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RESEARCH

Times of trouble—seasonal variation in number and severity of attacks on sheep caused by large carnivores and eagles in Sweden

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Abstract

Wildlife managers and livestock owners can choose from a multitude of interventions to prevent carnivore attacks on domestic animals, ranging from light and sound deterrents to fencing and lethal control. To guide management and make the best and most cost-effective choice of interventions, knowledge about where and when these measures are needed the most is important. By identifying spatiotemporal patterns of carnivore attacks, resources can be used more efficiently to prevent such attacks. We used a Swedish nationwide, long-term data set to identify inter- and intra-seasonal variation in probability, number, and severity (number of killed or injured per attack) of large carnivore attacks on sheep. Our results show that there are specific "times of trouble", regarding the number of attacks from golden eagle (*Aquila chrysaetos*) in late spring, and from brown bears (*Ursus arctos*), lynx (*Lynx lynx*), and wolves (*Canis lupus*) in late summer. Additionally, for brown bears and wolves, the severity of attacks varied throughout the grazing season with a peak in the latter part of the summer. The results can be used for guidance of temporal prioritisation of preventive interventions to reduce the probability, number, and severity of large carnivore attacks on sheep.

Keywords Large carnivores · Carnivore attack · Wildlife impact · Wildlife damage

Introduction

Conservation of large carnivores often depends on land sharing with other human interests and practices in multiuse landscapes (Chapron et al. 2014). This is the case in Sweden, where large carnivore populations have recovered from near extinction to favourable conservation status and now share land with various types of farming practices (Wabakken et al. 2001, 2022). The Swedish case is not unique and conflicts between conservation and other land use objectives are increasing globally (Woodroffe et al. 2005; Redpath et al. 2013; Redpath et al. 2015; Hemminger et al. 2022). Unless interventions are successfully implemented, increasing numbers and expanding distribution of large carnivores can lead to an increasing number of carnivore attacks on livestock. Impacts from wildlife on human livelihoods, such as carnivore predation on livestock, can lead to decreased acceptance for carnivores among farmers and fuel conflicts between stakeholders, e.g. livestock owners, and conservationists (Redpath et al. 2013; Eklund et al. 2023), thereby creating an obstacle for conservation (Kansky and Knight 2014).

Wildlife managers and livestock owners can choose from a multitude of interventions, such as light and sound deterrents, carnivore-deterrent fencing, and lethal control (van Eeden et al. 2018; Eklund et al. 2017; 2020a). However, all interventions come with costs, such as money and time, and they can be stressful to implement, in addition to other concerns regarding animal husbandry practices (Flykt et al. 2022). Therefore, knowledge is needed to guide livestock owners and management to prioritise among different interventions. Such prioritisation can be based on spatiotemporal patterns of carnivore attacks on livestock (Lischka et al. 2018). Moreover, intervention effectiveness will vary with how well the intervention is designed to the target carnivore species (Eklund et al. 2017). Therefore, understanding the patterns of species' specific behaviour is key to prioritise how, where, and when to implement interventions.

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Fig. 1 Maps showing **a** study area, Sweden, **b** sheep farm density, **c** location of sheep attacks by brown bears, **d** location of sheep attacks by golden eagles, **e** location of sheep attacks by lynx, **f** location of sheep attacks by wolves during 1997–2014

In Sweden, the number of large carnivores, and livestock attacks by large carnivores, has increased over the past 20 years (Fig. 1). Livestock farming is an important part of the rural economy and is in line with political intentions of increasing environmentally friendly and locally produced products supporting a prosperous countryside (Wretling and Clarin 2010). Grazing livestock also keeps the agricultural landscapes and wetlands open, enhancing biodiversity in the landscape and maintaining a cultural heritage (Lindborg et al. 2008). One of the main objectives in the 2013 Swedish government bill (2012/13:191) of sustainable large carnivore management is to facilitate coexistence between livestock farming and carnivore presence. It states that carnivore presence "should never make livestock husbandry considerably more difficult". The need to minimise livestock losses to carnivores in Sweden is thus essential and public expenditures are devoted to interventions intended to protect livestock from large carnivores. During the period 2010–2014, an annual average of 1–1.5 million Euros has been used on interventions to prevent attacks (Anon 2015[a]). In a European context, the number of attacks and compensation cost per individual carnivore in Sweden is relatively low (Bautista et al. 2019).

