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Original Research Article

The effectiveness of livestock protection measures against wolves (*Canis lupus*) and implications for their co-existence with humans

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Wolves (*Canis lupus*) can kill domestic livestock resulting in intense conflicts with humans. Damage to livestock should be reduced to facilitate human-wolf coexistence and ensure positive outcomes of conservation efforts. Current knowledge on the effectiveness of livestock protection measures from wolves is limited and scattered in the literature. In this study, we compiled a dataset of 30 cases describing the application of 11 measures of protecting cattle and smaller livestock against wolves, estimated their effectiveness as a relative risk of damage, and identified the best measures for damage reduction. We found that: (1) lethal control and translocation were less effective than other measures, (2) deterrents, especially fladry which is a fence with ropes marked by hanging colored flags that sway in the wind and provide a visual warning signal, were more effective than guarding dogs; (3) deterrents, fencing, calving control and herding were very effective, but the last two measures included only one case each; and (4) protection of cattle was more effective than that of small stock (sheep and goats, or sheep only) and mixed cattle and small stock. In all of these cases, the relative risk of damage was reduced by 50–100%. Considering Germany as an example of a country with a recovering wolf population and escalating human-wolf conflicts, we suggest electric fences and electrified fladry as the most promising measures, which under suitable conditions can be accompanied by well-trained livestock guarding dogs, and the temporary use of deterrents during critical periods such as calving and lambing seasons. Further research in this field is of paramount importance to efficiently mitigate human-wolf conflicts.

1. Introduction

Human views of nature and biodiversity conservation have undergone significant changes over time. An excellent example of this change is human attitudes towards large carnivores. These predators were formerly heavily persecuted by humans resulting in regional extinctions in many parts of their natural range throughout the 19–20th centuries. However, large carnivores began recovering in some historically occupied habitats beginning from the 1990s due to changes in legislation,

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policy and public attitudes (Chapron et al., 2014; Fechter and Storch, 2014). The grey wolf (*Canis lupus*), being protected by the Habitats Directive and Natura 2000, is currently increasing in numbers and expanding its range in Europe (Reinhardt and Kluth, 2007; Chapron et al., 2014; Andersen et al., 2015). Because of their territorial nature and ability to cover long distances for food and mating, wolves are able to live in diverse environments, even human-dominated landscapes (Fritts et al., 2003; Reinhardt et al., 2019).

The return of the wolf has seen a revival of conflicts with local human populations, mostly because of livestock depredation (Reinhardt et al., 2012; Morehouse and Boyce, 2017; DBBW, 2019a). Wolves feed mostly on large (240−650 kg) and medium (23−130 kg) wild prey, but also may kill livestock whose size varies around 500 kg for adult cattle and horses, 25 kg for sheep and 47 kg for goats depending on their breeds (Newsome et al., 2016). After over a century of living without large carnivores, livestock are very vulnerable to wolf attacks due to weakened anti-predator behavior (Flörcke and Grandin, 2013) and a paucity of protection measures (Reinhardt et al., 2012). Consequently, negative attitudes towards wolves, especially within the farming community, have provoked illegal retaliatory killing of wolves which poses a big challenge for conservation (Reinhardt and Kluth, 2007; Liberg et al., 2011; Kaczensky et al., 2012; Browne-Nuñez et al., 2015). Many traditional protection measures, such as herding and use of guarding dogs and corrals, are now rarely used by livestock owners (Breitenmoser et al., 2005; Reinhardt et al., 2012). Farmers from countries where wolves have persisted continuously are still making use of these measures (Ciucci and Boitani, 1998; Iliopoulos et al., 2009; Rigg et al., 2011). Lethal control, namely the killing of wolves by shooting or trapping, appears to be declining because of the legal status of the wolf in combination with ethical, emotional and financial factors (Bradley et al., 2015; Poudyal et al., 2016). Another potential control measure is fladry, which is a fence with ropes marked by hanging colored flags that sway in the wind and provide a visual warning signal (Reinhardt et al., 2012). For centuries, fladry had been used to corner and hunt down wolves in Eastern Europe (Okarma, 1993), but in recent years it has been adopted as a measure to fence off livestock and thus to prevent wolf attacks (Musiani et al., 2003; Iliopoulos et al., 2019). Additionally, new technological measures are proposed such as electric fences, shock collars put on wolves, or deterrents such as the radio-activated guard (RAG) box, a device which keeps wolves away by emitting strobe lights and sounds when triggered by a signal from radio collars (Breck et al., 2002; Schultz et al., 2005; Salvatori and Mertens, 2012). Depredation by wolves also can be managed by calving/lambing control to reduce the availability of preferentially taken young livestock (Breck et al., 2011) and by translocation of livestock-killing wolves to other areas (Bradley et al., 2005).

