



Original Research Paper

Machine Learning Analysis of Livestock Depredation and Carnivore Coexistence

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Key Words	Abstract
Carnivore conservation; human-wildlife conflict; livestock depredation; coexistence; pastoral communities; machine learning.	One of the most common and long-standing sources of human-wildlife conflict in pastoral settings is the depredation of livestock by large carnivores, which poses risks to both livelihoods and the long-term survival of threatened predator populations. The study presents a conceptual, data-driven approach to the analysis of livestock depredation and coexistence conditions based on ecological, household, and community-level data gathered from livestock-loss records, livestock household interviews, field observations, compensation claims, and wildlife occurrence data in a mixed pastoral-carnivore landscape. The study does not provide a technical description of the model architecture but instead sets the machine learning work in the context of a tool that identifies the complex, non-linear patterns of risk that are often missed by traditional statistical summaries, such as the influence of the combination of household attitude, seasonal grazing patterns, herd management practices and proximity to habitat on the risk of depredation. The findings show that the risk of depredation is greatest in communities close to grazing areas at the forest edge, that herds with poor enclosure or community management are particularly vulnerable, and that community tolerance is linked to satisfaction with compensation and previous experience of loss. The results indicate that the problem of livestock depredation is not exclusively ecological; it must be approached with an integrated perspective, taking into account the ecological context, husbandry practices and social perception. The paper concludes that a coexistence-oriented approach is the most viable path forward moving towards a reduction of conflict without compromising carnivore conservation in shared landscapes, to be achieved through strengthened enclosures, supervised grazing, locally appropriate deterrent measures, transparent compensation, and active participation of the community.

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Introduction

Large carnivores play an important ecological role as top predators in regulating prey populations and ecosystem structure, and their presence is considered a measure of landscape health. However, in pastoral areas in many parts of the world the survival of these species is now being jeopardised by clashes with livestock-keepers Hamdani Harahap et al., 2025. Livestock depredation directly affects the property of herders, and often results in retaliatory killing, which has been reported throughout wolf, leopard, tiger, puma, jaguar and snow leopard range states (König et al., 2023, Balbuena-Serrano et al., 2021, Franchini and Guerisoli, 2023). Livestock have a significant contribution to the livelihoods and food security of pastoral societies, which means sporadic losses can jeopardize livelihoods and tolerance of coexistence (Hamza, 2025; Harahap et al., 2025). The repeated exposure to depredation causes a decrease in cultural tolerance towards carnivores and puts pressure on the wildlife authorities to allow for lethal control of carnivores, which in turn negatively impacts on the livelihoods and survival of carnivores (Mbise, 2022; Chinchilla et al., 2022). Descriptive statistics and simple spatial overlays have been the mainstay of conventional depredation assessments and often fail to account for the interaction between ecological, managerial and social factors that all collectively contribute to risk (Kuiper, Loveridge and Macdonald, 2022; Miller, 2015). The non-linear interactions that occur between habitat, herd management and human behaviour have made pattern-recognition methods like machine

learning and occupancy modelling attractive as tools that can detect high-risk conditions that go beyond the scope of traditional approaches (Kachel, Anderson, and Shokirov, 2022; Tripathi et al., 2026; Pokkuluri et al., 2025). This paper will use a conceptual approach to explore the situation of livestock depredation and coexistence in a pastoral–carnivore landscape. It includes aspects of ecological, household and community-level indicators to describe depredation risk and coexistence potential, and it is not a technical exercise in machine learning but an analytical framing device that helps to recognize patterns.

Livestock Depredation and Coexistence Context

Carnivore and Livestock Interactions

Incidents involving carnivores and livestock occur mainly in areas where movement corridors for carnivores overlap with livestock grazing areas and where natural prey is limited. Carnivores, especially when wild prey densities are low, tend to switch to livestock as an easy food source and this has been documented for landscapes that are shared by wolves, leopards and big cats (König et al., 2023; Franchini and Guerisoli, 2023). The frequency and intensity of these interactions are also influenced by the availability of livestock, the density of livestock and the size of the grazing range, with higher frequency occurring on unrestricted or extensive grazing systems than on more tightly managed systems (Kuiper, Loveridge, and Macdonald, 2022).

