and ranging of domestic cats (Felis catus) in rural and urban environments. *Animal Biotelemetry*, *12*(1), Article 1. https://doi.org/10.1186/s40317-024-00367-0

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ*, *315*(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Emerson, L. C., Thady, R. G., Robertson, B. A., & Swaddle, J. P. (2022). Do lighting conditions influence bird–window collisions? *Avian Conservation and Ecology*, *17*(2). https://doi.org/10.5751/ACE-02167-170203

Esler, K. J., Prozesky, H., Sharma, G. P., & McGeoch, M. (2010). How wide is the "knowing-doing" gap in invasion biology? *Biological Invasions*, *12*(12), 4065–4075. https://doi.org/10.1007/s10530-010-9812-x

Fragkias, M., Güneralp, B., Seto, K. C., & Goodness, J. (2013). A Synthesis of Global Urbanization Projections. In *Urbanization, Biodiversity and Ecosystem Services:*

Challenges and Opportunities (pp. 409–435). Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7088-1_21

Gearty, W., & Chamberlain, S. (2025). *rredlist: 'IUCN Red List' Client* (Version 1.0.0) [Computer software]. https://doi.org/10.32614/CRAN.package.rredlist

Geiger, M., Kistler, C., Mattmann, P., Jenni, L., Hegglin, D., & Bontadina, F. (2022). Colorful Collar-Covers and Bells Reduce Wildlife Predation by Domestic Cats in a Continental European Setting. *Frontiers in Ecology and Evolution*, *10*. https://doi.org/10.3389/fevo.2022.850442

Glista, D. J., DeVault, T. L., & DeWoody, J. A. (2009). A review of mitigation measures for reducing wildlife mortality on roadways. *Landscape and Urban Planning*, *91*(1), 1–7. https://doi.org/10.1016/j.landurbplan.2008.11.001

Glue. (1971). Ringing Recovery Circumstances of Small Birds of Prey. *Taylor & Francis*, *18*(3). https://doi.org/10.1080/00063657109476307

Gordon, J. K., Matthaei, C., & Heezik, Y. van. (2010). Belled collars reduce catch of domestic cats in New Zealand by half. *Wildlife Research*, *37*(5), 372–378. https://doi.org/10.1071/WR09127

Gregory, R. D., & Strien, A. van. (2010). Wild Bird Indicators: Using Composite Population Trends of Birds as Measures of Environmental Health. *Ornithological Science*, *9*(1), 3–22. https://doi.org/10.2326/osj.9.3

Groot, K. L. D., Wilson, A. G., McKibbin, R., Hudson, S. A., Dohms, K. M., Norris, A. R., Huang, A. C., Whitehorne, I. B. J., Fort, K. T., Roy, C., Bourque, J., & Wilson, S. (2022). Bird protection treatments reduce bird-window collision risk at low-rise buildings within a Pacific coastal protected area. *PeerJ*, *10*, e13142. https://doi.org/10.7717/peerj.13142

Haddaway, N. R., Macura, B., Whaley, P., & Pullin, A. S. (2018). ROSES RepOrting standards for Systematic Evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. *Environmental Evidence*, *7*(1), 7. https://doi.org/10.1186/s13750-018-0121-7

Hall, C. M., Fontaine, J. B., Bryant, K. A., & Calver, M. C. (2015). Assessing the effectiveness of the Birdsbesafe® anti-predation collar cover in reducing predation on wildlife by pet cats in Western Australia. *Applied Animal Behaviour Science*, *173*, 40–51. https://doi.org/10.1016/j.applanim.2015.01.004

Harper, M., Rytwinski, T., Taylor, J. J., Bennett, J. R., Smokorowski, K. E., Olden, J. D., Clarke, K. D., Pratt, T., Fisher, N., Leake, A., & Cooke, S. J. (2022). How do changes in flow magnitude due to hydropower operations affect fish abundance and biomass in temperate regions? A systematic review. *Environmental Evidence*, *11*(1), Article 1. https://doi.org/10.1186/s13750-021-00254-8

Harrod, M., Keown, A., & Farnworth, M. (2016). Use and perception of collars for companion cats in New Zealand. *New Zealand Veterinary Journal*, *64*(2), 121–124. https://doi.org/10.1080/00480169.2015.1110064

Husby, M. (2016). Factors affecting road mortality in birds. *Ornis Fennica*, *93*(4), Article 4. https://doi.org/10.51812/of.133902

International Union for Conservation of Nature. (2025). *The IUCN Red List of Threatened Species*. IUCN Red List of Threatened Species. https://www.iucnredlist.org/en

Jacobson, S. L. (2022). Mitigation measures for highway-caused impacts to birds. *In: Ralph, C. John; Rich, Terrell D., Editors 2005. Bird Conservation Implementation and Integration in the Americas: Proceedings of the Third International Partners in Flight Conference.*

2002 March 20-24; Asilomar, California, Volume 2 Gen. Tech. Rep. PSW-GTR-191. Albany, CA: U.S. Dept. of Agriculture, Forest Service, Pacific Southwest Research Station: P. 1043-1050, *191*. https://research.fs.usda.gov/treesearch/32104

Jensen, H. A., Meilby, H., Nielsen, S. S., & Sandøe, P. (2022). Movement Patterns of Roaming Companion Cats in Denmark—A Study Based on GPS Tracking. *Animals : An Open Access Journal from MDPI*, *12*(14), 1748. https://doi.org/10.3390/ani12141748

Jokimäki, J., Suhonen, J., & Kaisanlahti-Jokimäki, M.-L. (2018). Urban core areas are important for species conservation: A European-level analysis of breeding bird species. *Landscape and Urban Planning*, *178*, 73–81. https://doi.org/10.1016/j.landurbplan.2018.05.020

Jones, D. N., Griffiths ,M.R., Griffiths ,J.R., Hacker ,J.L.F., & and Hacker, J. B. (2014). Implications of upgrading a minor forest road on traffic and road-kill in southeast Queensland. *Australasian Journal of Environmental Management*, *21*(4), 429–440. https://doi.org/10.1080/14486563.2014.944590

Kernbach, M. E., Cassone, V. M., Unnasch, T. R., & Martin, L. B. (2020). Broad-spectrum light pollution suppresses melatonin and increases West Nile virus–induced mortality in House Sparrows (Passer domesticus). *The Condor: Ornithological Applications*, *122*(3), duaa018. https://doi.org/10.1093/condor/duaa018

Klem, D. (1989). Bird: Window collisions. *The Wilson Bulletin*, 606–620.

