A framework of most effective practices in protecting human assets from predators

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A framework of most effective practices in protecting human assets from predators

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ABSTRACT

Widespread damage by large mammalian predators to human assets (e.g., livestock, crops, neighborhood safety) requires the application of non-invasive (i.e., without direct contact with predators) and targeted interventions to promote predator conservation and local livelihoods. We compiled 117 cases from 23 countries describing the effectiveness of 12 interventions designed to protect human assets from 21 predators. We found: (a) the most effective interventions were electric fences, guarding animals, calving control, and physical deterrents (protective collars and shocking devices); (b) the most effectively protected asset was livestock; and (c) the most effective interventions being used were to protect assets from cheetahs (*Acinonyx jubatus*), Eurasian lynx (*Lynx lynx*), gray wolves (*Canis lupus*), and lions (*Panthera leo*). In all of these cases, the relative risk of damage was reduced by 50–100%. We combined these outcomes into a novel framework of most effective practices and discussed its structure, practicality, and future applications.

KEYWORDS

Carnivore; depredation; effectiveness; human-wildlife conflict; mitigation; non-invasive; non-lethal intervention

Introduction

Large mammalian predators act as conservation flagships, but also suffer from human persecution fueled by perceived threats to personal safety due to the presence of predators in human-inhabited places, depredation of domestic animals and crops, competition for game species, or even actual attacks on humans (Lute, Carter, López-Bao, & Linnell, 2018; Sergio et al., 2008). Despite a plethora of research and conservation efforts, human-caused mortality is still the main factor threatening 28 large predators to lose their grounds and 61% of species with extinction (IUCN, 2018). Therefore, best practices in protecting domestic livestock, agricultural crops, and human neighborhoods are essential to reduce negative impacts on predators, mitigate human-caused threats, and prevent local extirpations and even extinction of these large mammals (Breitenmoser et al., 2005).

Mitigation of human-predator conflicts requires the application, validation, and comparative evaluation of interventions that are designed to protect people and their assets (e.g., livestock, crops, neighborhood safety) from predators. Priority interventions should be non-invasive (i.e., excluding direct contact with predators) to address the globally threatened status

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of many predators and to avoid ethical, emotional, and economic constraints of invasive interventions. Invasive interventions such as lethal (e.g., shooting, poisoning, trapping) and non-lethal control (e.g., shock collars, sterilization, translocation) are often disliked by the public, expensive, destructive for predator populations, and counter-productive by triggering further conflicts (Allen, 2014; Athreya, Odden, Linnell, & Karanth, 2010; Rust, Whitehouse-Tedd, & MacMillan, 2013; Treves, Krofel, & McManus, 2016).

Recent systematic reviews of the effectiveness of non-invasive and invasive anti-predator interventions have shown that relevant studies are limited and use incomparable metrics of predator-caused damage and intervention effectiveness (Eklund, López-Bao, Tourani, Chapron, & Frank, 2017; Miller et al., 2016; Treves et al., 2016; Van Eeden et al., 2017, 2018). These reviews quantified and considered the effectiveness for each study, but little was done to standardize efforts by using a single metric or to find common patterns for particular interventions, assets, and predators. The most recent discussion of these reviews admitted methodological inconsistencies and data scarcity, and suggested overcoming these problems by standardizing application of interventions with the involvement of scientists and practitioners (Van Eeden et al., 2018).

A useful platform for the standardized application of interventions can be a framework summarizing which: (a) interventions are most effective, (b) assets are most effectively protected, and (c) interventions work best against specific predators (Figure 1). This approach may offer the most effective practices for particular assets, predators, and interventions (e.g., the most effective way to protect the asset A from the predator B is to apply the intervention C). Having such a framework is important to optimally channel available resources when addressing particular agricultural settings and predators (Lute et al., 2018). An important step toward the standardization of interventions is to borrow relevant approaches from medical science where the measurement and evaluation of effectiveness is common (Sutherland & Wordley, 2018). This can be done, *inter alia*, by measuring the relative risk (RR) (Knol, Le Cessie, Angra, Vandenbroucke, & Groenwold, 2012) of predator-caused damage and by applying confidence intervals as a measure of variation and uncertainty of estimated metrics (Fidler, Cumming, Burgman, & Thomason, 2004).

