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Tools and Technology

Effectiveness of Contemporary Techniques for Reducing Livestock Depredations by Large Carnivores

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ABSTRACT Mitigation of large carnivore depredation is essential to increasing stakeholder support for human–carnivore coexistence. Lethal and non-lethal techniques are implemented by managers, livestock producers, and other stakeholders to reduce livestock depredations by large carnivores. However, information regarding the relative effectiveness of techniques commonly used to reduce livestock depredations is currently lacking. We evaluated 66 published, peer-reviewed research papers that quantitatively measured livestock depredation before and after employing 4 categories of lethal and non-lethal mitigation techniques (livestock husbandry, predator deterrents and removal, and indirect management of land or wild prey) to assess their relative effectiveness as livestock protection strategies. Effectiveness of each technique was measured as the reported percent change in livestock losses. Husbandry (42–100% effective) and deterrents (0–100% effective) demonstrated the greatest potential but also the widest variability in effectiveness in reducing livestock losses. Removal of large carnivores never achieved 100% effectiveness but exhibited the lowest variation (67–83%). Although explicit measures of effectiveness were not reported for indirect management, livestock depredations commonly decreased with sparser and greater distances from vegetation cover, at greater distances from protected areas, and in areas with greater wild prey abundance. Information on time duration of effects was available only for deterrents; a tradeoff existed between the effectiveness of tools and the length of time a tool remained effective. Our assessment revealed numerous sources of bias regarding the effectiveness of techniques as reported in the peer-reviewed literature, including a lack of replication across species and geographic regions, a focus on Canid carnivores in the United States, Europe, and Africa, and a publication bias toward studies reporting positive effects. Given these limitations, we encourage managers and conservationists to work with livestock producers to more consistently and quantitatively measure and report the impacts of mitigation techniques under a wider range of environmental, economic, and sociological conditions. © 2016 The Wildlife Society.

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Large carnivore species are common priorities for landscape-scale conservation because of their importance as keystone drivers of ecosystem function, revered cultural symbols, and susceptible targets of extinction threats (Di Minin et al. 2016). Of the 31 largest terrestrial carnivores (body mass >15 kg, Ripple et al. 2014; Table S1 in Supporting Information Appendix A1, available online at www.onlinelibrary.wiley.com), most (77%) are undergoing continued population declines and many (61%) are listed by the International Union for the Conservation of Nature as vulnerable, endangered, or critically endangered and threatened with local or global extinction (Ripple et al. 2014). The loss of large carnivore species can destabilize ecological and human communities by altering the structure of food webs, disrupting ecosystem services, and exacerbating social

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conflicts between people through the decrease or redistribution of natural resources (Brashares et al. 2014, Ripple et al. 2014). Declines in these valuable species are due to a suite of biological traits, including large body size, high energy constraints, large area requirements, low densities, and slow population growth rates, compounded by exposure to anthropogenic threats such as habitat degradation and fragmentation, loss of prey, persecution, and overexploitation by humans (Cardillo et al. 2004, Marshall et al. 2015). Many of these anthropogenic threats are facilitated by human–carnivore conflict, often stemming from the need to stop carnivores from attacking livestock and affecting human livelihoods.

Large carnivore livestock depredations can result in substantial economic hardships for livestock producers and ultimately weaken local support for conservation (Wang and Macdonald 2006, Lindsey et al. 2013). Stakeholders tend to hold especially negative attitudes toward large carnivores in part because of predators' reputation for attacking large-bodied, high-value livestock. Livestock depredation can undermine stakeholder support for conservation as a whole as well as result in retaliatory killing of predators by livestock owners (Treves and Karanth 2003, Baker et al. 2008, Inskip and Zimmermann 2009). Reducing conflict between large carnivores and livestock is thus critical for maintaining viable ecosystems and human communities that depend on them.

Global stakeholder interest in reducing large carnivore depredation on livestock has led to the development of numerous mitigation techniques. These include preventive husbandry (e.g., guard dogs or fencing), deterrents (e.g., light–sound devices or shock collars), removal (translocation or lethal population–problem animal control), and indirect management of land (e.g., habitat improvements, zoning for designated land uses and protected areas), and wildlife (e.g., increasing the wild prey base; Shivik 2006, Linnell et al. 2012). Effective implementation of these techniques can reduce large carnivore attacks on livestock depredations and encourage species conservation (Hazzah et al. 2014, Lichtenfeld et al. 2014).

Human–carnivore conflicts are complex and shaped by a suite of cultural, economic, historical, and ecological factors that may affect the use and effectiveness of techniques for mitigating livestock depredations (Messmer 2000, Messmer et al. 2001, Dickman 2010). Previous syntheses of the published literature have discussed the relative advantages and disadvantages of different techniques, but have not quantitatively compared or contrasted situational effectiveness (Breitenmoser et al. 2005, Shivik 2006, Sillero-Zubiri et al. 2007, Inskip and Zimmermann 2009, Pettigrew et al. 2012, Redpath et al. 2012). There is currently no consensus as to which techniques are most useful and under what circumstances, or on the associated tradeoffs between time duration and effectiveness level. This information could assist stakeholders in selecting objective-based strategies that optimize livestock protection benefits. To evaluate the relative effectiveness of techniques used to mitigate livestock depredation by large wild carnivores, we compared the results of quantitative studies of technique effectiveness (i.e., percent change in livestock losses or carnivore behavior and the duration of the effects) as reported in the peer-reviewed scientific literature. We examined the utility of each technique based on its effectiveness in reducing livestock losses in an attempt to identify patterns of use that might facilitate more informed selection by potential users.

METHODS

Literature Search

We searched Web of Science (www.webofknowledge.com) and the database Carnivore Ecology and Conservation (www.carnivoreconservation.org) for peer-reviewed articles that examined techniques for reducing depredations of livestock by wild large carnivores. We used compound search terms that included the technique (e.g., deterrent) or a specific tool (e.g., aversive stimuli or behavior conditioning; see Table 1) plus 1 of 7 general keywords related to livestock depredation conflict (human–carnivore conflict, live stock depredation, human–carnivore coexistence, mitigation, depredation management, depredation prevention, or depredation control). We defined a large carnivore as one with body mass >15 kg (Ripple et al. 2014). Our searches followed the formula: (technique or tool name) and (conflict

Table 1. Conflict mitigation techniques and tools used as search keywords for literature review assessing the effectiveness of methods for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014).

