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► **To cite this version:**

Charlotte Lorand, Alexandre Robert, Adrienne Gastineau, Jean-Baptiste Mihoub, Carmen Bessa-Gomes. Effectiveness of interventions for managing human-large carnivore conflicts worldwide: Scare them off, don't remove them. *Science of the Total Environment*, 2022, 838, pp.156195. 10.1016/j.scitotenv.2022.156195 . hal-03883940

HAL Id: hal-03883940

<https://agroparistech.hal.science/hal-03883940>

Submitted on 13 Oct 2023

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Effectiveness of interventions for managing human-large carnivore conflicts worldwide: Scare them off, don't remove them

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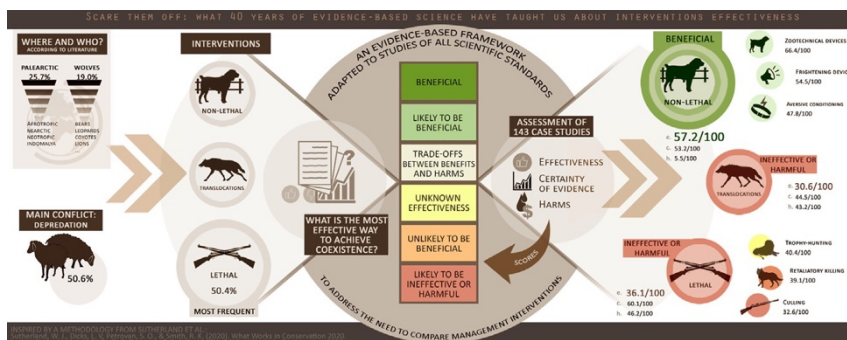
Keywords: Human-carnivore coexistence Lethal control; Non-lethal management Conservation interventions Effectiveness; Evidence-based

Manuscript published on
 Science of the Total Environment 838 (2022) 156195
<http://dx.doi.org/10.1016/j.scitotenv.2022.156195>

ABSTRACT

Human-wildlife conflicts are associated with a threat to large carnivores, as well as with economic and social costs, thus challenging conservation management around the world. In this study, we explored the effectiveness of common management interventions used worldwide for the purpose of conflict reduction using an evidence-based framework combining expert assessment of intervention effectiveness, impact and uncertainty of assessment. We first conducted a literature review of human-large carnivore conflicts across the world. Based on this review, we identified three main types of management interventions (non-lethal, translocations, and lethal management) and we assessed their effectiveness. Our review indicates that, although the characteristics of conflicts with large carnivores are heavily influenced by the local context and the species, the main issues are depredation on livestock, space-sharing, and attacks on humans. Non-lethal interventions are more likely to reduce conflict, whereas translocations and lethal interventions are mostly ineffective and/or harmful to carnivore populations, without fostering successful long-term coexistence. The literature on conflict management is often imprecise and lacks consistency between studies or situations, which generally makes comparisons difficult. Our protocol allows for the reliable comparison of experiments characterized by heterogeneous standards, response variables, protocols, and quality of evidence. Nevertheless, we encourage the use of systematic protocols with common good standards in order to provide more reliable empirical evidence. This would clarify the relative effectiveness of conflict management strategies and contribute to the global reduction in the occurrence of human-large carnivore conflicts across the world.

GRAPHICAL ABSTRACT



1. Introduction

Recent studies have revealed that the decline of biodiversity is more dramatic than previously thought, particularly when considering biomass and population decline in terrestrial invertebrates (Leather, 2018; Sánchez-Bayo and Wyckhuys, 2019) or population extirpation and range shrinking in vertebrates (Ceballos et al., 2017). Among vertebrates, large carnivores are globally declining because of the continuous human-induced fragmentation and destruction of wild habitats (Fernández-Gil et al., 2016; Maxwell et al., 2016; Proctor et al., 2005), the decrease in natural prey populations, and direct persecutions (Woodroffe and Ginsberg, 1998; Treves et al., 2010, 2016). Although the exact ecological role played by carnivores has been recently debated and may remain context-specific (Marris, 2014), they are still largely known to shape landscape structure and composition through the regulation of herbivore populations and their impact on vegetation (Atkins et al., 2019; Ripple et al., 2001; Ripple and Beschta, 2012). The combined effects of suitable habitats decline on the one hand and conservation efforts on the other hand can result in a local increase of large carnivores' population densities, intensifying the potential overlap with human territories and activities (Thirgood et al., 2005; Dickman, 2010; Jonzén et al., 2013; Chapron et al., 2014; Ordiz et al., 2014; Moss et al., 2016; Garshelis et al., 2020). Appropriate management solutions to mitigate conflicts that arise in co-occurrence situations (Harihar et al., 2013) are mandatory for preserving human interests and safety as well as conserving large carnivore populations and promoting coexistence (i.e., tolerance of the spatial and temporal overlap of human and large carnivore activities, not to be confused with co-occurrence, which refers to the overlap itself; Harihar et al., 2013; Gastineau, 2019).

We refer here to human-wildlife conflict as any interaction between wild animals and humans or their activities, with negative consequences for people, wildlife, or both. For humans, these negative consequences are tangible economic costs, direct costs in terms of human life, and also encompass an altered sense of well-being or a negative perception of coexistence (Khorozyan and Waltert, 2019). The intensity and emotional impact of the conflict are usually correlated with the size and charismatic status of the species involved (Naughton-Treves and Treves, 2005; Nyhus, 2016; Woodroffe and Frank, 2005). Specifically considering human-large carnivore conflicts, this bias stems from the presumption that large carnivores might be a danger to human life and/or livestock (Nyhus, 2016; Støen et al., 2018), not to mention their overall strong emotional impact rooted in a cultural and historical context of co-occurrence (Dickman, 2010; Woodroffe and Frank, 2005). Where prey depletion occurs, large carnivores might forage closer to habitations or predate on domestic animals more often, which can lead to even more constraints in the use of space (i.e., abandonment of grazing or recreational area) (Thirgood et al., 2005; Moss et al., 2016). Such proximity is susceptible to induce defensive behavior (e.g., for protecting cubs) (Coltrane and Sinnott, 2015; Herrero et al., 2005; Kojola and Heikkinen, 2012; Pătrașcu et al., 2015; Quenette et al., 2011; Rauer, 1999), and the resulting situations can lead to the injury or death of the carnivores involved (Khorozyan and Waltert, 2020; Lennox et al., 2018; Treves et al., 2009). Their conservation is therefore all the more complex, although it remains important both at the species level and in terms of their structuring role in ecosystems (Ripple et al., 2014).

