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Missing shots: has the possibility of shooting wolves been lacking for 20 years in France's livestock protection measures?

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Abstract. Wolves were exterminated in France in the late 19th and early 20th centuries. Therefore, livestock breeders and herders were unprepared when wolves arrived from Italy in 1993, the year after France committed to the European Union (EU) to protect wolves. Today, ~580 wolves, whose numbers are growing exponentially, are present in over one-third of France. During the last 10 years, livestock deaths from wolves have grown linearly from 3215 in 2009 to 12 451 in 2019, despite France implementing extensive damage protection measures since 2004, including reinforced human presence, livestock guard dogs, secured pasture fencing and electrified night pens. The failure to prevent damage is clear. Wolves enter mosaic landscapes where grazing livestock are abundant and easy prey. Wolves are intelligent and opportunistic. As a strictly protected species, it seems they no longer associate livestock with humans and humans with danger. Half of the successful attacks now occur during the day, notwithstanding the presence of dogs and humans. Considering the high costs of unsatisfactory protection, France recently modified its wolf management policy. In addition to non-lethal means of protection, breeders that have suffered several attacks by wolves are now permitted, by derogation to the law, to defensively shoot wolves. Based upon evidence from other countries, we suggest re-establishing a reciprocal relationship with wolves. Breeders and herders should be allowed to shoot wolves to defend their herds against wolf attacks, not after several successful predation events. Defence shooting would also upgrade the efficiency of non-lethal means, as warning signals for wolves to respect. Rather than passive coexistence, we need to embrace a dynamic and ever-evolving process of coadaptation between humans and wolves, relying on the adaptive capacities of both.

Keywords: adaptive management, damage prevention, defensive shooting, grey wolf, livestock, non-lethal, predation, public policies, wolf.

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Introduction

Wolves have been linked to humans for several millennia throughout the northern hemisphere, occupying the same ecological niche during the Palaeolithic (Fritts *et al.* 2003) and sharing the same habitat. In France, until the second half of the 19th century, wolves were present in almost all regions and mixed, not without conflict, with the inhabitants of densely populated rural areas (de Beaufort 1988; Moriceau 2007). Not only do wolves adapt easily to human presence, they manage to benefit from their food resources, whether by attacking livestock, foraging on deceased farm animals, or digging through human food waste (Peterson and Ciucci 2003). Ever since livestock were domesticated, wolves have probably been a relatively significant challenge requiring additional work to protect animals, help injured animals, and search for missing ones after wolf attacks. In Eurasia, livestock owners have shown imagination and creativity in implementing various tactics to protect their animals (Fritts *et al.* 2003). Pastoralists also applied constant pressure on wolves by killing those that attacked their herds (Mech 1995; Breitenmoser 1998; Stépanoff 2018).

In western Europe, grey wolf populations declined substantially. They were exterminated in countries such as France by the late 19th and early 20th centuries. Along with Germany and other EU countries, France had no wild wolf populations in its continental territory for about a century. In 1990, when wolves were not yet officially present, French authorities ratified the international Bern Convention on the Conservation of Wildlife and Natural Habitats in Europe. In 1992, France began implementing the EU

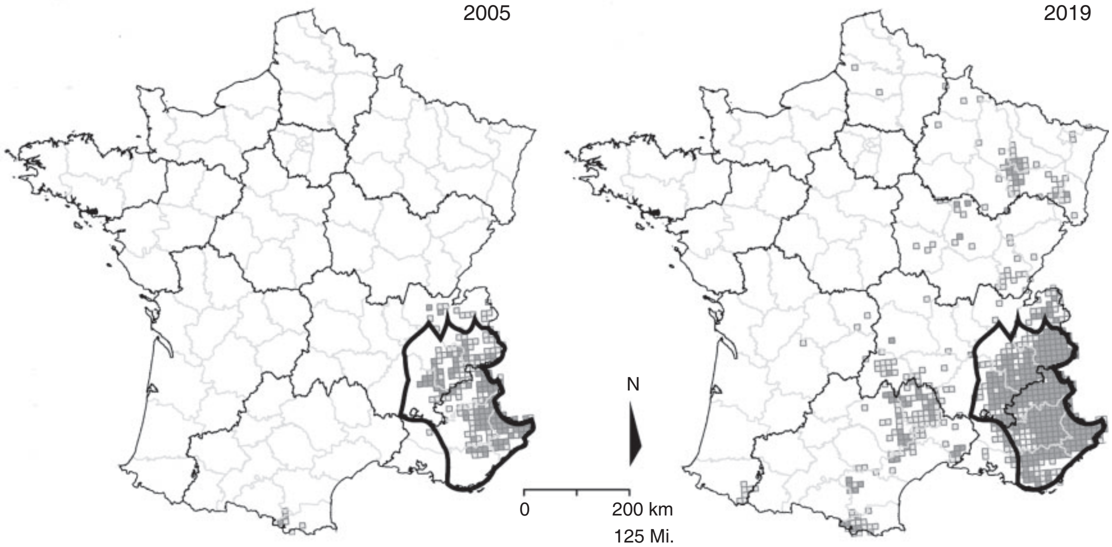

Fig. 1. Presence of wolves detected by biennial period for 2005 (data from March 2002 to March 2005) and 2019 (data from March 2016 to March 2019) at the scale of 10×10 km grids and according to a criterion of the quantity of presence indices, including attacks on livestock. A grid cell is considered regular (dark grey) if at least two indices have been collected during each of the last two biennials considered (2005: $n = 112$; 2019: $n = 382$), otherwise it is classified as irregular presence (light grey) (2005: $n = 99$; 2019: $n = 257$). Data source: OFB Wolf-Lynx Network. The most predated area (seven administrative departments: Alpes-Maritimes, Alpes-de-Haute-Provence, Hautes-Alpes, Isère, Savoie, Drôme and Var), located in the French Alps and Provence, is circled by a thick black line.

Habitats Directive and its Annex II as a legal duty of conserving outstanding wildlife habitats and their species. The grey wolf was on the list, having at that time a population assessed as 'Vulnerable' by the IUCN Red list (Boitani *et al.* 2018).

The presence of wolves in France was publicly disclosed in the spring 1993 by a popular magazine. Its editorial (Peillon and Carbone 1993) highlighted that, 'for the safety of the wolves', their arrival across the Italian border into the Mercantour National Park was kept secret by the authorities. Four years later, it was disclosed that a pack of six to eight wolves had already been established in that Park during the year of the first public announcement (Poulle *et al.* 1997, 1999). Since their arrival was not anticipated, farmers were totally unprepared to cope with wolves, particularly sheep and goat breeders who grazed in or around the Park. At that time, farmers were already suffering from unusual depredation, attributed by authorities to poorly controlled domestic dogs (Garde 1997).