Klem, D. (1990). *COLLISIONS BETWEEN BIRDS AND WINDOWS: MORTALITY AND PREVENTION.*

Klem, D. (2009). Preventing Bird–Window Collisions. *The Wilson Journal of Ornithology*, *121*(2), 314–321. https://doi.org/10.1676/08-118.1

Klem, D., Keck, D. C., Marty, K. L., Ball, A. J. M., Niciu, E. E., & Platt, C. T. (2004). EFFECTS OF WINDOW ANGLING, FEEDER PLACEMENT, AND SCAVENGERS ON AVIAN MORTALITY AT PLATE GLASS. *The Wilson Bulletin*, *116*(1), 69–73. https://doi.org/10.1676/0043-5643(2004)116%5B0069:EOWAFP%5D2.0.CO;2

Konno, K., Akasaka, M., Koshida, C., Katayama, N., Osada, N., Spake, R., & Amano, T. (2020). Ignoring non-English-language studies may bias ecological meta-analyses. *Ecology and Evolution*, *10*(13), 6373–6384. https://doi.org/10.1002/ece3.6368

Koricheva, J., Gurevitch, J., & Mengersen, K. (2013). *Handbook of Meta-analysis in Ecology and Evolution*. Princeton University Press. https://www.jstor.org/stable/j.ctt24hq6n

Lilith, M., Calver, M., & Garkaklis, M. (2010). Do cat restrictions lead to increased species diversity or abundance of small and medium-sized mammals in remnant urban bushland? *Pacific Conservation Biology*, *16*(3), 162–172. https://doi.org/10.1071/pc100162

Liu, G., Peng, X., Ren, Z., Liu, M., Dang, R., Chen, Y., & Liu, F. (2019). The effect of artificial light with different SPDs and intensities on the sleep onset of silvereyes. *Biological Rhythm Research*, *50*(5), 787–804. https://doi.org/10.1080/09291016.2018.1498201

Loss, S. R., Will, T., & Marra, P. P. (2013). The impact of free-ranging domestic cats on wildlife of the United States. *Nature Communications*, *4*(1), 1396. https://doi.org/10.1038/ncomms2380

Luzardo, O. P., Vara-Rascón, M., Dufau, A., Infante, E., & Travieso-Aja, M. del M. (2025). Four Years of Promising Trap–Neuter–Return (TNR) in Córdoba, Spain: A Scalable Model for Urban Feline Management. *Animals*, *15*(4), Article 4. https://doi.org/10.3390/ani15040482

Lysyk, A., Khan, A. I., Conners, D., & Buxton, R. (2025). *Barriers and opportunities to preventing residential bird-window collisions*. https://ecoevorxiv.org/repository/view/9317/

Marjakangas, E.-L., Johnston, A., Santangeli, A., & Lehikoinen, A. (2024). Bird species' tolerance to human pressures and associations with population change. *Global Ecology and Biogeography*, *33*(5), e13816. https://doi.org/10.1111/geb.13816

Marzluff, J. M. (2001). Worldwide urbanization and its effects on birds. In J. M. Marzluff, R. Bowman, & R. Donnelly (Eds.), *Avian Ecology and Conservation in an Urbanizing World* (pp. 19–47). Springer US. https://doi.org/10.1007/978-1-4615-1531-9_2

McKinney, M. L. (2006). Urbanization as a major cause of biotic homogenization. *Biological Conservation, Urbanization*, *127*(3), 247–260. https://doi.org/10.1016/j.biocon.2005.09.005

Meckstroth, A. M., & Miles, A. K. (2005). Predator Removal and Nesting Waterbird Success at San Francisco Bay, California. *Waterbirds: The International Journal of Waterbird Biology*, *28*(2), 250–255.

Morgan, S. A., Hansen, C. M., Ross, J. G., Hickling, G. J., Ogilvie, S. C., & Paterson, A. M. (2009). Urban cat (Felis catus) movement and predation activity associated with a wetland reserve in New Zealand. *Wildlife Research*, *36*(7), 574–580. https://doi.org/10.1071/WR09023

Nature Canada. (2025). Bird Friendly City: A Certification Program. *Nature Canada*. https://naturecanada.ca/defend-nature/how-you-help-us-take-action/bfc/

Nelson, S. H., Evans, A. D., & Bradbury, R. B. (2005). The efficacy of collar-mounted devices in reducing the rate of predation of wildlife by domestic cats. *Applied Animal Behaviour Science*, *94*(3), 273–285. https://doi.org/10.1016/j.applanim.2005.04.003

Nogales, M., Martín, A., Tershy, B. R., Donlan, C. J., Veitch, D., Puerta, N., Wood, B., & Alonso, J. (2004). A Review of Feral Cat Eradication on Islands. *Conservation Biology*, *18*(2), 310–319. https://doi.org/10.1111/j.1523-1739.2004.00442.x

Ocampo-Peñuela, N., Peñuela-Recio, L., & Ocampo-Durán, Á. (2016). Decals prevent bird-window collisions at residences: A successful case study from Colombia. *Ornitología Colombiana*, *15*.

