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REVIEW

Methods to mitigate human–wildlife conflicts involving common mesopredators: a meta-analysis

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Abstract

Conflicts between humans and mesopredators are frequent and widespread. Over the last decades, conflicts have led to the development and application of different mitigation methods to diminish the costs and damage caused by such conflicts. We conducted a systematic literature search and meta-analysis to assess the influence of different mitigation methods on 3 common nuisance species: raccoons (*Procyon lotor*), red foxes (*Vulpes vulpes*), and striped skunks (*Mephitis mephitis*). A majority of the studies, from 1963–2022, were conducted in North America, followed by Australia and Europe. The predation of wildlife species of conservation concern by nuisance species is the main reported source of conflict in the published literature. Lethal control is the most commonly tested method and is generally effective at reducing conflicts based on the calculated effect size. Barriers have mixed effects, with electric fences and nest exclosures both being effective, whereas conventional fences seem to be less effective. Repellents mimicking predators (e.g., guard animal, predator smell) are also effective. Conditioned taste aversion is a promising approach, but no precise product or chemical has proven to be effective. Many interventions suffered from a lack of validation through experimental approach. Research on human–mesopredator conflict mitigation would benefit from repeated studies using the same methods in similar contexts, thus reducing heterogeneity in the results, and by testing new and innovative methods.

KEYWORDS

management, *Mephitis mephitis*, mitigation, *Procyon lotor*, raccoon, red fox, striped skunk, *Vulpes vulpes*

In the era of the Anthropocene, coexistence between humans and wildlife inevitably leads to interactions. They vary in scale and intensity, and can be positive, negative, or neutral (Peterson et al. 2010, Prescott 2011, Nyhus 2016, Lozano et al. 2019, Hill 2021). The term human–wildlife conflict (HWC) is used when there is a real or perceived threat to humans or their interests, leading to negative effects on humans and frequent retaliation against fauna (International Union for Conservation of Nature [IUCN] 2020, Su et al. 2022). Human–wildlife conflicts often prompt the introduction of mitigation measures, which seek to reduce, contain, or remove damages (Messmer 2000, Marchini 2014, Conover and Conover 2022).

Increasing human tolerance to interactions with wildlife would be an important first step to deal with HWCs but is either underemphasized or overlooked completely (Messmer 2000, Treves et al. 2009, Curtis and Hadidian 2010, Baruch-Mordo et al. 2011, Dubois et al. 2017). Historically, lethal solutions have been put forward to mitigate HWCs (Treves and Naughton-Treves 2005, McManus et al. 2015), and their use persists today. Lethal methods have the advantage of directly decreasing the size of the problematic population, thus reducing the risk of damage in the short-term (Drake 2014). A survey among ranchers in Wyoming, USA, demonstrated that lethal methods were perceived to be more effective than nonlethal ones against a range of predators, including foxes (Scasta et al. 2017). They have also been reported to be more simple and cheaper to implement, but this is not always the case (McManus et al. 2015). Lethal methods are often effective and yield concrete welfare benefits for remaining animals (Hampton et al. 2018). Despite its extensive use, lethal management has been increasingly unpopular and controversial with the public and is currently under regulatory oversight and ethical considerations (Liss 1997, Reiter et al. 1999, Dubois et al. 2017, Boulet et al. 2021, Conover and Conover 2022). Lethal control remains more acceptable against mesopredators compared to more charismatic megafauna (Glas 2016) and is more acceptable toward introduced or pest species (van Eeden et al. 2020). Acceptability also differs by the demographics and attitudes toward wildlife of the person surveyed (van Eeden et al. 2019, Baker et al. 2020).

For social acceptability and ethical considerations, nonlethal management approaches should be considered if not currently prioritized in mitigating human–wildlife conflicts (Shivik 2006, Drake 2014). Even for the control of large predators, nonlethal approaches are favored by the public, from rural to urban areas in Ohio, USA (Stanger et al. 2022). Such methods are novel and largely untested, or established but understudied, and their effectiveness needs to be compared to lethal methods in a scientifically sound manner (Sillero-Zubiri et al. 2007). Nonlethal methods include physical barriers (i.e., any structure that can impede access to a particular place or object [fences, exclosures]), aversive and disruptive stimuli, guard animals, and conditioned taste aversion (CTA; Treves and Karanth 2003, Baker et al. 2007*a*). Apart from barriers, nonlethal methods are often based on cognitive mechanisms such as learning, neophobia (fear of novelty), and categorization (process of classifying or differentiating cues; Greggor et al. 2014). For example, by combining food with a chemical compound resulting in a negative stimulus, CTA draws on the cognitive mechanisms of association and learning (Schulte 2016, Snijders et al. 2021). Although animal cognition is extensively studied, its applicability to wildlife management has been the subject of investigation less often.

In North America, 3 native mammalian species are often mentioned in HWCs: the common raccoon (*Procyon lotor*), the striped skunk (*Mephitis mephitis*), and the red fox (*Vulpes vulpes*; Gehrt et al. 2010, Bateman and Fleming 2012, Glas 2016). The distribution of the raccoon extends to Central America, and it was introduced in Europe and Asia, approximately 100 and 50 years ago, respectively (Lotze and Anderson 1979, Ikeda et al. 2004). The red fox was originally found in North America, Europe, North Africa, and Asia and was introduced to Australia in the nineteenth century, making it the terrestrial carnivore with the widest geographical distribution (Larivière and Pasitschniak-Arts 1996, Macdonald and Reynolds 2004). Among terrestrial vertebrate species in the United States, raccoons, striped skunks, and red foxes ranked second, third, and tenth, respectively, in the number of complaints received by the United States Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS) Wildlife Services between 2014–2021 (Cassini 2022). Those species qualify as mesopredators: a mid-ranking predator within an ecosystem (Prugh et al. 2009). More restrictive definitions only include members of the order Carnivora, weighing between 1–15 kg (Buskirk and Zielinski 2003, Gehrt and Clark 2003, Roemer et al. 2009). In addition, a mesopredator cannot self-regulate its population density, in comparison to large apex predators (Wallach et al. 2015).

