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Predictors of brown bear predation events on livestock in the Romanian Carpathians

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Abstract

Livestock depredation by brown bears is one of the main source of human–wildlife conflict in rural Eastern Europe. Thus, identifying environmental and anthropogenic drivers of human–bear conflict, and developing spatial predictions for predation intensity are critical to mitigate such conflicts. We used 756 records of bear-caused livestock predation collected between 2008 and 2016 in the Romanian Carpathians and evaluated predictors and spatial distribution of bear livestock predation events (BPEs) using separate binomial generalized linear mixed models for cows, sheep, and other livestock. Despite differences in the direction and magnitude of the effect, the prevalence of BPE for all livestock was driven by the interaction between environmental drivers along with relative bear abundance. Distance from forest was a strong negative predictor for cows and sheep, while distance to villages was a strong negative predictor for cows. Landscape heterogeneity was positively associated with cow and other livestock predation and negatively associated with sheep. Relative bear abundance data collected by wildlife managers was a positive predictor for predation on all livestock. Livestock damage was more prevalent near villages, showcasing plasticity of food resources sought by bears. Our work informs brown bear and livestock management strategies to develop awareness and implement damage prevention measures.

KEYWORDS

human–carnivore conflict, landscape heterogeneity, large carnivores, livestock management, predation, *Ursus arctos*

1 | INTRODUCTION

Expansion of human activities into carnivore habitats, along with land use change, habitat loss and fragmentation, and loss of connectivity, lead to increased negative interactions between terrestrial carnivores and human populations (Karanth & Chellam, 2009; Linnell, 2013; Linnell et al., 2008; Morales-González et al., 2020). Ursids, due to their omnivorous diets and widespread distribution, pose particular challenges to carnivore conservation and management

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(Redpath et al., 2013), with livestock depredation having a psychological impact on human populations (Dickman, 2010). Brown bears (*Ursus arctos*) persist in Europe's heterogeneous human-dominated landscapes (Chapron et al., 2014), and proximity to human settlements often leads to human property losses even in areas where bears occur at low densities (Can et al., 2014; Linnell et al., 2008). Brown bears forage naturally across large areas and shift their space use seasonally to match food resources (Bojarska & Selva, 2012; Morehouse & Boyce, 2017; Pop, Iosif, et al., 2018), and therefore have access to food resources of anthropogenic origin such as livestock, apiaries, crops, and human food waste (Bereczky et al., 2011; Kavčič et al., 2015; Lewis et al., 2015). Human–bear negative interactions are thus common in human-dominated landscapes (Dorresteijn et al., 2016), and they are likely to continue to rise in the absence of adequate mitigation strategies or measures to facilitate co-existence (Chapron & López-Bao, 2016; Garshelis et al., 2017).

For brown bears, the spatial and temporal patterns of negative interactions with livestock (hereafter, bear predation events [BPEs]) are driven by a complex suite of factors acting independently or in synergy (Wilson et al., 2006), typically leading to a nonrandom distribution of BPEs (Gastineau et al., 2019). Factors related to brown bear life history, biology, and ecology (Elfström et al., 2014), affect bear movements, food requirements, and thus their spatial ecology and interactions with humans and livestock. However, human activities, infrastructure, livestock management, and presence of preventative measures can influence the intensity and prevalence of negative interactions and BPEs (McFadden-Hiller et al., 2016; Miller, 2015; Rigg et al., 2011). These factors likely lead to a heterogeneous conflict landscape, and bear-caused damage can range from livestock and domestic animal attacks (BPEs), to crop (including fruit trees and beehives) damage, and in rare instances, human injuries or casualties (Bombieri et al., 2019; Can et al., 2014). Livestock predation has received increasing attention and human–wildlife interactions literature (Can et al., 2014) because of the negative socio-economic and psychologic impacts (Bautista et al., 2019; Dickman, 2010), which influence conservation policy and social acceptance of carnivores (Redpath et al., 2017).

Romania harbors the largest brown bear population in Europe (outside European Russia; Kaczensky et al., 2012). While national estimates suggest densities of 7 bears/100 km^2 (Bombieri et al., 2019), some areas in the Eastern and Southern Romanian Carpathians can reach high densities of 12.4 (8.6–16.3) bears/100 km^2 (Popescu et al., 2017), or 16.9 (13.7–22.5) bears/100 km^2 (Skrbinšek et al., 2019). The population likely follows an increasing trend (Cazacu et al., 2014), with the ban on trophy hunting imposed in 2016 adding to the uncertainty about the overall population trajectory (Popescu et al., 2019). After 2016, Romania instated a system of derogation for lethal intervention in cases of "problem" bears, which entails removal of animals with repeat attacks on livestock (Popescu et al., 2019). The Carpathian Mountains, a stronghold for the European brown bear population, are characterized by a low, but dispersed human footprint, is mostly rural, and raising cows and sheep represents the livelihood for many local rural communities. As such, BPEs on livestock, is one of the main sources of human–carnivores conflict in the Romanian Carpathians (Dorresteijn et al., 2016). In Romania, data on livestock damage is collected by local Environmental Protection Agencies (EPAs); the government compensates livestock losses, although the process is tenuous, and many local communities do not take advantage of it. Despite high interest from stakeholders and local communities in guidelines for reducing BPE prevalence (Hartel et al., 2019; Pop et al., 2013), there has been no assessment of determinants of BPE in a high brown bear density region such as the Romanian Carpathians. The identification of conflict-prone areas can influence bear habitat and population management decisions, as they can highlight the existence of source and sink areas (Penteriani et al., 2018), and provide decision-support for BPE mitigation actions (e.g., habitat preservation, livestock management, damage compensation, or targeted harvesting; Miller, 2015).