The effectiveness of current conflict mitigation strategies is, however, frequently being challenged, due to important knowledge gaps and lack of consistent evidence regarding their effectiveness (Khorozyan and Waltert, 2020; Moreira-Arce et al., 2018). Due to this lack of support in decision-making processes, management interventions are often applied based on factors such as economical or logistical feasibility, ethics, and perception, rather than on proof-based evaluations (Van Eeden et al., 2018a). The choice of the most suitable intervention is nevertheless of primary importance to achieve the expected outcomes, such as damage reductions. Otherwise, inefficient intervention might become a financial burden or create social mistrust, ultimately hindering carnivore conservation (Dickman, 2010). Previous studies and reviews have identified great heterogeneity in the available information and scientific standards used for quantitative comparison (Khorozyan and Waltert, 2019; Lennox et al., 2018; Treves et al., 2019). To overcome this hindrance to solid proof-based evaluations, the authors of said reviews usually only considered case studies reporting experiments with high scientific standards (preferably "gold" or BACI). However, doing so led to the exclusion of numerous studies and may have discarded a large part of available information from quantitative analyses.

In this study we propose to assess the effectiveness of specific types of interventions used to reduce human-large carnivore conflicts, following an alternative standardized quantitative approach that will allow us to exploit a wider dataset. To this end, the generic features of these conflicts documented across the world

were first characterized through an analysis of the emerging literature. An evidence-based framework was then applied to specific case studies, inspired by the conservation evidence methods proposed by Sutherland and collaborators to evaluate and improve conservation strategies (www.conservationevidence.com, 2021). This approach enables the comparison of studies with different standards, thus extending the usable panel to be considered. For the purpose of consistency and consensus, and in line with other studies (Khorozyan and Waltert, 2019, 2020; Lennox et al., 2018; Moreira-Arce et al., 2018), we focused on three of the most used and documented interventions (i.e., lethal interventions, nonlethal interventions, and translocations), related to human-large carnivore conflicts at the global scale.

2. Methods

2.1. Literature search

To create an extensive overview of human-large carnivore conflict in literature (i.e., species, places, situations, management interventions), and a correct proxy for the entire body of literature available on the subject up to 2021, we performed a detailed search for peer-reviewed scientific literature in English, French and Spanish, on Thomson Reuters Web of Science, first with subject descriptors “human-wildlife conflict* OR humancarnivore* conflict*”, then narrowing the search with descriptors “conflict management OR translocation* OR non-lethal OR lethal control OR aversive conditioning OR conditioned taste aversion OR frightening device* OR repellent* OR deterrent* OR shock collar* OR zootechnical device* OR guarding animal* OR hunting OR culling OR retaliatory OR trophy-hunting OR depredation” and reduced the resulting set (N = 40,206) with descriptors “carnivore* OR predator* OR dingo* OR wolf OR wolves OR bear* OR puma* OR leopard* OR cheetah OR hyena* OR lynx OR tiger* OR lion* OR coyote* OR jaguar* OR wild dog*”. We performed a manual scanning of the remaining literature (N = 26,043) to eliminate off-subject items, and completed it using a “snowball” method through articles' references and suggestions from publishers' websites. The resulting database (N = 525) was read in full and origins, issues, and solutions to human-carnivore conflict were summarized. The combination of generic and specific keywords was assumed to minimize biases related to subjectivity and title matching.

2.2. Assessment of intervention effectiveness

2.2.1. Types of interventions

Based on the outcomes of the literature search, we defined three main categories of interventions currently used to address human-large carnivore conflict: non-lethal interventions, lethal interventions, and translocations (refer to Table 1 for details).

2.2.1.1. Non-lethal. This panel of interventions aims at preventing, altering, or removing unwanted behaviors (e.g., preying on domestic herds). It divides into three sub-techniques. First, aversive conditioning creates a learned association between negative experiences and specific unwanted behaviors, in the intention of inducing their long-term reduction (Shivik et al., 2003; Shivik and Martin, 2000), and relies on devices such as shock collars and radio-activated guards, or even on conditioned taste aversion. Second, frightening devices (repellents), usually visual or acoustic, as well as chemicals and projectiles, produce disruptive stimuli to immediately stop the predator's action through discomfort, pain, or neophobia. Third, zootechnical devices (deterrents) such as fences or livestock-guarding animals, usually target an entire area rather than specific behavior (Smith et al., 2000) and rely on permanent dissuasion.

2.2.1.2. Translocations. The International Union for Conservation of Nature (IUCN) defines translocation as “the human-mediated movement of living organisms from one area, with release in another.” Translocations of wildlife can be considered when damage-causing individuals (i.e., a recurrent livestock killer or an animal that poses an unquestionable threat to human safety) has been identified and usually when other management interventions to reduce the conflict have failed or are not applicable. Translocations entail substantial logistical and economical costs, require preliminary studies to minimize the potential impacts on the targeted ecosystems, and must be conducted in the indigenous range of the species (IUCN/SSC, 2013; Weise et al., 2014; Boast et al., 2016).

Table 1. Interventions formally assessed in this paper, their specificities, and associated references.

Strategy	Intervention	Sub-technique	Methods	Species	Reference
Reactive	<u>Non-lethal</u>	<u>Aversive conditioning:</u> associating a specific unwanted behavior with a negative experience to induce learning and avoidance in the targeted individual	Conditioned taste aversion, chemicals, shock collars, radio-activated guards	Wolves, coyotes, bears, others	Bangs, 2006 Bourne, 1982 Breck, 2006 Burns, 1980 Cornell, 1979 Dorrance, 1975 Ellins, 1977 Gehring, 2006 Gustavson, 1976 Hawley, 2009 Jelinski, 1983 Leigh, 2008 Mason, 2001 Miller, 1978 Rossier, 2012 Shivik, 2003 Smith, 2000 Williamson, 2002 Wooldridge, 1976
Reactive		<u>Frightening devices:</u> immediate disruption of unwanted behavior	Projectiles, gas exploders, chasing, yelling	Wolves, coyotes, leopards, bears, pumas, others	Bangs, 2006 Beckmann, 2004 Linhart, 1993 Mason, 2001 Mazur, 2010 Naha, 2020 Ohrens, 2016 Petracca, 2012 Rauer, 2003 Smith, 2000 Stenhouse, 1983 Wooldridge, 1975
Preventive		<u>Zootechnical devices:</u> permanent dissuasion to prevent unwanted behavior in a given zone	Husbandry, guarding animals, fences, fladry, irregular alarms	Coyotes, cheetahs, jaguars, leopards, lions, wolves, lynx, bears, others	Ausband, 2013 Cavalcanti, 2012 Davidson-Nelson, 2010 Davies, 1992 Dorrance, 1976 Garrote, 2012 Gehring, 2006, 2010 Hazzah, 2014 Kassilly, 2007 Kesch, 2014 Khorozyan, 2010, 2017 Kissui, 2019 Lichtenfield, 2014 Manoa, 2015 McManus, 2013 Meadows, 2009 Musiani, 2004 Nass, 1988 Ogada, 2003 Potgieter, 2016 Rust, 2013 Spencer, 2020 Stone, 2017 Van Bommel, 2012 Viollaz, 2021 Wang, 2018 Weise, 2018 Woodroffe, 2007 Wooldridge, 1978
Reactive		<u>Translocations:</u> “The human-mediated movement of living organisms from one area, with release in another” (IUCN, 2014), usually targeting damage-causing animals to stop unwanted behavior.		Leopards, wolves, tigers, bears, lions, jaguars, pumas, lynx, hyenas, cheetah, others	Athreya, 2011 Bangs, 2006 Boast, 2016 Bradley, 2005 Brichieri-Colombi, 2015a, 2015b, 2015c Dhungana, 2016 Linnell, 1997 Massei, 2010 Viollaz, 2021 Voyles, 2015 Weilenmann, 2010 Weise, 2014 Wolf, 1996
Reactive	<u>Lethal</u>	<u>Culling:</u> regular hunting of non-specific individuals (usually mature) with the purpose of limiting the local population		Wolves, coyotes, lynx, bears, pumas, others	Bangs, 2006 Bergstrom, 2014 Chapron, 2016 Creel, 2010 Garshelis, 2020 Herfindal, 2005 Huygens, 2004 Louchouart, 2021 Poudyal, 2016 Raithel, 2016 Robinson, 2014 Teichman, 2016 Treves, 2009, 2010, 2016 Wagner, 1999 Wielgus, 2014
Reactive		<u>Retaliatory killing:</u> specific targeting of a damage-causing individual to stop unwanted behavior		Wolves, bears, leopards, coyotes, lynx, others	Bangs, 2006 Blejwas, 2002 Harper, 2008 McManus, 2013 Raithel, 2016 Santiago, 2020 Smith, 2012 Stahl, 2001 Swan, 2017 Swanepoel, 2014 Viollaz, 2021 Woodroffe, 2005
Reactive		<u>Trophy hunting:</u> hunt for sport, usually targeting specific individuals for their physical attributes, but possibly targeting damage-causing animals to stop unwanted behavior		Lions, leopards, others	Di Minin, 2016 Funston, 2013 Lindsey, 2006 Loveridge, 2016 Muposhi, 2017 Swanepoel, 2014