Under the mesopredator release hypothesis, environmental changes, including anthropogenic effects, force large carnivores away from a territory, releasing competition and creating an expansion in density or distribution of mesopredators (Crooks and Soulé 1999, Prugh et al. 2009). This can lead to more frequent HWCs with mesopredators as they become more pervasive in an area (Curtis and Hadidian 2010). These common species are important to study because of their ecological influences as widespread keystone components of their communities (Lidicker 2015). Literature on human–carnivore conflicts is strongly biased toward large species (such as wolves, bears, and big cats), whereas the medium-sized families Mephitidae and Procyonidae are underrepresented (Lozano et al. 2019). Furthermore, we included raccoons, red foxes, and striped skunks in the same study because any mitigation method used against one could be relatively easily adapted to the others. We excluded coyotes (*Canis latrans*) from the study despite them being sometimes classified as mesopredators (Buskirk and Zielinski 2003, Prugh et al. 2009, Bateman and Fleming 2012, Glas 2016). Because of their larger size, the severity of the conflicts, and more negative human perception (Fox 2006, Curtis et al. 2007, Bateman and Fleming 2012, Elliot et al. 2016), they require mitigation methods that are not easily transferable to the 3 selected species. Furthermore, with the range contraction of wolves (*Canis lupus*) and other large carnivores in North America (Berger and Gese 2007, Ripple et al. 2014), coyotes are now functionally and ecologically apex predators in many ecosystems (Crooks and Soulé 1999, Roemer et al. 2009, Prugh et al. 2009, Wallach et al. 2015).

A lot of HWC management actions are based on a limited and informal transmission of information based on discussions with various stakeholders (e.g., trappers, pest control professionals, protected area managers). Human–wildlife conflict management is very context-dependent, so the accumulation of studies produces a corpus of data from experiments varying in terms of species, habitats, sample characteristics, research designs, analytic strategies, and sampling errors (Cooper and Hedges 2009, IUCN 2020). An ideal HWC management plan needs to select appropriate mitigation methods and tools and elaborate on their known (or unknown) effectiveness (Can 2021). Systematic surveys and meta-analyses are powerful tools to regroup and synthetize research evidence (Pullin and Stewart 2006, Koricheva et al. 2013, Pullin et al. 2013). In the past, they have covered topics such as wildlife conservation, natural resources management, animal behavior, and more recently HWCs (Inskip and Zimmermann 2009, Kansky et al. 2014, Seoraj-Pillai and Pillay 2016, Snijders et al. 2019). A systematic review is therefore important in exploring the link between mitigation methods and the animal behavioral responses to determine the efficacy of the intervention (Greggor et al. 2016).

Here, we present an analytical review of mitigation methods toward 3 common mammal mesopredators (raccoon, red fox, striped skunk). Our objectives were to survey the mitigation methods that have been tested and the context in which the studies have been conducted, obtain a general picture of their efficacy, and identify knowledge gaps.

METHODS

We first conducted a systematic literature search and then conducted a meta-analysis on a subset of selected studies (Pullin and Stewart 2006). We designed a rigorous search methodology to handle unavoidable challenges in exploring an ecologically and sociologically complex topic such as inconsistent reporting, and disparity in the methods and contexts between studies (Inskip and Zimmermann 2009, Holland et al. 2018).

Literature search

We followed the guidelines and standards for systematic reviews and maps (Haddaway et al. 2018; Review Report S1, available in Supporting Information). We gathered articles and other documents published in English and French in Web of Science, ProQuest, bioRxiv, and Google Scholar. In addition, we consulted 35 websites related to wildlife conservation and management (Reference List S1, available in Supporting Information). In search engines, we combined 2 keywords: 1 corresponding to the focus species (common or scientific name) and 1 corresponding to the topic of interest, among the following terms: conflict, control, habituation, mitigation, nuisance, persecution, pest, and problem. Additionally, we analyzed the reference sections of retrieved articles, allowing us to incorporate additional articles in our study. We first screened the retrieved literature based on their title, then the abstract, and finally the full text. Inclusion was conservative, meaning that when in doubt, we included an article to be reviewed in the next stage. An article containing quantitative data on a method's effectiveness was eligible for inclusion. We included studies with before–after, control–impact or a combined research design, and that explicitly stated the studied population, intervention, comparison, and outcome (Berger-Tal et al. 2019). Causes of exclusion at the full-text screening stage included incompatible goal of study, wrong species or context, issue in research design, missing methodological details, unreported sample size, inadequate comparators, and not reporting new data.

Data extraction and synthesis

We read selected studies and coded extracted data to manage the discrepancy in measures from one study to another (Table 1). We assigned each study to a conflict type: wildlife killing (when the mesopredator preys are species of conservation concerns, which conservationists are monitoring or actively managing for their protection), livestock killing, disease spread, vehicle collision, annoyance, or multiple concurrent conflicts. We did not quantitatively evaluate the severity of conflicts for each publication. Instead, we described the severity using criteria reported by previous studies (Inskip and Zimmerman 2009, Seoraj-Pillai and Pillay 2016), which was quite subjective given that only limited information was provided by each study. We categorized mitigation methods in the following categories (and sub-categories within parenthesis): lethal methods (poison, shooting, traps), barriers

TABLE 1 Extracted data from selected publications after a systematic literature search on mitigation of conflicts with common mammal mesopredators worldwide (1963–2022) to describe literature on human–mesopredator conflicts, describe the context of the conflicts, report mitigation experiments, and calculate effect sizes.

Literature	Conflict	Mitigation	Effect size
Authors	Habitat	Method (main types)	Sample size
Country	Species	Method (sub-types)	Mean of control-after group
Journal (or type of publication)	Human antagonist	Experimental design	Mean of treatment-before group
Title	Severity of conflict	Response variables	Standard deviation of control-after group
Year of publication	Type of conflict	Duration of experiment	Standard deviation of treatment-before group
		Effect as reported by authors	
		Variation (%) of outcome	

(conventional fences, electric fences, exclosures), repellents (competitor signals, predator signals, sensory stimuli, guard animals), CTA (different chemical compounds), diversionary feeding, reduction of attractants, and the combination of >1 method applied simultaneously. We then recorded if these methods were reported by the authors as successful at reducing HWCs, made them worse, or had no effect. We collected metadata on a variety of aspects of the study, including bibliographical information, study year, location characteristics, target species, and intervention (Snijders et al. 2019). We calculated descriptive statistics of the metadata, allowing us to better understand the published literature on human–mesopredator conflict and its management.

