PERSPECTIVE

Carnivore conservation needs evidence-based livestock protection

Lily M. van Eeden, Ann Eklund, Jennifer R. B. Miller, José Vicente López-Bao, Guillaume Chapron, Mikael R. Cejtin, Mathew S. Crowther, Christopher R. Dickman, Jens Frank, Miha Krofel, David W. Macdonald, Jeannine McManus, Tara K. Meyer, Arthur D. Middleton, Thomas M. Newsome, William J. Ripple, Euan G. Ritchie, Oswald J. Schmitz, Kelly J. Stoner, Mahdieh Tourani, Adrian Treves

1 Desert Ecology Research Group, School of Life and Environmental Sciences, University of Sydney, Camperdown, Australia, 2 Grimsö Wildlife Research Station, Department of Ecology, Swedish University of Agricultural Sciences, Riddarhyttan, Sweden, 3 Department of Environmental Science, Policy, and Management, University of California—Berkeley, Berkeley, California, United States of America, 4 Center for Conservation Innovation, Defenders of Wildlife, Washington, DC, United States of America, 5 Research Unit of Biodiversity, Oviedo University, Gonzalo Gutiérrez Quiróz, Mieres, Spain, 6 Department of Natural Sciences, Paul Smith’s College, Paul Smiths, New York, United States of America, 7 Lake Placid Land Conservancy, Lake Placid, New York, United States of America, 8 Biotechnical Faculty, Department of Forestry, University of Ljubljana, Ljubljana, Slovenia, 9 Wildlife Conservation Research Unit, Department of Zoology, University of Oxford, The Recanati-Kaplan Centre, Tubney House, Tubney, Abingdon, United Kingdom, 10 Research Department, Landmark Foundation, Riversdale, South Africa, 11 School of Animal, Plants and Environmental Sciences, University of Witwatersrand, Braamfontein, Johannesburg, South Africa, 12 Yale School of Forestry and Environmental Studies, New Haven, Connecticut, United States of America, 13 School of Environmental and Forest Sciences, University of Washington, Seattle, Washington, United States of America, 14 Global Trophic Cascades Program, Department of Forest Ecosystems and Society, Oregon State University, Corvallis, Oregon, United States of America, 15 Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Burwood, Victoria, Australia, 16 Wildlife Conservation Society Rocky Mountain Regional Program, Bozeman, Montana, United States of America, 17 Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway, 18 Nelson Institute for Environmental Studies, University of Wisconsin, Madison, Wisconsin, United States of America

Open Access

Citation: van Eeden LM, Eklund A, Miller JRB, López-Bao JV, Chapron G, Cejtin MR, et al. (2018) Carnivore conservation needs evidence-based livestock protection. PLoS Biol 16(9): e2005577. https://doi.org/10.1371/journal.pbio.2005577

Published: September 18, 2018

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Funding: National Science Foundation Couple Human and Natural Systems (grant number 115057). Received by JRBM. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Ramon & Cajal research contract from the Spanish Ministry of Economy, Industry and Competitiveness (grant number RYC-2015-18932). Received by JVLB. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. National Geographic Society (Grant WW-100C-17), and the George B. Storer Foundation, received by ADM. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Derse Foundation and US Fulbright program in Sweden. Received by AT. The funder had no role in study design, data collection and analysis, decision to publish, or

Abstract

Carnivore predation on livestock often leads people to retaliate. Persecution by humans has contributed strongly to global endangerment of carnivores. Preventing livestock losses would help to achieve three goals common to many human societies: preserve nature, protect animal welfare, and safeguard human livelihoods. Between 2016 and 2018, four independent reviews evaluated >40 years of research on lethal and nonlethal interventions for reducing predation on livestock. From 114 studies, we find a striking conclusion: scarce quantitative comparisons of interventions and scarce comparisons against experimental controls preclude strong inference about the effectiveness of methods. For wise investment of public resources in protecting livestock and carnivores, evidence of effectiveness should be a prerequisite to policy making or large-scale funding of any method or, at a minimum, should be measured during implementation. An appropriate evidence base is needed, and
we recommend a coalition of scientists and managers be formed to establish and encourage use of consistent standards in future experimental evaluations.

