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Canid livestock predation research has become more robust, but gaps remain

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ABSTRACT

Livestock have been and continue to be an important part of the agricultural landscape in North America. Research on how to mitigate livestock predation by North American carnivores developed quickly during the 20th century. We collected information on 75 field-based experiments published since 1970 that evaluated strategies to mitigate livestock predation by wolves and coyotes. Collected research came from journal articles and grey literature, and we identified 22 mitigation strategies. We developed a 'robustness index' to compare each experiment based on its empirical design, temporal/spatial coverage, and sample size. We found the robustness index values increased over time, particularly for lethal mitigation strategies. Overall robustness of research on lethal mitigation strategies was similar to the robustness of research on non-lethal mitigation strategies. Some strategies were not well evaluated as 12 of the 22 mitigation strategies were evaluated only once or twice; some common lethal mitigation strategies (e.g., shooting) were not formally evaluated until the 1990s. We identified some robust assessments of mitigation strategies that reported positive effects (e.g., predator sterilization, protection llamas). In some cases, these were the only evaluation or the only robust evaluation of a strategy. In the few cases where there were multiple robust assessments for a single strategy, the outcomes were inconsistent. No strategies evaluated more than once had consistently high robustness index values and positive outcomes. Importantly, older practices based on less robust research should be re-evaluated or discarded.

1. Introduction

Wolves (*Canis lupus*) and coyotes (*Canis latrans*) have been persecuted in Canada and the United States (US) since European arrival due to their propensity to prey on livestock, particularly cattle and sheep (Fogleman, 1989). The issue of predation in livestock production has persisted with upwards of 16% of calf deaths attributable to predation on some US operations (USDA, 2017). Although coyotes are now responsible for the largest percentage of cattle and calf predation in the US, campaigns to kill wolves to reduce their

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impact on livestock were common for centuries (Fogleman, 1989; USDA, 2017). A broader push for co-existence with predators began after the 1950s' environmental movement and changing sentiments towards some predators led to legislative changes that acknowledged the ecological importance of these species. Examples include the 1973 Wildlife Act in Canada and the Endangered Species Act (ESA) in the US that aimed to protect the habitat of at-risk species. Similarly, restrictions on the use of poison on federal lands reduced the ability of managers to lethally control predators, particularly coyotes and wolves (van Eeden et al., 2018a). Coyotes have always been more difficult to extirpate than wolves due to the coyote's resiliency and adaptability; thus, only wolves became endangered and, subsequently, protected in the continental US while coyotes have continued to be seen as pests and killed regularly in many areas (Fox and Papouchis, 2005; Johnson et al., 2001; Macdonald and Sillero-Zubiri, 2004).

Contemporary wildlife management decisions in North America are expected to be based on scientific evidence (Kadykalo et al., 2021; Organ et al., 2012) balanced with ethical considerations (Bennett et al., 2017). The reduced ability to conduct lethal predator control due to US and Canadian legislative changes (c1970s) spawned a need for predator management research (van Eeden et al., 2018a). Funding was provided by the government in the US to identify which traditional lethal strategies (e.g., shooting, poisoning) and alternative non-lethal strategies (e.g., livestock protection animals) effectively reduced livestock predation (Fagerstone and Keirn, 2012).

Several reviews on managing various predator species in various locales have been published in the last decade. The general consensus has been that there is a lack of high-quality experimental evidence for managing livestock predation (e.g., Eklund et al., 2017; Lennox et al., 2018; Treves et al., 2016; van Eeden et al., 2018b). Notably, this problem goes beyond livestock predation as it has been identified in ecology work more broadly with impacts on the reliability of conclusions (Christie et al., 2020, 2019). Some reviews of livestock predation research have been broad in what predator species and locations are the focus (Eklund et al., 2017; Khorozyan, 2022; Miller et al., 2016; Moreira-Arce et al., 2018). For instance, Miller et al. (2016) included 16 predator species and van Eeden et al. (2018a) included research conducted in any region of the world. In comparison, some reviews have focused on specific predator species, such as bears (Khorozyan and Waltert, 2020), or particular geographic regions, such as North America and Europe (Treves et al., 2016). Few reviews have simultaneously focused on specific predator species and geographic regions.