In this study, we attempted to understand which interventions are most effective for particular assets and predators (Figure 1). For this, we applied a thorough literature search, standardized the metrics of predator-caused damage, and conducted a global meta-analysis of RR as a standardized metric quantifying the effectiveness of non-invasive interventions (hereafter, interventions) to protect human assets from mammalian predators. We report patterns of effectiveness for predator species, different interventions, and affected assets on the basis of comparisons of the metric's confidence intervals. Ultimately, we propose a framework of best practices combining the most effective interventions, protected assets, and

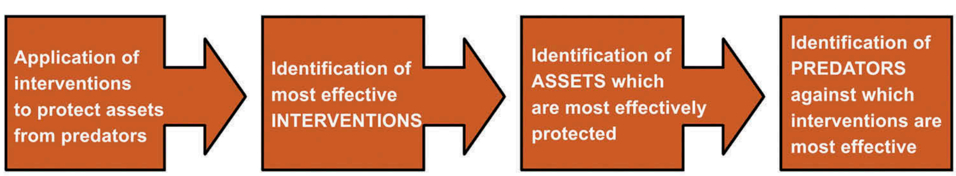

Figure 1. The conceptual framework of most effective practices.

interventions against specific predators. We anticipate that this study may provide an important step toward finding the best possible interventions for protecting an asset from a particular predator species. Standardization of damage and effectiveness metrics may significantly strengthen interventions when this is done in unison with standardization of study design.

Methods

We used data on the effectiveness of interventions directed toward the protection of assets (e.g., domestic and game animals, beehives and crops from depredation, neighborhood safety from nuisance animals). We considered only information related to terrestrial mammalian predators in wild conditions.

We attempted to maximize the number of relevant source publications through several steps. First, we extracted data from the source literature of the four known scientific reviews of the effectiveness of predator-targeted interventions (Eklund et al., 2017; Miller et al., 2016; Treves et al., 2016; Van Eeden et al., 2017). Then, we searched for relevant publications in Web of Science (www.webofknowledge.com) in 2000–2018 using the keywords "livestock" AND "effectiveness" OR "efficacy" AND *predat*. We also read through all issues of the online journal Conservation Evidence (www.conservationevidence.com, 2004–2018) and the newsletter Carnivore Damage Prevention News (www.lcie.org, 2000–2005 and 2014–2016). Moreover, we retrieved relevant papers from Human-Wildlife Conflict Resource Library of the IUCN/SSC Human-Wildlife Conflict Task Force (www.hwctf.org) placed under the key topics "Electric fences," "Other barriers," "Livestock guarding," and "Deterrents and repellents." Finally, we excluded 20 publications from Miller et al. (2016) that did not estimate effectiveness, but only implied it from correlation analysis, and seven publications from Van Eeden et al. (2017) that were not available.

We identified three categories of interventions (aversion, husbandry, management) and each category was comprised of three to five types of interventions (Table 1). Each case in the dataset described an effect of a particular type of intervention on the protection of a particular asset from a predator species in a site. Some cases included generalized assets and/or groups of predators as they were described in the original studies (e.g., livestock [Salvatori & Mertens, 2012] and puma [*Puma concolor*] and jaguar [*Panthera onca*] [Zarco-González & Monroy-Vilchis, 2014]). We considered small stock as one species, namely sheep only, goats only, or sheep and goats grazing together, depending on local circumstances (Iliopoulos, Sgardelis, Koutis, & Savaris, 2009).

For each case, we measured the effectiveness of an intervention as the relative risk of damage RR suggested by Eklund et al. (2017):

$$RR = \frac{A/N_t}{B/N_c}$$

where A is the metric of damage (e.g., number of livestock individuals killed by predators) with a given intervention, B is the same metric without the intervention, N_t is the treatment sample size (e.g., number of livestock exposed to the intervention), and N_c is the control sample size (e.g., number of livestock not exposed to the intervention or before the intervention is applied). So, RR represents a ratio of the probability of damage risk with the

Table 1. Categories and types of non-invasive interventions used for protecting assets from predators in this study. Sample sizes (numbers of cases) are indicated in the parentheses.