France currently has a wolf population of around 580 adults (see survey method in ONCFS 2017), living permanently or occasionally on about a third of its continental territory (French Biodiversity Agency (OFB 2020)). The number of zones in which there is a permanent wolf presence (i.e. at least three evidences of presence during two consecutive winters) is growing exponentially, reaching 100 at the end of winter 2019–2020 (Fig. 1). Among them, 81 zones of permanent presence correspond to wolf packs territories, all but one located in the French Alps and Provence (OFB 2020). The number of slain livestock remains mostly concentrated in the French Alps and Provence, and particularly in the seven administrative departments were wolves first arrived and settled in the south-east of France (Figs 1, 2).

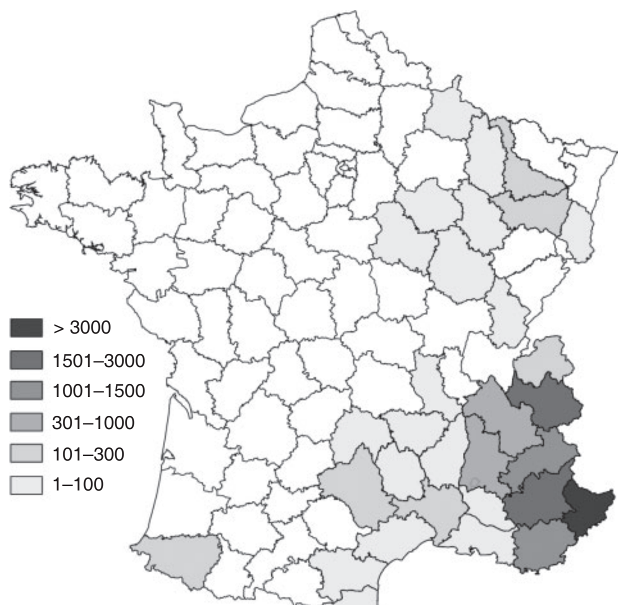

Fig. 2. Map of the number of livestock retrieved after being killed or lethally injured by wolves in 2018 according to the administrative departments of France (data source: DREAL and DDT(M) Auvergne Rhône-Alpes).

Wolves have been under strict protection status in France since 1992, benefiting from a prohibition on any form of deliberate perturbation, capture or killing. The illegal destruction of a wolf is punishable by two years' imprisonment and a fine of €150 000. European legal texts nevertheless consider the possibility of derogation 'in order to prevent serious damage if the [wolf] population is in a good state of conservation and in the absence of satisfactory alternatives.' (EU Council 1992). Although France had respected wolf protection status, in 2014–2015 France allowed farmers who were substantially and regularly affected by predation, despite using non-lethal means of protection, to implement lethal control. Wolf removal and herd defence shootings occurred, but in an administratively supervised manner, up to a ceiling of authorised shootings, calculated and fixed each year at the national level (DREAL Auvergne Rhône-Alpes 2019*c*).

Since the late 1990s, France has developed elaborate measures of herd protection such as livestock guard dogs (LGDs), reinforced human presence, secure pasture fencing, and herd groupings in electrified night pens or secure buildings. All farmers are strongly encouraged to apply these measures, with financial support from both France and the EU. Since 2002, thousands of livestock deaths, mostly sheep, but also goats, cattle, horses and llamas, have been compensated after being attributed to wolves (DREAL Auvergne Rhône-Alpes 2019*a*), with the number of predated animals increasing linearly over the last 11 years. The protection of herds committed €24.67 million of public funds in 2018. Total compensation to farmers for livestock losses was only €3.5 million more (DREAL Auvergne Rhône-Alpes 2019*b*).

How can the failure of the French livestock protection policy be explained, despite increasing and significant amounts of money allocated annually? Beyond the inevitable imperfection of protective measures, we suggest that the main reason arises from the wolves' adaptability, notably their ability to take advantage of their strict protection. In France, wolves have adapted to 20 years of favourable conditions.

We hypothesise that wolves, after having been subjected to poaching pressure in Italy (Boitani 2000; Galaverni *et al.* 2015; Hindrikson *et al.* 2016), became more secure in the French Alps. They first arrived in a mountainous National Park, well stocked with naïve wild ungulates and free from hunting of any kind. Wolves gradually dispersed, where their presence was new and unexpected, and wolf poaching much less developed than in Italy. During the first two decades of their presence, wolves were not confronted by hostile humans, such as those prepared to shoot to defend their herds and/or engage in wolf hunting operations. Would this have led them to modify their behaviour, targeting domestic animals as relatively easy prey, and no longer associating humans, and especially livestock breeders and herders, with danger?

How, then, can avoidance of humans and their livestock be re-established in wolves, and so develop a more acceptable relationship? The objective of this paper is to go beyond the opposition between livestock protection measures and lethal measures against wolves. Based on our experience in France and other countries, French government official data, and the scientific literature, we suggest that defensive shootings in close vicinity of herds should be integrated into the livestock protection toolbox in order to provoke and maintain wolves' fear of humans and thus reinforce the efficiency of non-lethal protection measures. Our analysis aims to contribute to the debate on the management of wolves and their damage to livestock, considering the paths already taken, their results and their possible changes.

Data and analyses on livestock protection and wolf damage

Sources of data

Since 1997, France has encouraged and financed successive national schemes to ensure wolf recovery and viability while protecting livestock. The current National Wolf Plan 2018–2023 (DREAL Auvergne Rhône-Alpes 2018) is a highly administered framework of protection contracts for farmers who benefit from public money, and a monthly update about the number of attacks resulting in livestock deaths, and the number of recovered dead animals, when wolf depredation is not excluded by damage control officials.

All damage control officials are trained and responsible to the French Game and Wildlife Agency (ONCFS), which since 2020 is part of the French Biodiversity Agency (OFB). They evaluate the origin of depredation and whether predated animals were protected against wolves. Their work is often quite complex and detailed (Doré 2015).

The locations and numbers of attacks resulting in livestock deaths, and the number of recovered dead animals, are made public about every month for each French administrative department. These reviews come from a national database, named 'GeoLoup', completed by the damage control officials who work on each location after farmers notify local authorities. They record all predation events and their conditions at the scale of grazing plots or night pens. This information is unavailable to the general public, but most state administrations have access to it, including researchers from public institutions. We exclusively refer to this official database for the graphs and analyses presented below.

The GeoLoup database does not consider missing animals (not found in uneven terrain and/or in deep wooded and brushy locations), or those found dead after an attack but where the origin of predation cannot be certified (late findings, after consumption by vultures, crows or foxes). This can be up to half of the animals found in uneven or steep terrain (Bacha *et al.* 2007). The compensation currently covers 20% of the value of animals not found after the attack, in addition to animals found dead or mortally wounded.