2.2.1.3. Lethal. Lethal interventions cover all means to manage conflicts by killing individuals, either to control the size of predator populations, or to decrease the societal tension of the conflict (e.g., retaliatory killing). Lethal interventions can either be targeted toward damage-causing individuals, specific types of individuals in a population, or random individuals from the focal species. Some authors distinguish culling from hunting depending on whether the animal is killed by a governmental agency or a private citizen (Treves et al., 2016). Here, we did not make this distinction, instead focusing on differences in the killing process itself. For example, randomly killing several individuals at once or targeting a specific individual might not have the same consequences in terms of both the damage reduction and the eco-evolutionary dynamics of predator populations. Hence, we divided lethal interventions into the following subcategories:

(i) culling, i.e., hunting individuals up to a pre-determined amount to impose official limitations on the predator population (randomly or based on sex and age); (ii) retaliatory killing that targets specific and usually damage causing individuals; and (iii) trophy hunting, in which governmental authorities and/or agencies provide permits to private sport hunters (often focusing on individuals with remarkable features).

All these interventions are important components of the wider framework of remediation strategies, which are the main types of response currently employed to address conflict worldwide (summarized in Fig. 1; Kartika and Koopmans, 2016). First, (i) preventive strategies are aimed at preventing conflict before it even arises, and include landscape engineering, prey management, husbandry (including zootechnical devices), and the creation of protected areas. Once the conflict has arisen, (ii) reactive strategies are intended to reduce the impacts of large carnivores through non-lethal interventions, lethal interventions, and translocations. Meanwhile, (iii) mitigation strategies can be put into place to reduce the severity of the conflict through counterbalancing with compensation programs. Finally, (iv) integrated programs are meant to combine all the previous methods and help facing the impacts of co-occurrence by integrating carnivores in a framework including human activities and local economy.

This scheme in hand, we extracted from the 525 articles those i) describing specific interventions instances, or experiments based on these interventions, ii) focusing on human-large carnivore conflict management, and conducted on iii) wild large carnivores as described by Ripple et al. (2014) (i.e., weighing more than 15 kg on average), iv) with protocols and outcomes, and regardless of the scientific standards. We compiled a database of 103 articles matching these criteria, for a total of 143 “case studies” (19 articles presented several distinct case studies, sometimes involving multiple zones, species, issues/situations, interventions).

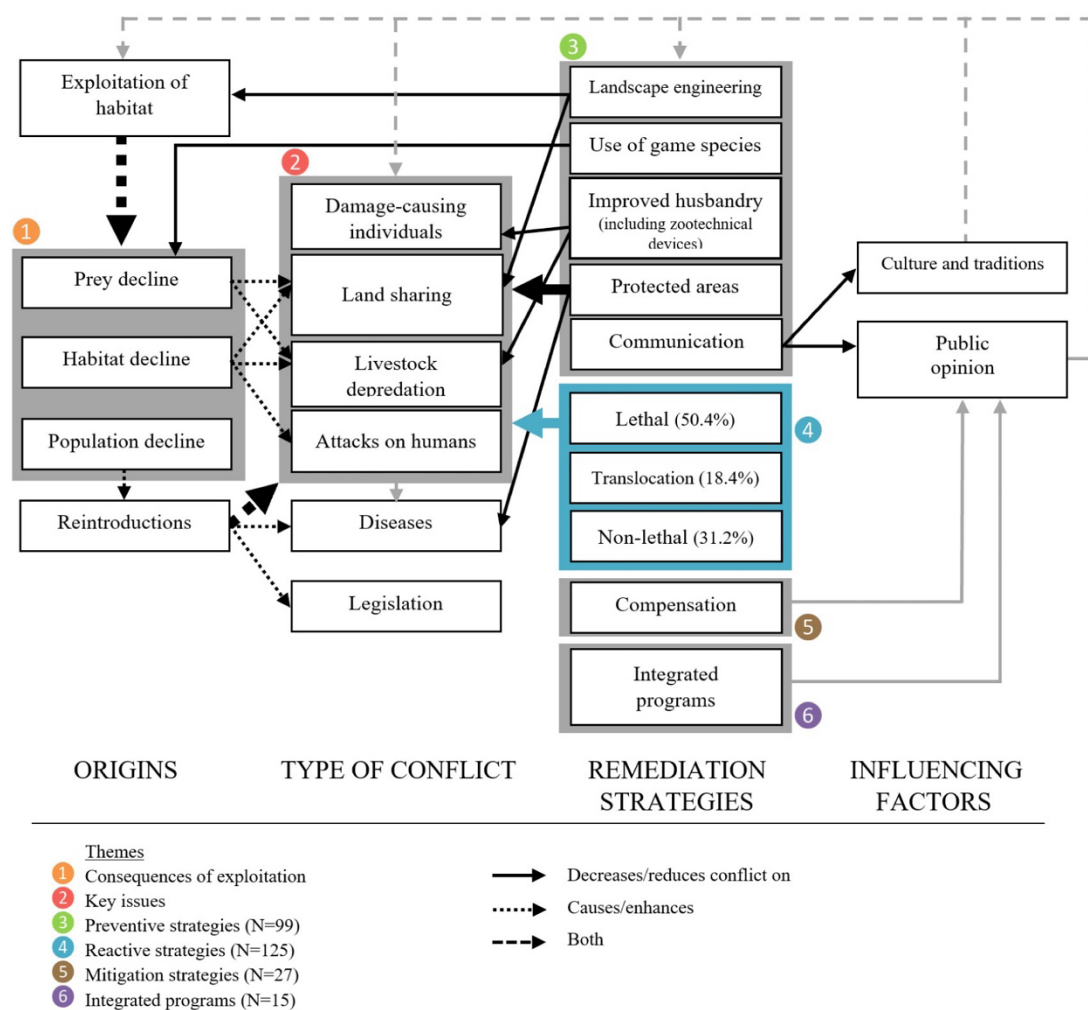


Fig. 1. Overview of main sources, issues, and response strategies relating to human-large carnivore conflicts according to literature (N = 525).