In Sweden (Fig. 2), four large carnivores, brown bears (*Ursus arctos*), golden eagles (*Aquila chrysaetos*), lynx (*Lynx lynx*), and wolves (*Canis lupus*), are involved in predation on domestic livestock outside the reindeer husbandry areas (Frank et al. 2015). The fifth large

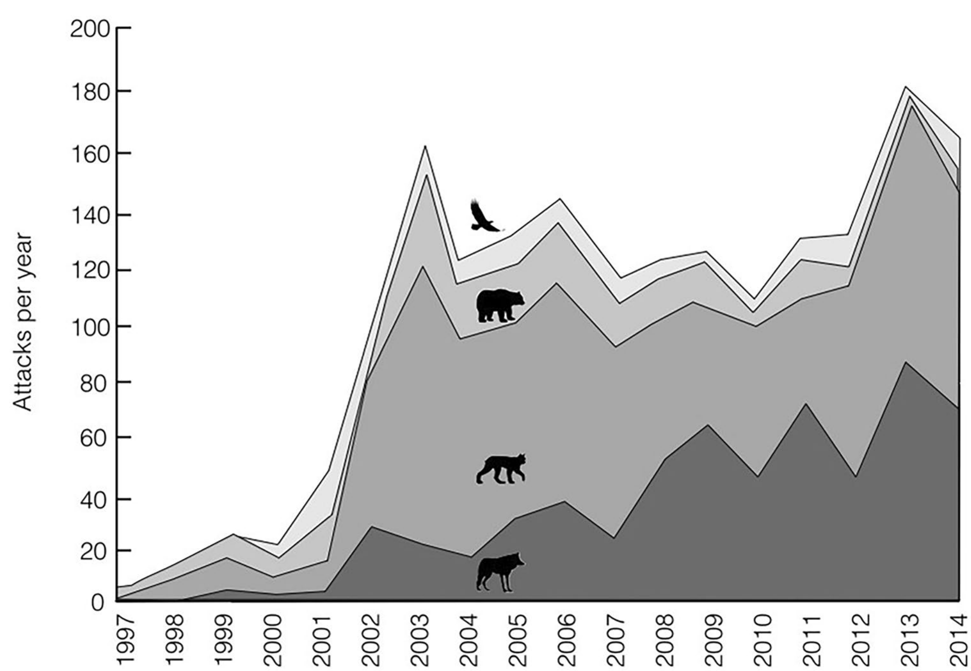

Fig. 2 Annual number of attacks on sheep for bears, golden eagles, lynx, and wolves in Sweden 1997–2014

carnivore, the wolverine (*Gulo gulo*), mainly occurs in the northern mountainous areas, where domestic livestock, other than domestic, free-ranging reindeer (*Rangifer tarandus*), are less common and wolverine attacks on livestock other than reindeer are rare (Mattisson et al. 2020). Golden eagles and lynx reproduce throughout Sweden (Åsbrink and Hellström 2020, Frank and Tovmo 2021), bears reproduce in the northern half (Kindberg et al. 2011), and wolf reproduction is mainly restricted to the south-central parts of the country (Wabakken et al. 2022). However, all these species have capacity for long-range movements and dispersal (Wabakken et al. 2007; Samelius et al. 2012), and sporadic occurrence of, for example, wolves can be expected in the entire country. In Sweden, livestock farming occurs with the highest intensity in the southern and coastal parts of the country and becomes gradually less common along the south-north gradient (Fig. 2).

The geographical overlap of livestock farming and large carnivore distributions, but also farm characteristics, habitat composition, and individual behaviour of carnivores (i.e. problem individuals) can influence the risk of where in the landscape predation events may occur (i.e. problem areas) (Linnell et al. 1999; Treves et al. 2004, 2017). Such information can guide decision-making about where to put effort on interventions. Similarly, information about temporal variation in predation patterns, "times of trouble", can guide decisions by managers and livestock owners. Temporal variation in the number of attacks may, for example, depend on seasonality, both in the livestock production practices (e.g. whether there is free-ranging livestock or presence of juveniles) and in the population dynamics and needs of carnivores (e.g. dispersal phases or presence of juveniles; Musiani et al. 2005, or the availability of wild prey; Patterson et al. 2004). In many geographical regions, the livestock grazing season is divided into more and less intense periods, where during an intense period livestock are dispersed on grazing grounds and during a less intense period kept on the farm, depending on for instance the climatic impacts on grass availability and the breeding season. This seasonality may affect the number of available grazing livestock throughout the year and, in turn, the number of large carnivore attacks (Chen et al. 2016; Musiani et al. 2003).

The aim of this study is to investigate the occurrence of "times of trouble", i.e. seasonality in (1) the probability of a carnivore attack on sheep, (2) the number of attacks, and (3) severity of carnivore attacks (i.e. sheep affected per attack), to allow an informed allocation of resources to prevent such attacks. To achieve this aim, we use Swedish national long-term data of killed, injured, or missing sheep for each of the large carnivore species in Sweden.