Beyond the GeoLoup database, we used the two other existing databases. Estimated wolf numbers are published annually by OFB (see methodology in ONCFS 2017), from the observations of the Wolf – Lynx network, as is the number of protection contracts. Farmers apply for a five-year protection contract with the Departmental Direction of Territories of the administrative department where their farms are located. Data on protection contracts are then gathered at the national level by the DRAAF (Regional Direction of Agriculture, Agrifood and Forest) Auvergne-Rhône-Alpes.

Data analysis

We tested several models to fit the changes in the number of predated livestock. We first tested an exponential model through linear regression analysis. We then tested a compound model constructed of two or three different intersecting equations.

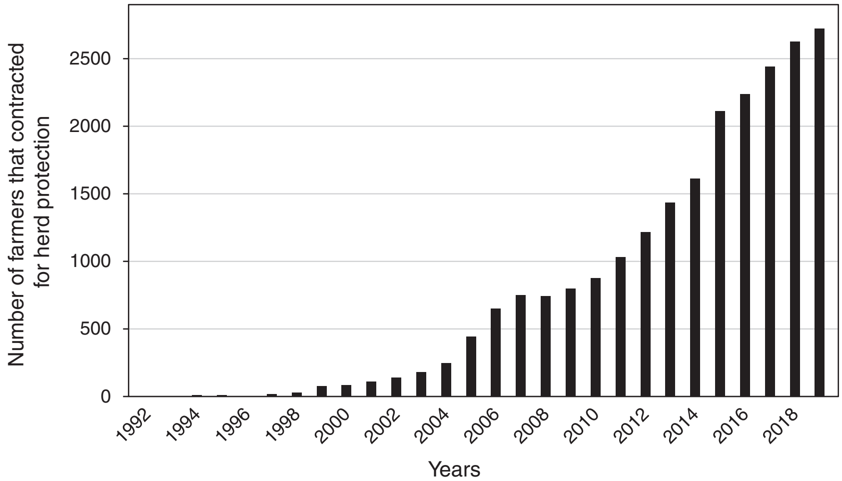

Fig. 3. Number of livestock farmers that have contracted non-lethal protective measures against wolves in France (Source: DRAAF Auvergne Rhône-Alpes).

Linear, exponential and power functions were tested for the two or three different sections of the curve. Compound models were fitted to the data by deviance minimisation with the 'optim' function from the 'stats' package in R (R Core Team 2018). We compared the various models predicting the changes in the number of predated livestock with the modified Akaike's information criterion for small sample sizes (AICc), selecting the model respecting assumptions of residual normality and homogeneity, and with the lowest AICc as the best. The relationship between the number of predated livestock and the estimated average number of wolves was further investigated through linear regression, as causal relationship can be assumed between wolf and prey numbers. The significance of the relationship and the existence of distinct historical periods for this relationship was tested through ANCOVA with contrasts analysis, with 'Historical period' as the categorical explanatory variable. Finally, we assessed the effect of time of attack (day or night) on the number of successful attacks through ANCOVA, with 'Number of successful attacks' as the response variable, 'Year of attack' as the continuous explanatory variable, and 'Time of the day' as the categorical explanatory variable. All analyses were conducted on R 3.5.1 (R Core Team 2018). The AICc was computed using the AICcmodavg ver. 2.3-1 R package. All models were tested for residual normality and homogeneity.

The implementation of protective measures

Protective measures were based on traditional livestock protection practices (Mech 1995). These are interrelated techniques based on three postulates concerning wolf behaviour: (i) a reinforced and continuous human presence with the herd or flock is sufficient to keep wolves at a distance: the assistant herder; (ii) an additional obstacle, often more attentive and vigilant than humans, discourages bold wolves: livestock guard dogs (LGDs); (iii) a herd locked up at night under the watch of humans and dogs no longer undergoes attack: the electrified night pen. The use of these protective measures has been increasingly widespread (Fig. 3), particularly in the French Alps and Provence. This increase of protection contracts occurred in a general context of farm number decrease. The number of sheep farms in the French Alps and Provence decreased by 38% between 1988 and 2000 and by 27% between 2000 and 2010 (Statistical Service of the French Ministry of Agriculture 2020). Currently, there is widespread commitment by breeders to protect themselves against wolves in the French Alps and Provence, as the number of protection contracts corresponds closely to the number of 'Pastoral Units' (the French term for grazing places) in regions subject to predation, particularly on high mountain summer pastures (Dobremez *et al.* 2016).

The role of an assistant herder is to relieve the main herder of additional tasks related to protection from wolves, and to deal with the many consequences of attacks, including searching for injured or dead animals, first aid, protection of bodies from scavengers, and field assistance for officials in charge of damage control and reports (Vincent 2014). These tasks require ~200 hours per month for a collective sheep flock herded during summer on high mountain pasture (Silhol *et al.* 2007), and at least 100 hours per month for an individual sheep or goat herd during all other seasons (Garde *et al.* 2007). On an individual livestock farm, and outside the summer season in high mountains, additional work periods generally occur in the early morning, evening and night. Since all neighbouring farmers have similar work requirements, they cannot share an employee.

Livestock guard dogs were absent for over a century in the French Alps and in the Massif Central areas of France. They were urgently introduced into herds in the Alps and Provence from the late 1990s. According to administrative data from the national funding support, 4258 LGDs were recorded in France in 2019, 92% in the French Alps and Provence. As some farmers exceed the maximal funding cap of LGDs allowed per farm, which depends on conditions and herd size (MAA-DGPE 2018), we estimate the total number in France at around 5000 LGDs.