Onar, V., Köroğlu, G., Armutak, A., Öncü, Ö. E., Siddiq, A. B., & Chrószcz, A. (2021). A Cat Skeleton from the Balatlar Church Excavation, Sinop, Turkey. *Animals*, *11*(2), 288. https://doi.org/10.3390/ani11020288

Orłowski, G. (2008). Roadside hedgerows and trees as factors increasing road mortality of birds: Implications for management of roadside vegetation in rural landscapes. *Landscape and Urban Planning*, *86*(2), 153–161. https://doi.org/10.1016/j.landurbplan.2008.02.003

Ouyang, J. Q., de Jong, M., van Grunsven, R. H. A., Matson, K. D., Haussmann, M. F., Meerlo, P., Visser, M. E., & Spoelstra, K. (2017). Restless roosts: Light pollution affects behavior, sleep, and physiology in a free-living songbird. *Global Change Biology*, *23*(11), 4987–4994. https://doi.org/10.1111/gcb.13756

Perkins, G. C., Martin, A. E., Smith, A. C., & Fahrig, L. (2021). Weak Effects of Owned Outdoor Cat Density on Urban Bird Richness and Abundance. *Land*, *10*(5), Article 5. https://doi.org/10.3390/land10050507

Pons, P. (2000). Height of the road embankment affects probability of traffic collision by birds. *Bird Study*, *47*(1), 122–125. https://doi.org/10.1080/00063650009461167

Poot, H., Ens, B. J., de Vries, H., Donners, M. A. H., Wernand, M. R., & Marquenie, J. M. (2008). Green Light for Nocturnally Migrating Birds. *Ecology and Society*, *13*(2). https://www.jstor.org/stable/26267982

PORBITAL. (n.d.). *PlotDigitizer: Extract Data from Graph Image Online* [Computer software]. Retrieved August 13, 2025, from https://plotdigitizer.com/

Rabie, P. A., Welsch, M. M., Stone, N., & Derby, C. (2024). Novel approach to estimating avian mortality from vehicle–bird collisions on U.S. roads. *Journal of Field Ornithology*, *95*(3). https://doi.org/10.5751/JFO-00498-950301

Rebke, M., Dierschke, V., Weiner, C. N., Aumüller, R., Hill, K., & Hill, R. (2019). Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions. *Biological Conservation*, *233*, 220–227. https://doi.org/10.1016/j.biocon.2019.02.029

Ren, Z., Su, C., Cen, C., Jia, Y., & Liu, G. (2021). Impact of artificial light on night-time singing behaviour of the swifts. *IOP Conference Series: Earth and Environmental Science*, *864*(1), 012021. https://doi.org/10.1088/1755-1315/864/1/012021

Riggs, G. J., Barton, C. M., Riding, C. S., O'Connell, T. J., & Loss, S. R. (2023). Field-testing effectiveness of window markers in reducing bird-window collisions. *Urban Ecosystems*, *26*(3), 713–723. https://doi.org/10.1007/s11252-022-01304-w

Rosenberg, M. S. (2005). The File-Drawer Problem Revisited: A General Weighted Method for Calculating Fail-Safe Numbers in Meta-Analysis. *Evolution*, *59*(2), 464–468. https://doi.org/10.1111/j.0014-3820.2005.tb01004.x

Rytwinski, T., Lin, H.-Y., Harper, M., Smokorowski, K. E., Smith, A., Reid, J. L., Taylor, J. J., Birnie-Gauvin, K., Bradford, M. J., Crossman, J. A., Kavanagh, R., Lapointe, N. W. R., Turgeon, K., & Cooke, S. J. (2023). How do natural changes in flow magnitude affect fish abundance and biomass in temperate regions? A systematic review. *Ecological Solutions and Evidence*, *4*(1), e12216. https://doi.org/10.1002/2688-8319.12216

Rytwinski, T., Soanes, K., Jaeger, J. A. G., Fahrig, L., Findlay, C. S., Houlahan, J., Ree, R. van der, & Grift, E. A. van der. (2016). How Effective Is Road Mitigation at Reducing Road-Kill? A Meta-Analysis. *PLOS ONE*, *11*(11), e0166941. https://doi.org/10.1371/journal.pone.0166941

Samuels, B. (2025). *Characterising Bird-Window Collisions from an Avian Visual Perspective* [Western University]. https://ir.lib.uwo.ca/etd/10808

Seymoure, B. M., Buxton, R., White, J. M., Linares, C. R., Fristrup, K., Crooks, K., Wittemyer, G., & Angeloni, L. (2025). Global artificial light masks biologically important light cycles of animals. *Frontiers in Ecology and the Environment*, *23*(4), e2832. https://doi.org/10.1002/fee.2832

Sim, J., & Wright, C. C. (2005). The Kappa Statistic in Reliability Studies: Use, Interpretation, and Sample Size Requirements. *Physical Therapy*, *85*(3), 257–268. https://doi.org/10.1093/ptj/85.3.257

Simmonds, M. (2015). Quantifying the risk of error when interpreting funnel plots. *Systematic Reviews*, *4*(1), 24. https://doi.org/10.1186/s13643-015-0004-8

Spehar, D. D., & Wolf, P. J. (2018). A Case Study in Citizen Science: The Effectiveness of a Trap-Neuter-Return Program in a Chicago Neighborhood. *Animals*, *8*(1), Article 1. https://doi.org/10.3390/ani8010014

Ulgezen, Z. N., Käpylä, T., Meerlo, P., Spoelstra, K., Visser, M. E., & Dominoni, D. M. (2019). The preference and costs of sleeping under light at night in forest and urban great tits. *Proceedings of the Royal Society B: Biological Sciences*, *286*(1905), 20190872. https://doi.org/10.1098/rspb.2019.0872

United Nations Statistics Division. (2005). *Definition of "urban."* https://unstats.un.org/unsd/demographic/products/dyb/dyb2005.htm

Van Doren, B. M., Willard, D. E., Hennen, M., Horton, K. G., Stuber, E. F., Sheldon, D., Sivakumar, A. H., Wang, J., Farnsworth, A., & Winger, B. M. (2021). Drivers of fatal bird collisions in an urban center. *Proceedings of the National Academy of Sciences*, *118*(24), e2101666118. https://doi.org/10.1073/pnas.2101666118

Viechtbauer, W. (2010). Conducting Meta-Analyses in R with the metafor Package. *Journal of Statistical Software*, *36*, 1–48. https://doi.org/10.18637/jss.v036.i03

Wenny, D. G., Devault, T. L., Johnson, M. D., Kelly, D., Sekercioglu, C. H., Tomback, D. F., & Whelan, C. J. (2011). The Need to Quantify Ecosystem Services Provided By Birds. *The Auk*, *128*(1), 1–14. https://doi.org/10.1525/auk.2011.10248

Williams, D. R., Balmford, A., & Wilcove, D. S. (2020). The past and future role of conservation science in saving biodiversity. *Conservation Letters*, *13*(4), e12720. https://doi.org/10.1111/conl.12720

Willson, S. K., Okunlola, I. A., & Novak, J. A. (2015). Birds be safe: Can a novel cat collar reduce avian mortality by domestic cats (Felis catus)? *Global Ecology and Conservation*, *3*, 359–366.