Material and methods

Data collection

We used the official Swedish statistics (Frank et al. 2015) of confirmed livestock attacks by large carnivores (brown bear, golden eagles, lynx, and wolves). Since 1997, market value compensation has been paid for all sheep that are killed, injured, or missing following a large carnivore attack. A prerequisite for compensation is that each reported carcass or injury is examined in the field by trained official inspectors to confirm a large carnivore attack. During the examination, all livestock carcasses are skinned to find the cause of death, based on bite and/or claw marks with haematoma on the body (Levin et al. 2008). Injured animals are often examined in cooperation with a veterinarian. Based on the on-site examination and documentation, the inspectors assess whether injury or death was caused by a large carnivore and which species was involved. Missing livestock are compensated only if they are missing after a confirmed large carnivore attack, i.e. in cases where (1) large carnivores have killed or injured other animals during the attack, (2) visible carnivore tracks are found, or (3) when carnivore tracks are verified by trained and certified dogs. A study using DNA from saliva to validate the accuracy of the inspectors' assessment concluded that the inspectors correctly identified the culprit species in more than 80% of the cases (López-Bao et al. 2017). The number of unreported attacks by large carnivores is expected to be small, as farmers are compensated for confirmed kills, and because livestock owners are obliged to check and count their livestock daily according to the Swedish Animal Welfare Act (SFS 1988:534). Farmers are encouraged by the authorities to report all cases of suspected carnivore attacks, and all reported cases are examined without any cost to the farmer. All documentation is collected in a national database hosted by the Swedish Environmental Protection Agency (www.rovbase.se).

We included all cases where the official inspector deemed large carnivores to be the cause of death or injury from long-term data in the national database collected between 1997 and 2014 in our analyses. In addition to culprit species, the data includes date and the number of sheep killed, injured, or missing per attack. Golden eagles, lynx, and wolves can attack livestock year around, whereas the data for brown bears only included April to November (8 months), due to winter hibernation.

Study area

The study area comprised all of Sweden, ranging between latitude 55°–69°N and longitude 10°–24°E (Fig. 1a). The study area ranges from the boreal to nemoral zone (Swedish Environmental Protection Agency 1999) with altitudes between 0 and 1000 m.a.s.l. The climate is temperate with four different seasons and average temperatures of about 8–18 °C in July and between − 15 and 2 °C in January, depending on location (Swedish Meteorological and Hydrological Institute 2022). From December to March, the ground is generally covered with snow of varying depths (5–50 cm). The main part of the study area is covered by boreal coniferous forests. The most common tree species are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), mixed with birches (*Betula pendula* and *B. pubescens*), aspen (*Populus tremula*), and alders (*Alnus incana* and *A. glutinosa*). The area is characterised by intensive forestry with even-aged forest stands, clearcuts, and a high density of forest roads. Pastures with grazing livestock constitute approximately 1% of the Swedish land surface. Sheep are mainly kept for grazing in fenced pastures (less than 1% are free ranging). The number of sheep per farm is relatively small, 92% of the sheep farms hold less than 50 ewes (Statistics Sweden 2015).

The main wild prey species for large carnivores in the study area are moose (*Alces alces*), roe deer (*Capreolus capreolus*), fallow deer (*Dama dama*), red deer (*Cervus elaphus*), badger (*Meles meles*), beaver (*Castor fiber*), brown hare (*Lepus europaeus*), mountain hare (*Lepus timidus*), capercaillie (*Tetrao urogallus*), and black grouse (*Tetrao tetrix*) (Olsson et al. 1997). Population numbers of large carnivore have varied during the study period (1997–2014); the estimated lynx population was 1700 in year 1998 and 1300 in 2015 (Frank and Tovmo 2021); brown bears were estimated to approximately 2200 individuals in 2000 (Kindberg et al. 2011) and 2800 individuals in 2013 (Kindberg and Swenson 2014) and the number of wolves were estimated at 50 in 1998 and 340 in 2015 (Svensson et al. 2023); the estimated population of golden eagles was 1200 in 2002 and 1700 in 2015 (Åsbrink and Hellström 2021).

Statistical analysis

We used three separate model structures (steps 1–3) to manage the zero-inflated and overdispersed data of number of attacks documented per month. We tested for seasonal variation in the probability (step 1), number (step 2), and severity (step 3) of attacks on sheep, separately for each carnivore species. In step 1, we used generalised linear models with binomial error structures and logit link functions (R package lme4; Bates et al. 2015) to assess the variation in probability of an attack occurring during a certain month of the year (factor; 12 months (Jan–Dec) for golden eagles, lynx, and wolves and 8 months (Mar–Nov) for brown bears). In step 2, we excluded all zeros (i.e. months with absence of attacks some years) to estimate the variation in number of occurring attacks over the months (factor; 12 months (Jan–Dec) for lynx and wolves, 10 months for golden eagles (Jan, Apr–Dec), and 8 months (Mar–Nov) for brown bears), using generalised linear models with a negative binomial error structure with log links. In step 3, we analysed the variation in severity of the attacks (i.e. number of sheep killed or injured per attack) over the months (factor; 12 months (Jan–Dec) for lynx and wolves, 10 months for golden eagles (Jan, Apr–Dec), and 8 months (Mar–Nov) for brown bears), using generalised linear models with a negative binomial error structures with log links (R package lme4; Bates et al. 2015). To model the predicted probability, number, and severity of attacks per month and their 95% confidence intervals, we used the R package "glm.predict" (Schlegel 2022). All analyses were done in R version 3.6.3 (R Core Team 2020).