	Categories of interventions (*n* = 117)		
	Aversion (*n* = 20)	Husbandry (*n* = 88)	Management (*n* = 9)
Types of interventions	1. Acoustical deterrents (*n* = 3): animal/other sounds, cracker shells, explosives, freon horn, noise and ultrasound 2. Chemical deterrents (*n* = 6): commercial animal deterrents, household chemicals, lithium chloride, pepper spray 3. Physical deterrents (*n* = 2): protective collars and shocking devices 4. Visual deterrents (*n* = 3): flash light, scarecrows and fladry 5. Mixed deterrents (*n* = 6): several types applied simultaneously in a study	1. Electric fences (*n* = 17) 2. Fences (*n* = 19): daytime enclosures, night corrals and swing gates 3. Guarding animals (*n* = 46): dogs, llamas and alpacas 4. Herding (*n* = 6)	1. Livestock breed replacement (*n* = 3) 2. Calving control (*n* = 4) 3. Supplemental feeding of predators by carrion (*n* = 2)

intervention to the probability of damage risk without the intervention. Interventions are ineffective at RR > 1, effective at RR < 1, and become most effective at RR = 0 when A = 0. When no damage records were obtained in control samples (i.e., B = 0), RR was undefined and we excluded such studies from the analysis. We took the odds ratios from Woodroffe, Frank, Lindsey, Ole Ranah, and Romañach (2007) as the surrogates of RR because odds ratios tend to approach RR when incidences are rare, as with predator-related events (Knol et al., 2012). In some before-and-after comparison studies (e.g., Bauer, de Iongh, & Sogbohossou, 2010), N_t and N_c were not indicated, but as the same households were affected by interventions, it was assumed that $N_t = N_c$, making RR = A/B.

We standardized the study by using only three metrics of damage to calculate RR. These metrics were the number of: (a) livestock individuals killed in livestock depredation studies, (b) damage records in beehive and crop damage studies, and (c) individuals resuming nuisance behavior after an intervention in nuisance animal studies. We considered only damage related to losses of affected assets and excluded non-lethal economic losses (e.g. those caused by weight loss, abortions, or reduced milk productivity) resulted from the stress associated with the presence of predators (Allen, 2014; Ramler, Hebblewhite, Kellenberg, & Sime, 2014). We analyzed how RR differed between categories and types of interventions, predator species, and affected assets. When comparing RR among predator species, we used only cases with RR for individual species. We used the one-sample chi-square (χ^2) test for frequency comparisons and measured the 95% confidence interval (CI) of the median RR by bootstrapping with 1000 repetitions in iNZight 3.2.1 (University of Auckland, New Zealand). We categorized interventions as very effective if the 95% CI was within 0-.49, moderately effective if .50-.89, and ineffective if higher than .90. This means that very effective interventions reduce the damage by 51–100%, effective interventions reduce it by 11–50%, and ineffective interventions reduce the damage by less than 10% or even increase damage (Table 2). Ultimately, we developed a set of best practices combining the most effective interventions, protected assets, and predators.

Results

We retrieved fully required information from 56 scientific publications that provided 117 cases from 23 countries describing the effectiveness of 12 types of interventions designed

Table 2. Differentiation between most effective, moderately effective, and ineffective interventions used in this study on the basis of associated damage reduction.

Interventions	Damage reduction (%)
Very effective	51–100
Moderately effective	11–50
Ineffective	< 10% to damage increase

for protection from 21 predator species. Significantly more cases came from the USA (*n* = 41), Canada (*n* = 12), and Kenya (*n* = 12) than from other countries (χ^2 = 308.60, $p < .001$). The most heavily represented continents were North America (*n* = 53 cases), Europe (*n* = 28), and Africa (*n* = 28), with the contribution of Latin America (*n* = 5), Asia (*n* = 2), and Australia (*n* = 1) much lower (χ^2 = 109.00, $p < .001$). Interventions were strongly dominated by husbandry (*n* = 88 cases), followed by aversion (*n* = 20) and management (*n* = 9) (χ^2 = 93.90, $p < .001$; Table 1). Significantly more interventions were applied against coyotes (*Canis latrans; n* = 20 cases), wolves (*Canis lupus; n* = 17), American black bears (*Ursus americanus; n* = 12), pumas (*n* = 12), and brown bears (*Ursus arctos, n* = 10) than against other predators (χ^2 = 94.33, $p < .001$). Most of the interventions were used for protecting small stock (*n* = 72 cases), mixed livestock composed of cattle and small stock (*n* = 17), cattle (*n* = 12), and neighborhood safety from nuisance animals (*n* = 10) (χ^2 = 323.39, $p < .001$).