Technique	Tool
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

keyword); for example, "deterrent human carnivore conflict" or "aversive stimuli livestock depredation." We found additional literature that matched our criteria by reviewing articles cited in the articles from our searches that seemed relevant from their title or context in the article (snowball sampling; Goodman 1961).

We assessed only primary literature in English that provided numeric metrics (or values for calculating numeric metrics) of effectiveness; reviews were omitted from analysis. We defined effectiveness as the 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. In addition to measures of effectiveness, we also recorded the amount of time that techniques were effective in reducing depredation if available. We noted articles that analyzed correlations between the implementation of tools and livestock depredation to supplement our analysis of the effectiveness of different tools. We recorded the large carnivore species involved and country where the study occurred for each article.

Data Analysis

We compared the effectiveness of techniques by calculating the magnitude of change between conditions before and after a technique was applied. We calculated the magnitude of change (D) as the percentage deviation from initial conditions following the formula (adapted from Jones and Schmitz 2009):

$$D = ([B - A]/B) \times 100$$

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. We compared the differences between magnitudes of change among techniques using boxplots.

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. Units from articles were most commonly expressed in terms of livestock depredation (e.g., no. of livestock lost or no. of farms with depredation; original units reported by articles are listed in Table S2). If a study reported the effectiveness of a technique on a community of predators (e.g., guard dog effects on combined rates of depredation by brown bear [*Ursus arctos*], gray wolf [*Canis lupus*], and Eurasian lynx [*Lynx lynx*]; Otstavel et al. 2009), we reported the effectiveness for the predator community as a whole.

RESULTS

Our literature search yielded 66 articles that matched our criteria (Supporting Information Appendix A1). These articles primarily assessed husbandry (39% of articles), followed by indirect management (26%), deterrents (23%), and removal (20%; percentages reported in this section exceed 100% because some articles addressed >1 category). An equal number of articles reported on the effectiveness of techniques (measured numerically before and after implementation) as on the associations between technique use and depredation (correlation statistics), and 4% of articles reported both metrics. Both metrics were reported in relatively comparable proportions in articles on husbandry (54% of articles reported effectiveness, 46% correlations) and removal (50% effectiveness, 67% correlations), but articles on deterrents exclusively reported effectiveness while articles on indirect management reported only correlations. The time duration of effects was explored in 20% of articles, all of which focused on deterrents.

Articles addressed 16 large carnivore species (59% of all species investigated; Table S1) across 27 countries and 6 continents (Fig. S1). Gray wolf was the most studied species (38% of articles), followed by lion (*Panthera leo,* 14%), brown bear (12%), American black bear (*U. americanus*, 12%), leopard (*Panthera pardus*, 11%), Eurasian lynx (11%), and puma (*Puma concolor,* 9%; Fig. S1A). The number of articles featuring Canids (47%) nearly equaled those on Felids (42%), and fewer studies examined Ursids (26%) and Hyaenids (5%). Twenty-five percent of the articles described the effects of techniques on multiple predators (2–5 species). Articles revealed a publication bias in favor of species located in North America (39%; primarily in the United States [33% of all articles]), Europe (23%; primarily in Norway [8%]), and Africa (18%; primarily in Kenya [6%]; Fig. S1B).

Technique Effectiveness

Husbandry reduced livestock depredation by between 42% and 100% (note that 1 outlier reported 3% effectiveness; Hansen and Smith 1999; Fig. 1A). The effectiveness of guard dogs ranged from 3% to 100% ($n = 7$ studies), electric fences from 58% to 100% ($n = 2$), night enclosures from 50% to 89% ($n = 4$), and non-electric fences from 51% to 78% ($n = 2$), and human guards were 70% effective (note that $n = 1$; Fig. 1B). Correlation studies revealed that enclosing livestock at night, as well as the presence of human and animal guards, was associated with decreased depredation, but that the abundance of livestock (total no. or density) had mixed effects on depredation (Table 2). Articles on husbandry mainly investigated depredation by Canids (56%) and Felids (50%), with less than 1/3 of studies on Ursids (23%) and Hyenids (11%; percentages exceed 100 because some articles addressed multiple species). Articles explored effects on 2 or 3 carnivore species except for livestock night enclosures, which were tested on 4 species (brown bear, gray wolf, lion, puma), and guard dogs, which were tested on 8 species (American black bear, brown bear, cheetah [*Acinonyx jubatus*], dingo [*Canis lupus dingo*], Eurasian lynx, gray wolf, puma, spotted hyena [*Crocuta crocuta*]; Fig. 1B).

Carnivore removal showed the least overall variation, with 5 of 6 articles reporting 67–83% effectiveness (Fig. 1A; note that 1 outlier on leopard translocation reported an increase in livestock depredation by 56%; Athreya et al. 2010). Most removal studies focused on translocation (5 of 6 articles). Correlation studies on translocations reported fewer