2.2.2. Evaluating success: “What works in conservation practices”

Many definitions and criteria have been used to characterize the success of large carnivore management interventions (e.g., translocations costs or reproduction outputs; Massei et al., 2010; Weise et al., 2015b; Lennox et al., 2018), although not all are relevant to our research question. We defined success as the durable (preferably months or years before a new occurrence; Khorozyan and Waltert, 2019; Rossler et al., 2012; Shivik et al., 2003; Miller et al., 2016; Bangs et al., 2006) reduction of the negative consequences resulting from human-large carnivore co-occurrence after the implementation of the intervention.

Drawing on the evidence and interpretations provided by the authors of the original case studies, each case was blindly and independently assessed by three out of a panel of five academics specialized in conservation ecology. In this process, in line with the features, evidence and conclusions provided by the original author, each evaluator attributed quantitative scores to indicate the reported effectiveness of the intervention (criterion 1, “Effectiveness”), the evaluated certainty of the conclusions given the quality of evidence provided by the author (criterion 2, “Certainty of evidence” or CoE), as well as the reported negative side effects (criterion 3, “Harm”).

In line with our definition of success, the first criterion (Effectiveness) was assessed as a reduction in the negative impacts of large carnivores' activity on human livelihood after implementing the intervention, based on the reported outcomes of each case study, and supported by complementary clues such as whether the sources or impacts of the conflict were removed or reduced, whether the conflict was delocalized, and the length of time before recurrence. When an intervention was effective only in the short term or the conflict was delocalized, the score was lower. The quality of evidence provided by the authors (criterion 2, CoE) was scored with specific attention paid to scientific standards (e.g., lower scores when purely qualitative, small sample size, or absence of control group), study designs, peer-review, and solidity of evidence (i.e., non-significance, small effect size).

Finally, to reflect proper conflict resolution, criterion 3 (Harm) combined two potential types of harm, namely: criterion 3a, “harm to the large carnivore population” (HP), including potential ecological damage to the life and integrity of individuals or the viability of the entire population; and criterion 3b, “harm to cohabitation” (HC), including economic damage and impacts on human tolerance. These two criteria were then averaged to obtain an equivalence to the criterion 3 “Harm” score proposed by Sutherland et al. (2020).

The scores ranged from 0 to 100 for each criterion (Effectiveness: 0% = not effective, 100% = highly effective; CoE: 0% = no evidence, 100% = high-quality evidence and complete certainty; Harm: 0% = none, 100% = major undesirable effects; Sutherland et al., 2020). Based on the mean scores of the case studies in each intervention category (i.e., non-lethal, translocations, lethal), the interventions were classified according to one of the six success categories defined by Sutherland et al. (2020): beneficial, likely to be beneficial, trade-offs between benefits and harm, unknown effectiveness, unlikely to be beneficial, and likely to be ineffective or harmful. In most cases, the intervention category would be considered effective with a mean effectiveness score above 40/100, and harmful with a mean harm score above 20/100. The minimum threshold for good evidence (CoE) would usually be 40/100 (Sutherland et al., 2020).

2.3. Data analysis

To assess the consistency of the evaluators' scores (i.e., variability and means), their repeatability was analyzed based on 1000 parametric bootstraps as implemented in the rptR package of R (Stoffel et al., 2018). The statistical significance of the repeatability of each metric was tested by a likelihood ratio test that compared the model fit with and without a grouping factor (here, the case study ID).

In addition to the scoring consistency of evaluators, we investigated whether average Effectiveness, CoE, HC, and HP scores changed over the time period covered by our study cases (1975–2021) or differed according to the intervention considered (lethal and non-lethal interventions, translocations). We modeled the scores for the four metrics as functions of the intervention type and time (year of publication of the case study) based on the mixed-effects linear regression models with the evaluator ID and case study ID used as random factors and the intervention type and publication year respectively incorporated as qualitative and quantitative fixed-effects explanatory variables. Models were implemented using the lmer function of the lme4 R package (Bates et al., 2015).

3. Results

3.1. Features of human-large carnivore conflicts around the world

From our literature search, we examined 525 articles describing the features of human-large carnivore conflict and found a great heterogeneity in numbers of published studies depending on the geographic location of the conflict, as well as the species involved (refer to Appendix 1 for details).

3.1.1. Geographic range

Literature was skewed toward conflicts in the Palearctic (25.7%), Nearctic (22.9%), and Afrotropic (22.5%). Conflicts in the Indomalaya (8.4%), Neotropic (7.0%), and Australasia (2.1%) were reported more rarely.

3.1.2. Species involved

The frequency of involvement in reported conflicts depending on the species (total of 13 species) was highly unbalanced toward wolves (*Canis lupus*, 19.0%), bears (*Ursus sp.*, 15.0%) and leopards (*Panthera pardus*, 12.6%). Among the other species, lions (*Panthera leo*, 9.3%) were the most frequently dealt with, followed by tigers (*Panthera tigris*, 6.7%), pumas (*Puma concolor*, 5.1%) and coyotes (*Canis latrans*, 5.1%). Other species such as lynx (*Lynx lynx*), hyenas (*Hyaena sp.*) or cheetah (*Acinonyx jubatus*) were found in 5.0% of the articles or less (Fig. 2).

