The peri-urban leopards of Kathmandu: assessing determinants of presence and predation on domestic animals

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Abstract The conservation of large carnivores in human-dominated landscapes needs to be reconciled with the safety of humans and domestic animals. This is especially true for the leopard *Panthera pardus*, which occurs extensively in agricultural landscapes and remnant forest tracts embedded within peri-urban areas such as Kathmandu district in Nepal. We carried out interviews in 321 households in this district to determine the extent of leopard habitat use and predation on domestic animals (dogs and goats) during October 2015–April 2016. We used multi-state occupancy models, and estimated probabilities of leopard habitat use (Ψ_1) and predation on domestic animals (Ψ_2) as a function of covariates, while accounting for imperfect detection. Our findings indicate that the rapidly urbanizing outskirts of Kathmandu city are used extensively by leopards. The estimated probability of fine-scale habitat use in 2 km² sample units was $0.96 \pm SE\ 0.05$ and the probability of predation on domestic animals was $0.76 \pm SE\ 0.15$. Leopard attacks occurred in areas with high vegetation cover and abundant goats. Addressing the problem of leopard attacks on domestic animals will require developing a comprehensive mitigation plan that includes educational activities to raise awareness, measures to address grievances of affected local communities, interventions to prevent attacks on livestock, compensation programmes, and rapid response teams to ensure human and animal welfare in conflict-prone areas. Land-use planning in these peri-urban landscapes needs to facilitate the safe sharing of space between people and leopards.

Keywords Carnivore conservation, habitat use, human–leopard conflict, Kathmandu, leopard, occupancy models, *Panthera pardus*, urban wildlife

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Introduction

Humans and large carnivores co-occur extensively where urban areas expand into or surround wildlife habitats (Zérah, 2007). Although large mammals do not always persist in areas with high anthropogenic pressure (Woodroffe, 2000; Ripple et al., 2017), they sometimes adapt to human-modified habitats including the edges of populous towns and farmlands, often sheltering, feeding and breeding in such areas (Gehrt, 2007; Beckmann & Lackey, 2008; Bateman & Fleming, 2012; Athreya et al., 2014; Odden et al., 2014). The conservation of large carnivores presents a conundrum for wildlife managers and local administrators who are tasked with protecting wildlife and ensuring the safety of local communities (Allendorf, 2010). This task is especially challenging when carnivores occur on privately owned land (Enserink & Vogel, 2006), where there is an elevated risk of negative interactions with people (Nyhus & Tilson, 2004).

The leopard *Panthera pardus* commonly occurs in close proximity to human settlements (Odden & Wegge, 2005; Odden et al., 2014). There are many drivers for leopard occurrence in human-dominated landscapes, including habitat fragmentation, wild prey depletion, attraction to domestic animals as easy prey and competitive displacement as a result of inter- or intra-species interactions (Seidensticker, 1976; Odden et al., 2010; Ripple et al., 2014). Several studies show that home ranges of leopards sometimes overlap partially or completely with human-use areas (e.g. Odden et al., 2010, 2014), which is facilitated by the species' dietary plasticity. Leopards readily adapt to prey on domestic animals, particularly dogs, which may comprise as much as 70% of their diet (Karanth & Sunquist, 2000; Edgaonkar & Chellam, 2002; Dickman & Marker, 2005; Athreya et al., 2014; Kumbhojkar et al., 2020).

Predation of domestic animals by leopards is common across many Asian and African range countries (Kissui, 2008; Dar et al., 2009; Khorozyan et al., 2017; Kshettry et al., 2017). Such predation, especially on livestock, causes economic losses (Dar et al., 2009), can affect the livelihoods and social well-being of people (Barua et al., 2013; Kshettry et al., 2018), engenders negative attitudes of people towards carnivores (Megaze et al., 2017) and may catalyse retaliatory killing by poisoning or other means (Ogada et al., 2003).

In Nepal, human–leopard conflict is a serious issue (Acharya et al., 2016). Adverse interactions with humans

are more likely when leopards occur in densely populated peri-urban areas (Soulsbury & White, 2016), such as Kathmandu district. Inclusive of Kathmandu, the country's capital city, this district has a population of > 1.7 million people, with a population density of 4,416 people/km² (25 times higher than the national average; CBS, 2014). The city and its suburbs are surrounded by montane forests, most notably the Shivapuri-Nagarjun National Park and National Forest, which supports a leopard population (Pokharel, 2015). Leopards sometimes enter human settlements, including the fringes of Kathmandu city, and are subsequently captured and translocated to zoos or released back into the wild. Although leopards are routinely captured in the Kathmandu valley, the extent of their occurrence and predation on domestic animals has hitherto not been thoroughly investigated (Pokharel, 2015).

Here, we assessed the extent and determinants of leopard habitat use and predation on domestic animals in peri-urban areas within Kathmandu district, with the aim of assisting the Government of Nepal in devising strategies to mitigate future human–leopard conflict.