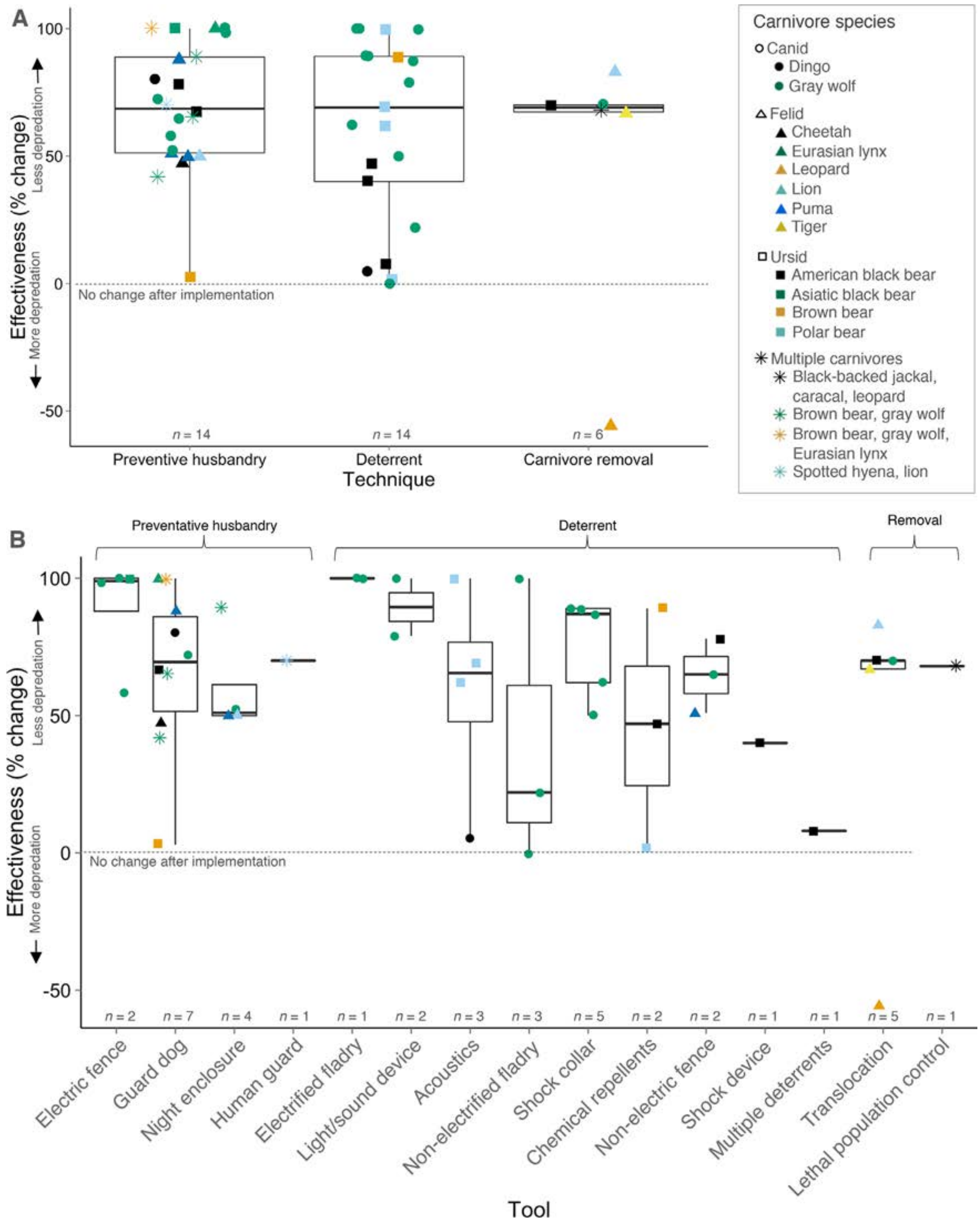

Figure 1. Assessment of the effectiveness of A) general techniques and B) specific tools for reducing large carnivore depredation on domestic livestock based on literature review conducted in 2015 with 66 peer-reviewed papers (published 1980–2014). Effectiveness was calculated as the percent magnitude of change after a tool was implemented. Positive effectiveness values indicate decreasing livestock depredation; negative values indicate increasing livestock depredation. "*n*" represents the number of studies for each technique or tool; data points indicate the values provided by studies (some studies reported multiple values, such as from different sites or species). Data are summarized as boxplots, where boxes indicate the lower, median, and upper quartiles; vertical lines represent the sample minimum and maximum. Original data are overlaid on boxplots, where symbol shape represents the carnivore family and symbol color represents species (see legend).

depredations by lions (Stander 1990) but not by brown bears (Sagor et al. 1997). Lethal population control of carnivores was quantitatively measured by only 1 study, which reported 68% effectiveness with black-backed jackal (*Canis mesomelas*), caracal (*Caracal caracal*), and leopard (McManus et al. 2014; Fig. 1B). Lethal control was associated with decreases in depredation by brown bear, dingo, and Eurasian lynx but had no effect on livestock killed by Asiatic black bear (*Ursus thibetanus*) or gray wolf (Table 2). Removal studies examined Felids (50% of removal studies), Ursids (33%), and Canids (25%), but no Hyenid species.

Table 2. Results from correlation studies found in literature review assessing the effectiveness of techniques for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014). Negative or positive associations indicate that a factor was negatively or positively statistically correlated with livestock depredation, respectively.

		Relationship to carnivore attacks on livestock		
Tool type	**Factor**	**Negatively associated (depredation decreases if factor present or increased)**	**Positively associated (depredation increases if factor present or increased)**	**No effect**
Livestock management	No. or density of livestock	African wild dog[10], cheetah[10], lion[10], leopard[10], puma[34], spotted hyena[10]	African wild dog[33], cheetah[32], gray wolf [6]; jaguar[19], leopard[15,32], lion[32], puma[19], snow leopard[4], spotted hyena[16,32]	Gray wolf [17,28]
	Mixed herd composition		Gray wolf [17]	
	Amount of free-grazing livestock		Jaguar[34]	
	Year-round calving		Gray wolf [7]	
	Calving season		Jagur[19], puma[19]	
	Presence of unmanaged boneyards		Brown bear[31]	
	Presence of beehive		Brown bear[31]	
Grazing management	Pasture size		Gray wolf [6]	Leopard[16]
	Confining livestock at night		Cheetah[22], gray wolf [18], leopard[22], lion[22], spotted hyena[22]	
	Confining livestock at night with ≥ 5 guard dogs	Gray wolf[8]		
	Confining livestock at night with <5 guard dogs		Gray wolf [8]	
	Presence of pole enclosure	Spotted hyena[16]	Leopard[16]	
	Presence of bush enclosure	Leopard[16]	Spotted hyena[16]	
	Distance to other enclosures–dwellings	Spotted hyena[16]	Gray wolf [18], spotted hyena[16]	
	Presence of electric fence		Gray wolf [18]	
Guarding	Human guards and guard animals (combined)	Leopard[15], tiger[15]		
	Presence or no. of human guards	Gray wolf [14], lion[22,29,32], spotted hyena[22,29]		
	Presence or no. of guard dogs	Gray wolf [14], leopard[32], lion[22,29,32], spotted hyena[16,29,32]	African wild dog[33]	Leopard[22]; spotted hyena[22,32]
	Presence of firearms	Leopards[22], spotted hyena[22]	Lion[22]	
Land-use management	Distance to cover	Eurasian lynx[25], jaguar[3,19], lion[10], puma[19], spotted hyena[10,22,]	Gray wolf [28]	Leopard[16,22], lion[16,22], spotted hyena[16]
	Amount of vegetation		African wild dog[33], brown bear[31], puma[34], jaguar[34], leopard[32], spotted hyena[32]	Cheetah[32], lion[32]
	Distance to protected area	Leopard[15], lion[10], tiger[15], spotted hyena[10]	Lion[5]	
Wild prey management	No. or density of wild prey	African wild dog[32], gray wolf [9], Eurasian lynx[21], lion[30], snow leopard[4]	Eurasian lynx[20,] , snow leopard[27]	
Carnivore removal	Population control	Brown bear[23], dingo[1], Eurasian lynx[12],		Asiatic black bear[13], gray wolf [11]
	Problem animal control	Brown bear[2], Eurasian lynx[24]		Brown bear[23]
	Translocation	Lion[26]		Brown bear[23]