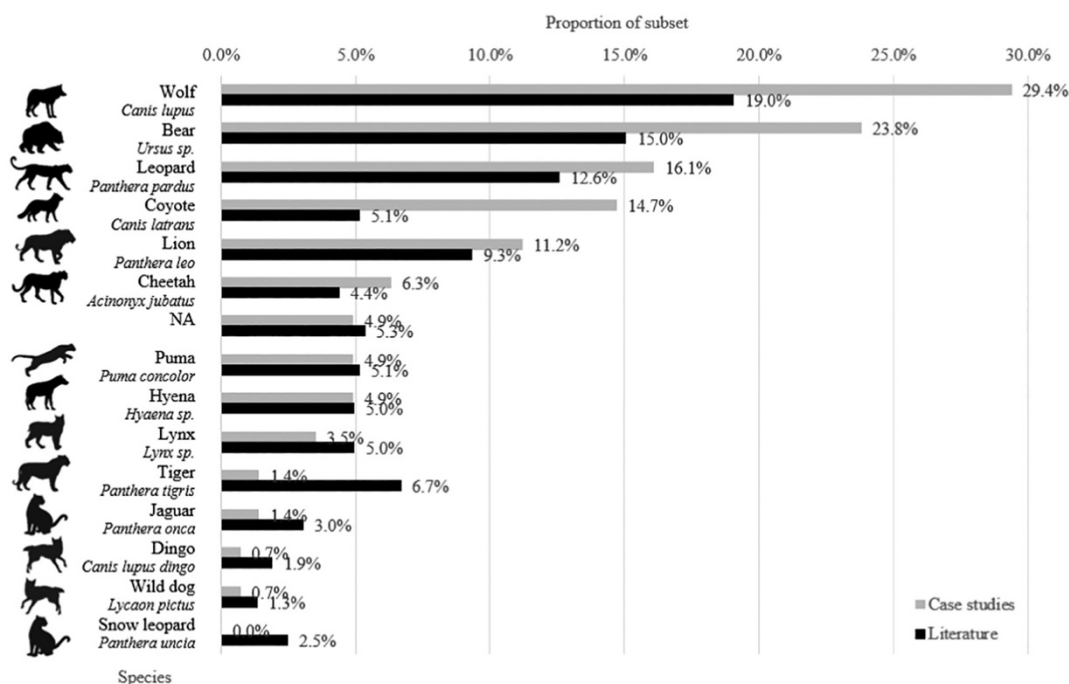


Fig. 2. Species prevalence in literature (black bars, N = 525) and case studies (gray bars, N = 143).

3.1.3. Types of conflicts and impacts

By far, depredation on livestock was the major issue depicted in literature, reported in 25.0% of all the articles considered (N = 525), and 50.6% of articles describing conflict (N = 259; see Fig. 1 for details and main findings), all disregarding the species involved. The other predominant issues were the management of damage-causing individuals, attacks on humans (both 8.5%), urban coexistence, legislative disagreement or disease control.

3.1.4. Remediation strategies

In the whole panel of articles focusing on specific remediation strategies (N = 266; Fig. 1), preventive and reactive strategies were the most documented (37.2% and 47.0%, respectively). In particular, reactive strategies have been used historically, with a predominance of lethal control (50.4%). Meanwhile, mitigation strategies and integrated programs were less documented (10.2% and 5.6%, respectively).

3.2. Effectiveness assessment

We assessed 143 case studies (selected according to the method described in Section 2.2) from 103 articles (listed in Appendix 3) published between 1975 and 2021. Overall, 57.3% (N = 82) of the case studies focused on non-lethal interventions, of which 35.4% on aversive conditioning (N = 29), 22.0% on frightening devices (N = 18), and 4342.74% on zootechnical devices (N = 35). Translocations and lethal interventions made for 18.2% and 24.5% of the case studies (N = 26 and N = 35 respectively) and among lethal interventions, 48.6% investigated culling (N = 17), 34.3% retaliatory killing (N = 12), and 17.1% trophy-hunting (N = 6).

Contrary to the whole body of literature, most of these case studies were located in the Nearctic (63.6%) followed by the Afrotropic (24.5%) and Palearctic (7.7%) (Fig. 3). Nonetheless, the species included in the case studies reflected the general findings, with most of the management experiments being conducted on wolves (29.4%) followed by bears (23.8%) and leopards (16.1%) (Fig. 2). Surprisingly, almost none of the experiments were conducted on tigers, despite their strong presence in the whole literature and their heavy impact, including attacks on humans (Dhungana et al., 2016).

Each of the four criteria considered in the assessment received 429 scores (Effectiveness, CoE, HC, and HP; Table 2) (refer to Appendix 4 for all scores).

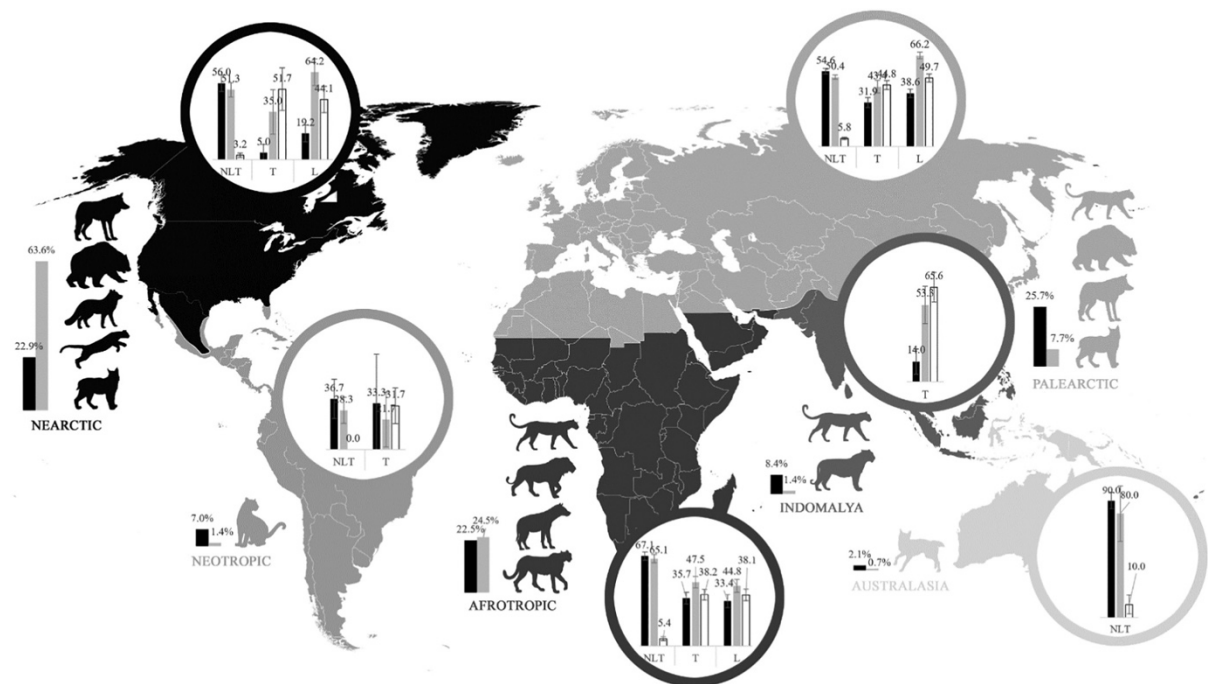


Fig. 3. Geographic prevalence in literature (black bars, N = 525) and case studies (gray bars, N = 143), with species involved per geographic area. In circles, mean results of effectiveness (black bars), certainty of evidence (gray bars) and harm (white bars) assessments for each geographical area (NLT: non-lethal interventions; T: translocations; L: lethal interventions).

3.2.1. Effectiveness

The most effective interventions were found to be non-lethal interventions (mean score = 57.2/100, “Likely to be beneficial”), and more specifically, zootechnical devices (mean score = 66.4/100 “Likely to be beneficial”). Aversive conditioning and frightening devices were both assessed as “Likely to be beneficial,” with intermediate effectiveness (mean scores = 47.8/100 and 54.5/100, respectively). By contrast, translocations and lethal interventions were found largely ineffective (mean scores = 30.6/100 and 36.1/100, respectively). The least effective lethal subtechnique was culling, with a mean score of 32.6/100 (“Likely to be ineffective or harmful”), and none of them exceeded the effectiveness threshold of 40.0/100 (retaliatory killing = 39.1/100 and trophy-hunting = 40.4/100).

