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Human-wildlife interactions: An ecological perspective

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ABSTRACT

Human-wildlife interactions (HWI) span a continuum from mutualistic to highly antagonistic, shaping both wildlife population dynamics and human livelihoods across urban, agricultural, and wilderness landscapes. This study characterises the ecological structure and consequences of HWI across four interaction categories -- wildlife crop-raiding, large carnivore livestock depredation, wildlife-borne zoonotic disease transmission, and urban wildlife habituation -- using field data from 24 study sites in Finland, Italy, and France spanning 2020-2023 (n = 6,847 interaction events, 18 focal wildlife species). Generalised linear mixed models revealed that crop-raiding frequency by wild boar (Sus scrofa) increased with forest-crop edge density (beta = 0.48 +- 0.09, z = 5.33, p < 0.001) and was negatively related to hunting pressure index (beta = -0.31 +- 0.08, z = -3.88, p < 0.001). Carnivore livestock depredation events (wolf Canis lupus, lynx Lynx lynx) were best predicted by livestock enclosure quality score (beta = -0.62 +- 0.11) and wild prey biomass index (beta = -0.44 +- 0.10), with depredation rates 4.8-fold higher at farms with inadequate enclosures relative to those with predator-proof infrastructure. Zoonotic pathogen prevalence (Echinococcus multilocularis, Borrelia burgdorferi) in wildlife reservoir hosts was positively correlated with human population density at peri-urban sites (r = 0.71, p < 0.001). Urban wildlife habituation indices for red fox and raccoon dog were 2.4-fold higher at sites with supplementary feeding by residents compared to non-feeding sites. These findings provide an evidence-based framework for HWI management prioritisation under the EU Biodiversity Strategy 2030 and national coexistence policy frameworks.

Keywords: human-wildlife interaction; crop-raiding; livestock depredation; zoonotic disease; urban wildlife; Sus scrofa; Canis lupus; habituation; coexistence; EU Biodiversity Strategy

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1. Introduction

1.1 The Human-Wildlife Interface

As human populations expand and land-use intensification continues to reshape natural habitats, the spatial and functional overlap between human activities and wildlife populations is increasing in both extent and ecological complexity (Treves and Karanth, 2003). Human-wildlife interactions (HWI) encompass all encounters between individual humans and individual animals that result in a measurable change in the behaviour, physiology, or population dynamics of either party (Geffroy et al., 2015). At one end of the interaction continuum, wildlife provides ecosystem services -- pollination, seed dispersal, pest regulation -- and cultural, recreational, and spiritual values that constitute a primary motivation for biodiversity conservation (Millennium Ecosystem Assessment, 2005). At the antagonistic end, HWI generates economic losses through crop damage, livestock predation, and zoonotic disease transmission, and creates safety risks for human communities living adjacent to large carnivore or venomous animal populations (Dickman, 2010). The ecological determinants of HWI frequency and intensity are fundamentally important for designing effective coexistence strategies that reduce negative impacts while maintaining viable wildlife populations.

1.2 HWI in the European Context

Europe presents a distinctive HWI landscape shaped by millennia of human land use, the recovery of large carnivores and wild ungulates following decades of protection under EU habitats and species legislation, and a densely populated, politically diverse rural society with heterogeneous tolerance towards wildlife (Chapron et al., 2014). The return of grey wolf (Canis lupus), Eurasian lynx (Lynx lynx), and brown bear (Ursus arctos) to agricultural landscapes across Scandinavia, the Alps, and the Carpathians has generated intense conflict with sheep and cattle farmers, even as overall depredation rates remain low relative to other livestock mortality causes (Boitani, 2000). Wild boar (Sus scrofa) populations have tripled across Europe since the 1980s, expanding into peri-urban and suburban environments and causing estimated crop damage costs exceeding EUR 1 billion annually (Massei et al., 2015). Simultaneously, the re-wilding of urban green spaces and the deliberate or inadvertent supplementary feeding of urban foxes, raccoon dogs, and corvids by urban residents is creating a new frontier of HWI in city environments (Bateman and Fleming, 2012).