The overarching goal of this study was to assess predictors and spatial distribution of BPE in a high brown bear density landscape in the Eastern Romanian Carpathians using a dataset of reported livestock predation events collected between 2008 and 2016. The main expectation is that livestock BPE will occur where suitable habitats for bears overlap with suitable habitats for grazing. In our study area, human settlements are embedded within a heterogeneous landscape with strong altitudinal and land cover gradients, and traditional livestock management predisposes cows and sheep to different levels of predation risk by brown bears. While cows are mostly pastured around villages, sheep undergo migration or short *transhumance* between higher altitude meadows during summer and lowland villages during winter. Other target domestic animals (pigs, horses, chickens) are largely associated with villages. As such, we expect that landscape factors, such as distance to forest and habitat heterogeneity will affect the three groups of target species differently, and that prevalence of BPE will increase with increase in brown bear population size in the area (Garshelis et al., 2020). Specifically, we hypothesize that (1) higher relative brown bear abundance will lead to higher levels of BPE (Garshelis et al., 2020;

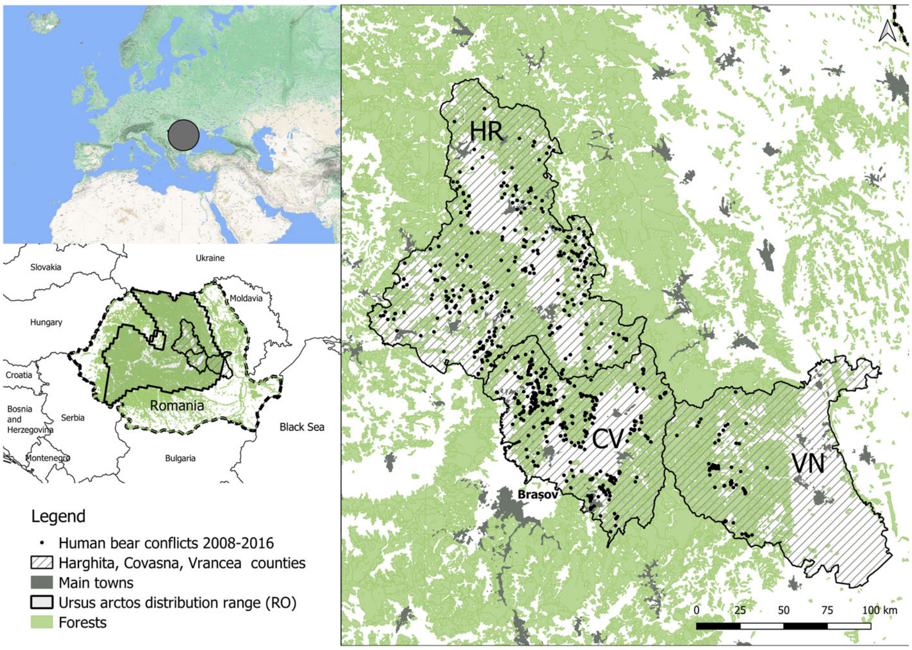

FIGURE 1 Distribution of recorded bear predation events in Eastern Carpathians, Romania, 2008–2016.

Gastineau et al., 2019) for all livestock types. Based on cow grazing practices, we hypothesize that (2) heterogeneous habitats close to settlements and forest edges will have a higher likelihood of BPE (Gastineau et al., 2019; McFadden-Hiller et al., 2016; Wilson et al., 2005). For sheep, we hypothesize that (3) heterogeneous landscapes with forest intermixed with open habitat farther from settlements but near forest edges will have a higher likelihood of BPE (Gastineau et al., 2019). For other domestic animals, we hypothesize that (4) agricultural areas closer to settlements and forest edges will have a higher likelihood of BPE. Overall, determining factors influencing BPE risk in the Romanian Carpathians provides an opportunity to provide local communities and managers with spatial information to identify practices that minimize predation risk and lead to lower occurrence of BPEs, add much needed scientific information into a data-poor system, and promote coexistence.

2 | METHODS

2.1 | Study area

The study area covers 15,206 km^2 in the Eastern Romanian Carpathians and Sub-Carpathian region, in the Covasna, Harghita and Vrancea Counties (Figure 1). Forest habitat covers 39% of the study area (greater than national average of 31.9%), while pasture and grasslands represent 34% and built areas ~2%. The study area has a diverse vegetation across an elevation gradient: deciduous forest (200 to ~1000 m), mixed deciduous-coniferous forest (800–1200 m), coniferous forest (1000–1100 to ~1600 m), and the subalpine meadows (upper limit of natural forest up to ~1800 m). The Sub-Carpathian region (the eastern limit of brown bear distribution), 400–800 m in altitude, and is characterized by ridges alternating with wide lowland areas and is by human presence and non-forested habitats such as agriculture and pasture. Traditional, subsistence farming is common in the study area, with small property lots (~2.15 hectares per household), and small numbers of livestock (in average two to four cows and 10–12 sheep) within individual small farms (Membretti & Iancu, 2017). The study area is also characterized by a medium human density (Covasna: 56.7 people/km^2, Harghita: 46 people/km^2, Vrancea: 70 people /km^2), which is lower than the national average (84.4 people/km^2), a low level of urbanization, and by an increasing abandonment of traditional land use, leading to significant changes in the habitat (Angelstam et al., 2013).

2.2 | Livestock damage and environmental data

We used a dataset of 756 BPEs (i.e., livestock kills or injuries) by brown bears collected between 2008 and 2016 by three local EPAs within the framework of the EU LIFE Nature project LIFEURSUS LIFE08/NAT/RO/000500, during the preparation of grant request, project implementation and postproject monitoring (http://lifeursus.

carnivoremari.ro/home.php/; Figure 1) and 2268 (3xBPE) pseudoabsence points randomly non-stratified distributed in the study area (Barbet-Massin et al., 2012). The process of collecting the BPE data was standardized across the EPA's and includes collecting GPS location and the investigation in the field of the reported animal loss or injury and predation context by a committee composed of EPA personnel, game managers, and local authorities with the goal of assessing whether the damage was caused by a brown bear, and if and what amount of money will be compensated to the livestock owner.

