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Balancing act: navigating increasing human-wildlife conflict amidst megafauna recovery in the tropical lowlands of Nepal

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Human-wildlife conflict (HWC) involving megafauna is a global conservation concern. In the tropical lowlands of Nepal (Terai), the megafauna populations are increasing due to successful conservation efforts, introducing the potential for greater HWC. We analyzed the spatio-temporal trend of reported HWC incidents from 2013 to 2022 in the buffer zones of Bardia and Chitwan National Parks in the Terai. Of the total 14,989 reported HWC incidents, crop raiding ($n=8,129$) and livestock depredation ($n=4,611$) were the most common. Elephants were responsible for 42.8% of all incidents. Total HWC incidents increased over the 10-year period, and there was a significant association between total population estimates of rhino and tiger and total HWC incidents involving those species. At the site level, this association held except for rhino HWC in Bardia. Similarly, incidents of livestock depredation driven by leopard and tiger, and crop damage incidents from elephant, rhino, and boar, increased over the study period. In contrast, property damage—exclusively by elephants—remained relatively stable in Chitwan but decreased in Bardia, possibly reflecting seasonal and transboundary movement patterns of elephants, or the effectiveness of targeted mitigation measures that have reduced elephant intrusions into settlements. Conflict hotspots—defined as the wards in the top quantile of HWC incidents—indicated priority areas for focused mitigation and remedial efforts. Habitat restoration in the buffer zones and corridors outside PAs could potentially mitigate HWC, but it might simultaneously export HWC to new areas outside the PAs. Targeted community-based mitigation measures should be implemented in the peak raiding periods, and predator-proof sheds would reduce livestock losses; both initiatives require substantial external financial support. Finally, the widespread adoption of livestock insurance that responds to spatiotemporal risk should be considered, along with funding and coordination by government and conservation organizations. Overall, the evidence suggests that successful megafauna conservation may be associated with increased HWC. Nevertheless, our findings offer practical insights to guide species-specific conflict mitigation and HWC management in tropical landscapes where megafauna populations are recovering, and conflicts are intensifying.

Keywords Megafauna, Hotspot, Habitat restoration, Corridors and livestock insurance

Human-wildlife conflict (HWC) is a globally prevalent challenge for conservation authorities managing protected areas (PAs) and for people living in the surrounding settlements^{1–4}. HWC is especially severe in rural communities of low-income countries, where the costs in terms of both finance and food security are disproportionately high^{5,6}. In the buffer zones or areas surrounding PAs - particularly in low-income countries like Nepal - the burden of conservation success can be substantial^{7–10}. This underscores the importance of developing policies that sustain conservation success while addressing the economic challenges faced by rural communities^{11,12}.

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Populations of large mammals have been increasing in some countries^{13,14} and HWC involving megafauna species has similarly been increasing (e.g.^{4,15–18}). In Nepal, early research in two important PAs of the tropical lowlands (Terai) indicated that there has been an increase in the number of reported HWC incidents in the buffer zones^{7,19}. While studies have provided compelling qualitative data to suggest that the rise in conflict incidents may be linked to growing wildlife populations (e.g.²⁰), to our knowledge research on quantifying this association is very limited. Understanding this relationship is important because management efforts focus on large flagship species as key contributors to tourism revenue in several countries (e.g.^{21,22}), and yet increasing HWC incidents may manifest in negative attitudes among local communities toward conservation, potentially resulting in retaliatory killings^{23–26}.

Beyond critical population-conflict associations, a greater understanding of species- and site-specific conflict dynamics is essential in assessing potential HWC mitigation responses. For example, the type of damage incurred by wildlife species varies across both ecological and geographic contexts. Similarly, activity patterns may differ across species, leading to different hotspots of HWC (e.g.^{1,4,7,19,27}). A clearer understanding of the spatiotemporal dynamics of HWC is crucial to inform policymakers and managers prioritizing conservation activities to not only restore megafauna populations, but also to develop mitigation strategies and reduce HWC incidents, thereby contributing to human-wildlife coexistence and long-term conservation success.

Among the seven PAs in Nepal's Terai, Bardia National Park (BNP) and Chitwan National Park (CNP) are the largest, comprising more than 50% of the protected landscapes of the Terai and protecting significant populations of megafauna (See Fig. 1)²⁸. Both PAs lie within the Terai Arc Landscape (TAL), a priority landscape for tiger conservation^{29,30}. These PAs are the biodiversity hotspots that harbor some of the most iconic species of Asia³¹. The core area of the PAs is strictly protected by the national army, whereas the multiple-use buffer zone forests are restored and managed by the buffer zone communities³². In addition to the strict protection of protected areas by the national army, community volunteers have made significant contributions to wildlife protection, management, and conflict mitigation efforts³³. These strategies have facilitated the recovery of globally recognized megafauna species such as tiger (*Panthera tigris tigris*), leopard (*P. pardus*), rhino (*Rhinoceros unicornis*), and