For all seasons and places where flocks are grazed on fenced pastures and not under constant care of a herder, the recommendation is to secure the fences by ensuring reliable electrification, with a reinforcement wire at the top and bottom, and eventually to raise fence height to ~1.2 m (Garde 2012). LGDs should be

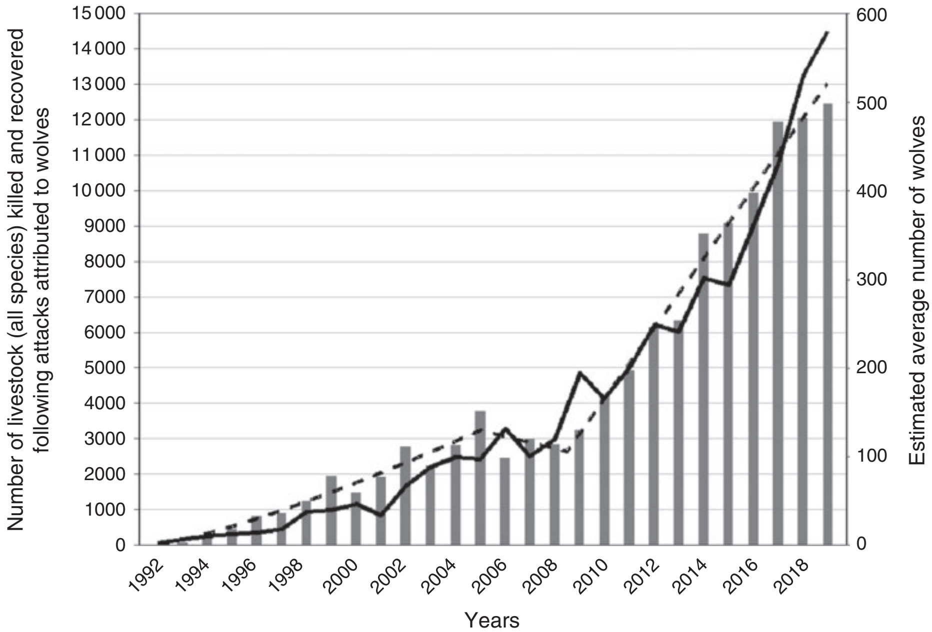

Fig. 4. Number of livestock killed and recovered following attacks attributed to wolves (grey bars) (source: DREAL Auvergne Rhône-Alpes); estimate of the average annual number of wolves in France (solid line): source, OFB; model prediction of the variation in the number of livestock killed and recovered following attacks attributed to wolves (dashed line). For 1992–2005, $y = 126 \times x^{1.26}$; for 2005–2009, $y = 5473 - 173x$; for 2009–2018, $y = -13713 + 991x$.

kept within each pasture, and also sometimes allowed to patrol in nearby areas.

Large electrified night pens have been widely adopted by farmers who are unable to contain animals in a secure building, especially on high mountain pastures. These pens should not crowd sheep or goats, and sometimes with a double fenced compound, livestock, dogs and humans are all in close proximity (Garde 2012; Vincent 2014).

The extent of wolf damage on livestock

Since 1992, the number of livestock killed and recovered following attacks attributed to wolves increased constantly in relation with the increase of the wolf population (Fig. 4). In 2019, 12 451 domestic animals' deaths or lethal injuries were attributed to wolves. The total is probably higher, as missing animals are not counted after wolf attacks. This increase in livestock killed by wolves occurred in a context of national and regional decrease in sheep numbers (sheep account for 90% of livestock compensated as wolf damage). As a whole, the sheep herd in France consisted of 6 877 000 sheep in 2017 (Idele 2019). This national herd has been decreasing for decades at a rate of 1 to 1.5% every year since 1980. From 1988–2000, the herd of French Alps and Provence stagnated or increased very slightly (+ 1.1% over the period), but it fell by 10.3% from 2000–2010 and by 3.6% between 2010 and 2017 (Statistical Service of the French Ministry of Agriculture 2020).

The best model to predict the evolution in the number of predated livestock was a compound model (AICc = 428) composed of three sections: a power function for the 1992–2005 period (a power function allows starting with zero victims in the year of wolves' arrival), a linear function for 2005–2009, and a linear function for 2009–2019 (Fig. 4). The slope of the linear function for 2005–2009 was not significant (t-value $= -1.26$, $P = 0.22$). The yearly number of predated livestock during this period can therefore be considered as constant. A simple exponential model (AICc = 448) did not recognise assumptions of residual normality and homogeneity and it systematically underestimated observed data between 1998 and 2005, and overestimated data between 2006 and 2012. This model was therefore rejected.

Four different periods were observed in the relationship between the number of predated livestock and the estimated average wolf number (Fig. 5). The number of livestock killed was positively related to the estimated average number of wolves through 1992–2005 and 2010–2017 (Tables 1, 2). During these two periods, the two coefficients of the relationship were non-significantly different (Table 2). Conversely, the intercept of the relationship was significantly different (Table 2), indicating that the mean number of livestock killed per wolf decreased between the 1992–2005 and 2010–2017 periods. The relationship was non-significant through the 2006–2009 and 2017–2019 periods (Table 2). Over that time, the estimated average number of wolves doubled or increased by 1/3, respectively, whereas the number of livestock killed remained relatively constant (Fig. 5).

During the thirteen years after wolf arrival in France (1992–2005), the number of predated livestock grew in direct relationship with wolf numbers (Fig. 5). The adoption of protective measures by farmers was limited during this period, with fewer than 300 protection contracts in 2004 (Fig. 3). Between 2005 and

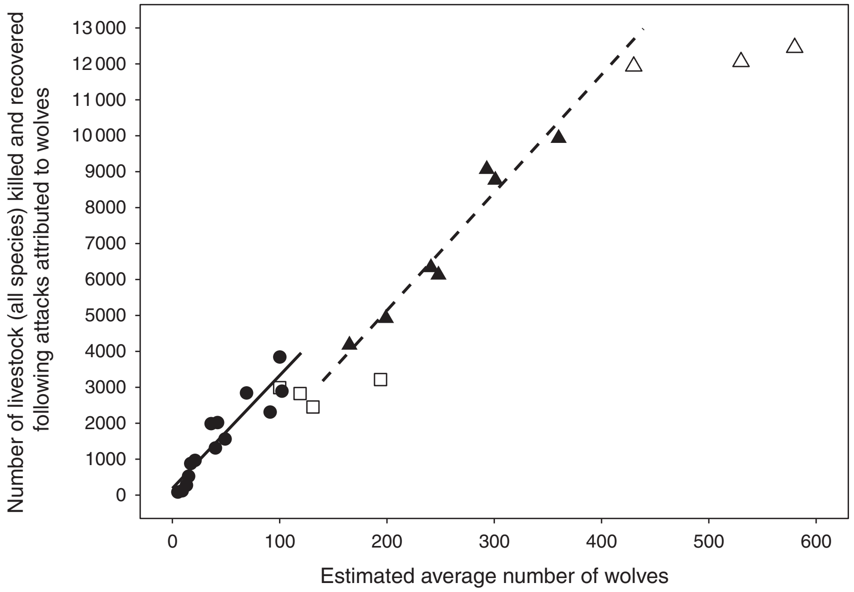

Fig. 5. Linear regression of the number of livestock killed and recovered following attacks attributed to wolves against the estimated average number of wolves in France. Observed values 1992–2005 (closed circles); 2006–2009 (open squares); 2010–2016 (closed triangles); 2017–2019 (open triangles); linear regression for the 1992–2005 period (solid line); linear regression for the 2010–2017 period (dashed line).