To test our hypotheses, we considered the major habitat categories from CORINE Land Cover 2012 (CLC) European database (level-three CLC nomenclature [European Environmental Agency, Copenhagen, Denmark]). We reclassified the level-three CLC classes into several categories: artificial surfaces (discontinuous urban fabric, industrial or commercial units, and mineral extraction sites), agriculture (nonirrigated arable land, vineyards, fruit trees, and berry plantations), open habitat (pastures and natural grasslands), heterogeneous agriculture (complex cultivation patterns and land principally occupied by agriculture with significant areas of natural vegetation), and forests (broad-leaved forests, coniferous forests, mixed forests, and transitional habitat). We evaluated the proportion of each habitat type at multiple scales using a moving window approach. We selected three moving window sizes: 1 km^2—representing an area that can be routinely covered by an individual during daily movements (mean daily movement = 1.5 km; Pop, Bereczky, et al., 2018), 5 and 10 km^2—representing areas that could be traversed by brown bears during longer movements in the active season (Pop, Bereczky, et al., 2018). We also selected these moving window sizes to evaluate the level of landscape heterogeneity at fine, medium, and coarse scales using the Shannon Diversity Index (SDI; Table S1).

We extracted the Euclidian distance from forest edge to each BPE location, as forests are the main habitat type selected by bears on a seasonal and yearly basis (Pop, Bereczky, et al., 2018), as well as distance to human settlements (considered in this category both villages and cities; Table S1). Last, we considered the relative abundance of brown bears at a Game Management Unit (GMU) level based on official data for year 2016, as higher bear abundance is thought to induce higher BPE; we standardized the raw brown bear abundance estimates from managers on a 0–1 scale, because the official absolute brown bear abundance data in Romania has been shown to be frequently overestimated (Popescu et al., 2016). We used the abundance estimates, rather than density data because GMUs are relatively equal in size (∼100 km^2; Pop, Bereczky, et al., 2018).

2.3 | Statistical methods

We evaluated the occurrence and predictors of BPE by brown bears using binomial generalized linear mixed effects models (GLMM). We ran separate models for different types of livestock: cows, sheep, and others (i.e., pigs, horses, and chickens) because we hypothesized that different variables would be predictive of BPE for each species. We combined the reports for BPEs of each livestock type with a random sample of pseudoabsences from our full data set, so that each data set contained three times the number of pseudoabsences as BEP points (Barbet-Massin et al., 2012).

We ran binomial GLMM's for each livestock type in program R version 4.4.1 (R Core Team, 2019) using package *lme4* (Bates et al., 2015). We included *year* and *CLC* as separate random effects to account for latent variation between years and between land cover types that could not be accounted for by the fixed effects. We omitted correlated variables that were highly correlated (Spearman's $r > |.7|$; Zuur et al., 2010) and scaled and centered all variables to compare effect sizes (mean = 0, SD = 1). We tested the importance of spatial scale by running scale-specific models using proportions of various land cover types and the SDI. This preliminary investigation using suggested that land cover variables extracted at the 10 km^2 scale performed best (second-best model had ΔAICc >10), and given the high correlations between variables across scales, we decided to retain only the 10 km^2 scale variables.

We developed a set of 11 models, a priori, that tested hypotheses regarding influences of environmental and anthropogenic variables on the presence of BPEs for each livestock type. We compared these models to null and global models using an information-theoretic approach based on the Akaike Information Criterion adjusted for small sample size (AICc; Burnham & Anderson, 2002) with package *MuMIn* (Barton, 2020). After preliminary model selection, we included additional models (based on the top model and global model) that included an interaction between distance to settlements and distance to forest as we expect this to be biologically relevant given our hypotheses (i.e., areas close to town and close to forest have higher BPE for cows). We tested both the full interaction (both variables independently and their interaction) and just the interaction in these models. If no clear top model emerged (i.e., one or more models within two AICc units of the top model), we conducted model averaging using models with an AICc cumulative weight of 0.95 for model predictions. We evaluated the influence of different variables on the occurrence of BPE by examining conditional odds ratios based on model or model-averaged coefficients (i.e., averaging across models