Study area

We conducted this study in 10 of 11 municipalities in Kathmandu district, Nepal (395 km²; Fig. 1). Kathmandu district is one amongst three districts located within the Kathmandu valley, and is home to > 72,000 households (CBS, 2014). The predominant land-use types are forest (42%), farmland (42%) and built-up areas (14%; Wang et al., 2020). Along with a rapid increase in the human population, urban areas expanded by 412% in the
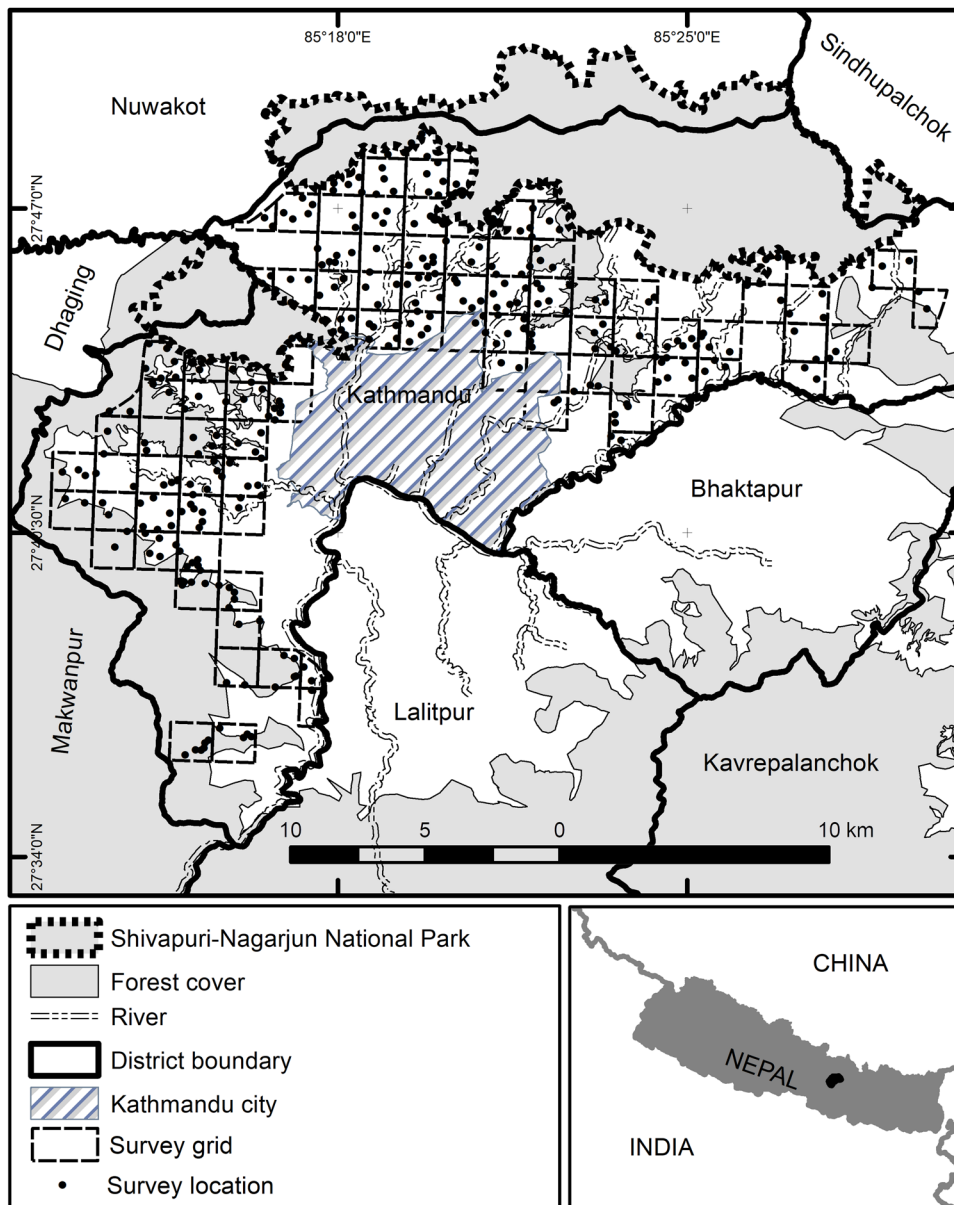

FIG. 1 Study area showing Kathmandu district, Kathmandu city and survey locations within 90 2-km² grid cells. The inset map shows the location of the study area within Nepal.

Kathmandu valley since 1989, with conversion of 31% of farmlands (Ishtiaque et al., 2017). Most communities in Kathmandu district outside the city are agrarian, with rice, wheat, maize, potato and mustard being the main crops.

The forested hills around Kathmandu district (Fig. 1) are managed by the administration of Shivapuri-Nagarjun National Park (159 km²) and the Kathmandu District Forest Office as National Forest, Community Forest and others (132 km²). These forests support diverse mammalian and avian communities. The vegetation is sub-tropical/temperate forest dominated by *Pinus* spp., *Quercus* spp. and *Castanopsis* spp. (Shrestha, 2001). These forests contribute to the provision of drinking water and clean air for the 1.7 million inhabitants of Kathmandu district, and are valuable for religious and cultural reasons (SSNP, 2017).