Results

During the study period, 1761 large carnivore attacks on sheep were confirmed in Sweden (Fig. 1c–f). Lynx accounted for the highest number of attacks ($n=813$), followed by wolves ($n=614$), brown bears ($n=257$), and golden eagles ($n=77$). The annual number of attacks by lynx and wolves increased during the study period, but was constant for brown bears and golden eagles (Fig. 2). The increase in wolf and lynx numbers and the population range expansion into areas in southern Sweden, where sheep farms are more common, likely explains a part of the increasing number of attacks. This is particularly evident for the rapid increase in the number of attacks between 2001 and 2002. However, a more prominent factor is likely that during this time the development of a new system for investigating suspected attacks on livestock by large carnivores was coming into practice. The new compensation scheme, based on field personnel verification, was launched in 1997 but only 3–4 years later were sufficient field personnel trained and available in the southern parts of Sweden. Furthermore, when establishing the new scheme, it also took some time for livestock owners to become aware of the system and who to contact in case of suspected large carnivore attacks.

Attacks on sheep in fenced pastures were more common than attacks on free-ranging sheep for all carnivore species (brown bears: 64%, golden eagle: 100%, lynx: 98%, wolves: 86%). However, the proportion of unfenced grazing areas in Sweden is very low (< 1%) and spatially limited to forest and mountain areas. Geographically, this area corresponds well with the distribution of brown bears, but overlaps the distribution range of other carnivores to a lesser extent.

Probability of carnivore attacks on sheep (step 1)

The probability of attacks on sheep varied between months, but with considerable variation around the predicted means for all species. The attack probability distribution peaked in July/August for brown bears and September for wolves (Fig. 3, Table S1 Supplementary Information). The probability of lynx attacks increased during the summer, but without a pronounced peak. The probability of attacks by golden eagles peaked earlier (April) and then decreased throughout the year. The predicted probability of an attack on sheep by golden eagles was surrounded by wide confidence intervals (95% CI: 0–1) for February, March, and December, resulting from events of attacks being absent or extremely rare, and thus poor fits of the models for these months (Fig. 3, Table S1 Supplementary Information).

Number of carnivore attacks on sheep (step 2)

The number of attacks by brown bears and wolves followed a similar symmetrical peak-shaped pattern like that for the probability of attacks, with a peak in August for both species (wolves predicted mean 8.7 attacks, 95% CI: 6.8–11.3 and brown bears 4.8 attacks, 95% CI: 3.8–6.1). There were no clear peaks for golden eagles and lynx (Fig. 4, Table S1 Supplementary Information). The predicted number of attacks in January was surrounded by wide confidence intervals (95% CI: 0.1–6.4), due to attacks being absent or extremely rare, resulting in poor model fit for that month.

Severity of carnivore attacks on sheep (step 3)

Overall, wolf attacks resulted in the largest number of individual sheep being killed, injured, or lost per attack (median = 3, range: 1–46), followed by attacks by brown bears (2, range: 1–33), lynx (2, range: 1–20), and golden eagles (1, range: 1–8) (Figs. 5 and 6). Attacks from golden eagles and lynx most often resulted in a single sheep being killed or injured (golden eagles 59% and lynx 61% of the attacks), whereas only 34% of bear attacks and 35% of wolf attacks were limited to a single sheep. There was an intermonthly difference in the number of sheep per attack for brown bear and wolf attacks, whereas the number of sheep affected per attack did not vary among months for lynx or golden eagle attacks (Fig. 6, Table S1 Supplementary Information). A symmetrical peak-shaped pattern was observed for the number of sheep per wolf attack, and the peak occurred in June (predicted mean = 7.8 sheep per attack, 95% CI: 6.2–9.6) and thereby peaked earlier than the number of attacks (Figs. 4 and 6, Table S1 Supplementary Information).