3.2.2. Certainty of evidence

The mean CoE observed in our case studies ranged from 38.1/100 (trophy-hunting) to 68.5/100 (culling), with an overall average of 53.7/100. Zootechnical devices, retaliatory killing and culling experiments provided the most solid evidence, whereas the effectiveness of trophy-hunting, aversive conditioning and translocations was less certain.

Table 2. Results of the effectiveness assessment. Numbers within brackets correspond to the 95% interval of each distribution (main interventions in bold).

Intervention	Effectiveness	CoE	HC	HP	Category
Non-lethal	57.2	53.2	5.7	5.3	Likely to be beneficial
	[55.5;58.7]	[51.8;54.5]	[4.7;6.5]	[4.5;6]	
Aversive conditioning	47.8	45.2	6.9	7.5	Likely to be beneficial
	[44.7;50.8]	[42.9;47.4]	[5.2;8.5]	[5.9;9]	
Frightening devices	54.5	55.4	8.7	6.5	Likely to be beneficial
	[51.4;57.5]	[52.5;58.1]	[6.2;11.2]	[4.7;8.2]	
Zootechnical devices	66.4	58.7	3.3	3.2	Likely to be beneficial
	[64.1;68.6]	[56.7;60.7]	[2.2;4.2]	[2.2;4.1]	
Translocations	30.6	44.5	37.2	49.3	Likely to be ineffective or harmful
	[28;33.1]	[41.7;47.1]	[34;40.2]	[46;52.5]	
Lethal	36.1	60.1	32.3	60.2	Likely to be ineffective or harmful
	[33.6;38.4]	[57.8;62.4]	[28.9;35.6]	[57.4;62.8]	
Culling	32.6	68.5	39.6	64.5	Likely to be ineffective or harmful
	[29.1;36]	[65.7;71.3]	[34.4;44.8]	[60.5;68.4]	
Retaliatory killing	39.1	59.3	30.5	61.0	Likely to be ineffective or harmful
	[34.9;43.1]	[56.3;62.2]	[25.2;35.7]	[56.3;65.6]	
Trophy-hunting	40.4	38.1	14.3	47.0	Unknown effectiveness
	[33.3;47.3]	[30.9;45.1]	[7.4;21.1]	[40.3;53.6]	

3.2.3. Harm

High disparities between interventions outcomes were found regarding harm on large carnivore populations (HP) and cohabitation (HC). Indeed, while non-lethal interventions showed low harm scores (mean score = 6.0/100) below the threshold of 20.0/100, translocations and lethal interventions were generally found harmful (mean scores = 43.2/100 and 42.8/100, respectively), with culling qualifying as the most damaging sub-technique (52.1/100).

Repeatability analysis indicated that the case study assessments were generally consistent between evaluators. The repeatability of scores ranged from 0.35 to 0.73, and all differed significantly from zero (Table 3). Further analysis based on mixed-effects regressions according to the type of intervention still held true even when accounting for the evaluator. Considering lethal interventions as the intercept of the regression model, results indicated that non-lethal interventions were associated with higher effectiveness ($\beta = -24.2 \pm 4.8, p < 10^{-4}$), less harm on cohabitation ($\beta = -24.02 \pm 4.4, p < 10^{-4}$) and less population harm ($\beta = -54.1 \pm 3.49, p < 10^{-4}$), and that translocations led to more harm on cohabitation ($\beta = 9.29 \pm 4.3, p = 0.03$) ($\beta = 17.6 \pm 7.3, p = 0.02$) and less population harm ($\beta = -10.5 \pm 4.21, p = 0.01$). Using regression models weighted by CoE to assess the effectiveness, HC, and HP scores, we found similar results for effectiveness, qualitatively similar effect of non-lethal interventions for HP and HC, but no more significant effects of translocations on HP and HC (refer to Appendix 2 for details).

Table 3. Median repeatability (R) of Effectiveness, certainty of evidence (CoE), harm to cohabitation (HC), and harm to the large carnivore population (HP) scores. Lower and upper confidence intervals (CI) are the 2.5% and 97.5% percentiles, respectively, and p-val is the p-value of the likelihood ratio test.

	R	Lower CI	Upper CI	p-val
Effectiveness	0.70	0.62	0.76	$<10^{-4}$
CoE	0.38	0.27	0.47	$<10^{-4}$
HC	0.35	0.22	0.46	$<10^{-4}$
HP	0.73	0.64	0.79	$<10^{-4}$

3.3. Accuracy of research and quality of evidence

The overall assessment of the three types of interventions presented a correct level of confidence, with scores ranging from 38.1 (trophy hunting) to 68.5/100 (culling). In the regression models, CoE was the only metric showing a significant effect with time (year of publication of each case study), with an increase observed from 1975 to 2021 (Fig. 4).

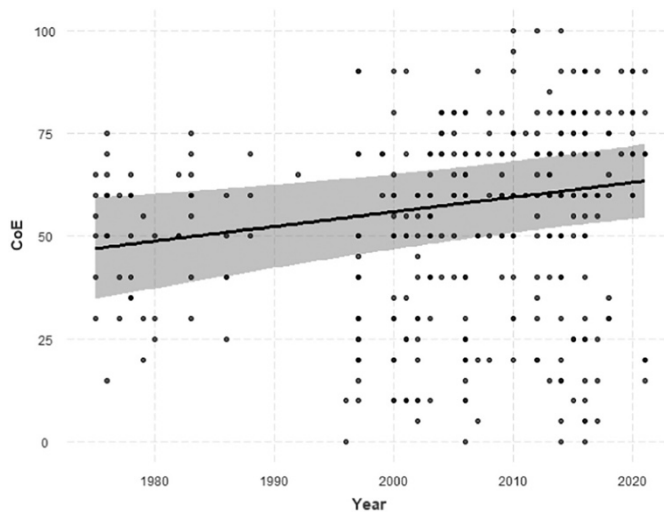


Fig. 4. Certainty of evidence (CoE) in our case studies depending on the year of publication. Black dots represent raw data (score provided by evaluators for all case studies). The black line is the prediction line obtained from CoE modelling, with the 95% confidence interval in gray.

4. Discussion

Contrasting with the frequent use of carnivore removal (i.e. lethal interventions and translocations), our evidence-based assessment revealed that they are outperformed by non-lethal interventions, which were likely to be beneficial and with limited impact on carnivore populations, whereas carnivore removal was often ineffective and/or harmful.

4.1. Human-large carnivore conflict management interventions in present literature

In our study, the literature focusing on solving human-large carnivore conflicts over-represented Europe and, to a lesser extent, the Nearctic and Africa (Fig. 3), a geographic imbalance also observed in similar metareviews (e.g., Van Eeden et al., 2018a, 2018b; Eklund et al., 2017; Miller et al., 2016). Similarly, the most documented species were wolves, bears, and tigers (Fig. 2). Although this imbalance may be partially explained by an unintended bias in the choice of keywords or languages, it still highlights real heterogeneity in the conflicts reported with large carnivores as well as ways to solve them. Beyond the literature search choices made here, geographic and species bias are likely to reveal variations in the deployment of management interventions due to the available resources for both solving conflicts and conducting and publishing research, regardless of the severity of the conflict.

