



## RESEARCH ARTICLE

# Anthropogenic and environmental factors determine occupancy and rarity of large carnivores in the Omo Valley, southwest Ethiopia

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**Abstract**

1. Large carnivores in Ethiopia are declining in numbers and range due to human population pressure, habitat fragmentation and loss, compounded by low political interest for conservation. To conserve large carnivores, it is important to study the impact of these factors on their occupancy.
2. For this purpose, un-baited camera traps were deployed in Chebera Churchura, Maze and Omo National Parks and Tama Community Conservation Area using a 25 km<sup>2</sup> grid for 2-month periods in each Protected Area from 2020 to 2022. We tested the effects of environmental and anthropogenic covariates on carnivore occupancy while accounting for imperfect detection using a multispecies occupancy model.
3. We recorded all six large carnivores from Omo Valley. However, the number of large carnivores and their level of detection vary across the study sites; Omo National Park is the only Protected Area where all species were recorded.
4. Maze National Park had the highest number of lion detections and the lowest number of leopard and spotted hyaena detections, but its small size led to inconclusive results from any further analysis.
5. Due to low densities, detections were insufficient to analyse the occupancy of lion, cheetah, striped hyaena and African wild dog in Omo and Chebera Churchura National Parks and the occupancy of any large carnivores in Maze and Tama.
6. The mean marginal occupancy probability of the leopard was highest in Chebera Churchura and lowest in Omo, and this was the reverse for the spotted hyaena. The occupancy of the spotted hyaena and leopard was determined by prey in Omo and by elevation in Chebera Churchura National Parks. Furthermore, both species visit areas with human settlement in Omo and Chebera Churchura National Parks.

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7. *Practical implication:* We explore strategies to improve large carnivore conservation in the area. We highlight the limitations of camera trapping and the importance of conserving large carnivores in the larger landscape of Omo Valley.

#### KEYWORDS

camera trap, large carnivore, leopard, lion, Omo Valley, spotted hyaena

## 1 | INTRODUCTION

Current global species extinction rates are comparable to the five previous mass extinctions in the earth's history (Ceballos et al., 2015). Large carnivore species are among the most threatened mammals because of their wide-ranging behaviour, low densities and propensity for conflict (Ripple et al., 2014). For instance, all African large carnivores are declining in number and range (Wolf & Ripple, 2018) with African wild dogs (*Lycaon pictus*) and cheetahs (*Acinonyx jubatus*) listed as Endangered on the IUCN Red List (Durant et al., 2023; Woodroffe & Sillero-Zubiri, 2020), whereas lions (*Panthera leo*) and leopards (*P. pardus*) are listed as Vulnerable (Nicholson et al., 2023; Stein et al., 2017). While the precise ecological roles of carnivores have been a topic of recent debate and may vary depending on the context, they are widely recognized for shaping landscape structure and composition by regulating herbivore populations and affecting vegetation (Atkins et al., 2019; Ripple et al., 2014). They are also prominent in shaping sympatric carnivores in carnivore-rich ecosystems (Curveira-Santos et al., 2022). Considering their cascading ecological roles (Dickman et al., 2019), our study focused on understanding the ecological integrity of an ecologically and socially important but neglected landscape in eastern Africa.

Large carnivores in Ethiopia are patchily distributed and often found at low density (Yirga et al., 2021). Prey populations are declining, leading to further declining of large carnivore populations, except for spotted hyaenas (*Crocuta Crocuta*) which have adapted to anthropogenic landscapes (Yirga et al., 2012). Ethiopia's wildlife, by and large, is declining in numbers and range, due to human population pressure, fragmentation, urbanization and habitat loss, compounded by low political interest for wildlife conservation (Ethiopian Wildlife Conservation Authority, 2012; Gebresenbet et al., 2013). In a country like Ethiopia, pressure for land continues to increase, available habitat for wildlife is reduced and wide-ranging species like carnivores are vulnerable to edge effects (Kelboro & Stellmacher, 2015). The existing land use changes can restrict available habitat for many species, particularly wide-ranging large carnivores. Thus, to mitigate these threats and formulate meaningful large carnivore conservation strategies, there is a need for a better understanding of basic ecological parameters such as species occupancy, abundance and factors affecting it (Ethiopian Wildlife Conservation Authority, 2012).

In view of the fast habitat destruction in the country, occupancy studies on Ethiopian large carnivores are important and urgent to understand what influences the distribution of large carnivores. To date, few such studies have been conducted, with the notable exception of spotted hyaenas (Yirga et al., 2013). There are a few studies on human-wildlife conflicts in general (Eshete et al., 2017; Megaze et al., 2017) and on human-large carnivore interactions in specific (Gebresenbet et al., 2017, 2018; Yirga et al., 2021) from Ethiopia.

Southern Ethiopia is considered relatively intact, partially due to its remoteness and better Protected Area coverage. Despite its potential, we lack information on wildlife populations, habitats and threats, including large carnivore occupancy and factors affecting it. This is most acute in the most diverse ecosystem, the 12,924 km<sup>2</sup> Omo Valley. This biologically diverse region supports one of the largest concentrations of wildlife species in East Africa (Ghiglieri, 1981; Urban & Brown, 1968). Wildlife populations and natural habitats in the Omo Valley have been negatively affected by a combination of human activities, including cattle grazing, poaching, seasonal settlements and land use changes (Gil-Romera et al., 2011). The scale of the latter is particularly serious due to the development of the Omo-Kuraz sugar project (sugar cane plantations, sugar factories and a large canal) and the Gibes III and IV hydroelectric dam projects (Armaw & Molla, 2022). However, except for the study by Ghiglieri (1981) and Urban and Brown (1968) on the potential of the region in supporting wildlife populations, there is no empirical study conducted to elucidate the distribution of large carnivores in this region. Given the lack of information on the distribution of large carnivores in the area, we conducted a camera trap survey to analyse how the anthropogenic and natural factors influence large carnivore occupancy.

There are several practical applications of fundamental studies of large carnivore occupancy modelling using camera trap surveys. First, the occupancy model may help estimate the distribution and habitat use of large carnivores and their prey species, even in regions with limited data and with a prediction of long-term changes in natural habitats (Penjor et al., 2019; Rota et al., 2016). Second, this research may identify critical habitats and human-wildlife conflict hotspots, which can guide targeted conservation efforts, such as mitigation strategies to reduce human-wildlife conflicts (Penjor et al., 2019). Finally, understanding the spatial dynamics of large carnivores helps in designing protected area networks and corridors, ensuring connectivity and gene flow between populations.

We hypothesize that prey abundance, elevation, habitat type and human influence through settlements and large-scale infrastructure developments are the most important covariates of large carnivore occupancy in our study area.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area description

Our study was conducted in the watershed of the Omo River, between 35°28'00"–37°52'00" E and 5°53'00"–7°11'00" N. The Omo River flows south from the southern Ethiopian highlands to Lake Turkana in North Kenya. Despite growing human and livestock populations, recurring and severe ethnic conflicts have resulted in people avoiding a large area that has become a wildlife refuge (Engeman & Evangelista, 2007).