Carnivores, such as lions and wolves, are killed in many regions over real or perceived threats to human interests. Combined with habitat loss and fragmentation, human-induced mortality has contributed to widespread carnivore population declines, along with declines of their important ecosystem functions [1]. Balancing the goals of nature preservation, livelihood protection, and welfare of carnivores and domestic animals depends on policies that foster coexistence between humans and carnivores in multiuse landscapes [2, 3]. Central to this aim is a need for rigorous scientific evidence that interventions are effective in preventing predation on livestock. Such policies should be based on strong inference [4, 5], otherwise, we risk wasting resources on ineffective interventions that might harm all involved.

Between 2016 and 2018, we independently published four reviews examining evidence for the effectiveness of interventions to reduce livestock predation by carnivores [6–9]. Here, we focus on the results for livestock losses or carnivore incursions into livestock enclosures (hereafter, “functional effectiveness” [8]). Since each review offered a unique perspective, we reconcile differences to synthesize three messages common to the reviews. First, despite the immense resources spent globally to protect livestock from carnivores, few peer-reviewed studies have produced strong inference about the functional effectiveness of interventions. Second, there was scant consistency of standards of evidence in our four reviews, hindering scientific consensus, and hence clear recommendations to policy-makers, about the relative functional effectiveness of different interventions. Finally, we identified several interventions that were found consistently effective, which deserve promotion in policy, even if only in the general conditions under which they have already been tested, as well as prioritization for further research under conditions in which evidence is lacking.

We suspect that the striking paucity of rigorous evaluation is due to the tendency for decisions about predator control to depend on factors other than evidence-based evaluation of whether a given intervention effectively protects livestock. These other factors—including ethics (should one implement the intervention?), feasibility (can one implement the intervention?), and perception (does one believe the intervention will work?)—might be important subsequent considerations in the implementation and decision-making processes. However, objective scientific evidence of an intervention’s functional effectiveness must remain a foundational prerequisite on which subjective inquiries later build. The lack of scientific synthesis and consensus about functional effectiveness has allowed more subjective factors to dominate decision-making about predator control and likely wasted time and money on interventions that do not optimally protect livestock. Furthermore, shifting ethics and public values in some communities are enabling the return of carnivores to landscapes worldwide or leading to the increased use of nonlethal predator control interventions. We support these initiatives from the perspective of conserving carnivores but insist that scientific evidence for functional effectiveness be considered first to ensure that interventions intended to protect livestock accomplish that goal. This will prevent the inefficient—or worse yet, counterproductive—use of limited resources to protect animals long term.

Additionally, although our reviews collectively reveal a need for more evidence, scientists alone cannot fill this gap. Livestock owners, natural resource managers, and decision-makers each have an important role to play in research partnerships to collaboratively guide the testing of predator control interventions. Here, we appeal to these groups by summarizing the
advantages of evidence-based effective interventions, the best practices of scientific inference, and the role of policy in promoting effective predator control strategies. We start by synthesizing the results of our four independent reviews to provide scientific consensus on the evaluations of predator control interventions. We urge managers and policy decision-makers to use this discussion as a basis for creating policy that promotes evidence-based, effective strategies for protecting domestic animals from carnivore predation.

Synthesis of the science on functional effectiveness

Our four reviews [6–9] jointly screened >27,000 candidate studies. The four sets of inclusion criteria differed in geographic coverage, carnivore species, and standards of evidence and research design (see S1 Table), which limited overlap in the studies that passed screening (only 19% of studies were included in two or more of the four reviews; no study was included in all four, S1 Fig). The differing inclusion criteria also meant that it was not possible to conduct a quantitative comparison (meta-analysis) combining the data from our four reviews, but we suggest that such an analysis should be conducted in the future as evidence increases. Nonetheless, our reviews came to remarkably similar conclusions, irrespective of methods, suggesting that our conclusions are robust.

Among the 114 studies that passed screening in one or more reviews (S2 Table), representing >40 years of research, we found few that yielded strong inference about functional effectiveness. Surprisingly, many widely used methods have not been evaluated using controlled experiments. Also, few interventions have been compared side by side or tested singly under diverse conditions. These deficiencies in the literature are further compounded by disagreement among scientists, managers, and peer-reviewed journals about standards of evidence, such as which study designs produce strong inference [8]. We acknowledge the challenges of regional experiments amid dynamic, complex ecologies, publics, and jurisdictions. However, a handful of random-assignment experimental studies without bias (“gold standard”) have proven that the obstacles are surmountable [8, 10, 11, 12].