Methods

Interview surveys

We divided the study area into 2-km² grid cells (Fig. 1) and carried out interview surveys in 90 of these cells (sites), to collect information on leopard occurrence and predation on domestic animals. A two-member survey team was trained to undertake the interview surveys. The team interviewed 2–6 households in each grid cell during October 2015–April 2016. Following Athreya et al. (2015) and Zeller

et al. (2011), each household was treated as a discrete sampling occasion. Adult residents in each household were asked whether they had detected leopard presence or knew of leopard predation on domestic animals in the immediate neighbourhood (within c. 500 m of their home) over the past year. We only considered the immediate neighbourhood so that we could reliably assign reported predation events to individual grid cells. To avoid ambiguity regarding the identity of the predator, respondents were asked to provide clear descriptions of the species and its signs, or distinguish these from images of various carnivores and their pugmarks. We only recorded leopard presence and/or predation when respondents provided an accurate description of the species. In the case of reported depredation of domestic animals, the interviewers recorded information on the species of domestic animal, count of events and their locations. All interviews were carried out in Nepali.

Covariates and hypotheses

We collated data for a total of five covariates (Table 1). We determined the relative abundance of dogs and goats (covariates *dog* and *goat*, respectively) during field surveys and derived the other three covariates from remotely sensed data: normalized difference vegetation index (NDVI; covariate *ndvi*), Euclidean distance from the centre of the grid cell

TABLE 1 List of covariates used to model probabilities of leopard *Panthera pardus* habitat use (Ψ_1) and predation on domestic animals (Ψ_2) in Kathmandu district, Nepal.

Covariates associated with occurrence of leopards and predation on domestic animals (range)	Expected influence on habitat use Ψ_1	Expected influence on the occurrence of predation Ψ_2	Expected influence on detecting use when true occupancy state is 1 (p_1) & 2 (p_2)
Distance to forest (0–3.1 km)	Leopards are more likely to use sites close to forest, which is their primary habitat	Higher predation of domestic animals is expected closer to forests	Sites close to forest are expected to be associated with higher detection of leopard presence & predation (p_1) (p_2)
Normalized difference vegetation index (including forest & cultivated land) in human-dominated landscape (0.01–0.95)	Grids with greater vegetation cover will be associated with higher leopard presence	Sites with higher vegetation cover will have higher predation	Detection probability of leopards likely to be higher in grid cells with more vegetation
Dog abundance (0–2.5)	Leopard use is expected to be higher in sites with higher relative abundance of dogs	Sites with more dogs will have higher rates of predation	
Goat abundance (0–18.6)	Habitat use is expected to be higher in sites with higher relative abundance of goats	Sites with more goats will have higher rates of predation	
River length (0–5.0 km)	Leopards will extensively use rivers & drainage features, which provide cover, & access to food sources around human settlements	Higher rates of predation are expected in grid cells with greater cumulative length of rivers because of higher leopard presence	

to the nearest forest patch (covariate *distoforest*), and the cumulative length of rivers in each grid cell (covariate *river*). We used *ArcGIS 10.2* (Esri, Redlands, USA) for spatial analyses.

We hypothesized that dogs were likely to attract leopards to settlements (Table 1), as they are important in the leopard's diet (Edgaonkar & Chellam, 2002; Athreya et al., 2014). However, in grid cells with high dog numbers (beyond a certain threshold) we speculated that leopard predation on dogs may decline as packs of dogs are known to chase off leopards and alert people to the felids' presence (Young et al., 2011; Potgieter et al., 2015). We counted all dogs within 150 m of surveyed homes and calculated an encounter rate following Krishna et al. (2008):

$$\text{Index} = \frac{\text{No. of dogs}}{\text{No. of households surveyed in grid cell}}$$

Leopards prefer medium-sized prey (Karanth & Sunquist, 1995; Hayward et al., 2006). During interviews, we therefore recorded the number of goats kept by respondents. We then calculated a goat abundance index as described above for dog abundance. We expected high probabilities of leopard presence and predation on domestic animals in grid cells with higher goat abundance (Hayward et al., 2006; Sangay & Vernes, 2008; Table 1). In addition, we predicted that probabilities of leopard occurrence and predation on domestic animals would both decline as a function of distance to forest edge, because urban and built-up areas provide less suitable cover for leopards (Table 1). The NDVI is an indicator of green vegetation (Krishna et al., 2008), which we used as a proxy for cover. We predicted that areas with dense vegetation cover would be more likely to harbour leopards (Kshettry et al., 2017). We also predicted that cells with more vegetation cover would have higher rates of predation on goats and dogs, because leopards can remain concealed while stalking or feeding on prey (Table 1). Carnivores commonly use water courses as movement routes (Smith, 1993), and we thus expected the cumulative length of rivers in a grid cell to positively influence habitat use by leopards and predation. We expected higher detection probabilities near forests because people residing there were more likely to encounter and report leopards. We also expected that detectability would be higher in cells with high vegetation cover as leopard presence would be reported more frequently in such grid cells, because we expected greater leopard occurrence in cells with higher NDVI (Table 1).