The review reported here stands apart from many other reviews as we use narrow topic (i.e., livestock predations), species (i.e., coyotes, wolves) and geographic (i.e., Canada, United States) foci. We analyzed which wolf and coyote livestock predation management strategies were experimentally evaluated from 1970 onwards, including whether those evaluations used 'robust' experimental designs and can be considered successful. A robust design allows for more confidence in whether a research outcome (e.g., changes in livestock losses) is attributable to a management strategy or to other factors, such as environmental variability or chance (Christie et al., 2019; Graham et al., 2005; Kedron et al., 2021; Muhly et al., 2010; Plotsky et al., 2022). We created an index to function as a hypothesized estimator of robustness that included: study length, number of locations tested, the spatial extent of those locations, and experimental design (i.e., controlled versus non-controlled). The political and social changes around 1970 led to increased interest in effective predation management strategies. The initial research after the legislative changes may have had important influences on subsequent management and policy. With this in mind, we believe it is important to know if this earlier research was reported as being successful and whether it used robust methods compared to later research. Our review and analysis aimed to answer the following questions: 1) What canid mitigation strategies were experimentally evaluated between 1970 and 2018?; 2) Which strategies have been evaluated the most?; 3) What was the temporal distribution of the research across the five decades?; 4) Did the robustness of those evaluations change over time?; 5) Were those strategies successful and was success related to robustness?

2. Materials and methods

We collected documents describing evaluations of mitigation strategies used to ameliorate livestock predation by wolves and coyotes. Our approach to collecting and analyzing documents was in line with some, but not all, steps of a systematic review (Pullin et al., 2022). We had a specific review question and our search and eligibility criteria as well as appraisal and data extraction methods are described here. Other appropriate steps for a systematic review, such as utilizing multiple reviewers, were not feasible.

We conducted searches on Google Scholar and Science Direct. Search terms included combinations of words that described livestock depredation/conflict, general methods (lethal, non-lethal), specific strategies (scare device, taste aversion, trapping, aerial shooting), and species (wolf, coyote). We included both wolves and coyotes based on their similar evolutionary histories and shared behaviors, including predation on livestock (Crabtree and Sheldon, 1999; Gese, 2004; Wang et al., 2004). Grey literature documents (e.g., conference proceedings, research reports) were identified through search engines, internet records, and hard copies of conference proceedings. We focused on consistent well-known conferences, including the Vertebrate Pest Conference, the Eastern Wildlife Damage Control Conference, and the Wildlife Damage Management Conference. Additional research was identified from references in collected documents. A request was placed with the authors' university library to retrieve documents that could not be found online.

To be included in our analysis, the title or abstract of the document had to indicate that the research focused on reducing livestock predation by coyotes or wolves. The research also had to be field-based (i.e., with predators free-ranging, not in enclosures as in controlled-conditions experiments) with the associated document including information on methods, results, and an evaluation of changes in livestock losses from coyotes or wolves. Document publication dates ranged from 1970 to 2018 and the geographic extent of the research was Canada and the US.

Individual documents might have included multiple evaluations of a single or multiple strategies. Each unique identifiable result for a specific deterrence method was considered a unique evaluation and separate research finding. For example, multiple implementations of a single strategy on different livestock or the same livestock at different times, with varying experimental designs, predator species, or sample sizes reported in a single document were considered different research findings. Multiple mitigation strategies tested on the same livestock simultaneously were classified as instances of a 'Combination' strategy rather than multiple research findings for separate strategies. Of the 75 research findings included in our analysis, 55 were from individual documents and 20 findings were from 10 documents. We recorded multiple characteristics for each research finding: 1) lethality; 2) experimental design; 3) year of publication; and 4) outcome rating (Table 1).

2.1. Estimating relative research robustness

We created a composite variable to estimate each research finding's hypothetical robustness relative to the other research collected. We label this composite variable a robustness index. Although the research we collected is focused on a narrow topic, there was still a large amount of variability in which and how information was reported. We chose four characteristics— experimental length and design, sample size and spatial distribution— that are important to experimental robustness and that would often be identifiable in research findings. Importantly, we acknowledge that the research characteristics included in the index reflect our own methodological perspectives and what information we considered extractable from the research while performing our review. Experimental length and design were included in the index as study length may be an important component of effectiveness and controlled experiments are important for reducing bias in ecological work (Christie et al., 2019; Miller et al., 2016; Treves et al., 2019, 2016). Other work has compared the effectiveness of several unique experimental designs (e.g., Christie et al., 2019; Khorozyan, 2022); we took a simpler dichotomous approach (i.e., with/without control) due to the high degree of variability in method descriptions and our desire for the index to be straightforward. Sample size and spatial distribution also were included as measures in the composite variable as both can affect the reliability of conclusions (e.g., Albert et al., 2010; Bissonette, 1999; Christie et al., 2019; Hurlbert, 1984). We assumed that replication across larger spatial extents would likely include more diverse abiotic and biotic (e.g., terrain, wild prey; Muhly et al., 2010) environmental characteristics helping make a study more generalizable (Albert et al., 2010).