We summarize our four sets of results by category of intervention in Fig 1. Our reviews agree that several methods have been tested numerous times with high standards of evidence and have been found effective: livestock guardian animals, enclosures for livestock, and a visual deterrent called fladry. Importantly, we should recognize that the effectiveness of different methods will vary under different contexts, and there is currently a bias among research toward certain geographic regions and predator types (Fig 2). Further, we agree that standards of evidence have been higher for nonlethal methods, and there remains a need to ensure data on all interventions are collected appropriately and consistently. As such, building on existing criticism of the lack of appropriate data collection in environmental management [13–16], our reviews collectively highlight the need to improve standards of evidence used in evaluating interventions. We need to develop a comprehensive evidence base that allows us to compare the effectiveness of interventions for reducing carnivore predation on livestock and inform consistent policy in any jurisdiction.

Importance of rigorous experimental design and evaluation

Societal values and, accordingly, policies for human–carnivore coexistence have changed over the millennia. The almost exclusive use of lethal interventions has given way to nonlethal interventions as important supplements to or replacements for prior lethal methods. Immense logistical and financial resources are invested in protecting livestock and carnivores, so the scarcity of rigorous scientific evidence for effectiveness should be a concern. We encourage governments to adopt proven methods from similar systems of carnivores and human
interests, with systems in place to review and adapt management actions as new evidence becomes available. When governments contemplate large-scale implementation or funding for interventions, scientific evidence of functional effectiveness deserves priority to avoid wasting...
resources on ineffective methods, no matter if the latter are ethical or easy to implement.
When no proven method is available, scientific evaluation of functional effectiveness should coincide with implementation.

Strong inference in any scientific field demands control over potentially confounding variables and testable claims about functional effectiveness of interventions [8]. In our context, all methods present opposable hypotheses, i.e., method X works or does not work. Several experimental design components are essential to strong inference about that hypothesis, and we focus here on the three of topmost priority for yielding strong inference about livestock protection interventions: controls, randomization, and replication.

The strongest inference results from experiments that achieve the "gold standard" through "random assignment to control and treatment groups without bias (systematic error) in sampling, treatment, measurement, or reporting" [8]. This requires that an intervention be used to protect a livestock herd (treatment) and that its effectiveness is compared against a livestock herd that is not exposed to the intervention (placebo control). Both treatment and control should be replicated using multiple independent herds of livestock that are distributed so that the effects of treatment on one herd do not confound the effects on another herd, which would eliminate independence. Random assignment of treatments avoids sampling or selection bias that is common in our field [8], as in others [18]. Implementing random assignment for actual
livestock herds can be challenging, but several studies have succeeded, such as those conducted by Davidson-Nelson and Gehring [10] and Gehring and colleagues [11]. In the Chilean altiplano, 11 owners of alpacas (*Vicugna pacos*) and llamas (*Lama glama*) joined a randomized reverse treatment (crossover) experiment to evaluate light devices in deterring carnivores [12]. Moreover, if large numbers of replicates are infeasible or replicates are unavoidably heterogeneous, then crossover, reverse treatment designs should help to increase the strength of inference about interventions [8, 12, S2 Table].

“Silver standard” designs provide weaker inference because of nonrandom assignment to treatment and then repeated measures of the replicate at two or more time points (before-and-after comparison of impact or quasiexperimental designs, also called case control). Both time passing and the treatment might explain changes in replicates, in addition to the extraneous “nuisance” variables present in agro-ecosystems at the outset [8].

The weakest standard of evidence is the correlational study, which compares livestock predation among herds that varied haphazardly in past protection or varied systematically if people intervened only where livestock had died. In correlational studies, confounding variables inevitably create selection or sampling bias. Although correlational studies may be useful as an initial exploratory step and help direct further research, confidence in their findings should be low, especially if there is large variation in the results. Correlational studies cannot substitute for the silver or gold standards described above.

Implementation of interventions must be consistent to avoid treatment bias. For example, the functional effectiveness of livestock-guarding dogs might vary with breed, individual, training, and maintenance of the dog. Likewise, tests of lethal methods have never controlled the simultaneous use of several methods of intervention (e.g., pooling shooting and trapping as one treatment), which is inadvisable for strong inference. Consistent maintenance of interventions throughout a study should also minimize treatment bias [18].