The selected studies covered different contexts, species, methods, durations, and response variables. As a result, heterogeneity (confounding factors) in the data is high and raises issues of comparability. To address these concerns, we took 4 precautions: we described the different contexts and methods seen in the literature; we analyzed the data at different levels, by mitigation methods and by species; we explored the potential of publication bias and knowledge gap; and we carefully and conservatively interpreted the results.

We organized the data and determined the response variables used by the authors to test mitigation efficacy. This could reflect a direct (e.g., mesopredator density) or indirect (e.g., survival of a prey species) effect. We then calculated the mean results, the standard deviations, and sample sizes for the control and treatment.

Estimating effect sizes

To assess the effectiveness of mitigation methods, we calculated the Hedges' *d* effect size from each study (Rosenberg et al. 2013). We extracted the mean of the conflict metric when mitigation was applied (treatment, Y_t) or not (control, Y_c) and applied the following formula:

$$d = \frac{\overline{Y_t} - \overline{Y_c}}{\sqrt{\frac{(n_t - 1)s_t^2 + (n_c - 1)s_c^2}{n_t + n_c - 2}}} J$$

where, n is the sample size, s is the standard deviation, and J is a correction for small sample size.

$$J = 1 - \frac{3}{4(n_t + n_c - 2) - 1}$$

Hedges' *d* effect size ranges from −∞ to +∞. We interpreted the magnitude of effect size using the following conventional and expanded rule of thumb (Sawilowsky 2009, Cohen 2013): 0.2 is small, 0.5 is medium, 0.8 is large, 1.2 is very large, and 2.0 is huge. We interpreted the directionality (positive or negative) depending on the metric calculated in each study.

We calculated the sampling variance (v_d) as (Rosenberg et al. 2013):

$$v_d = \frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{2(n_1 + n_2)}.$$

We calculated the inverse of the variance to weight observations:

$$w_i = \frac{1}{s_i^2}$$

We used them to calculate a grand mean effect size ($\overline{\theta}$) by combining effect sizes using a random effects model (Rosenberg et al. 2013):

$$\overline{\theta} = \frac{\sum w_i \theta_i}{\sum w_i},$$

with variance

$$s_{\bar{\theta}}^2 = \frac{1}{\sum w_i}.$$

We conducted categorical meta-analyses where we treated categorical variables as random effects because we expected the true effect may vary among studies (Gurevitch and Hedges 1999, Borenstein et al. 2009). We refer to methods with a positive mean effect size and 95% confidence intervals as effective. Alternatively, a method will be considered more effective relative to another if its mean effect size is greater. After obtaining Hedges' *d* effect size values, we calculated heterogeneity to characterize the data in more details. We calculated 2 distinct relative measures:

$$Q_T = \sum w_i (\theta_i - \bar{\theta})^2$$

and

$$I^2 = \max\left[0.100 \times \frac{Q_T - (n-1)}{Q_T}\right].$$

The Q test (Q_T) assesses the heterogeneity among effect sizes, by following a chi-square distribution (Huedo-Medina et al. 2006), and the I^2 index describes the percentage of variation across studies that is due to heterogeneity rather than chance (Higgins et al. 2003) and is complementary to Q_T (Huedo-Medina et al. 2006). A significant Q_T or high I^2 suggests that there may be some additional unexamined factor influencing the effect sizes (Higgins and Thompson 2002).

We used the MetaWin software (version 3.0.7) to perform the meta-analysis calculations (Rosenberg 2022). We also assessed whether the outcome reported by the authors (i.e., was the effect of the mitigation method good, bad, mixed, or neutral) aligned with calculated effect sizes. To do this, we calculated a 1-way analysis of variance comparing effect sizes of the 4 possible outcomes. We followed up with a *post hoc* Tukey honestly significant difference test for pairwise comparisons between the outcomes reported in the publications. We conducted a linear regression between effect size and experiment duration (squared root days) to determine if long-term mitigation methods yielded greater effect sizes than short-term techniques. We used R (4.2.3; R Core Team 2023) to calculate the analysis of variance and linear regression, and set the significance level at $\alpha = 0.05$.

Assessing publication bias

We used a rank correlation test (Spearman's ρ) to determine whether there was a significant correlation between sample size and effect size, which would suggest a bias toward publication of tests with larger effects (Begg and Mazumdar 1994, Branton and Richardson 2011). We also performed a cumulative meta-analysis, ordered by year of publication (Leimu and Koricheva 2004). We randomly assigned orders to experiments published within the same paper. We also used 2 methods to estimate the number of missing studies necessary to change the results of the meta-analysis from significant to nonsignificant. We performed the trim-and-fill procedures to find unpublished results (Møller and Jennions 2001, Jennions and Møller 2002). We used 3 estimators (R_O, L_O, Q_O) and reported the 3 results (Duval and Tweedie 2000, Shi and Lin 2019). We also calculated a fail-safe number (Rosenberg method, N_+) to estimate the number of unreported non-significant studies needed to change an overall significance to non-significance (Rosenthal 1979, Rosenberg 2005, Branton and Richardson 2011). We compared N_+ to the Rosenthal (1979) rule of thumb of $5k + 10$ (k = number of studies in the meta-analysis) indicating vulnerability to publication bias. We calculated Spearman's ρ with the program R (4.2.3; R Core Team 2023) and ran the other analyses with MetaWin (Rosenberg 2022).

RESULTS

As expected, we obtained a low specificity (proportion of retrieved material judged relevant; Pullin and Stewart 2006; Figure S1, available in Supporting Information). We retained 218 experiments from 148 different published sources in the descriptive review (Reference List S2). The 3 oldest papers selected were from Balser et al. (1968), Chessness et al. (1968), and Mann (1968). There was a steady increase (from 0.5–1.43 times) in the number of papers over the decades up until the 2000s, and a plateau between the 2000s and 2010s. Scientific journals were the main source of data (129/148), followed by proceedings (7), reports (5), theses (5), patent (1), and book (1). Among peer-reviewed articles, wildlife management journals were the most common including *The Journal of Wildlife Management* (21/129), *Wildlife Society Bulletin* (11), *Wildlife Research* (11), *Biological Conservation* (10), and *Journal of Applied Ecology* (9) with all other sources representing <5 each. The United States was the most represented country in the literature (74/148; Figure 1), followed by Australia (38), the United Kingdom (11), and Canada (7).