Among the categories of interventions, husbandry was very effective, aversion was moderately to very effective, and management was nearly ineffective to very effective (Figure 2a). The most effective interventions were electric fences (median RR = .14, 95% CI = .00-.40), guarding animals (.33, .24-.44), physical deterrents (.16, .00-.32), and calving control (.00, undefined because in all applications the RR was 0 inferring 100% reduction of damage; Figure 2b). Interventions that were moderately to very effective included fences and acoustic, mixed, and chemical deterrents, whereas livestock breed replacement was moderately effective. Visual deterrents and herding ranged widely from ineffective to very effective. Supplementary feeding by carrion was ineffective (Figure 2b).

Interventions were most effective when they protected assets from cheetahs (*Acinonyx jubatus*; median RR = .00, 95% CI = .00-.28), wolves (.15, .01-.29), lions (*Panthera leo*; .33, .04-.50), and Eurasian lynx (*Lynx lynx*; .14, .00-.36; Figure 2c). Protection from coyotes and polar bears (*Ursus maritimus*) was moderately to very effective, and protection from wolverines (*Gulo gulo*) was moderately effective. Protection from as many as six species ranged from ineffective to very effective: American black bear, brown bear, domestic dog (*Canis familiaris*), leopard (*Panthera pardus*), puma, and spotted hyena (*Crocuta crocuta*). Protection from African wild dogs (*Lycaon pictus*) was ineffective (Figure 2c).

Protection was very effective for cattle (median RR = .00, 95% CI = .00-.31), small stock (.33, .20-.45), and mixed cattle and small stock (.32, .04-.50). Protection of beehives was ineffective to moderately effective, and protection of neighborhood safety from nuisance animals ranged from almost ineffective to very effective (Figure 2d).

We defined the most effective practices as the application of electric fences, guarding animals, calving control, and physical deterrents (protective collars and shocking devices) to protect livestock from cheetahs, Eurasian lynx, wolves, and lions (Figure 3). Out of 28 cases of livestock protection from these predators in our study, 16 described these