Negative effects of depredation by wolves on public perceptions and rural livelihoods have been further aggravated by the bad reputation of these predators fueled by fairytales, myths, customs and traditions, which are still persisting (Boitani, 1995; Fritts et al., 2003; Schöller, 2017; Faß, 2018). Public attitudes towards these canids improve and tolerance increases over time, but mostly in the urban population while rural people still tend to dislike wolves (Williams et al., 2002; Chavez et al., 2005; Houston et al., 2010).

In spite of a diverse range of research projects on human-wolf interactions (Ericsson and Heberlein, 2003; Ansorge et al., 2006; Kaczensky, 2006; Houston et al., 2010; Andersen et al., 2015; Wilson et al., 2017; DeCesare et al., 2018), mostly in North America and Europe, scientific research on the effectiveness of livestock protection measures is limited (e.g., Iliopoulos et al., 2009; Davidson-Nelson and Gehring, 2010; Gehring et al., 2010b). In fact, respective studies are limited for the whole guild of carnivores, methodologically disparate and often focused on large carnivores in general rather than on particular species (Miller et al., 2016; Treves et al., 2016; Eklund et al., 2017; Van Eeden et al., 2017; Van Eeden et al., 2018). Khorozyan and Waltert (2019a) made the first attempt to standardize the analysis of anti-predator measures and concluded that there is empirical evidence that electric fences, calving control and physical deterrents can be the most effective non-invasive measures against wolves. Reinhardt et al. (2012) summarized the applicability of protection measures against wolves in Germany based on an evaluation of effectiveness according to the perceptions of interviewed experts. Recommendations based on rigorous scientific analyses are still limited (Van Eeden et al., 2018; Khorozyan and Waltert, 2019a, b) but essential for the application of meaningful measures to reduce livestock killings and sustainable solutions that will enable farmers to adequately protect their animals and thereby their livelihoods.

The current study sought to address the issue of finding sustainable solutions to prevent the killing of livestock by wolves. The specific aims of the study were to (1) estimate the effectiveness of various livestock (cattle, sheep and goats) protection measures against wolves in different countries, (2) identify the most effective measures to protect livestock from wolves, and (3) recommend appropriate actions for countries with recovering wolf populations, using Germany as an example (Reinhardt et al., 2012). Further, we tested the hypothesis that non-lethal protection measures are more effective than lethal control in reducing livestock losses as wolf removal leads to recolonization of the territory by other packs and necessitates further protection actions (Bjorge and Gunson, 1985; Kuijper et al., 2019).

2. Material and methods

2.1. Literature search

We obtained publications from the reviews of Miller et al. (2016), Treves et al. (2016), Eklund et al. (2017) and Van Eeden et al. (2017), and used a structured search on the Web of Science (www.webofknowledge.com) with the combinations of words "wolf", "*Canis lupus*", "livestock", "protection", "eff*" (aiming for "effectiveness", "efficiency" or "efficacy") and "*predat*" (aiming for "predation" or "depredation") within the period from 1980 to April 2019. We used only studies that explicitly described depredation by wolves and excluded those where data from several predators, including wolves, were lumped.

To be included in the analysis, publications had to be peer-reviewed, published in English, cover studies conducted in the wild without baiting, contain sufficient information to calculate the relative risk (*RR*, see below), and describe one of three experimental designs of livestock protection measures: (1) treatment (affected by a measure) and control groups (not affected by a measure); (2) before-after outcome (same group before and after a measure is applied); and (3) passive with-without outcome (a group with a measure and a group without a measure). We included studies regardless of differences in durations of measure applications.