We conducted fieldworks in Omo National Park (ONP), Tama Community Conservation Area (TCCA), Maze NP (MNP) and Chebera Churchura NP (CCNP); these Protected Areas are not connected but are close to the Omo River (Figure 1). We could not work in Mago NP due to high levels of encroachment by armed and hostile people. It should be noted that protected areas in Ethiopia are generally

poorly developed, with low levels of infrastructure and law enforcement, and these parks all have considerable human activity inside and around them (Ethiopian Wildlife Conservation Authority, 2012).

Omo National Park covers 4068 km<sup>2</sup> and lies in the Lower Omo Valley through to the west of the main Rift Valley (Figure 1). Its main vegetation types include savanna grassland, riparian forest and deciduous woodlands (Armaw & Molla, 2022). ONP shelters 312 species of birds and 73 mammalian species (<https://ethiopian-elephants.com/omo-national-park/>, accessed 25/4/2023). However, most of the Park's area has been taken by Kuraz sugar factory, and the core habitat is destroyed for sugarcane plantation and to build factory and canal. Tama Wildlife Reserve was one of Ethiopia's wildlife reserves with no management intervention until Indigenous communities from the Lower Omo Valley took ownership and management responsibilities through the creation of the TCCA (Asfaw et al., 2023). The area covers a total of 1968 km<sup>2</sup> and became Ethiopia's largest community conservation area. MNP (210 km<sup>2</sup>) and CCNP (1410 km<sup>2</sup>) are in the Upper Omo Valley. CCNP is covered by wooded grassland, woodland, montane forest and riparian forest that harbour 134 bird species (Dereje, 2006) and 50 mammal species (Datiko & Bekele, 2013). MNP is dominated by savanna grassland with scattered deciduous broad-leaved trees and riverine forests along the main watercourses. This small protected

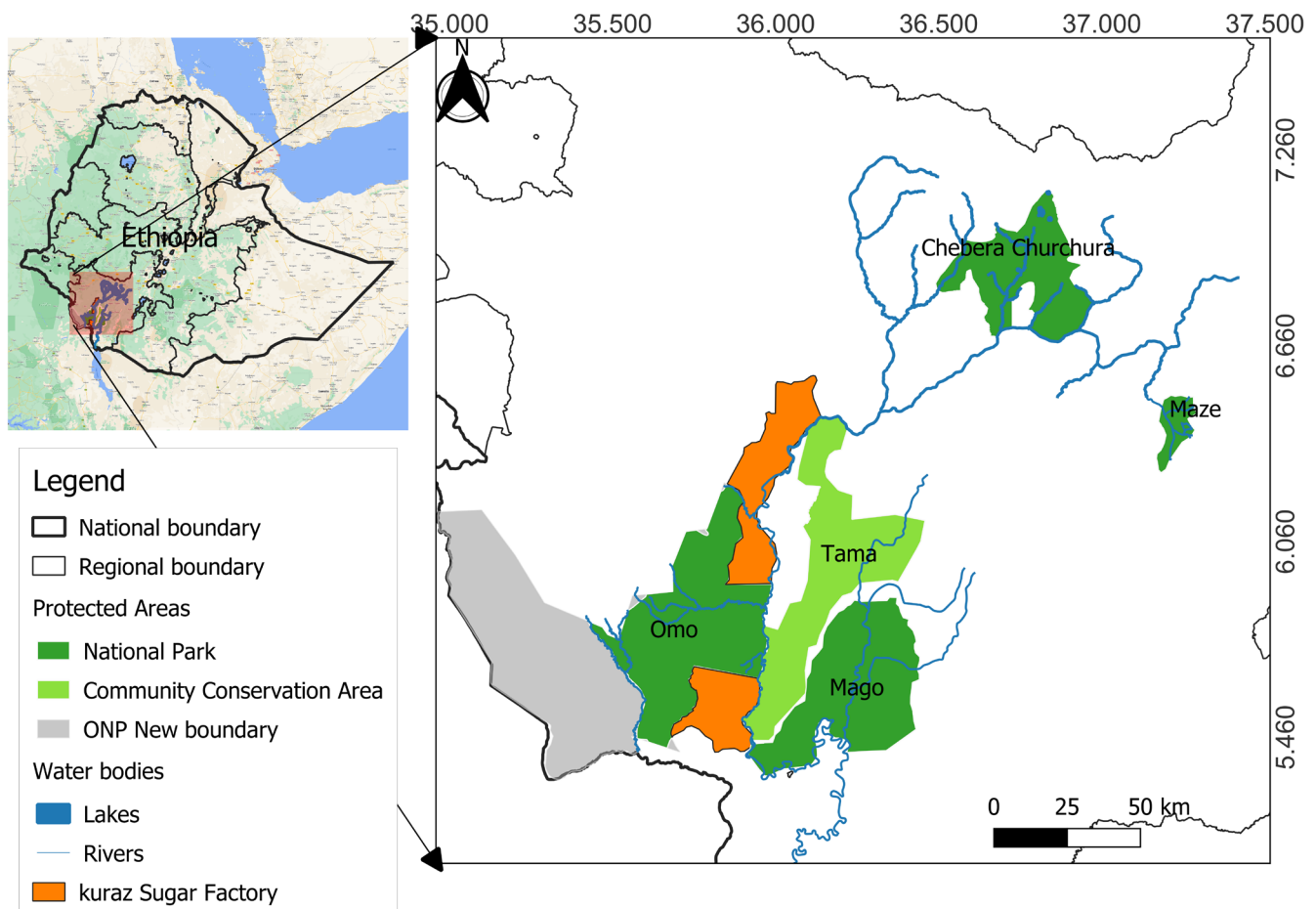


FIGURE 1 A map of the study area showing protected area borders (new and old) and Kuraz sugar factory.

area is home to 144 species of vascular plants (Siraj et al., 2017), 39 mammals and 196 bird species (Ethiopian Wildlife Conservation Authority, 2012).

## 2.2 | Camera trap surveys

Camera traps were deployed in CCNP, MNP, TCCA and ONP for a 2-month period each from 2020 to 2022. Grid size was informed by the home range sizes of large carnivores (Bauer & de longh, 2005; Penjor et al., 2019) but these are unknown for Ethiopia. We reviewed literature on home range size and found a large variation with estimates for male cheetahs from 494 to 849 km<sup>2</sup> on farmland and a game reserve in Botswana (Houser et al., 2009) to 11 and 23 km<sup>2</sup> in female cheetahs in Matusadona National Park, Zimbabwe (Purchase et al., 2017); lion 96–403 km<sup>2</sup> at Pendjari Biosphere Reserve, Benin (Sogbohossou, 2011) to 630 km<sup>2</sup> in Waza National Park (Bauer & de longh, 2005); leopard 26–66 km<sup>2</sup> in females to 42–108 km<sup>2</sup> in males (Simcharoen et al., 2008; Stein et al., 2011); African wild dog (150–3800 km<sup>2</sup>) (Fuller et al., 1992) and spotted hyaena (360–816 km<sup>2</sup>) (Gasaway et al., 1989; Tilson & Henschel, 1986). Since the density of medium and large prey species is low in Ethiopia (Bauer, 2016), we selected 25 km<sup>2</sup> as our camera trap grid size based on the least female home range size of a leopard.