Table 1. Results of the ANCOVA of the effect of the estimated average number of wolves (Wolves) on the number of predated livestock with historical period (Period) as a categorical variable

Source of variation	df	*F*-value	*P*-value
Wolves	1	1849	<0.001
Period	3	8	0.001
Wolves × period	3	16	<0.001

Table 2. Contrast analyse following ANCOVA of the effect of the estimated average number of wolves (Wolves) on the number of predated livestock with historical period (Period) as a categorical variable

Historical periods correspond to the following interval of years: period 1 = 1992–2005; period 2 = 2006–2009; period 3 = 2010–2016; period 4 = 2017–2019

Interval of years	*t*-value	*P*-value
Effect of wolves (significance of the slope)		
Period 1	8.48	<0.001
Period 2	0.57	0.57
Period 3	11.56	<0.001
Period 4	0.74	0.47
Differences in the slope		
Period 1 vs 2	−3.71	<0.001
Period 1 vs 3	0.30	0.77
Period 1 vs 4	−5.03	<0.001
Period 2 vs 4	−0.08	0.94
Difference in the intercept		
Period 1 vs 3	−2.44	0.025

2009, a new financial scheme initiated by the French Ministry of Agriculture to implement protective measures became available to all farmers in areas with wolves. It more than tripled the number of farmers who contracted for combined herd protection measures (Fig. 3). Even if the causal relationship cannot be tested between the two processes, this period corresponded to the stabilisation in the number of predated livestock, while the estimated average number of wolves doubled. Unfortunately, this encouraging possible effect of protective measures did not persist.

From 2009–2017, the situation sharply deteriorated. The number of predated livestock again increased linearly with the number of wolves. If the mean number of victims per wolf was slightly lower than during 1992–2005, the rate of increase was identical. One commonly stated hypothesis is that wolves reached other areas of France where farmers were poorly prepared to protect flocks or herds. However, data invalidate this hypothesis, as the seven administrative departments where wolves first occurred in France (i.e. Alpes-Maritimes, Alpes-de-Haute-Provence, Hautes-Alpes, Isère, Savoie, Drôme and Var, see Fig. 1) that suffered 99.5% of losses in 2001 and 99% in 2005, still suffered 87% of the total losses in 2019 and concentrated 78 of the 81 wolf packs identified in France during the same year. So most of the increase in the number of victims comes from the historically predated area of France. Another commonly stated hypothesis is that wolf attacks occur in unprotected herds, but that hypothesis is invalidated by the census of conditions for each successful attack. In the most predated area (the historically predated area that include the seven administrative departments cited above), the majority of wolf attacks (>92%) occurred in herds assessed as protected by damage control officials implementing the GeoLoup national database (Fig. 6). A herd recognised as protected belongs to a

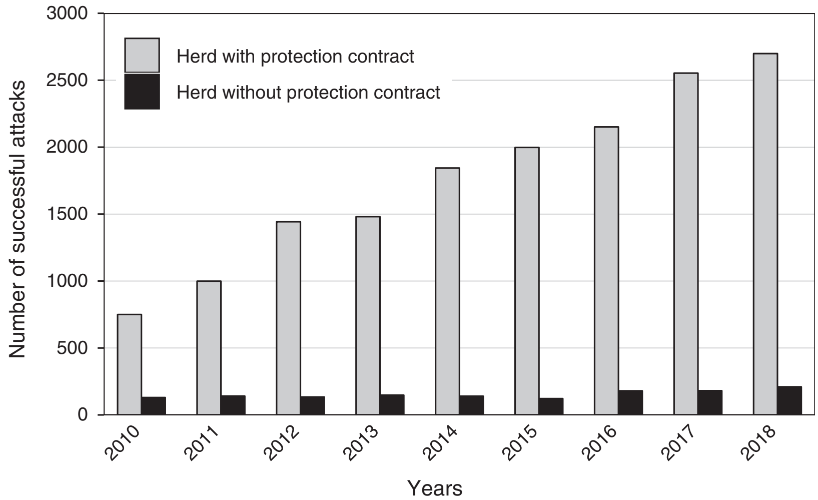

Fig. 6. Number of successful wolf attacks on livestock between 2010 and 2018 in the most predated area of France (administrative departments of Alpes-Maritimes, Alpes-de-Haute-Provence, Hautes-Alpes, Isère, Savoie, Drôme and Var concentrating 90% of the attacks), distinguishing between herds belonging to a farmer with or without a protection contract (data source: GéoLoup database, DREAL Auvergne Rhône-Alpes).

farmer and/or a farmers' grazing trust that has subscribed to an effectively implemented protection contract, that condition being most frequently checked by damage control officials.

Why then did the number of livestock killed return to a linear increase with wolf number, and at the same rate as before implementation of protective measures? And despite widespread use of such measures that appeared successful from 2005–2009 among farmers exposed to wolf predation? Which process, in the complex relationship between livestock, protective measures and wolves, explains the sharp deterioration of the situation post-2009?

The late adaptation of wolf-livestock management policy

From 1993 to 2013, France was reluctant to allow lethal wolf control, due to legal commitments in 1992 to host a wolf population in a favourable conservation status. However, from 2004 to 2013, several orders to remove particularly offending wolves, sent to the French Game and Wildlife Agency (ONCFS), resulted in very limited wolf shooting (Fig. 7). This was due to lack of experience and equipment, and legal actions by pro-wolf associations (Audrain-Demey 2016). Poaching incidents were also reported during this period (Doré 2015).

In 2014, and especially in 2015, the total number of wolves increased significantly, averaging 300, and the Minister of the Environment drastically modified the management policy to try to reduce livestock damage without jeopardising the wolf restoration process. Subsequently, when all non-lethal protection measures had been implemented on farms or mountain pasture grazing areas, and appeared to have failed, shots in the vicinity of these predated herds were gradually allowed. Until 2016, the majority of shootings were wolf removals (open bars, Fig. 7), mostly though wolf hunting drives entrusted to local hunting societies under the supervision of ONCFS. At that time, authorisations for defence shooting in close proximity of herds by the breeders themselves, acting alone or with the help of some authorised local hunters (closed bars, Fig. 7), were still a minority. In autumn 2015, a national wolf brigade was created, under ONCFS supervision. Having skills and proper material for day and night interventions, the brigade uses paired-agents to support a breeder who had already implemented non-lethal protection measures and then obtained official permission to defend his herd by shooting wolves that persistently came in close proximity, e.g. along or even within an electrified pen when livestock were regrouped at night under protection of dogs.