Habitat use states and model parameters

We used multi-state occupancy models to concurrently test our hypotheses about the predictors of leopard habitat use and predation on domestic animals (Nichols et al., 2007; Athreya et al., 2015). We interpret the parameter Ψ_1 as

estimated proportion of habitat use and parameter Ψ_2 as probability of depredation in sites with habitat use, rather than occupancy, because the size of the sample unit is small relative to the home range of leopards (MacKenzie et al., 2006; Zeller et al., 2011). We defined three discrete habitat-use and predation states in our detection matrix: unoccupied (state 0), occupied with no predation on domestic animals (state 1) and occupied with predation on domestic animals (state 2). For each interview survey, we recorded '0' when no leopard presence was reported, and '2' when one or more events of predation on domestic animals were reported. We recorded '1' when leopard presence was reported without mention of depredation. State 1 carries a level of uncertainty: it could either be a correct assignment (leopards present but not preying on domestic animals), or an incorrect assignment (actual situation is state 2, but respondent is unaware of depredation event).

Our multi-state occupancy model included five parameters (following Nichols et al., 2007). Ψ_1 is the probability of site use by leopards, regardless of whether or not predation on domestic animals occurs. Ψ_2 is the probability that depredation occurs, in the event that the site is used by leopards. The parameter p_1 is the probability of leopard presence being reported in cases where the true state is 1, and p_2 is the probability of leopard presence being reported where the true state is 2. The parameters p_1 and p_2 address state uncertainty because depredation events may or may not be reported in sites where leopards are present. We also estimated δ, which is the probability of finding evidence for leopard predation on domestic animals in cells where the true state is 2 (leopards are present and predating on livestock).

Data analysis

Prior to model-building, we tested for collinearity among the covariates, and found they were not correlated ($r < 0.5$). We adopted a two-step process to model the effects of covariates to estimate model parameters (Athreya et al., 2015). Firstly, we sought to explain variation in the detection process by modelling distance to forest and NDVI, by building 15 alternate models (covariates modelled singly, additively and a null model; Table 2). In this step, we used a global model for the parameters habitat use ($\Psi_{1\ ndvi+dog+goat+river+distoforest}$) and predation on domestic animals ($\Psi_{2\ ndvi+dog+goat+river+distoforest}$). We compared models using the Akaike information criterion adjusted for small sample size (AICc), to determine the optimal detection parameterization, which was retained in the next modelling step (Table 2).

In the second step, we tested our hypotheses about the spatial variation in leopard habitat use and predation on domestic animals. For this, we retained the covariate combination for detection parameters from the best supported model from the previous step, and tested our hypotheses

TABLE 2 Model results for detection parameters, p_1 (leopard detection probability) and p_2 (detection probability of predation on domestic animals). Two covariates *ndvi* and *distoforest* were modelled with global model $\Psi_1(dog+goat+ndvi+river+distoforest)$, $\Psi_2(dog+goat+ndvi+river+distoforest)$.

Model[1]	AICc[2]	ΔAICc[3]	Akaike weight	Model likelihood	No. of parameters	Deviance
$p_1(.), p_2(distoforest), \delta(.)$	516.39	0.00	0.25	1.00	16	476.94
$p_1(.), p_2(ndvi+distoforest), \delta(.)$	517.37	0.98	0.15	0.61	17	474.87
$p_1(distoforest), p_2(.), \delta(.)$	517.38	0.99	0.15	0.60	10	494.60
$p_1(distoforest), p_2(distoforest), \delta(.)$	517.62	1.22	0.13	0.54	17	475.86
$p_1(disstoforest), p_2(ndvi+distoforest), \delta(.)$	518.24	1.85	0.10	0.39	18	472.61
$p_1(ndvi), p_2(distoforest), \delta(.)$	518.36	1.97	0.09	0.37	17	475.86
$p_1(ndvi+distoforest), p_2(distoforest), \delta(.)$	520.61	4.21	0.03	0.12	18	474.97
$p_1(ndvi+distoforest), p_2(ndvi+distoforest), \delta(.)$	521.31	4.92	0.02	0.08	19	472.45
$p_1(.), p_2(ndvi), \delta(.)$	521.34	4.94	0.02	0.08	16	481.89
$p_1(ndvi), p_2(ndvi), \delta(.)$	532.27	5.26	0.01	0.07	17	479.15
$p_1(.), p_2(.), \delta(.)$	532.27	15.88	0.00	0.00	15	495.79
$p_1(ndvi), p_2(.), \delta(.)$	532.32	15.92	0.00	0.00	16	492.86
$p_1(distoforest), p_2(ndvi), \delta(.)$	535.10	18.71	0.00	0.00	17	492.60
$p_1(ndvi+distforest), p_2(.), \delta(.)$	535.20	18.80	0.00	0.00	17	492.70
$p_1(ndvi+distoforest), p_2(ndvi), \delta(.)$	536.91	20.52	0.00	0.00	18	491.28

[1]Covariates: *distoforest*, distance to nearest forest patch; *dog*, relative abundance of dogs; *goat*, relative abundance of goats; *ndvi*, normalized difference vegetation index; *river*, cumulative length of rivers in a grid cell.
[2]Akaike information criterion adjusted for small sample size.
[3]Difference in AICc to best performing model.

about factors influencing spatial variation on Ψ_1 and Ψ_2. We used a logit link function to assess model parameters as a function of covariates (Mackenzie et al., 2002). Nineteen alternate models were implemented to test our hypothesis.