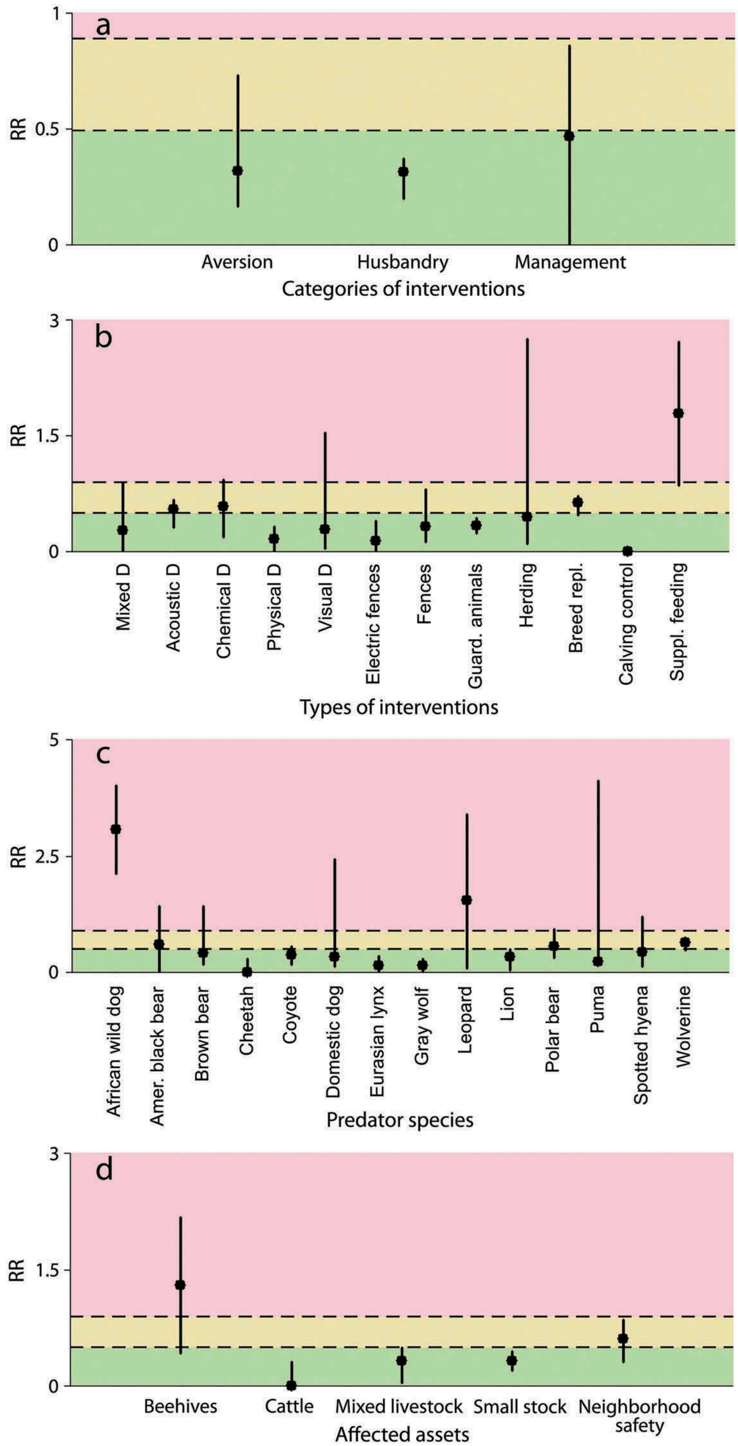

Figure 2. The distribution of the median relative risk of damage (RR) and its 95% confidence interval across the: (a) categories of non-invasive interventions, (b) types of non-invasive interventions, (c) predator species, and (d) affected assets. The species and assets including only one case are excluded. The dashed lines indicate RR = .49 separating very effective and moderately effective interventions, and RR = .89 separating moderately effective and ineffective interventions. Abbreviations: Amer. – American, D – deterrents, guard. – guarding, repl. – replacement, suppl. – supplementary.

practices: guarding animals versus cheetahs (n = 5), wolves (n = 4), and lynx (n = 1); electric fences versus wolves (n = 5); and calving control versus wolves (n = 1) (Table 3). There was no information in the literature about other relationships (e.g., electric fences vs. cheetahs; physical deterrents, electric fences, guarding animals, and calving control vs. lions; physical deterrents vs. cheetahs, wolves, and lynx), and it was not possible to judge their effectiveness. In all 16 cases, interventions were very effective (median RR = 0.07, 95% CI = .00 - .14).

Discussion

The Framework

Our study demonstrated that the most effective interventions are electric fences, guarding animals, calving control, and physical deterrents (protective collars and shocking devices). The most effectively protected asset is livestock, and the most effective interventions are those to protect assets from cheetahs, Eurasian lynx, gray wolves, and lions. In all of these cases, the relative risk of damage caused by predators is reduced by 50–100%. We combined these three outcomes of predators, assets, and the most effective interventions into a single framework of most effective practices that may protect livestock and save predators in the best way.

Naturally, not all interventions are tested on all predator species, as their application is determined by local practicality and availability of resources. Interventions can be potentially effective, but not used if they are socially unacceptable, financially not viable, or scientists did not have a chance to test the interventions. For example, herding is not practiced in areas where depredation is quite low and the costs of shepherd hiring do not offset the costs of livestock loss (Breitenmoser et al., 2005). Although herding is widely perceived as one of the best interventions preventing depredation, it is becoming increasingly rare and socially problematic due to limited workforce, job searching in towns, and less interest in animal husbandry than in other agricultural businesses (Khorozyan et al., 2017; Tumenta, de Iongh, Funston, & Udo de Haes, 2013). The use of guarding dogs is ineffectual in areas where proper dog training is not customary (Khorozyan et al., 2017).

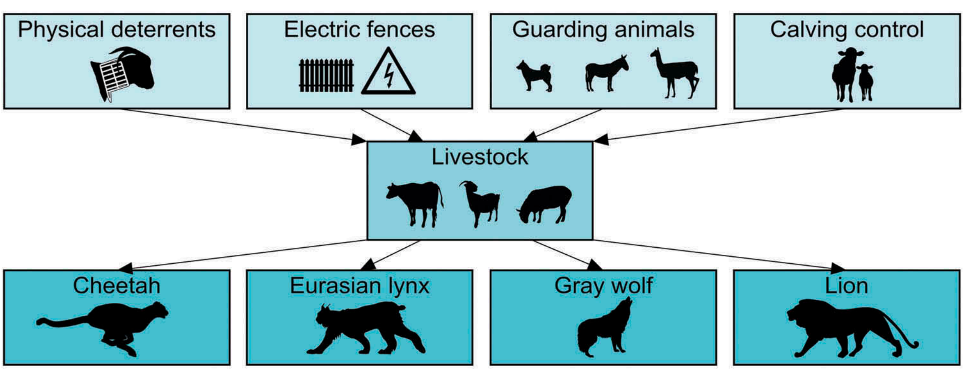

Figure 3. A set of most effective practices combining the most effective interventions, most effectively protected assets, and predators against which interventions are most effective.