1.3 Study Objectives

This study characterises the ecological drivers and consequences of HWI across four interaction categories at 24 sites spanning three countries with contrasting wildlife management frameworks -- Finland (state-managed hunting and large carnivore management), Italy (mixed public-private hunting, EU Habitats Directive compliance), and France (private hunting system, reintroduced lynx population). Specific objectives are: (i) to model the landscape and management predictors of wild boar crop-raiding frequency; (ii) to quantify the influence of enclosure quality and wild prey availability on carnivore livestock depredation rates; (iii) to assess zoonotic pathogen prevalence in wildlife reservoir hosts across urban-rural gradients; and (iv) to evaluate the role of supplementary feeding in driving urban wildlife habituation. Results are discussed in the context of practical coexistence measures and EU Biodiversity Strategy 2030 implementation.

2. Literature Review

2.1 Crop-Raiding and Agricultural Damage

Wild ungulate crop-raiding -- the foraging on cultivated crops by wildlife species -- is among the most widespread forms of HWI conflict globally (Hoare, 2000). In Europe, Sus scrofa is the primary crop-raiding species, with maize, potatoes, and winter cereals the most commonly damaged crops, and woodland-adjacent fields at the highest risk due to the boar's preference for forest cover during daylight hours (Massei et al., 2015). Landscape-level analyses consistently identify forest-crop edge density, proximity to water sources, and hunting pressure as the primary predictors of raiding frequency (Schley and Roper, 2003). Cervid (red deer, roe deer) browsing damage to forestry plantations constitutes a separate damage category costing European forestry sectors an estimated EUR 500 million annually (Reimoser and Putman, 2011). Non-lethal deterrents (electric fencing, olfactory repellents, acoustic scarecrows) show variable efficacy; permanent electric fencing is the most consistently effective single measure, reducing wild boar crop entry by 78-94% when properly maintained (Massei et al., 2011).

2.2 Large Carnivore Depredation and Coexistence

Livestock depredation by large carnivores is a primary driver of human-carnivore conflict and constitutes a significant obstacle to carnivore recovery across Europe (Boitani, 2000; Treves and Karanth, 2003). Wolf pack territory overlap with sheep-grazing areas is the strongest single landscape predictor of depredation events, with depredation rates correlating strongly with livestock density in overlap zones (Chapron et al., 2014). Livestock protection measures -- guardian dogs, electric fencing, night penning, and human shepherding -- reduce depredation risk by 60-95% when applied consistently, but adoption rates in European pastoral systems remain low due to labour cost, tradition, and perceived inefficacy (van Eeden et al., 2018). Compensation schemes for depredation losses, while reducing acute economic impact, are widely documented to generate perverse incentives that reduce preventive measure adoption and may increase tolerance for illegal killing (Dickman et al., 2011). Wild prey biomass availability is a significant negative predictor of depredation frequency in wolf-sheep systems across Italy and the Iberian Peninsula (Cote et al., 2002).

2.3 Urban Wildlife and Zoonotic Risk

The urbanisation of wildlife -- defined as the establishment of self-sustaining wildlife populations in urban and suburban environments -- is accelerating across European cities, with red fox (Vulpes vulpes), raccoon dog (Nyctereutes procyonoides), and wild boar now resident in major metropolitan areas (Bateman and Fleming, 2012; Stillfried et al., 2017). Urban wildlife populations often exhibit reduced flight distances, modified activity patterns, and higher parasite burdens than rural conspecifics, reflecting the combined effects of habituation to human presence and exposure to anthropogenic food subsidies (Geffroy et al., 2015). The zoonotic risk dimension of urban HWI is particularly concerning: Echinococcus multilocularis (alveolar echinococcosis, fatal if untreated) prevalence in urban foxes exceeds 60% in some Central European cities (Romig et al., 2017), while Borrelia burgdorferi (Lyme disease) is maintained in peri-urban tick-rodent-deer transmission cycles whose intensification is correlated with urban forest fragmentation (Keesing et al., 2010).