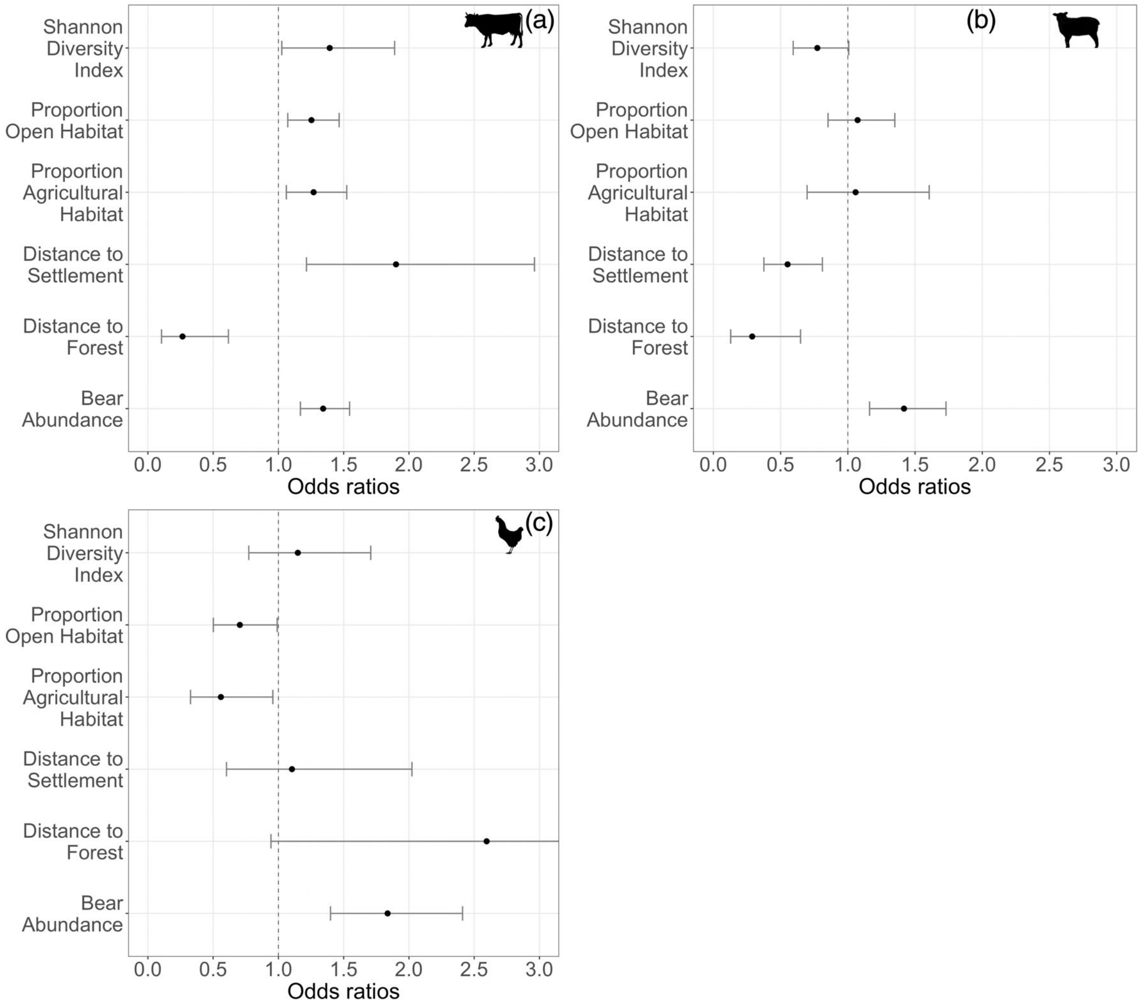

FIGURE 2 Odds ratios from the top model or model average for predicting bear predation events for three types of livestock, cows, sheep, and others (horses, pigs, and chickens) in the Eastern Carpathians, Romania, 2006–2018. Odds >1 indicate a positive effect on predation, odds < 1 indicate a negative effect on predation, and odds overlapping 1 have no significant effect on predation

that include a particular variable). We assessed model fit using conditional (variation explained by both fixed and random effects) and marginal (variation explained by fixed effects only) pseudo-R-square (Nakagawa & Schielzeth, 2013) using package *MuMIn*. We also tested the predictive capacity and accuracy of the models in the 95% confidence set using the area under the curve of the receiver operating characteristic (AUC ROC) calculated with package *pROC* (Robin et al., 2011); AUC ROC values >0.8 denote good predictive ability. We further created livestock predation risk maps for each type of livestock using model or model-averaged predictions to identify areas with higher prevalence of BPE.

3 | RESULTS

From 756 total reports of BPEs, *cows* were the most common type of livestock reported with 410 incidents (54.2%), followed by *sheep* ($n = 211$, 27.9%), and *other* livestock ($n = 135$, 17.9%). Within each livestock type, reports of BPE varied by year, with the most reports for cows and sheep in 2012 ($n = 96$; 23.4% of cow BPEs), $n = 37$ (17.5% of sheep BPEs), respectively), and the fewest reports for cows in 2008 ($n = 8$) and sheep in 2010 ($n = 11$). The other livestock group had the highest reported damages in 2008 ($n = 33$; 24.4% of other livestock BPEs) and the fewest in 2011 ($n = 1$). BPE also varied seasonally and between livestock groups; for cows and sheep, 43% of the reported damage occurred in August–September, with >90% BPE between April and October. For other livestock, two peaks in predation occurred in July (23%) and September (20%). The land cover type at the site of BPE varied between livestock types as a reflection of the local grazing techniques and habitats availability; reports were highest for both cows and sheep in open areas [$n = 227$ (55.4% of cow BPEs) and $n = 80$ (37.9% of sheep BPEs, respectively] and