Table 3. Empirically proved high effectiveness of livestock protection interventions against the wolf (*Canis lupus*), cheetah (*Acinonyx jubatus*), and Eurasian lynx (*Lynx lynx*) within the framework of most effective practices (Figure 3). We found no publications about the effectiveness of these interventions against the lion (*Panthera leo*).

Interventions	Damage reduction (%)	Predators	Countries	Sources
Calving control	100	Wolf	USA	Breck et al. (2011)
Electric fences	100	Wolf	Portugal	Salvatori and Mertens (2012)
	100	Wolf	Croatia	Salvatori and Mertens (2012)
	99.0	Wolf	Spain	Salvatori and Mertens (2012)
	57.8	Wolf	Italy	Salvatori and Mertens (2012)
	86.1	Wolf	Norway	Wam, Dokk, and Hjeljord (2004)
Guarding dogs	79.4	Wolf	Italy	Ciucci and Boitani (1998)
	79.0	Wolf	Greece	Iliopoulos et al. (2009)
	42.3	Wolf	Portugal	Salvatori and Mertens (2012)
	64.9	Wolf	Spain	Salvatori and Mertens (2012)
	72.0	Cheetah	Kenya	Woodroffe et al. (2007)
	99.7–100*	Cheetah	South Africa	Rust et al. (2013)
	85.9	Lynx	Switzerland	Landry and Raydelet (2010)

Note: * four cases with different livestock species: cattle, sheep, goats, and sheep and goats kept together.

Proper implementation of intervention experiments to test their effectiveness based on random controlled study designs is rare (Van Eeden et al., 2018), but feasible (Ohrens, Bonacic, & Treves, 2019; Treves et al., 2016).

This is why, in our study, the framework of most effective practices was supported by only 57% of known cases, whereas the other 43% were not found by us in the literature and, apparently, were not tested. For example, guarding animals were tested against cheetahs, but not against lions, and calving control was tested against wolves, but not against the other three predators. Whenever such practices were known and evaluated for a given predator species, they were highly effective and reduced damage by 50–100%, except for one case of using guarding dogs against wolves in Portugal that was moderately effective and reduced damage by 42%. Calving control, which means shortening the calving season to several months and limiting calf accessibility to open grazing grounds, was 100% effective to reduce livestock losses caused not only by wolves, but also by other predators such as pumas, American black bears, and coyotes (Breck et al., 2011). Electric fences producing high-voltage shocks to deter predators reduced livestock losses by 58–100% and livestock-guarding dogs did so by 42–100%.

Visual deterrents, herding, and protection from American black bear, brown bear, domestic dog, leopard, puma, and spotted hyena performed variably from ineffective to very effective. This was a result of different effects of interventions on different predators. Visual deterrents varied from very effective flashlights against lions (Lesilau et al., 2018) to ineffective scarecrows against leopards (Woodroffe et al., 2007). Herding was very effective by adult men (Ciucci & Boitani, 1998) and highly ineffective by children (Tumenta et al., 2013; Woodroffe et al., 2007). Bears, domestic dogs, and pumas are behaviorally flexible and capable of living near people, so they habituated quickly to guarding animals and could be effectively deterred mainly by the interventions that reliably limited access to assets, such as fencing and calving control (Andelt, 1999; Breck et al., 2011; Hansen & Smith, 1999; Meadows & Knowlton, 2000). Leopards have exceptional climbing abilities and fencing was generally futile against them, but dogs deterred them effectively (Kolowski & Holekamp, 2006; Woodroffe et al., 2007). Spotted hyenas snuck through poorly constructed fences, but could not penetrate through solid ones (Bauer et al., 2010; Woodroffe et al., 2007).