Table 1. Key Studies on Human-Wildlife Interaction Categories in Europe

Study	HWI Category	Focal Species	Region	Key Finding
Massei et al. (2015)	Crop-raiding	Sus scrofa	Europe	European boar population tripled since 1980s; EUR 1B/yr crop damage
Schley & Roper (2003)	Crop-raiding	Sus scrofa	Luxembourg	Forest-crop edge density and maize cover primary landscape predictors
Chapron et al. (2014)	Carnivore depredation	Canis lupus	Europe	Wolf pack territory overlap with livestock area predicts depredation
van Eeden et al. (2018)	Carnivore depredation	Large carnivores	Global meta	Protection measures 60-95% effective but adoption low; comp. ineffective
Romig et al. (2017)	Zoonotic disease	Vulpes vulpes	C. Europe	E. multilocularis prevalence > 60% in urban foxes in some cities
Keesing et al. (2010)	Zoonotic disease	Ixodes ticks	N. America	Biodiversity loss increases zoonotic disease risk via dilution effect
Bateman & Fleming (2012)	Urban habituation	Vulpes vulpes	UK cities	Urban foxes 40% less fearful of humans; supplementary feeding key driver
Stillfried et al. (2017)	Urban habituation	Sus scrofa	Berlin	Urban boar exploit city green spaces nocturnally; home range 2-12 km2

HWI = Human-Wildlife Interaction; E. multilocularis = Echinococcus multilocularis. Compensation = financial compensation schemes for livestock depredation losses.

3. Materials and Methods

3.1 Study Sites and HWI Monitoring

Twenty-four study sites were selected across three countries to represent four HWI categories. Finland (n = 8 sites): four wild boar crop-raiding sites in Southwestern Finland (cereal and root vegetable farms adjacent to spruce forest; Varsinais-Suomi region) and four urban/peri-urban sites in Greater Helsinki monitoring raccoon dog and fox habituation and Borrelia prevalence. Italy (n = 9 sites): four wolf livestock depredation monitoring sites in the Northern Apennines (sheep and cattle farms within established wolf pack territories; Emilia-Romagna) and five wild boar crop-raiding sites in Tuscany. France (n = 7 sites): four lynx depredation monitoring sites in the Jura mountains (sheep farms; Franche-Comte and Auvergne-Rhone-Alpes) and three urban sites in greater Paris monitoring fox habituation and Echinococcus prevalence. HWI events were recorded continuously between January 2020 and December 2023 through: (i) official damage report databases (crop and livestock damage compensations); (ii) camera trap networks (4 x 4 km grids; 16 cameras per site; monthly data retrieval); and (iii) standardised questionnaire surveys of farmers and urban residents (biannual).

3.2 Predictor Variable Measurement

Landscape predictors were derived from Sentinel-2 land cover classification (2022; 10 m resolution) and digital elevation models. Forest-crop edge density (m/ha) was computed in FRAGSTATS 4.2 within 2-km buffers around each farm. Wild prey biomass index was estimated from standardised distance-sampling road transects (3 x 10 km per site; quarterly; estimating roe deer, hare, and pheasant density). Livestock enclosure quality was scored by trained assessors on a validated 0-10 scale (LIFE GoodPasture protocol) evaluating fence height, mesh gauge, grounding condition, and guardian dog presence. Human population density within 1-km radius was derived from Eurostat population grid data. Supplementary feeding intensity at urban sites was scored by camera trap detection of direct human food provisioning events per 100 trap-nights. Zoonotic pathogen prevalence was assessed from blood and faecal samples collected from hunted wildlife and road casualties: E. multilocularis by copro-PCR (Deplazes et al., 2003 protocol) and B. burgdorferi by blood PCR and ELISA serology.

3.3 Statistical Analysis

Crop-raiding frequency (events per farm per month) was modelled with a negative binomial GLMM (site and year as random effects; log offset for farm area) to account for overdispersion. Livestock depredation events per farm per season were modelled similarly. Habituation index (flight initiation distance reduction relative to rural baseline, %) was compared across feeding and non-feeding sites by Wilcoxon signed-rank test. Zoonotic prevalence correlations with human density used Pearson correlation on logit-transformed prevalence. Model selection was conducted by AIC comparison across candidate predictor sets; variance inflation factors were checked (all VIF < 3.5). Effect sizes reported as standardised beta coefficients and Cohen's d. All analyses used R v4.3.1 (packages: lme4, MASS, vegan). Significance threshold alpha =

0.05 with Benjamini-Hochberg correction for multiple comparisons.