[1]Allen and Sparkes (2001); [2]Anderson et al. (2002); [3]Azevedo and Murray (2007); [4]Bagchi and Mishra (2006); [5]Van Bommel et al. (2007); [6]Bradley and Pletscher (2005); [7]Breck et al. (2011); [8]Espuno et al. (2004); [9]Gula (2008); [10]Gusset et al. (2009); [11]Harper et al. (2008); [12]Herfindal et al. (2005); [13]Huygens et al. (2004); [14]Iliopoulos et al. (2009); [15]Karanth et al. (2013); [16]Kolowski and Holekamp (2006); [17]Van Liere et al. (2013); [18]Mech et al. (2000); [19]Michalski et al. (2006); [20]Odden et al. (2008); [21]Odden et al. (2013); [22]Ogada et al. (2003); [23]Sagor et al. (1997); [24]Stahl et al. (2001); [25]Stahl et al. (2002); [26]Stander (1990); [27]Suryawanshi et al. (2013); [28]Treves et al. (2011); [29]Tumenta et al. (2013); [30]Valeix et al. (2012); [31]Wilson et al. (2005); [32]Woodroffe et al. (2005); [33]Woodroffe et al. (2006); [34]Zarco-González et al. (2013).

Carnivore deterrents overall demonstrated wide variation, ranging from 0% to 100% in effectiveness, although most tools (75%) reduced depredation by ≥30%. In contrast to preventive husbandry techniques, where a single tool was often effective on multiple carnivore species, deterrent tools were usually tested on a single species (Fig. 1A). The most effective deterrents were electrified fladry (100% effective, but note that $n = 1$), light and sound devices (79–100%; $n = 2$), and shock collars (50–87%; $n = 5$); these were tested only on gray wolves (Fig. 1B). Chemicals were highly effective in deterring brown bears (89%) but less effective for American black bears (47%) and polar bears (*Ursus maritimus*; 2%; $n = 2$). Combining multiple deterrents (sounds, chemicals, rubber bullets, and guard dogs) did not deter American black bears (8%; note that $n = 1$); however, the effects were longer lasting than any other combination of deterrents tested (Fig. 2). Studies involving deterrent techniques examined Canids (50% of articles) and Ursids (47%) but not Felids or Hyaenids.

No quantitative measures of effectiveness were available for assessing indirect management but correlation-based studies revealed associations with several environmental factors (Table 2). Distance to vegetation cover was associated with the number of livestock losses, with more depredations occurring closer to cover for Eurasian lynx, jaguar (*Panthera onca*), lion, puma, and spotted hyena (Stahl et al. 2002, Ogada et al. 2003, Michalski et al. 2006, Gusset et al. 2009) and farther from cover for gray wolf (Treves et al. 2011).