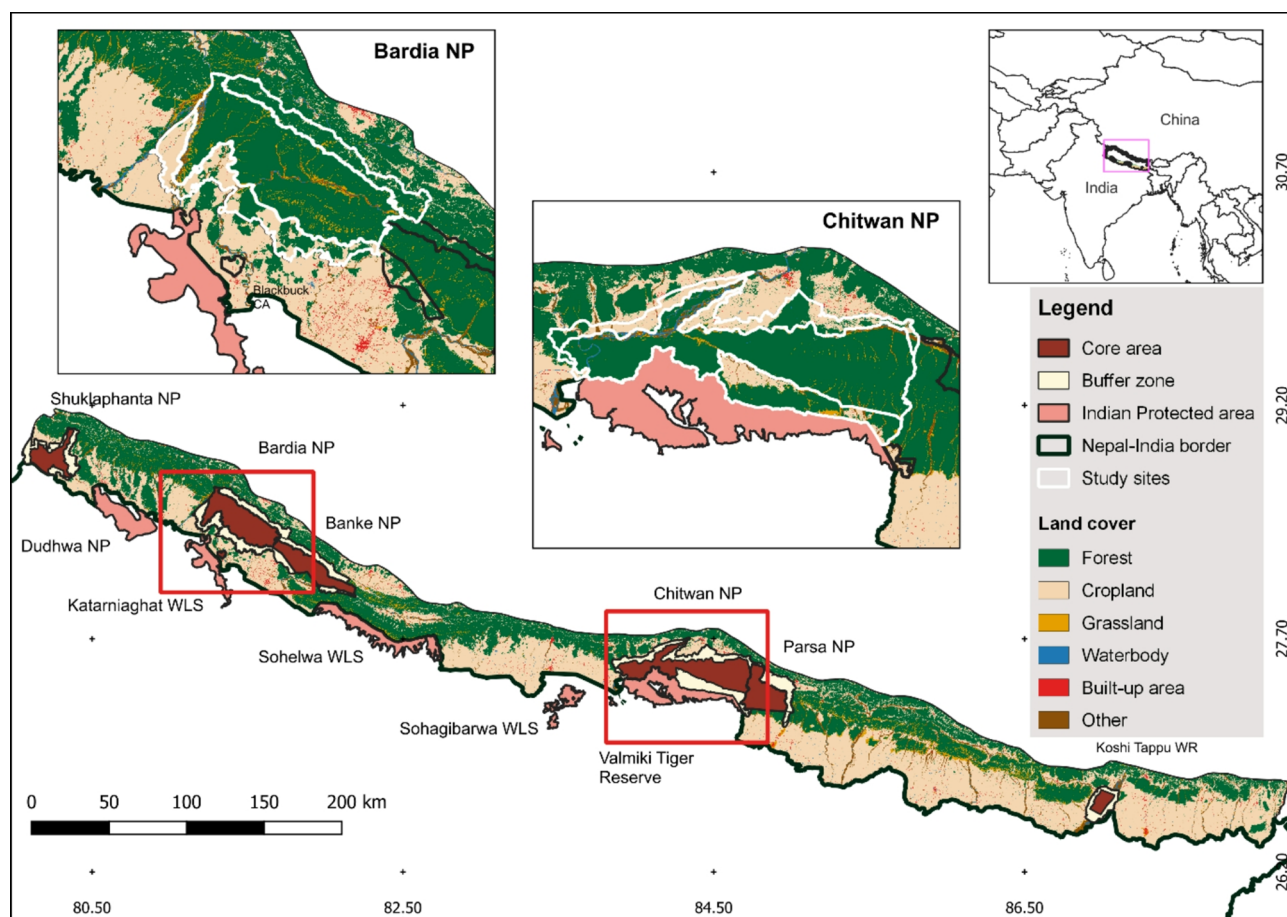


Fig. 1. Location map of Bardia and Chitwan National Parks and their buffer zones in Nepal. The land cover map highlights the Terai region of Nepal, showing its connection to other protected areas within Nepal and India. Map generated using QGIS version 3.28 (<https://qgis.org>); Land cover data⁸⁷; protected areas in Nepal⁸⁸; Indian PAs: Protected Planet (<https://www.protectedplanet.net/country/IND>); administrative boundaries: GADM (<https://gadm.org>).

elephant (*Elephas maximus*)^{28,29,34,35}. Preliminary evidence suggests that HWC may be increasing⁷ possibly in association with the successful conservation outcomes in those PAs.

In this research, we utilized a decade-long dataset (2013–2022) to test the following hypotheses about HWC in BNP and CNP: (1) HWC has increased over the past decade; (2) the temporal trends in HWC incidents are associated with the population trends of megafauna; (3) the incident rates for crop species and livestock prey vary across megafauna species; (4) there is a detectable spatiotemporally-explicit pattern in HWC incidents (“hotspots”) in the PA buffer zones.

Results

Temporal trends in wildlife populations and HWC incidents

Combined across both PAs, a total of 14,989 HWC incidents was reported from 2013 to 2022 (Table 1), increasing from 1,061 in 2013 to 1,939 in 2022 (Fig. 2). Summed across both PAs, both tiger and rhino populations increased between 2005 and 2022, with tigers more than doubling from an estimated 100 to ~250 ($r=0.96$, $P<0.01$), and rhino populations increasing from 400 to more than 700 ($r=0.99$, $P<0.001$) (Fig. 3). Concomitantly, the number of reported incidents involving tigers increased from <100 in 2013 to more than 200 in 2022 (Pearson $r=0.78$, $P<0.01$) and incidents involving rhino increased from <100 to ~400 (Pearson $r=0.75$, $P<0.05$). Leopard incidents also increased from <300 to more than 600 ($r=0.80$, $P<0.01$) (Fig. 3). Elephant incidents, on the contrary, showed a declining trend over the 10 years, although there was no statistically significant trend owing to high interannual variation (Fig. 3).

When analyzed by site, in Bardia tiger populations increased steadily from approximately 60 to over 120 individuals between 2005 and 2022 ($r=0.75$, $P<0.01$), while rhino populations remained relatively stable over the same period (Fig. 3). Also, reported incidents involving tigers and leopards exhibited significant increasing trends ($r=0.70$ – 0.75 , $P<0.05$), whereas rhino and elephant-related incidents showed a declining trend. In Chitwan, both tiger and rhino populations showed strong positive increases, with tiger numbers rising from ~30 to over 100 ($r=0.82$, $P<0.01$), and rhino from ~400 to nearly 700 ($r=0.99$, $P<0.001$). In addition, incidents involving rhinos and leopards increased significantly ($r=0.83$, $P<0.001$ and $r=0.79$, $P<0.001$ respectively), while tiger-related incidents showed non-significant increase, and elephant incidents remained stable with no discernible trend (Fig. 3).

Temporal trends of HWC incidents differed across incident types and between Bardia and Chitwan Parks (Fig. S1). Average annual crop raiding rates were similar between the two sites (424.9/year in Bardia and 388/year in Chitwan). They increased significantly over time in Chitwan but showed no temporal trend in Bardia. At both sites, livestock depredation increased significantly over the 10 years, although the average annual rates were

Incident type	Damage	Bardia	Chitwan	Total	Percent
Crop raiding	Paddy	1848	2075	3923	48.3
	Wheat	1273	755	2028	24.9
	Maize	956	554	1510	18.6
	Mustard	72	297	369	4.5
	Others	93	171	264	3.2
	Banana	7	26	33	0.4
	Millet		2	2	0.0
	Total	4249	3880	8129	
Livestock depredation	Goat	2172	637	2809	60.9
	Pig	736	35	771	16.7
	Cattle	523	180	703	15.2
	Buffalo	70	95	165	3.6
	Sheep	153	4	157	3.4
	Fowl	5		5	0.1
	Rabbit	1		1	0.0
	Total	3660	951	4611	
Human attack	Injury	76	301	377	74.5
	Death	41	88	129	25.5
	Total	117	389	506	
Property damage	House	1360	328	1688	96.8
	Livestock shed	17	30	47	2.7
	Vehicle	4		4	0.2
	Water tank		4	4	0.2
	Total	1381	362	1743	
Grand total		9407	5582	14,989	

Table 1. The number of human attack, livestock depredation, crop raiding, and property damage incidents by wildlife from 2013–2022 in the buffer zones of Bardia and Chitwan National Parks, Nepal.