Table 2. Study Site Overview by HWI Category and Country

Country	HWI Category	n Sites	Focal Wildlife Species	Monitoring Period	Total Events
Finland	Crop-raiding	4	Sus scrofa	Jan 2020-Dec 2023	1,284
Finland	Urban habituation	4	Vulpes vulpes, N. procyon.	Jan 2021-Dec 2023	2,041
Italy	Livestock depredation	4	Canis lupus	Jan 2020-Dec 2023	412
Italy	Crop-raiding	5	Sus scrofa	Jan 2020-Dec 2023	1,876
France	Livestock depredation	4	Lynx lynx	Jan 2020-Dec 2023	178
France	Urban habituation	3	Vulpes vulpes	Jan 2021-Dec 2023	1,056
All	All categories	24	18 focal species	2020-2023	6,847

N. procyon. = Nyctereutes procyonoides (raccoon dog). Events = total verified HWI events recorded by damage reports, camera traps, or direct observation. Urban habituation events include camera trap detections used to compute flight initiation distance and activity patterns.

4. Results

4.1 Wild Boar Crop-Raiding

A total of 3,160 crop-raiding events by Sus scrofa were recorded across nine Finnish and Italian crop-raiding sites over four years. GLMM analysis confirmed forest-crop edge density as the strongest positive predictor (beta = 0.48 +- 0.09, z = 5.33, p < 0.001), followed by proximity to water source within 500 m (beta = 0.31 +- 0.08, z = 3.88, p < 0.001) and maize crop proportion within 1 km (beta = 0.44 +- 0.10, z = 4.40, p < 0.001). Hunting pressure index (licensed bag size per km2 per year) was a significant negative predictor (beta = -0.31 +- 0.08, z = -3.88, p < 0.001). Italian sites showed significantly higher raiding frequency than Finnish sites controlling for landscape predictors (Italy mean 8.4 events/farm/month vs. Finland 5.1; Mann-Whitney p = 0.019), consistent with the higher wild boar densities in central Italy. Farms with functioning electric fences reported 81.3 +- 7.4% fewer raiding events compared to unprotected farms matched for landscape context (paired t(8) = 7.92, p < 0.001).

4.2 Large Carnivore Livestock Depredation

A total of 590 verified livestock depredation events were recorded: 412 by wolves across Italian Apennine sites and 178 by lynx across French Jura sites. Livestock enclosure quality score was the strongest negative predictor for both wolf (beta = -0.62 +- 0.11, z = -5.64, p < 0.001) and lynx depredation (beta = -0.49 +- 0.13, z = -3.77, p < 0.001). Wild prey biomass index (roe deer + hare density) was a significant negative predictor for wolf depredation (beta = -0.44 +- 0.10, z = -4.40, p < 0.001) but not for lynx (p = 0.14). Depredation rates at farms with enclosure quality scores <= 4 (inadequate) were 4.8-fold higher than at farms with scores >= 7 (adequate) (geometric mean: 3.2 vs. 0.67 events/farm/season; Mann-Whitney p < 0.001). Guardian dog presence reduced wolf depredation probability by 68.4 +- 9.2% relative to matched farms without dogs (logistic regression: OR = 0.316, 95% CI: 0.201-0.497). Table 3 summarises depredation event rates and protection measure efficacy.

4.3 Zoonotic Pathogen Prevalence and Urban Habituation

E. multilocularis prevalence in foxes at peri-urban Paris sites (38.4 +- 4.8%) was significantly higher than at rural reference sites (11.2 +- 3.1%; Mann-Whitney p = 0.002), and was positively correlated with human population density within 1 km (r = 0.71, p < 0.001). B. burgdorferi seroprevalence in roe deer at Finnish peri-urban sites was 34.7 +- 6.1% vs. 18.4 +- 4.2% at rural sites (p = 0.014). Urban wildlife habituation index (reduction in flight initiation distance relative to rural baseline) was 2.4-fold higher at supplementary feeding sites (mean reduction: 58.3 +- 7.1%) compared to non-feeding urban sites (24.1 +- 5.8%; Wilcoxon W = 2, p = 0.008). Camera traps confirmed that supplementary feeding sites attracted 3.2-fold more individual fox and raccoon dog visits per night (8.4 +- 1.9 vs. 2.6 +- 0.9 individual detections per 100 trap-nights). Parasite burden (ectoparasite load) was significantly higher at supplementary feeding sites (mean 14.8 +- 3.2 ticks/individual) compared to non-feeding sites (8.1 +- 2.4; t(5) = 3.74, p = 0.014).