To avoid autocorrelation, we did not consider the study by Gehring et al. (2006) as it formed part of two larger studies, which we included in our analysis (Gehring et al., 2010a; Davidson-Nelson and Gehring, 2010). The publications by Wielgus and Peebles (2014) and Poudyal et al. (2016) were based on the same set, but we used only data from Poudyal et al. (2016) as the results of Wielgus and Peebles (2014) were found by Poudyal et al. (2016) to be incorrect.

2.2. Data analysis

To increase sample sizes, we grouped livestock protection measures into eight categories: lethal control, calving control, deterrents, fencing, mixed measures, guarding dogs, herding, and translocation. Each study case in the dataset included the application of an individual livestock protection measure for a specific livestock species in a specific place.

To quantify the effectiveness of tested protection measures, we used the relative risk (*RR*) of damage caused by wolves (Eklund et al., 2017; Khorozyan and Waltert, 2019a, b):

$$RR = (n_{killed}/(n_{killed} + n_{live}))/(N_{killed}/(N_{killed} + N_{live})) \quad (1)$$

where n_{killed} is the amount of damage (e.g., number of livestock killed) in a treatment (experimental design 1), “after” (experimental design 2) or “with” (experimental design 3) group, n_{live} is the amount of non-damage in the same group, N_{killed} is the amount of damage in a control, “before” or “without” group, and N_{live} is the amount of non-damage in the same group. So, the sum $n_{killed} + n_{live}$ is the total size of the treatment, “after” or “with” group and the sum $N_{killed} + N_{live}$ is the total size of the control, “before” or “without” group.

If a measure is ineffective then *RR* is close to 1 meaning no difference of damage between the affected (treatment/after/with) and unaffected (control/before/without) groups. A measure is effective when $RR < 1$ and becomes most effective when $RR = 0$. If $RR > 1$ then a measure is counter-productive (Stare and Maucort-Boulch, 2016; Eklund et al., 2017; Khorozyan and Waltert, 2019a, b).

We transformed *RR* to the % of damage reduction to make it more practical:

$$\%\ of\ damage\ reduction = 100 \times (1 - RR) \quad (2)$$

When the data necessary for calculations of *RR* and % of damage reduction were not available in the text or tables of the source publications, we retrieved them from supplementary information files and figures (Espuno et al., 2004; Gehring et al., 2010b). In cases for which we could not calculate *RR* directly (Iliopoulos et al., 2009; Rigg et al., 2011), we took respective *RR* estimates from Eklund et al. (2017).

When papers quantified the effectiveness as the hazard ratio (Bradley et al., 2015; Santiago-Avila et al., 2018) or odds ratio (Wielgus and Peebles, 2014), we used these ratios as the equivalents of *RR* because the hazard ratio and *RR* are generally equal (Stare and Maucort-Boulch, 2016; Eklund et al., 2017) and the odds ratio is equal to *RR* when events are rare (Stare and Maucort-Boulch, 2016), as in the case of depredation.

We applied the Kruskal-Wallis test to compare the % of damage reduction across protection categories and livestock species and the Mann-Whitney test to conduct pairwise comparisons of effectiveness (Dytham, 2011), using IBM SPSS Statistics v. 24 (IBM Corp., www.ibm.com). We applied iNZight v. 3.3.6 (University of Auckland, www.stat.auckland.ac.nz) to produce 95% confidence intervals (CI) of the median % of damage reduction using non-parametric bootstrapping with 1000 randomizations (Khorozyan and Waltert, 2019a, b). For this analysis, we used samples with at least three cases.

3. Results

The literature search resulted in 395 publications, of which 19 publications representing 30 cases were used in this study (Appendix A). These 19 publications were geographically biased towards North America (n = 11 in the USA and n = 2 in Canada), with only six papers from Europe. However, there was no bias between 30 cases which were distributed in a similar manner between North America (n = 14 and n = 3 in Canada) and Europe (n = 13). There were no data from Asia.