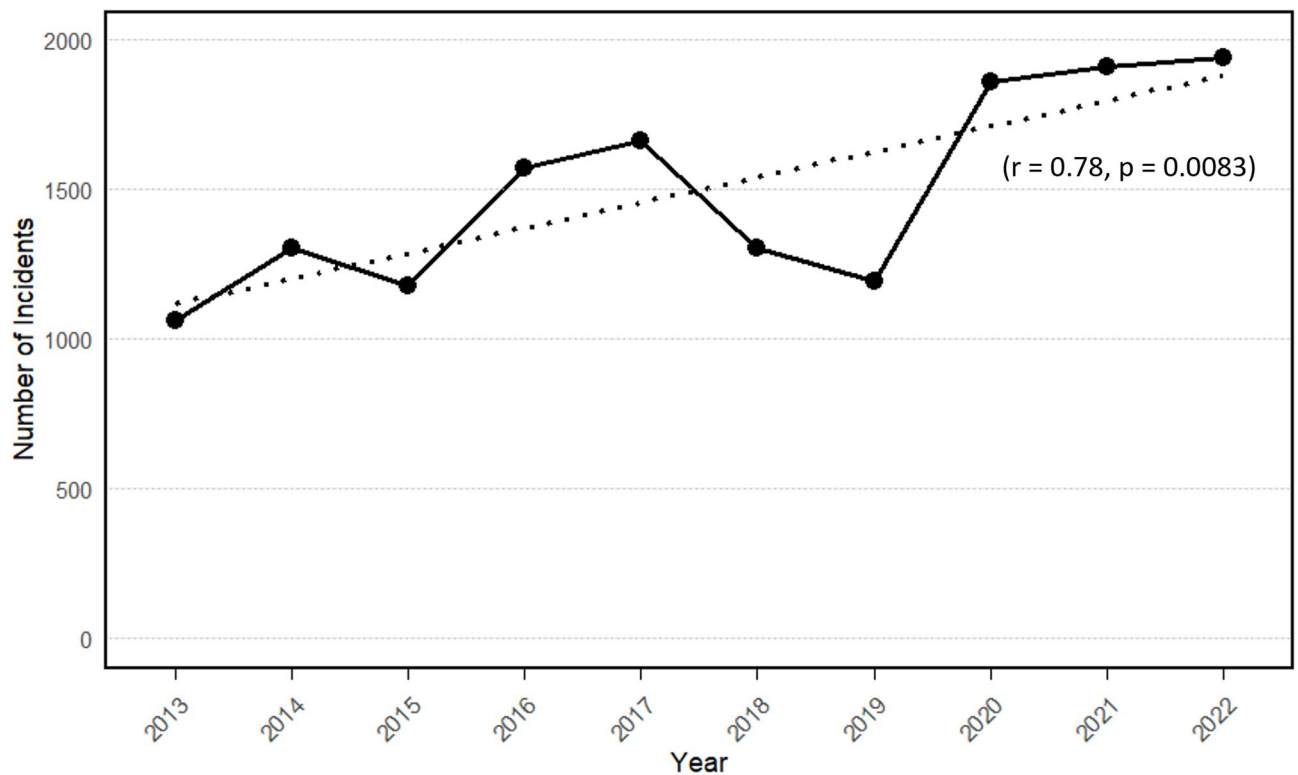


Fig. 2. Total HWC incidents reported in Bardia and Chitwan National Parks of Nepal over 10 years (2013–2022). The dotted line is the linear trend.

several times greater in Bardia as compared to Chitwan (366/year versus 95.1/year). The average rate of human attacks differed between Bardia and Chitwan, and neither PA showed any temporal trend in this HWC incident type. Property damage showed a significant decline in Bardia, whereas Chitwan had very low annual rates of property damage and no trend.

Species-specific incident dynamics

Seven wildlife species were involved in four incident types (Fig. 4). The most common incident type was crop raiding ($n=8,129$), especially of paddy rice (48.3%), wheat (24.9%) and maize (18.6%) (Table 1). Elephants were responsible for 56.1% of crop-raiding incidents, with the remainder of raids evenly split between rhino and wild boar (Fig. 4). The crop raiding frequency was variable across these three species: while elephants mostly raided paddy, which accounted for 68% of their raids (Fig. 5a), rhino mostly raided wheat followed by paddy, and wild boar mostly raided maize, followed by wheat and paddy (Fig. 5a).

There were 4,611 incidents of livestock depredation, dominated by goat predation (60.9%) followed by pig (16.7%) and cattle (15.2%) predation (Table 1). Livestock depredation was largely attributable to leopards (>75%) (Fig. 4), which strongly preferred goats, with the remainder of wildlife depredation due to tigers, which preferred cattle over goats (Fig. 5b). Buffalo, which are very large prey, accounted for less than 15% of all predation cases, and very small prey such as rabbits and fowl, which are kept in enclosures, were rarely preyed upon (Table 1).

Among the four reported incident types, human attacks were the least frequent ($n=506$), with fatalities occurring in 26% of incidents (Table S1). Seven wildlife species attacked humans, with rhino accounting for 31.8% of all cases, followed by elephant (21.5%) and tiger (17.3%) (Fig. 4). Mortality from wildlife attack varied greatly depending on the wildlife species encountered: 45% percent of encounters with tigers and elephants and 19.9% of encounters with rhino resulted in a human fatality (Table S1).

Elephants were involved in all 1,743 property damage incidents, and they were also the only species involved in three types of incidents (Table 2). Of the property damage incidents, 96.8% involved damage to housing, likely because the animals were seeking stored food (e.g. harvested rice) within the structure (Table 1).

Conflict hotspots and spatial heterogeneity of HWC incidents

The cumulative incident density in Bardia (range: 30.5–163 km^{-2} ; mean $\pm$ SE = 79.97 $\pm$ 15.99 km^{-2}) was notably higher than in Chitwan (range: 7.6–88.2 km^{-2} ; mean $\pm$ SE = 20.31 $\pm$ 3.96 km^{-2}) (Table S2). Spatially, the hotspot wards of incident densities accounted for 14% of buffer zone area (8 wards) in Bardia and 25% of the buffer zone area (20 wards) in Chitwan (Fig. 6a). The hotspot wards in Bardia were clustered in the southwestern sector of the buffer zone, and in Chitwan there was a cluster along the southern border along with scattered wards along the northern buffer (Fig. 6a). When stratified by megafauna species, some regions or wards showed particularly high density of conflict: tigers and leopards had high incident densities in the NW buffer zone of Bardia and