Mesopredator–human conflicts description

The red fox was the most common subject of the studies (106/218), followed by raccoons (38) and skunks (15). An additional 59 studies looked at mitigation aimed at multiple species, including ≥2 of the species of interest. In North America, all 3 species were identified in the publications, often concomitantly (raccoons in 36 studies, striped skunks 14, red fox 12, and 58 studies with ≥1 species). In Australia, Europe, and the Middle East, all interactions were about red fox. Overall, severity levels qualified as low or moderate. Most experiments related to conflicts over wildlife killing (154), especially predation of shorebird and turtle nests. Other types of conflicts that prompted testing mitigation methods were livestock killing (19), annoyance or nuisance (6), risk of disease transmission (6), and collision with vehicles (3). In urbanized settings, material damage and annoyance were the most common form of nuisance. Some conflicts were multifaceted (7), and 22 studies did not report a specific conflict. Different types of conflicts affected all species, but foxes were involved in all livestock killing and multifaceted conflicts and were

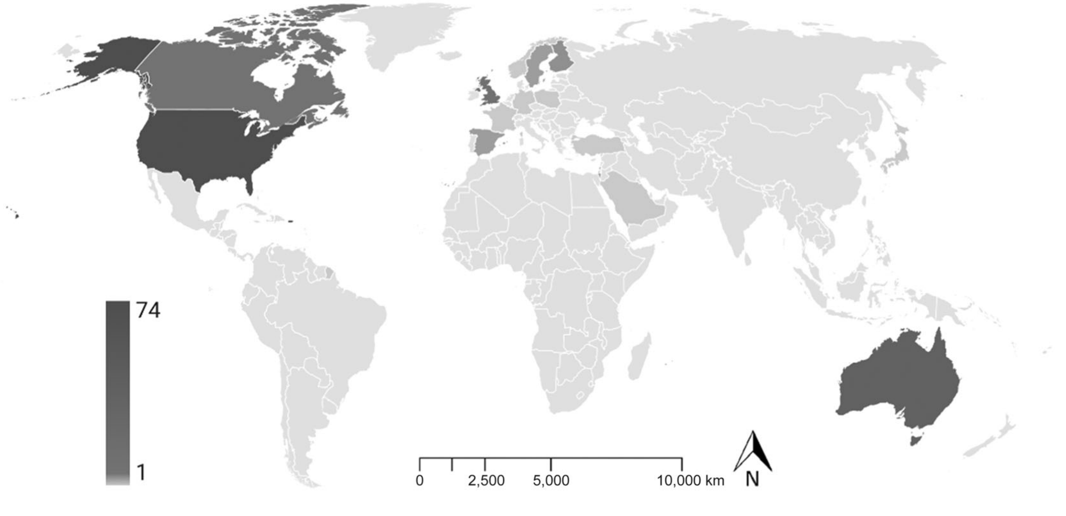

FIGURE 1 Source countries of studies found through a systematic review from 1968 to 2022 regarding mitigation methods to manage human–wildlife conflicts involving raccoons, red foxes, and striped skunks. The legend represents the number of articles per country. Scale is only true at the Equator.

never reported as a source of annoyance. Wildlife managers were the most common group of people involved in conflicts with mesopredators (156), whereas farmers and ranchers were the second most affected group (20). Other groups (<6 each) included public health managers, pest control professionals, hunters, drivers, and the general public. No specific human antagonists were identified in 20 studies. Studies were most commonly carried out in forests (62), followed in order by agricultural lands (32), seashores (32), prairies (26), wetlands (25), arid regions (12), urban and suburban areas (11), freshwater ecosystems (7), and captivity (4); in 7 studies, location was not specified.

Mitigation methods

A wide range of mitigation methods has been tested, with lethal methods representing 112 studies. The relative number of lethal method evaluations remained between 36% and 86% every decade up until the 2020s. The other represented mitigation methods were barriers (36), repellents (26), CTA (19), and diversionary feeding (9). Most studies (121) collected data ≥1 year from the start of the experiment. Very few (6) tested immediate effects (<1 day). On average, experiments and the monitoring of effects lasted slightly >3 years. A majority (58%) of the studies measured mitigation effects (response variable) through indirect measures such as nest success, prey population size, and predation rates. Most experiments were designed as control–impact (122), others being before–after (38) or the combination of both designs (43). A remaining 15 studies did not provide information on the study design or involved another type of study (e.g., modeling).

Effectiveness of interventions

We included 137 experiments in the meta-analysis, from 88 distinct publications. Mean global effect size (ES) was 1.019 (95% CI = 0.830–1.209), which is a large effect. Heterogeneity measures were Q_T = 213.07 (df = 136, $P < 0.001$) and I^2 = 36.17%. When we pooled all species together, some mitigation methods stood out as being effective (Figure 2). Lethal methods produced a large effect size (ES = 1.161, 95% CI = 0.899–1.424; Figure 2). Exclosures over nests (ES = 1.219, 95% CI = 0.714–1.723) and electric fences (ES = 1.192, 95% CI = 0.607–1.777) seemed to be effective, whereas traditional fences were not (ES = 0.224, 95% CI = −0.587–1.034). Guard animals (ES = 1.983, 95% CI = 0.132–3.834) and predator mimics (ES = 1.415, 95% CI = 0.356–2.473) were very efficient methods to repel mesopredators, whereas competitor smell (ES = −0.934, 95% CI = −2.457–0.590) and lights (ES = −0.105, 95% CI = −2.312–2.103) were not. Conditioned taste aversion was effective (ES = 0.849, 95% CI = 0.262–1.436), but no single product was sufficiently tested to prove to be a good option. Diversionary feeding (ES = 0.387, 95% CI = −0.556–1.329), reduction of attractants (ES = 1.437, 95% CI = −0.650–3.524), and the combination of >1 method (ES = 1.242, 95% CI = −0.480–2.964) all had non-significant results. Other mitigation methods that were reported in the literature but were not included in the meta-analysis (e.g., not tested, not adequately reported, insufficient sample size) are field borders, sensory-based repellents, fertility control, human presence, and other combinations of different methods.