The main measures used to protect livestock from wolves were guarding dogs (n = 7), deterrents, fencing and lethal control (n = 6 for each) (Table 1).

Out of measures with three or more cases, deterrents reduced damage by 95.9–100%, fences by 66.4–100%, guarding dogs by 42.3–79.4% and lethal control by 2.7–73.0% (Fig. 1).

Table 1
Sample sizes of cases describing the applications of livestock protection measures against wolves in this study.

Categories of measures	Sample size
Calving control	1
Deterrents (radio-activate guard RAG box, shock collar, fladry)	6
Fencing (night shelter, electric fence, electrified fladry)	6
Guarding dogs	7
Herding	1
Lethal control	6
Mixed measures (herding, dogs and deterrents; dogs and fencing)	2
Translocation	1
Total	30

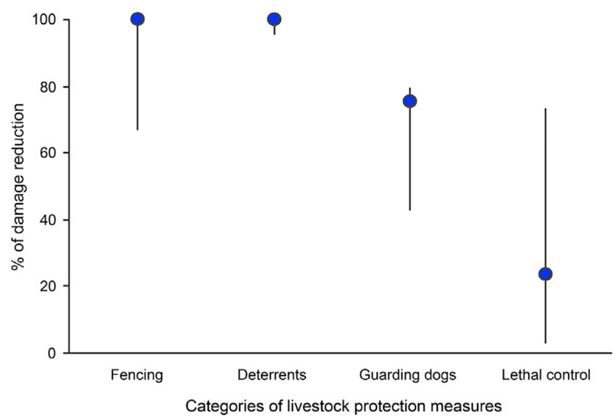

Fig. 1. The 95% confidence interval of the median % of damage reduction in the categories of livestock protection measures with ≥3 cases.

Some single-case measures were very effective, reducing damage by 100% (calving control) and 96.8% (herding), but translocations were ineffective and reduced damage only by 38.4%.

A comparison between protection categories showed that lethal control and translocation were significantly less effective than other measures (Kruskal-Wallis $\chi^2 = 17.76$, $p = 0.013$). A pairwise comparison between protection categories revealed that the application of deterrents was significantly more effective than the use of guarding dogs (Mann-Whitney $U = 3.50$, $p = 0.008$) and lethal control ($U = 0.00$, $p = 0.002$). Fencing was significantly more effective in reducing damage than lethal control ($U = 3.00$, $p = 0.015$). The effectiveness of guarding dogs had the highest variation of all studied protection categories, ranging from an increase of damage by 23.3% to a decrease of damage by 100% (Appendix A).

The application of protection measures reduced damage by 83.5–100% in cattle, 38.4–99.0% in mixed cattle and small stock, and by 73.1–90.0% in small stock (Fig. 2).

A comparison between livestock species showed that the protection of cattle was most effective (Kruskal-Wallis $\chi^2 = 7.56$, $p = 0.023$). A pairwise comparison between livestock species showed that the protection of cattle was significantly more effective than that of mixed cattle and small stock (Mann-Whitney $U = 24.00$, $p = 0.029$) and small stock only ($U = 15.00$, $p = 0.013$). The effectiveness of protection of mixed cattle and small stock was most variable (Appendix A).

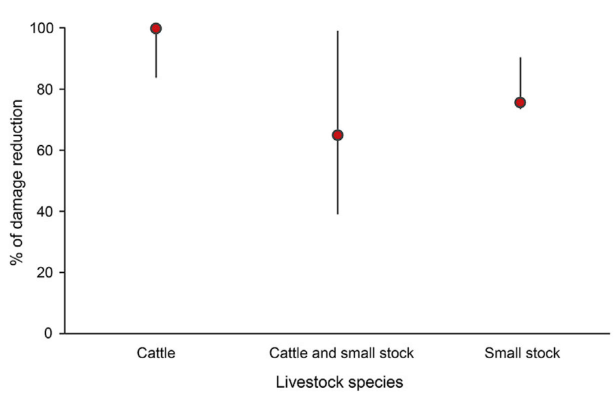

Fig. 2. The 95% confidence interval of the median % of damage reduction in livestock species.