Local Practicality of the Framework

Our most effective practices should be validated by independent studies, particularly in those intervention-predator combinations that have not been tested so far. This validation needs to be based on the most practical and potentially sustainable local solutions, especially for cheetahs and lions in African and Asian (i.e., cheetahs in Iran, lions in India) countries with low to medium income where the spectrum of applicable interventions is limited. Eurasian lynx and gray wolf are still of least conservation concern, but they constitute many locally threatened or recolonizing populations that demand urgent attention to their protection and safety of human assets (Chapron et al., 2014; Gippoliti et al., 2018; Mech, 2017). As lynx and wolves live in more economically developed countries, the choice of suitable interventions appears not to be of primary concern to address these predators.

Cheetahs and lions are globally vulnerable (IUCN, 2018), and their populations are at risk of extinction due to retaliatory or preventative killing by pastoralists who lose their livestock to depredation. The plight is particularly evident for (critically) endangered lions (*P. l. leo*) in West Africa, Saharan cheetahs (*A. j. hecki*) in North and West Africa, Asiatic cheetahs (*A. j. venaticus*) in Iran, and Asiatic lions (*P. l. persica*) in India (Farhadinia et al., 2017; IUCN, 2018). Livestock losses to these predators can reach substantial scales in prey-lean areas and provoke retribution (Banerjee, Jhala, Chauhan, & Dave, 2013; Farhadinia et al., 2012; Rust et al., 2013; Tumenta et al., 2013), but depredation by cheetahs also can be overestimated as they are falsely blamed due to high visibility during the daytime (Marker, Muntifering, Dickman, Mills, & Macdonald, 2003). Thus, non-invasive interventions are urgently needed for promoting the conservation of lions and cheetahs, and their coexistence with local livelihoods.

The framework of most effective practices suggests that livestock depredation by lions, cheetahs, gray wolves, and Eurasian lynx can be effectively reduced by electric fences, physical deterrents, guarding animals, and calving control. However, their local applicability is context-dependent. Electric fences, for example, require substantial initial investments and maintenance costs (Frank & Eklund, 2017), so they are most suitable for more economically developed areas of predator ranges.

Calving and lambing control is feasible, but it takes some time to synchronize livestock reproductive timing with the seasonality of market and husbandry conditions (Jacobs & Main, 2015). As young livestock are highly vulnerable to depredation, limiting access to open ranges is essential to keep depredation losses down (Andelt, 1999; Breck et al., 2011; Jacobs & Main, 2015).

Lightweight metal collars put on a domestic animal's neck to prevent killing by suffocation represent a very effective and affordable physical deterrent, but they have only been tested so far against black-backed jackals (*Canis mesomelas*), caracals (*Caracal caracal*), and leopards in South Africa (McManus, Dickman, Gaynor, Smuts, & Macdonald, 2015). In addition, testing of metal-studded leather collars against leopards is now underway in Iran (our data). These collars may be effective against cheetahs, lions, Eurasian lynx, and other felids that kill by puncturing the neck, but probably not against wolves and other canids that normally attack the rear or flanks of their prey. Another physical deterrent, a battery-triggered shocking device, was used for deterring American black bears from concentrated human food sources (Breck, Lance, & Callahan, 2006), but their use on large stationary objects such as corrals and fences is problematic.

Guarding dogs have been used for protecting livestock for millennia, but proper training for attentiveness, trustworthiness, and aggressiveness toward predators is essential (Khorozyan et al., 2017; Marker, Dickman, & Macdonald, 2005; Potgieter, Kerley, & Marker, 2016; Rust et al., 2013). Loosely trained guarding dogs can also kill wildlife, including cheetahs (Potgieter et al., 2016), which reduces their usefulness. These dogs can also be killed by predators such as wolves (Ciucci & Boitani, 1998; Iliopoulos et al., 2009). Shepherd dogs are among the main mortality factors for cheetahs in Iran (Farhadinia et al., 2017).

It is important to note that the application of interventions, even the most effective ones, can be confronted by low cultural acceptance of targeted predators and/or interventions by local people. Some predators, such as wolves and lions, can be demonized by deeply-rooted cultural beliefs or high visibility of animals that makes them intuitively perceived as dangerous (Dickman, 2010). People living in areas where predators became locally extinct in the past, but begin to be recolonized now, can have particularly negative views toward predators because they lost the indigenous knowledge of co-existence (Houston, Bruskotter, & Fan, 2010). For this reason, predators can be disliked even if their actual damage to humans is minimal, and as a result, killing these animals can be a common practice. When such hostility is an issue, livestock protection alone is often ineffective and it should be preceded by efforts aimed at raising awareness and improving acceptance of predators (Marchini & Macdonald, 2018; Thorn, Green, Dalerum, Bateman, & Scott, 2012). In spite of much effort in improving public attitudes toward predators, there is still much resentment among local people, especially livestock producers and hunters living close to the animals (Browne-Nuñez, Treves, MacFarland, Voyles, & Turng, 2015; Marchini & Macdonald, 2018).