Zhao, X., Zhang, M., Che, X., & Zou, F. (2020). Blue light attracts nocturnally migrating birds. *The Condor: Ornithological Applications*, *122*(2), duaa002. https://doi.org/10.1093/condor/duaa002

Zuberogoitia, I., del Real, J., Torres, J. J., Rodríguez, L., Alonso, M., de Alba, V., Azahara, C., & Zabala, J. (2015). Testing pole barriers as feasible mitigation measure to avoid bird vehicle collisions (BVC). *Ecological Engineering*, *83*, 144–151. https://doi.org/10.1016/j.ecoleng.2015.06.026

Zyśk-Gorczyńska, E., & Żmihorski, M. (2022). Ultraviolet film reduces bird–glass collision risk. *Ornis Fennica*, *99*(2–3), 95–103. https://doi.org/10.51812/of.115995

A global evidence synthesis of outcomes of urban bird conservation interventions:

Supplementary materials

Supplementary Material Table S1. List of search terms for each threat category in ISI Web of Science Core Collections and Scopus, along with the number of articles retrieved from each database, the total number of articles, and the date of the search performed using Carleton University's institutional subscription.

Topic	Search Terms (Web of Science)	Search Terms (Scopus)	# Articles (Web of Science)	# Articles (Scopus)	Total	Date of search
Cat Predation	(*bird* OR avian OR aves) AND (domestic cat$ OR pet cat$ OR feral cat$ OR feline OR "Felis catus" OR "Felis domesticus") NOT	(*bird* OR avian OR aves) AND ((domestic AND cat) OR (pet AND cat) OR (feral AND cat) OR feline OR "Felis catus" OR "Felis domesticus") AND NOT (influenza OR virus OR	886	1127	1640	April 29, 2024

	(influenza OR virus OR disease OR flu OR toxoplasm*)	disease OR flu OR toxoplasm*)				
Window Collisions	(*bird* OR avian OR aves) AND (glass OR window$) AND (collision$ OR strik* OR mortalit* OR death$) NOT (aircraft$)	(*bird* OR avian OR aves) AND (glass OR window) AND (collision OR strik* OR mortalit* OR death) AND NOT (aircraft)	312	458	577	April 29, 2024
Light Pollution	(*bird* OR avian OR aves) AND (((pollution OR artificial OR anthropogenic) NEAR	(*bird* OR avian OR aves) AND (((artificial OR anthropogenic) PRE/1 (light*)) OR "light pollution" OR streetlight	655	889	1125	April 28, 2024

	(light*)) OR streetlight$ OR "ALAN") NOT (poultry)	OR "ALAN") AND NOT (poultry)				
Collisions with Vehicles	(*bird* OR avian OR aves) AND (car OR cars OR vehic* OR road$ OR street$ OR windshield$ OR traffic) AND (collision$ OR strik* OR mortalit* OR death$) NOT (poultry OR aircraft$ OR virus)	(*bird* OR avian OR aves) AND (car OR cars OR vehic* OR road OR street OR windshield OR traffic) AND (collision OR strik* OR mortalit* OR death) AND NOT (poultry OR aircraft$)	767	1141	1470	May 2, 2024

Supplementary Material Table S2. PE/ICO and setting criteria for abstract and full-text screening. Note, no studies were excluded based on the presence or absence of a comparator.

Population	WILD BIRDS. This included terms like songbirds, raptors, waterbirds, shorebirds, ground birds, “aerial insectivores”, and specific species names of non-captive birds. *Included if an experiment was done on birds in captivity to understand effects on wild birds *Included historical/archaeological evidence *Anything involving chickens was excluded
Setting	**URBAN ENVIRONMENT.** We followed the definition for “urban” outlined by the country in which each study takes place • List of definitions for “urban” under each country: https://unstats.un.org/unsd/demographic/sconcerns/densurb/defintion_of%20urban.pdf *Included University campuses *Included if an experiment was done in a non-urban environment if the study specifically stated that its goal was to better understand what the outcomes would be in an urban environment (particularly important for ALAN studies). *Excluded if study was conducted explicitly in “agricultural” or “farmland” or “rural” habitats

Threat Category	**Bird-window collisions**	**Light pollution**	**Bird-vehicle collisions**	**Cat predation**
Exposure	**WINDOWS,** including but not limited to "windows", "buildings" (with windows), "glass"	**ARTIFICIAL LIGHTS,** including but not limited to "ALAN", "artificial light at night", "City lights", "Streetlights"	**VEHICLES ON ROADS,** including but not limited to "cars", "trucks", "roads", "streets", "traffic", including urban trains and railways	**DOMESTIC OR FERAL CATS,** including but not limited to "pet cats", *"Felis catus",* and *"Felis domesticus"*
Intervention	Any action that seeks to prevent a bird-window collision.	Any action that seeks to reduce the effects of artificial light pollution on birds.	Any action that seeks to reduce bird-vehicle collisions.	Any action that seeks to reduce the effects of cat predation on birds.
Outcome	Any sort of **collision** or **collision-associated** behaviour (e.g., study on	**Any sort of effect** from **artificial light pollution on birds** (e.g., collisions,	Any sort of **collision** or **collision-associated behaviour** (e.g., stress	**Any sort of predation by cats on birds** or **behavior by birds in response to the**

	birds trying to avoid collisions), which has an effect on the population (bird). Alternatively, any sort of outcome caused by the intervention on birds.	migratory cycle disruption, changes to sleeping patterns or vocalization, changes to abundance). Alternatively, any sort of outcome caused by the intervention on birds.	response or avoidance behaviour). Alternatively, any sort of outcome caused by the intervention on birds.	**presence of cats** (e.g., mortality, various stress responses, abundance/diversity counts, etc)

Supplementary Material Table S3. Definitions for exclusions other than PI/ECO and setting criteria for full-text screening.