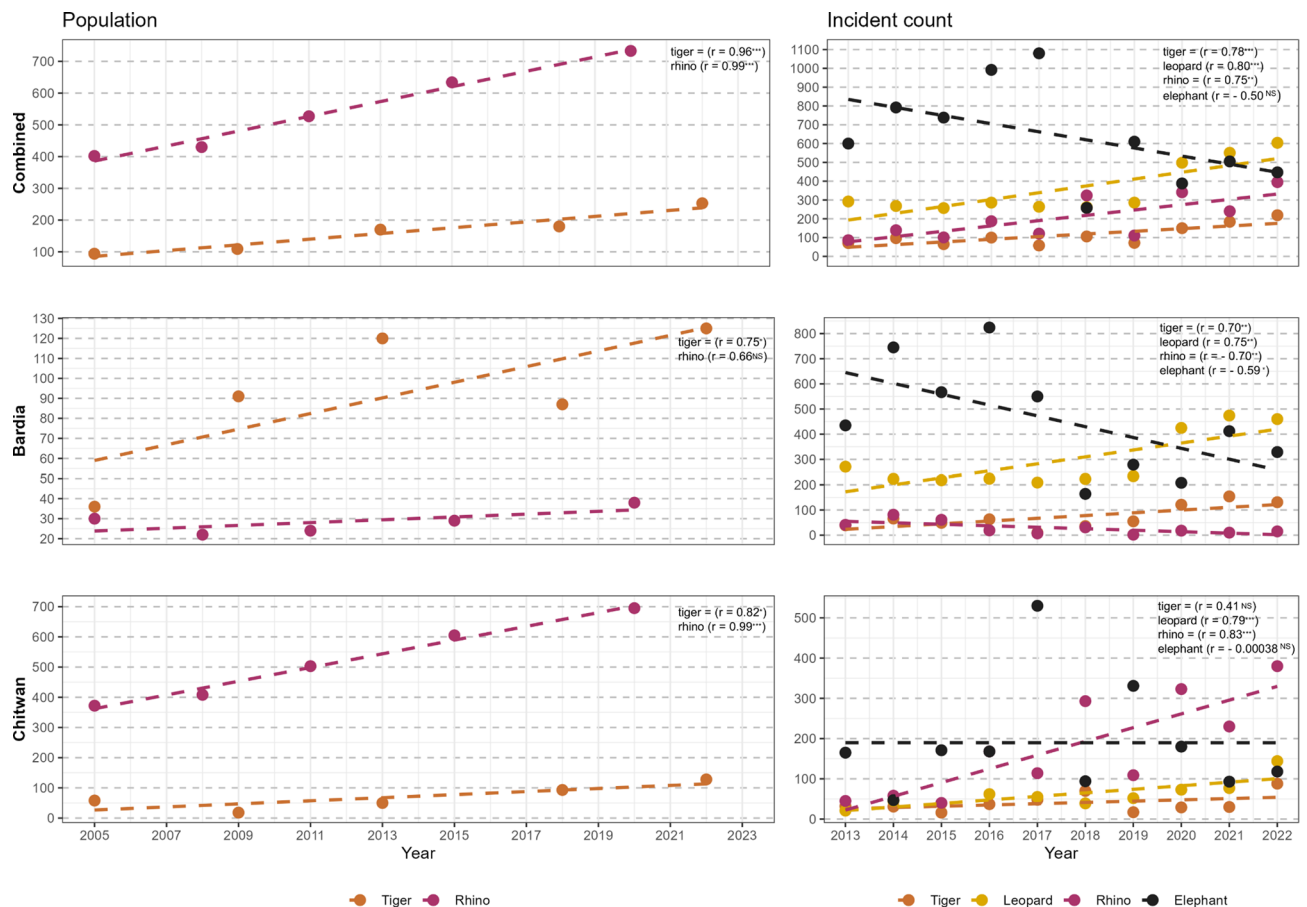


Fig. 3. Trends in rhino and tiger populations combined across both sites, and separately for Bardia and Chitwan (left), alongside reported incident counts caused by four megafauna species over the decade 2013–2022, combined and separately for Bardia and Chitwan (right). The significance level for correlation between population or incidents and year is denoted by 'NS', '*', '**', and '***' which represent non-significant, 90%, 95%, and 99% significance levels respectively. Sources of data for left panels are:^{76,77,83–85}.

scattered wards of high incident rates for leopards around Chitwan (Fig. 6b). On the contrary, elephants and rhinos showed strong clustering of hotspots in SW Bardia and in the southern buffer of Chitwan (Fig. 6b).

Discussion and recommendations

In this study, we found a significant positive correlation between rhino and tiger population estimates and the number of incidents reporting their involvement. Overall, conservation intervention in both Bardia and Chitwan has increased tiger population estimates from approximately 100 to 250, and for rhino from 400 to over 700 between 2005 and 2022^{34,36}. Correspondingly, the number of incidents involving tigers increased from 71 to 219, and those involving rhinos increased from 86 to 395 between 2013 and 2022. Site-specific results are also consistent with population-incident trend associations except for rhino in Bardia. Thus, while conservation policies, and government and local community efforts have led to the recovery of globally important megafauna in Nepal's PAs, this case highlights the significant long-term challenges of managing such conservation gains, viz. rising wildlife populations and the associated increase in HWC. The challenge extends beyond tiger and rhino, however: though Nepal lacks official census data for leopards (a co-habiting species with tiger), the sharp rise in livestock depredation (less than 300 to over 600 in the last decade 2013–2022) suggests that their numbers have also grown. As megafauna populations grow, they may reach or exceed the carrying capacity of a PA, especially when crops and livestock supplement their diets. This increases competition for limited habitat and resources, pushing megafauna into settlement areas and potentially leading to more HWC incidents^{37,38}. Consequently, higher losses (e.g. of high-value livestock) can foster negative attitudes towards wildlife conservation and raise concerns about the sustainability of conservation efforts³⁹.

In contrast to rising conflict trends involving tiger, rhino and leopard, we observed a declining trend in elephant-related conflict incidents in our study. This decline likely reflects the seasonal and transboundary movement patterns of elephants^{40,41} which migrate between Nepal and adjoining Indian protected areas, including Katarniaghat Wildlife Sanctuary and Valmiki Tiger Reserve (Fig. 1). Their sporadic presence in the study area may lead to fewer conflict reports in certain years. Additionally, field observations and discussions with local people in Bardia indicated that reinforced concrete fences prevented elephants from entering settlements along