From 2016, the national policy has been to favour defensive shooting by breeders alone, or with the help of authorised hunters around close herd perimeters (closed bars, Fig. 7), rather than attempting to remove wolves through rather unsuccessful and non-targeted wolf hunting drives. In the Alps, because of high wolf density, hunting did not ensure that the wolves being removed were the ones causing recurring damage to livestock. Until 2018, wolf shooting permits, two categories combined, were capped nationally each year at a maximum of 10% of the annual average wolf population estimated at the end of winter (March–April). This figure was assessed as relatively safe for a wolf population growing at around 15–22% per year. Increased shooting from 2015 to 2018 did not significantly reduce the wolf population growth rate (Fig. 7).

In 2019, the national policy was changed once again, following evaluation by the Minister of the Environment. First, the total number of wolves had reached 527 (IC 477-576), exceeding a threshold of 500 wolves considered satisfactory to ensure a favourable wolf conservation status, and second, wolf population growth rate remained satisfactory. The annual ceiling on the number of wolf shots authorised was raised to 17% of the estimated total average wolf population, approximatively double the number of wolves in 2018 (de Rugy and Guillaume 2019).

As people allowed to shoot wolves have gained skills, and numerous breeders have applied for defence shooting authorisations in addition to their non-lethal means of protection, the

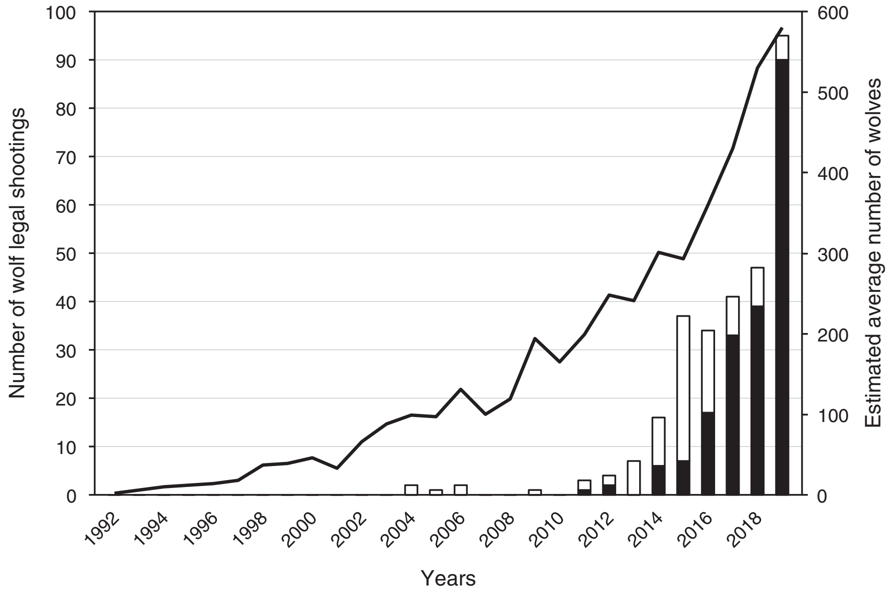

Fig. 7. Number of legal shootings of wolves in France (closed bars, herd defence; open bars, wolf removal) and estimated average number of wolves (solid line) at the end of winter (year/year + 1) (Sources: DREAL Auvergne-Rhône-Alpes and OFB).

annual ceiling has been almost reached. Wolf legal shootings have been in great majority achieved in 2019 though defensive shots close to the herds (closed bars, Fig. 7). From 2018 to the end of winter 2019–2020, the wolf population growth rate has slowed to 9%, and the estimated total number of wolves reached 580 (IC 528-633) (OFB 2020). The same wolf shooting authorisation ceiling was renewed for 2020, with the objective of maintaining a rather stable wolf population number, while much reducing the predation damage to herds.

Further, the period with a strong increase in the number of defensive shootings (from 2016) was closely followed by a stabilisation in the number of livestock killed by wolves, whereas the wolf population continued to increase (Fig. 5). We must be cautious of this last relationship as it only concerns the last two years of our data series and we cannot test the potential relation of causality.

How to explain the failure of protective measures?

Protective measures have been advocated by numerous actors in large carnivore conservation. However, as noted by Eklund *et al.* (2017), experimental and quasi experimental studies are still rare in the field, with very few applying a case-control study design. A more recent review by Khorozyan and Waltert (2019) suggests 100% damage reduction from electric fences, and a high percentage of damage reduction from using livestock guard dogs. However, results were based on publications (Ciucci and Boitani 1998; Wam *et al.* 2004; Iliopoulos *et al.* 2009; Salvatori and Mertens 2012) that do not satisfy the criteria advocated by Eklund *et al.* (2017), notably because no control treatment was provided. Even with a control, results are difficult to interpret, such as those of Wam *et al.* (2004) where attacks apparently stopped in pastures equipped with electric opposed to traditional fences. Considering this study was done in only one wolf territory, it is quite possible that predation was transferred from equipped pastures to non-equipped pastures, with total predation remaining stable. Therefore, it is difficult to consider this a success, or evaluate electric fence effectiveness once all pastures are equipped. In general, it is difficult to assess the absolute efficiency of a protection method at small scale, since predation can be transferred to non-protected flocks as long as the area is not saturated with protected flocks. To our knowledge, no study has been conducted suggesting depredation decreased after implementation of protection measures within large areas where all flocks are protected. Based on DREAL AURA data (Auvergne Rhône-Alpes 2019*b*), it appears that almost all flocks are protected in the French Alps, although we acknowledge data concerning the proper application of protection measures on some farms are sometimes lacking.

Not only are efficacy or protection measures not clearly proven, but the first postulate underlying herd protection measures during 20 years in France, i.e. 'an additional and continuous human presence with the herd is sufficient to keep the wolves at bay' was clearly incorrect. It came from observations made in countries where humans (farmers, herders, hunters) can and do actively repel large carnivores for various reasons, including threat to livestock, thus building a landscape of coexistence where large carnivores notably adapt to humans through spatio-temporal segregation (Oriol-Cotterill *et al.* 2015). 'The wolf fears man' is a hackneyed assumption, transposed from countries where wolves have always been present and abundant, such as Canada, Russia, and Scandinavia (Linnell *et al.* 2002), and more importantly actively controlled, especially when they approach humans and their domestic animals.