Exclusion Term	**Definition**
Duplicate	Papers that were not already screened out by Covidence as “duplicates”. Errata and corrections were checked for information relevant to data extraction, then placed in this category.
Full-text inaccessible	Papers that could not be accessed via Carleton University’s institutional journal access, SciHub, ResearchGate or any other miscellaneous tools available at the review team’s disposal.

	Where possible, corresponding authors of inaccessible papers were emailed. Papers were excluded if corresponding authors could not be reached within 14 days.
Full-text unavailable in English	Full-text articles which could be accessed but were written in a language besides English. Papers were excluded if the full-text was unavailable in English even when the abstract was available in English.
Not primary research	Any research that primarily used data that was previously published in a peer-reviewed setting. This includes reviews, perspectives pieces, or response papers that only used previously peer-reviewed and published research. Studies that would be considered "primary research" include original experiments and field collections, as well as "reviews"/meta-analyses/modelling papers that use broadly available citizen science data, data provided by the government or other forms of gray literature.
Intervention-based paper with wrong population or setting	Any paper that investigated an intervention to one of our threats but was missing the population (birds) or setting (urban) [later sorted into wrong population, setting or outcome]
Not peer-reviewed	Papers that were not peer-reviewed (e.g., magazine articles or theses and dissertations).
Conference paper	Meeting abstracts or papers in conference journals that were not peer-reviewed.

Supplementary Material Table S4. Quality assessment rubric for intervention-based studies on cat predation of birds, bird-window collisions, and bird-vehicle collisions.

Pre-assessment filter				
Question/Criterion	Response to Question/Criterion	Cat Predation	Bird Window Collisions	Vehicle Collisions
A. **Is the methodological description sufficient to allow study quality assessment?**	**YES** or **NO** *If **NO**, study is excluded from further assessment.*	Must include clear description of: - Study design (e.g., repeated measures, BACI) - Sampling units (cats, households) - Data collection methods (owner logs, cameras)	Must include clear description of: - Collision monitoring methods (daily searches, etc..) - Sampling units (windows, buildings) - Timing and duration of study	Must include clear description of: - Collision monitoring methods (daily searches, etc..) - Sampling units (road section, birds)

		- Timing and duration of study		- Timing and duration of study
B. Is the intervention description sufficient to allow study quality assessment? *(i.e., is the intervention clearly related to cats and well described/easy to interpret?)*	**YES** or **NO** *If* ***NO,*** *study is excluded from further assessment.*	Must clearly describe intervention details, e.g.: - Type of collar (bell, bib, etc.) - Duration and consistency of use - Whether other cat behaviors or conditions were changed	Must clearly describe intervention details, e.g.: - Type of window treatment (film, decals) - Placement (inside/outside glass) - Installation timing relative to migration	Must clearly describe intervention details, e.g.: - Type of traffic barrier/mitigation
C. Is the outcome data sufficient to allow study quality assessment?	**YES** or **NO** *If* ***NO,*** *study is excluded from further assessment.*	Bird-specific outcomes must be reported separately	Bird collision or avoidance data must be quantitative and specific	Bird-specific outcomes must be reported

(i.e., does the study clearly provide a direct empirical link between the intervention and outcome for birds, specifically?)		(e.g., number of birds caught, species).	to intervention and control windows.	
Study validity assessment (risk of bias)				
Selection Bias (study design)				
1.0. Is the study design well controlled?	HIGH (1) – BACI OR repeated-measures crossover design MEDIUM (0.5) – BA or CI LOW (0) – Correlative or anecdotal	A good cat study is BACI or repeated-measures crossover (cats act as own controls).	A good collision study is BACI, or RCT-like tunnel tests if applicable.	A good bird-vehicle collisions study would be BACI. Medium score for BA or CI

				Low score for correlative or anecdotal.
1.1. Is there **true** replication in the study at the level of the intervention? (*i.e., pseudo-replication would be "NO"*)	**YES** or **NO** *Where "YES" gives the study a score of "1" and "NO" gives the study a score of "0"*	True replication = multiple cats independently tested.	True replication = multiple windows or tunnels independently tested. For tunnel tests, replication at bird level.	Replication = multiple roads or multiple settings in case of trial tests Pseudoreplication = multiple road segments
1.2. Are the comparator and intervention replicates/samples well-matched?	**YES** or **NO** or **UNCLEAR**	Matching or control for: - Outdoor access time	Matching or control for: - Window orientation and characteristics	Matching or control for:

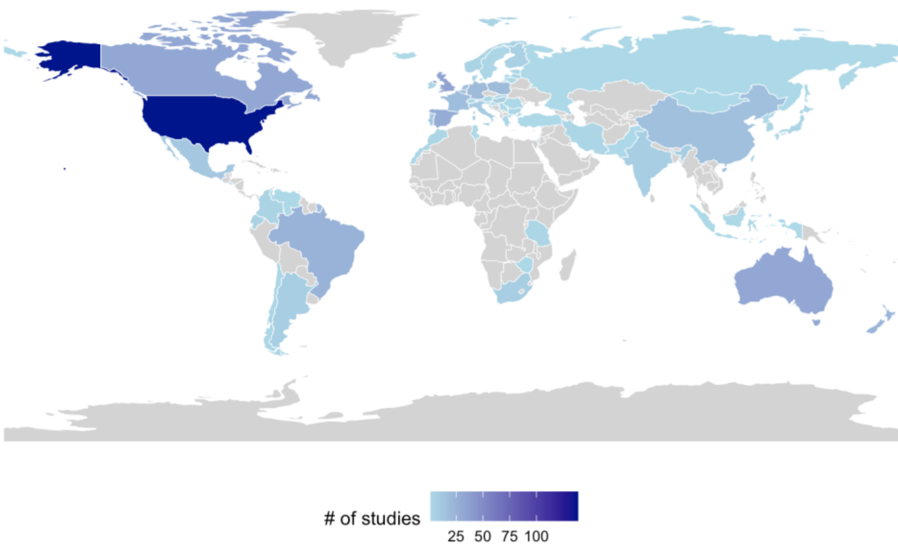
(i.e., at the comparator and treatment samples similar at baseline with regards to confounding factors; otherwise, are these factors appropriately controlled for or addressed?)	***If UNCLEAR**, treat as NO . Where "YES" gives the study a score of "1" and "NO" gives the study a score of "0"*	- Cat age - Previous hunting experience Score 0 if factors reported but not randomized, controlled or statistically dealt with post-hoc. Score 0 if not reported/controlled.	including color and size/area Score 0 if reported but not controlled. Score 0 if unreported/uncontrolled.	Road setting (adjacent habitat type, surrounding landscape)
Assessment Bias				
2.0 Is the study consistent in its sampling method(s) between the intervention and comparator(s)?	**YES** or **NO** or **UNCLEAR** *Where "YES" gives the study a score of "1";*	For example, prey measured similarly for both conditions (e.g., owner logs both	Collision data collected consistently for all windows (same observers, frequency).	Collision data collected consistently for all roads/road