The formula for the robustness index (Table 2) utilized: 1) temporal scale (ranked 2–5); 2) experimental design (ranked 2–3); 3) unique locations tested (ranked 1–4); and 4) spatial extent of the research area (ranked 1–4). We doubled the weight of the Temporal Scale (T) and Experimental Design (D) values in the formula given their importance in ecology and predator management research (Table 2) (Christie et al., 2019; Treves et al., 2016). Category limits for the temporal, spatial, and sample size measures (e.g., number of locations for small versus medium studies) often were based on patterns we noted in the collected canid management research. For instance, there were multiple findings that were classed as having sample sizes of around 15, almost none with samples in the mid-twenties, and multiple with samples greater than 30. We considered this to constitute a natural break in the data and used it as a cut-off point for medium versus large studies.

2.2. Statistical testing

Calculated robustness index values were normally distributed with no outliers (i.e., no standardized values > 3.29 or < -3.29). Linear regression (Altman and Krzywinski, 2015) was used to evaluate trends in the robustness index across time (from 1970 and 2018). A non-parametric Kendal-tau b (Agresti, 2010) was used to support the regression findings by evaluating the overall association between the robustness index and year of publication. T-tests and Mann-Whitney U tests (Anderson et al., 2011) were used to look for differences in the robustness index values of lethal and non-lethal research findings. A chi-square test (Anderson et al., 2011) was used to compare the frequency of outcome ratings between the research findings in the lethal and non-lethal categories. Analysis of Variance (ANOVA) and Kruskall-Wallis tests (Anderson et al., 2011) were used to evaluate if research findings grouped by their outcome ratings had different levels of robustness (Anderson et al., 2011). Statistical analyses were conducted in SPSS (Statistical Package for the Social Sciences) (IBM Corp., 2017).

Table 1

Characteristics, and analyzed categories for those characteristics, that were recorded for each research finding that reported on field-based experiments evaluating strategies to reduce livestock predations by coyotes and wolves in Canada and the United States.

Characteristic	Description of characteristic	Categories	Examples
Lethality	Was the management strategy designed to reduce livestock losses by killing the predator or by altering its behavior?	Lethal	Shooting, poisoning, trapping
		Non-lethal	Livestock protection animal, light-sound device
Experimental Design	What type of experiment is reported?	Quasi-experiment	Before-after comparison
		Controlled experiment	Intervention areas compared to control areas
Year of Publication	What year/decade was the research published?	Year	1983, 1995
		Decade	1970s, 1980s, 2000s
Outcome Rating	To what degree did livestock losses change and was the change in the desired direction?	Positive	> 75% change in desired direction
		Mixed	25–75% change in desired direction
		Negative	< 25% change in desired direction or change in undesired direction

Table 2
The formula and variables used to calculate a robustness index value for each research finding that reported an experimental field-based evaluation of a strategy to mitigate livestock predation by wolves and coyotes in Canada and the United States.

Index = 2(T) + 2(D) + L + S				
Value in formula	Temporal scale (T)[a]	Experimental design (D)	Unique locations tested (L)[b]	Spatial extent (S)
1	–[c]	–[c]	1	< 10 km^2 (Individual/Localized)
2	< 6 months (e.g., single season)	Quasi-Experiment	2–9 (Small study)	> 10 km^2 (Multiple Counties/Partial Area of State or Province)
3	6 months–1 year (e.g., multiple seasons)	Controlled Experiment	10–29 (Medium study)	State or Province Wide
4	1–2 years	–	≥ 30 (Large study)	Multiple States or Provinces
5	> 2 years	–	–	–

[a] Quasi-experimental research was assigned a temporal value based on the total pre and post intervention timeframe rather than the length of the pre or post intervention periods individually.
[b] Number of locations (i.e., sample size) based on the number of the smallest identifiable spatial units (e.g., herds, pastures, study sites) included in a research finding.
[c] These cells are blank in the current analysis as they would be used if the current analysis included non-experimental research (i.e., comparison of livestock losses at a single point in time).

3. Results

3.1. Temporal distribution of livestock predation management research

We cataloged 75 field-based research findings that evaluated whether livestock predation mitigation strategies reduced livestock losses by coyotes and wolves. Nineteen of these findings used a controlled experimental design and 56 used a quasi-experimental design. The highest number of findings occurred in the 1980s (n = 29; 39%), followed by the 1970 s (n = 17; 23%), the 2000 s (n = 12; 16%), the 1990s (n = 9; 12%), and the 2010s (n = 8; 11%) (Table 3).

We identified 15 non-lethal management strategies and seven lethal management strategies (Table 3); no strategy had research published in all five decades. For non-lethal strategies, Fencing was the most frequently evaluated strategy with findings published across four decades. The second and third most evaluated non-lethal strategies were Taste Aversion and Livestock Protection Dogs. Taste Aversion was only published in the 1970 s and 1980s. In comparison, research on Livestock Protection Dogs was published in the 1970s, 1980s, and 1990s. The only other non-lethal strategy with research published in three decades was Unspecified Scare Device in the 1980s, 1990s, and 2000s. Of the other 11 non-lethal strategies, seven had research published in only one decade; the remaining four strategies had findings published in only two of the five decades. We did not find experimental evaluations of predator shock collars, sterilization, and behavior contingent light-sound devices published prior to the 2000s. The Chemical Repellent strategy had the largest temporal gap with findings in the 1970s and one in the 2000s.