The majority of most effective measures was either applied to cattle or to cattle and small stock. Calving control (n = 1 case) was tested only on cattle. Deterrents (n = 6) were applied to cattle in 83% of cases, fencing (n = 6) was applied to cattle in one case (17%) and to cattle and small stock in 5 cases (83%), while herding (n = 1) was applied only to small stock.

4. Discussion

Our study showed that the most effective measures against wolves were fencing, deterrents (Fig. 1), calving control and herding, but the last two measures were tested in only one case each showing the need of much more research on their application. Protection of cattle was more successful than that of small stock or mixed livestock (Fig. 2) because most of the effective measures were applied to cattle. Variation in the effectiveness of fencing was most likely caused by the structure, maintenance and flaws of fences. It is essential to ensure that fences do not have weak points, such as holes or insufficient voltage, as wolves are creative and will learn to find a weak spot in an otherwise impeccable fence (Faß, 2018). Wolves are able to jump over fences but prefer to dig under fences in an attempt to enter pastures (Reinhardt et al., 2012) and it is important to integrate protection that inhibits such behavior, such as the use of low-stretched electrical wires and dug-in barriers. To prevent jumping of wolves into pastures, it is advisable to have fences of a height of at least 1.2 m, but recommendations on optimal heights of wolf-proof fences differ between countries (Reinhardt et al., 2012; Salvatori and Mertens, 2012). The advantage of electric fences and electrified fladry over non-electric fences is the conditioning effect they have on wolves. An immediate negative experience after coming into contact with the electric wires may provide long-term protection because wolves learn to avoid such structures (Lance et al., 2010) and retreat to hunt more easily available prey, ideally wild ungulates. Electric fences remain very effective up to three years, but this period can be underestimated when fencing projects finish earlier than the effectiveness begins to erode (Khorozyan and Waltert, 2019b). As a trade-off, these fences are usually more expensive and require more time for maintenance, such as the repair of damaged wire and regular grass mowing and moisture control beneath the fence to keep up appropriate grounding and voltage (Lance et al., 2010; Russo et al., 2014; Frank and Eklund, 2017; Faß, 2018).

In the tested cases, deterrents were proven to be effective in reducing damage to livestock and, as with fences, their functionality and performance strongly depended on the correct set-up of the devices. The RAG box study has shown that attacks on livestock occurred almost immediately after devices showed technical flaws (Breck et al., 2002). Another issue is the process of habituation, which is rather quick in regard to deterrents and makes them effective only during up to five months (Khorozyan and Waltert, 2019b). In the experiment conducted by Musiani et al. (2003), the fladry barrier was effective in deterring wolves for 60 days, but then livestock was killed on the 61st day. Wolves are highly intelligent animals and it is to be expected that a continuous exposure to a stationary visual or auditory stimulus will eventually lead to habituation and a decline in effectiveness (Musiani et al., 2003; Davidson-Nelson and Gehring, 2010; Stone et al., 2017). Therefore, these measures should be used predominantly as a temporary solution during the critical phases such as calving or lambing seasons. Shock collars were highly effective as all collared wolves fled when exposed to the collar-triggered beeper sound and none of them attacked livestock during the trials (Schultz et al., 2005). However, the practicality of shock collars has been compromised by limited battery life, extensive effort to identify and collar livestock-killing wolves, and high costs of capturing and collaring wolves. While only shock-collared wolves can be kept away from pastures with shock-transmission towers, non-collared pack members or members of a neighboring pack may still attack livestock on such a pasture (Schultz et al., 2005).