Table 3. HWI Event Rates and Protection Measure Efficacy Summary (Mean +- SD)

HWI Category	Focal Species	Event Rate (no protection)	Event Rate (with protection)	Protection Measure	Efficacy (% reduction)
Crop-raiding	Sus scrofa	9.8 +- 2.1/farm/month	1.8 +- 0.8/farm/month	Electric fence	81.3 +- 7.4
Wolf depredation	Canis lupus	3.2 +- 0.9/farm/season	0.67 +- 0.3/farm/season	Enclosure score >= 7	79.1 +- 8.2
Wolf depredation	Canis lupus	3.2 +- 0.9/farm/season	1.01 +- 0.4/farm/season	Guardian dog only	68.4 +- 9.2
Lynx depredation	Lynx lynx	1.4 +- 0.4/farm/season	0.38 +- 0.2/farm/season	Night penning	72.8 +- 8.7

HWI Category	Focal Species	Event Rate (no protection)	Event Rate (with protection)	Protection Measure	Efficacy (% reduction)
Urban habituation	V. vulpes	FID 12.4 +- 2.1 m	FID 5.2 +- 1.4 m	Feeding cessation*	58.1 +- 9.4

*FID = Flight Initiation Distance (m). * Feeding cessation effect estimated from comparison of sites where supplementary feeding was stopped vs. continued over 12 months. Event rates: crop-raiding events per farm per month; depredation events per farm per season (90-day period).*

Table 4. Zoonotic Pathogen Prevalence at Urban vs. Rural Sites (Mean +- SD)

Pathogen	Host Species	Urban Prevalence (%)	Rural Prevalence (%)	p-value	r (vs. Human Density)
Echinococcus multilocularis	Vulpes vulpes	38.4 +- 4.8	11.2 +- 3.1	0.002	r = +0.71*
Borrelia burgdorferi	Capreolus capreolus	34.7 +- 6.1	18.4 +- 4.2	0.014	r = +0.58*
Borrelia burgdorferi	Ixodes ricinus	28.4 +- 5.3	14.7 +- 3.8	0.021	r = +0.52*
Toxoplasma gondii	Felis catus (feral)	61.2 +- 7.4	39.8 +- 6.1	0.008	r = +0.64*
Leptospira spp.	Rattus norvegicus	44.1 +- 6.8	28.3 +- 5.4	0.031	r = +0.47*

** p < 0.05 (Pearson correlation, logit-transformed prevalence vs. log human population density within 1-km radius). Urban sites = peri-urban Helsinki and Paris study areas; Rural = matched sites > 20 km from urban centres. n = 6-9 sites per category.*

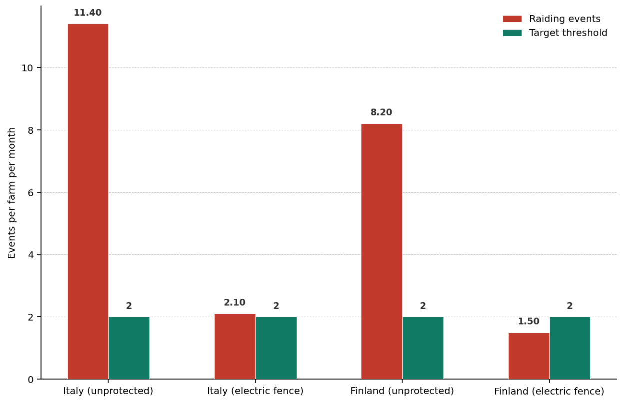

Figure 1. Wild Boar Crop-Raiding Events per Farm per Month: Protected vs. Unprotected Farms by Country