Environmental and Seasonal Drivers

Depredation risk is highly mediated by habitat characteristics. Carnivores are likely to be present near grazing areas where are close to forest cover, location of steep topography, and water sources; whereas open, low-cover landscapes tend to offer less ambush opportunities (Miller, 2015; Balbuena-Serrano et al., 2021). These are compounded by seasonal variation: seasonal rainfall patterns and the movement of vegetation change the distribution of prey and livestock grazing, resulting in distinct seasonal peaks in depredation incidents, especially during transitional wet seasons when herds are grazing further away from settlements (Kachel, Anderson, and Shokirov, 2022; Tripathi et al., 2026).

Household and Herd Management Factors

Herd size, livestock species composition, and husbandry practices have significant impacts on household level vulnerability. Smaller ruminants like sheep and goats are more vulnerable to predation than cattle and those without an enclosure or active guard are disproportionately affected. The frequency of depredation has been successfully minimised by the use of deterrents, such as guard animals, noise devices, or reinforced enclosures, with herders being actively engaged during grazing hours, highlighting the need to balance ecological concerns with proactive management of livestock (Chinchilla et al., 2022; Pokkuluri et al., 2025).

Social Dimensions of Coexistence

Coexistence outcomes are not solely a function of ecological and managerial conditions but rather are also influenced by community perceptions. Tolerance thresholds are determined by perceived severity of losses, satisfaction with compensation schemes, cultural attitudes to carnivores and awareness of conservation value (Mbise, 2022). Delayed, inconsistent or perceived inadequate compensation is associated with a decreased tolerance and underreporting of losses, which can result in biased depredation records and compromises conflict-mitigation planning (Hamza, 2025; Chinchilla et al., 2022).

Conceptual Framework and Study Approach

Study Area and Target Carnivores

The conceptual landscape of this study consists of a mosaic of mixed pastoralists and forest, with patches of livestock grazing adjacent to carnivore habitat (forest edge areas and open grazing plains, and seasonal water points). Medium and large bodied carnivores (such as leopards and wild canids) which prey opportunistically on livestock are targeted. Local communities rely on cattle, goats and sheep for food and livelihood and the management of their flocks ranges from controlled herding to free range.

Information Collection

The conceptual analysis draws on five complementary sources of information: livestock-loss records, structured household interviews, field-based observations of grazing,

enclosure practices, carnivore occurrence records from patrol data and camera-trap records. These sources enable the ecological exposure, household vulnerability, and social response to be taken into account simultaneously.

Machine Learning–Supported Analysis

The use of machine learning here is fundamentally conceptually, and not technically, for the purpose of risk pattern recognition. Pattern-recognition methods are useful because depredation risk is a product of the interaction of ecological exposure, management practice, and social context which is often non-linear and cannot be adequately captured in a simple cross-tabulation of these factors. In this context, machine learning can serve three purposes: identify combinations of conditions that have a high probability of being associated with higher risk, uncover recurring spatial and seasonal patterns in the study landscape, and tell us which factors of coexistence are most important in relative terms. There is no algorithmic description, equation, or architecture of a model,

which is in line with the conceptual nature of this paper.

Patterns of Depredation Risk and Coexistence

Spatial and Seasonal Depredation Patterns

Depredation events do not occur equally throughout the study area. Incident counts are always higher in the forest-edge grazing areas compared with the open areas, and both grazing areas consistently exhibit a high peak in the early wet season when herds are extending their range to access fresh pasture and when carnivore movement is increased with increased prey movement. The frequency of incidents decreases during the peak wet season when there is dense vegetation and abundant natural prey which seems to lessen the need for livestock, and increases again in the post-harvest season as grazing returns close to crop boundaries.