The main topic dealt with in literature was depredation on livestock (as underlined by Van Eeden et al., 2018a; Van Eeden et al., 2018b; Eklund et al., 2017; Miller et al., 2016; Treves et al., 2016; Lennox et al., 2018; Moreira-Arce et al., 2018), followed by other topics of concern such as attacks on humans and urban coexistence. The relative difference in the topics of concern indicates that the severity of the conflict not only depends on the gravity of the impact but also on its frequency (e.g., attacks resulting in human death are more difficult to tolerate but much rarer than livestock killing, which affects the everyday life of a landowner and endangers their income). Even though the number of case studies included in our assessment was rather equivalent for lethal interventions, translocations, and non-lethal interventions, lethal interventions remain the most widely used interventions reported in literature.

4.2. Quality of evidence in human-large carnivore conflict studies

Our assessment of the effectiveness of management interventions revealed disparities in the mean confidence level of the studied cases (38.1–68.5/100): we encountered considerable variations in protocols and, most importantly, the lack of rigorous experimental designs. “Gold standards,” as described by Treves et al. (2016) (i.e., “random assignment to control and treatment groups with experimental designs that avoid biases in sampling, treatment, measurement, or reporting”), were rarely achieved. Experimental protocols are often more likely to be implemented opportunistically and irrespective of the possibility to accurately make rigorous scientific assessment, for instance to fulfill existing policies (especially for lethal interventions), and often all requirements cannot be satisfied in field conditions (because of restrictions in means, time, or social equity and ethics), as opposed to a carefully planned and developed protocol for the purpose of evidence-based research (more often using non-lethal interventions, as these are less commonly acknowledged as being useful and need scientific backup to be implemented). Hence, BACI (Before– After and Control–Impact) designs tend to be more frequent. Nevertheless, the confidence level of studies documenting conflict from 1975 to 2021 significantly increased over time (Fig. 4). Many articles published before 2000 were mostly descriptive, whereas recent articles provided greater precision when describing the consequences of management and reported more quantitative evidence and analyses. They were also more likely to use systematic experiments with more rigorous methodologies and reporting.

4.3. Quality of evidence and hindrances to evidence-based science

The literature dealing with human-large carnivore conflict quantifies conflict in many different ways, with a lack of agreement among practitioners even regarding terms, concepts, and most of all the metrics of an intervention’s success (e.g., survival, reproduction, damage costs; Linnell et al., 1997; Massei et al., 2010). In the present article, success is defined as a function of the negative consequences resulting from human-large carnivore co-occurrence after the implementation of an intervention. However, few studies detailed the effects of the interventions on the actual conflict, and they rarely reported any changes in the metrics at the end of experiments (see also Miller et al., 2016) or only for a short duration, thus resulting in insufficient follow-up of the conflict reduction (Khorozyan and Waltert, 2019; Linnell et al., 1997) and/or the potential harm inflicted on large carnivore populations over the long term. The heterogeneity of case studies in terms of protocols, response variables, and metrics is also a major hindrance in the available literature.

Overall, this inconsistency in the reporting of management outcomes means that many experiments are anecdotal and/or impossible to compare. Assessing the effectiveness of management interventions thus proves to be all the more complex. Many cannot be taken into account in protocols requiring more rigorous approaches, as discussed in previous reviews (Linnell et al., 1997, and more recently, Van Eeden et al., 2018a; Eklund et al., 2017; Miller et al., 2016; Treves et al., 2016; Khorozyan and Waltert, 2020; Treves et al., 2019). Consequently, the authors of these reviews based their assessments on case studies reporting experiments with high scientific standards (preferably “gold” or BACI). These assessments included conventional approaches such as risk ratio (Eklund et al., 2017), “magnitude of change” based on response variables (Miller et al., 2016), standardized mean differences (Van Eeden et al., 2018a), or mere counting (Treves et al., 2016).

However, consensus regarding effectiveness of mitigation strategies to solve human-large carnivore conflict must be given to operational agents in as little time and as much accuracy as possible. The method proposed by Sutherland and adapted in this paper stands as an attempt to reach a middle ground between the precision of high-quality standards experiments, and the availability of an abundance of qualitative resources, to give an accurate overview of global findings to date. It enables the comparison of experiments

with different qualities of evidence through the “certainty of evidence” score, which allows the assessment of articles irrespective of their scientific standard. This approach allowed us to expand the scope of our review and encompass a large diversity of interventions. The availability of our scores data (Appendix 4) allows other researchers and managers to use it to increase the number of scores and case studies and thus continue to evaluate methods for managing these conflicts.

4.4. Effectiveness of human-large carnivore conflict management interventions

4.4.1. Lethal interventions

Despite the weak evidence about their capacity to effectively reduce conflicts, lethal interventions are still the most frequently used, promoted in the literature as generally successful, and are even regarded as an incentive to finance large carnivore conservation (Funston et al., 2013; Lindsey et al., 2007; Treves and Martin, 2010). Although lethal interventions could increase local tolerance in the short term by removing the perceived threat, whether a damage-causing animal or not, the literature generally focuses on the potential harm of hunting carnivore populations while remaining comparatively vague about its likeliness to solve conflict (Khorozyan and Waltert, 2020; Lennox et al., 2018). Carnivore removal is assumed to fall under the compensatory mortality hypothesis (i.e., by easing intraspecific competition), and offtakes are thus assumed to do no harm to carnivore populations (Robinson et al., 2014). However, lethal control must be regularly repeated (Khorozyan and Waltert, 2020), which maintains the ongoing conflict (Creel and Rotella, 2010) and often fails to reduce the impacts of damage-causing individuals (Huygens et al., 2004), since targeting a specific individual is challenging, if not nearly impossible (Treves et al., 2016).

Finally, lethal control of individuals has been shown to increase damage by perturbing the social structure of large carnivore groups through the loss of breeder individuals (Stahl et al., 2001; Teichman et al., 2016). This can alter the behavior of carnivores by favoring infanticide and recolonization (Bangs et al., 2006; Steyaert et al., 2012; Teichman et al., 2016), thus intensifying the conflict and worsening the threat to carnivore conservation.

4.4.2. Translocations

Since translocations avoid the killing of damage-causing animals, they are quite popular and widely used at a global scale: for example, 700 translocation programs for all types of animals were already operated in North America in 1996 (Wolf et al., 1996). However, animal translocations are expensive (Linnell et al., 1997) and require specific studies to ensure the suitability of the release site and minimize the risk of spreading diseases to humans, wildlife, or livestock (Massei et al., 2010). More importantly, our results indicate that translocations were found ineffective at solving conflicts and could even be harmful to carnivore populations. Empty territories left by translocated individuals are quickly colonized by other conspecifics, and similarly to lethal interventions, translocations can induce behavioral changes in territorial species or disturb social structures, leading to infanticides (e.g., lions, bears) or pack break-up (e.g., wolves) (Dhungana et al., 2016). Regarding translocated individuals, the mortality probability during the translocation process or after release is high (Dhungana et al., 2016; Linnell et al., 1997; Weilenmann et al., 2010; Weise et al., 2015a; Weise et al., 2015c). Translocated animals may display extensive post-release movements due to intense prospecting in their new environment or homing behavior back to more familiar places (Le Gouar et al., 2011). These behaviors result in suboptimal energy allocation for their vital requirements such as feeding, and lead to a substantial amount of road kills (Linnell et al., 1997; Massei et al., 2010).