We included covariates for Ψ_1 and Ψ_2 singly, or in additive combinations (see Table 3 for a complete list of models). Again we evaluated model support using AICc. Analysis was carried out in *MARK 8.0* (White, 2019).

TABLE 3 Model results for probabilities of leopard habitat use (Ψ_1) and predation on domestic animals (Ψ_2), based on a priori hypotheses. For all models, covariates *ndvi* and *distoforest* were used to explain variation in detection probability.

Model[1]	AICc[2]	ΔAICc[3]	Akaike weight	Model likelihood	No. of parameters	Deviance
$\Psi_1(dog+ndvi), \Psi_2(goat+river)$	513.68	0.00	0.19	1.00	13	482.89
$\Psi_1(dog+ndvi), \Psi_2(goat+dog)$	513.96	0.27	0.17	0.87	13	483.17
$\Psi_1(dog+ndvi), \Psi_2(goat+ndvi)$	514.29	0.60	0.14	0.74	13	483.50
$\Psi_1(dog+goat+ndvi), \Psi_2(goat+ndvi)$	514.87	1.18	0.10	0.55	14	481.27
$\Psi_1(dog+ndvi), \Psi_2(dog+goat+ndvi)$	515.50	1.81	0.08	0.40	14	481.90
$\Psi_1(dog+ndvi), \Psi_2(dog+goat+river)$	515.62	1.93	0.07	0.37	14	482.02
$\Psi_1(distoforest+river+ndvi), \Psi_2(goat+ndvi)$	516.06	2.37	0.06	0.30	14	482.46
$\Psi_1(dog+dog \times dog+ndvi), \Psi_2(goat+ndvi)$	516.81	3.12	0.04	0.20	14	483.21
$\Psi_1(dog+goat+ndvi), \Psi_2(dog+goat+ndvi)$	517.20	3.51	0.03	0.17	15	480.72
$\Psi_1(distoforest+river+ndvi), \Psi_2(goat+river+ndvi)$	517.58	3.89	0.02	0.14	15	481.09
$\Psi_1(dog+goat), \Psi_2(dog+goat)$	517.67	3.98	0.02	0.13	13	486.88
$\Psi_1(distoforest+river+ndvi+dog), \Psi_2(goat+river)$	519.83	6.14	0.00	0.04	15	483.34
$\Psi_1(distoforest+river+ndvi+dog+goat),$ $\Psi_2(distoforest+river+ndvi+dog+goat)$	521.31	7.62	0.00	0.02	19	472.45
Intercept only	521.56	7.87	0.00	0.01	9	501.31
$\Psi_1(distoforest+river+ndvi+dog), \Psi_2(dog+goat+ndvi)$	521.59	7.90	0.00	0.01	15	485.10
$\Psi_1(distoforest+ndvi), \Psi_2(distoforest+ndvi)$	523.57	9.88	0.00	0.00	13	492.78
$\Psi_1(river+ndvi), \Psi_2(river+ndvi)$	523.83	10.14	0.00	0.00	13	493.04
$\Psi_1(distoforest+river), \Psi_2(distoforest+ndvi)$	524.41	10.72	0.00	0.00	13	493.62
$\Psi_1(distoforest+river+ndvi), \Psi_2(distoforest+river+ndvi)$	525.38	11.69	0.00	0.00	15	488.89

[1]Covariates: *distoforest*, distance to nearest forest patch; *dog*, relative abundance of dogs; *goat*, relative abundance of goats; *ndvi*, normalized difference vegetation index; *river*, cumulative length of rivers in a grid cell.
[2]Akaike information criterion adjusted for small sample size.
[3]Difference in AICc to best performing model.

Results

We conducted interviews in 321 households in 90 grid cells, covering 10 municipalities within Kathmandu district. Sixty per cent of the respondents were farmers primarily dependent on agriculture, and others were engaged in livelihoods such as business and service in government institutions or private enterprises. Mean land holding size of respondents 0.12 ha (range 0–2.1 ha), and 69% of respondents identified themselves as middle class, with a monthly income of USD 100–300. Interviewees were aged 18–80 years, with a mean age of 39 years. Seventy-eight per cent of interviewees were men and 22% women.

The naïve probability of leopard habitat use was 63% and predation on domestic animals was recorded in 34% of the surveyed cells. Respondents reported leopard predation on goats (14% of respondents) and dogs (18%), but no human deaths or injuries. The reported losses resulting from depredation of goats were valued at a total of USD 5,790.