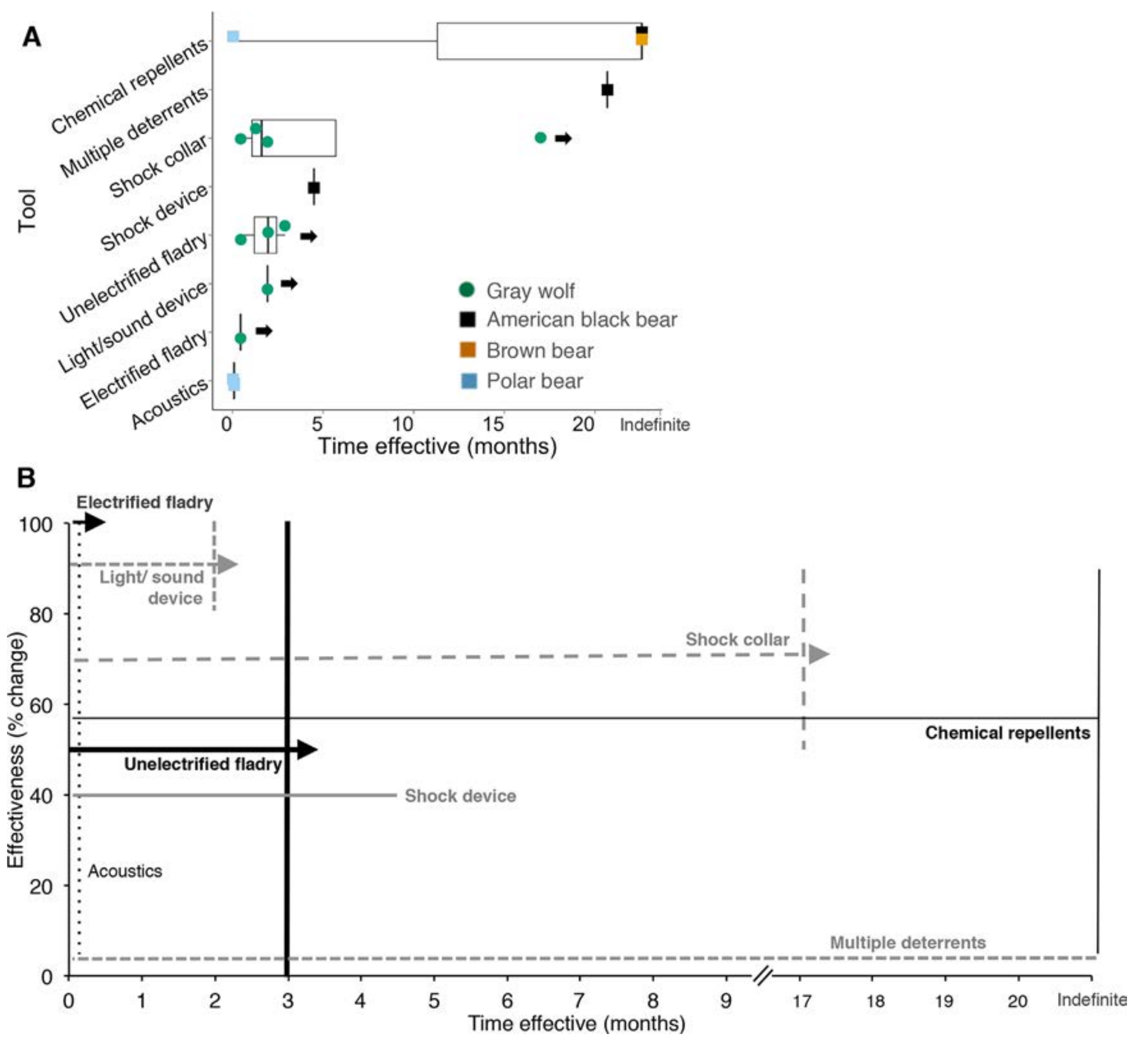

Figure 2. Assessment of the effectiveness of carnivore deterrents in reducing livestock depredation compared with the time duration of effectiveness based on literature review conducted in 2015 with 66 peer-reviewed papers (published 1980–2014). Panel A shows the variation in the amount of time that techniques were effective for different carnivore species. Data are summarized as boxplots, where boxes indicate the lower, median, and upper quartiles; horizontal lines represent the sample minimum and maximum. Original data are overlaid on boxplots, where symbol shape represents the carnivore family and symbol color represents species (see legend). Panel B displays the overall level of effectiveness versus the amount of time that tool effects lasted. Lines represent ranges of values on the *x*- or *y*-axis. Grayscale colors and dashing are meant to help distinguish between lines and do not represent species. In both panels, arrows demarcate techniques that were tested during timed trials, which measured the minimum time length of effectiveness. Effectiveness was calculated as the percent change in depredated animals or carnivore behavior when techniques were implemented, where larger effectiveness values indicate decreasing depredation. The multiple deterrents treatment included a combination of pepper spray, 12-gauge rubber buckshot, rubber slugs, cracker shells, human shouting, and guard dogs.

Sites with more vegetation cover reported greater rates of livestock depredation by African wild dog (*Lycaon pictus*), brown bear, jaguar, leopard, puma, and spotted hyena (Wilson et al. 2005, Woodroffe et al. 2006, Zarco-González et al. 2013). Closer proximity to a protected area was associated with an increased chance of livestock attacks by leopard, tiger (*Panthera tigris*), and spotted hyena (Gusset et al. 2009, Karanth et al. 2013) but showed positive and negative associations for lion (Van Bommel et al. 2007, Gusset et al. 2009). Increased abundance of wild prey correlated with fewer depredations by African wild dog (Woodroffe et al. 2005; Table 2), gray wolf, and lion (Gula 2008, Valeix et al. 2012), but varied for Eurasian lynx and snow leopards (*Uncia uncia*; Stahl et al. 2002; Bagchi and Mishra 2006; Odden et al. 2008, 2013; Suryawanshi et al. 2013). Articles on indirect management primarily examined Felids (78%), followed by Canids (28%), Hyenids (11%), and Ursids (6%).

Time Duration of Effectiveness

Data on time duration were only reported for deterrents and by a small number of studies ($n = 13$). Chemical repellents ($n = 2$) had the longest lasting effects on carnivores but the duration of effects from these tools varied widely, with some tools deterring carnivores permanently and others for only 5 min (Fig. 1A; Table S2). The use of multiple deterrents (note that $n = 1$) and shock collars ($n = 4$) also showed long-term effects, preventing revisits for $\geq$21 and $\geq$17 months, respectively. Advanced technology did not necessarily improve the longevity of tool effectiveness. For example, non-electrified fladry lasted up to 6 times longer than electric fladry (90 compared with 14 days, where $n = 3$ and 1, respectively). Acoustics ($n = 2$) had the briefest effect on carnivore behavior, deterring bears 1–3 days at most. When comparing deterrents by the time and level of effectiveness, tools that ranked highest on both scales were shock collars (tested only on gray wolves) and chemical repellents (tested only on Ursid species; Fig. 1B; Table S2). Electric fladry and light–sound devices decreased depredation (>80%) over short periods ($\leq$2 months). Acoustics ranked low on both scales (5% effective for up to 3 days). Note that because some tools were tested during timed trials, which measured the minimum time length of effectiveness, values from these studies likely underestimated the length of time that tools remain effective (Fig. 2).

DISCUSSION

Our review revealed high variability in the reported effectiveness of techniques for reducing livestock depredation across a range of large carnivore species, geographic locations, and environmental conditions. Across all techniques, husbandry and deterrents showed the greatest upper limits of effectiveness in reducing livestock losses; removal showed the least variation.

Several tools consistently demonstrated great effectiveness ($\geq$50% change) across multiple studies: light–sound devices, night enclosures, shock collars, electric and non-electric fences, and translocation. Electrified fladry, human guards, and lethal control demonstrated high effectiveness in a single study but require further testing to explore consistency. The effectiveness of non-electrified fladry varied across 1 carnivore species (gray wolves), suggesting that this method may be highly sensitive to field conditions or prone to problems with implementation. In contrast, the effectiveness of guard dogs, acoustics, and chemical repellents varied across different carnivore species, indicating that the success of these tools may be limited to a few species. All the tools in our assessment reduced depredation by some positive measure except for non-electrified fladry, where 1 study had no effect, and translocation, where 1 study increased conflict, reportedly because of behavioral changes after leopards were translocated to sites where residential leopards held pre-established territories (Athreya et al. 2010). Considering the low sample size of studies for carnivore removal, as well as evidence of translocation increasing conflict, carnivore removal should be implemented with close monitoring and more rigorous testing to determine whether the necessary resources and potential impacts on the broader ecosystem are worthwhile (Treves and Karanth 2003, Herfindal et al. 2005).