An analysis by species showed that mitigation methods tended to be successful against raccoons (ES = 1.213, 95% CI = 0.712–1.715, n = 20) and red foxes (ES = 1.138, 95% CI = 0.852–1.425, n = 65). Lethal methods and repellents showed very large effect sizes against raccoons, unlike barriers and CTA (Table 2). Barriers, diversionary feeding, reduction of attractants, and repellents did not show significant effect size against red foxes; on the other hand, CTA and lethal methods (more precisely the use of poison baits) had very large effect sizes (Table 2). There have been fewer experiments conducted with skunks, and there was no indication that mitigation methods have been successful (ES = 0.128, 95% CI = −0.696–0.951, n = 8). The efficacy of mitigation also differed depending on the type of conflict (Table 3).

When considering the effect sizes, 75% of study results were positive, 14% neutral, and 11% negative. Reported outcomes were mostly positive (62% of experiments), while a third (33%) of the studies reported no

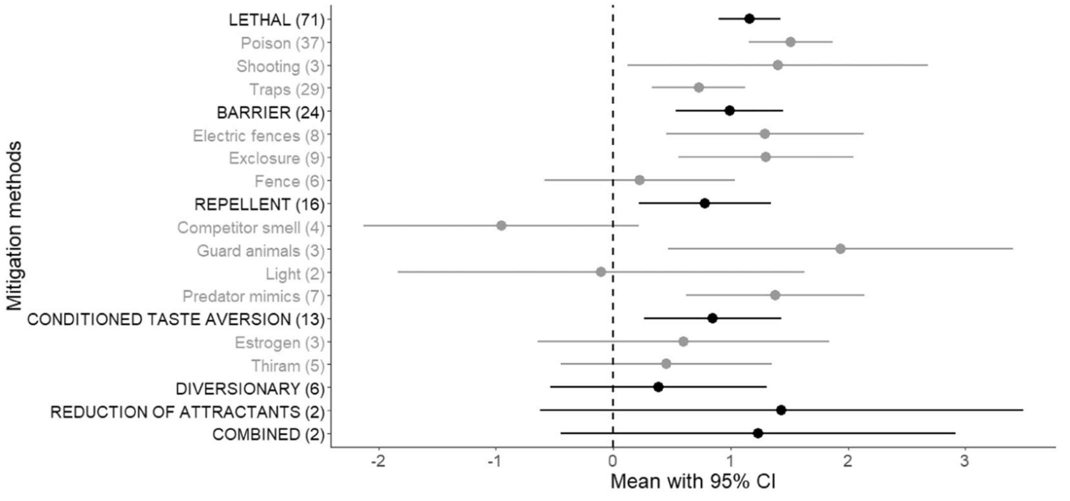

FIGURE 2 Effect sizes (mean with 95% CI) by types (black) and sub-types (if $n > 1$; grey) of mitigation methods against human–wildlife conflicts involving raccoons, red foxes, and striped skunks, following a meta-analysis covering 1963–2022. The sample size is within the parenthesis next to the methods.

effect or mixed results of mitigation methods, and 5% obtained worse results following mitigation actions. The relationship between mean effect size and the reported outcome was very strong ($F_{3,127} = 23.68$, $P < 0.001$): better (ES = 1.618, 95% CI = 1.418–1.817, n = 82), mixed (ES = 0.750, 95% CI = 0.189–1.311, n = 11), none (ES = 0.037, 95% CI = −0.264–0.337, n = 33), and worse (ES = −1.494, 95% CI = −2.266–−0.722, n = 6). Most pairwise comparisons showed moderate to very strong evidence that they differed, except for better versus mixed (P = 0.059) and mixed versus none (P = 0.400), which showed moderate to no evidence. There were little to no evidence of a relation between experiment duration and effect size ($F_{1,123} = 0.05$, $P = 0.826$; Figure 3). Direct (ES = 0.956, 95% CI = 0.646–1.266, n = 48) and indirect (ES = 1.053, 95% CI = 0.873–1.288, n = 89) measures yielded similar effect sizes.

Publication bias

There is strong evidence that studies with larger effect sizes were more likely to be published than those with smaller effect sizes (Spearman's $\rho = 0.32$, $P < 0.001$; Koricheva et al. 2013). In the cumulative analysis, we attained a significant and positive effect size (the 95% CI was >0) starting at the combination of 8 studies (published by 1972). The global effect size reached a very high level (>1) and remained high by the 79th study (published in 2008). The trim-and-fill method found missing studies (n = 2) with only 1 (R_0) of the 3 calculated estimators, reducing the mean effect size to 0.956 (95% CI = 0.760–1.152). The fail-safe number N_+ = 2,448 was higher than the threshold set at 655, indicating more stable and robust results.

DISCUSSION

Lethal methods have been the focus of most of the mitigation evaluations and that they proved to be effective. Based on our results, nonlethal alternatives that also contribute to reducing conflicts include nest exclosures, electric fences, and some variations on CTA and repellents. We are still lacking data on behavioral-based mitigation, and from studies conducted in urban and suburban settings.

TABLE 2 Effect size (with 95% CI) and sample size of different types and sub-types of mitigation measures from a meta-analysis of literature investigating human–wildlife conflict of 3 common mammal mesopredators worldwide (1963–2022).