	***Where UNCLEAR**, treat as NO; and "NO" gives the study a score of "0"*	intervention and control cats).		segments (same observers, frequency).
2.1 Does the study provide a measured quantitative outcome between the intervention and comparator?	**YES or NO** *In case of a qualitative outcome being provided, score of 0 is given 0.5 if a quantitative approximation is given only*	Quantitative counts of birds caught per cat or per time period. Qualitative or indirect estimates get 0. Score 0 if for whatever reason not all birds are included in the final outcome.	Quantitative counts of collisions or avoidance.	Quantitative counts of collisions or avoidance.
Performance Bias				
3.0 Is the study free of extenuating circumstances	**YES** or **NO** or **UNCLEAR**			

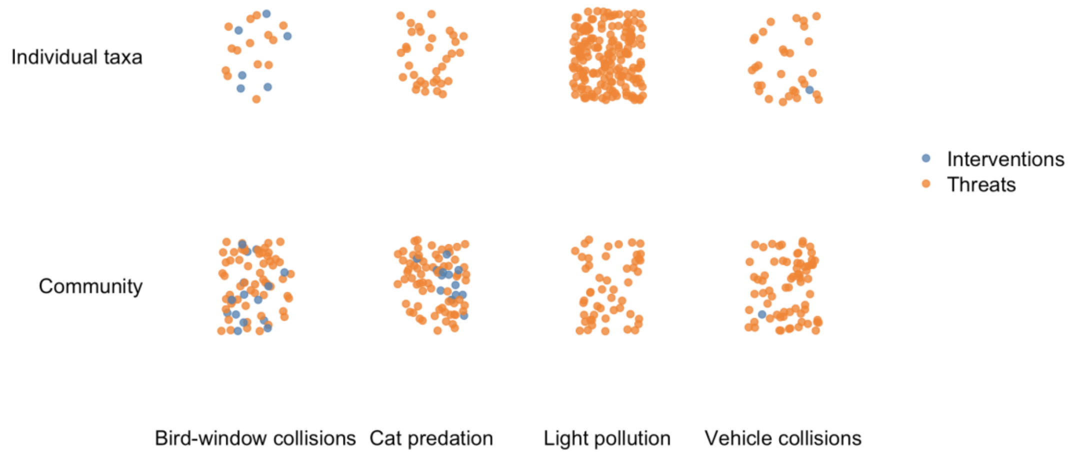
following initiation of the study, or otherwise appropriately controlled or addressed? *(i.e.., severe confounding factors such as weather events, unplanned human alterations; after study initiation)*	***If UNCLEAR**, treat as NO* ***If NO,** describe extenuating circumstance (e.g., severe weather event, demolition of building shortening timespan of intervention tested).* *Where "YES" gives the study a score of "1" and "NO" gives the study a score of "0"*			
3.1 Do the study settings of the intervention and comparator(s) match?	**YES** or **NO** or **UNCLEAR**	Intervention and control cats should have similar housing,	Intervention and control windows/buildings should be similar in	Intervention and control road settings should be

(i.e., do the comparator and intervention sites have similar characteristics; otherwise, were important confounding variables controlled by using randomization?) (risk of confounding biases)	*Where "YES" gives the study a score of "1",* ***Where UNCLEAR****, treat as NO; and "NO" gives the study a score of "0".*	neighborhood, and outdoor conditions; differences should be dealt with via randomization or statistically.	exposure, surroundings, and season; differences should be dealt with via randomization or statistically.	similar (adjacent habitat type, surrounding landscape)
Attrition Bias				
4.1. (For cat predation only) Were all cats originally enrolled in the study accounted for in the outcome data, or were missing data properly addressed?	**YES** or **NO** or **UNCLEAR** *Where "YES" gives the study a score of "1",* ***Where UNCLEAR****, treat as NO; and "NO" gives the study a score of "0".*	Studies should describe whether cats had to be withdrawn during trials and what the resulting final sample sizes were for treatment and control	NA	NA

	groups. Studies should have appropriate statistical adjustments to deal with missing data.



Supplementary Material Figure S1. Choropleth map showing the geographic distribution of 533 studies in a global evidence synthesis of peer-reviewed literature on key urban threats to bird populations and their interventions. Darker blue shading represents regions with a higher density of studies.



Supplementary Material Figure S2. Distribution of 533 papers based on whether research targeted individual taxa or bird communities. Each point represents an individual paper and is colored based on whether the study was categorized as a threat-based paper or an intervention-based paper.

Supplementary Material Table S5. Summary of vote-count of 11 types of cat predation interventions across 13 papers showing the percentage of studies reporting statistically significant positive results (i.e., a significant reduction in birds brought home by cats following intervention), non-significant results, and cases where statistical significance is not provided. Statistical significance is considered at $p < 0.05$.