Fourteen of the 25 lethal research findings were published in the 1970s and 1980s. Of the seven lethal strategies identified, four had findings only published in one decade and two strategies had findings published in two decades (Table 3). Evaluating combinations of lethal strategies was relatively common in the 1970s and was the only lethal strategy with findings published after 2000. Research evaluating the use of traditional shooting or trapping as individual strategies was not published until the 1990s.

3.2. Research finding robustness and outcomes

Hypothesized robustness index values were calculable for 68 research findings. Those robustness values were associated with year of publication ($\tau_b = 0.280$, p = 0.001) and increased from 1970 to 2018 across all research findings (Fig. 1; $R^2 = 0.136$, $F(1, 66) = 10.417$, $p = 0.002$). Lethal and non-lethal management strategies had similar overall levels of robustness (Table 3). When lethal and non-lethal research findings were analyzed separately, only lethal research findings showed a pattern of robustness being associated with year of publication ($\tau_b = 0.523$, $p < 0.001$) and increasing robustness over time (Fig. 1; $R^2 = 0.422$, $F(1, 21) = 15.314$, $p = 0.001$).

Robustness index values ranged from 10 to 24, matching the minimum and maximum possible using our formula. Eight research findings, evenly split between lethal and non-lethal strategies, were assigned the lowest possible value. Three of the four non-lethal research findings assigned a robustness index of 10 evaluated a taste aversion management strategy. The only research finding assigned a robustness index value of 24 was an aerial shooting research finding from the 1990s. No non-lethal research finding achieved a 24 in our composite robustness index. More non-lethal than lethal research findings were assigned the next highest robustness index value of 22.

There was a high degree of variability in the average robustness index values across the strategies. The two strategies with the lowest average robustness were poison collars with an average robustness of 10 and bonding sheep to cattle with an average index of 12, each based on two research findings. The three lethal management strategies with the highest robustness index values were traditional shooting, denning, and trapping; all three were based on single research findings. Similarly, the three highest average robustness index values in the non-lethal strategies were based on one (i.e., sterilization) or two research findings (i.e., protection

Table 3
Number of research findings published from 1970 to 2018 reporting on experimental field-based evaluations of non-lethal and lethal strategies to mitigate livestock predation by wolves and coyotes in Canada and the United States.

Decade		1970s[a]	1980s[a]	1990s[a]	2000s[a]	2010s[a]	Total	Average robustness index[b]
Non-lethal Strategies	Fencing (e.g., Linhart et al., 1982)	1 [P(16)]	6 [P(22), P(19), P(-), M(12), M(12), M(-)]	2[P(16), M(-)]	-	1 [P(12)]	10	15.63
	Conditioned Taste Aversion (e.g., Gustavson et al., 1982)	3 [M(12), M(10), M(10)]	5 [P(12), M(19), M(10), M(-), N(22)]	-	-	-	8	13.38
	Livestock Protection Dogs (e.g., Green and Woodruff, 1983)	1 [M(14)]	4 [P(21), M(22), M(22), M(14)]	1 [M(19)]	-	-	6	18.67
	Avoidance of Livestock or Area via Chemical Repellent (e.g., Martin and O'Brien, 2000)	3 [M(-), N(19), N(16)]	-	-	1 [M(18)]	-	4	17.67
	Fladry (e.g., Musiani et al., 2003)	-	-	-	2 [P(16), M(10)]	2 [P(18), N(-)]	4	15.50
	Other Husbandry (e.g., Todd and Keith, 1976)	1 [M(22)]	2 [M(14), N(-)]	-	-	-	3	16.67
	Unspecified Scare Device (e.g., Linhart et al., 1984)	-	1 [M(21)]	1 [P(19)]	1 [P(14)]	-	3	18
	Bonding Sheep to Cattle (Hulet et al., 1987)	-	2 [P(12), P(12)]	-	-	-	2	12
	Combination of Other Non-lethal Strategies (e.g., Wyckoff et al., 2016)	-	-	-	-	2 [P(20), M(19)]	2	19.50
	Livestock Protection Donkey (Green, 1989)	-	2 [P(-), N(-)]	-	-	-	2	—
	Livestock Protection Llama (e.g., Franklin and Powell, 1994)	-	-	1 [P(22)]	1 [M(21)]	-	2	21.50
	Behavior Contingent Light-Sound (Breck et al., 2002)	-	-	-	1 [P(17)]	-	1	17
	Interval Light-Sound (Pfeifer and Goos, 1982)	-	1 [M(15)]	-	-	-	1	15
	Predator Shock Collar (Schultz et al., 2005)	-	-	-	1 [M(17)]	-	1	17
	Predator Sterilization (Bromley and Gese, 2001)	-	-	-	1 [P(20)]	-	1	20
Total		**9**	**23**	**5**	**8**	**5**	**50**	**16.40 SD = 3.92**
Lethal Strategies	Combination of Other Lethal Strategies (e.g., Guthery and Beasom, 1978)	6 [M(15), M(17), N(18), N(14), N(12), N(10)]	1 [M(19)]	-	4 [P(17), P(16), M(22), N(-)]	3 [M(22), M(21), N(22)]	14	17.31
	Aerial Shooting (e.g., Wagner and Conover, 1999)	1 [M(10)]	-	2 [P(24), M(-)]	-	-	3	17
	Poison Bait (e.g., Bjorge and Gunson, 1985)	-	3 [M(19), M(18), N(-)]	-	-	-	3	18.67
	Poison Collar (e.g., Connolly et al., 1978)	1 [P(10)]	1 [M(10)]	-	-	-	2	10
	Killing Predators in Den (Till and Knowlton, 1983)	-	1 [P(20)]	-	-	-	1	20
	Traditional Shooting (Sacks et al., 1999)	-	-	1 [M(19)]	-	-	1	19
	Trapping (Fritts et al., 1992)	-	-	1 [M(21)]	-	-	1	21
Total		**8**	**6**	**4**	**4**	**3**	**25**	**17.17 SD = 4.35**