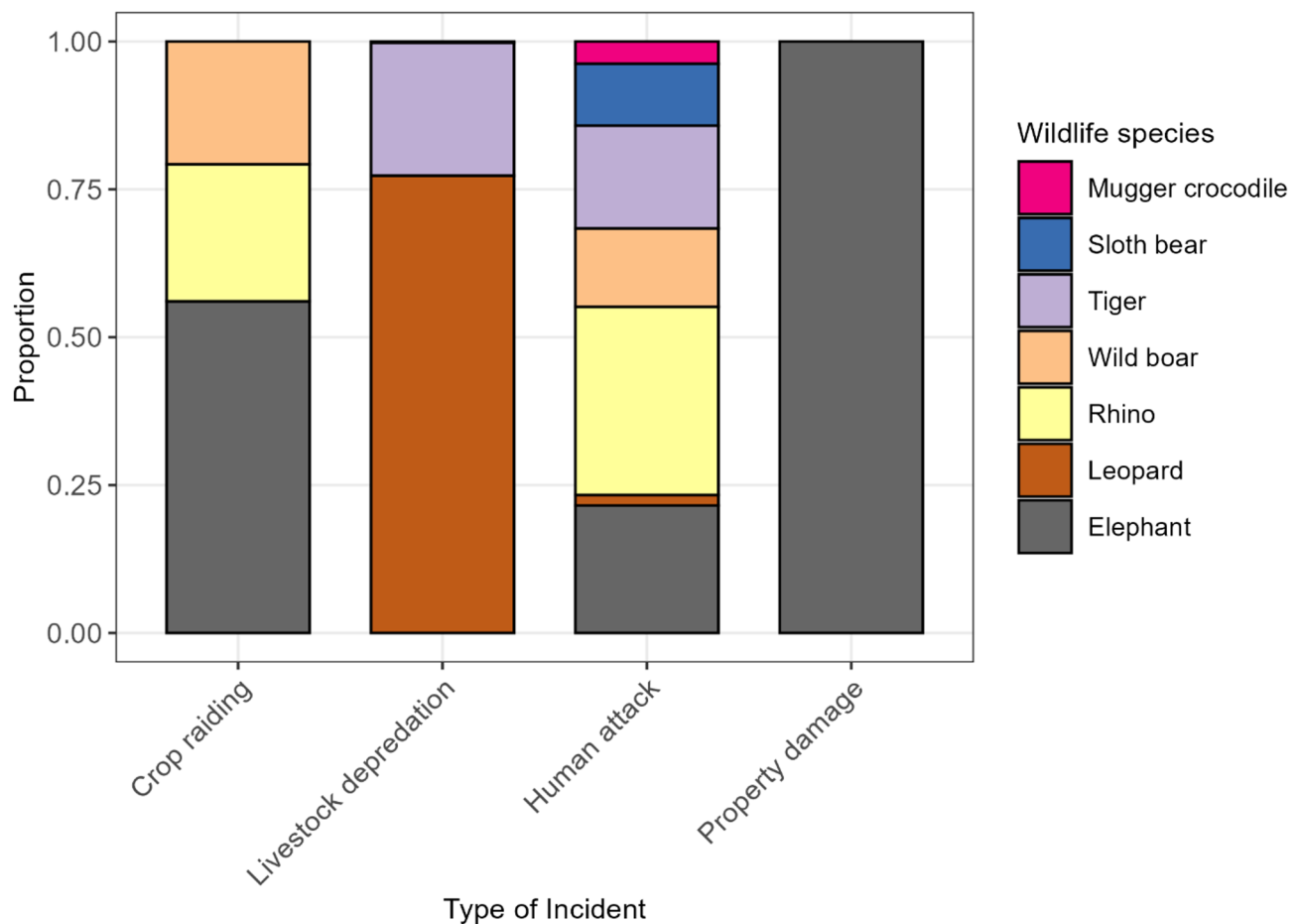


Fig. 4. Proportion of contribution of wildlife species to conflict incidents in Bardia and Chitwan National Parks.

with community-based initiatives, including the mobilization of rapid response teams and awareness programs like “*Hatti Mero Sathi*”. These initiatives may have contributed to the decline in property damage incidents in Bardia, in contrast to Chitwan, where such incidents did not decline. However, to better understand the elephant movements and associated incidents, we recommend real-time migration tracking along transboundary routes. In addition, further studies are required to evaluate the effectiveness of concrete fences and community-based initiatives in the study area.

When comparing the two sites, Chitwan had a higher number of human attacks, while Bardia had more crop raiding and livestock depredation cases (Fig. S1). This may be due to differences in wildlife population densities. Chitwan holds over 90% of Nepal’s rhino population, and rhino were responsible for the highest proportion of human attacks combined across both PAs (Fig. 4), likely reflecting higher human attacks due to their high local abundance in Chitwan. In contrast, there was higher livestock depredation and crop damage in Bardia, possibly due to greater densities of leopards and elephants. Leopards, which caused the majority of livestock losses (Fig. 4), were reported to depredate livestock about seven times more frequently than tigers in Bardia⁴². Additionally, tiger density in Bardia ($7.15/100 \text{ km}^2$) exceeds that of Chitwan ($4.06/100 \text{ km}^2$)⁴³ possibly indicating higher densities of coexisting leopards because in prey-rich areas like Bardia, leopards can coexist with tigers through spatial or dietary partitioning⁴⁴. Similarly, Bardia’s estimated resident elephant population—reported to be more than double that of Chitwan—may explain the higher frequency of elephant-related crop damage observed in Bardia⁴⁵. Despite these differences, HWC was found to be increasing on both sites.

To address the conservation success challenges, key conservation efforts should be focused on habitat expansion outside PA boundaries through habitat restoration, particularly in buffer zones and biological corridors⁴⁶. Past studies demonstrate that prey densities are lower in corridor forests outside protected areas compared to core zones⁴⁷. In addition, previous studies from both Nepal and other regions have documented that conservation efforts such as maintaining habitat connectivity through forest corridors and protecting remnant forest patches have facilitated habitat use by megafauna not only within protected areas but also in human-modified landscapes outside these boundaries^{48,49}. Restoring habitat outside protected areas can increase forage availability during resource-scarce periods, which may reduce megafauna reliance on agricultural lands and decrease crop raiding incidents. Additionally, enhancing prey density outside PAs may help reduce large carnivore (e.g. tiger and leopard) movements into human-dominated landscapes⁵⁰. In Nepal’s Terai, WWF has