4.4.3. Non-lethal interventions

Non-lethal interventions were usually reported as less employed than animal removal, which might be because they are more resource consuming in terms of both time and money, more complex to design, and may not provide as much primary appeasement to local communities as killing the animal viewed as responsible for the damage. However, non-lethal interventions were found to be more effective at solving conflict than both lethal interventions and translocations. The successful repelling of damage-causing animals by scaring them away from specific areas confirms that wildlife and especially large carnivores are sensitive to environmental changes and tend to avoid potential dangers (Smith et al., 2000). This type of intervention could be reinforced in some species through learning by the transmission of behaviors

between individuals (e.g., Black bear *Ursus americanus*; Hopkins and Kalinowski, 2002; Noyce and Garshelis, 2014). Nonetheless, several issues were raised in the case studies: many reported habituation behaviors, with animals becoming familiar with the repellent devices, whether permanent (aversive conditioning) or sporadic (frightening devices). Aversive conditioning and frightening devices might have been considered to be very effective, but experiments conducted over several years showed the lack of long-term effectiveness (Khorozyan and Waltert, 2019; Shivik et al., 2003). Results varied greatly, from habituation to fladry after a few weeks (Bangs et al., 2006) to electric collars effective for 4 months on coyotes and wolves (Rossler et al., 2012). Miller et al. (2016) suggested the existence of a trade-off between the momentary effectiveness of a non-lethal tool and its long-term effectiveness. Therefore, aversive conditioning through the systematic and continuous repelling of unwanted behavior would be more effective over the long-term than opportunistic frightening devices. Our assessment, however, did not reveal any significant differences between these techniques, partly because of the lack of precision about long-term effectiveness in the literature. Moreover, targeting specific behavior is also difficult: taste aversion, for instance, affects food consumption rather than livestock killing (Mason et al., 2001; Shivik et al., 2003), and strategies such as equipping live animals with a combination of taste-aversion devices and visual/olfactory stimuli to enhance association could be employed to maximize effectiveness (Read et al., 2016; Snijders et al., 2021). Aversive conditioning might tend to make large carnivores avoid the device itself rather than the whole area to be protected (Shivik et al., 2003). Furthermore, some limits can arise from technical implementations: for instance, several intervention types involved the collaring of animals, which is costly and requires specific training for proper use (Williamson et al., 2002). Regarding zootechnical devices, guarding dogs have notably been reported harassing livestock, hunting and killing target and non-target species in various occasions (Woodroffe et al., 2006; Urbigkit and Urbigkit, 2010; Marker et al., 2015; Potgieter et al., 2016; Viollaz et al., 2021). However, Whitehouse-Tedd et al. (2020) also suggest that when properly trained, guarding dogs are able to discriminate target species, with limited non-lethal incidents involving predators due to defensive behavior, and lethal incidents on herbivores that can be limited by corrective training. Spencer et al. (2020) also report that the presence of guarding dogs does not significantly affect carnivores' spatial distribution. Overall, more research remains necessary to investigate the impact of guarding animals on carnivore populations and nontarget species. The main issues encountered with zootechnical devices thus relate to behavioral problems, to purchasing and maintenance costs of a sufficient number of adequate tools and/or animals (depending on the country, dogs are often offered or funded by NGOs or governments programs, or for research purposes; Gehring et al., 2010; Van Bommel and Johnson, 2012; Rust et al., 2013; Marker et al., 2015; McManus et al., 2015; Spencer et al., 2020), and to the availability of proper training (Marker et al., 2015; McManus et al., 2015; Khorozyan et al., 2017; Whitehouse-Tedd et al., 2020). However, guarding animals remain truly effective, provide a constant deterrence over a large area, and their mobility and independence enable them to target predation and induce learned behavioral responses of avoidance in large carnivores (McManus et al., 2015; Spencer et al., 2020).

4.5. Recommendations, background, and opinions

According to our results and in agreement with similar studies, zootechnical devices and non-lethal interventions would be more effective in mitigating conflict than the translocations and killing of large carnivores to mitigate human-large carnivore conflict (Eklund et al., 2017; Khorozyan and Waltert, 2019, 2020; Moreira-Arce et al., 2018; Treves et al., 2016). They would also ensure permanent dissuasion over a large area (Shivik et al., 2003) and often be cheaper over the long term (Weise et al., 2015b). We therefore advocate their use, while removal interventions should only be used when absolutely necessary, as they are likely to worsen the situation in many cases and require context-specific preliminary evaluation (especially as the response to lethal control varies between species, Lennox et al., 2018). The combination of several sub-techniques is likely to be more effective than a single one (Miller et al., 2016): for instance, radio-activated guards can be implemented with shock collars (Mason et al., 2001; Shivik and Martin, 2000) or used only for detection purposes followed by the actions of landowners to scare away the large carnivores (Williamson et al., 2002). As proposed by Miller et al. (2016), if the effect of the combined interventions continues, then an optimal strategy across different systems and species could involve implementing a baseline step by step (here, for depredation conflicts) with (i) preventive measures (e.g., electric fences, livestock guardian dogs), (ii) supplementary deterrents when needed, and (iii) removal interventions (lethal or translocation) only when specific damage-causing individuals are identified. In line with Eklund et al. (2017), we also recommend the generalization of adaptive management approaches. To maximize efficiency and minimize costs, and taking advantage of implementation by government agencies, each step should be subject to an upstream and local assessment of the situation, and a protocol allowing for an

evaluation of the intervention procedure, effectiveness, and consequences, from the moment it is implemented and over the long term. This follow-up would condition the allowance to continue or terminate the program depending on its tangible success.

The reduction of human-large carnivore conflict, however, requires more than the mere reduction of impacts (Dickman, 2010). Each conflict is the result of a unique combination of factors (Kartika and Koopmans, 2016) and must be treated as such, as this combination shapes the perceived risk from which local tolerance is most likely to depend (Dickman, 2010; Delibes-Mateos et al., 2013). Perception and tolerance condition the severity of the conflict and should have a decisive influence on any management strategy (Van Eeden et al., 2018a), to ensure the crucial collaboration of livestock owners, local managers, and researchers. In addition to integrated programs with local communities (Treves et al., 2009), human-large carnivores conflict's management should, finally, include efficient knowledge-sharing systems, and even financial incentives (Van Eeden et al., 2018a) if we are to transition from fragile co-occurrence to actual coexistence.

Acknowledgements

We thank Guillaume Chapron, Jon Swenson, and our reviewers for their insightful comments over the early version of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2022.156195>.

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