Type of Intervention	# of Papers	# of Studies	Statistically significant positive results (%)	Statistically non-significant results (%)	Statistical significance not provided (%)

Rainbow Birdsbesafe	5	6	100	0	0
Mixed Interventions	2	3	66.67	0	33.33
CatBib	1	2	100	0	0
Collar with Sonar Device	2	2	100	0	0
High-protein food	1	1	100	0	0
Collar with Bell	5	5	60	40	0
Red Birdbesafe	1	1	0	100	0
Yellow Birdbesafe	1	1	0	100	0
Puzzle feeder	1	1	0	100	0
Object play	1	1	0	100	0
Predator Removal	1	1	0	100	0

Supplementary Material Table S6. Pooled effect estimates from multi-level mixed effects model with Hedges' g effect of outcomes of collar-based interventions to reduce cat predation from 13 studies with intervention type as a moderator. The number of asterisks (*) indicates the degree of significance (i.e., "***" corresponds to $p < 0.001$, "**" corresponds to $p < 0.01$, and "*" corresponds to $p < 0.05$).

Intervention Type	Estimate ± SE	p-value
Rainbow BBS	0.46 ± 0.13	<0.05***
Catbib with Bell	0.72 ± 0.23	<0.05**
Bell	0.41 ± 0.15	<0.05**
Sonar Device	0.40 ± 0.20	<0.05*
Ranbow BBS with Bell	0.19 ± 0.37	0.61
Red BBS	0.15 ± 0.26	0.58
Yellow BBS	–0.13 ± 0.34	0.69

Supplementary Material Table S7. Summary vote-count of effectiveness of 15 types of bird-window collision interventions across 20 papers showing the percentage of studies reporting statistically significant positive results (i.e., a significant reduction in recorded bird-window collisions following intervention), non-significant results, and cases where statistical significance is not provided. Statistical significance is considered at $p < 0.05$.

Type of Intervention	# of Papers	# of Field Studies	# of Tunnel Test Studies	Statistically Significant Positive Results (%)	Statistically Non-significant Results (%)	Significance Not Provided (%)
Circular decals	9	8	2	90	0	10

UV reflective coating or film	8	7	5	91.67	8.33	0
Horizontal stripes	4	1	4	100	0	0
Vertical stripes	4	1	5	83.33	16.67	0
Miscellaneous window artwork and artifacts	4	3	4	57.14	42.86	0
Fritted glass (circular)	3	3	0	66.67	33.33	0
Grid	3	0	8	37.5	62.5	0
Bird-of-prey decals	3	3	2		80	20
Vertical shades	1	1		100	0	0
Square decals	1	0	2	100		0
Orange film	1		2	50	50	0
Miscellaneous objects placed near window	1	3	3	16.67	83.33	0
UV absorbing film	1	12		16.67		83.33

Fritted glass (vertical)	1	1	0	0	0	100
Lighting conditions	1		2	50	50	0

Supplementary Material Table S8. Pooled effect estimates from multi-level mixed effects model with odds ratio effect on outcomes of window treatments on bird-window collisions from 36 studies with intervention type as a moderator. "Other" refers to non-geometric coral design, single UV maple leaf in center, UV maple leaf rows, monofilament covered feathers.

Intervention Type	**Estimate ± SE**	**p-value**
Vertical stripes	-3.92 ± 0.57	<.0001
Circle or square decals	-3.80 ± 0.60	<.0001
Horizontal stripes	-2.15 ± 0.56	0.0001
Other	-2.04 ± 0.63	0.0013
UV reflecting film	-1.35 ± 0.56	0.0166
Fritted glass	-1.38 ± 0.59	0.0199
Orange film	-0.55 ± 1.03	0.5895
Grid	0.74 ± 0.62	0.2322

Supplementary Material Table S9. Results from tests of overall heterogeneity from 13 effect estimates across seven studies in a meta-analysis of interventions to reduce predation of birds by cats.

Test	**Statistic**
QM (df, p- value)	32.39 (df = 7), $p < 0.001$
QE (df, p-value)	7.41 (df = 6), $p = 0.284$
τ^2 (between-study variance)	0.0156
τ^2 (within-study variance)	0.000
I^2	13.93%

Supplementary Material Table S10. Results from tests of heterogeneity within each intervention type from meta-analysis of interventions to reduce predation of birds by cats. Heterogeneity statistics are only reported for intervention types with more than one effect estimate.

Intervention type	**# of effect estimates**	**QE**	τ^2	I^2 **(%)**
Bell	3	3.58 ($p = 0.167$)	0.059	46.26
Rainbow Birdbesafe™	5	3.84 ($p = 0.429$)	0.000	0.01

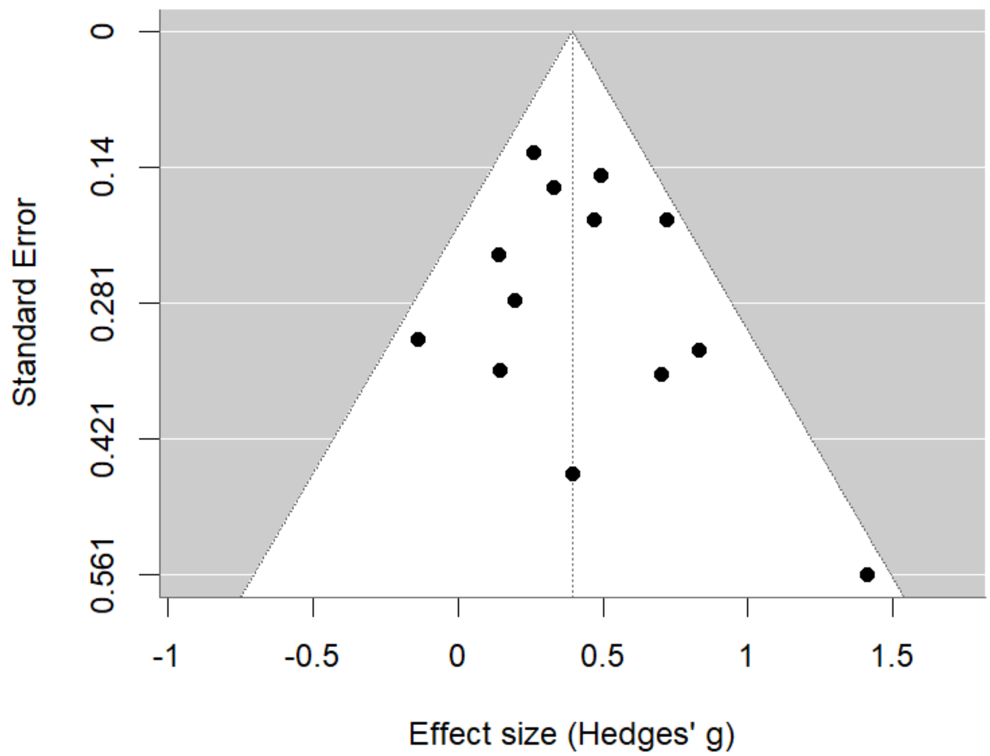
Supplementary Material Table S11. Results from tests of overall heterogeneity from 36 effect estimates across eight studies in a meta-analysis of interventions to reduce bird-window collisions.