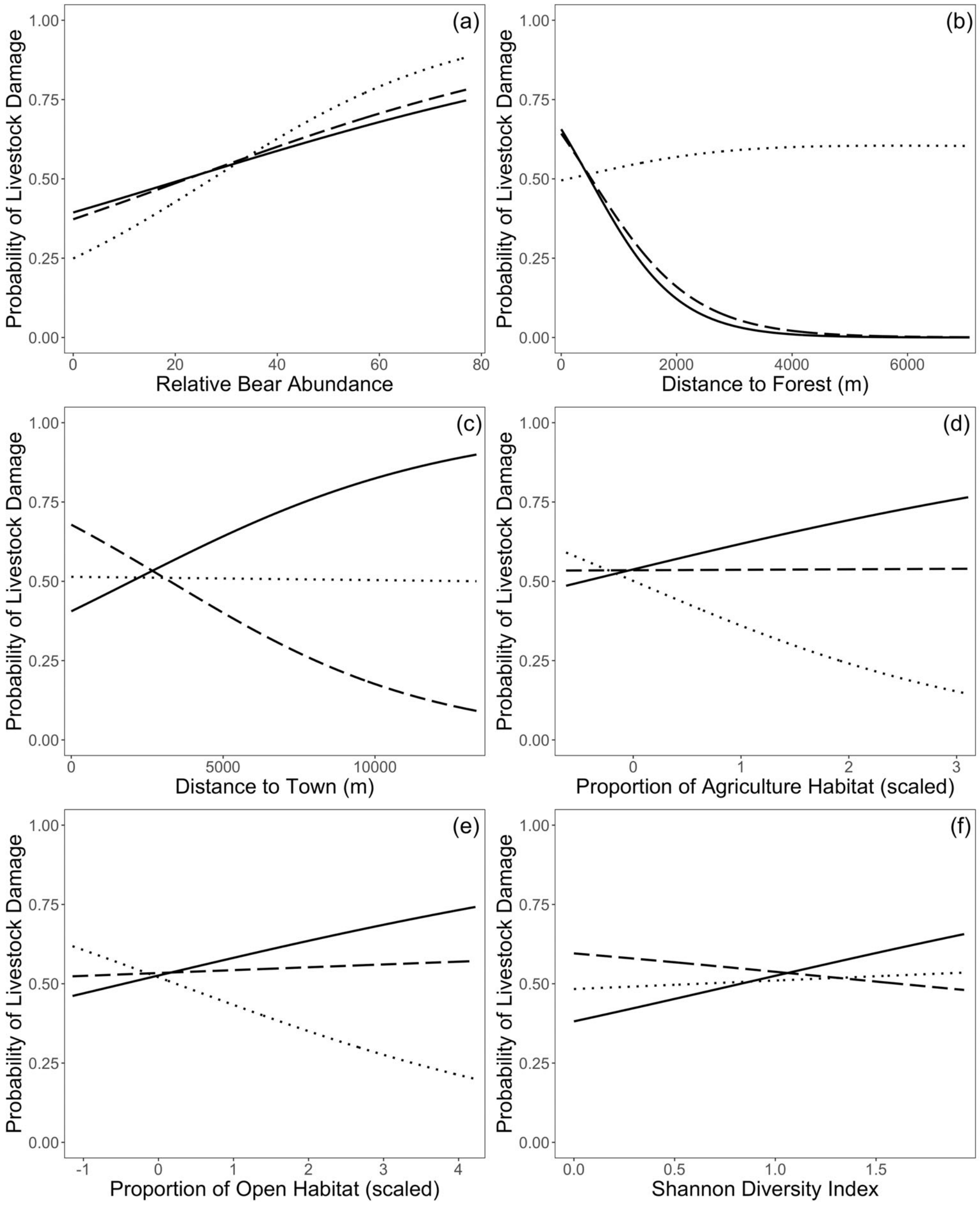

FIGURE 3 Predicted probability of bear livestock predation events as a function of environmental and human-related variables, inferred from logistic regression models (solid line, cows; dashed line, sheep; dotted line, other livestock [horses, pigs, and chickens]). The variables were included in the best-performing model for cows and were part of the confidence model set used to perform model averaging for sheep and other livestock. Models for each livestock type were run separately; for each plot, we fixed all the variables not included in a plot at their observed mean

highest for other livestock in developed areas (i.e., within village boundaries, $n = 52$ [38.5% of other livestock BPEs]).

3.1 | Predictors of cow damage

The global model with the full interaction between distance to town and distance to forest was the best model for predicting BPEs with cows and had good fit (AUC ROC = 0.815; marginal $r^2 = .53$ and conditional $r^2 = .70$). The global model included a total of seven predictive variables: relative bear abundance, proportion open habitat, proportion of agriculture, and SDI, as well as distance to forest, distance to settlement, and their interaction (Table S2). All variables were significant for predicting BPEs with cows ($p < .05$, odds not overlapping 1; Figure 2a). Distance to forest had the strongest overall negative effect on the likelihood of cow predation (Figure 2a), with the odds of damage decreasing in average by 75% for each additional Standard Deviation (SD = 942 m) increase in distance to forest (Figure 3b). However, this relationship changed based on distance to settlement; cow predation decreased with distance to forest for areas close to settlements but increases with distance to forest for areas far from settlements (Figure 4a). All other variables were positively related with cow predation (Figure 2a). For relative bear abundance, the odds of predation increased in average by 34% for each additional SD (SD = 0.23; Figure 3a). Proportion of agriculture and open habitat led to an increase in predation, by 39% and 25%, respectively, for each increase in