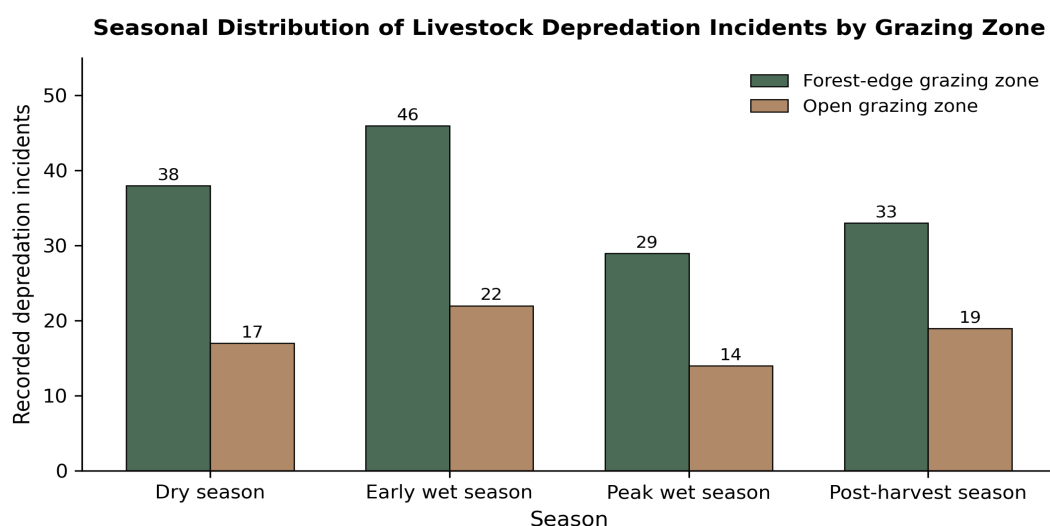


Figure 1: Seasonal Distribution of Livestock Depredation Incidents Across Forest-Edge and Open Grazing Zones

Figure 1 illustrates the frequency of events is about twice as high in the forest-edge zone as in the open grazing zone in all four seasons, which further emphasizes that the proximity to habitat is an important spatial predictor of risk.

Livestock and Herding Vulnerability

There is significant variation in vulnerability among livestock types and husbandry systems. Loss rates are significantly higher for small ruminants grazing in loosely managed herds, and not under active supervision, than for cattle in the same situation, but in a supervised, enclosed system. Unattended herds suffer higher losses than herds which have herders with them during the grazing day, and herds which have reinforced nighttime enclosures suffer lower losses than herds in open or partially fenced enclosures.

Major Factors Associated with Depredation

Proximity to forest habitat and quality of night enclosure are by far the two most important ecological and managerial factors that determine the likelihood of depredation, followed by the presence of active herding and the amount of available natural prey. These are exacerbated by grazing behaviour (ranging into forest-adjacent pasture during seasonal transitions) indicating that risk is neither solely a function of fixed habitat exposure, nor of human decision-making alone.

Community Responses and Coexistence Potential

Prior loss experience and satisfaction with the compensation is closely associated with community tolerance of carnivores.

Table 1: Summary of Key Risk Factors, Observed Depredation Patterns, Coexistence Implications, And Recommended Management Responses

Risk Factor	Observed Depredation Pattern	Coexistence Implication	Recommended Response
Proximity to Forest Edge	Higher Incident Frequency within 1–2 km of Forest Boundary	Elevated Encounter Probability Reduces Tolerance Near Boundary Zones	Buffer Grazing Zones; Boundary Monitoring
Enclosure Quality	lose or Open Bomas Show Markedly Higher Night Losses	Preventable losses fuel resentment toward carnivores	Predator-Proof Enclosure Upgrades
Herder presence	Unattended Herds Lose 2–3x More Livestock Than Guarded Herds	Supervision gaps linked to seasonal labour shortages	Rotational or Shared Herding Schemes
Seasonality	Peaks During Early Wet Season Grazing Dispersal	Seasonal Grazing Habits Misaligned with Carnivore Movement	Season-Specific Grazing Schedules
Compensation satisfaction	Delayed or Partial Payouts Correlate with Lower Reporting Rates	Distrust in Schemes Reduces Willingness to Coexist	Transparent, Timely Compensation Process