[a] Each superscript letter(#) combination shows the success rating and robustness index value of a research finding published in that decade. Research findings where a robustness index was not calculable are indicated by (-). P = Positive outcome; M = Mixed outcome; N = Negative outcome.
[b] Averages do not include research findings not assigned a robustness index value.

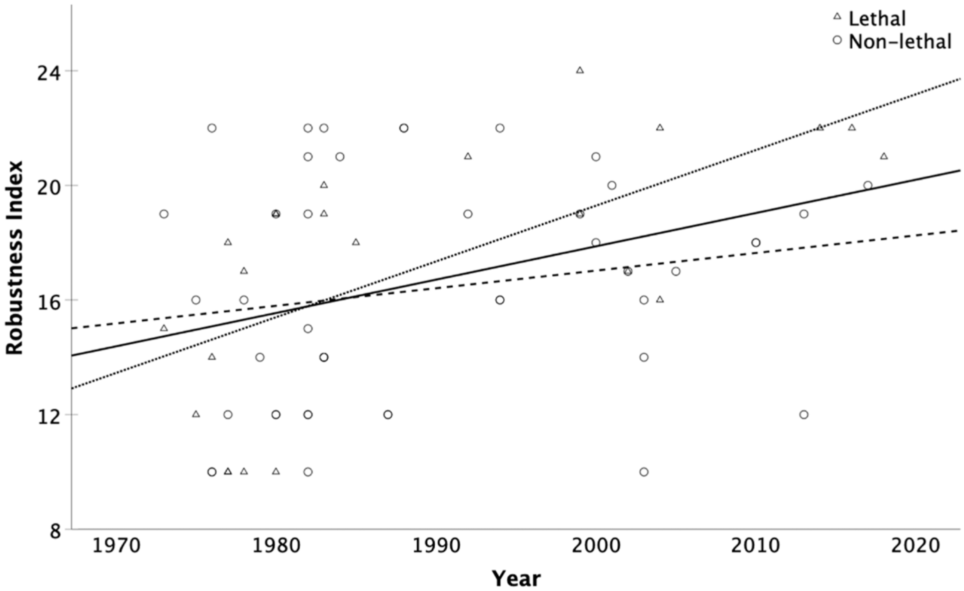

Fig. 1. Robustness index values of field-based experiments on strategies to reduce livestock predations by coyotes and wolves in Canada and the United States plotted against the year the research finding was published (1970–2018). Linear lines of best fit are reported for all research findings (solid line; $y = -215 + 0.116x$; $p = 0.002$;), lethal research findings (dotted line; $y = -370 + 0.195x$; $p < 0.001$), and non-lethal research findings (dashed line; $y = -106 + 0.061x$; $p = 0.212$). Instances where research findings have identical robustness index values and years of publication are shown as a single marker.

llamas, combination).

Both lethal and non-lethal research findings reported similar frequencies of the three outcome ratings (Fig. 2). Although there were differences in the frequency of positive and negative outcomes between lethal and non-lethal research findings, the differences were not significant. We also did not find significant differences in research robustness between positive, mixed, or negative outcome ratings when analyzing all research findings, only lethal research findings, or only non-lethal research findings. No strategy was robustly (e.g., robustness index > 20) evaluated multiple times and also assigned repeated positive outcome ratings. The highest average robustness for any strategy was livestock protection llamas with two research findings, one positive and one mixed.