The single case of calving control identified in our literature review demonstrated a 100% reduction of damage to livestock over three years, but like in electric fences, this period could be underestimated (Khorozyan and Waltert, 2019b). This complete effectiveness of synchronized calving is explained by the fact that calves are at a higher risk of getting attacked by wolves due to their weak anti-predator vigilance and small size, so that the limited availability of calves due to calving control keeps depredation down (Breck et al., 2011; Jacobs and Main, 2015; WZI, 2019). Synchronizing birth rhythms within the herd enables farmers to keep a closer watch over the calves in the critical period and to limit the time calves are exposed to predators (Breck et al., 2011). The use of temporary protection measures, e.g. deterrents such as fladry, might reduce livestock losses even further. Once calves have surpassed a critical size and weight, these additional measures can be abandoned, reducing the time wolves are exposed to the stimuli and become habituated to them (Davidson-Nelson and Gehring, 2010). It might be interesting to investigate the effect of synchronized lambing in sheep in relation to livestock losses as well, but its effectiveness might be lower because adult sheep are also of suitable body range for wolves and lambs can be too small to hunt (Ciucci and Boitani, 1998; Fritts et al., 2003; Stone et al., 2017). Although changing birthing cycles may require time and management adjustments (Barnes, 2015; Jacobs and Main, 2015), a positive outcome in form of damage reduction can be worth the initial inconvenience.

Another single-case effective measure was herding (Ciucci and Boitani, 1998). Wolves are generally shy, and while they do not avoid human landscapes and structures (Ronnenberg et al., 2017) they do not normally approach humans (Reinhardt and Kluth, 2007). Therefore, human presence may keep wolves at a safe distance. As shepherds are low-paid and the availability of men wishing to become shepherds is low, the practice of constant herding is common mostly in developing countries, but rare in European and other developed countries where wolves tend to recover (Reinhardt et al., 2012; Salvatori and Mertens, 2012).

Guarding dogs have been used as protection against wolves for millennia (Iliopoulos et al., 2009; Gehring et al., 2010b; Reinhardt et al., 2012), however, their effectiveness is considered to be only low to moderate (Fig. 1). This can be caused by an array of factors, such as the level of training, care and handling (Rigg et al., 2011), the breeds involved (Van Eeden et al., 2018), and the time and money invested (Salvatori and Mertens, 2012). Depending on herd size, at least two dogs need to be purchased and trained to protect sheep, although the optimal number of dogs may be even higher, which is associated with more costs and efforts (Iliopoulos et al., 2009). Potentially, dogs are expected to be more effective in protecting sheep and goats grazing in compact flocks than cattle which usually disperse. Also, even aggressive and well-trained guarding dogs can fail to deter wolves, or even be killed by wolves, when the number of wolves in an attacking pack is much higher than the number of dogs (Ciucci and Boitani, 1998; Iliopoulos et al., 2009; Van Liere et al., 2013).

We found that translocation and lethal control were significantly less effective against wolves than other measures, but we had only one translocation case at our disposal (Bradley et al., 2005). Therefore, the conclusion is tentative for this method. Translocation can weaken pack structure and make other pack members still reliant on livestock, promote depredation and create new conflicts in release sites, increase wolf mortality, and be impractical because of high demand for time, financial and human resources (Bradley et al., 2005). In our sample, lethal control was the least effective measure to reduce damage to livestock (Fig. 1). Failure of lethal control to reduce livestock losses can ensue from a suppressed ability of surviving pack members to hunt wild prey and their need to kill livestock (Wielgus and Peebles, 2014; Poudyal et al., 2016). Importantly, it is very difficult to recognize livestock-killing wolves and kill them selectively, so that the opportunistic shooting upon encounters can be most practical, but ineffective by removing innocent individuals and leaving livestock-killing wolves alive (Santiago-Avila et al., 2018). Removal of an entire pack may solve the issue in the short term (Bradley et al., 2015), but after some time a new pack will take over a territory and resume depredation in the area (Eklund et al., 2017). To be most effective, lethal control should target definitely known individuals responsible for livestock losses (Eklund et al., 2017). A serious and long-lasting disadvantage of lethal control of wolves is its incompliance with legal frameworks, such as EU Habitats Directive, and a strong public backlash even for culling of culprit individuals (Kaczensky, 2006).

As indicated earlier, combinations of measures may magnify the overall effectiveness of livestock protection in comparison with the application of single measures. However, in scientific studies it is essential to apply measures separately and to define specific conditions where they are combined so that it is possible to disentangle their effects and shed light on how to intervene in different depredation scenarios. In our study, we had two cases of mixed measures (Table 1; Espuno et al., 2004; Stone et al., 2017) from which it is hard to determine which measures worked well, when and how.