Species	Mitigation[a]	Effect size	95% CI	Sample size
Raccoon	Barriers	0.764	−0.689–2.218	3
	CTA	0.695	−0.501–1.891	4
	Estrogen	0.608	−0.935–2.150	3
	Lethal	1.323	0.398–2.248	7
	Traps	1.306	0.230–2.382	6
	Repellents	1.835	0.776–2.894	5
	Predator mimic	2.037	0.775–3.299	4
Red fox	Barriers	0.426	−0.646–1.498	6
	Exclosures	0.800	−0.755–2.354	3
	Fences	−0.143	−1.929–1.643	2
	CTA	1.195	0.349–2.042	8
	Thiram	0.081	−0.649–1.538	5
	Diversionary feeding	1.376	−0.135–2.887	3
	Lethal	1.375	0.971–1.778	38
	Poison	1.657	1.191–2.123	30
	Shooting	1.342	−0.459–3.143	2
	Traps	0.081	−0.932–1.094	6
	Reduction of attractants	1.439	−0.787–3.665	2
	Repellents	0.033	−0.976–1.043	7
	Competitor mimic	−1.404	−3.228–0.421	2
	Guard animals	1.373	−0.664–3.410	2
	Light	−0.105	−2.092–1.883	2
Striped skunk	Lethal	0.570	−0.525–1.664	3
	Traps	0.647	−0.539–1.834	2
	Repellents	−0.078	−0.947–0.790	3
	Predator mimic	0.226	−0.633–1.084	2

[a]CTA = conditioned taste aversion.

Raccoons, red foxes, and striped skunks are found in various landscapes, and their carnivorous or omnivorous diets make them important predators of other species of conservation and agricultural interest; wildlife and livestock killings are the most often reported source of conflicts in all regions of the world. Mesopredators are known to often prey on eggs from bird and turtle nests (Conover and Conover 2022). Mitigation was generally effective when the goal was to control livestock and wildlife killing, and disease spread. On the contrary, vehicle collisions, annoyance and nuisance, and complex conflicts (>1 type) were more difficult to mitigate.

TABLE 3 Effect size (with 95% CI) and sample size of mitigation efforts on different types of conflicts involving common mammal mesopredators worldwide (1963–2022).

Type of conflict	Effect size	95% CI	Sample size per type of mitigation used[a]
Annoyance	−0.347	−2.145–1.451	2 repellent
Vehicle collision	−0.057	−1.129–1.015	3 barrier
Disease spread	1.153	0.248–2.059	4 lethal 1 CTA
Livestock killing	0.939	0.137–1.740	5 repellent 2 reduction attractants 2 lethal 1 barrier
Multiple concurrent conflicts	0.657	−0.624–1.937	2 lethal 1 barrier
Wildlife killing	1.080	0.864–1.297	61 lethal 18 barrier 11 CTA 6 diversionary feeding 3 not defined 2 combined
Not defined	1.061	0.449–1.673	9 repellent 2 lethal 1 CTA

[a]CTA = conditioned taste aversion.

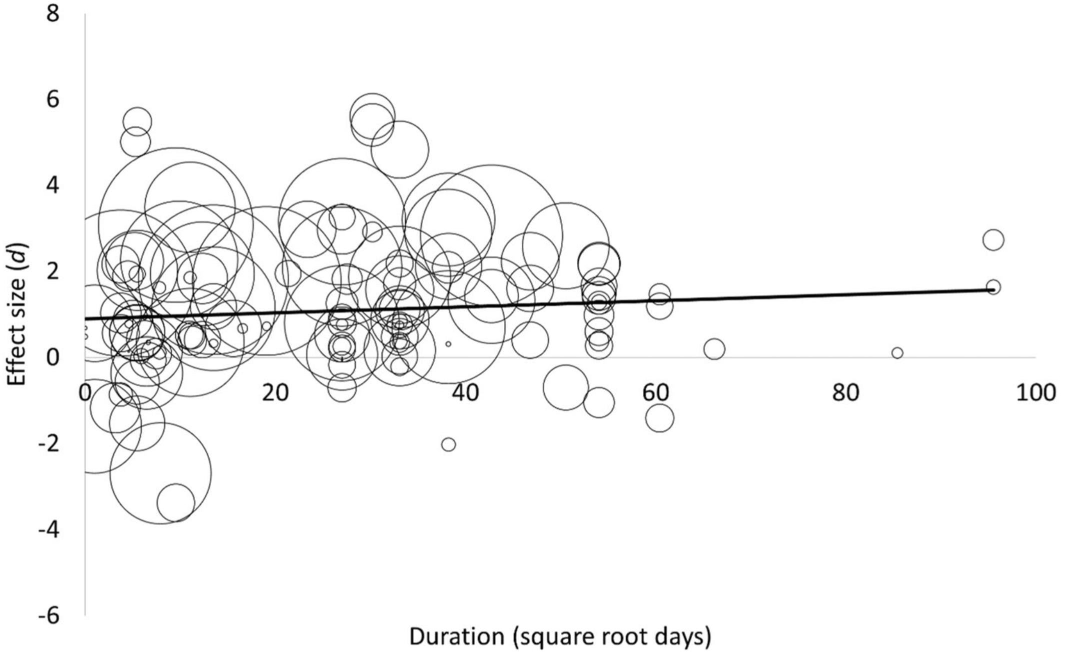

FIGURE 3 Scatterplot, including trendline, of effect size (d) versus total study duration (square root days) of mitigation methods against human–wildlife conflicts involving red foxes, raccoons, and striped skunks, following a meta-analysis covering 1963–2022. Symbol size is proportional to the variance (V_d) weight of each effect size.

Effectiveness of mitigation methods

We identified strong support for a positive effect size for mitigation measures in 74% percent of studies. This is high considering studies on large carnivores did not find most mitigation methods effective in protecting livestock (Eklund et al. 2017) and would indicate that conflicts with mesopredators are easier to manage. There was not support for a relationship between the duration of an experiment and the reported effectiveness of mitigation methods. This could be explained by the nature of the target species, especially raccoons. Animals with high cognitive abilities have the potential to find a solution to circumvent an imperfect mitigation method (Blumstein 2016, Barrett et al. 2019). It is possible that long-term application, consistency, and repetitions are necessary for successful mitigation.

Combining different methods is one area where testing has not been explicit and sufficient to draw conclusions, but some propose that it might be the key to dealing with problematic animals (Madden 2004, Shivik 2006, Blackwell et al. 2016, Miller et al. 2016, Baynham-Herd et al. 2019). Our very limited sample (n = 2) of studies combining multiple methods does not allow for any conclusion on effectiveness. Multiple methods must be deployed simultaneously, must be designed and installed with a particular species in mind, and must be modified periodically to avoid habituation by target species (Treves and Karanth 2003, Baker et al. 2007*b*). A combination of techniques might also be more effective and last longer (Stringham and Robinson 2015, Miller et al. 2016). A random rotation of methods could also avoid habituation (Greggor et al. 2014), and multiple methods can account for individual behavior differences (Merrick and Koprowski 2017).