In addition, protection measures have not been considering the great adaptability of wolves. Indeed, wolves have been described as very intelligent, and endowed with a social life in families (packs), therefore suitable for individual and collective

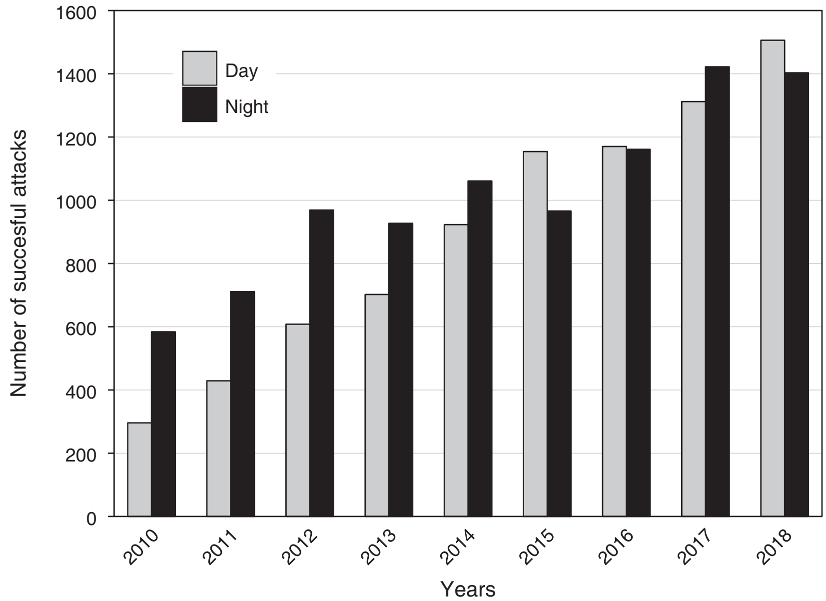

Fig. 8. Number of successful attacks by wolves on livestock in the most predated area of France (administrative departments of Alpes-Maritimes, Alpes-de-Haute-Provence, Hautes-Alpes, Isère, Savoie, Drôme and Var concentrating 90% of the attacks) between 2010 and 2018, according to whether the attacks took place at night or during daytime (Source: GéoLoup database).

learning, particularly adaptable, very opportunistic, often unpredictable, and otherwise prolific (Mech and Boitani 2003).

One example of wolves' ability to opportunistically change their behaviour is the increasing number of successful attacks made during the day in France (Fig. 8). Daytime attacks increased more rapidly than night attacks from 2010 to 2018 (as indicated by the significant interaction between 'Year of attack' and 'Time of the day', Table 3). Whereas the number of successful attacks was greater during the night before 2014, this number was equivalent between day and night after 2014 (as indicated by the effect of Time of the day during these two periods, Table 3). The combination of night confinement with three to four LGDs can provide some protection during the night from wolf attacks (Espuno *et al.* 2004). However, wolves adapt to this protection by shifting to daytime attacks. Another opportunistic change is attacks still occur on high mountain pastures, but are ever more frequent in valleys and plains during nearly all seasons in regions without much snow, a phenomenon also reported by Kyrgyz herders (Lescureux 2006). Grazing a group of sheep, goats, or even cattle and their calves in the immediate vicinity of a farm, village, or suburban subdivision, no longer means tranquillity for farmers.

Table 3. Results of the ANCOVA of the evolution of the number of successful attacks with time (Year of attack) with time of the day (daytime vs night) as a categorical variable

Source of variation	*t*-value	*P*-value
Year of attack	15.6	<0.001
Time of the day	3.9	0.001
Year of attack × time of the day	–3.9	0.001
During the 2010–2013 period		
Year of attack	7.1	<0.001
Time of the day	6.8	0.001
During the 2014–2018 period		
Year of attack	6.7	<0.001
Time of the day	-0.2	0.85

Is there a solution pathway?

Be it through conscious phenomenon or not (Appleby *et al.* 2013; Gonçalves and Biro 2018), the death of a conspecific certainly drives individuals to perceive a threat associated with particular situations or contexts, like the presence of humans and livestock.

For 20 years, farmers and herders in France, however motivated, were unable to demonstrate any serious threat to wolves. In recent years, some farmers became authorised to conduct herd defensive shooting, but only when wolves had defeated other means of protection. An expert conservationist from Montana (USA) advised us however, 'When a wolf has already got a feed profit on livestock in a given location and season, it becomes much more difficult to repel it from that place.' (M. Barnes, pers. comm.), a phenomenon known in ethology and psychology as positive reinforcement (see, for example, Vasconcellos *et al.* 2016).

Evidence elsewhere suggests that coexistence between livestock and wolves requires the establishment, or re-establishment, of reciprocal relationships in order to maintain an acceptable distance and minimise conflicts (Lescureux 2006, 2007; Lescureux *et al.* 2018). Reciprocity corresponds to a proportional adjustment between the impact related to predation (ecological, economic, social and psychological) and the legal means of exercising direct control over predation and predators. Reciprocity also involves keeping predators at a distance when their behaviour represents a threat (i.e. close proximity to farms, towns, suburbs and/or domestic herds).

Reciprocity implies the possible use of lethal means (shooting and/or trapping) before, during or just after an attack on livestock, to eliminate the most reckless individuals or groups, and associate the presence of humans working with herds with an immediate, expected and severe threat (Bangs *et al.* 2006; Lescureux *et al.* 2018). Reciprocity also implies a rather direct relationship between local humans sharing the territory with wolves. As reported by Stépanoff (2018), the Siberian hunter-herder assumes relationships with wolves to imply respect, rivalry and justice, and will eliminate wolves attacking the flock or herd by all possible means. Therefore, the re-establishment of reciprocity in France would imply that defensive shooting in close proximity to herds or flocks would be granted in areas with wolves under temporal and spatial conditions adapted to the local context in a reactive way. Defensive shooting would be considered protection on the same basis as current non-lethal means. Defensive shooting and other protection measures could complement and reinforce each other.

It can be difficult to assess the efficacy of lethal control. Studies suggest diverse results at varying scales and control intensity. Nonetheless, in the USA, attack recurrence decreases for farms equipped with traps as compared with non-equipped farms, but with no effect at the state level (Harper *et al.* 2008). DeCesare *et al.* (2018) showed that increasing levels of targeted lethal removal of wolves following depredation reduced the probability of their recurrence at the level of a hunting district. Although Wielgus and Peebles (2014) found a counter-intuitive result with lethal control leading to an increase in livestock depredation, their analysis has been contested by both Poudyal *et al.* (2016) and Kompaniyets and Evans (2017) who found statistically negative effects of lethal removal on subsequent depredation. Bradley *et al.* (2015) also found a long-term effect of wolf removal on livestock depredation, notably from full pack removal and removal immediately (<7 days) following a depredation event. Considering these various results, it appears that, as mentioned by Treves *et al.* (2016), predator control should not be a 'shot in the dark.' It has to be targeted at individuals or packs attacking livestock, and the effect of the removal must be evaluated in the long-term. However, contrary to Treves *et al.* (2016), we consider that to evaluate the effect of wolf removal, removal has to be authorised and implemented. As recently stated in the case of France by Grente *et al.* (2020), evaluation of wolf removal must consider the general context (herding practices, livestock species, existing protection measures …) and evaluate the effect at various spatial and temporal scales to consider the potential transfer of depredation to other flocks.