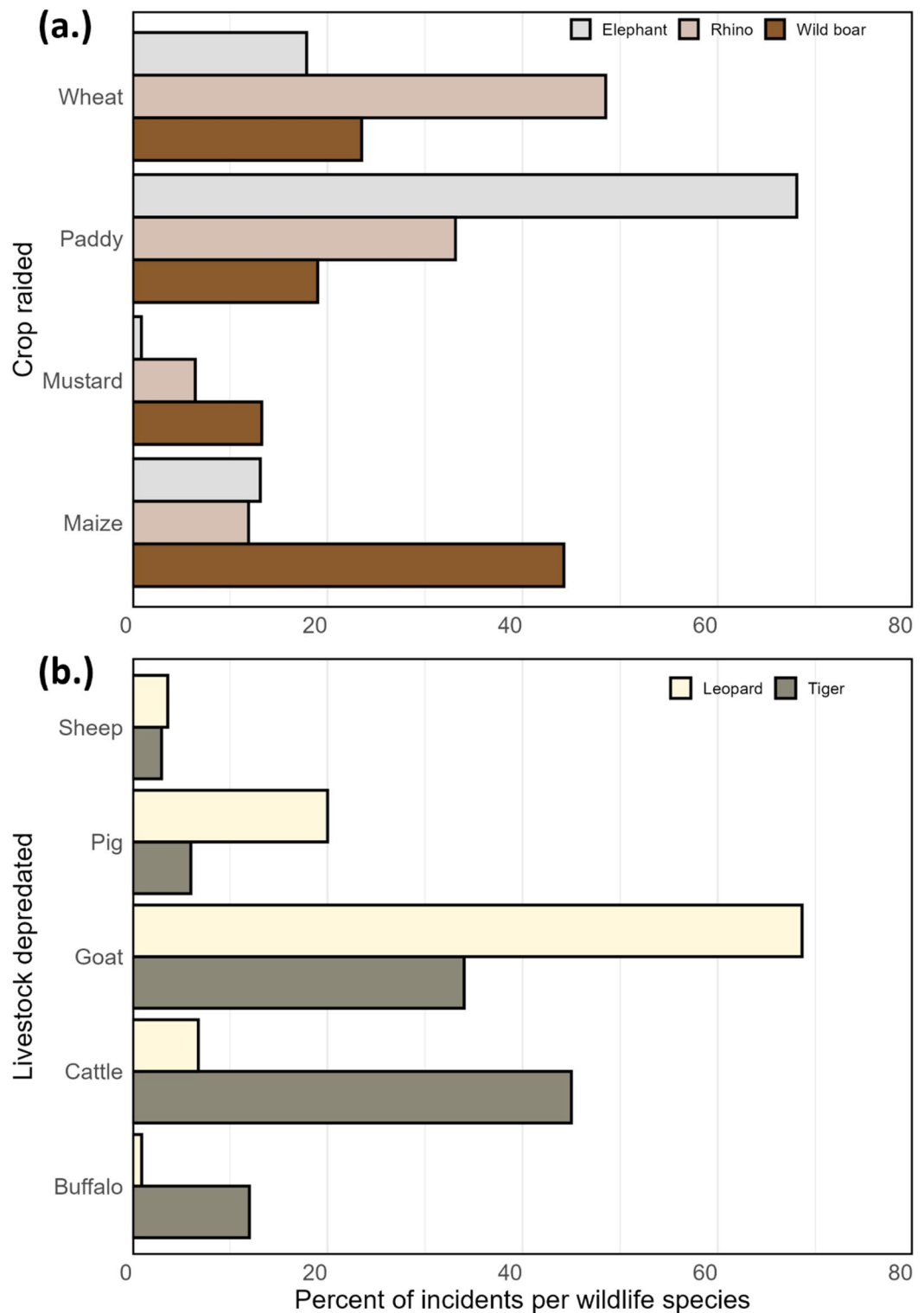


Fig. 5. (a) Incident rates involving crop types by elephant, rhino, and wild boar. (b) Incident rates involving livestock types by leopard and tiger.

initiated habitat restoration activities in buffer zone forests⁵¹ and expanding those efforts will further benefit megafauna with large home ranges. Afforestation or reforestation of corridors can effectively connect with protected areas, facilitating the movement of megafauna between PAs, including across borders, which will also contribute to increasing carrying capacity of a particular PA⁵². For example, in Nepal, protecting and effectively managing the Khata Corridor and forests surrounding Bardia could enhance the frequency of megafauna movement between Bardia and India's Katarniaghat Wildlife Sanctuary. Similarly, safeguarding the Shikaribas

Species	Crop Raiding		Livestock Depredation		Human Attack		Property Damage		Total	Percent
	BNP	CNP	BNP	CNP	BNP	CNP	BNP	CNP		
Elephant	3078	1480			54	55	1381	362	6410	42.8
Leopard			2959	600	2	7			3568	23.8
Rhino	270	1614			15	146			2045	13.6
Boar	901	786			13	54			1754	11.7
Tiger			696	338	28	60			1122	7.5
Sloth bear					5	48			53	0.4
Mugger crocodile			2	8		19			29	0.2
Not identified			3	5					8	0.1
Total (all species)	4249	3880	3660	951	117	389	1381	362	14,989	

Table 2. Number of incidents by each wildlife species from 2013–2022 in Bardia and Chitwan National Parks, Nepal.