Lethal practices

Lethal management practices commonly include shooting, trapping (either immediately lethal or followed by euthanasia), and poison. Lethal methods show high efficiency in addressing HWCs involving raccoons or red foxes. They are also the most common methods used to address conflicts related to wildlife killing and disease spread, and probably influence the large positive effect sizes associated with these conflicts (Table 3). This efficiency might be limited in time, such as in the control campaign described in Rosatte et al. (2007), which saw a return to pre-control population levels after only 1 year. Baiting campaigns, especially against the red fox in Australia, and lethal trapping have relatively consistent results. Shooting for control and hunting tend to have a positive effect as well, but with more variability in the results. Controlling at the population level through lethal practices is very labor-intensive and must be maintained over the long-term (Conover and Conover 2022). On the other hand, individual-based (selective) lethal methods can be more challenging but might be more readily socially accepted (Swan et al. 2017). Although lethal methods can be effective, their social and ethical concerns should incite wildlife managers to explore nonlethal methods before implementing lethal actions. Lethal control is negatively perceived by an increasing portion of the public and warrants a conservative approach in its application (Treves and Naughton-Treves 2005). For proponents of animal rights ethics, lethal methods should not even be considered, whereas a cost-benefit analysis might make it the best option for proponents of conservation or welfare ethics (Hutchins 2007, Hampton et al. 2018), which still makes them relevant albeit unpopular.

Barriers

Two main types of barriers are used as mitigation methods: fences and exclosures. Fences are a traditional and widely used method to keep wildlife away (Breitenmoser et al. 2005, Hayward and Kerley 2009, Somers and Hayward 2012, Vantassel and Groepper 2016). The addition of electric wires is common, and Khorozyan and Waltert (2019) reported a sustained positive effect of electric fences against larger carnivore species. Exclosures, as described in the literature, are relatively small devices placed on the ground, commonly used to protect bird or turtle nests for the duration of incubation (Yerli et al. 1997, Mabee and Estelle 2000, Beaulieu et al. 2014, Stringham and Robinson 2015, Bougie et al. 2020). Our results indicate that electric fences and exclosures are more effective against mesopredators than regular fences. Electric fences should be designed to optimize efficiency based on height and tension (Tsukada et al. 2019, Honda 2022); however, there are obvious limitations to an electric fence versus a non-electric fence. Other than the increased cost, the reliability of the electrical system (e.g., faulty wires, limited battery life, insufficient solar power) can potentially reduce their efficacy. Care must be taken when considering barriers because when applied at large scales they can have unintended, negative consequences such as limiting movement of other species, disrupting daily activity and migration, causing injuries, or impending gene flow (Somers and Hayward 2012, Schell et al. 2020).

CTA

Our results indicate an overall positive effect of CTA, but this is when considering results from many different chemicals and in different contexts. The application of conditioning is typically aimed at being aversive to a unique target species and relies on using the appropriate product (Snijders et al. 2021). We therefore cannot point to an effective chemical to use with mesopredators in general or for a specific species, thus highlighting the need for more research on the subject. Nevertheless, CTA is promoted as a relevant tool to manage endangered species rehabilitation, pest or invasive species, crop-raiding, and animal tourism (Sarabian et al. 2023). Snijders et al. (2021) offer guidelines in implementing a CTA program.

Diversionary feeding

In line with our results, the review by Kubasiewicz et al. (2015) concluded that supplementary food is inconsistently taken by target species (mammals, birds); and even when taken, it does not always reduce conflicts. In the western United States, diversionary feeding was partially successful to protect duck nests using dead fish to lure skunks in Utah (Crabtree and Wolfe 1988) but inefficient against mesopredators in another experiment in North Dakota (Conover et al. 2005). A study on larger carnivores indicated that supplementary feeding even led to an increase in damage (Khorozyan and Waltert 2019). Over longer periods of time, supplemental feeding may have a counterproductive effect by increasing local population size (Conover and Conover 2022). There is also a risk of spreading disease by concentrating individuals at a feeding site (Castillo et al. 2011, Møller et al. 2014). Because of the poor success reported, the high cost, and the risk of worsening conflicts by using diversionary feeding, a thorough evaluation of the target species and context of HWC is essential if this mitigation is considered (Kubasiewicz et al. 2015, Conover and Conover 2022).

Repellents

Repellents are a very appealing method to the public because they are nonlethal and seen as humane (Liss 1997). Methods mimicking predators (smell or sound, guard animal), were more efficient than methods mimicking competitors and artificial lights, underlining that incorporating biologically relevant stimuli to the target animal might be more successful (Baker et al. 2007*b*). In a comparison of multiple methods, chemical repellents yielded the best results against larger carnivore species but with huge variability between studies (Miller et al. 2016). Chemical repellents also wear off over time and need to be reapplied (Conover and Conover 2022). The effect of repelling strategies is thought to be short-term and labor-intensive, with animals habituating (Draulans 1987, Vantassel and Groepper 2016, Khorozyan and Waltert 2019, Petracca et al. 2019, Conover and Conover 2022) or acquiring a coping mechanism through their cognition (Daniels 2016, Barrett et al. 2019). In addition, because of their conspicuous visual, olfactory, or auditory components, repellents can disturb other wildlife and people (Conover and Conover 2022).