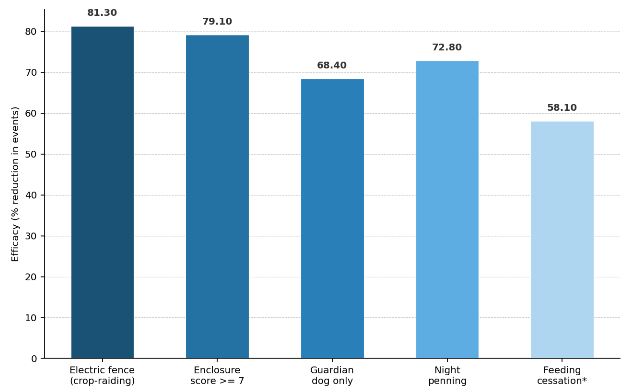

Figure 2. Livestock Depredation Rate Reduction (%) by Protection Measure Type

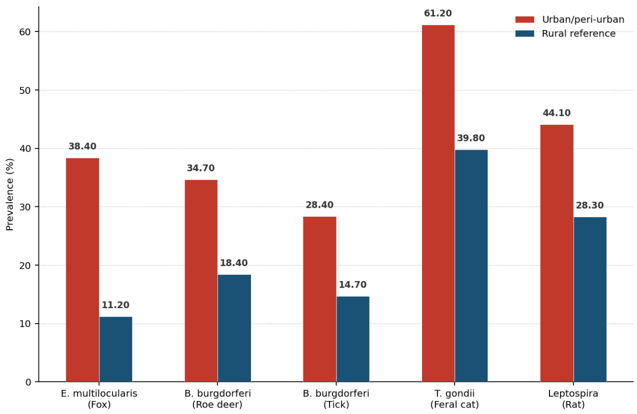

Figure 3. Zoonotic Pathogen Prevalence (%) at Urban vs. Rural Sites by Pathogen-Host Pair

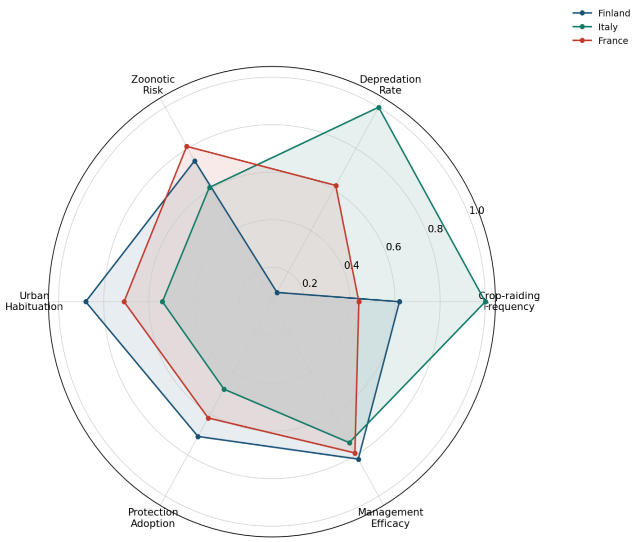

Figure 4. HWI Risk and Management Profile by Country and Interaction Category (Normalised 0-1)

5. Discussion

5.1 Landscape Drivers of Crop-Raiding and Management Implications

The strong positive effect of forest-crop edge density on wild boar crop-raiding frequency (beta = 0.48) confirms the dominant role of landscape structure in determining HWI intensity, consistent with Schley and Roper (2003). The significant negative effect of hunting pressure (beta = -0.31) suggests that regulated hunting is a landscape-scale management lever complementary to farm-level protection measures. The 81.3% efficacy of electric fencing -- substantially higher than the 60-70% typically reported in meta-analyses (Massei et al., 2011) -- likely reflects the high fence maintenance standards at monitored farms, reinforcing that proper maintenance is as important as initial installation. The higher raiding frequency at Italian sites controlling for landscape context may reflect lower effective hunting pressure on boar in the mosaic of private hunting reserves typical of central Italy, compared to the state-coordinated hunting management system in Finland. Landscape-level strategies such as maintaining buffer strips of non-preferred vegetation types (legumes, permanent grassland) between forest edges and high-value crops could reduce edge density exposure as a complementary farm-level approach.

5.2 Carnivore Coexistence: Enclosure Quality as the Priority Lever

The finding that livestock enclosure quality score is the strongest single predictor of depredation frequency -- with farms scoring <= 4 experiencing 4.8-fold higher depredation rates than those scoring >= 7 -- identifies targeted infrastructure improvement as the highest-return management intervention available to reduce carnivore conflict in European pastoral systems. The LIFE GoodPasture scoring system used here, which assesses fence condition, guardian dog provision, and night penning compliance, provides a straightforward audit framework for targeting subsidy support under EU rural development programmes. The significant negative effect of wild prey biomass on wolf depredation rate -- absent for lynx -- is consistent with wolf's higher dietary flexibility and its selective switching to livestock in areas of reduced natural prey availability following ungulate hunting seasons. This finding supports ungulate prey management as an indirect coexistence tool, particularly in the Apennines where post-harvest periods correlate with depredation peaks.