For deterrents, where the time length of effects was measured consistently across studies, a tradeoff appears to exist between the effectiveness of tools in reducing livestock losses and the length of time a tool remains effective. Tools with the greatest effectiveness often lasted for only a few hours, weeks, or months. These results match the findings of other reviews (Breitenmoser et al. 2005, Shivik 2006) and indicate that deterrents may be most optimally implemented during brief times of high risk, such as the calving or lambing season (Schultz et al. 2005), when short-term protection would achieve the greatest financial benefits. Assessments of the time duration of effects from preventative husbandry, carnivore removal, and indirect management are needed to weigh tradeoffs between effectiveness level and duration for these techniques.

We found some evidence to suggest that combining techniques may increase the longevity of effects by providing different types of stimuli and protecting against multiple carnivore species. If the effectiveness of tools in our assessment holds when multiple techniques are combined, an optimal strategy for protecting livestock across carnivore species and systems could be to implement a baseline of preventative husbandry (e.g., electric fences with animal or human guards) supplemented by deterrents to briefly boost effectiveness during key times (e.g., shock collars and sound–light devices) and the use of translocation or lethal control when specific problem animals are identified. Though the effectiveness levels of indirect management of land use and wild prey have not yet been measured quantitatively, environmental conditions and prey availability have direct ties to livestock depredation and should also be managed to reduce the likelihood of livestock loss (Inskip and Zimmermann 2009, Linnell et al. 2012, Pettigrew et al. 2012).

We encountered several inherent biases in the peer-review literature that constrained our ability to compare effectiveness evenly across techniques. One-third of techniques reported in the literature were tested by only 1 study, with techniques that were often repeatedly tested on a single carnivore species. Articles also focused heavily on Canid carnivores in the United States, Europe, and Africa. These biases toward species and locations prevented us from drawing general conclusions about the effectiveness of techniques or tools on carnivore species or locations.

Our analysis could have been affected by a publication bias toward positive effects (Møller and Jennions 2001), which may have reduced the number of published articles reporting low or no effectiveness of techniques. Also, the articles we reviewed were inevitably biased toward recently published articles (95% were published after 1995), which are more often indexed in search engines than older papers. Though our assessment represents the best available quantitative comparison of technique effectiveness in the peer-review literature, these biases should be considered when applying our results to select the most optimal livestock-depredation mitigation techniques.

Though the literature on human–carnivore conflict has greatly matured over the past decade, one of our most important observations was the lack of frequency, consistency, and depth in how livestock depredation mitigation efforts were measured and evaluated in the scientific literature (Graham et al. 2005). Measuring rates of depredation before and after implementing mitigation techniques and the time duration of effects is critical for understanding and comparing effectiveness among methods. It may be that these types of studies have been published more extensively as grey literature, such as government agency reports or educational pamphlets for landowners, but not evaluated through peer-review. The call for consistent measures and rigorous assessment has been repeatedly sounded before (Graham et al. 2005, Inskip and Zimmermann 2009); therefore, we suggest that concerted funding and policy initiatives may now be necessary to fill the existing knowledge gaps if conflict management techniques are to become more efficient and effective worldwide.

MANAGEMENT IMPLICATIONS

We compared mitigation techniques by their reported effectiveness, but we encourage future studies to also consider examining other important indicators of human–carnivore coexistence such as carnivore population size, livestock producer attitudes toward carnivores, and broader effects on the environment. We also encourage researchers to partner with livestock producers to take advantage of real-world conditions where depredation mitigation is needed. Priority should be given to testing the effectiveness of human guards, indirect management of land use and wild prey, and lethal carnivore population control because these techniques can involve large financial and time costs and have detrimental impacts on carnivore populations and ecosystems, sometimes without realized reductions in human–carnivore conflict. Lethal population control especially warrants attention because it is used so commonly and yet its effectiveness is poorly studied. Finally, economic analyses of the tradeoffs between effectiveness and cost are also critically needed to help stakeholders weigh the financial burdens of implementing mitigation techniques. As we continue to improve our base of quantitative, evidence-based insight, we will ultimately strengthen our ability to reduce livestock losses, prevent retaliations against predators, and achieve more sustainable coexistence between people and carnivores.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site. The supporting information consists of Supporting Information Appendix 1, which includes

Table S1. Large carnivore species with body mass >15 kg included in the review.

Table S2. Data and original units from articles used in Figure 2 on technique effectiveness.

Figure S1. Number of assessed articles by (A) large carnivore species and (B) country.

Appendix A1. Articles included in the assessment.

16 November 2016

Effectiveness of Contemporary Techniques for Reducing Livestock Depredations by Large Carnivores

Jennifer R. B. Miller, Kelly J. Stoner, Mikael R. Cejtin, Tara K. Meyer, Arthur D. Middleton, and Oswald J. Schmitz

Wildlife Society Bulletin

Supporting Information

Table S1. Large carnivore species with body mass >15 kg included in literature review assessing the effectiveness of techniques for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014).

Family	Scientific name	Common name
Canidae	*Canis lupus*	Gray wolf
	Canis rufus	Red wolf
	Chrysocyon brachyurus	Maned wolf
	Lycaon pictus	African wild dog
	Cuon alpinus	Dhole
	Canis lupus dingo	Dingo
	Canis simensis	Ethiopian wolf
Felidae	*Panthera tigris*	Tiger

	Panthera leo	Lion
	Panthera onca	Jaguar
	Acinonyx jubatus	Cheetah
	Panthera pardus	Leopard
	Puma concolor	Puma
	Uncia uncia	Snow leopard
	Neofelis nebulosa	Clouded leopard
	Neofelis diardi	Sunda clouded leopard
	Lynx lynx	Eurasian lynx
Hyaenidae	*Crocuta crocuta*	Spotted hyena
	Hyaena brunnea	Brown hyena
	Hyaena hyaena	Striped hyena
Ursidae	*Ursus maritimus*	Polar bear
	Ursus arctos	Brown bear
	Ursus americanus	American black bear
	Tremarctos ornatus	Andean bear
	Ursus thibetanus	Asiatic black bear
	Melursus ursinus	Sloth bear
	Helarctos malayanus	Sun bear

Table S2. Data and original units used in Fig. 2A and 2B on technique effectiveness from articles in literature review assessing the methods for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014).