We installed one un-baited camera trap in the centroid of every grid cell; in our study, camera trap is synonymous with the term camera station used by some authors. We put each camera station in a location with a feature that optimized detection (presence of water or wildlife spoor, absence of signs of anthropogenic activity) whenever possible. We mainly used the Bushnell Trophy Trail Camera 119717cw (Bushnell, California, USA), but in CCNP, we also used 3 Minox DTC 550 (Minox, Wetzlar, Germany), 2 Dorr Snapshot Trail Camera (DÖRR, Hamburg, Germany) and 9 Rollei WK 10 cameras (Rollei, Hamburg, Germany) and in MNP, 5 Rollei cameras. Cameras were left in the field for at least 60 continuous days, but the exact number of operation days was calculated for each camera separately based on the first and last pictures. We discarded camera locations that were inaccessible or near settlements to reduce the risk of camera loss, except in the smaller MNP where almost every grid cell was close to people and where we appointed guards to ensure the recovery of cameras. In total, 137 cameras (from 19 to 46 in each site) were placed and effectively retrieved. The mean distance between camera traps was 4.3 km in ONP, 4.5 km in MNP, 4.23 km in CCNP and 4.6 km in TCCA. After the cameras were retrieved, all wildlife images were identified to the species level. We used DigiKam software (<https://bugs.kde.org/>) for image tagging; image metadata extraction was performed using exiftoolr package in R studio (<https://exiftool.org>), and the camtrapR package (Niedballa et al., 2016) was used to efficiently organize and manage the larger datasets collected from camera traps in R studio. In compliance with ethical guidelines and to protect the privacy of individuals, all pictures of humans were deleted from our dataset.

## 2.3 | Covariates

We hypothesized that anthropogenic factors (livestock, sugar factories, human settlements and roads) and ecological factors (inter-specific interactions, prey availability, elevation, habitat and water) would influence the occupancy probability of large carnivores (Penjor et al., 2019). In ONP, we incorporated Euclidian distance to the Omo-Kuraz sugar factory, and in TCCA, we included distance to settlements in addition to the Omo-Kuraz sugar factory as an anthropogenic factor, and those related to habitat, prey and distance to river as ecological factors. In CCNP, distance to settlement was the anthropogenic factor, while habitat, elevation, prey abundance and distance to river were included as ecological covariates. In MNP, since there were significantly more human and livestock sightings in MNP, we considered distance to road and human disturbance (the abundance of livestock and number of local people photographed in camera traps) as anthropogenic factors, while habitat, prey abundance and elevation were considered as ecological factors.

Euclidean distance was calculated to generate distance to sugar factory, road and river covariates in ArcMap for each camera trap using ArcGIS (10.7, ESRI). For the prey covariate, we used the daily replicated counts of prey species in our camera traps and estimated abundance following Royle and Nichols (2003) to assess the effect of prey availability on the occupancy probability of large carnivores. Royle and Nichols (2003) propose a hierarchical model to estimate the abundance of species using repeated presence-absence data. This hierarchical modelling framework allows for more accurate estimation by accounting for imperfect detection and providing a robust method for linking prey availability to carnivore occupancy. Thus, using the hierarchical model, we estimate the abundance of prey species at each site as:

$$N_i \sim \text{Poisson}(\lambda_i), \quad (1)$$

where  $N_i$  is the abundance at site  $i$ , and  $\lambda_i$  is the expected abundance. Prey species were grouped into two size classes, following Bauer et al. (2008). Large prey (>200kg) included African buffalo (*Syncerus caffer*), common eland (*Tragelaphus oryx*), waterbuck (*Kobus ellipsiprymnus*), giant forest hog (*Hylochoerus meinertzhageni*) and greater kudu (*Tragelaphus strepsiceros*). Medium-sized prey (<200kg) included common warthog (*Phacochoerus africanus*), aardvark (*Orycteropus afer*), lesser kudu (*Tragelaphus imberbis*), bushpig (*Potamochoerus larvatus*), common duiker (*Sylvicapra grimmia*), grant's gazelle (*Nanger granti*), Guenther's dik-dik (*Madoqua guentheri*), klipspringer (*Oreotragus oreotragus*), olive baboon (*Papio anubis*), oribi (*Ourebia ourebi*), bushbuck (*Tragelaphus scriptus*) and topi (*Damaliscus lunatus*). We hypothesized that local habitat cover at each station may influence the probability of detection and occupancy probability of large carnivores; therefore, the major habitat type for each grid was derived from a 10m resolution land cover map raster layer (ESA, 2016) (<http://2020africallandcover20m.esrin.esa.int/download.php>, accessed March 11/2022) and assign for respective camera trap station using ArcGIS (Figure 2).