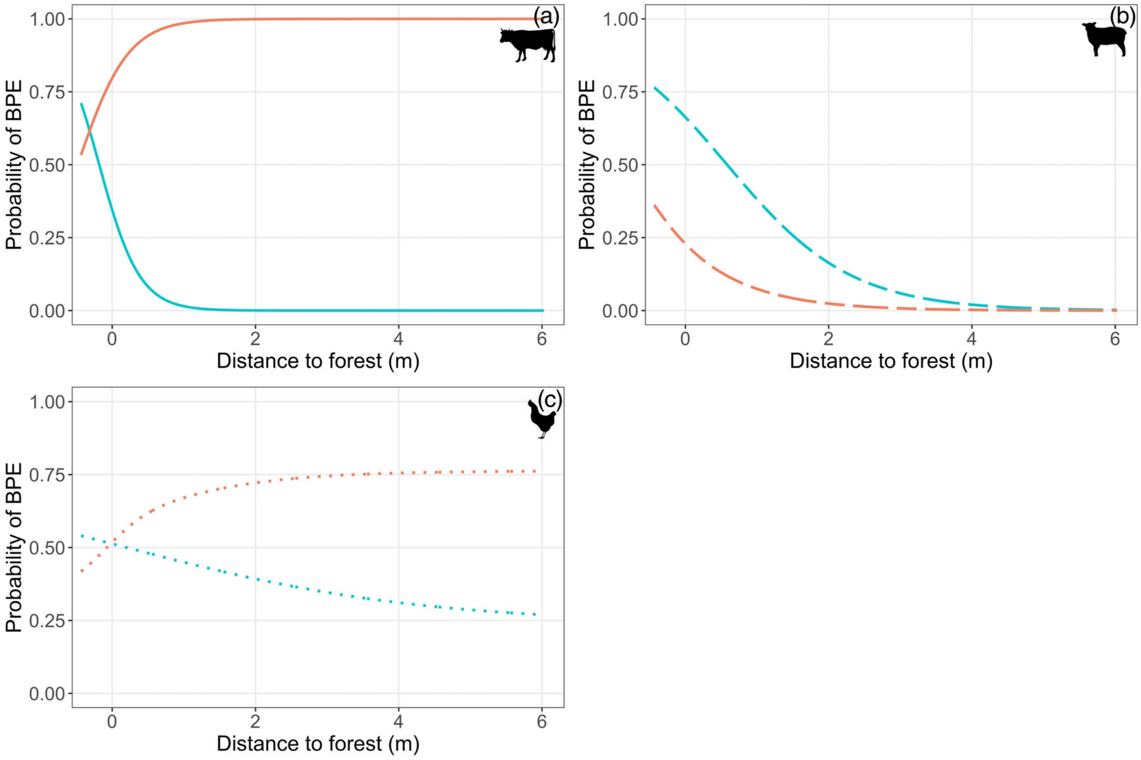

FIGURE 4 Predicted probability of bear livestock predation events (BPEs) for each livestock type (cows, sheep, and other: horses, pigs, and chickens) based on the interaction of distance to forest and distance to town. The interaction was calculated based on the low (5th percentile—blue) and high (95th percentile—red) distance to town. For cows, the probability of predation increased with distance to forest when in BPEs occurred away from town and decreased with distance to forest when BPEs occurred near town. A similar, but weaker interaction was detected for other livestock. For sheep, the probability of predation decreased with distance to forest regardless of the distance to town

standard deviation (SD = 0.19 and 0.13, respectively; Figure 3d,e). The likelihood of cow predation increased with landscape heterogeneity (SDI) by 27% for each increased in SD (SD = 0.97; Figure 3f).

3.2 | Predictors for sheep damage

Multiple models were within two delta AICc of the top model therefore, we used the six with a cumulative weight of 0.95 for model averaging, which included the global model with the interaction between distance to forest and distance to settlement (Table S1). The global model had a good fit with AUC ROC = 0.86; marginal r^2 = .18 and conditional r^2 = .60. Relative bear abundance, distance to forest, and distance to settlement were significant variables for predicting BPEs with sheep. Both distance to forest and distance to settlement had strong negative effects on the likelihood of sheep predation (Figure 2b). Sheep predation decreased in average by 72% for each additional SD (SD = 942 m) increase in distance from forest (Figure 3b) and an average of 46% for each additional SD (SD = 2349) increase in distance from settlement (Figure 3c). For relative bear abundance, the odds of predation increased in average by 42% for each additional SD (SD = 0.23). Proportion open habitat and agriculture had a positive but weak effect on sheep predation, while landscape heterogeneity (SDI) had a slightly negative effect (Figure 2b).

3.3 | Predictors for other livestock (pigs, horses, and chickens) damage

Seven models were within one AICc unit and had a cumulative AICc weight of >0.95, including the global model (Table S1) therefore, we used all seven models for model averaging. The global model had a good fit with AUC ROC = 0.90; marginal r^2 = .12 and conditional r^2 = .61. The most important predictor for predation of other livestock was the relative bear abundance (Figure 2c), with the odds for predation increasing by 84% for each increase in additional SD (SD = 0.23). Proportion of agriculture and open habitat were also important and were negatively associated with predation of