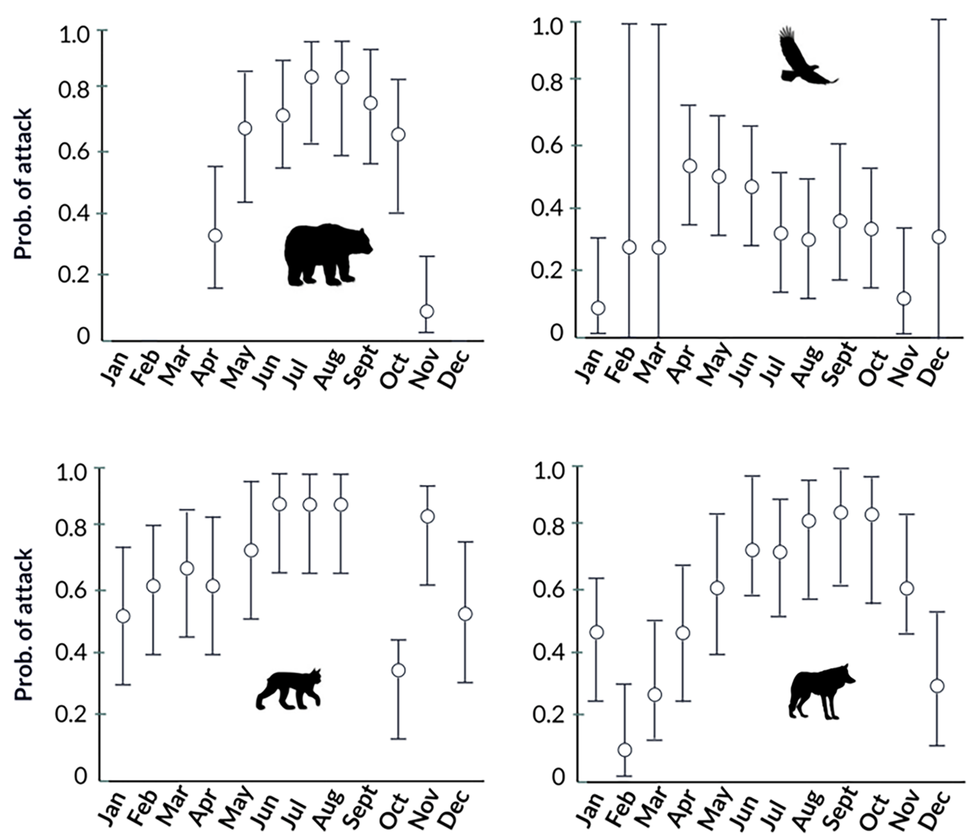

Fig. 3 Predicted probabilities of attack on sheep per month in an average year at a national scale for brown bear, golden eagle, lynx, and wolf during 1997–2014. Predictions (circles) and confidence intervals (95%) are derived from the binomial generalised linear model for each carnivore species (step 1)