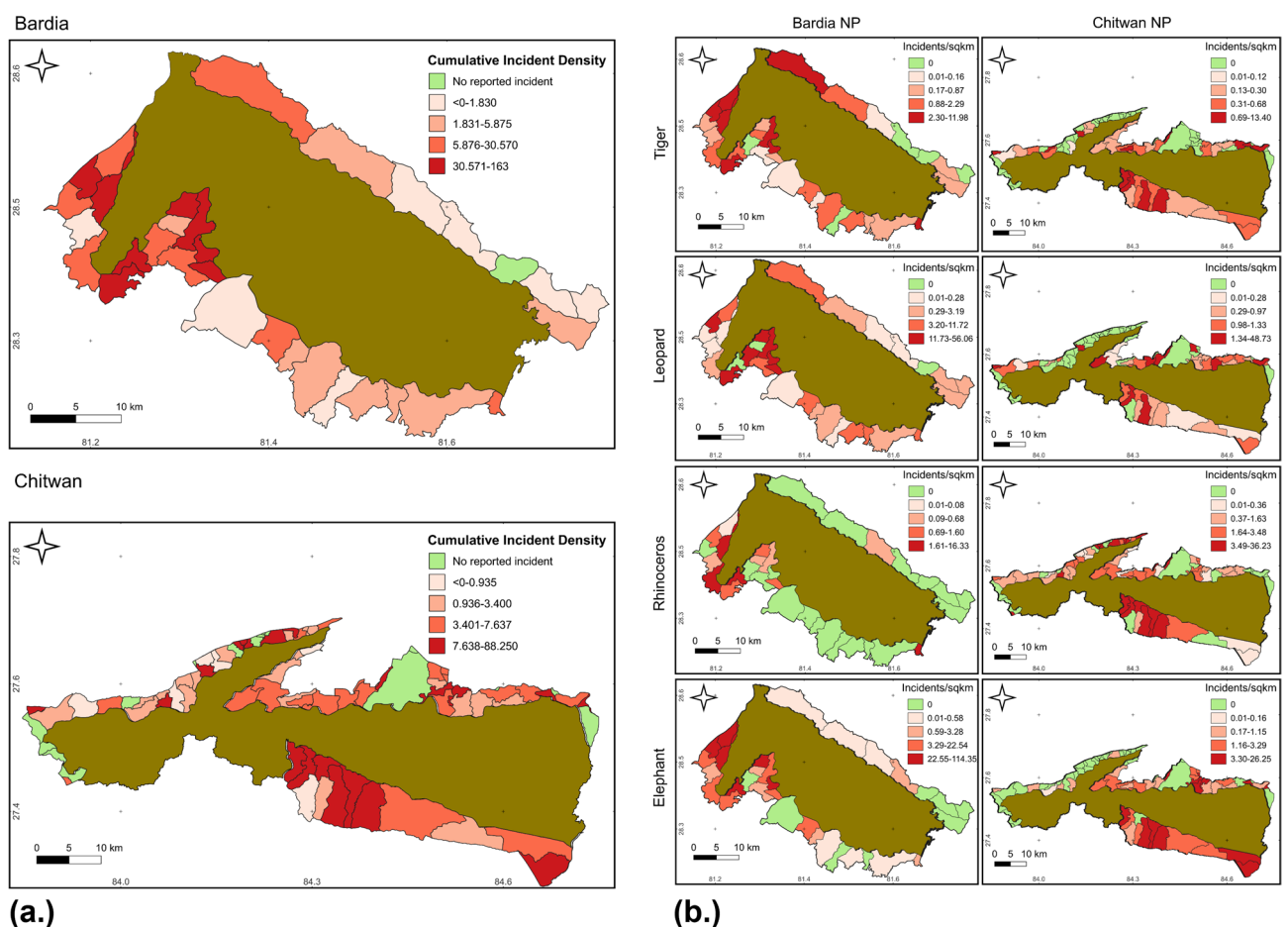


Fig. 6. (a) Spatial distribution of cumulative incident density across wards in the buffer zones of Bardia and Chitwan National Parks, caused by four megafauna species (tiger, leopard, rhino, and elephant). (b) Species-specific incident density (number of incidents per square kilometer) by ward. Each polygon within the buffer zone represents a ward—the smallest administrative unit in Nepal. Dark red polygons indicate conflict hotspots, green polygons indicate no reported incidents (“0”), and brown represents the core protected areas. Breaks were defined using the “classInt” package in R with the “quantile” method⁸⁶. Map generated using QGIS version 3.28 (<https://qgis.org>); Protected area boundaries⁸⁸; administrative boundaries of Nepal: Open Data Nepal [<https://opendatanepal.com/dataset/nepal-municipalities-wise-geographic-data-shp-geojson-topojson-kml>]. This map figure was made by BN (first author).

Corridor would enhance connectivity between Chitwan and India's Balmiki Tiger Reserve. This connectivity is also essential for maintaining genetic diversity and ensuring the long-term sustainability of species⁵². It is recognized, however, that by increasing habitat area and connectivity outside of PAs, there is the likelihood that HWC will be exported further afield from the PAs themselves, as wildlife populations expand into those new habitats and corridors². Thus, additional interventions need to safeguard lives and property of rural residents as wildlife populations continue to expand.

Beyond habitat expansion through restorations, species-specific conflict rates by crop and livestock type should be considered to effectively mitigate losses to crops and livestock. For example, understanding the feeding frequencies of wildlife species is crucial for designing mitigation measures. We found that certain herbivorous megafauna species raid particular crop more frequently than others: while elephants raid paddy rice more often than other crops, rhinos raid wheat, and wild boar raid maize more often than other crops. Further, our results revealed the intra-annual or monthly patterns of crop raiding for these three major crops, highlighting their distinct peak raiding periods (Figure S2). Previous studies have also reported that elephants tend to raid paddy fields during the peak harvesting period (Sept–Nov) in the Terai, when the paddy is most nutritious and palatable⁸; see also^{53,54}. Rhinos, on the other hand, target wheat during young and intermediate growth stages^{55,56} which in the Terai is Dec–Feb, when less forage is available in the natural habitats. Wild boar was found to raid maize during the maturing stage when it is ripe and easily digestible⁵⁷. In our study, we did not use camera traps and telemetry to assess the species-specific habitat uses or ranging patterns of megafauna involved in conflicts. Thus, understanding wildlife behavior—such as why certain crop types are preferred over others—remains a critical research need. However, the temporal raiding patterns shown by our study can be addressed efficiently through temporal deterrent strategies. For example, community-based guarding activities involving watchtowers (Machans) during peak seasons of crop raiding can be an effective and low-cost solution for protecting crops from wildlife⁵⁸, especially when local governments and organizations employ local people for such guarding activities. From our field observations and evaluations, this mitigation approach would be more affordable than fencing and could both enhance crop security and provide livelihood support for low-income and unemployed individuals in buffer zone communities.

Livestock depredation is a function of both the ecological niche of the predator, as well as the availability of preferred prey species. Leopards depredate mostly goats (see^{59–62} and tiger attack larger-sized prey species (cattle) (see^{63–65}). In the buffer zones of Bardia and Chitwan, most livestock depredations occurred in livestock sheds rather than in grazing lands and forests^{7,66}, which suggests that the type of shed structures can mitigate predation risk. Cattle are typically kept in open or unprotected sheds with minimal or no walls, making them more vulnerable to tiger attacks. In contrast, goats and sheep are usually kept in closed sheds, constructed from traditional materials such as brittle wood and bamboo, or more sturdy materials like hardwood and gabion wire, which are considered “predator-proof” (see Fig. S3). An obvious remedial measure would be to build protective structures (predator-proof sheds) for the livestock. However, while buffer zone programs receive government support (30–50% of park revenue) along with grants and subsidies from conservation organizations, only a small portion (13.7%) of this budget was allocated to HWC prevention and mitigation^{67,68}. Non-government conservation organizations have supported some households to build predator-proof sheds for small livestock in the buffer zones of Bardia and Chitwan^{51,69}. Overall, however, the support is insufficient to meet the needs of all victims affected by livestock depredation, especially those of lower-income households who struggle to afford mitigation measures. Thus, increased funding and support for construction of predator-proof sheds is required from both the government and conservation organizations⁷⁰.

Combined with habitat restoration and species-specific mitigation, a conflict hotspot-based management strategy could contribute to enhanced HWC mitigation. The southwestern sector of Bardia and the southern region of Chitwan have emerged as conflict hotspots, characterized by overlapping conflicts involving multiple species. The movement of megafauna from protected areas of India connecting to the southern region of Bardia and Chitwan through corridors may be the cause of spatial overlap of incident hotspots⁷¹. The connectivity provided by wildlife corridors, such as the Khata Corridor from the Katarniaghat Wildlife Sanctuary and the Shikaribas Corridor from the Valmiki Tiger Reserve, facilitates movement between habitats, increasing the pressure in conflict zones in both PAs^{72,73}. We also found higher incident rates involving tigers and leopards in the northern buffer zone of Bardia, and higher incident rates scattered along the northern Chitwan, specifically for leopards. This pattern can be associated with livelihood strategies of local people. Based on our fieldwork in Bardia, we observed that the northern region of Bardia exhibited a high concentration of livestock holdings, which might contribute to an increased frequency of livestock depredation by tigers and leopards⁶⁶. However, detailed studies are required to further understand the relationship between the density of livestock and predation risk. Besides, studies have reported that seasonal trans-border migratory movements of elephants can cause damages to crop and property^{40,41} so the clustering of their conflict hotspots in SW Bardia and the southern buffer of Chitwan may result from their migration from Indian's PAs. We recommend fine-scale research to understand megafauna movement and damage patterns in corridors and buffer zone forests.