Fear conditioning, through frightening devices, is a variation of the repellent methods, as it teaches animals to anticipate a negative consequence (aversive stimulus) by responding to a neutral stimulus (Greggor et al. 2020). The creation of a landscape of fear implies that an animal will avoid or reduce its activities in an area where perceived risks are higher (e.g., predation) and secured places within the habitat are removed (Conover and Conover 2022). Fear conditioning is difficult to implement because managers must be cautious about what associations are being taught and habituation may occur (Greggor et al. 2020). Against species with higher cognitive capacities, frightening devices that incorporate different sensory stimuli may be among the most promising nonlethal mitigation methods to test (Blumstein 2016). Some other repelling mitigation methods that were not tested within the systematic review include pyrotechnics, effigies and scarecrows, sounds, bright or flashing lights, lasers, reflectors, shock collars, fladry and flags, gas guns, drones, motion-activated devices, predator models, ultrasounds, hazing by humans, and high-pressure water sprayers (Smith et al. 2000, Baker et al. 2007*b*, Reidinger and Miller 2013, Blumstein 2016, Conover and Conover 2022). Fladry barriers seem effective against larger canids (Musiani et al. 2003, Young et al. 2019, Windell et al. 2021); therefore, this might have potential against foxes.

Reduction of attractants

Attractive signals (most often food odors) are often at the root of HWCs. The distribution of carnivores in urban and agricultural areas is closely related to anthropogenic food resources (Rivest and Bergeron 1981, Prange et al. 2004, Curtis and Hadidian 2010). Although our measure of the effect size from a single paper is imprecise, sound waste disposal appears to be very effective in reducing conflicts with the red fox (Bino et al. 2010). Generally, feeding wildlife poses high risks of causing conflicts and should be avoided in most cases (Dubois and Fraser 2013, Griffin and Ciuti 2023). Management already integrates this principle in some contexts (national parks, campgrounds, cities), but more research is required to validate this approach.

Other potential methods

Other mitigation methods were not included in our meta-analysis because of a lack of published studies evaluating them, such as fertility control (Ransom et al. 2014), evolutionary traps attracting a target species to a fitness-negative resource or situation, thus reducing survival or reproductive success (Robertson et al. 2017), chemical camouflage by covering a naturally attractive odor with non-rewarding odors (Selonen et al. 2022), or translocation (Massei et al. 2010).

Because some methods such as barriers and population reduction measures (e.g., trapping and poison-baiting campaign) might have far-reaching and unintended consequences, a targeted approach towards problematic individuals (selective management, profiling) might be sufficient and is increasingly favored (Sillero-Zubiri et al. 2007, Curtis and Hadidian 2010, Swan et al. 2017, Barrett et al. 2019, Conover and Conover 2022). For innovative species or individuals, there is a risk that mitigation efforts create novel challenges and only provide a temporary solution (Barrett et al. 2019). The integration of cognition in developing innovative mitigation methods is needed and could be promising (Greggor et al. 2020).

Improved reporting

Good data analysis and reporting is dependent on properly conducted studies and experiments (Reddiex and Forsyth 2006, Warburton and Norton 2010). In our meta-analysis, we had to exclude 62% of the studies at the full-text screening level, mostly because of issues with the study design, choice of comparative treatments, and goal of the study. These are missed opportunities to learn, what Warburton and Norton (2010) called a failure to increase knowledge and achieve outcomes. The literature on the mitigation of human–mesopredator conflicts has increased over time and will likely increase in the coming years as seen in the HWC literature in general (Su et al. 2022). Wildlife management publications remain favored scientific outlets to evaluate and report management practices and techniques; however, the literature still lacks in its diversity of contexts studied. Although a variety of landscapes are covered in the literature, research in urban settings is underrepresented considering that mesopredators are strongly associated with cities (Prange et al. 2004, Bateman and Fleming 2012, Drake 2014, Barrett et al. 2019, Schell et al. 2020). Additionally, most studies come from North America, Australia, and a few European countries. Red foxes and raccoons are found in numerous countries as native and introduced species (Lotze and Anderson 1979, Larivière and Pasitschniak-Arts 1996, Hohmann et al. 2002, Ikeda et al. 2004, Stope 2023). This could be due to a language barrier, but searching French literature did not contribute any additional studies to the meta-analysis data set. A single thesis from Québec (Bélanger-Smith 2014) and 1 article from France (Lieury et al. 2015) were published in English.

Heterogeneity measures suggest that there is substantial heterogeneity and that all studies do not share a common effect size. This level of heterogeneity makes it more difficult to draw overall conclusions (Higgins and Thompson 2002), which is expected given the variety of species, contexts, and methods used in the analyses. Measures of robustness against publication bias (trim-and-fill method and fail-safe number) do not indicate vulnerability. On the other hand, we believe that the early positive effect of mitigation measures, as reported by the cumulative meta-analysis, is explained by a bias of publishing highly successful methods. It is essential to publish unsuccessful methods and the reason why these methods were unsuccessful (Dubois 2019). A meta-analysis on the effectiveness of road-kill mitigation also showed a publication bias toward effectiveness in peer-reviewed publications (Rytwinski et al. 2016). Transparency (by sharing inefficient or failed mitigation experiments and attempts) and more transdisciplinary approaches will contribute to finding solutions to HWCs (König et al. 2020). As in many other disciplines, we highlight the importance to publish results in easily accessible repositories, such as scientific publications. On the other hand, pest control specialists and wildlife managers might not always be able to conduct in-depth research or have access to scholarly publications; therefore, great efforts should be deployed to broadcast relevant results and assist with integrating supported mitigation methods (Haddaway et al. 2017). In relation to the meta-analysis, complex experimental designs and data analyses from more recent papers make the extraction and interpretation of data more difficult. Complex models with multiple covariables complicate the extraction of means and standard deviations from control and experimental samples necessary to calculate effect size.

MANAGEMENT IMPLICATIONS

Human–wildlife conflicts are complex and not easy to solve, and a poorly designed intervention can make matters worse. There is no magic bullet to resolve HWC, and a single technique cannot be expected to work in all situations. Mitigation methods need to be chosen based on the species involved, the environment within which it exists, and the type of conflict. In many cases, highly technical interventions are not practical within the socioeconomic constraints of developing countries or rural communities, but we demonstrate that rather simple and accessible methods can be efficient. The integration of more animal behavior and cognition studies has the potential to lead to more targeted and efficient mitigation methods, and steer away from lethal interventions. Successful mitigation methods should facilitate respectful engagement with wildlife by considering a species' ecological requirements, behavior, and preferences to find a common solution to conflicts.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

The work summarized in this manuscript did not analyze new data collected from studies of wildlife or humans.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request. A list of the primary sources of data is available in the supplementary material of this article.

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