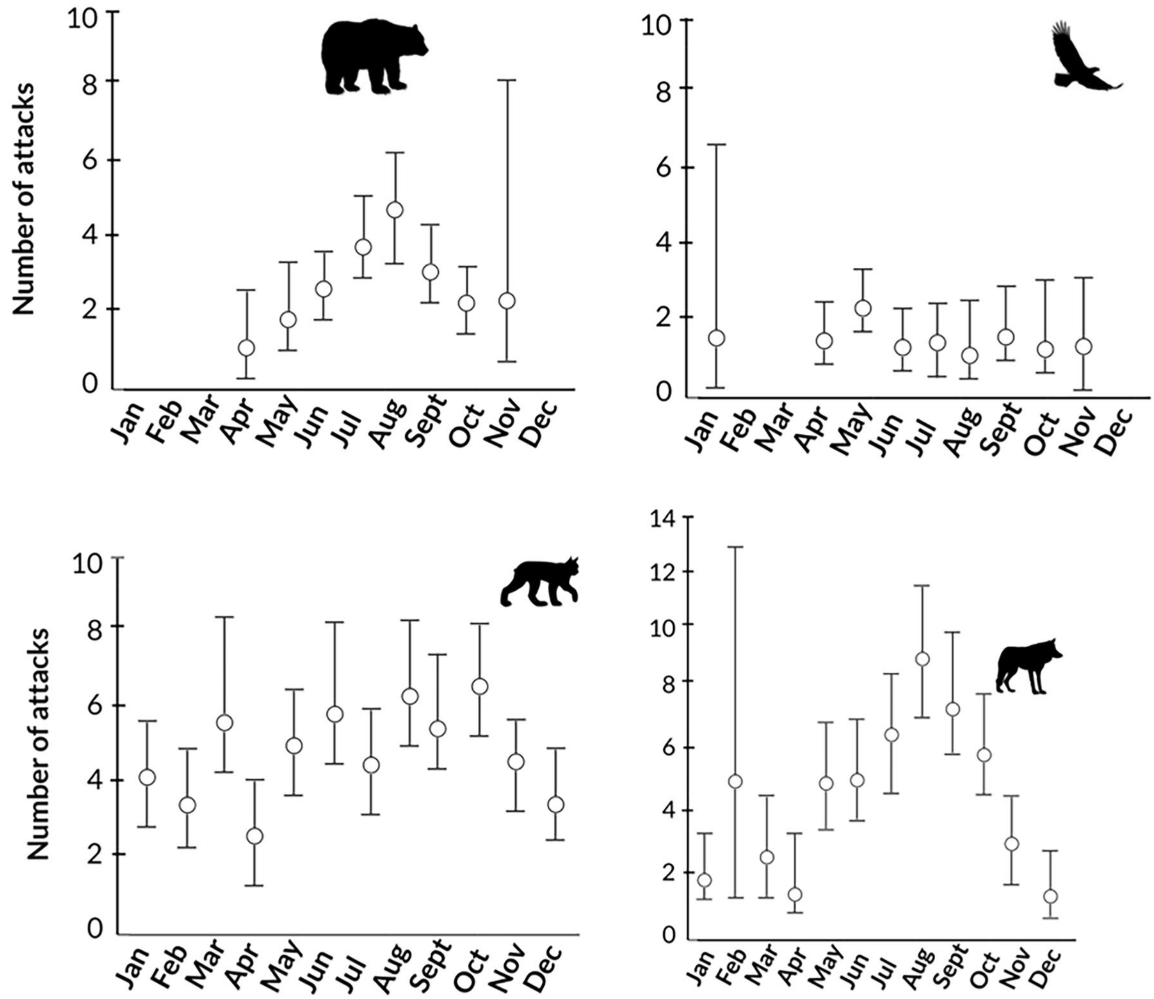

Fig. 4 Predicted number of attacks on sheep per month in an average year at a national scale, after exclusion months during 1997–2014 with no attacks, for brown bear, golden eagle, lynx, and wolf. Predictions (circles) and confidence intervals (95%) are derived from the negative binomial generalised linear model for each carnivore species (step 2)

Discussion

Successful mitigation that leads to reduced impact on livestock caused by large carnivore predation depends on the implementation of suitable and timely interventions (Eklund et al. 2017). In our study, we show that there are some distinct "times of trouble", i.e. periods of higher risk of attacks and impact on livestock, for at least some of the Scandinavian large carnivores. Our study therefore adds to earlier findings about spatial risk patterns of predation. Resources for interventions would thus likely be used more cost-effectively if they are not only allocated to target risk sites, but also to times of trouble (Suryawanshi et al. 2013).

Attacks from all large carnivores in Sweden mainly occur during the grazing season (May 1st–October 15th; Swedish Board of Agriculture). Most likely, one mechanism behind this pattern is the relative availability of sheep, because sheep numbers on grazing lands are substantially lower in the period before lambing in May and after lambs are slaughtered in October. Moreover, during winter, sheep are most often kept in small pastures close to farms, or kept indoors, making them less accessible to predation. However, also within the grazing season, there is some variation in probability of attacks, both among months and carnivore species.

For all large carnivore species included in our study, there are species-specific patterns of "times of trouble" regarding the number of attacks. Although there were some shared patterns (e.g. brown bear and wolves), these were not generalisable among all the species. The patterns are likely a combination of the carnivores' biology and the sheep husbandry practices. For example, in Sweden, bears hibernate in winter (Sahlén et al. 2014) and no attacks were observed between November and March. For golden eagles, the number of

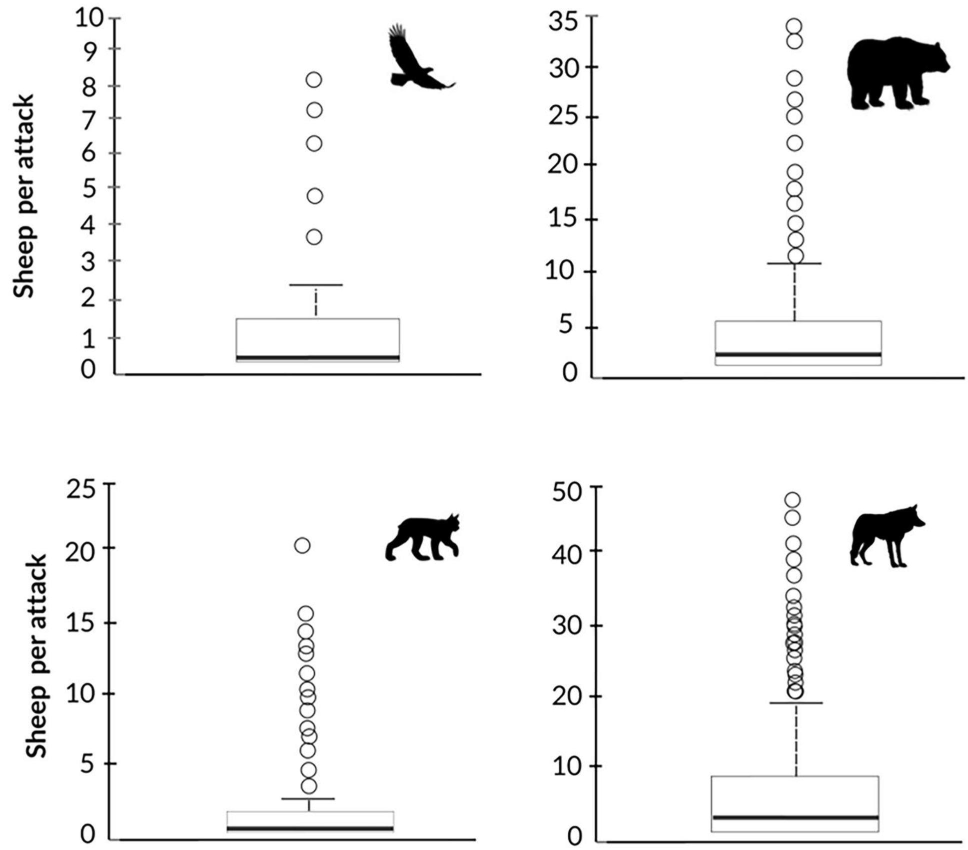

Fig. 5 Boxplots (median, lower and upper quartiles and whiskers showing 1.5 interquartile range) of number of sheep per carnivore attack during 1997–2014, for brown bear, golden eagle, lynx, and wolf. Note that the scale of the y-axis varies among the species