Well-designed experiments should incorporate evaluation along multiple dimensions. Was the intervention implemented as planned? Did attacks on livestock diminish? Measurement bias arises from systematic error in documenting implementation or losses in treatment or response variables. As in biomedical research, which sometimes uses patient self-reports as a subjective measure of effectiveness alongside objective measures of health outcomes, there are valid reasons to measure owners’ perceptions of effectiveness of interventions. In human–wildlife interactions, people’s attitudes can influence the adoption or rejection of interventions independently of scientific evidence [14,19]. Several of the reviews included metrics of perceived effectiveness among livestock owners, yet perception alone is not a reliable measure of functional effectiveness because of widespread placebo effects, whereby patients feel better simply because they have participated. Studies should therefore either “blind” their participants or use an independent, verifiable measure of effectiveness (i.e., livestock loss).

We recognize that gold or silver standards may be difficult to achieve. Systematic errors can be difficult to eliminate entirely, so we urge careful consideration of methods during the design process, including peer review prior to initiation. Ethical considerations about exposing animals to lethal risks may limit experimental designs. This inherent difficulty for controlled experiments may explain why some published experiments were completed in artificial settings (e.g., using captive carnivores or measuring bait consumption rather than livestock loss). Although most of our reviews omitted experiments for protecting property other than livestock, strong inference from such studies merit tests for livestock protection. Nonetheless, given that several examples of gold standard experiments overcame the complexities of people and wild ecosystems [5, 10, 11, 12], we urge greater effort and recommend government support and accolades for the highest standards of experimentation.
Incorporating science into conflict mitigation and conservation

Many governments have institutionalized support for livestock protection from predators and implemented various interventions at landscape scales. The European Council Directive 98/58/EC, concerning protection of animals kept for farming purposes, states that “animals not kept in buildings shall where necessary and possible be given protection from adverse weather conditions, predators and risks to their health.” The Swedish Animal Welfare Act of 1988 mandates care should be given to injured animals as soon as possible. This obligation is in practice relevant subsequent to carnivore attacks. When trained field observers confirm livestock attacks by large carnivores, they also implement rapid response interventions, such as fladry and portable electric fences, to prevent recurrent attacks [20]. In the United States, in 2013 alone, the US Department of Agriculture killed >75,000 coyotes, 320 gray wolves (Canis lupus), and 345 cougars (Puma concolor) [21]. Similarly, in some Australian states, landowners and managers are required by law to actively control dingoes (C. dingo) on their property.

Given the weak state of current evidence about effectiveness, decisions to use interventions are most likely based on subjective factors (e.g., ethics, opinions, or perceptions) or nonscientific (and thus possibly biased) evidence. For example, many people have deeply rooted perceptions that an intervention is effective or not [19]. Therefore, research, promoted by policy, is needed to validate that perceptions align with measurable and scientifically defensible outcomes [14]. This is especially crucial in cases of lethal interventions, which entail multiple drawbacks, including ethical criticisms and the potential to hasten carnivore declines and impede population recoveries.

However, scientists alone cannot transform policies for implementation. The pursuit of science-based management must be truly interdisciplinary and involve carnivore ecologists, animal husbandry scientists, social scientists, natural resource managers, ethicists, and other scholars and practitioners. Political leaders can also play a role to prioritize, coordinate, and fund partnerships across government agencies and nongovernment organizations. Because we anticipate continued debate over the standards of effectiveness, we recommend a coalition be formed to clearly distinguish standards for evaluation and experimental protocols, which would be distinct from coalitions convened to consider local factors that affect decisions. Through collaboration, scientists, managers, and policy leaders can help to protect livestock within healthy ecosystems that include carnivores. Constituents worldwide increasingly support the restoration of carnivore populations and accordingly are calling for human–carnivore coexistence and minimizing conflicts [2]. Enabling coexistence through evidence-based solutions will give the public strong confidence in methods promoted by scientists and governments, particularly when implementation is difficult or the ethics are controversial.

Supporting information

S1 Table. Methods used by authors’ reviews. Methods have been simplified for comparison. Refer to the original articles for a full account of methods used and justification for the use of these methods.

S2 Table. Studies included in the four reviews.