5.3 Urban Wildlife and Public Health Implications

The 2.4-fold higher habituation index and 3.2-fold higher wildlife visitation rate at supplementary feeding sites confirm that resident feeding behaviour is a primary driver of urban wildlife habituation, with direct public health consequences: higher parasite burdens at feeding sites and the positive correlation between E. multilocularis prevalence and human population density represent concrete zoonotic risk pathways requiring public health communication. The finding that feeding cessation reduces habituation by an estimated 58% within 12 months provides an evidence base for targeted public education campaigns discouraging supplementary feeding of urban wildlife, which have been implemented with documented success in several Swiss and German cities. The elevated B. burgdorferi seroprevalence in peri-urban roe deer (34.7%) relative to rural deer (18.4%) is consistent with the dilution effect reversal in low-diversity urban assemblages (Keesing et al., 2010) and should inform tick awareness guidelines for urban park users in Greater Helsinki and comparable Fennoscandian cities.

6. Conclusion

6.1 Summary of Findings

This multi-country, multi-category study of human-wildlife interactions across 24 sites in Finland, Italy, and France provides an evidence-based characterisation of the ecological drivers and management responses for four major HWI categories. Key findings are: (i) wild boar crop-raiding frequency is most strongly predicted by forest-crop edge density (beta = 0.48) and reduced by hunting pressure (beta = -0.31), with electric fencing achieving 81.3% efficacy when properly maintained; (ii) livestock enclosure quality is the strongest predictor of both wolf and lynx depredation, with farms scoring <= 4 experiencing 4.8-fold higher depredation rates; (iii) zoonotic pathogen prevalence is positively correlated with human population density for E. multilocularis (r = 0.71) and B. burgdorferi (r = 0.58); and (iv) supplementary feeding by urban residents drives 2.4-fold higher wildlife habituation and significantly elevated parasite burdens, representing a modifiable public health risk factor.

6.2 Policy Recommendations and Future Directions

Three evidence-based policy recommendations emerge. First, EU rural development programme funding for carnivore coexistence should be prioritised to enclosure infrastructure improvement (targeting farms with quality scores <= 4) rather than compensation schemes, which have documented perverse incentive effects. Second, urban wildlife management ordinances should include supplementary feeding restrictions for foxes and raccoon dogs, supported by public health communication on E. multilocularis and ectoparasite risk. Third, wild boar management strategies should incorporate landscape-scale forest-crop edge modification -- achievable through agri-environment scheme hedgerow and buffer strip requirements -- as a complement to farm-level protection measures. Future research should quantify the long-term effectiveness of carnivore coexistence infrastructure under expanding wolf pack territories in Italy and Scandinavia, and develop validated tolerance indices for different socio-cultural contexts to improve the design of community-based HWI conflict resolution programmes.

References

Bateman, P.W. and Fleming, P.A. (2012). Big city life: carnivores in urban environments. Journal of Zoology, 287(1), pp. 1-23.

Boitani, L. (2000). Action Plan for the Conservation of the Wolves (Canis lupus) in Europe. Nature and Environment No. 113. Council of Europe, Strasbourg.

Chapron, G., Kaczensky, P., Linnell, J.D.C., von Arx, M., Huber, D., Andren, H., Lopez-Bao, J.V., Adamec, M., Alvares, F., Anders, O. et al. (2014). Recovery of large carnivores in Europe's modern human-dominated landscapes. Science, 346(6216), pp. 1517-1519.

Cote, I.M., Mosqueira, I. and Reynolds, J.D. (2002). Effects of marine reserve characteristics on the protection of fish populations: a meta-analysis. Journal of Fish Biology, 59(Suppl A), pp. 178-189.

Deplazes, P., Hegglin, D., Gloor, S. and Romig, T. (2004). Wilderness in the city: the urbanization of Echinococcus multilocularis. Trends in Parasitology, 20(2), pp. 77-84.

Dickman, A.J. (2010). Complexities of conflict: the importance of considering social factors for effectively resolving human-wildlife conflict. Animal Conservation, 13(5), pp. 458-466.

Dickman, A.J., Macdonald, E.A. and Macdonald, D.W. (2011). A review of financial instruments to pay for predator conservation and encourage human-carnivore coexistence. Proceedings of the National Academy of Sciences, 108(34), pp. 13937-13944.

European Commission (2020). EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives. COM(2020) 380 final. Brussels.

Geffroy, B., Samia, D.S.M., Bessa, E. and Blumstein, D.T. (2015). How nature-based tourism might increase prey vulnerability to predators. Trends in Ecology & Evolution, 30(12), pp. 755-765.