Technique	Tool	Carnivore species	Units for measuring change	Before tool use	After tool use	Effectiveness (% change)[a]	Time effective	Source[b]
Preventive husbandry	Electric fence	Asiatic black bear	No. of bears raiding fenced field	NA	100	100	NA	Huygens and Hayashi 1999
	Electric fence	Gray wolf	No. of attacks/year	6.6	0	100	NA	Salvatori and Mertens 2012
	Electric fence	Gray wolf	Frequency of attacks	NA	NA	98	NA	Salvatori and Mertens 2012
	Electric fence	Gray wolf	No. of livestock lost	NA	NA	58	NA	Salvatori and Mertens 2012
	Non-electric fence	American black bear	Percent ewes and lambs depredated	1.15	0.25	78	NA	Andelt and Hopper 2000
	Non-electric fence	Gray wolf	No. of attacks	304	106	65	NA	Ciucci and Boitani 1998
	Non-electric fence	Puma	Percent ewes and lambs depredated	1.08	0.53	51	NA	Andelt and Hopper 2000
	Guard dog	American black bear	Percent livestock lost	1.2	0.4	67	NA	Andelt and Hopper 2000
	Guard dog	Brown bear	Percent decrease in depredation compared to control	NA	3	3	NA	Hansen and Smith 1999
	Guard dog	Cheetah	Percent farms with livestock losses	82	35	47	NA	Marker et al 2005
	Guard dog	Dingo	No. farms with livestock losses	93	19	80	NA	Van Bommel and Johnson 2012
	Guard dog	Eurasian lynx	Proportion of farms with depredation	0.13	0	100	NA	Otstavel et al 2009
	Guard dog	Gray wolf	Wolf visits to pasture/day	0.05	0.013	72	NA	Gehring et al. 2010
	Guard dog	Brown bear, gray wolf	Average livestock killed/year	11	6	42	NA	Salvatori and Mertens 2012
	Guard dog	Brown bear, gray wolf	Average livestock killed/year	15	5	65	NA	Salvatori and Mertens 2012

Technique	Tool	Carnivore species	Units for measuring change	Before tool use	After tool use	Effectiveness (% change)[a]	Time effective	Source[b]
	Guard dog	Brown bear, gray wolf, Eurasian lynx	Proportion of farms with depredation	0.25	0	100	NA	Otstavel et al 2009
	Guard dog	Puma	Percent livestock losses	0.8	0.1	88	NA	Andelt and Hopper 2000
	Human guard	Spotted hyena, lion	No. of livestock lost	60	18	70	NA	Bauer et al 2010
	Night enclosure	Gray wolf	Percent of farms attacked	61	29	52	NA	Van Liere et al. 2013
	Night enclosure	Brown bear, gray wolf	Average no. of livestock lost	3.6	0.4	89	NA	Rigg et al. 2011
	Night enclosure	Lion	Average no. of livestock lost	2	1	50	NA	Tumenta et al. 2013
	Night enclosure	Puma	Percent of ranches attacked	100	50	50	NA	Mazzolli et al 2002
Carnivore removal	Lethal population control	Black-backed jackal, caracal, leopard	Percent of stock depredated	13.6	4.4	68	NA	McManus et al. 2014
	Translocation	American black bear	No. of bears involved in nuisance event	123	37	70	NA	Landriault et al. 2009
	Translocation	Gray wolf	No. of wolves preying on livestock	63	19	70	NA	Bradley et al. 2005
	Translocation	Leopard	No. of attacks on livestock	NA	NA	−56	NA	Athreya et al. 2010
	Translocation	Lion	No. of lions preying on livestock	18	3	83	NA	Stander 1990
	Translocation	Tiger	No. of tigers preying on livestock	3	1	67	NA	Goodrich and Miquelle 2005
Deterrent[b]	Acoustics	Dingo	No. dingos consuming bait after treatment	60	57	5	NA	Edgar et al. 2006
	Chemical repellents	American black bear	No. of bears remaining in area after spraying	30	16	47	1 day	Herrero and Higgins 1998
	Chemical repellents	Brown bear	No. of bears remaining in area after spraying	36	4	89	1 day	Herrero and Higgins 1998
	Electrified fladry	Gray wolf	No. of days wolves inside control versus treatment (fladry) pastures	2	0	100	1–14 days	Lance et al. 2010
	Frightening (light/sound) device	Gray wolf	No. of calves killed in pastures with or without devices	16	0	100	30–60 days	Breck et al. 2002