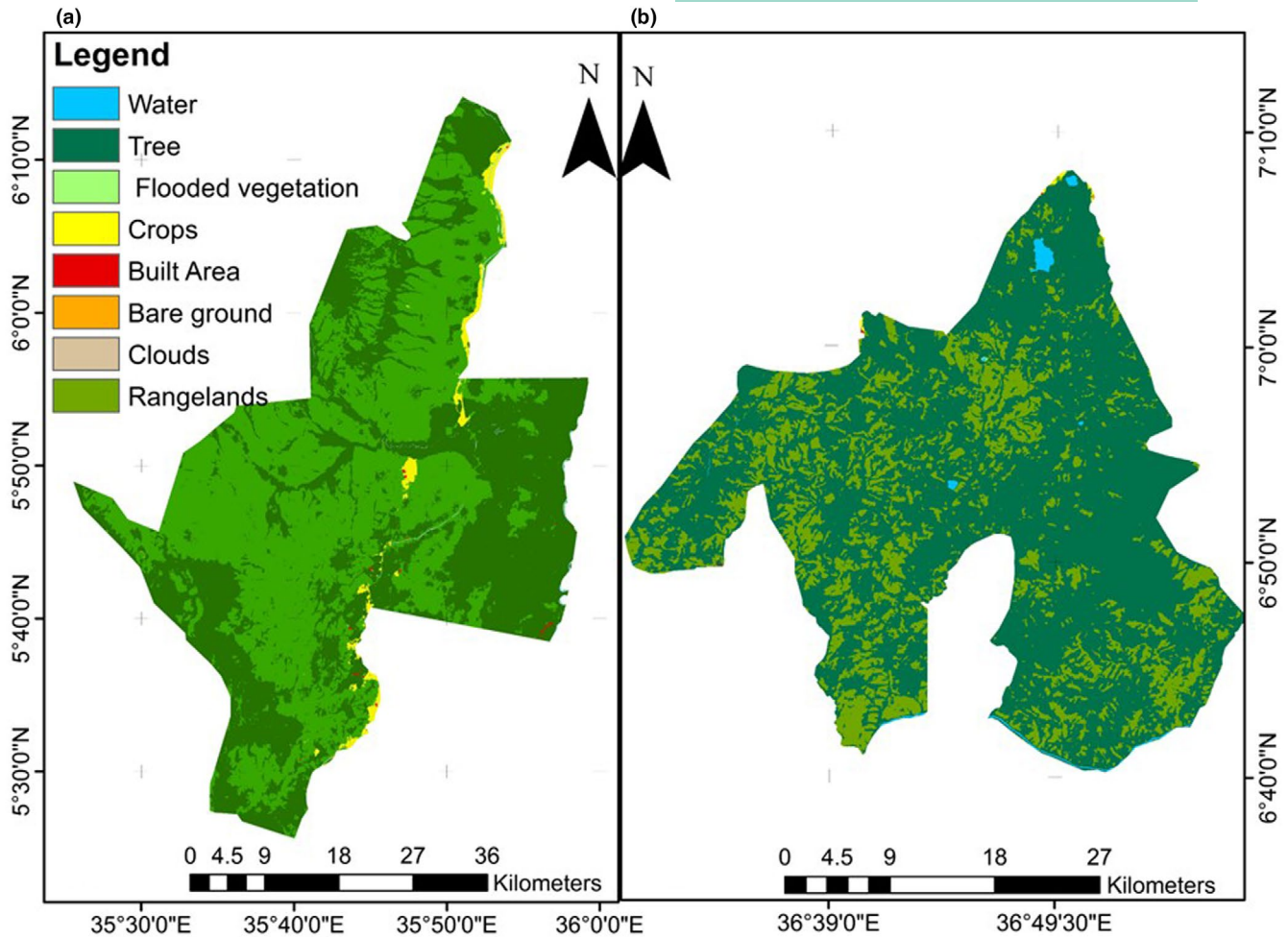


FIGURE 2 Land cover map of ONP (a) and CCNP (b). CCNP, Chebera Churchura NP; ONP, Omo National Park.

## 2.4 | Occupancy modelling

To reduce overdispersion in the data, detection ( $Y_{sit}=1$ ) and non-detection ( $Y_{sit}=0$ ) data (of carnivore  $s$ , at site  $i$ , during replicate survey  $t$ ) for each camera trap was recorded, modelled and binned into 3-day periods for CCNP and ONP and 5-day periods for MNP per sampling occasion to reduce the scatter-ness of the detection/non-detection data. This resulted in survey replicates of 5–40, 23–30 and 4–8 occasions per site, respectively. The occupancy probability of large carnivores at any one site during the study period were then modelled using a multispecies occupancy model following Rota et al. (2016). Prior to modelling, we tested for multicollinearity using Pearson's correlation and determined that covariates used in our models were independent and not correlated ( $r \leq |0.7|$ ) (Dormann et al., 2013).

The occupancy probability of large carnivores and their pairwise interaction were modelled as a function of site covariates and detection covariates at each site following a multispecies occupancy model by Rota et al. (2016) using the Unmarked package in R studio (Kellner, 2021). Rota et al. (2016) introduces a multispecies occupancy model that allows for the analysis of the presence or absence of multiple interacting species while accounting for environmental covariates. The model accounts for pairwise interactions among species and their

individual occupancy probabilities. For two species, the model parameters can be described as follows: Marginal occupancy probability for species 1  $\psi_1$  and species 2  $\psi_2$  can be expressed as:

$$\psi_1 = \text{logit}^{-1}(\beta_0 + \beta_1 \times x) \quad (2a)$$

and

$$\psi_2 = \text{logit}^{-1}(\gamma_0 + \gamma_1 \times x), \quad (2b)$$

where  $\beta_0$  and  $\gamma_0$  are the intercepts,  $\beta_1$  and  $\gamma_1$  are the coefficients for covariate  $x$  and  $\text{logit}^{-1}$  denotes the inverse logit function. Interaction parameter  $\varphi$  accounts for the interaction between the two species expressed as:

$$\varphi_{12} = \text{logit}^{-1}(\delta_0 + \delta_1 \times x), \quad (3)$$

where  $\delta_0$  is the intercept,  $\delta_1$  is the coefficient for covariate  $x$ . Joint occupancy probability  $\psi_{12}$  for both species occupying the same site can be expressed as:

$$\psi_{12} = \text{logit}^{-1}(\psi_1 \times \psi_2 \times \varphi_{12}). \quad (4)$$

To break the model, the result of the unpenalized multispecies model was fit into penalized multispecies models; we stored estimated slope coefficients and 95% confidence interval (CI) limits (Clipp et al., 2021). We ranked our models based on the Watanabe–Akaike information criterion (WAIC) (Hooten & Hobbs, 2015) and selected the models with low WAIC values. The relationship between covariates and occupancy probability was assessed from model coefficients produced by prior variance with the lowest WAIC score. We also compared the parameter estimates between penalized and unpenalized models using WAIC (lower WAIC values are preferred). Based on the best-fit model, marginal and conditional occupancy probabilities were then developed and illustrated. All the modelling and statistical analysis carried out in R programming language (R Core Team, 2022).

### 3 | RESULTS

#### 3.1 | Large carnivores recorded in the Omo Valley

We recorded six large carnivores from a total of 137 camera traps for a total effort of 10,301 trap nights (Table 1). However, the number of large carnivore species recorded and their level of detection vary across the study sites, with the highest detection and number of species in ONP and the lowest in MNP. We recorded 86 independent leopard observations from 25 stations and 123 independent spotted hyaena observations from 27 stations across the four sites; five striped hyaenas from three stations in ONP; 18 lions from six stations in ONP and MNP; six cheetahs from two stations in ONP; and one African wild dog from ONP (Table 1). The numbers of lion, cheetah and wild dog detections were too low to analyse the occupancy of the carnivores. Compared to ONP and CCNP, the number of lion detections was high in the much smaller MNP, but

we unfortunately had to exclude MNP from further analysis because the confidence interval for marginal occupancy probability of all large carnivores was too high (from 0 to 1). On the other hand, the low detection rates of leopards and spotted hyaenas in TCCA compelled us to exclude this area from further analysis. Therefore, henceforth we present the results for leopard and spotted hyaena from ONP and CCNP only.

#### 3.2 | Covariates in ONP

We recorded six large carnivores from 36 cameras from 8 May to 3 July 2021. Marginal occupancy (the occupancy without accounting for interactions with other species) was 0.09 (95% CI: 0–1) for lion, 0.07 (95% CI: 0–1) for cheetah, 0.33 (95% CI: 0.13–0.43) for spotted hyaena and 0.27 (95% CI: 0.2–0.5) for leopard. We retained all anthropogenic and environmental covariates in ONP because none of them showed significant collinearity (Pearson's value <0.04).