4. Discussion

4.1. Many strategies, few evaluations

Livestock likely have an important role in the sustainability of agriculture moving forward (Ominski et al., 2021). Those livestock would co-exist with their environment in an ideal world, but livestock predation can have negative impacts on producer profit margins and lead to conflict. There are many questions remaining about how best to manage livestock predation. We have helped to address one knowledge gap by cataloging when canid livestock predation mitigation strategies were evaluated, how hypothetically robust those evaluations were, and whether the research outcomes were positive. Evaluations of multiple unique non-lethal strategies were published in the 1970s; in contrast, evaluations of some common lethal strategies (e.g., shooting) were not published until the 1990s. Robustness index scores showed that from 1970 to 2018 research findings increasingly used more robust experimental methods compared to previous research. However, this trend was primarily due to increasing robustness in research on lethal mitigation strategies rather than the non-lethal mitigation strategies. The similar average robustness of lethal and non-lethal research findings indicates that differences between the two types of findings was eventually evened out. Lethal and non-lethal research findings also were assigned positive, mixed, and negative outcomes at similar rates as one another. Importantly, no strategy had more than one research findings assigned both positive outcome ratings and high robustness index values. This likely shows both the lack of consistent evaluations of strategies and the difficulty with managing livestock predation.

Less than half of the strategies identified in the experimental field research have been evaluated on more than two occasions. Similarly, only two strategies, fencing and combination of lethal strategies, were evaluated in more than three decades. The relatively high number of research findings focused on these two strategies is likely due to the broad nature of the strategies themselves. Fencing can encompass a large number of unique designs (e.g., 7-wire (Dorrance and Bourne, 1980); woven, electrical (Linhart et al., 1982)) and combination of lethal strategies is non-descript with various potential combinations of other strategies. There were two other individual strategies evaluated six or more times, conditioned taste aversion and livestock protection dogs. Conditioned taste aversion included a large number of mixed outcomes with half of the research findings being assigned robustness values less than 12. Comparatively, most livestock protection dog research findings were more robust with four of the six findings being assigned a

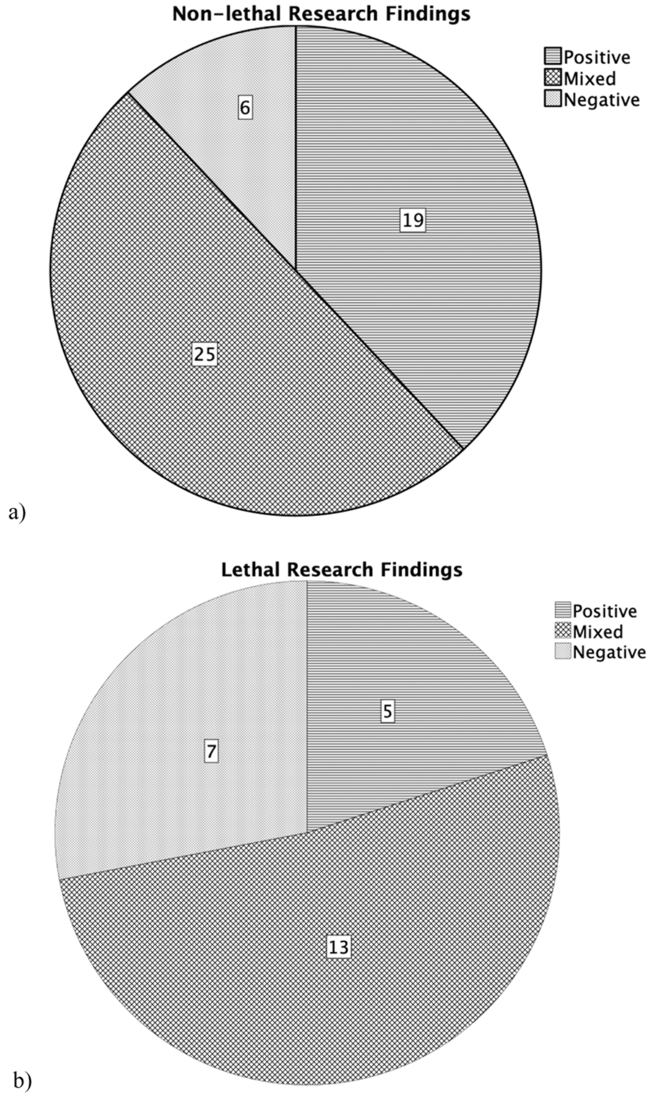

Fig. 2. Number of lethal and non-lethal research findings assigned each of the outcome ratings.

robustness value of 19 or greater. None of these six research findings reported a negative outcome. Other reviews have highlighted the potential of guarding dogs to reduce livestock predations (Moreira-Arce et al., 2018).