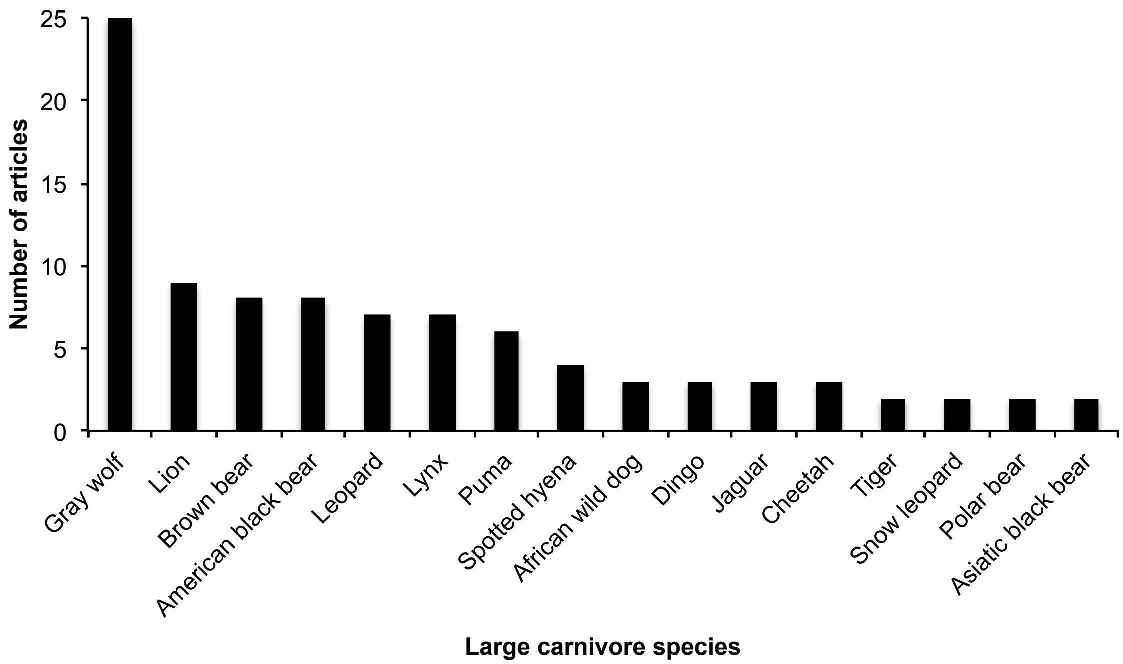
Technique	Tool	Carnivore species	Units for measuring change	Before tool use	After tool use	Effectiveness (% change)[a]	Time effective	Source[b]
	Frightening (light or sound) device	Gray wolf	Proportion food consumed by control versus shock treated wolves	0.84	0.18	79	NA	Shivik et al. 2003
	Multiple deterrents	American black bear	No. of bears returning to area	62	57	8	1–641 days	Beckmann et al. 2004
	Rubber bullets	American black bear	Return time after repelling	NA	NA	NA	1–44 days	Leigh 2007
	Shock collar	Gray wolf	Mean no. of visits during 40-day postshock period for control versus shock treated wolf	17.5	2.2	87	14–60 days	Gehring et al. 2006
	Shock collar	Gray wolf	Mean no. visits to shock zone before and after shock treatment (shock treated animals)	50	19	62	≥14 days	Hawley et al. 2009
	Shock collar	Gray wolf	No. calves killed in year before (1998) and after (1999) shock collar on alpha wolf	9	1	89	≥17 months	Schultz et al. 2005
	Shock collar	Gray wolf	Mean no. of visits/day in postshock period for control vs. shock treated wolves	1.8	0.2	89	≥40 days	Rossler et al. 2012
	Shock collar	Gray wolf	Proportion food consumed by control versus shock treated wolves	0.84	0.42	50	NA	Shivik et al. 2003
	Shock device	American black bear	No. of feeders remaining when protected versus unprotected by shock device	10	6	40	4.5 months	Breck et al. 2006
	Unelectrified fladry	Gray wolf	No. of wolf approaches that resulted in crossing fladry	23	0	100	61 days	Musiani et al. 2003
	Unelectrified fladry	Gray wolf	Amount of food consumed (kg) by wolves in absence or presence of fladry	3.2	2.5	22	NA	Shivik et al. 2003
	Unelectrified fladry	Gray wolf	Time with no wolf crossing	NA	NA	NA	90 days	Gehring et al. 2006
	Unelectrified fladry	Gray wolf	No. of times crossing fladry	5	5	0	2 weeks	Lance et al. 2010

'NA' indicates that values were not provided by the study. In some cases, effectiveness (magnitude of change) was directly mentioned in the study and did not need to be calculated.

[a] Positive values indicate decreasing livestock depredation; negative values indicate increasing livestock depredation. See text for formula and methods.

[b] Citation details are included in Appendix 1.

(A)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15
10
5
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Number of articles
Gray wolf
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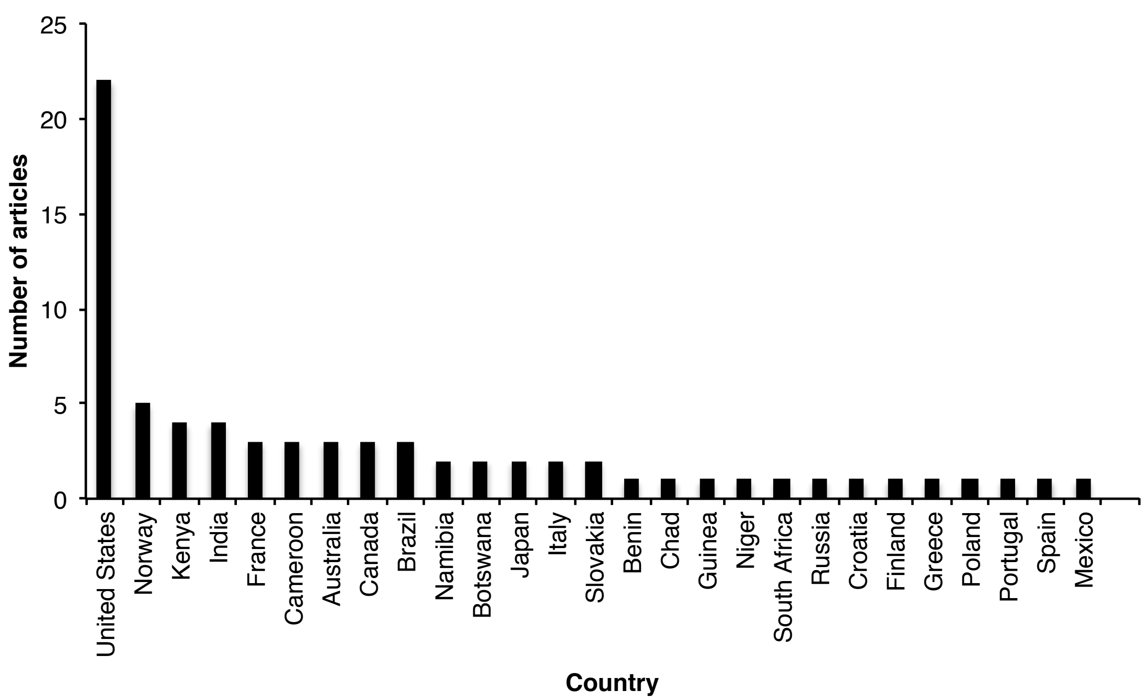
Brown bear
American black bear
Leopard
Lynx
Puma
Spotted hyena
African wild dog
Dingo
Jaguar
Cheetah
Tiger
Snow leopard
Polar bear
Asiatic black bear
Large carnivore species

(B)


25
20
15
10
5
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Number of articles
United States
Norway
Kenya
India
France
Cameroon
Australia
Canada
Brazil
Namibia
Botswana
Japan
Italy
Slovakia
Benin
Chad
Guinea
Niger
South Africa
Russia
Croatia
Finland
Greece
Poland
Portugal
Spain
Mexico
Country

Figure S1. Number of articles by (A) large carnivore species and (B) country assessed in literature review on the effectiveness of techniques for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014).

Appendix 1. Articles included in the literature review assessing the effectiveness of techniques for reducing livestock depredations by large carnivores, conducted in 2015 with 66 peer-reviewed papers (published 1980–2014).

Allen, L. R., and E. C. Sparkes. 2001. The effect of dingo control on sheep and beef cattle in Queensland. Journal of Applied Ecology 38:76–87.

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