attacks peak at the time when they are rearing young and when the lambs are small and therefore more accessible to predation. Lynx and wolves, however, are active all year around and are large enough to kill sheep of all age groups, but there are still differences in their predation patterns. Compared to all the other large carnivore species, the lynx predatory behaviour appears to be the least affected by season. Wolves, on the other hand, cause a larger number of attacks and kill more sheep per attack during the summer grazing season than they do in winter. This may be an effect of an increased likelihood of encountering sheep in the summer in comparison to winter. When lambs are born in the spring, sheep numbers more than double. As sheep are often kept on summer pastures further from the farm (Eklund et al. 2020b), wolves also have larger opportunity to hunt and kill sheep undisturbed than during the winter, when the sheep are kept closer to, or on, the farm. Lynx, on the other hand, are ambush predators (Pedersen et al. 1999) that generally kill a smaller number of animals per attack, and the behaviour is consistent throughout the year.

There are some similarities in summer predation patterns between brown bears and wolves, for which the number of attacks peaks in the middle of the grazing season. We suggest three possible reasons for this peak; (1) the number of sheep being approximately doubled in the summer season after lambing (Statistics Sweden 2020) and more sheep are hence available for predation, (2) the grazing pastures (where the farmer needs to separate ewes from lambs and ewes from rams) cover an area that is many times larger compared to the rest of the year, so that sheep are more likely to interact with carnivores (Vatn 2009), and (3) that the carnivores' young of the year move increasingly greater distances as they grow older in the summer compared to early in the grazing season when they are less mobile. These suggested reasons to explain similarities in the predation peaks are the same regardless of the carnivore species. However, the peaks may also reflect the physiological and behavioural needs of the carnivores, which may differ but generate a similar observed predation pattern. Bears that hibernate in winter are known to switch to a more energy-rich diet towards the end of the summer season to gain weight, and where sheep are available these can provide a lipid and protein-rich diet (Dahle et al. 1998). The peak in wolf predation could relate to a similarly increasing nutritional demand during the latter part of the summer, as wolf pups will be larger and their diet is less constricted (Roffler et al. 2023). The temporal pattern also corresponds to a lower availability of young wild ungulates, not least moose calves, which could lead wolves to shift their diet towards other prey (Gable et al. 2018; Sand et al. 2008). Although these biological factors