Overall, we identified a large number of findings focused on managing livestock predation by coyotes and wolves in Canada or the US. These findings were distributed across a large number of strategies with no strategy showing consistently robust evaluations. Our findings are consistent with the conclusions of other reviews that have highlighted the limited experimental evidence and replication in livestock predation research for any particular management strategy (e.g., Bruns et al., 2020; Eklund et al., 2017; Miller et al., 2016; Treves et al., 2016). This is troublesome for carnivore management as generalizing one or two research findings to all contexts can hamper our understanding of the effectiveness of a strategy and how situational variability may impair that effectiveness (Graham et al., 2005; Kedron et al., 2021; Plotsky et al., 2022). Parsing out the effects of a strategy from the effects of context likely requires robust controlled replications with varying study area characteristics.

Our results suggest a potential role of human dimension biases in what strategies have been evaluated. For example, dogs have a high standing within society, have been used historically and presently to protect livestock in other areas of the world, and were evaluated most often compared to other livestock protection animals (Cunningham-Smith and Emery, 2020; Green, 1990). Similarly, a potential influence of researcher social environment can be seen when looking at when evaluations of individual lethal or non-lethal strategies, as opposed to combinations of those strategies, were published. Researchers focused on evaluating individual non-lethal strategies before experimentally evaluating combinations of those strategies. In contrast, this pattern was reversed for lethal strategies; evaluations of using multiple lethal strategies simultaneously (e.g., Guthery and Beasom, 1978) were published before evaluations of some of the individual component strategies, particularly shooting and trapping (Fritts et al., 1992; Sacks et al., 1999).

Non-lethal research shows a focus on the strategies themselves while the lethal research indicates a focus on the efficiency of predator removal, which also was the focus of pre-1970s predation management research (Fagerstone and Keirn, 2012).

4.2. Research robustness and outcomes

There have been other approaches to understanding bias and robustness in ecological and predator management research, including various risk-based concepts and simulations (Christie et al., 2019; Eklund et al., 2017; Khorozyan, 2021; Khorozyan and Waltert, 2020). Our work and other past research have similar goals, but approach the assessment of research robustness in different ways, which limits comparisons of the concept across studies. We aimed to create a relatively simple robustness measure informed by the research we evaluated and that utilizes information identifiable in the research we reviewed. We acknowledge that the characteristics we included in the index represent our own methodological perspectives and are not an exhaustive list of characteristics important to experimental robustness. The four characteristics we chose kept the index straightforward with the information being typically retrievable. Using four characteristics also helped avoid potential pitfalls around focusing on a singular characteristic of research as determining robustness. Most robustness index values can be achieved through various combinations of the categories; for example, a large spatial scale with a smaller sample size could contribute the same amount to the index as the reverse, a smaller spatial scale with a larger sample. This was part of our intention with the index as the reliability of research based on one strong experimental characteristic may be misleading (Christie et al., 2019).

We found that robustness of canid livestock predation management increased over time when all research findings are evaluated. The fact that five of the eight research findings assigned a robustness index value of 10 (i.e., the lowest possible) were published in the 1970s exemplifies this trend. Compared to the analysis of all research findings, a stronger trend of increasing robustness was identified in the lethal research findings. Interestingly, there was no similar trend among the non-lethal research findings, even though a similar number of non-lethal and lethal research findings were assigned a robustness index value of 10. The presence of a strong trend in lethal, but not non-lethal, research findings shows that the trend in all available research findings likely was attributable to the lethal research findings.

We were surprised that lethal and non-lethal research findings had similar overall levels of robustness, given this improvement in lethal research finding robustness over time. The lack of a trend in the robustness of non-lethal research findings may be attributable to the novelty of the non-lethal management strategies compared to lethal management strategies that were used prior to the 1970s. Research on these lethal management strategies could have been developed around what was already being done (e.g., shooting, trapping, poisoning). In contrast, investigating non-lethal strategies likely required research be developed from the ground up. Designing research around what was already being done (i.e., a pragmatic approach to research) may have led to lower overall robustness in the first few decades and provides an explanation for the preponderance of combination lethal research findings in the 1970s. Similar ideas have been discussed with regard to reports on haphazard culling activities (Lennox et al., 2018).

Whereas robustness was related to when a research finding was published, we did not find evidence that research assigned different outcome ratings differed in robustness. We expected less robust research may be more likely to report positive effects than more robust research. For instance, the conclusions of less robust research may be more susceptible to short term localized changes in predation patterns. Analyses comparing robustness and outcomes were across multiple strategies rather than within individual strategies. If more research findings were available for a particular strategy, it may be possible to parse out a potential influence of robustness on outcomes. We were not able to do this more reliable analysis because of the limited number of research findings for any given strategy.