Model selection provided clear evidence of interspecific dependence among leopard and spotted hyaena, supported by our WAIC values (Table 2). Our top model is Model M6, where the occupancy of spotted hyaena varied as a function of the abundance of all prey species and distance to the Kuraz sugar factory, while leopard occupancy varied as a function of medium-sized prey abundance and distance to the Kuraz sugar factory; plus, pairwise dependence between these two species was constant. The remaining models were ranked  $\geq 19.77$   $\Delta$ WAIC units from model M6, giving weak support that occupancy probabilities were independent between species (model M1) or that the occupancy probabilities of spotted hyaena varied as a function of the presence/absence of leopard following different covariates (models M3, M4, M5, M7, M8 and M9). Therefore, hereafter we only report results from M6.

	ONP	CCNP	TCCA	MNP
Total trapping period	May–August 21	January–April 20	October–December 2022	January–March 21
Total number of cameras deployed	53	46	56	22
Total number of cameras retrieved	36	36	46	19
Number of operational cameras	36	36	40	13
No. nights (operational or not)	2799	3620	3312	717
No. active trap nights	2572	2814	2817	717
African wild dog	1	0	0	0
Cheetah	6	0	0	0
African lion	10	0	0	8
Leopard	43	38	1	2
Spotted hyaena	37	60		1
Striped hyaena	5	0	0	0

TABLE 1 Details of the camera trap survey and the number of large carnivore detections in the four National Parks.

Abbreviations: CCNP, Chebera Churchura NP; MNP, Maze NP; ONP, Omo National Park; TCCA, Tama Community Conservation Area.

TABLE 2 WAIC model rank in Omo and Chebera Churchura National Park.

	ONP				CCNP			
	nPars	AIC	$\Delta$ WAIC	WAIC	nPars	AIC	$\Delta$ WAIC	WAIC
M6	29	455.24	0	1	10	520.95	0	0.9900
M2	5	475.01	19.77	0.0001	5	533.73	12.78	0.0017
M1	4	484.29	29.05	0.0001	4	540.23	19.29	0.0001
M4	12	482.7	27.46	0.0000	14	926.17	405.22	0.0000
M7	20	486.04	30.8	0.0000	17	560.49	39.54	0.0000
M8	11	499.97	44.73	0.0000	10	537.3	16.35	0.0003
M3	21	506.73	51.49	0.0000	9	607.36	86.41	0.0000
M5	30	494.72	39.48	0.0000	13	559.98	39.04	0.0000
M9	9	563.13	107.89	0.0000	17	533.45	12.5	0.0019
M10					12	533.48	12.54	0.0019

Abbreviations: CCNP, Chebera Churchura NP; ONP, Omo National Park; WAIC, Watanabe–Akaike information criterion.

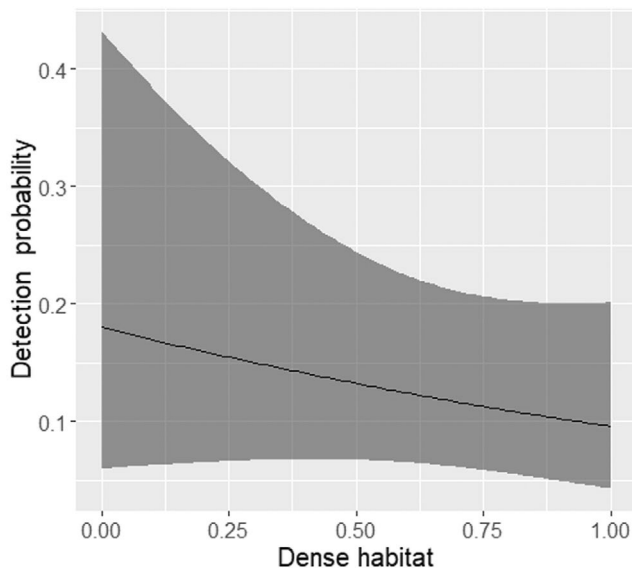


FIGURE 3 Daily detection probability of spotted hyaena in Omo National Park.

Based on the best-fit model, the daily detection probability of spotted hyaena was higher in wooded grassland habitat than in dense forest, while the model showed a constant detection probability for leopard (Figure 3). The model showed that marginal occupancy probabilities of spotted hyaena varied across different prey species' abundances; a strong positive association with grant's gazelle ( $\beta=4.5$ ;  $SE=1.5$ ;  $p=0.003$ ) and a strong negative association with bushbuck ( $\beta=-2.13$ ;  $SE=0.7$ ;  $p=0.0002$ ) and common eland ( $\beta=-2.4$ ;  $SE=0.9$ ;  $p=0.02$ ) (Table 3). Other prey species' abundances were weakly associated with the occupancy probability of spotted hyaena. Marginal occupancy probabilities of leopard were positively related to the availability of olive baboon ( $\beta=2.6$ ;  $SE=0.9$ ;  $p=0.005$ ) and guenther's dik-dik ( $\beta=2.3$ ;  $SE=0.8$ ;  $p=0.001$ ) and strongly negatively associated with bushbuck ( $\beta=-1.5$ ;  $SE=0.5$ ;  $p=0.0007$ ), oribi ( $\beta=-1.6$ ;  $SE=0.6$ ;  $p=0.0001$ ), common duiker ( $\beta=-2.2$ ;  $SE=0.7$ ;  $p=0.001$ ), topi ( $\beta=-1.8$ ;  $SE=0.6$ ;  $p=0.0002$ ) and grant's gazelle ( $\beta=-1.5$ ;  $SE=0.5$ ;  $p=0.006$ )

(Table 4). The marginal occupancy probability for both carnivores exhibited weak relationships with all of the anthropogenic disturbance variables we examined, except for the strong negative relationship between leopard and the distance to Kuraz sugar factory ( $\beta=-0.07$ ;  $SE=0.04$ ;  $p=0.04$ ) (Table 3). The result showed evidence of independent interactions between the two species. Occupancy probabilities of leopard were related mainly to prey abundance and distance to Kuraz sugar factory variables, and these did not vary markedly depending on whether spotted hyaena was present (Figures 4 and 5).

### 3.3 | Covariates in CCNP

Only three large carnivores (spotted hyaena, leopard and striped hyaena) were recorded from 36 camera traps during the end of January to the end of April 2020. The marginal occupancy of spotted hyaena and leopard was 0.21 (95% CI: 0.08–0.42) and 0.34 (95% CI: 0.16–0.55), respectively.

Model selection provided clear evidence of interspecific dependence among the two species considered, supported by our WAIC values. Our top model is Model M6, which assumed that habitat use of leopard and spotted hyaena was pairwise dependent and varied with elevation. The remaining models were ranked  $\geq 12.5$   $\Delta$ WAIC units apart from M6 (Table 2), indicating there was weak evidence that occupancy probabilities were independent between species (model M1) or that occupancy probabilities of either species varied with prey abundance (models M2, M3, M4, M5, M7, M8 and M9). Therefore, hereafter we report results from M6 only.