Amongst 15 candidate models to assess the influence of covariates on detection probabilities associated with p_1 (leopard detection probability when true state is 1) and p_2 (detection probability when true state is 2), eight models (with combination of covariates distance to forest and NDVI) accumulated $> 95\%$ Akaike weight (Table 2). Because both distance to forest and NDVI covariates appeared in the eight best supported models, the model carried forward into the next step of analysis included these covariates (additively) to address heterogeneity in p_1 and p_2. No single model was particularly well supported (Table 2). The model averaged estimate of p_1 was $0.28 \pm$ SE 0.09 and p_2 was $0.51 \pm$ SE 0.06. The model averaged estimate for δ (probability of finding evidence of leopard predation on domestic animals) was $0.46 \pm$ SE 0.05.

Of 19 candidate models run to estimate leopard habitat use with and without predation on domestic animals (Ψ_1 and Ψ_2), no single model was particularly well supported. The best model, $\Psi_1(dog+ndvi)$, $\Psi_2(goat+river)$, had 19% of the overall model weight. The additive covariates relative abundance of dogs and NDVI were associated with Ψ_1 in the six best supported models (which cumulatively accounted for $> 75\%$ of the overall support). For the parameter Ψ_2, the relative abundance of goats was associated with these top six models, in combination with one or more of the other covariates (dog abundance, river length and NDVI; Table 3). The model averaged estimate (across all 19 models) of Ψ_1 was $0.96 +$ SE 0.05, indicating near-ubiquitous leopard presence across the study area. The corresponding estimate for Ψ_2 was $0.76 +$ SE 0.15, indicating that depredation on domestic animals occurs in many cells with leopard use.

Given extensive leopard occurrence, none of the covariates in our models had statistically significant influence on the parameter Ψ_1 (MacKenzie et al., 2002; Table 4). The parameter Ψ_2 was positively associated with goat abundance $\hat{\beta} = 2.28 \pm$ SE 0.92. Probability of habitat use with predation increased when the goat encounter rate was > 4, and fell away steeply at lower values of this covariate (Fig. 2). Relative abundance of dogs and normalized difference vegetation index were positively associated with probability of livestock depredation in cells with leopard site use $\hat{\beta} = 0.70 \pm$ SE 0.57; $\hat{\beta} = 0.54 \pm$ SE 0.49, although there was considerable uncertainty in these estimates. River length and distance to forest did not have any discernible effect on the parameters Ψ_1 and Ψ_2 based on these data.

Discussion

Our finding that leopards occur extensively in areas with high human densities in Kathmandu district is of significance for a number of reasons. Firstly, it establishes that this leopard population is well adapted to exploiting farmlands and human settlements in a densely populated landscape, with near-ubiquitous occurrence over the study area. Our findings corroborate those of Athreya et al. (2013) from Maharashtra state in India, where leopards move extensively within an agricultural landscape. We note, however, that the Kathmandu valley is more densely populated than areas such as rural Maharashtra. Secondly, we ascertained that c. 76% of the area around Kathmandu city is subject to varying levels of leopard predation on domestic animals (Fig. 3). Remarkably, despite the widespread distribution of leopards, attacks on people are infrequent. Our findings, however, do suggest that leopards may use both adjacent forests and peri-urban habitats, where they prey upon domestic animals and gain access to additional food resources. This leads us to conjecture that leopards have a predilection to spend longer periods in these peri-urban areas.

We found that the relationship between leopard habitat use and relative abundance of dogs is variable. Although dogs attract leopards (Athreya et al., 2014), they may also repel leopards. Dogs in Kathmandu occur in a density of 5 animals/ha (Kakati, 2010) and our observations indicate that they generally form packs and live in clusters. An explanation for the possible ambiguity in the relationship between leopard habitat use and relative abundance of dogs could be that dog packs may detect and repel leopards away from human settlements. In addition, reporting of predation on stray dogs may be incomplete. More research is required to obtain robust, spatially explicit estimates of dog and leopard populations in the study area, and examine the interactions of these species in peri-urban areas.

Our research raises an important question: if leopards are widely distributed and frequently predate on dogs and goats, why are encounters between people and leopards rare in the Kathmandu valley? This is in contrast to some other areas of the Himalayas (Naha et al., 2018), where people have

TABLE 4 Estimates of β-coefficient values (with standard errors) for individual covariates associated with probabilities of leopard presence (Ψ_1) and predation on domestic animals (Ψ_2) for 19 models. For all models, covariates *ndvi* and *distoforest* were fixed with detection probabilities p_1 and p_2.