Given the variable, but ever-present, risk of wildlife predation throughout the buffer zone, the broader adoption of community insurance could be a relevant strategy for buffer zone households. Insurance is currently adopted by only a few commercial livestock farmers in buffer zones. Our informal interviews and discussions with local stakeholders during fieldwork revealed that the widespread adoption of insurance by households has been limited by unaffordable annual premiums. Research should investigate the potential to create a spatially explicit community-based, multi-stakeholder insurance compensation model to compensate for high-value crop and livestock losses by wildlife (see⁷⁴). Stakeholders include local governments, park authorities, Buffer Zone User Committees (BZUCs), and conservation organizations such as WWF, NTNC (National Trust for Nature Conservation), and ZSL (Zoological Society of London), all of which have been supporting mitigation efforts in

the study area. To mitigate the high premiums, policy can further consider levying fees on ecotourism to help fund community-based insurance or relief from livestock depredation.

In conclusion, our study highlights the need for balancing conservation success and mitigation of HWC in rural communities. We provide the first quantitative association between wildlife population estimates and HWC for tigers and rhinos, suggesting that this trend is likely to be experienced where megafauna populations are rebounding or restored. Further, our work strengthens the call for greater attention on habitat expansion through restoration outside the protected areas in the buffer zones and corridor forest, which can help to extend wildlife habitat and enhance connectivity of populations, thus increasing carrying capacity and potentially mitigating HWC in the short term. In addition, mitigation must be enhanced: cost-effective community-based mitigation measures should be implemented in the peak raiding periods and predator-proof sheds are important to save the large livestock with high market value. Additionally, establishing community-based, multi-stakeholder livestock insurance schemes, is required in conflict hotspots to optimize resources and mitigate HWC impacts, which will secure the long-term conservation efforts.

Methods

Study area

The study was conducted in the buffer zones of BNP (28° 15' to 28° 35.5' N and 80° 10' to 81° 45' E, established in 1988 with an area of 968 km² and CNP (27° 16.56' to 27° 42.14' N and 83° 50.23' to 84° 46.25' E; established in 1973 with an area of 953 km² (Fig. 1). Both protected areas lie within the Terai Arc Landscape (TAL) of the tropical lowland (Terai) region of Nepal, a priority landscape for tiger conservation^{29,30}. The Terai region has a subtropical climate characterized by a mean annual temperature range of 20–28 °C and annual rainfall of 1500–2000 mm⁷⁵. The dominant forest type of lowland Terai is dry seasonal Sal (*Shorea robusta*) forest followed by riverine forest and mixed hardwood forest. Both protected areas have similar vegetation, landscape features, and rich biodiversity including several threatened megafauna species of global concern like Royal Bengal tiger (*Panthera tigris tigris*), common leopard (*P. pardus*), Asian elephant (*Elephas maximus*), and one-horned rhino (*Rhinoceros unicornis*), etc. These megafaunas have been frequently involved in HWC incidents within the buffer zones^{7,9,19}. There is a high human population density within the buffer zone with the record of 263 people km⁻¹ in BNP and 297 people km⁻¹ in CNP^{76,77}. BNP lies within the western region and is connected to the Katarniaghat Wildlife Sanctuary in India via the Khata corridor, ungazetted national forest, and community forests⁷². CNP lies within the central region of Nepal and is connected to the Balmiki Tiger Reserve of India via the Shikaribas corridor (Fig. 1)⁷³. Each buffer zone is subdivided into wards, which is the smallest unit of local government in Nepal. Within the two buffer zones, agriculture is a major livelihood strategy. In the Terai region, the primary crops cultivated include paddy, wheat, maize, and mustard for both subsistence and commercial use⁷⁸. Major livestock raised by local communities include goat, sheep, pig, cattle, and buffalo, primarily for milk, meat, manure, and draught power⁷⁹.

Data collection

After obtaining the research permit from the Department of National Parks and Wildlife Conservation (DNPWC), Nepal, we visited the central offices of BNP and CNP in January 2023 to obtain the park-specific research permits. These permits allowed us to access the records of the respective PA while adhering to the protocols and guidelines of the National Park and Wildlife Conservation Act 1973⁸⁰.

We reviewed and extracted data from the relief claims of victims, a method that has been employed in similar studies investigating HWC^{7,81}. Each PA headquarter or main office (Thakurdwara in BNP and Kasara in CNP) has a “Buffer Zone and Monitoring Section” for collecting claims of wildlife victims and processing them for the distribution of relief funds. Victims must file their relief claims within 35 days of the incident occurrence for the approval of processing their paper-based relief claim applications⁸². Between January and April 2023, we gathered all the paper-based relief claims from 2013 to 2022 from the PA central offices. We then entered all claims into a database and classified each claim into one of the four main types of HWC incidents recognized by the PA main offices: human attack, livestock depredation, crop raiding, or structural property damage. From each incident type, we recorded the victim's municipality and ward number, the damage or loss, the wildlife species involved, and the date of occurrence. Since our study focused on officially reported relief claims, it does not capture unreported cases of human fatalities and livestock depredation occurring within national park boundaries. Additionally, it excludes crop-raiding incidents on public lands cultivated by landless communities, who are ineligible for government relief under the current legal provisions.

We also obtained population census data of tigers and rhinos from the annual reports of BNP and CNP, species conservation action plans for tigers and rhinos, and relevant literature^{76,77,83–85}. These two megafauna species (tiger and rhino) are the only ones for which periodic population censuses are conducted within our two study sites.

Data management and analysis

We quantified the total number of HWC incidents by species and by incident type across all years. Within each incident type the livestock species killed, crop species damaged, human casualty and injury incurred, or property damaged was further identified. A Pearson correlation was applied to both the tiger and rhino populations over time, to test for association between population estimates and the number of reported incidents. Similarly, a correlation test was run on the number of HWC incidents across years for leopard and elephant. We also computed incident density (no. incidents/km²) in each buffer zone ward for tiger, leopard, rhino, and elephant. Then, we joined a table of cumulative incident density of these four megafaunas for each ward to the shapefile of the ward. We defined the breaks for cumulative incident density using the “classInt” package in R, using the “quantile” method⁸⁶. Conflict hotspots were defined as those wards in the top quantile, i.e. those with the

highest density of incidents involving four megafauna species³. These spatial analyses were conducted using QGIS version 3.22. We adhered to the data storage and management protocols established by DNPWC, Nepal, and the University of Helsinki, Finland.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available to protect the anonymity of individuals affected by wildlife incidents but are available from the corresponding author upon reasonable request.

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Author contributions

Conceptualization and methodology design – B.N. and E.L.W.; Data collection, material acquisition, and data curation – B.N.; Data analysis and visualization – B.N., J.J., and E.L.W.; Writing – original draft – B.N.; Supervision (lead) – E.L.W.; Writing – review and editing – led by E.L.W., with equal contributions from J.J., A.P.G., D.S. and N.J.H.; Funding acquisition – B.N.; Finalization and approval for submission – all authors.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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