Our review indicates that, currently, there are strong limitations to draw meaningful conclusions on the comparative effectiveness of livestock protection measures against wolves. These are related to small sample size, geographical bias, different periods of measure applications and a possible publication bias. This is also the case for other predators (Van Eeden et al., 2018). For this reason, we tried not to generalize beyond individual study cases and applied a rather simple comparative analysis instead of more advanced approaches. Furthermore, all our information came from North America and Europe and we are not aware of similar studies from Asia. Although Asia is a densely populated continent with numerous conflicts with wolves arising from depredation (Ali et al., 2016; Newsome et al., 2016), the effectiveness of livestock protection measures is poorly studied there and such investigations should be encouraged and widely publicized. A publication bias, i.e. publication of mostly positive results (Haddaway, 2015) and hence a potentially inflated effectiveness of protection measures, is also possible but was probably minimal as our data came also from the studies with low effectiveness and even counter-productive outcomes.

4.1. *Conservation implications: Germany as an example*

Despite of human density being as high as 234 people per km^2 and landscapes almost completely anthropogenically transformed (Bundeszentrale für politische Bildung, 2018), Germany has experienced a rapid recolonization by wolves and thus may serve as a relevant example of increasing human-wolf conflicts in densely populated countries. From 2000 to 2017–2018, the German wolf population increased from one breeding pair to 75 packs, 30 territorial pairs and three territorial individuals in ten of the 16 states (DBBW, 2019b). Wolves are not bound to protected areas and are expanding from the east to the north-west and south of Germany into unprotected agricultural lands, further increasing depredation records and conflict situations (Reinhardt et al., 2012; Chapron et al., 2014; Görner, 2017; Faß, 2018; Reinhardt et al., 2019; WZI, 2019).

Current livestock husbandry practices in Germany vary with livestock and landscapes. Small stock, mostly sheep, is usually kept in pastures fenced with mobile electric fences without shepherds or dogs (Reinhardt et al., 2012). Transhumant herding and free-grazing sheep are uncommon, although in the Alps unguarded sheep flocks still occur during the summer time (Reinhardt et al., 2012). Cattle, mainly cows and calves, are kept on pastures during summer and in sheds during winter, mostly without shepherds or dogs (Faß, 2018). Fencing methods include electric fences with a varying number of wires and non-electric barriers made from wood, barbed wire or mesh wire (Wagner et al., 2012; Faß, 2018). Considering these practices, fencing is a promising option to reduce livestock losses to wolves because most livestock is already kept in fenced pastures and only slight improvements are required. Electric fences and electrified fladry are effective and may provide long-term protection by offering site aversive conditioning for wolves (Lance et al., 2010; Salvatori and Mertens, 2012).

Fladry is another practical measure as it is less costly than other measures, more easily applicable and very effective (Musiani et al., 2003; Davidson-Nelson and Gehring, 2010; Iliopoulos et al., 2019). However, as wolves habituate quickly to fladry and other deterrents, their application should be limited mostly to the periods when livestock is most vulnerable to wolf attacks like calving and lambing seasons. In this context, it might be worth to shorten the calving or lambing season to synchronize the periods of high depredation and fladry application.

Livestock guarding dogs should be used in addition to existing fences, as is already practiced in some areas (Espuno et al., 2004). If properly trained and handled, they may provide extra protection and in some German states, like Brandenburg and Sachsen-Anhalt, handler training and dog aptitude tests compliant to state regulations are offered by guarding dog initiatives (Arbeitsgemeinschaft Herdenschutzhund, 2013; Interessengemeinschaft Herdenschutz+Hund e.V, 2018; DBBW, 2019a). It is a general recommendation to use guarding dogs mostly on remote and infrequently visited pastures to reduce contact with tourists and other people (Gehring et al., 2010a; Faß, 2018). Herding is not a suitable option for Germany as it is rather uncommon, impractical, low-paid and time-consuming (Salvatori and Mertens, 2012).

Declaration of competing interest

This publication has no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00868.

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