S1 Fig. Overlap of studies included in each of the four independent reviews that evaluated evidence of functional effectiveness of interventions in reducing carnivore attacks on livestock.
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| Author(s) & Year | Title | Country | Intervention | Species Affected | Livestock Type | Duration of Study | Source/Source | Action Type | Effect (Notes) |
|-----------------|-------|---------|--------------|-----------------|----------------|------------------|---------------|-------------|---------------|
| Anderson et al. | 2009  | Italy    | Coyote fencing | Sheep, Goats, Deer | Cattle, Sheep, Goat | 1 year | Carnivore Damage Prevention News | Lethal control, Translocation | Effectiveness of selective removal of breeding coyotes in reducing sheep predation | 1 |
| Anderson et al. | 2010  | United States | Coyote culling | Coyote | Coyote | 1 year | Wildlife Society Bulletin | Lethal control | Effect of coyote removal on sheep depredation in northern California | 1 |
| Braden & Pletscher | 2001  | United States | Coyote fencing | Coyote | Coyote | 1 year | Wildlife Biology | Lethal control, Fencing | Effectiveness of wolf contraception on livestock from black bear predation | 1 |
| Bagchi & Mishra | 2000  | India    | Coyote culling | Coyote | Coyote | 1 year | Wildlife Society Bulletin | Lethal control | Effectiveness of wolf contraception on livestock from black bear predation | 1 |
| Breck et al. | 1997  | Switzerland | Coyote fencing | Coyote | Coyote | 1 year | Wildlife Biology | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Beckmann et al. | 2015  | Botswana | Deterrents | Deterrents | Deterrents | 1 year | Wildlife Biology | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| van Eeden et al. | 2009  | Kenya    | Livestock guard dogs | Cattle, Water Buffalo, Goats, Fowl | Cattle, Water Buffalo, Goats, Fowl | 1 year | Wildlife Biology | Lethal control | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2010  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2004  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2009  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2008  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2007  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 2006  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
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| Anderson et al. | 1999  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Anderson et al. | 1998  | United States | Electric fencing | Coyote | Coyote | 1 year | Biological Conservation | Lethal control, Fencing | Effect of coyote removal on sheep depredation in northern California | 1 |
| Author                      | Year | Title                                                                 | Country     | Intervention                              | Livestock                             | Guardian Animals | Study Type | Duration of study | Journal/Source                                | Topic                                                                 |
|----------------------------|------|------------------------------------------------------------------------|-------------|-------------------------------------------|---------------------------------------|-----------------|------------|------------------|-----------------------------------------------|----------------------------------------------------------------------|
| Treves et al.              | 1998 | Development of a comprehensive scheme to bring about positive attitudes to farms     | United States | Nonlethal hunting and habitat management | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Extension Farming Systems Journal            | affecting wolf depredation on livestock in the United States          |
| Williamson et al.          | 2011 | Effectiveness of scaring and fencing in reducing wolf depredation on livestock | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2012 | Lethal control as a means of controlling small carnivores            | United States | Lethal control                           | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2013 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2014 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
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| Miller                     | 2017 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2018 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2019 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2020 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2021 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2022 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2023 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2024 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2025 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2026 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2027 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2028 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2029 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
| Miller                     | 2030 | Nonlethal control as a means of controlling large carnivores         | United States | Nonlethal hunting                         | Cattle, sheep, goats, poultry          | Yes              | Research    | 3 years           | Journal of Wildlife Management                | preventing wolf depredation on livestock in the United States          |
## Supplementary Information
Carnivore conservation needs evidence-based livestock protection
Van Eeden et al.

Table S1. Methods used by authors’ reviews. Methods have been simplified for comparison. Refer to the original articles for a full account of methods used and justification for the use of these methods.

| Databases searched and other sources | Miller et al. 2016 [1] | Treves et al. 2016 [2] | Eklund et al. 2017 [3] | Van Eeden et al. 2018 [4] |
|-------------------------------------|------------------------|------------------------|------------------------|-------------------------|
| Web of Science (All databases)      |                        |                        |                        | Web of Science (All databases) |
| Carnivore Ecology and Conservation database |                        |                        |                        | SCOPUS                  |
| Snow-ball sampling                  |                        |                        |                        | Google Scholar          |
|                                    |                        |                        |                        | European LIFE Commission Project database |
|                                    |                        |                        |                        | Snow-ball sampling       |
|                                    |                        |                        |                        | Contacted authors and organizations |