The other side of the problem is that local people can be culturally sensitive and conservative, which often makes them perceive novel approaches, such as non-invasive livestock protection interventions, with caution and skepticism. In the context of our study, we believe that the acceptance of physical deterrents, electric fences, and calving control would be determined mainly by their economic profitability versus lethal control, which is still practiced by many farmers (McManus et al., 2015; Potgieter et al., 2016). In contrast, the use of guarding dogs can be controversial. Dogs are often used only as the "alert systems" by barking to inform about threats, but not to deter predators from livestock. In addition, their maintenance by feeding leftovers and no veterinary care is inadequate. When cultures have attitudes in opposition to dogs or local people do not care for dogs, it makes little sense to introduce guarding dogs as an intervention to curb depredation losses.

Future Applications

Our research opens pathways to enlarge and deepen the research and practical application of non-invasive interventions to protect human assets, especially livestock, from predators. This is a particularly striking need as part of the efforts to preserve globally threatened large predators. Our framework of most effective practices shows that cheetahs and lions, the two vulnerable predators with regionally (critically) endangered populations, can be effectively protected through the application of protective collars, electric fences, guarding animals, and calving/lambing control. These practices should be a priority for applied research, especially in West and North Africa, India and Iran, and widely publicized even if their results are negative. This is required to reduce publication bias that may inflate the effectiveness of interventions from meta-analyses if publications deal mostly with positive results (Haddaway, Woodcock, Macura, & Collins, 2015).

Application and validation of the framework of most effective practices is also important to protect livestock from Eurasian lynx and gray wolf in places of conflicts with humans. This is particularly topical for Europe and North America where the comeback of predators through natural recolonization or reintroductions brings new, forgotten-over-time issues of livestock losses and confrontations between farmers and conservationists (Chapron et al., 2014; Gippoliti et al., 2018; Mech, 2017).

We found that most of the intervention effectiveness studies were conducted in the USA, Canada, and Kenya, whereas single cases were reported from China, Japan, Tanzania, and Australia with none from India, Russia, and Iran even though human-predator conflicts are widespread in these countries. Data paucity might be caused by wide application of invasive techniques, such as lethal control in Australia (Allen, 2014) and translocations in Russia (Goodrich, Seryodkin, Miquelle, & Bereznuk, 2011), or by the existence of relevant literature in national languages, which we missed because we focused mostly on English-language publications. A strong North American bias of intervention studies makes the gray wolf, coyote, brown bear, American black bear, and puma (cougar) much better studied on this continent than elsewhere. At the same time, little is known about the effectiveness of interventions against wolves and brown bears in Eurasia, and puma in Central and South America, and studies on these species and locations are essential.

The effectiveness of interventions against such a versatile predator as the leopard is insufficiently known, but such studies are pivotal to address the escalating reports of human-leopard conflict across Asia (Jacobson et al., 2016). Given that Central and South America, Asia, and Australia are heavily underrepresented, predators living only on these continents deserve more research and applications of interventions, including jaguar in Central and South America, and snow leopard (*Panthera uncia*), tiger (*P. tigris*), sloth bear (*Melursus ursinus*), and Asiatic black bear (*Ursus thibetanus*) in Asia. India holds all conflict-triggering large predators in Asia and should become a key actor in studies and applications of non-invasive interventions. Currently, the most common techniques to resolve human-predator conflicts in India are translocations (leopard – Athreya et al., 2010) and compensation payments (Asiatic lion – Banerjee et al., 2013), but non-invasive interventions are important for securing local sustainability and reducing financial burdens. The dingo (*Canis dingo*), an endemic Australian predator, has been widely managed by means of lethal control (Allen, 2014), whereas the effectiveness of non-invasive interventions (fencing) has been compromised by fluctuations of livestock numbers in response to economic conditions (Allen & Sparkes, 2001).

We conclude that our framework of most effective non-invasive interventions may serve as a useful guide for protecting livestock from particular predators. We also invite more practical research on applying these interventions to predators, especially in regard to little studied species and underrepresented regions.

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