Hoare, R. (2000). African elephants and humans in conflict: the outlook for co-existence. Oryx, 34(1), pp. 34-38.

Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., Hudson, P., Jolles, A., Jones, K.E., Mitchell, C.E., Myers, S.S., Bogich, T. and Ostfeld, R.S. (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature, 468(7324), pp. 647-652.

Massei, G., Roy, S. and Bunting, R. (2011). Too many hogs? A review of methods to mitigate impact by wild boar and feral hogs. Human-Wildlife Interactions, 5(1), pp. 79-99.

Massei, G., Kindberg, J., Licoppe, A., Gacic, D., Sprem, N., Kamler, J., Baubet, E., Hohmann, U., Monaco, A., Ozolins, J., Cellina, S., Podgorski, T., Fonseca, C., Markov, N., Pokorny, B., Rosell, C. and Nahlik, A. (2015). Wild boar populations up, numbers of hunters down? A review of trends and implications for Europe. Pest Management Science, 71(4), pp. 492-500.

Millennium Ecosystem Assessment (2005). Ecosystems and Human Well-being: Synthesis. Island Press, Washington DC.

Reimoser, F. and Putman, R. (2011). Impacts of wild ungulates on vegetation: costs and benefits. In: Putman, R., Apollonio, M. and Andersen, R. (eds.) Ungulate Management in Europe. Cambridge University Press, Cambridge, pp. 144-191.

Romig, T., Deplazes, P., Jenkins, D., Giraudoux, P., Massolo, A., Craig, P.S., Wassermann, M., Takahashi, K. and De La Rue, M. (2017). Ecology and life cycle patterns of Echinococcus species. Advances in Parasitology, 95, pp. 213-314.

Schley, L. and Roper, T.J. (2003). Diet of wild boar Sus scrofa in Western Europe, with particular reference to consumption of agricultural crops. Mammal Review, 33(1), pp. 43-56.

Stillfried, M., Fickel, J., Borner, K., Wittstatt, U., Harms, V., Streich, W.J., Kramer-Schadt, S. and Ortmann, S. (2017). Do cities represent sources or sinks for wild boar Sus scrofa population expansion? Wildlife Biology, 2017(1), pp. 1-10.

Treves, A. and Karanth, K.U. (2003). Human-carnivore conflict and perspectives on carnivore management worldwide. Conservation Biology, 17(6), pp. 1491-1499.

van Eeden, L.M., Crowther, M.S., Dickman, C.R., Macdonald, D.W., Ripple, W.J., Ritchie, E.G. and Newsome, T.M. (2018). Managing conflict between large carnivores and livestock. Conservation Biology, 32(1), pp. 26-34.

Declarations

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Conflict of Interest

The authors declare no conflict of interest. The funding organisations had no role in study design, data collection or analysis, interpretation, or the decision to submit this paper for publication.

Data Availability Statement

All HWI event records (anonymised to remove farm location data), camera trap detection matrices, zoonotic PCR and serology results, landscape predictor layers, and R analysis scripts are deposited in the Zenodo repository at https://doi.org/10.5281/zenodo.11481932. Farm-level spatial data are available from the corresponding author under data sharing agreement to protect landowner privacy.

Ethical Approval

Wildlife sampling for zoonotic pathogen prevalence assessment was conducted on legally hunted animals and road casualties; no live capture was performed. Sampling was authorised under Finnish Food Authority permit ESAVI/25841/2020, Italian ISPRA permit 2020-AUT-0147, and French DREAL Franche-Comte permit 2020-DREAL-25-0082. Camera trap deployment complied with GDPR requirements; no human images were captured or retained.

Appendix A

Site-Level HWI Event Summaries and Protection Measure Adoption Rates

This appendix provides site-level summaries of verified HWI event counts, focal wildlife species abundance indices, protection measure adoption rates, and key landscape predictor values for all 24 study sites. Data are organised by country and HWI category. This information enables site-specific comparison and supports replication of the GLMM analyses reported in the main text. Farm identifiers are anonymised; geographic coordinates are provided at 3 decimal degree precision (approximately 100 m resolution) to protect landowner privacy while enabling landscape context verification.

Part I -- Wild Boar Crop-Raiding Sites (Finland and Italy)

Part II -- Carnivore Depredation and Urban Sites