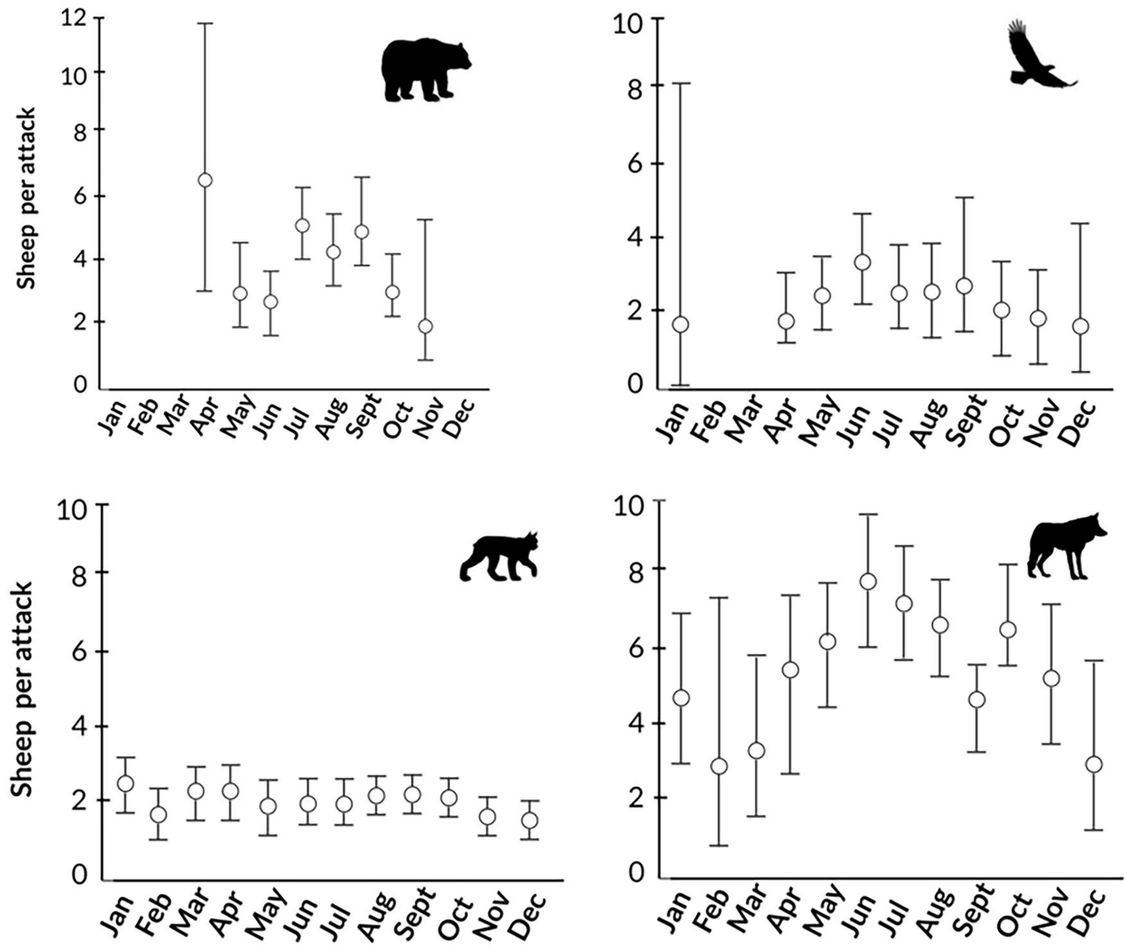

Fig. 6 Predicted number of sheep per attack per month for an average year during 1997–2014 for the brown bear, golden eagle, lynx, and wolf. Predictions (circles) and confidence intervals (95%) are derived from the negative binomial generalised linear model for each carnivore species (step 3)

may explain part of the observed patterns, it should be noted that carnivores in Sweden do not generally rely on sheep for their survival. Even in the years with the largest number of attacks, the annual number of sheep killed (but not necessarily consumed) per wolf in the population is 1, and the number of sheep killed per bear in the population is 0.01.

The reproductive cycle of the carnivores may also explain why lynx attacks have a small peak in March. The lynx mating season peaks in March and lynx males actively roam around during this time (Schmidt 1999) causing them to come interact with sheep at a greater scale. Male lynx predate on sheep more often than other categories of lynx (Odden et al. 2002), which could further enhance the pattern. Another hypothesis would be that mating lynx have a higher nutritional demand than outside the mating season, but this hypothesis is not supported in prior studies (López-Bao et al. 2009).

Based on the analysis of our long-term data set, we conclude that interventions targeting attacks from wolves and bears on sheep will have a larger effect when the main effort is focused on the grazing season, from May to October. To mitigate the number of lynx attacks, it would be more cost-effective to focus interventions on winter pastures, as there is no big seasonal difference and the proximity to buildings and the smaller pasture size during winter could imply lower costs of installation and maintenance of interventions, such as electrical fences. To reduce the number of golden eagle attacks, interventions should be implemented during early grazing season.

Some care should be taken when comparing the impact of different species, as brown bears have their main distribution in the northern half of the study area, where the density of sheep farms is low (Fig. 1b), whereas golden eagles, lynx, and wolves are abundant in the south where sheep densities are higher. It is thus difficult to compare the probability for an attack between different large carnivore species and conclude about the interspecific impact potential. It is also practically difficult to compare differences in the number of attacks on farms with free-ranging sheep compared to sheep in fenced pastures in our study area (Widman and Elofsson 2018). However, in areas where a single carnivore species causes the main part of attacks, it might be reasonable to focus the interventions according to these patterns. When several carnivore species co-occur, a combination of approaches might be needed, as an intervention which is effectively prevent attacks from one species might be less effective to prevent attacks from another (Kolowski and Holekamp 2006). Such multi-species approaches need more attention in future research.

Large carnivore conservation relies on co-occurrence with human activities in multiuse landscapes, because their large home ranges often do not occur only in protected areas (Sanderson et al. 2002). To support sufficiently large carnivore populations for sustainable conservation of the species, impacts caused on human activities, such as livestock farming, need to be mitigated. In comparison to the situation in some other European countries, where more sheep are free ranging, the Swedish carnivore populations cause relatively fewer attacks on sheep (Bautista et al. 2019). Nevertheless, prioritisation of mitigation efforts is still needed, and the current study provides insight into temporal patterns of carnivore attacks on sheep in a Swedish context. This knowledge sheds light on when interventions should be prepared and implemented to reduce the impact of specific species in "times of trouble".

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Author contribution All authors contributed to the conceptualisation and methodology of the paper, as well as writing the original draft, review, and editing of the manuscript. A.E., J.F., L.N., and A.Z. contributed to data curation. A.E., J.F., and L.N. contributed to the investigation. J.F., L.N., and A.Z. contributed to visualisation of the results. L.N. undertook the formal analysis, and A.E. the project administration.

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Availability of data and materials Data is available upon request from the authors.

Declarations

Competing interests The authors have no competing interests to declare.

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