| Search methods and terms            | Miller et al. 2016 [1] | Treves et al. 2016 [2] | Eklund et al. 2017 [3] | Van Eeden et al. 2018 [4] |
|-------------------------------------|------------------------|------------------------|------------------------|-------------------------|
| Compound search terms               |                        |                        |                        | Combinations of search terms from the following categories: |
| included the technique (e.g., deterrent) or a specific intervention (e.g., aversive stimuli or behavior conditioning) plus 1 of 7 general keywords related to livestock depredation conflict: Human–carnivore conflict, livestock depredation, human–carnivore coexistence, mitigation, depredation management, depredation prevention, or depredation control. |                        |                        | Carnivore: Bear*, Canid*, Canis, Carnivore*, Cheetah*, Cougar or puma, Coyote*, Crocuta, Dingo*, Fox*, Hyena or hyaena, Jaguar*, Leopard*, Lion*, Lycaeon or Lycaon, Panthera, Predat*, Tiger*, Uncia, Wild dog*, Wildlife, Wolf, Wolves. |
|                                    |                        |                        |                        | Livestock: Beef, Calf, Calves, Cattle, Chicken, Cows, Farm*, Lamb*, |
| Repeated searches, followed by a snowball method using the reference lists of >100 articles identified in the search. |                        |                        |                        | |
| Search using key words: (Control, Damage, Depredation, Lethal, Non-lethal, Removal, or Livestock) AND (Predat*, Carnivor*). |                        |                        |                        | |
| These items were then refined using the following search string: “depredation OR stock OR poultry OR damage OR mitigation OR conflict OR control OR cull OR cow OR bull OR |                        |                        |                        | |
| Searches using the subject descriptors: Carnivora OR Canidae OR Felidae OR Hyaenidae OR Mustelidae OR Procyonidae OR Ursidae OR Viverridae |                        |                        |                        | |
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| | |
Searches followed the formula: (technique or intervention) and (conflict keyword).

**Deterrents:** Aversive stimuli, Behavior conditioning, Behavior modification, Disruptive stimuli, Repellent.

**Indirect management of land or prey:** Buffer zone, Core zone, Grazing areas, Land use conflict, Wild prey, Wild ungulate.

**Predator removal:** Contraception, Lethal control, Population control, Problem animal, Retaliation, Retaliatory killing, Translocation

**Preventive husbandry:** Barrier, Grazing, Guard animal, Guard dog, Guards, Herd, Herder, Hotspot, Husbandry, Livestock breed, Penning, Sensory deterrent or repellent, Separation, Shepherd.

calf OR calves OR chicken OR hen OR ewe OR lamb OR pet OR cat OR hound OR pony OR ponies OR mule OR reindeer OR llama OR yak OR buffalo OR livestock OR cattle OR sheep OR goat OR horse OR pig OR dog OR attack OR camel OR donkey”.

**Impact:** Conflict, Damag*, Loss.

**Intervention:** 1080, Bait*, Chemical repellent, Compensation, Condition NEAR/2 aversion, Control, Cull, Denning, Dogging, Donkey, Farm*, Fenc*, Fladry, Guard* dog, Hunt*, Husbandry, Insurance, Livestock guard*, Livestock protect*, Llama, M-44, Management, Non$lethal, Poison, Protection collar, Range rid*, Scaring, Shoot*, Sterili*, Translocat*, Trap*

**Excluded terms:** Arthropod, Beetle*, Fish*, *flies, *fly, Hemiptera, Heteroptera, Insect*, Parasit*, Pesticide.

| Publications | Peer-reviewed | Peer-reviewed | Peer-reviewed | Peer-reviewed, gray literature, and raw data |
| Languages | English | English and Slovenian | English | English search terms only; 3 non-English language studies were identified and included. |
| Time period | All years (through 2015). | All years (through 2016). | 1990-2016 | All years (through 2016). |
| Geographic scope | Global | North America and Europe | Global | Global |
**Table S1**

| Carnivore species considered | • Large carnivores with body mass >15 kg [5].  
• 28 species (all considered) | • Free- ranging, native carnivores of North America and Europe > 5 kg.  
• 6 species (final review) | Terrestrial mammalian large carnivore species with body mass >15 kg (Ripple, Estes (5), plus coyotes and wolverines.  
• 30 species (all considered) | • Focused on large carnivores as defined by Ripple, Estes (5) but some studies considered small and large species (e.g. foxes, coyotes).  
• 11 species (final review) |

| Definition of technique effectiveness | Change in livestock losses or the potential for an attack (e.g., percent reduction in livestock losses or carnivore visits to a pasture) after techniques were applied. | Whether intervention will protect property owners from future losses. | Change in livestock losses (number of livestock killed, the number of livestock units attacked) or the potential for an attack (manipulation of carnivore behaviour/movement in a way that is expected to reduce exposure of livestock to carnivore predation). | • Change in livestock loss (e.g., percent loss of stock, loss of stock per period, or financial loss) and carnivore incursions into corrals or bomas.  
• Change in number of retaliatory killings of carnivores.  
• Facilitation of coexistence measured as reduction in livestock loss or retaliatory killing of carnivores. |