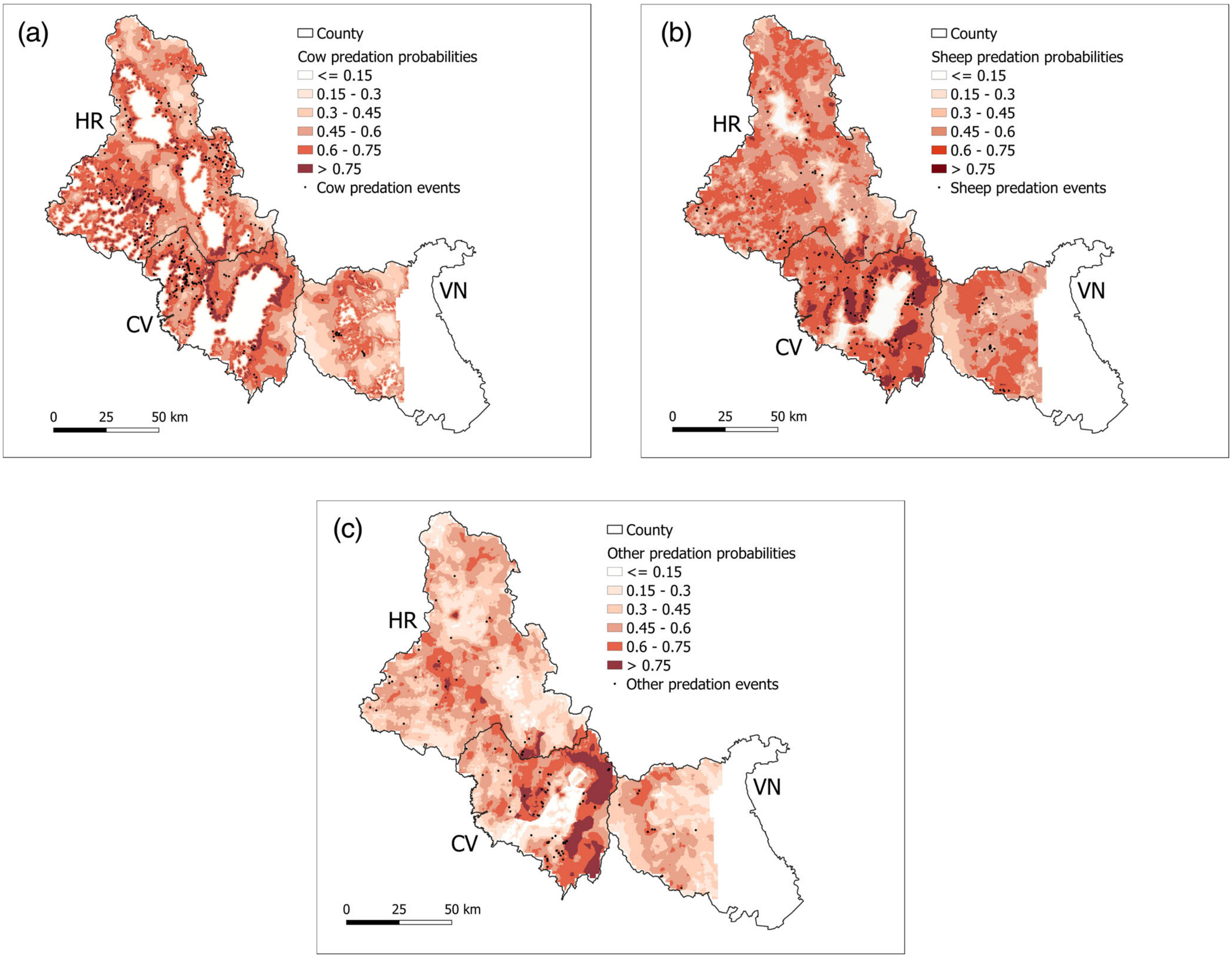

FIGURE 5 Model-averaged predictions of bear livestock predation prevalence for (a) cows, (b) sheep, and (c) other livestock. CV, Covasna County; HR, Harghita County; VN, Vrancea County

other livestock (Figure 2c). Each increase in additional SD in proportion of agriculture (SD = 0.19) and open habitat (SD = 0.13) led to a 44% and 30%, respectively, decrease in odds of predation for other livestock.

4 | DISCUSSION

This is the first quantitative study of brown bear livestock depredation in the Romanian Carpathians, a stronghold for European large carnivores, and a region with some of the highest brown bear densities worldwide, a likely outcome of five decades of regulated hunting accompanied by years with strict protection and traditional supplementary feeding. Using a 9-year dataset collected with using a standardized methodology across three counties, our study revealed that the likelihood of BPE caused by bears to livestock in Romania is influenced by a combination of landscape factors (type of habitats and forest cover), local relative brown bear abundance, topography, and approaches to livestock management and our results corroborates with other studies (Gastineau et al., 2019; Gervasi et al., 2021; Miller, 2015; Naves et al., 2018). Our predictions showed differences in the importance of factors affecting the prevalence of damage for cows, sheep, and other livestock, but the interaction between distance from forest and distance from settlements, landscape heterogeneity (SDI), and composition, along with relative brown bear abundance are common to all livestock. While the likelihood of predation increased or decreased with various variables included in our models, relative brown bear density had a positive relationship for all livestock groups (Figure 2). The BPE risk maps, a first for this region of the brown bear range in Europe have the potential to support decisions of stakeholders and decision makers to improve brown bear conflict mitigation strategies.

4.1 | Landscape setting and heterogeneity

As predicted, distance to forest had high predictive power for cows and sheep; the further cows and sheep were from the forest edge the lower the likelihood of predation (Figures 2 and 3). As such, the decisions on where to graze, where to locate livestock holdings pen, or where to install the night enclosure are highly important to prevent predation; proximity to forest increases the likelihood of encounters between bears and livestock, as brown bears select for deciduous and mixed forest throughout the year in our region (Pop, Iosif, et al., 2018). The distance to settlements also had high predictive power for cows and sheep, but in opposite direction; the farther cows were from settlements, the lower the likelihood of predation, and vice versa for sheep. The strong positive interaction between distance from forest and distance from settlement for cows (Figure 4a) suggests that the likelihood of BPE is much higher when cows being grazed close to forest but farther away from settlements. Potentially, this situation offers an ideal opportunity for brown bears (Zimmermann et al., 2003), which may not venture far from forest into open habitats (Bombieri et al., 2021), to encounter cows that are not well guarded. Thus, grazing cows near villages and farther from forest edge offers the least likelihood of BPE. For sheep, the closer they were from forest edge and settlements, the higher the likelihood of predation (Figures 2 and 3), but the interaction was not significant (Figure 4). Therefore, most sheep BPE occurs in situations when sheep are grazed close to forest edges (Rigg et al., 2011), but also close to villages (thus when villages occur in landscapes with high proportion of forest). This was contrary to our hypothesis that most sheep BPE would occur more often in remote regions (high-elevation pastures) away from settlements (Gervasi et al., 2021). It is likely that sheep flocks in more remote areas have better protection via guard dogs, electric fences, as well as constant human presence (van Eeden et al., 2018). The differences between sheep and cows BPE in terms of the effect of distance to settlements is likely due to the very different grazing and management regime. Cows are often less well guarded, even when grazed away from settlements, with minimal human supervision. In contrast, sheep are well guarded when in remote areas, with constant supervision from sheepherders and guard dogs, who sometimes are present during nighttime in the same corral with sheep and guard dogs. For other livestock, distance from forest had no impact on the likelihood of BPE (Figure 3), and the intensive use of agriculture and open land have a weak (negative) impact on likelihood. Overall this result suggests predation might be a result of specific bear behavior (i.e., habituation of individuals; Hopkins et al., 2010), rather than landscape setting. Our findings indicate that bears tend to predate on smaller livestock in the proximity of settlements, especially in areas where settlements are embedded in a heavily forested landscape; these livestock can be captured and consumed fast or transported easily to a safer feeding area (Bereczky et al., 2011; Gastineau et al., 2019). Such events likely happen during the hyperphagia season (see below), when bears tend to travel more in search of food sources (Morales-González et al., 2020; Pop, Bereczky, et al., 2018; Zarzo-Arias et al., 2018).