Households who have been paid on time and in full are more likely to be willing to implement preventive measures and report on these in a consistent way, while households who are waiting for compensation or missing out on payouts report less willingness to take preventive measures and less consistency in reporting. Where carnivores are known, awareness of their ecological function is associated with positive attitudes to non-lethal management. Table 1 provides an overview of the main risk factors, how were seen in operation, their coexistence implications and suggested responses.

Discussion and Conservation

Implications

This is very similar to the patterns found in previous carnivore-conflict studies. Depredation has mainly occurred near forest edges, reflecting landscape-level risk mapping for wolves and other carnivores, which consistently showed that proximity to forest cover and habitat is a primary risk factor for conflict (König et al., 2023; Kuiper, Loveridge, and Macdonald, 2022). In turn, the high risk of unattended and loosely enclosed herds supports hotspot and occupancy studies indicating that the quality of husbandry often has a greater influence on the likelihood of a loss occurring than raw carnivore density (Kachel, Anderson, and Shokirov, 2022; Balbuena-Serrano et al., 2021). At the ecological level, it seems to be a combination of habitat overlap and seasonal lack of prey species, and at the livelihood level, it is related to lack of supervision and investment in enclosures due to labour and resource limitations (Hamza, 2025; Harahap et al., 2025). Losses can be directly

reduced through preventive husbandry measures such as predator-proof enclosures and constant herder presence, similar to the findings of intervention-based research in other high conflict contexts in Mongolia and elsewhere (Franchini et al., 2026). While complementary, compensation, awareness-building and community participation serve different purposes: compensation helps to offset the immediate economic loss, awareness-building helps to change long-term attitudes and participative mechanisms help to build trust and foster long-term cooperation (Mbise, 2022; Chinchilla et al., 2022). Risk and tolerance can differ by location and time, and measures for coexistence should therefore be adapted to specific areas of the landscape, such as focussing on enclosure support in forest edge areas in the early wet season rather than implementing a uniform measure across the landscape. Several limits caution the interpretation of these patterns. Depredation records are subject to household reporting, and may be influenced by compensation expectations or underreporting of small losses (Chinchilla et al., 2022). The spatial extent or distribution of samples may be variable in both season and grazing zone, and the conclusions derived from a particular landscape may not readily be applicable to other carnivore–livestock systems in which species composition and/or land-use differ (Miller, 2015). Future studies should expand this conceptual framework to other seasons, other carnivores, and should expand to include longitudinal household data to better depict changes in tolerance over time (Franchini and Guerisoli, 2023; Tripathi et al., 2026).

Conclusion

An integrated, conceptually framed approach to examining ecological, husbandry and social indicators to understand livestock depredation and carnivore coexistence has been attempted in this paper. The results show that depredation risk is high in the forest edge grazing areas, peaks during seasonal transition periods, is heavily influenced by the quality of enclosure and presence of the herder, and community tolerance is greatly influenced by the adequacy of compensation and conservation awareness. A depredation outcome is not solely a result of one of the three factors (ecological, managerial, or social) but rather a result of a combination of the three factors. Conceptually, but not technically, machine learning can be a valuable way of identifying these multidimensional patterns and of focusing on the factors that are most important. The practical recommendations to come out of this analysis are the need to increase enclosure security during the night in areas at high risk, supervised or rotational grazing during times of highest risk, the need for locally appropriate deterrents, and transparent and timely compensation, along with a need for community-based carnivore conservation initiatives to facilitate long-term tolerance. Combined, these measures provide a viable locally adaptable route to mitigating livestock losses whilst maintaining viable carnivore populations in shared landscapes.

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