| Inclusion criteria | • Primary literature that provided numeric metrics (or values for calculating numeric metrics) of effectiveness  
• Reviews were omitted from analysis  
• Correlative studies were included. | Criteria for including studies:  
1. Studies used experimental or quasi- experimental control with a design that allowed strong inference;  
2. Studies occurred on working livestock operations with free- ranging, native carnivores, and  
3. Studies verified livestock losses.  
• Correlative studies were excluded, as well as those based only on unverified estimates of livestock loss | Included studies were:  
• Included an empirical study of wild (i.e., not captive) carnivores;  
• Included a quantitative evaluation of interventions to prevent/reduce depredation of livestock (excluding apiaries);  
• Included a matched control to which the treatment was compared, i.e. have an experimental or quasi-experimental design. Experimental studies include a  
• Did not analyze changes in human tolerance or perceptions of carnivores; rather, included self-reported changes in livestock losses following introduction of a mitigation measure.  
• Studies had to be replicated with a before–after or control–impact (BACI) design.  
• Studies had to be field trials on livestock and at least 2 months in duration.  
• Excluded studies involving... |
| Data screening and harvesting | Recorded measures of effectiveness, amount of time techniques were effective, large carnivore species involved and country where the study occurred. | • Regarding criterion (1), described in the text why any test was deemed unreliable based on selection, treatment, measurement, or reporting biases (see above).  
• Regarding criterion (2), defined a working livestock operation as one in which livestock, land, and predators were managed in ways characteristic of a private livestock producer. That criterion excluded tests with captive predators [6].  
• Regarding criterion (3), excluded studies measuring self-reported livestock losses or perceptions of effectiveness from Table 1. | • 48,894 titles retrieved from primary search.  
• Initial manual screening of titles reduced number to 27,781.  
• Second manual screening (English language, depredation of domestic animals by included carnivores) left 562 publications.  
• Two authors read papers in full to identify correlational, quasi-experimental, or experimental studies, and identify quantitatively evaluated studies. | • Database searches returned 3146 records; 175 were added through less-structured sampling.  
• Mitigation methods were grouped into 5 predefined categories for the meta-analysis: lethal control, livestock guardian animals, fencing, shepherding by humans, and deterrents (e.g. aversive conditioning, repellents, and protection devices.  
• 40 papers describing financial incentives were discovered, including 3 that measured success, but these were not considered appropriate for comparison with other mitigation |
After close reading, excluded >11 studies because they did not provide reliable inference. Several tests were excluded because they were not peer-reviewed, published descriptions of all methods and results. Measures because the response variables were changes in farmer attitudes or retaliatory killing rather than livestock loss.

| Statistical units of effectiveness | Measures of livestock loss (e.g. number or percent livestock stock killed) | Livestock loss: number of livestock injured or killed by carnivores. | Mean number of animals or livestock units (e.g. herds) depredated by carnivores, or number of trespasses by carnivores. | Measures of livestock loss, e.g. percent loss of stock, loss of stock per period, or financial loss. |
|-----------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------------|
| • After close reading, excluded >11 studies because they did not provide reliable inference. Several tests were excluded because they were not peer-reviewed, published descriptions of all methods and results. | • Measures of livestock loss (e.g. number or percent livestock stock killed) | Livestock loss: number of livestock injured or killed by carnivores. | Mean number of animals or livestock units (e.g. herds) depredated by carnivores, or number of trespasses by carnivores. | • Measures of livestock loss, e.g. percent loss of stock, loss of stock per period, or financial loss. |
| • For studies reporting the effectiveness on a community of predators, reported the effectiveness for the predator community as a whole. | |
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| Data Analysis                                                                 | Counted tests in various categories. Did not perform a quantitative meta-analysis of effects, because there is no standard for consistent application of treatments and because the variety of methods used even within one category (e.g. different types of traps, or breeds of livestock-guarding dogs [LGDs]) would introduce uncontrollable variation. Furthermore, tests using the silver standard offer weaker inference than those using the gold standard but to an unknown degree. | Relative risk (or risk ratio, RR) for carnivore depredation or incursions in treatment vs. control groups for each study [8]. RR defined as the ratio between the probability of depredation by large carnivores in the treatment group and the probability of livestock depredation by large carnivores in the control group: Relative Risk(RR) = \( \frac{a/(a + b)}{c/(c + d)} \)