Test	**Statistic**

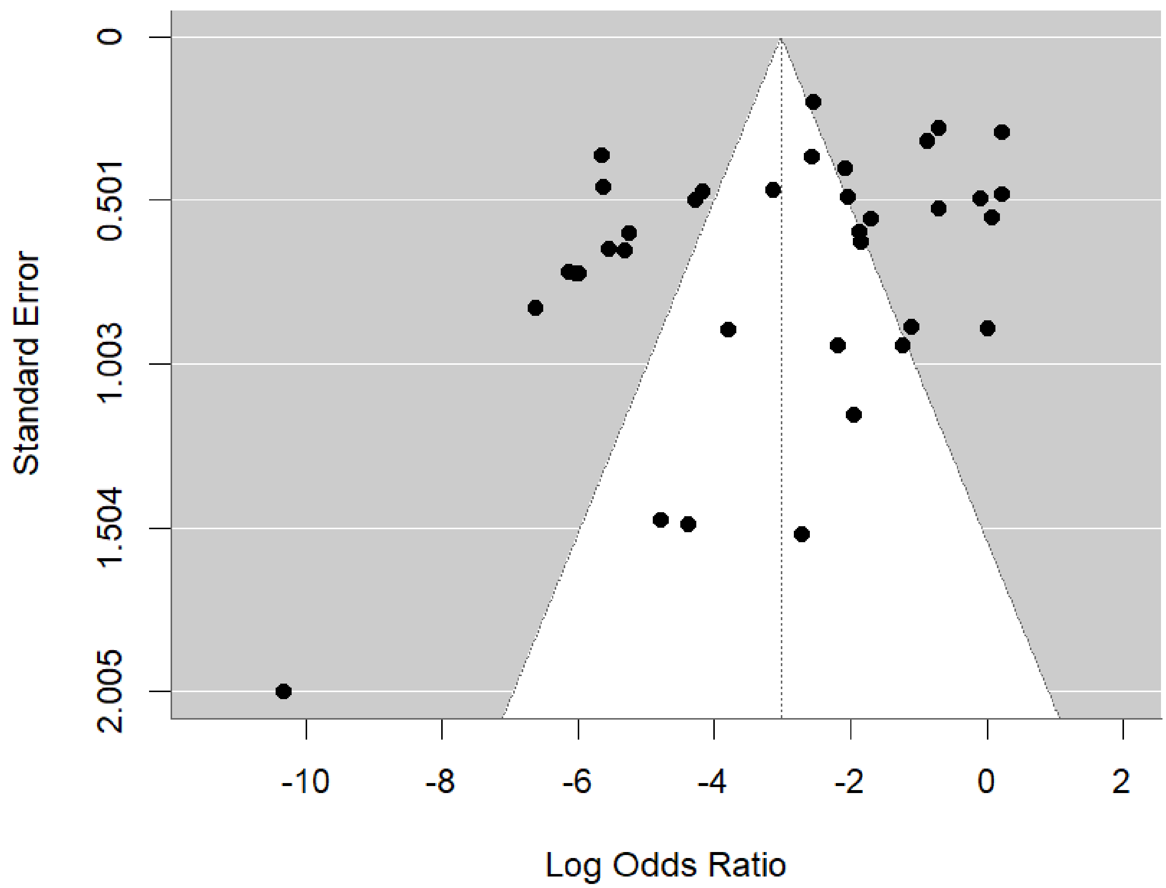
QM	255.77 (df = 8), p < 0.001
QE	340.59 (df = 28), p < 0.001
τ^2 (between-study variance)	1.876
τ^2 (within-study variance)	2.721
I^2	74.96%

Supplementary Material Table S12. Results from heterogeneity tests within each of the eight intervention types from meta-analysis of interventions to reduce bird-window collisions.

Intervention Type	**# of effect estimates**	**QE**	**τ^2**	**I^2 (%)**
Vertical Stripes	6	87.82 (p < 0.001)	4.341	94.31
Circle or Square Decals	7	37.70 (p < 0.001)	6.141	84.08
Horizontal Stripes	4	20.58 (p < 0.001)	1.759	85.42
UV Reflecting Film	8	25.06 (p < 0.001)	0.806	72.07
Fritted Glass	3	42.12 (p < 0.001)	5.529	95.25
Orange Film	2	2.87 (p = 0.090)	1.576	65.13
Grid	2	64.14 (p < 0.001)	19.288	98.44
Other	4	60.31 (< 0.001)	8.585	95.02



Supplementary Material Figure S3. Relationship between effect estimates and standard error to assess publication bias in meta-analysis of interventions to reduce cat predation of birds. Dashed line is the summary mean-weighted effect estimate from meta-analysis across 13 effect estimates from seven studies. Egger's test result was significant ($z = 0.83$, $p = 0.41$), suggesting there is no significant funnel plot asymmetry or publication bias. Results should be interpreted with caution due to the small sample size.



Supplementary Material Figure S4. Relationship between effect estimates and standard error to assess publication bias in meta-analysis of interventions to reduce bird-window collisions. Dashed line is the summary mean-weighted effect size from meta-analysis across 36 effect estimates from eight studies. Egger's test result was significant (z = -2.27, p = 0.02), suggesting there is significant asymmetry. Specifically, studies with higher standard errors tended to report more negative effect estimates (i.e., greater effectiveness of an intervention). Results should be interpreted with caution due to the small sample size.