Model[1]	Ψ_1 (.) ± SE	Ψ_1 *dog* ± SE	Ψ_1 *goat* ± SE	Ψ_1 *ndvi* ± SE	Ψ_1 *river* ± SE	Ψ_1 *distoforest* ± SE	Ψ_2 (.) ± SE	Ψ_2 *dog* ± SE	Ψ_2 *goat* ± SE	Ψ_2 *ndvi* ± SE	Ψ_2 *river* ± SE
Ψ_1(*dog+ndvi*), Ψ_2 (*goat+river*)	3.45 ± 1.65	−1.02 ± 0.69		2.31 ± 1.34			0.78 ± 0.56		2.28 ± 0.92		−0.67 ± 0.48
Ψ_1(*dog+ndvi*), Ψ_2(*goat+dog*)	3.18 ± 1.27	−1.02 ± 0.63		2.19 ± 1.08			1.09 ± 0.59	0.70 ± 0.57	2.32 ± 0.93		
Ψ_1(*dog+ndvi*), Ψ_2(*goat+ndvi*)	3.75 ± 2.05	−1.09 ± 0.79		2.36 ± 1.51			0.84 ± 0.59		2.29 ± 0.97	0.54 ± 0.49	
Ψ_1(*dog+goat+ndvi*), Ψ_2(*goat+ndvi*)	4.05 ± 2.03	1.51 ± 1.21	0.90 ± 0.90	−1.33 ± 0.99			2.38 ± 1.41		4.47 ± 2.06	1.99 ± 0.91	
Ψ_1(*dog+ndvi*), Ψ_2(*dog+goat+ndvi*)	3.34 ± 1.47	−1.04 ± 0.67		2.25 ± 1.19			0.93 ± 0.59	0.69 ± 0.56	2.21 ± 0.93	0.53 ± 0.48	
Ψ_1(*dog+ndvi*), Ψ_2(*dog+goat+river*)	3.31 ± 1.45	−1.01 ± 0.65		2.27 ± 1.20			0.83 ± 0.56	0.49 ± 0.53	2.24 ± 0.89		−0.54 ± 0.51
Ψ_1(*distoforest+river+ndvi*), Ψ_2(*goat+ndvi*)	3.41 ± 1.98			0.53 ± 0.65	−0.04 ± 0.72	2.67 ± 2.69	4.13 ± 3.36		6.75 ± 4.76	2.47 ± 1.45	
Ψ_1(*dog+dog × dog+ndvi*), Ψ_2(*goat+ndvi*)	3.43 ± 1.75	−1.36 ± 1.05		2.29 ± 1.30			0.86 ± 0.59		2.26 ± 0.98	0.52 ± 0.49	
Ψ_1(*dog+goat+ndvi*), Ψ_2(*dog+goat+ndvi*)	3.36 ± 1.37	−0.99 ± 0.65	1.29 ± 1.28	1.87 ± 1.07			0.94 ± 0.59	0.74 ± 0.57	2.07 ± 0.91	0.49 ± 0.47	
Ψ_1(*distoforest+river+ndvi*), Ψ_2(*goat+river+ndvi*)	3.16 ± 1.88			0.58 ± 0.62	−0.02 ± 0.66	2.44 ± 2.60	3.90 ± 2.95		6.62 ± 4.39	2.23 ± 1.42	−0.97 ± 0.79
Ψ_1(*dog+goat*), Ψ_2(*dog+goat*)	2.41 ± 0.97	−0.53 ± 0.60	1.75 ± 1.16				1.21 ± 0.74	0.72 ± 0.71	2.06 ± 1.05		

[1]Covariates: *distoforest*, distance to nearest forest patch; *dog*, relative abundance of dogs; *goat*, relative abundance of goats; *ndvi*, normalized difference vegetation index; *river*, cumulative length of rivers in a grid cell.
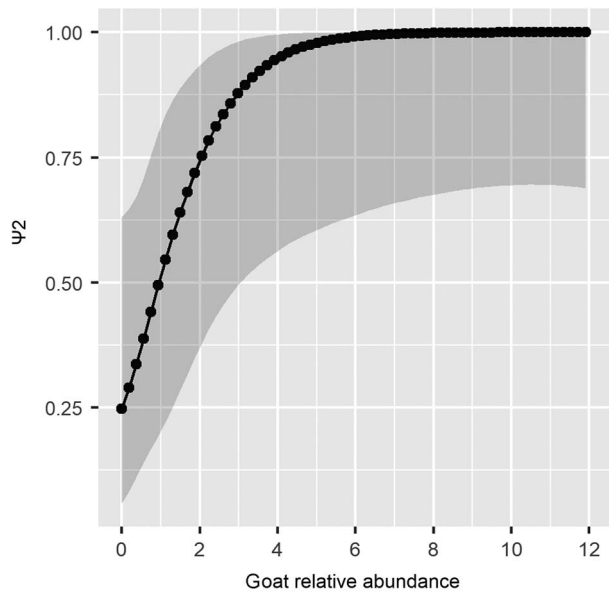
FIG. 2 Relationship between occurrence of predation (Ψ_2) and relative abundance of goats. The black dots and line show the mean value and the grey area represents the 95% CI.

FIG. 3 (a) Probability of habitat use of leopard in peri-urban Kathmandu within 2 km² survey grid cells, and (b) probability of occurrence of predation on domestic animals. These estimates are from the best-ranked model Ψ_1 (*dog+ndvi*), Ψ_2 (*goat+river*).

frequently been injured or killed by leopards. We posit that most settlements within our study area have amenities such as street lights and toilets within homes, which reduce close interaction between humans and leopards, even in shared spaces. Odden et al. (2014) reported that leopards adapt their behaviour to avoid humans, and predominantly use areas within settlements at night.