where \( a \) is the number of depredated animals/units in the treatment group, \( b \) is the number of unharmed animals/units in the treatment group, \( c \) is the number of depredated animals/units in the control group, and \( d \) is the number of unharmed animals/units in the control group. With no difference in the risk of depredation between treatment and control, the relative risk is 1. When RR > 1, the risk of depredation is more likely to occur in the treatment group. When RR < 1 depredation risk is | Sample sizes, means, and standard deviations were extracted from the text, tables, or figures from each article or calculated from the data provided. Calculated the standardized effect size as Hedges’ \( d \) [10] with MetaWin version 2.1 [11]. Hedges’ \( d \) is an estimate of the standardized mean difference between control and treatment and accounts for variation in study effort such that it is not biased by small sample size [10]. Negative values of \( d \) indicated the treatment successfully reduced conflict (e.g., livestock loss declined). Data were analyzed using a random-effects model except where pooled variance was 0 (fixed-effects model used). The mean effect size per category was weighted based on variance and sample size. Total heterogeneity (\( Q_T \)) was calculated for each category [11]. Summarized data on change in carnivore killing as a proxy for tolerance |
|---|---|---|---|---|
| • Compared the effectiveness of techniques by calculating the magnitude of change between conditions before and after a technique was applied. Calculated the magnitude of change (D) as the percentage deviation from initial conditions following the formula (adapted from Jones and Schmitz (7)): \( D = ([B - A]/B) \times 100 \) where \( B \) represents a quantitative measure of conditions (the change in livestock losses or the potential for an attack; e.g., no. of livestock killed) before the mitigation technique was applied and \( A \) represents conditions after the technique was applied. This metric afforded a common basis for comparing different techniques by standardizing measures of change in terms of a proportion to facilitate data integration from different studies that used different units in their response metrics. | • Counted tests in various categories. Did not perform a quantitative meta-analysis of effects, because there is no standard for consistent application of treatments and because the variety of methods used even within one category (e.g. different types of traps, or breeds of livestock-guarding dogs [LGDs]) would introduce uncontrollable variation. Furthermore, tests using the silver standard offer weaker inference than those using the gold standard but to an unknown degree. | • Relative risk (or risk ratio, RR) for carnivore depredation or incursions in treatment vs. control groups for each study [8]. RR defined as the ratio between the probability of depredation by large carnivores in the treatment group and the probability of livestock depredation by large carnivores in the control group: Relative Risk(RR) = \( \frac{a/(a + b)}{c/(c + d)} \)

where \( a \) is the number of depredated animals/units in the treatment group, \( b \) is the number of unharmed animals/units in the treatment group, \( c \) is the number of depredated animals/units in the control group, and \( d \) is the number of unharmed animals/units in the control group. With no difference in the risk of depredation between treatment and control, the relative risk is 1. When RR > 1, the risk of depredation is more likely to occur in the treatment group. When RR < 1 depredation risk is | • Sample sizes, means, and standard deviations were extracted from the text, tables, or figures from each article or calculated from the data provided. Calculated the standardized effect size as Hedges’ \( d \) [10] with MetaWin version 2.1 [11]. Hedges’ \( d \) is an estimate of the standardized mean difference between control and treatment and accounts for variation in study effort such that it is not biased by small sample size [10]. Negative values of \( d \) indicated the treatment successfully reduced conflict (e.g., livestock loss declined). Data were analyzed using a random-effects model except where pooled variance was 0 (fixed-effects model used). The mean effect size per category was weighted based on variance and sample size. Total heterogeneity (\( Q_T \)) was calculated for each category [11]. Summarized data on change in carnivore killing as a proxy for tolerance |
higher in the control group.
• For calculation of RR used the mean number of animals in treatment and control herds, as reported in the original studies (n = 1), or calculated from the reported true numbers for several herds (n = 11), as well as the number of livestock units (n = 2). Reported odds-ratios were converted to RR using an online odds ratio to risk ratio calculator [9], and Hazards Ratio were reported as in original study. Five papers did not report herd sizes; paper authors of two of these studies provided this data.

| Number of studies included | 67 | 12 | 21 | 37 |
|---------------------------|----|----|----|----|

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