Although we focused on livestock predation literature, the simplicity and standardized format of the index and our review—which does not replace other review and evaluation methodologies, such as meta-analyses— could make the index applicable to other predation management topics involving interventions. The index also can be adapted to canid predation research that utilizes methods not included here. For example, research on captive predators could be included by the addition of a field versus captive characteristic. Similarly, the robustness of non-experimental predation management research (e.g., producer surveys) could be included by utilizing the lowest value categories of the Temporal Scale and Experimental Design characteristics (e.g., snapshot and correlational, respectively). These categories were not utilized in the current analysis as we focused on experimental research.

4.3. Limitations

Our review only followed some steps of a systematic review (Pullin et al., 2022). The primary difference between our work and a formal systematic review is that data related activities (e.g., searching, eligibility, data extraction) were performed by one of the authors. It was not feasible to have an independent reviewer to confirm screening and data extraction consistency. We acknowledge that the processes involved in a systematic rather than systematized review are beneficial and create a limitation to our work. There may be research that we have missed and not included here due to the search engines we employed or research being rejected when a second reviewer may have included it. We did include grey literature in our analysis which helps broaden the included research and our conclusions.

There are a variety of ways to think about and review the robustness of experimental methods. Our index of hypothesized robustness utilized four characteristics that we viewed as important to experimental methodology. Other research also has indicated that these characteristics are important. We acknowledge that the creation of the index includes a level of subjectivity in design and implementation. For example, we combined the pre- and post-intervention periods to determine the study length of quasi-experimental research. We believe this reflects the amount of information that researchers were able to use to support their conclusions. However, the lengths of the two periods may have varied between studies making comparisons less compelling. We also do not know what the correlation is between our index and false positives rates –i.e. an important limitation affecting evaluations of robustness (e.g., Khorozyan, 2021). The index takes a simplistic approach to robustness, a complicated topic, and provides a hypothesized estimate of robustness for a research finding. We do not see this value as perfectly representing the robustness of that research finding. Similarly, two research findings having the same robustness index value does not, necessarily, mean they have identical levels of robustness. The same value across research findings means that we estimate their robustness as being similar, but not identical. Robustness is informed by a myriad of different aspects that are not always easily quantified or included in research reports (e.g., unintended researcher or producer bias). This inability to perfectly quantify robustness, along with the limited amount of research on most strategies, places a limit on our conclusions. Our work is part of an important broader discussion that has been ongoing within livestock depredation research and beyond in the broader ecological research.

A potential statistical issue is the number of lethal research findings being half the number of non-lethal research findings. When evaluating lethal research findings on their own, the limited number of findings meets some sample size guidelines for linear regression and not others (Tabachnick and Fidell, 2013). Thus, our analysis may be showing an unreliable effect within the lethal research findings that may change with a larger sample size. However, the fact that increasing robustness over time was only found for lethal research findings (i.e., a smaller sample size with less statistical power) and not the non-lethal research findings is reassuring.

Notably, there may be pseudo replication in a portion of the research findings we report upon; twenty research findings came from only 10 documents and research findings from the same document may be more likely to share characteristics. For instance, these documents often reported the results of multiple experiments that were conducted by the same research group. If these researchers used similar methods or the same livestock sample across experiments, it could cause some degree of pseudo replication in our data and reduce the potential generalizability of our conclusions. We see the impact of this pseudo replication on our conclusions as minor. All canid livestock predation management research findings are part of a singular body of research; our investigation focused on the entire body of research and not disproportionally on research conducted by independent unique researchers. Finally, the potential effect of pseudo replication could be exacerbated if research by non-academic investigators was less likely to be found in our literature search (Plotsky et al., 2023). However, our inclusion of grey literature was an attempt to minimize this potential selection bias by including all accessible research. Similar to many other reviews, we were not able to include research that was conducted and never reported upon or published.

5. Conclusions

Our effort adds to awareness of how weak the science has been for decades in canid livestock predation research and indicates the need for additional scientific scrutiny of methods. The index we utilized showed that the robustness of research conducted on mitigating livestock predation by wolves and coyotes increased over the last five decades, particularly for findings on lethal strategies. Nearly two dozen strategies have been evaluated and most only were evaluated a few times. It is possible that the problem of canid predation on livestock has no easy solution and that is why researchers have evaluated a variety of strategies rather than focusing on a few that are successful. Ultimately, managing livestock production to co-exist with predators in the same environment should be informed by the best possible evidence; management practices based on older (i.e., more likely to be lower quality) research or on a few non-replicated findings may need to be re-evaluated. We believe a worthwhile avenue of research would be to understand which predator management research has informed predator management policies and practices. Given our findings that older research may use less robust methods and that no strategy was robustly evaluated multiple times with positive outcomes, this future avenue of research would highlight which policies and practices are outdated. These policies and practices could then be updated with more recent resources and research to increase livestock producer co-existence with canid predators.

CRediT authorship contribution statement

Kyle Plotsky: Conceptualization, Investigation, and Writing – original draft. **Marco Musiani:** Writing – review & editing. **Shelley M. Alexander:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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