The daily detection probability of spotted hyaena was positively and strongly associated with dense habitat ( $p < 0.01$ ) while positively but weakly associated with the daily detection probability of leopard ( $p < 0.4$ ) (Table 4). The probability of occupancy by spotted hyaenas showed a strong negative association with elevation ( $\beta=-0.00177$ ;  $SE=0.000807$ ;  $p=0.028$ ) and a weak positive association with leopards ( $\beta=0.00$ ;  $SE=0.0.00$ ;  $p=0.9$ ). The mean marginal occupancy probability for spotted hyaena consistently

	<i>B</i>	SE	<i>z</i>	<i>p</i> (>  <i>z</i>  )
Occupancy				
[SH] African_Buffalo	1.0241	0.9397	1.09	2.76E-01
[SH] Bushback	-2.1278	0.6787	-3.135	1.72E-03***
[SH] Bush_Duiker	-0.6412	0.6508	-0.985	3.25E-01
[SH] Common_Warthog	1.1108	1.0799	1.029	3.04E-01
[SH] Eland	-2.3631	0.9797	-2.412	1.59E-02**
[SH] Grant_Gazelle	4.5143	1.5084	2.993	2.76E-03***
[SH] Gunther_dikdik	0.2303	0.9643	0.239	8.11E-01
[SH] Klipspringer	2.2606	1.3356	1.693	9.05E-02
[SH] Olive_Babbon	1.3947	1.278	1.091	2.75E-01
[SH] Waterbuck	1.2581	1.2244	1.028	3.04E-01
[SH] Lesser_kudu	1.1977	0.8846	1.354	1.76E-01
[SH] Oribi	-0.9175	0.9387	-0.977	3.28E-01
[SH] Topi	1.7087	1.0272	1.663	9.62E-02
[SH] Dist_to_Kuraz	0.0727	0.042	1.733	8.30E-02
[Leopard] (Intercept)	0.6939	1.0739	0.646	5.18E-01
[Leopard] Bushback	-2.7269	0.6797	-4.012	6.02E-05***
[Leopard] Topi	-1.8123	0.5774	-3.139	1.70E-03***
[Leopard] Bush_Duiker	-2.2412	0.7059	-3.175	1.50E-03***
[Leopard] Grant_Gazelle	-1.5157	0.5588	-2.712	6.68E-03***
[Leopard] Gunther_dikdik	2.3	0.8982	2.561	1.04E-02**
[Leopard] Klipspringer	-0.1449	0.6751	-0.215	8.30E-01
[Leopard] Olive_Babbon	2.6391	0.9323	2.831	4.65E-03***
[Leopard] Oribi	-1.5539	0.6315	-2.461	1.39E-02***
[Leopard] Dist_to_Kuraz	-0.0735	0.0364	-2.022	4.32E-02**
Detection				
[SH] (Intercept)	-1.956	0.348	-5.62	1.88E-08
[Leopard] (Intercept)	-2.572	0.506	-5.08	3.70E-07
[Leopard] Dense_habitat	0.713	0.611	1.17	2.43E-01

Note: Asterisks indicate statistically significant results.

declined with increasing levels of elevation (Figure 6) while leopard's mean marginal occupancy probability had a constant distribution across the elevation gradient (Figure 7). Occupancy of both species exhibited no strong relationship with any other ecological or anthropogenic disturbance variables. Constant pairwise inter-specific interactions are evident from the approximately parallel slopes presented in Figure 8, which also shows that the occupancy probabilities of leopard were related mainly to prey abundance variables.

## 4 | DISCUSSION

The Omo Valley is one of Ethiopia's prime conservation landscapes, characterized by diverse habitats and threats (Urban & Brown, 1968). Yet, due to its remote nature and lack of security, this is an area very difficult to work in. The existence of all the six large carnivores in the region indicated the importance of the landscape in the large

carnivore's conservation. However, lion, cheetah and wild dog detections were low, suggesting that these species are present at densities that are too low to make camera trapping a suitable method for their study.

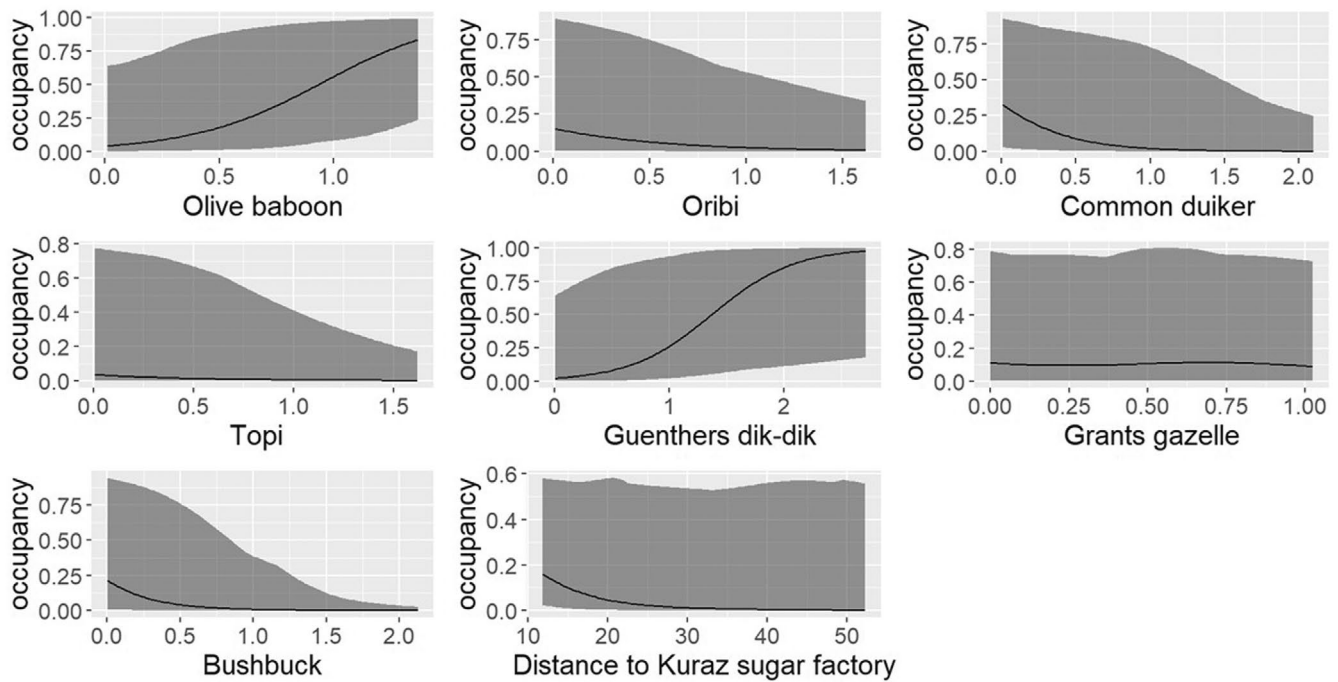
Our study indicated that the mean marginal occupancy probability of the leopard was highest in CCNP and lowest in ONP, and this was the reverse for the spotted hyaena. This might be due to the mountainous landscape of CCNP that provides an opportunity for the elusive nature of the leopard. Other studies found that rugged terrain positively influenced leopard occupancy in Chure, Nepal and in South Africa (Lamichhane et al., 2021; Swanepoel et al., 2013). The lower parts of CCNP, in contrast, had a higher spotted hyaena occupancy. Since the less mountainous areas of CCNP are occupied by human settlements, this is consistent with observations across Ethiopia that spotted hyaenas prefer human-dominated landscapes (Yirga et al., 2013). Nonetheless, the marginal occupancy probability of both the spotted hyaena and the leopard exhibited weak relationships with all anthropogenic and

TABLE 3 Coefficient estimates ( $\beta$ ), standard error, *z* score and *p* value on the probability of habitat use and detection for spotted hyaena and leopard in ONP based on model M6.