If, as we hypothesise, targeted wolf removal causes wolves to fear humans as well as human infrastructure and associated species, in what Oriol-Cotterill *et al.* (2015) consider as a landscape of coexistence, the effectiveness of non-lethal means would perhaps be enhanced. Indeed, without expected and tangible consequences for wolves (risk of injury/mortality), scare devices become useless. A review of numerous repellent techniques implemented over 15 years in the USA Rocky Mountains concluded that all techniques, visual, sound or olfactory, must be constantly associated with immediate and severe danger for wolves. Otherwise, after several days, wolves ignore them and return to usual predatory behaviours (Bangs *et al.* 2006).

The LGDs' ability to be vigilant, especially by smell, is superior to that of humans, but dogs are only effective when they function as a 'reminder'; wolves must have already learned that there is clear danger in approaching humans, LGDs, and livestock. If not, insistent wolves will eventually overcome the LGDs. Multiplying LGD numbers might be effective, but that would increasingly limit land use for recreational activities like hiking and mountain biking.

The suggested reciprocity-driven pathway would confront with the EU Habitats Directive (signed and implemented by France from 1992). This legal regulation imposes that direct control of wolves, including herd defence shootings by a farmer and assistants, be allowed only by derogation, i.e. sparingly, and '… in the absence of satisfactory alternatives.' (EU Council 1992).

The difficulty in re-establishing reciprocity in France is thus the consequence of two factors. The first involves the long history of having wolf population management under State responsibility in southern and Western Europe, a tradition dating back to at least the 6th Century BC in Greece and followed with the creation of wolf-hunting officers, first in the Roman antiquity and then in France (Stépanoff 2018). This centralised approach of human-wolf relationship management perpetuates today into a population management and regulation approach in France, which can both prevent killing wolves attacking livestock, and lead to killing harmless wolves. The rules do not favour the individual and reciprocal approach that would characterise the Kyrgyz herder or the Siberian hunter-herder who will only kill wolves attacking their herd without any regard for population regulation.

The second factor involves arming the farmers and herders, and the expectation of them for continuous attention to predators. In contrast to some other countries, this is generally not compatible with a livestock farmers' workload for other activities in France, and as well as antagonistic to herding activity of shepherds (Meuret and Provenza 2015*a*, 2015*b*). In several countries where shepherds or cattle herders act as 'vigilantes' against predators, their control of the livestock herd feeding and impact is reduced, herds being released from the night pen in the morning, monitored at a distance during the day, and then gathered in the evening with the help of sheepdogs (Ogada *et al.* 2003; Barnes and Hibbard 2016).

Our suggested solution pathway consists in generalising in France the authorisation of defensive shooting of wolves attacking livestock, or approaching herds and showing predatory behaviour (direction and speed of movement, attitudes), without having to wait for the repeated failure of non-lethal protection measures. Defensive shooting could be done by breeder with assistance from authorised local sworn hunters. In other words, the protection of herds against wolves would be managed collectively at a local scale in order to ensure the sustainability of the breeding and grazing activity on the land. The possible additional recourse to the national Wolf Brigade should also be encouraged. However, this brigade is often not able to act in the vicinity of a herd with the necessary rapid reactivity and flexibility. These agents are indeed sent on a grazing place only on nationally approved administrative request, then arriving on a place several days after the first attack, and they know the place much less than local hunters and breeders.

Conclusion

Protecting herds in France, framed by national regulations based on a European Directive, is based on the premise that wolves are afraid of humans. This fear is not, in reality, an intrinsic and permanent trait of the species. Rather, it is at least a partly acquired behaviour, which must be constantly reinforced by explicitly associating a close human presence with a real threat. Scare techniques, or non-lethal repulsion, are only worthwhile as a signal to recall the risk of death or severe injury due to non-compliance. Therefore, non-lethal and lethal techniques must be better integrated, or used in combination when necessary (Bangs *et al.* 2006; Lescureux *et al.* 2018).

Rather than a passive coexistence, a dynamic and ever-evolving process of coadaptation between humans and wolves, studied under real conditions and without omitting the effects of context, needs consideration (Lescureux and Linnell 2013; Garde and Meuret 2017; Mech 2017). Testing of livestock protection techniques becomes relevant when carried out on the predator's normal living and hunting territories, thus having knowledge of all the other attractors or repellents in the landscape, but within the context of existing, and for the most part predictable, human behaviour. The same applies to behavioural tests on LGDs. There are numerous breeds, but skills and motivations to alert and intervene depend on previous habits, acquired within their birth social group on a particular terrain and in a particular working context (Lescureux and Linnell 2014; van Bommel and Johnson 2014; Candy *et al.* 2019). The transmission of skills within groups of LGDs, in coordination with humans, is a promising research topic.

To deal simultaneously with both the adaptive capacities of wolves and those of herds, livestock breeders and herders urgently require help. Some forms of carefully designed adaptive management in real environments can be considered quasi-experiments (Williams and Brown 2014; Johnson *et al.* 2015), with researchers favouring surveys and comparative field monitoring. Given the extent and diversity of wolf-occupied land in Europe and elsewhere, numerous situations can be studied. They are instructive when results are rigorously contextualised and presented without overgeneralisation (Mech 2012; Allen *et al.* 2017). Experiential knowledge and know-how exist and can be collected and their efficiencies compared through ethno-ecological approaches. Countries or regions in political and cultural transition causing changes in livestock breeding, hunting and wildlife management practices present interesting situations where changes in regulation management and practice may or may not facilitate coadaptation with predators (Lescureux *et al.* 2018).

Wolves threaten the viability, liveability and reproducibility of French livestock farms which use combinations of natural and cultivated forages year-round. The majority of these graze separate groups of animals (e.g. sheep, cattle, goats, horses), dispersed over fenced pastures according to feed requirements and fodder resources. Faced with wolves, is it possible to conceive that all these cultivated herbages, natural meadows, scrublands, and woodlands be equipped with high electrified fences and multiple LGDs? The toll on livestock and farmers is already substantial, but that is only part of the story. The remainder is embedded in the physical and emotional fabric of livestock breeders, herders, and local communities (Dumez *et al.* 2017; Zahl-Thanem *et al.* 2020).

More broadly, this questions our way to interact with wildlife. Do we put various types of fences and walls as well as strict laws either to protect wildlife from humans or to protect human activities from wildlife, or do we interact with wildlife using various adaptive means, sometimes lethal ones, in order to maintain an acceptable distance and a more satisfactory and liveable coexistence?

Conflicts of interest

The authors declare no conflicts of interest.

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