Leopard habitat use and predation on domestic animals in Kathmandu district also needs to be understood in the context of the ecology of predators and prey in the forests around the city. Forests in the mid-hills of Nepal generally support sparse populations of wild prey (Acharya et al., 2016), which may push leopards into human-dominated habitats where they can predate upon domestic animals with relative ease (Kabir et al., 2013). There is no information on the distribution and abundance of wild prey species of leopards in the Shivapuri-Nagarjun National Park and Kathmandu Forest Division. Carrying out a baseline assessment of prey and predator populations in this forest is thus a priority area for future research, to examine the proximate drivers of predation on domestic animals in the Kathmandu valley. Moreover, expansion of human settlements into wilderness areas increases spatial overlap between people and carnivores, and the risk of negative interactions (Woodroffe, 2000). Our research calls for urban planners to consider these factors when delineating plans for urban development in the Kathmandu valley, to limit encroachment of human settlements into natural habitats.

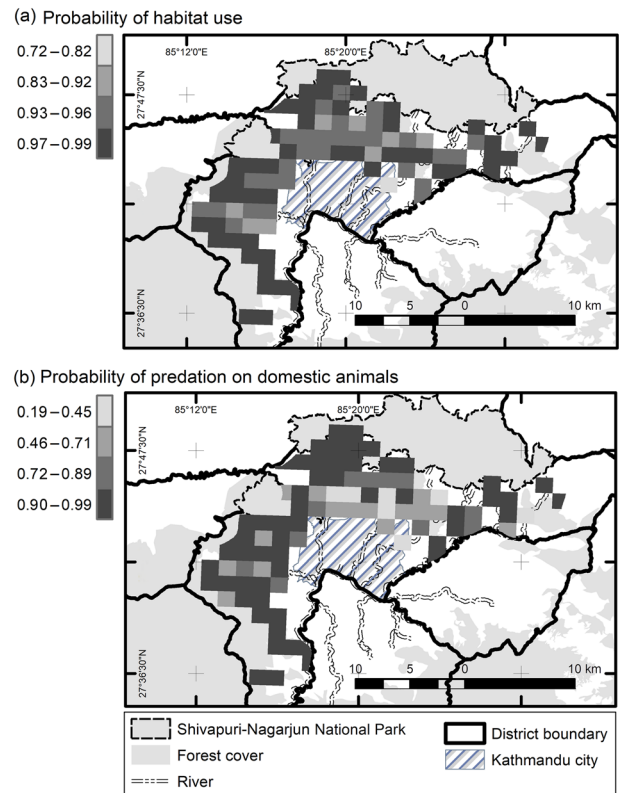A key limitation of our study is that it does not account for false positives in responses (leopard presence and predation on domestic animals may have been reported in areas where the true state was 0 or 1). This is because we do not have independent data sources (e.g. from camera traps or sign surveys) or information to differentiate between more and less reliable observers. False positives in the data can introduce bias in the parameter estimates (Royle & Link, 2006; Petracca et al., 2018). We note that our results are therefore preliminary, although it is common for occupancy surveys using interview data to not account for false positives, particularly when these are rapid surveys or studies carried out using modest budgets (Ghoshal et al., 2019; Srivathsa et al., 2019). Future studies should build on our initial work by combining sign surveys or camera trapping with interview data, to account for potential false positives. Robust estimates of dog abundance may be derived by rigorous sampling coupled with mark–resight models (Punjabi et al., 2012), in lieu of encounter rates.

Management and policy recommendations

Negative human–leopard interactions in Kathmandu district are an increasing problem. During our study period, leopards were captured and removed from three locations within urban areas. We anticipate that conflict may be

exacerbated by increasing human and livestock populations and progressive urbanization that may create ecological traps as the landscape is further fragmented. Thus comprehensive strategies are needed to mitigate conflict. We propose a two-pronged approach. Firstly, a framework is required for the systematic monitoring of leopards in the area, for which our study can serve as a template. Secondly, a comprehensive conflict mitigation plan should be created, including education and awareness programmes, control of free-ranging dogs (with monitoring to assess any potential unintended adverse effects such as increased predation on livestock), measures to prevent attacks on livestock (e.g. predator-proof corrals), compensation programmes and rapid response teams to ensure human and animal welfare in conflict-prone areas. These teams must include personnel trained in animal capture and crowd control. Careful deliberation is needed on whether and where captured leopards should be translocated (Athreya et al., 2011). Effective conflict mitigation planning and implementation of plans will require the collaboration of various stakeholders including government departments, veterinarians, ecologists and community representatives. Ultimately, plans will need to recognize that a strict separation of people and leopards may not be feasible in the Kathmandu valley, and they must therefore also include measures that enable coexistence in shared spaces.

Author contributions Study design and fieldwork: AB; data analysis: AB, PC; writing: AB; revisions: all authors.

Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards. We obtained verbal consent from each respondent before starting the interview.

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