Landscape composition at a 10 km^2 scale heavily influenced BPE for all species. In particular, heterogeneous habitats (Wilson et al., 2005) with high SDI values, had a positive effect on cows, a negative effect on sheep, and no effect on other livestock. Brown bear seasonal movements are highly influenced by food availability, both natural and human subsidized (Bojarska & Selva, 2012). In our study area, there is greater anthropogenic food availability in the proximity of human settlements (i.e., orchards and crops, waste), which influences the distribution of brown bears during the hyperphagia season (i.e., prior to denning; Pop, Iosif, et al., 2018). Brown bears foraging seasonally in these areas (usually with average of high SDI), which are often close to human settlements, have a high likelihood of encountering and predating upon livestock grazed in the immediate surroundings (e.g., sheep); sometimes bears may even enter villages and depredate other livestock. Thus, our hypothesis that landscape heterogeneity would increase BPE for cows held true; cows are often grazed in areas with small, secondary pastures interspersed with other agricultural uses and forest habitat, thus maximizing the likelihood of encounter with bears. For sheep, which are typically grazed on larger pastures and less heterogeneous areas, landscape heterogeneity had a negative effect. Proportion of agriculture and open habitat with natural vegetation was positively associated with cow predation (i.e., more heterogeneous habitats) and negatively with other livestock predation (i.e., in or near settlements in forested areas), which contributes to the overall hypothesis that different grazing regimes lead to different predation pressures.

There was interannual variation in the number of BPEs for all livestock types, which could be driven by both variation of environmental conditions (e.g., low natural food production, such as low-mast years; Krofel et al., 2020) and reporting of BPEs by livestock owners driven by changes in financial incentives (e.g., damage compensation schemes) or changes in the process of reporting BPEs (Bautista et al., 2017). However, no changes to either incentive or reporting process occurred during the study period. The variation in mast production has been associated with changes in frequency of human–bear conflicts (Bautista et al., 2022); while we do not have information on the temporal and spatial distribution of natural food availability in our study area, it is more likely that food availability has a larger effect on recorded BPEs than the human/economic factors.

4.2 | Relative bear abundance

One of the most consistent of BPE across all groups was the relative bear abundance, thus confirming our hypothesis that higher abundance results in greater predation. The greatest effect of relative bear abundance on predation was for other livestock, which are typically raised inside or in close proximity to settlements. As Garshelis et al. (2020) point out, there is high uncertainty associated with estimating bear abundances by wildlife managers; in our area, bear abundances are often overestimated (Popescu et al., 2016). Such uncertainty, associated with the lack of ecological information (i.e., natural food abundance, seasonal population dynamics), makes the case against using absolute abundances from wildlife managers, when data cannot be trusted for predicting BPE (Bautista et al., 2017; Gervasi et al., 2021). In particular, the influence of bear abundance and landscape scale should be interpreted in a rather qualitative, case-by-case basis. For example, for predation inside settlements, individual bear behavior (bold bears that are more likely to tolerate encounters with people; Bombieri et al., 2021) is more important than local bear abundance (Johnson et al., 2020). The high frequency of BPE near villages in our study raises questions about plasticity in feeding behavior of particular individuals (Lewis et al., 2015; Smith et al., 2005). In many situations, single individuals tend to return to damage site and may cause damage to livestock on multiple occasions (Swenson, 1999). Bereczky et al. (2011) assessed the bear attack patterns (e.g., livestock, distance, and periodicity) for 198 predation cases in 2008–2009, and showed that within our study area, a small number of bears were responsible for ~30% of the reported livestock predations. As such, individual predation behavior is likely an important driver of conflicts. Under current Romanian wildlife regulations (as of 2021), these "repeat offender" individuals are removed via lethal methods. This work supports that this approach may be more effective compared with decreasing local bear populations via hunting quotas (Treves et al., 2016). To improve the decision-making process, the risk maps provided here (Figure 5) can provide useful information for efforts to implement nonlethal prevention methods and planning the removal of problem animals.

4.3 | Management implications

The prevalence of BPEs on livestock and human–bear interactions in our study area is perceived as increasing due to likely increases in bear abundance (Salvatori et al., 2020) and the public perception on the response of authorities to problem bears following the 2016 trophy hunting ban. In this context, developing brown bear management strategies that deal with problem individuals swiftly, and adjusting livestock management to avoid high-risk areas and enhance damage prevention systems is critical to decrease BPE and increase human tolerance towards brown bears (Penteriani et al., 2018; Treves et al., 2016). For example, a combination of guard dogs, electric fences, and human presence is likely effective at preventing predation during the night-time (S. Chiriac, personal communication). Therefore, continuous monitoring of bear-caused predation, along with a science-based evaluation of brown bear density and habitat selection is key for sustainable management of Europe's largest brown bear population (Pop, Iosif, et al., 2018; Popescu et al., 2019). Our work is only one part of a complex human–carnivore coexistence story unfolding in this dynamic social–ecological system. Along with brown bear data, insights into governance of wildlife populations, stakeholder engagement, academic involvement, and social attitudes towards carnivores (Hartel et al., 2019) are critical for understanding pathways to human–bear coexistence.

AUTHOR CONTRIBUTIONS

Hereby, we acknowledge the involvement of the authors' individual contributions to the article as follows: **Mihai I. Pop:** Conceptualization, resources, investigation, and writing – original draft. **Marissa A. Dyck:** Methodology, formal analysis, and writing – original draft. **Silviu Chiriac:** Funding acquisition, resources, and review and editing; **Berde Lajos:** Data curation and resources. **Szabó Szilárd:** Data curation and resources. **Cristian I. Iojă**: Writing – review and editing. **Viorel D. Popescu:** Conceptualization, methodology, writing – original draft, and supervision.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

Data supporting the results and the R code used for the article is archived at: https://github.com/marissadyck/Brown_bear_predation_RO.

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SUPPORTING INFORMATION

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