**TABLE 4** Coefficient estimates ( $\beta$ ), standard error, z score and p value on the probability of occupancy and detection for spotted hyaena and leopard in Chebera Churchura National Park based on model M6.

	<i>B</i>	SE	<i>z</i>	<i>p</i> (>  <i>z</i>  )
Probability of habitat use ( $\Psi$ )				
[Hyaena] (Intercept)	0.688885	0.351159	1.962	0.0498
[Hyaena] Elevation	-0.00177	0.000807	-2.197	0.028**
[Leopard] (Intercept)	-0.7384	0.474644	-1.556	0.1198
[Leopard] Elevation	0.000121	0.000794	0.152	0.879
[Hyaena: Leopard] (Intercept)	0.025591	0.149457	0.171	0.864
[Hyaena: Leopard] Elevation	0.000405	0.00186	0.218	0.8275
Detection probability ( $P_i$ )				
[Hyaena] (Intercept)	-2.627	0.589	-4.459	8.22E-06
[Hyaena] Habitat	1.677	0.652	2.573	1.01E-02**
[Leopard] (Intercept)	-2.55	0.743	-3.431	6.01E-04
[Leopard] Habitat	0.585	0.772	0.757	4.49E-01

Note: Asterisk indicates the level of statistical significance of the result.



**FIGURE 4** Marginal probability of leopard in the Omo National Park as a function of different prey species abundances and distance to Kuraz sugar factory.

ecological (except for elevation) factors we examined in CCNP. In ONP, we identified medium-sized prey species availability (olive baboon and Guenther's dik-dik for leopard; Grant's gazelle for spotted hyaena) as positive and distance to Kuraz sugar factory as negative determinants. Our findings concur with literature that medium-sized prey items form an important prey source for leopards and spotted hyaenas (Clements et al., 2014; Hayward, 2006; Hayward et al., 2006).

Both ecological and anthropogenic factors influenced the occupancy of leopard and spotted hyaena in the Omo Valley, as predicted. Our findings show that conservation of medium-sized prey species such as Grant's gazelle, olive baboon and Guenther's

dik-dik is critical for leopards and spotted hyaena in ONP, as also reported by Crooks et al. (2011). On the other hand, this study highlights that both leopard and spotted hyaena potentially visit human-settlement areas in CCNP and Kuraz sugar factory in ONP, thus increasing the interface and possibly human-wildlife conflict. Large carnivores, especially leopards, occupying anthropogenic landscapes frequently come into conflict with humans, which often results in leopard mortality and human-wildlife conflict (Crooks et al., 2011). Conflict is indeed a predictable outcome of the overlap between leopards, spotted hyaena, people and livestock, and this finding underscores the need for further research to understand the underlying causes and dynamics of

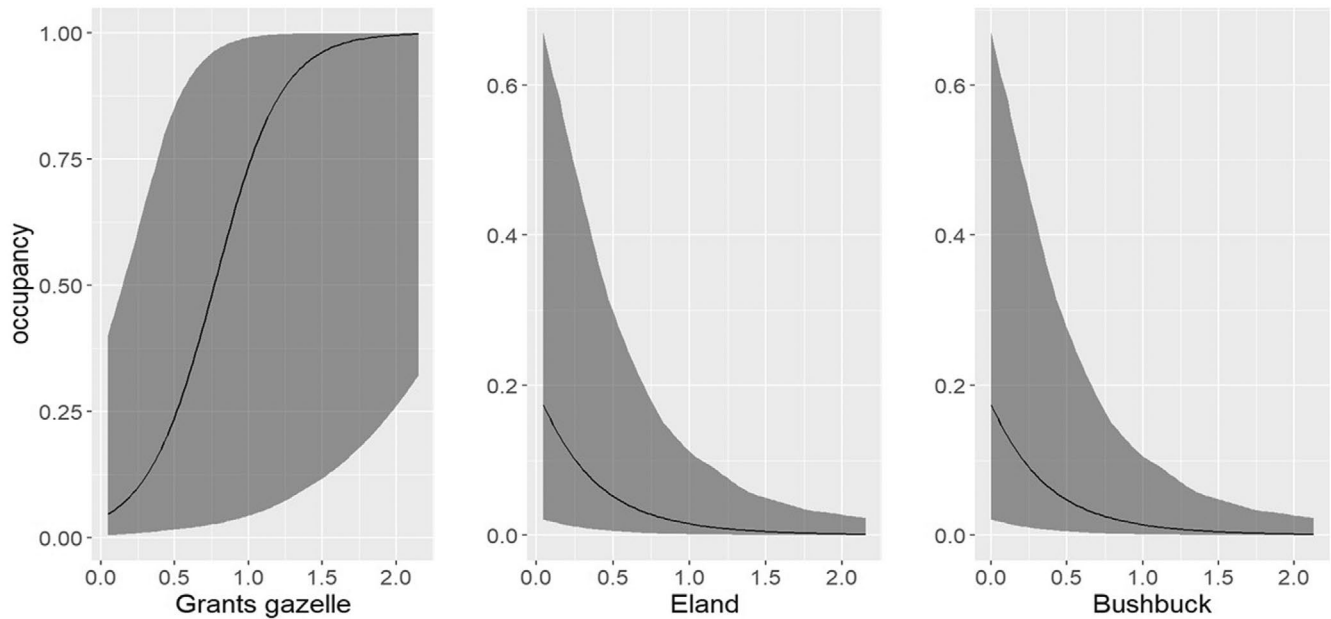


FIGURE 5 Marginal probability occupancy of spotted hyaena in the Omo National Park as a function of different prey species abundances.

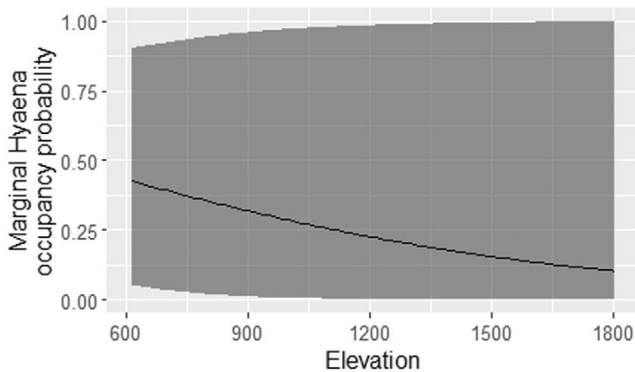


FIGURE 6 Marginal occupancy probability of spotted hyaena in the Chebera Churchura National Park as a function of elevation.

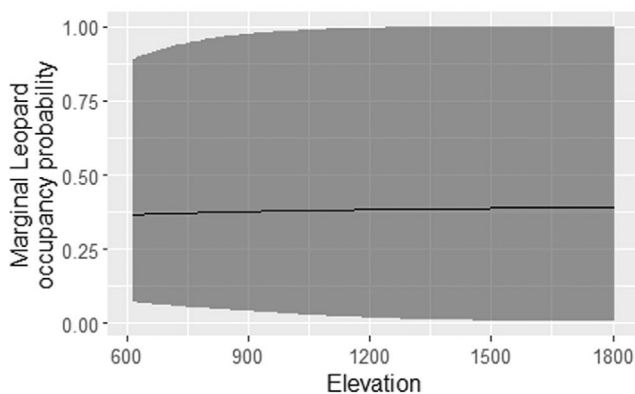


FIGURE 7 Marginal occupancy probability of leopard in the Chebera Churchura National Park as a function of elevation.

these conflicts. Human-wildlife conflicts, particularly involving large carnivores, can lead to significant economic losses for local communities and can result in retaliatory killings of wildlife, which

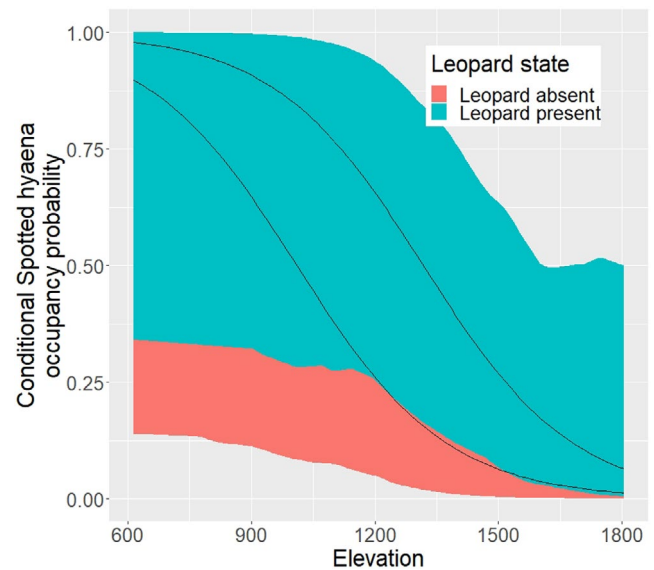


FIGURE 8 Occupancy probability of leopard conditional on the presence and absence of spotted hyaena as a function of Elevation in Chebera Churchura National Park.

further threatens their conservation status (Bauer et al., 2020; Yirga et al., 2021). Besides, our study showed the ongoing Kuraz Sugar Factory brought a negative impact for the conservation of wildlife by increasing the interface between humans and wildlife. Therefore, it is crucial to design proper land use management before we carry out any developmental project in and around protected areas. TCCA supports very few large carnivores while supporting a large density of ungulates. This also needs further study to understand why the density of large carnivores is below detection level. However, this could indirectly predict a high level of retaliatory killings of large carnivores in the area, following the

increased interface of large carnivores with local communities; this requires further study.

MNP, although small, had the highest number of lion detections and holds the bigger of only two existing populations of the endemic Swayne's hartebeest (Tekalign & Bekele, 2011). However, the success of this area appears to be mainly due to the nature-friendly attitudes of the local communities (Tekalign & Bekele, 2016; Pers. Obs.), and this requires further research. MNP is probably connected to CCNP through an impenetrable valley. Ecological connectivity is necessary for effective ecosystem functionality and is key for the survival of large carnivores and other wildlife by ensuring genetic diversity. However, no studies were conducted to evaluate the level of connectivity in the bigger landscape of the Omo Valley. It is therefore very important to further investigate the landscape connectivity of different protected areas in the Omo Valley.

Regardless of the factors affecting the two species' occupancy, the occupancy probability of the spotted hyaena did not change with the presence or absence of leopards in both parks. This suggests that leopards were able to coexist with the spotted hyaena. However, our results should be viewed with caution because the 95% CIs of the naïve occupancy were high. However, our main conclusion follows the recommendation to also report 'failures' in environmental science (Wood, 2020), namely the unusefulness of camera trap surveys to measure the occupancy of lions, cheetahs and African wild dogs in areas with very low densities of these species. As these species are at the top of the food chain, we caution against the notion that the Omo Valley is still a pristine wilderness with high concentrations of wildlife and call for increased efforts to conserve what is left.

The camera trap spacing we followed in this study works for leopard and potentially for spotted hyaena and cheetah, but we combine four grids in one to avoid the risk of deploying more than one camera station per lion and African wild dog home range. Although we have pooled grid cells to ensure the assumption of independence between sites (Mackenzie et al., 2005), we ended up not analysing occupancy for these species. Previous work also showed lion densities to be too low to be estimated with calling stations (Yirga et al., 2021), and we suggest future work to include different methods such as genomics (Bertola et al., 2022), collaring and spatially explicit capture–recapture (Royle & Young, 2008; Shams et al., 2024).

The camera trap survey was conducted after the main rainy season, when people and livestock incursions are lower as grass and water are widely available, to lower the probability of losing our camera traps. As a result, our data on the impact of human density and livestock abundance on the occupancy of large carnivores may not be representative of the situation later in the year. However, even during our study, we found effects of anthropogenic activity on large carnivore occupancy measured by distance from camera trap stations to settlements in CCNP and distance to Kuraz sugar factory and road in ONP.

In general, large carnivores are indispensable for the ecological integrity of the Omo Valley. The deficiency in data on these species

hinders effective conservation strategies. Our occupancy models partially filled this gap by providing valuable insights into the factors affecting large carnivore occupancy and into human–wildlife conflict in the area, despite limitations imposed by low detection rates. The identification of potential human–wildlife conflicts from our study highlights the need for continued research and adaptive management. We recommend integrating these findings into specific park management guidelines to develop more effective and sustainable conservation strategies that address both wildlife conservation and the livelihoods of local communities. Future research should also continue to explore the nature of these conflicts to inform adaptive management practices.

## AUTHOR CONTRIBUTIONS

Tsyon Asfaw conceived the idea and designed the methodology; Fikirte Gebresenbet, Hans Bauer and Tsyon Asfaw contributed to the acquisition of funding. Tsyon Asfaw and Hans Bauer collected the data. Tsyon Asfaw analysed and interpreted the data; Tsyon Asfaw led the writing of the manuscript. All authors checked the findings of this work and contributed critically to earlier drafts for important intellectual content and gave final approval for publication.

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## CONFLICT OF INTEREST STATEMENT

All authors declared that they have no conflicts of interest.

## PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70019>.

## DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.nk98sf83t> (Asfaw et al., 2025).

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